Use of heterogeneous fuel assemblies in the modular sodium-cooled fast reactor core

Ya.A. Kotov, P.N. Alekseev

National Research Centre “Kurchatov Institute”, Moscow, Russia

E-mail contact of main author: yaroslav.kotov@hotmail.com

Abstract: This paper presents computational neutronic data pertinent to a modular sodium-cooled fast reactor core consisting of jacketless heterogeneous fuel assemblies. With regard to neutronic parameters, the metallic uranium-plutonium-zirconium fuel is the most preferable – among known advanced fuels – for fast sodium-cooled reactor applications. Due to the absence of light nuclei, this fuel provides higher in-core amounts of fertile heavy nuclei and harder neutron spectra compared to other fuel types. However, the metallic fuel has not yet accumulated enough operating experience to allow for its industrial application. Use of heterogeneous fuel assemblies consisting of rods made of mixed oxide fuel (with Pu content <30%) combined with those made of either depleted metallic U or its alloy enables much higher intra-assembly fertile nuclei concentrations (compared to homogeneous MOX assemblies) that are close to those pertaining to homogeneous U-Pu-Zr fuel assemblies. The studies hereof compare heterogeneous assemblies consisting of MOX fuel rods plus those made of either depleted metallic U or metallic U-Zr alloy to homogeneous assemblies made of metallic U-Pu-Zr fuel. Use of Pu-free U-Zr alloy in fresh fuel assemblies – combined with this alloy’s relatively low burnup in spent assemblies – relieves the requirements applicable to metallic fuel and allows its operational licensing to be expected in the near term. Heterogeneous assemblies with oxide/metallic fuel may be at least an intermediate fuel option while shifting to the metal core – or even become a final choice, provided that they perform better than homogeneous metallic U-Pu-Zr assemblies.

Keywords: small modular reactor (SMR), metal(lic) fuel, fast reactor, intra-assembly heterogeneity

1. Introduction

This paper dwells on the prospects of advanced fuel applicationы with regard to the innovative small modular sodium-cooled fast reactor design.

Presently there is a growing interest worldwide to modular nuclear construction and to small and medium reactors that may open new markets and offer multiple advantages as concerns their safety, economy, nonproliferation and siting in remote areas or very close to consumers. Their small capacity enables serial factory fabrication of modules and accelerates NPP construction, thus considerably reducing loan interests; it also facilitates the decay heat removal – or makes it possible to organize it on passive principles. It is a common opinion that – as regards their fuel efficiency and breeding potential – SMRs would lose to conventional large reactors (this factor may become important in future due to depleted resources of cheap natural U). However, with flatter cores and advanced solutions currently implemented in large reactors, their difference from small ones may turn out to be not so large.

Compared to fast SMR designs (such as PRISM [1], 4S [1] etc.), the concept hereof – besides achieving higher safety and economic efficiency – puts a special emphasis on optimizing fuel efficiency, as well as enabling high breeding ratio and efficient operation together with thermal reactors within the fuel cycle, in compliance with the sustainable nuclear energy system development strategy.

Small cores combined with fast neutron spectra yield more escaping neutrons. This would certainly require more fuel to be loaded into the core to turn it critical, and would negatively affect the accumulation of radiation defects and the activation of structural materials surrounding the core. At the same time, the fast neutron flux escaping from the core could become useful and allow for high excess fuel breeding, provided that the core is surrounded with blankets. Shifting to dense fuel is one of the ways to reduce the neutron leak from the core, as well as its specific fuel load. The core geometry also influences neutron leaks considerably. To reduce the void reactivity effect, most sodium-cooled fast reactor designs feature flatter cores; however, for small reactors the core flattening is not so relevant. In terms of SMR efficiency and safety, good parameters can be obtained by varying the core geometry with account of void reactivity effects.

Proceeding from the above suggestions and requirements, this paper offers a small modular sodium-cooled fast reactor concept intended for efficient operation within the closed fuel cycle together with thermal reactors. Parametric optimization was performed to identify the optimal capacity range, best materials, structural arrangement and core configuration. The main focus hereof is on fuel selection for this reactor concept, since it’s the highly heat-conductive dense fuel that underlies many of advantages this reactor offers.

From all advanced fast reactor fuels known today, there are three mixed U-Pu fuel options – namely nitride, carbide and metallic Zr alloy – that seem potentially suitable at the moment. However, the nitride fuel yields insufficient burnup, since it swells and rods get depressurized when fuel pellets contact the cladding [2]. The carbide fuel has fabrication and processing issues, and also requires fuel cladding to be made of special steels (or coated) to prevent carbonization [2]. Though free from the above issues, the metal alloy has low melting temperature – and the temperature of its contact with fuel cladding is also limited to make this metallic fuel compatible with steels [3, 4] – but these disadvantages are offset by factors such as its high heat conductivity and absence of light nuclei that harden its neutron spectrum and improve its breeding properties. Since the reactor concept hereof is tailored for operation within the closed fuel cycle, yet another key advantage of the metallic fuel is the possibility to: use U, Pu and minor actinides combined; use dry reprocessing methods; robotize fuel fabrication in case of multiple recycling; and produce high average burnup (over 16% [2]).

2. Description of reactor concept

The study of the fast small reactor with dense fuel has identified the optimal capacity range for this SMR and offered the option – namely the small reactor of 410 MWt (about 180 MWe) capacity – meeting the relevant system requirements and estimated safety criteria. Its core consists of three groups of fuel assemblies that have two optional compositions: the central zone with its assemblies equipped with central control rods; the medium zone, whose assemblies are made of rods similar to those of the central one, but have no control rod guide channels; and the peripheral zone, whose fuel contains much Pu. Civil-grade plutonium from spent VVER fuel was chosen as the main fuel option, while radial and axial blankets were assumed to contain thorium dioxide to allow for excess breeding of U-233 as makeup fuel for thermal reactors.

The capacity and size of this reactor were also selected so as to enable its railway transportation in assembled condition, as well as passive decay heat removal through the reactor vessel.

Assuming its average fuel burnup to equal the amount of fertile nuclides in fresh fuel, this reactor option meets the fuel efficiency criteria – i.e.: low specific content of fissile isotopes and high breeding efficiency – that comply with system requirements of sustainable nuclear energy development, INPRO recommendations and criteria adopted with regard to Generation-4 reactor technologies.

3. Possible alternative to dense fuel

Insufficient operational practice is the main issue of the metallic fuel the concept discussed hereof is based on. Currently this fuel was selected as either the basic or optional one for small and medium reactor designs being developed, namely KALIMER, MDP, PEACER-300, PRISM, 4S, JSFR and others [5].

In 1970-80ies, this fuel has been studied in Los-Alamos [3] and Argonne [6] National Laboratories in the United States, in RIAR [7] (Dimitrovgrad) in the Soviet Union, and in some other countries. After the fast reactors became a matter of interest, India and South Korea have launched these studies and are pursuing them now. However, until today, the metallic U-Pu-Zr fuel has been used for research purposes only. Assessing the pace and scope of works intended to license commercial application of metallic fuel, one may expect the metallic U-Zr fuel without initial Pu content to be tested first. At the moment (and in the near term) the basic, most developed and already licensed fast reactor fuel type is MOX – $(U\text{-}Pu)O_2$ fuel, whose industrial fabrication technology is already proven. This fuel has low mass density and two light nuclei per single heavy one.

In-core density of fertile isotopes can be increased by using these two fuel types together, e.g. within the same assembly to make it heterogeneous (i.e. to create so-called intra-assembly heterogeneity). Efficient density of an assembly consisting of two-thirds of MOX (fueling) and one-third of dense metallic (breeding) rods would be only <18% below that of a homogeneous metallic assembly with rods of similar diameter. This difference can be further reduced by increasing the breeding rod diameter as far, as thermohydraulic limitations allow. Besides high fuel density within the core, this would separate fertile isotopes from fuel ones, thus enabling higher breeding rate and separate reprocessing of isotopes. U-Zr fuel fabrication requires neither complex equipment, nor hot cells, and is much simpler than fabrication of U-Pu-Zr rods. Moreover, the preset initial porosity of U-Zr fuel may be lower because of its lower burnup. Spent U-Zr fuel reprocessing could use both advanced and available technologies without increasing the dose burden on reprocessing enterprises due to high burnup or high Pu content. Use of breeding rods with larger diameter in heterogeneous assemblies can yield almost the same effective density of heavy isotopes as that yielded by homogeneous metallic assemblies.

As mentioned above, MOX is a well-known fuel with extensive experience of operation in fast reactors, and relevant studies confirm that it could yield the highest burnup of above 15% of heavy atoms [2]. At the same time, Pu content in the MOX is limited by the level, which, if exceeded, would produce negative migration effects and metallic plutonium zones within a fuel pellet [2]. This fact may also limit the extension of breeding rod diameter.

4. Neutronic computations

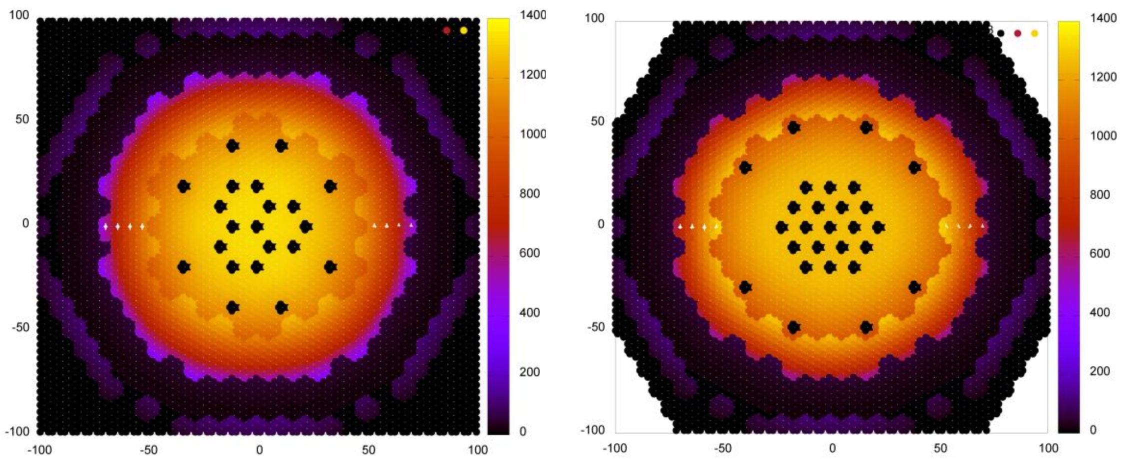
The JARFR code [8] based on diffusion approximation and licensed for fast reactor computations was selected for multivariate computations required for this study. To confirm the JARFR applicability, benchmark computations (Benchmark for Neutronic Analysis of Sodium-cooled Fast Reactor Cores with Various Fuel Types and Core Sizes, [9]) were also performed. The resulting computational models were validated using the codes based on the Monte-Carlo method.

First, the computations were performed for homogeneous fuel cores to identify their macroparameters and to assess the plutonium share required for fueling rods to turn critical.

Since the conventional power flattening by using fueling rods with different Pu shares yielded the Pu content in UO_2 in the peripheral zone above its highest admissible share, variative computations were performed to enable power flattening with account of this limitation. Since fuel assemblies consist of two rod types, by varying respective volumetric shares of fuel one may change the diameters of fueling and breeding rods both together and separately. According to thermohydraulic computations performed, further thickening of fueling rods that have low heat conductivity would lead to adverse reduction of the maximum temperature margin and to possible fuel meltdown in accident cases. At the same time, the main factor limiting the thickening of breeding rods is the sodium flow area that has a certain margin.

Proceeding from the results obtained, for radial flattening of the power field it was decided to use fueling rods with variable Pu content and breeding rods with different diameters in the central and peripheral assemblies, in combination with assembly positioning changed so as to extend the peripheral zone. This approach also has a disadvantage – variable breeding-to-fueling-isotope ratio in different zones produces additional breeding rate non-uniformity that may considerably change the in-core power distribution in the process of burnup. The final scenario hereof accounts for this effect.

Hence, the radial power peaking factor Kr=1.26 was achieved for heterogeneous assemblies (the highest value over the micro-cycle, Fig. 1a) compared to the initial homogeneous metallic assemblies that yielded Kr=1.21 (Fig. 1b).



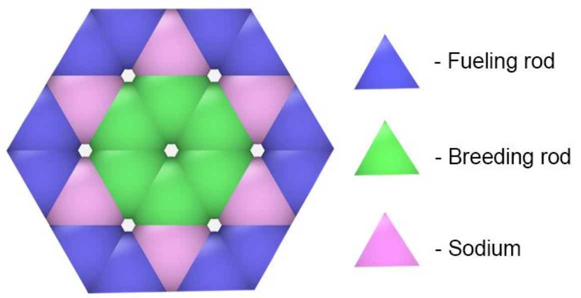
a) b)

Fig. 1. Power distribution in heterogeneous (a) and homogeneous metallic (b) core

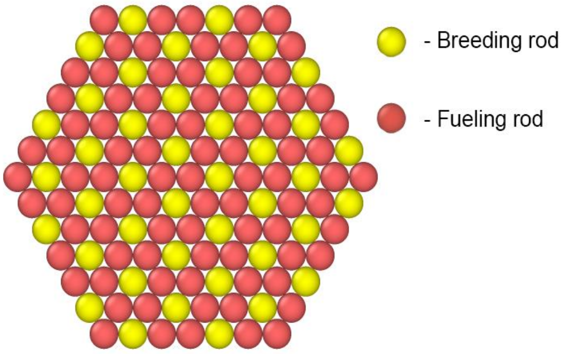
In parallel with the above studies, primitive cell computations were performed for different assembly types to assess their thermohydraulic and neutronic parameters. These computations were based on the model shown in Fig. 2a. This model is perfectly symmetrical and demonstrates a good solution convergence, in contrast to the model consisting of four triangles.

These computations allowed the power distribution between breeding and fueling rods, as well as its dynamical behavior throughout the whole fuel operation cycle, to be assessed. Initially, the power level in breeding rods makes 21% and 18% of that in fueling rods in the central and peripheral area, respectively. When the burnup of fueling rods achieves 3%, these share make 39% and 35%, respectively. By the end of cycle, the power in both types of rods becomes equal

– or even gets a little higher in breeding rods. Fig. 3 shows diagrams of power in different rods within a heterogeneous assembly depending on fueling rods' burnup.



a)



b)

Fig. 2. Models of primitive cell (a) and fuel assembly (b)

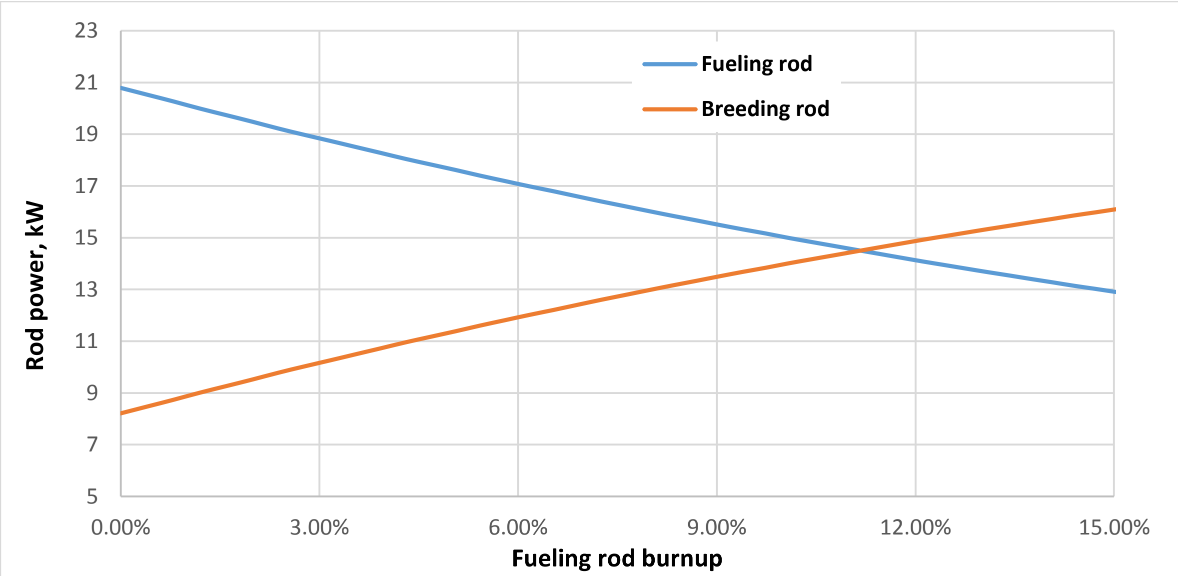


Fig. 3. Thermal power of breeding and fueling rods depending on the burnup of fueling rods

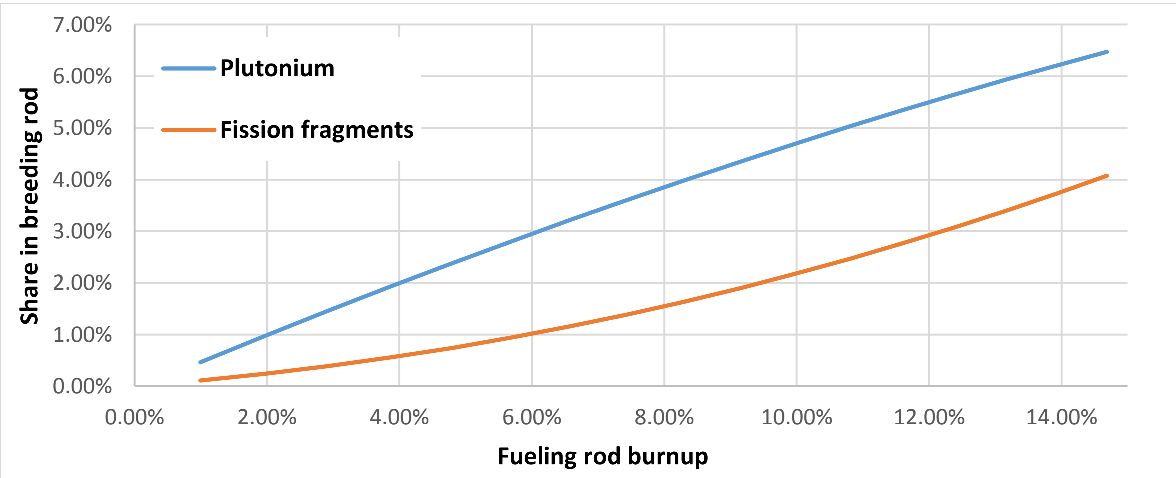


Fig. 4. Content of Pu and fission fragments depending on the burnup of fueling rods

Fig. 4 is a diagram of the content of Pu and fission fragments in breeding rods depending on the burnup of fueling rods.

It can be seen that, by the second half of the fuel operating cycle, power levels in breeding and fueling rods become almost equal. Computational results also confirm the possibility of efficient recycling of breeding rods after a shorter cooldown due to their low burnup. This operation is gainful because it allows for early return of Pu accumulated in these rods back to the reactor.

The model shown in Fig. 2b was developed to assess the axial power distribution in the central, intermediate and peripheral zones. Results yielded by this model made it possible to confirm and update the computational data pertinent to the primitive cell, and also to conclude that both the breeding rate and the burnup of breeding rods are distributed axially.

During the study, the final axial power distribution in breeding rods was found to be different from that existing in fueling rods (Fig. 5).

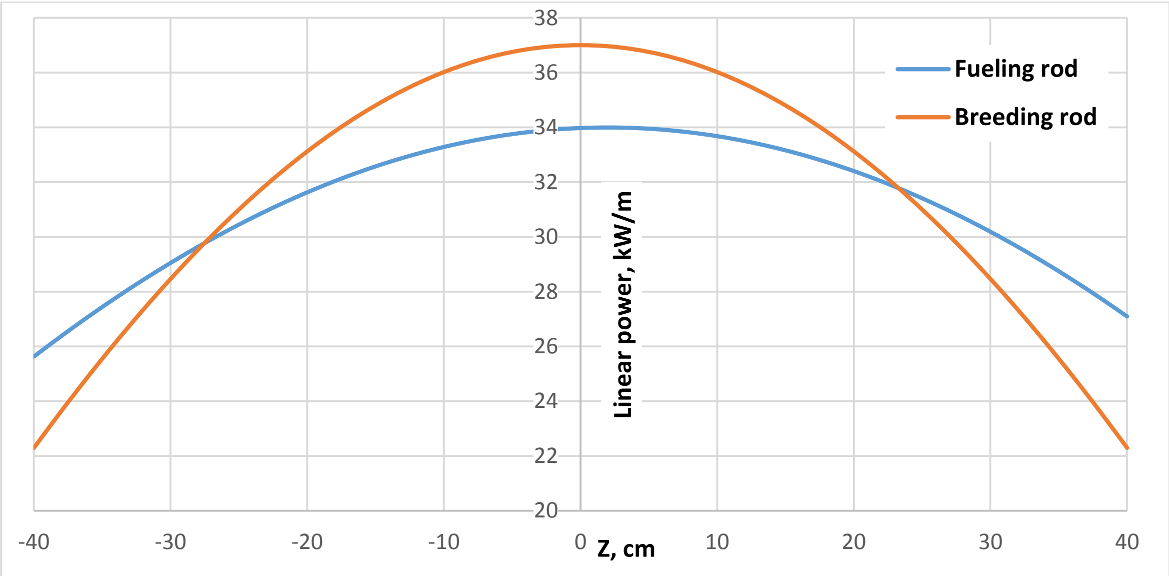


Fig. 5. Rod-heightwise linear power distribution

It can be seen that heightwise non-uniformity exceeds that of MOX fuel. This can be explained by the fact that in fueling rods the heightwise power distribution is mainly influenced by the burnup of fissile isotopes and the accumulation of neutron-absorbing fission products in the central area with the highest neutron flux density – this reduces the axial non-uniformity and flattens the power profile. As for breeding rods, the situation is quite different – in the highest neutron flux density area, the Pu breeding rate is at its highest, while the share of fission fragments is too small to produce any considerable effect.

On the whole, such power distribution in breeding metallic rods can be considered as positive, since – due to high heat conductivity of fuel – it doesn’t involve any considerable growth of temperature in the central area, while at the same time somewhat reduces the temperature in the upper core regions, where the coolant is at its hottest. However, by the second half of the cycle, heightwise Pu distribution in breeding rods affects the neutron flux and increases the heightwise power non-uniformity in fueling rods with MOX fuel. This effect was accounted for in thermophysical computations.

Mixing and even distribution of the sodium flow between different types of rods is provided by wire wrap. Combined with jacketless assemblies, this system is very complex and requires great effort to simulate its thermophysical parameters. Currently some updated thermohydraulic models are being developed to describe this core more accurately and in more detail.

5. Computational results

Table 1 compares the basic reactor parameters for the core with homogeneous metallic assemblies and for the core with heterogeneous assemblies.

TABLE 1. BASIC REACTOR PARAMETERS FOR DIFFERENT CORES.

Parameter	Homogeneous core	Heterogeneous core
Thermal power, MW	410	410
Fuel	U-Pu-Zr alloy	$(U,Pu)O_2$ + U-Zr alloy
Coolant inlet/outlet temperature, C	400/530	400/530
Specific load of fissile isotopes, kg/GWe	4150	4080
Reactivity margin for burnup, $	7.6	3.2
Radial peaking factor (Kr)	1.22	1.26
Max possible void reactivity effect, $	3.1	2.1
Doppler constant	-1340	-1950/-2140
Core breeding ratio	0.83	0.99
Blanket breeding ratio	0.85	0.51
Specific breeding (^{233}U in blankets), kg/GWe per year	290	170
Specific breeding (^{239}Pu in breeding rods), kg/Gwe per year	-	400
Average burnup in assemblies/fueling rods, % of heavy atoms	11.2/11.2	7.7/9.9
Civil-grade Pu consumption, kg/Gwe per year	1020	1390
Fuel cycle, years	6/7	4/5
Partial reload interval, days	330	330

These results make it possible to identify the basic advantages and disadvantages of heterogeneous assemblies consisting of MOX plus breeding metal compared to homogeneous metallic assemblies.

Advantages:

– Higher (close to 1) in-core breeding ratio – this relieves the requirements applicable to both the reactivity margin required for burnup and the efficiency of CPS control rods;

– Breeding rods produce additional power by absorbing gamma-quanta;

– Possibility to reprocess breeding and fueling rods separately, to reduce both the fuel cycle duration and the dose burden during reprocessing, and to allow for more efficient use of reprocessing capacities;

– Relieved requirements to fuel viability validation;

– Presence of light nuclei yields more resonance neutrons – this has a positive influence on the Doppler reactivity effect;

– Lower void reactivity effect due to permanent presence of light nuclei within the fuel;

– High in-core Pu breeding ratio;

– Small gain in specific load of fissile isotopes.

Disadvantages:

– Heterogeneous assemblies generally have lower breeding ratios – so that the fuel breeding in blankets reduces by about 40%;

– Heterogeneous assemblies consisting of different rods with different power levels are very complex to simulate and require further improvement of computational models and software;

– Limited Pu content and small size of the core yield higher radial power peaking factors (plus the power distribution additionally changes within the micro-cycle);

– At average power density of 300 kW/l, the value of 410 MWt is the lower boundary that meets the system requirements of sustainable development for small reactors with heterogeneous cores. At the same time, fast reactors with metallic fuel demonstrate good performance even when their thermal power makes 300 MW.

Summarized data hereof allow for the conclusion that heterogeneous assemblies could be efficiently used in small modular reactors, which could thus be deployed without any damage to their basic advantages regarding fuel efficiency, safety and economy even before the U-Pu-Zr fuel gets licensed. Depending on applicable requirements, the use of heterogeneous assemblies may be even preferable – first of all, due to their high in-core breeding ratio, which reduces the burnup reactivity margin and allows for accelerated reprocessing of breeding rods that have relatively high content of fissile Pu isotopes and low burnup. Such a reactor would be capable to produce about 400 kg of Pu-239 per GWe per year (in its core only, without accounting for recycling losses that reduce the amount of Pu in the external fuel cycle (i.e. reprocessing).

6. Heterogeneous metallic assemblies

Reviewing the works performed by RIAR with regard to different types of metallic fuel, one should note the positive results yielded by the irradiation of Zr-free metallic uranium [7]. At the moment, this type of breeding rods is considered as an alternative option. In addition to solving the issue of depleted metallic U fuel use before the U-Pu-Zr fuel gets licensed, purely metallic heterogeneous assemblies can further extend the application scope of metallic fuel, e.g., by using it as highly porous fueling rods to be accompanied by breeding rods made of denser zirconium-free metal. With account of its initial porosity, this fuel would have higher effective density than U-Pu-Zr one (assuming the same highest burnup). This option also enables separate reprocessing of breeding and fueling rods, as well as isotope separation for better breeding and lower dose burden and other linear burdens) during reprocessing.

7. Conclusion

The study hereof demonstrates that heterogeneous fuel assemblies can be efficiently used in small modular fast reactors to maintain or increase their fuel efficiency compared to homogeneous metallic assemblies. Results yielded by this study show that, even with the MOX fuel that has low density, heterogeneous assemblies would allow the core to achieve: breeding ratio BR~1; admissible specific initial loads of fissile plutonium isotopes; and high rate of excess plutonium breeding in blankets, i.e. to ultimately meet the system requirements that apply to fast reactors. Heterogeneous fuel assemblies pave the way for the deployment of closed fuel cycles without imposing any excessive additional requirements on spent fuel reprocessing technologies and facilities. Use of heterogeneous assemblies with dense fuel in fueling rods and high-density Zr-free uranium in breeding rods can yield core parameters better than those yielded by dense homogeneous assemblies. The intra-assembly heterogeneity of nuclear fuel is a promising area that requires further studies.

References

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Small and Medium Sized Reactor Designs, A Supplement to the IAEA Advanced Reactors Information System (ARIS), Vienna(2011).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Status and Trends of Nuclear Fuels Technology for Sodium Cooled Fast Reactors, IAEA Nuclear Energy Series No. NF-T-4.1, Vienna (2011).

[3] Harbur, D.R.; Anderson, J.W. & Maraman, W.J. *STUDIES ON THE U-Pu-Zr ALLOY SYSTEM FOR FAST BREEDER REACTOR APPLICATIONS.* New Mexico *(1970)*

[4] INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Environmental Impact of Stressors: IAEA Nuclear Energy Series No. Ng-t-3.15 2016

[5] INTERNATIONAL ATOMIC ENERGY AGENCY,Status of small reactor designs withouton-site refuelling,IAEA-TECDOC-1536, IAEA, Vienna(2007).

[6] Beck WN, Fousek RJ. The irradiation behavior of high-burnup uranium-plutonium alloy prototype fuel elements. Argonne National Laboratory 1968; Report ANL-7388

[7] Golovchenko Yu.M. “Some results of developments and investigations of fuel ping with metal fuel for heterogeneous core of fast reactors of BN-type”, Asias Nuclear Prospects 2010.

[8] Ярославцева Л.Н. Комплекс программ JARB для расчета нейтронно-физических характеристик ядерных реакторов. ВАНТ, сер. ФТЯР, вып. 8 (37), 1983, с. 41-43.

[9] W. Bernnat, D. Blanchet E. Brun, M.M. Uematsu. Technical Report: Benchmark for Neutronic Analysis of Sodium-cooled Fast Reactor Cores with Various Fuel Types and Core Sizes, Nuclear Science NEA/NSC/R(2015)9 February 2016