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Some considerations on the design of a small versatile fast reactor

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Introduction

IAEA compiled a list of around 56 Small Modular Reactors (SMR) currently under consideration across the world in the 2018 Supplement to its Advanced Reactors Information System (ARIS) [1]. Several of the reactors described in this reference are currently under construction or under licensing, while the majority of them are currently being designed. Out of these 56 SMR concepts, only 9 fast reactors designs are under consideration, with 7 of these designs considering the use of lead or lead-bismuth eutectic as a coolant. None of these reactors concepts are under construction as of now.

This disproportion can be explained by the industrial maturity of water-cooled reactors, which can build upon the significant experience return available from the industrial operation of current Light Water Reactors (LWR). On the other hand, fast reactors have a limited pool of the experience return to draw upon, with the Russians accruing around 80 reactor-years of operation of lead-cooled reactors in submarines [2] and various countries pooling around 400 reactors-years of operation of sodium-cooled fast reactors.

As with all SMRs, a Small Modular Sodium Fast Reactor (SMSFR) should be as small as possible, in order to limit the capital costs associated with the reactor, with a power level in the range of 400 MWth. Furthermore, it should be able to operate with a wide variety of fuels, considering the expected versatility of a fast neutron spectrum (see [3] for instance). Finally, MOX fuel is considered to leverage the experience return on the use of uranium-plutonium oxide in French LWR.

Indeed, one of the main historical arguments towards the use of fast reactor is the possibility to close the nuclear fuel cycle by using plutonium and eventually minor actinides as fuel. Using fast reactors, it is theoretically possible to limit the increase in plutonium production coming from the operation of UOX-fueled LWR or even to stabilize the plutonium inventory in the fuel cycle by using a so-called double-strata fleet where fast reactors consume the plutonium production of LWRs. Such scenarios, as described in [4] for instance, consider in the end the deployment of a reactor fleet entirely composed of fast reactors and the stabilization of both the plutonium inventory in the fuel cycle and the plutonium isotopic vector to be loaded in the reactors.

Such scenarios make the implicit hypothesis that industrial fast reactors can be fueled with a variety of plutonium isotopic vectors during their operational lifetime. Indeed, the plutonium isotopic vector coming from the reprocessing of MOX fuels irradiated in thermal reactors contains significantly less fissile isotopes than the plutonium coming from the reprocessing of UOX fuels. Consequently, it is necessary to increase the plutonium content in the fuel in order to maintain criticality of the cores.

If such a constraint is not an issue for industrial power cores, in which the large volume of the core leads to plutonium content in the range of 20 %, it may not be the case for a smaller fast reactor core. Indeed, the combination of a size constraint in the core volume with a maximum allowable plutonium content in the fuel due to reprocessing issues [5] may lead to non-critical core configurations over the lifetime of a small modular fast reactor. Consequently, it is necessary to consider the entirety of the reactor operational lifetime at the design stage in order to ensure criticality at all time.

One possible option which has been investigated in this work is to adapt the core size by adding or removing assemblies in the core within the maximal permitted volume to ensure criticality regardless of the isotopic vector considered. However, modifying the core assembly number may lead to issues related to excessively high linear heat rates, or conversely, rod-cladding mechanical interactions due to insufficient power generation in peripheral assemblies [6]. To alleviate this issue, modifications of the pin bundle depending on the plutonium isotopic vector have thus been investigated.

The aim of this paper is to investigate the specificities discussed above in the design of a sodium fast reactor with a limited power and to draw several general conclusions relative to the design of such a reactor. The various possibilities to ensure criticality over the reactor lifetime will be analyzed and discussed and an adaptive SMSFR design will be discussed.

Constraints on core design

Various constraints were considered for the design exercise carried out in this work. Although there is no upper power level for a reactor to be designed as a SMR, a power range between 300 and 600 MWth was considered here. This corresponds to an output of ranging between 126 and 252 MWe considering a thermodynamic efficiency similar to the one of bigger reactors such as the ASTRID reactor [7]. Secondly, in order to limit the cost of the reactor, a maximal core diameter of around 2 meters was considered. Indeed, if a rotating-plug technology is used for refueling and fuel-handling, such as it was done for Phénix and Superphénix plants, a wider active core requires the use of two rotating plugs nested inside the other. Such a solution would have a significant impact on the complexity and cost of the fuel handling systems and is ruled out here.

Considering the plutonium isotopic vector considered for core operations, two widely different vectors were used. Indeed, if we assume that the reactor has an operational lifetime of 60 years, it is reasonable to expect a modification in the available plutonium isotopic vector over the plant life. The starting isotopic vector was considered to be relatively good-quality plutonium coming from the reprocessing of spent UOX fuels irradiated in PWR, with a relatively short time between reprocessing and loading in the SFR to avoid ^{241}Am build-up. It was then considered that the reactor could be expected to operate with a plutonium isotopic vector coming from the reprocessing of spent MOX PWR fuels, which has significantly lower ^{239}Pu content. Furthermore, it was considered that these spent fuels had been stored for a significant period of time before reprocessing, which limits both the ^{241}Pu and the ^{241}Am fractions in the isotopic vector. These two isotopic vectors are shown below in Table 1.

It was finally considered that reprocessing uranium was used as the support matrix for the manufacturing of MOX fuels. The composition of the reprocessed uranium is also shown in Table 1. It should be mentioned here that the use of reprocessed uranium, which content in ^{235}U is around 0.84 %, has a positive impact on the amount of plutonium required to achieve criticality in the core. The use of depleted uranium would lead to an increase in the plutonium content between 0.5 and 1 point depending on the core and on the plutonium isotopic vector considered. A maximum plutonium content in the fuel of 30 % was considered in order to ensure the feasibility of fuel dissolution in nitrous acid [5].

	Rep. U
^{234}U	0.02 %
^{235}U	0.84 %

	Pu ex-PWR-UOX	**Pu ex-PWR-MOX**
^{238}Pu	2.59 %	3.71 %
^{239}Pu	55.2 %	39.47 %
^{240}Pu	25.85 %	35.04 %

^{236}U	0.36 %
^{238}U	98.78 %

^{241}Pu	7.27 %	7.91 %
^{242}Pu	7.87 %	13.07 %
^{241}Am	1.22 %	0.8 %

Table 1 : Isotopic composition of the fissile and fertile materials considered in this work.

Concerning the core and assembly geometrical designs, various constraints were considered, namely:

- The location of control rods in the core must remain constant over the core lifetime, as no modifications of the upper core plug, through the control rod mechanisms are passing, can be done during operations.
- The position of the interface between the inner and the outer core remain the same over the core lifetime so as to avoid constraints on the flow zones design.. Indeed, mechanical devices prevent the loading of an inner core assembly into an outer core assembly and conversely as a safety measure.
- The flat-to-flat size of the fuel assemblies must be kept constant over the core lifetime, but modifications of the pin bundle to adapt the fuel volume fraction in the assembly were evaluated, considering that the primary pumps were able to accommodate the modification of the pressure drop of the core. A 14 cm flat-to-flat length was considered in this work, as an intermediate value between the Phenix assemblies and the ASTRID assemblies. This leads to a number of assemblies ranging between around 60 and 130 considering a maximum core diameter of 2m and a fissile height of 80 cm. The minimal number of assemblies is given by limitations on the maximal power density in the core. It was considered that the number of assemblies in the core could be adjusted during operation within these boundaries. These values are consistent with the number of assemblies for reactors of similar size such as the PFR (78) or Phénix (73). Such a flat-to-flat length allows for fuel volume fraction ranging between 35 and 40 % depending on the pin diameter and number of rings in the pin bundle. Based on the Phénix and Astrid cores, two pin diameter were considered here, 7.23 mm and 8.77 mm with a 0.29 ratio between the pin and the central hole diameter. These two pin sizes correspond to bundle with respectively 169 and 127 pins.

An irradiation time of 900 EFPD was considered for all the cores, which leads to a mean burn-up around 80-90 GWd/t for a 400 MWth core with a power density around 250 W/cc. The calculations presented in this work were carried using the ERANOS code system for fast reactors [8] and the JEFF 3.1 nuclear data library [9].

Criticality and Core size

The first step in the design exercise is to evaluate the minimal number of assemblies required to achieve criticality regardless of the plutonium isotopic vector considered and of the Pu content maximum limit. An assembly design with eight fuel rings and a fuel volume fraction of 36 % was considered so as to be conservative in the number of assemblies required. Looking at Figure 1, various zones can be distinguished. In order to achieve criticality with plutonium from UOX spent fuel, a minimal number of 72 assemblies is required. However, such a small number of assemblies would require a significantly higher Pu content with plutonium from MOX spent fuel. With a constant assembly design, a minimal number of 103 assemblies appear to be necessary, which gives a lower boundary on the core size.

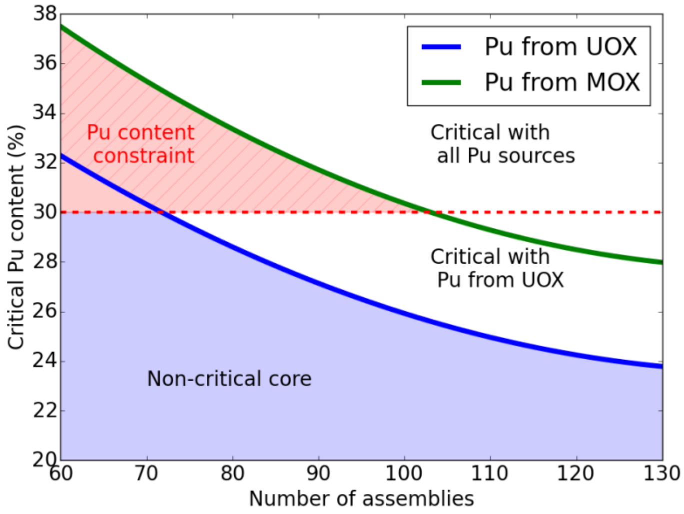

Figure 1 : Minimal plutonium content in the fuel to achieve criticality vs number of core assemblies with a 36 % fuel volume fraction in the assembly

Linear power rate

The next point to consider is the evolution of the linear heat rate (LHR) in the core over its lifetime. Two limitations must be taken into account:

- The maximum heat rate in the core must not go above 460 W/cm in order to keep a necessary margin to the fuel melting point [6].
- The minimal heat rate in the assemblies close to the control rods positions must go above an arbitrary limit of 300 W/cm in order to ensure an adequate fuel behavior under irradiation. Indeed, low fuel centerline temperature can limit the release of gaseous fission products in the pin free space while promoting significant fuel swelling [10].

Keeping the same fuel assembly design with 169 fuel pins, a 80 cm fissile column and a fuel volume fraction of 36 %, it is possible to obtain Figure 2, which plots the minimal and maximal power rate in the core at the beginning of an equilibrium fuel cycle. Calculations were carried out by increasing the number of assemblies in the core from 78 to 128 while maintaining as symmetrical a core as possible. This figure shows that, for a fixed number of assemblies in the core, a relatively narrow variation range in the core power is possible while maintaining adequate linear heat rates.

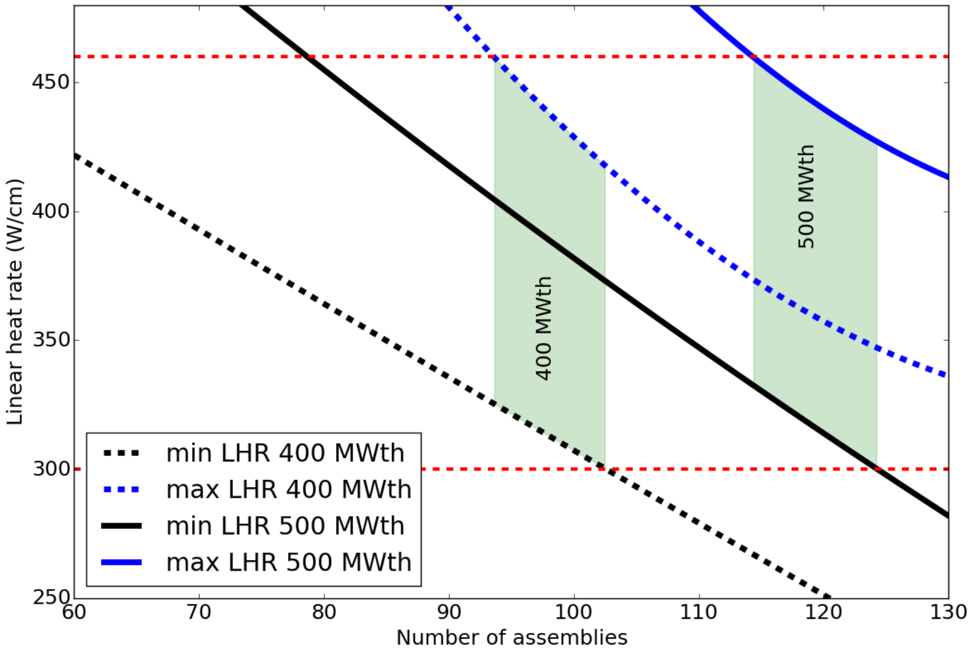

Figure 2 : Evolution of the maximum and minimum linear heat rate depending on the number of assemblies

Is it finally possible to combine the two graphs in Figure 1 and Figure 2 to obtain an acceptable design zones in term of power level and number and assemblies in which the core can be kept critical regardless of the plutonium isotopic vector and evolution of the number of assemblies during its operation. This is done in Figure 3. Most notably, it can be observed that the combination of the constraints on Pu content in the fuel and on minimal linear heat rules out small cores with power level lower than 400 MWth and less than around 102 assemblies.

As a conclusion of this preliminary design exercise, it can be observed that the core minimal size for a given assembly design and minimal power level is entirely decided by the combination of the maximal acceptable linear heat and the most penalizing plutonium isotopic vector to be loaded. In order to design core with lower power levels, the acceptable domain for linear heat rate and plutonium content must be extended.

One possible option to do so would be to modify the assembly design by increasing the fuel volume fraction when using lower quality plutonium, in order both to increase the linear heat rate in the pins and thus allow lower power levels, and to lower the requirements on plutonium content. Such an option is discussed in the next part.

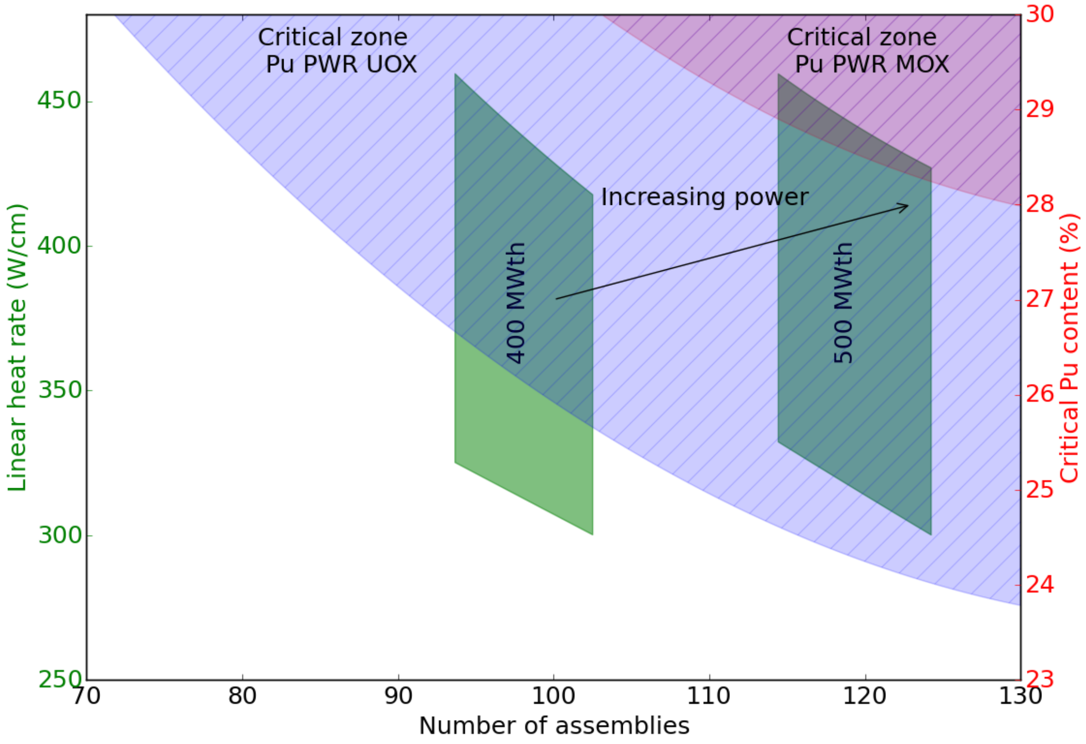

Figure 3 : Combination of the Pu content and linear heat rate constraints

In-operation assembly design modifications

As discussed in the previous, the requirements associated with the use of lower quality plutonium isotopic vector and acceptable linear heat rate leads to a constraint both on the core size and power level. Increasing the fuel volume fraction when the plutonium quality decreases would lessen the criticality constraints. However, such an increase may lead to a reduction in the number of pins in the assembly, which could lead to unacceptable maximum linear heat.

Consequently, we consider here a new assembly design with a similar flat-to-flat but a fuel volume of 40 %, which corresponds to a 127-pin-bundle. It is then possible to plot Figure 4, which is similar in shape and purpose to Figure 1 and clearly shows that the acceptable zone for criticality is extended by the use of a new pin bundle. Most notably, it is observed that core with only 80 assemblies can be critical with both plutonium isotopic vectors defined in Table 1 due to the increase in the fuel volume fraction. The use of a tighter fuel bundle also leads to a higher robustness of the core with regards to degraded plutonium isotopic vector.

Furthermore, looking at Figure 5, which is similar to Figure 3, we can observe that it is possible to reach lower power levels, as the lower number of pins leads to a higher mean linear heat rate. Using this new pin bundle, core with a power level as low a 300 MWth could be envisioned. However, this also means that it may not be possible to design a core with a power level equivalent to the one of a core with the initial pin bundle, as it would lead to unacceptable linear heat rates. Hence, there is no acceptable domain in the plot for a core with a power of 500 MWth

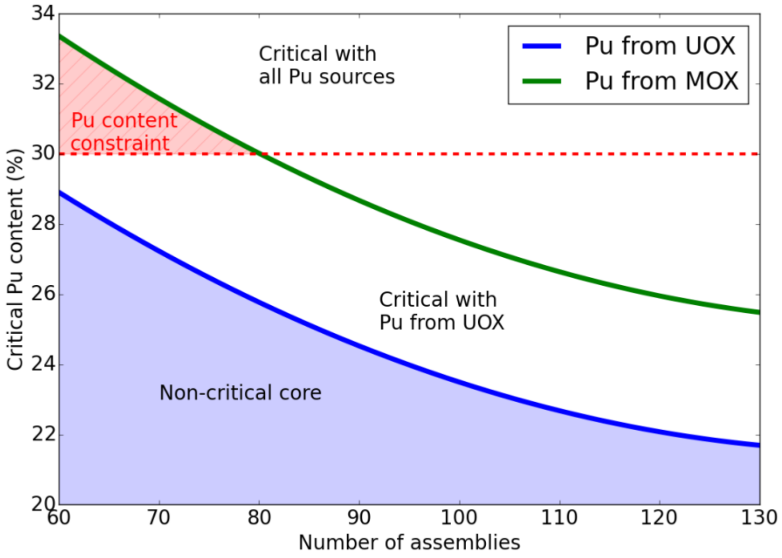

Figure 4 : Minimal plutonium content in the fuel to achieve criticality vs number of core assemblies with a 40 % fuel volume fraction in the assembly

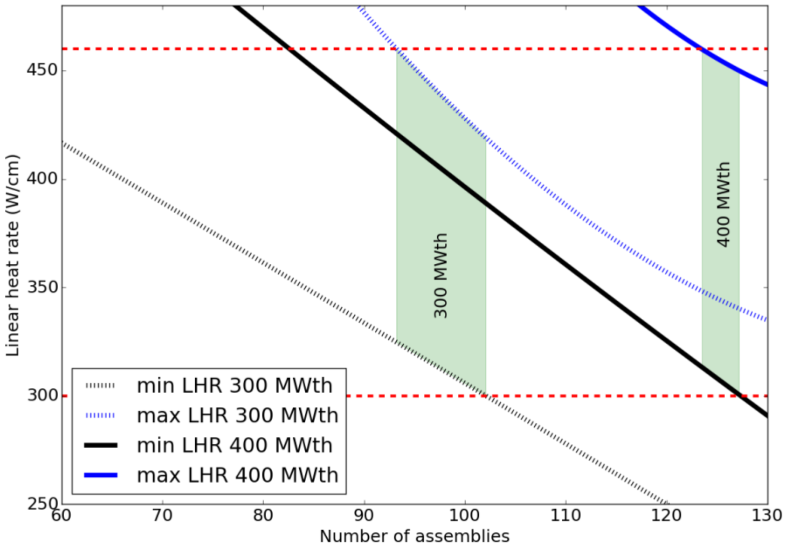

Figure 5 : Evolution of the maximum and minimum linear heat rate depending on the number of assemblies

The next step is to overlap the acceptable design zones in terms of power level and Pu content, as it is done in Figure 6. This schematic plot allows to simply evaluate the core design options available for a given core volume, the objective being to evaluate the resilience of a core to modification of its operating design (Pu isotopic vector, power level).. The various colored bars of this figure represent the feasibility domain of a core with a given number of assemblies. With a total of 96 fuel assemblies for instance, it thus appears to be possible to design a 400 MWth core with a 36 % fuel volume fraction bundle and good quality plutonium, or a 300 MWth core with a 40 % fuel volume with degraded quality plutonium. It also appears that for a 400 MWth core with around 100 assemblies initially designed with a low density fuel bundle and fueled with good quality plutonium, switching during operations to a tighter fuel bundle would lead to a severe reduction in the power level to maintain acceptable linear power rates, or an increase in the total number of assemblies to around 125 assemblies. Such a modification would have to be planned beforehand to ensure that enough positions on the supporting grid and enough pump head are available to add these assemblies into the core.

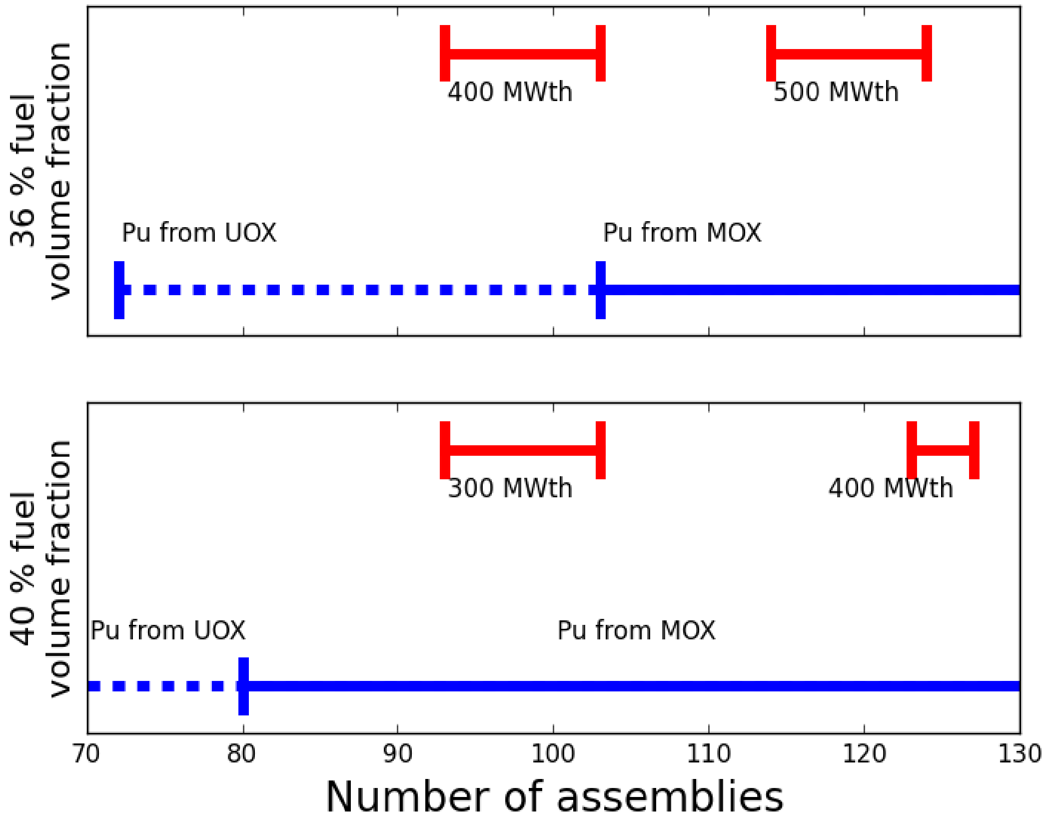

Figure 6 : Schematic representation of the acceptable design zones for two fuel volume fraction.

Conclusions

The aim of this paper was to highlight some specificities in the design of sodium fast cooled SMR, most notably the fact that these reactors are less versatile than “traditional” high-power sodium fast reactors. This observation stems from the fact:

- The small size of the core leads to a severe increase in the plutonium content in the fuel, which, for oxide fuels, is limited by reprocessing technology. This creates a lower boundary for the volume of a given core.
- The necessity to achieve as small as possible a core has significant impacts on the acceptable core power level. More specifically, the core power level has to be adapted to the number of assemblies so as to avoid having “cold” pins at the core periphery. Consequently, this also creates a lower boundary for the core volume.

Both the constraints are strongly dependent on the assembly design used here. It was found that the objective of designing a 400 MWth core as small as possible was antagonistic with the objective of being able to fuel the core with a variety of plutonium isotopic vectors with decreased quality. On the other hand, using a fuel bundle with wider pins allowed the use of nearly any kind of plutonium isotopic vector, at the cost of the core power level, which has to be reduced to maintain acceptable margin to fusion.

Such a strong relationship between the core power level and plutonium isotopic vector is much less visible in an industrial fast reactor core. In such a core, the core volume itself leads to lower plutonium content in the fuel, which gives more design margins. Another potentially critical point, which was not discussed in this work, is the design and implantation of the control rods. Indeed, the associated drive mechanisms occupy a given minimal space above the core upper plug, and the number of rods which can be physically loaded in the core can be limited, which may in turn have a negative impact on the core reactivity control for long irradiation times. It is planned to further investigate this point in the future.

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