CHARACTERIZATION OF THE MOLTEN CHLORIDE FAST REACTOR FUEL CYCLE OPTIONS

J. KREPEL
Paul Scherrer Institute
Villigen Switzerland
Email: jiri.krepel@psi.ch

J. DIETZ
Paul Scherrer Institute
Villigen Switzerland

R. DE OLIVEIRA
Paul Scherrer Institute
Villigen Switzerland

Abstract

Molten Salt Reactors, as a whole reactor category, belong to the GenIV reactors. They can be designed as thermal, epithermal or fast systems for variety of applications. Especially the Molten Chloride Fast Reactors (MCFRs) provide very hard neutron spectrum and good neutron economy. Hence, MCFRs can be operated as a breeder in the closed U-Pu and Th-U cycle or as a breed-and-burn reactor in open U-Pu fuel cycle. This high fuel cycle performance is, nonetheless, accompanied by unfavorable fuel salt transparency for neutrons and may result in bulky cores.

In this paper, several operating modes of homogeneous MCFR are simulated, analyzed, characterized and compared with fluoride fast reactors. The EQL0D routine, developed for this purpose at Paul Scherrer Institut, is applied to obtain the respective equilibrium states for these fuel cycle scenarios. The major evaluated parameters are the core size and achievable burnup. The results show that breeding in MCFRs is possible in both Th-U and U-Pu closed cycles. However, the Th-U cycle provides much lower k_{inf} and results thus in bulkier core. The MCFR core size in closed U-Pu cycle is comparable to the fluoride fast reactor operated in the Th-U cycle. The MCFR can be also operated in an open breed-and-burn cycle. Nevertheless, the tight neutron economy requires minimization of neutron leakage and the core can be thus extremely large. Furthermore, the standard definition of fuel burnup is not suitable for this cycle and needs new definition.

1. INTRODUCTION

Molten Salt Reactors can be generally divided into fluoride [1] and chloride [2] salt based concepts. The former were the object of a larger effort in the past and ultimately foreseen for breeding in the closed Th-U cycle. Nonetheless, fluoride salt concepts can be also fuelled by enriched uranium or applied for synthetic Actinides (Ac) minimization in dedicated waste burners. Since these three basic options can be combined, there are many fuel cycle concepts proposed in the literature. Closing the U-Pu cycle in a fluoride salt fuelled fast reactor is possible; however, it is rather problematic and only a minor research branch. The softer neutron spectra provided by properties of fluorine and some of the considered cations are not well suitable for this fuel cycle. Furthermore, the solubility of trivalent compounds like PuF_3 is often limited and the possible gap between solidus and liquidus temperatures may represent a safety concern due to local precipitation.

The performance of U-Pu closed cycle swiftly degenerates with neutron spectrum softening [3]. In opposite to the Th-U cycle, it is practically impossible to close the U-Pu cycle in thermal spectrum. At the same time, the U-Pu cycle strongly outperforms the Th-U cycle in very hard spectrum. Furthermore, the closed U-Pu cycle can be naturally started by enriched uranium. This is not possible for the Th-U cycle, where a fissile thorium nuclide comparable to ^{235}U does not exist. Accordingly, the closed fuel cycle is dominated by uranium fuelled fast breeder reactors. These are typically based on solid fuel in form of pins and liquid metal or gas coolants. In a fast reactor, with hard neutron spectrum, minimal parasitic neutron captures and minimal neutron leakage, very high breeding gain can be achieved. Ultimately the breeding can be so high, that it is not necessary to recycle the bred plutonium from discharged fuel. This kind of breeder can be thus operated in so called breed-and-burn cycle. This possibility was identified very early during the pioneering time [4]. The current status of breed-and-burn reactors is reviewed

in [5]. Homogeneous Molten Chloride Fast Reactors (MCFRs), which are the major objective of this study, enable operation in closed Th-U cycle, closed U-Pu cycle and in open U-Pu breed-and-burn cycle. The possibility to operate MCFR in breed-and-burn mode appear in literature around 2015 [6, 7, 8, 9, 10, 11, 12]. The Molten Salt Fast Reactors (MSFR) based on fluoride salts cannot be operated in this fuel cycle type [6, 7, 8].

According to IAEA, Molten Salt Reactors (MSRs) can be divided into three main classes [13]. The first one is defined by graphite utilization. Graphite moderated MSRs profit from its compatibility with the fluoride salt and have been subject of the largest research effort in the past. The second class are Homogeneous MSRs, where the core consists solely from the fuel salt and structural materials are not present in the core or do not have separating function. This class is addressed in this paper. The third class are Heterogeneous MSRs, where structural materials are needed to separate the fuel salt from dedicated coolant or moderator. In this paper MCFR and MSFR will be used as general labels for homogeneous chloride and fluoride salt based fast reactors, respectively. Already in the sixties and seventies authors have been seeking for a label for fast breeder based on MSRs. In 1974 the abbreviation MSFR appeared in a report dedicated to chloride fast MSR concepts [14]. In 1975 another author used MCFBR (Molten Chloride Fast Breeder Reactor) for similar concept [15]. Finally, in a PhD thesis from 1982 [16] the MCFR label is used for chloride salt based Th-U breeder. Even though MSFR and MCFR are general labels, they are often connected with specific concepts. Nonetheless, it is always a homogeneous MSR, where the active core is filled solely by the fuel salt, which has also the major heat transfer function. Since the U-Pu cycle performance in MSFR is mediocre and since the Th-U cycle in MCFR leads to bulky cores, each of the reactor types is traditionally foreseen for one type of closed cycle only.

The neutron spectrum of MCFR is determined by the nuclear properties of ^{35}Cl and ^{37}Cl nuclides. Both these nuclides have rather small scattering and capture cross-sections [2, 13]. The capture probability for ^{35}Cl is higher. Many MCFR concepts thus foresee operation with enriched ^{37}Cl and the enrichment is also required for the breed-and-burn cycle. This is similar to ^{7}Li enrichment in many MSFR concepts. The scattering cross-sections of ^{37}Cl is comparable to ^{16}O, ^{19}F or ^{23}Na. However, it has only narrow resonances and ^{37}Cl is also heavier that these nuclides. In [17], the neutron spectrum of an MCFR with and without ^{23}Na cation in the salt can be compared. Obviously the ^{23}Na presence partially softens the spectra. In the same document Sodium Fast Reactors (SFRs) with metallic and ceramic fuel are compared. The major difference is the spectrum suppression for the ceramic oxide-based fuel by ^{16}O scattering cross-section resonance at 434 keV. The absence of ^{16}O and of any other structural materials in the MCFR core together with ^{37}Cl properties and its homogeneous nature result in a very hard neutron spectrum. The lower scattering probably and the smaller energy decrement per interaction are both favourable for fast neutrons. At the same time, unlike the fluoride salts, the chloride salts are relatively transparent for these neutrons. This has a consequence for the core size. Two fuel salt mixtures with the same infinite neutron multiplication factor k_{inf}, will result in bigger critical core in case of chlorides than in case of fluorides. It is nicely illustrated for the case of iso-breeding closed cycle in this paper, but also in [3, 18], where the minimal critical iso-breeding core size was estimated.

2. MODELING TOOLS AND FUEL TAP REACTOR CONCEPT

The operation of a breed-and-burn MCFR concept was simulated by EQL0D [19] fuel cycle procedure. It is based on MATLAB and Serpent and dedicated to reactors with continuous fuel treatment. The breed-and-burn fuel cycle mode is simulated by simple removal of the fuel from the reactor and its replacement by fresh fertile fuel salt. Pure ^{238}U was selected as the actinides feed. Several different refiling rates, which are tailored for the power and volume of the selected core, have been analysed (see Table 1). It is the major removal path for Fission Products (FPs) soluble in the salt. The gaseous and metallic or actually non-soluble FPs have can be removed from the core independently. Since their behaviour in chloride salts is not well known, their removal constants adopted from the fluoride salts. However, even for fluoride salts these constant differ between concepts. The cycle time for gaseous FPs of 30s and the removal constant $\lambda = 1/30 = 3.33E\text{-}02$ is used in many MSFR concepts and can be traced back to the reference [20]. The metallic FPs are treated separately and the respective removal rates, adopted from [21, 22], are present in Table 1. Utilisation of these removal constants, especially for the metallic FPs, represents a major approximation and possibly the biggest inaccuracy of this study. It may introduce strong performance overestimation by the simulation or necessity of intensive salt treatment in reality by He sparging, metallic sponge filtration or other methods, or even their combination. However, such a treatment will be inevitable to enable the operation in breed-and-burn mode in single-fluid MCFR.

TABLE 1. Considered fuel salt removal rates from the breed-and-burn core and considered FPs removal constants from the fuel salt in the core.

Fuel salt removal from the core (fuel tap)				Fuel salt continuous treatment in the core (FPs removal)				
Case nr.	Cycle time (Y)	Removal constant λ (1/s)	Share removed (%/Y)	Case nr.	Gaseous FPs proton nr.	Gas. FPs rem. const. λ (1/s)	Metallic FPs proton nr.	Met. FPs rem. const. λ (1/s)
1	14.26	0.45E+09	7.01	All	1 2 7 8 10 18 36 54 86	1/30	30, 31, 32, 33, 34, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52	1/3600
2	28.51	0.90E+09	3.51					
3	42.77	1.35E+09	2.34					
4	57.03	1.80E+09	1.75					
5	71.28	2.25E+09	1.40					
6	85.54	2.70E+09	1.17					
7	99.80	3.15E+09	1.00					
8	114.06	3.60E+09	0.88					
9	128.31	4.05E+09	0.78					
10	142.57	4.50E+09	0.70					
11	156.83	4.95E+09	0.64					
12	171.08	5.40E+09	0.58					
13	185.34	5.84E+09	0.54					
14	199.60	6.29E+09	0.50					

There are only three basic design options for a core of any homogeneous MSR concept:

1. Fuel salt composition.
2. Neutron leakage utilization.
3. Core shape or actually Height to Diameter Ratio (HDR) for cylindrical cores.

Once these three options are fixed, the core size and the nominal fuel burnup are two remaining parameters, which are competing with each other. The system selected as a reference for simulation of the breed-and-burn cycle in this paper is the Fuel tap reactor [22]. It relies on $Na^{37}Cl$-$Ac^{37}Cl_3$ salt mixture with 60 mol% of NaCl and with 100% ^{37}Cl enrichment. The neutron leakage is minimized by 100 cm thick PbO reflector and HDR ratio of 2 is used. Results obtained for this concept are compared with MCFR and MSFR simulations in closed Th-U and U-Pu cycle adopted from [23, 24] and with breed-and-burn cycle simulations adopted from [8], where HDR is equal to 1 or 0.92, respectively. For simplicity only HDR=1 is used in later plots for these results. The Fuel tap reactor is rather specific concept proposed to address particular issues related to the thermal-hydraulics layout. It uses baffles to control the flow pattern of the salt in the bulky core and it relies on a tube-in-tube system and downcomer to keep the piping and outer vessel wall colder at the salt inlet temperature (see FIG. 1). Even though HDR=2, the diameter of the vessel is still large 4.8 m. The foreseen discharged burnup is around 33% of FIssile MAterial (FIMA %). The selected PbO reflector was not reviewed in [8]. It has slightly lower neutronics performance than the pure lead reflector. At the same time the melting temperature is increased from 601 K to 1161 K. Accordingly, the PbO reflector is applicable in concepts, where the melting of the reflector is unwanted and not needed from a thermal inertia perspective and where liquid lead is not used as a heat exchange medium in accidental conditions. In general, the Fuel tap MCFR is a rather academic concept designed to tackle particular issues and surely does not provide the minimal salt volume or the minimal salt melting temperature.

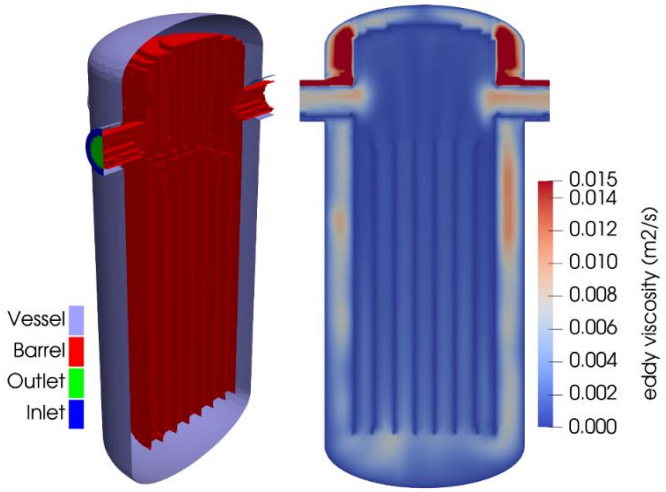

FIG. 1. Illustration of the Fuel tap MCFR concept and the impact of baffles on the flow pattern [22].

3. COMPARISON OF OPEN AND CLOSED BREEDING CYCLE

3.1. Minimal critical core size

MCFR and MSFR concepts are based on homogeneous layout, where the core is filled solely with fuel salt. Alternatively, there can be the baffles as in the case of the Fuel tap concept. However, their volume is minimal, they have not a separating function, and they can be probably avoided in matured designs. The volume of the active core, or actually the fuel salt volume in the core, is determined by criticality and depends on the k_{inf} and on a migration length. Migration length, as a measure of transparency for neutron, is tremendous in MCFR. It is 10x bigger than in MSFR or SFR and 5x bigger that in other fast reactors [18]. Reactors operated in open breed-and-burn cycle need better neutron efficiency than reactors operated in closed cycle. It must cover the respective losses of bred fissile fuel caused by the absence of recycling. Accordingly, neutron leakage should be minimized. The respective core of a breed-and-burn reactor is thus always bigger that the core of a breeder.

As a reference for the MCFR and MSFR breeder core size results from [21] are shown in FIG. 2 and for breed-and-burn MCFR the results from [7, 22] are shown in FIG. 3. The presented salt volumes core cross-sections in FIG. 2 correspond to the cylindrical cores with HDR=1. The salt volume needed for heat exchange purposes is not accounted for in all cases. Furthermore, the presented result in FIG. 2 were obtained for a single-salt concepts without blanket, with MSFR-like geometry [23], where the blanket volume was filled by Hastelloy. For more detail refer to [23, 25]. The general concept and size was adopted from a simple cylindrical cores simulated in [21]. The ^{7}LiF based MSFR provides the minimal core volume of 14 m^3 for the Th-U cycle and of 18 m^3 for the U-Pu cycle. For Na^{37}Cl based MCFR the volume is 19 m^3 and 66 m^3 for the U-Pu and Th-U cycles, respectively. In MCFR the migration area for neutrons is almost 10 times larger than in MSFR. In the U-Pu cycle it is compensated by very high k_{inf} and the resulting MCFR core volume is still comparable to MSFR cases. In the Th-U cycle case the combination of lower k_{inf} and large migration area results in bulky core. The much smaller migration area in MSFR is a consequence of ^{7}Li and ^{19}F broad resonances of scattering cross-section in fast neutrons energy range. The fluoride salts are thus much less transparent for neutrons. At the same time, these resonances suppress the fast spectrum component and MSFR has the softest spectrum of all fast reactors.

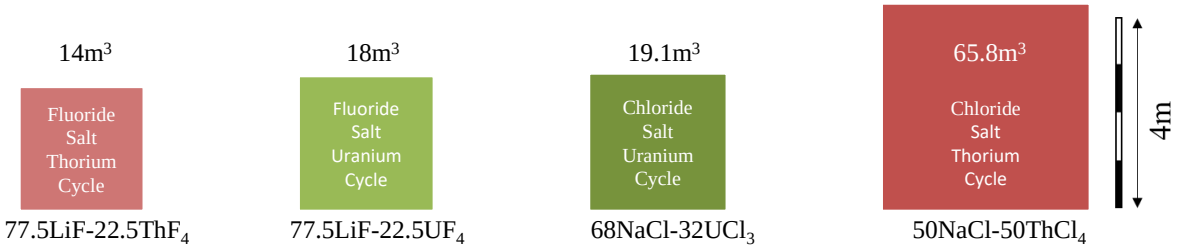

FIG. 2. Comparison of the critical core sizes for HDR=1 in closed Th-U and U-Pu cycles using fluoride and chloride salts in MSFR-like and MCFR-like breeders [21].

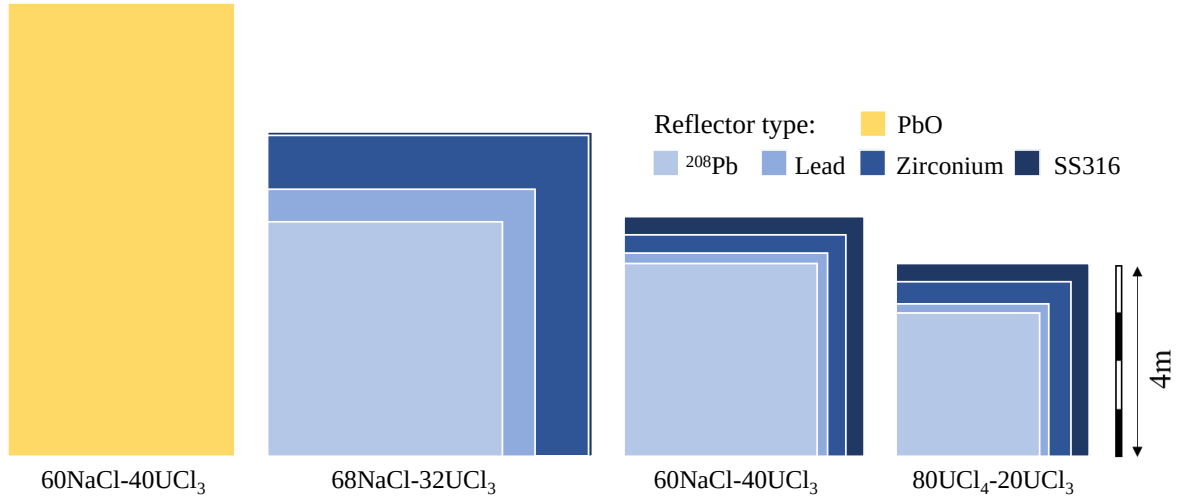

FIG. 3. Comparison of the critical core sizes for HDR=1 (HDR=2 for Fuel tap concept) in open breed-and-burn U-Pu cycle for several chloride salts and several reflector types, inclusive PbO used in the Fuel tap concept [7, 22].

The open breed-and-burn cycle mode requires higher neutron excess to sustain the breeding, because it should compensate the bred fuel losses and allow operation with higher fertile fuel share and at higher burnup levels [26]. Accordingly, the single-fluid MCFR breed-and-burn cores can be bulky. The size strongly depends on the selected salt and on the neutron reflector. To illustrate the volume range, results from [7] are adopted in FIG. 3 and compared with the size of Fuel tap concept from [22].

The result shown in FIG. 2 and FIG. 3 were simulated by EQL0D routine. The equilibrium fuel cycle was obtained for all cases. The achieved burnup differs between the cases and was selected so that k_{inf} is maximal. It is obvious that with growing Ac share in the fuel salt the respective k_{inf} increases. The higher Ac density also reduces the migration area. As a result, the breed-and-burn core is the smallest for the $80UCl_4$-$20UCl_3$ salt, where NaCl is absenting. From evaluated reflectors, the best performance is provided by enriched lead ^{208}Pb. However, it is not so different from natural lead, which leads to only small degradation of performance and core volume increase. The application of PbO introduces additional performance degradation when compared to natural lead [22]. Accordingly, it is not the reflector of choice, when core size is the ultimate priority. FIG. 3 also illustrates that the selection of HDR=2 is not optimal from a salt volume perspective.

3.2. Salt composition discussion

The $80UCl_4$-$20UCl_3$ salt mixture has practically the highest Ac density and one of the lowest liquidus temperature [2]. Also pure UCl_4 can has similar density and melting temperature. However, the UCl_4 compound is rather unstable and can cause problems related to redox control and corrosion. The more stable UCl_3 has already much higher liquidus temperature. The two salt mixtures based on NaCl differ by its molar share. The one with higher Ac molar share $60NaCl$-$40UCl_3$ provides smaller critical core than $68NaCl$-$32UCl_3$. Based on recent phase diagram [27], it seems that these salts correspond to the lowest melting temperature for pure uranium and pure plutonium, respectively. Accordingly, the second salt should be rather written as $60NaCl$-$40PuCl_3$. Pure uranium and plutonium salts can be suitable for MCFR breeder based on two-fluids with core-blanket layout. For a single fluid MCFR there will be always a mixture of plutonium and uranium, with exception of fresh fuel load, which may be in deed based on pure uranium. According to [27] and to the Pu/U ratios presented in Table 2 the lowest liquidus temperature for the closed U-Pu cycle (Pu/U~0.19) is provided by $66NaCl$-$5.4PuCl_3$-$28.6UCl_3$ and for the breed-and-burn cycle (Pu/U~0.15) by $66.1NaCl$-$4.4PuCl_3$-$29.5UCl_3$ salt mixtures. Accounting for the transition from fresh uranium fuel, NaCl molar share in the salt should range from 65% to 67%.

3.3. Actinide composition

The Ac composition differs between the four cases presented in FIG. 2 and the breed-and-burn reactor based on the Fuel tap concept. To illustrate these differences, several ratios between atomic concentrations of selected Ac nuclides or their groups in the fuel salt are presented in Table 2. This form of presentation follows the style of [3, 17, 27]. From a thermo-dynamic perspective the elemental share of major Ac is important. In the Th-U cycle the ratio between U and Th elements is 0.19 for fluoride salt and 0.12 for chloride salts. It is coherent with the $^{233}U/^{232}Th$ ratio, which is also lower for the chloride salts. It seems that the amount of higher Ac is larger in the chloride salt case; however, it may be biased by the lower absolute share of ^{233}U. The breed-and-burn cycle is not applicable with ^{232}Th feed; hence, it is presented only for the ^{238}U feed.

In the case of U-Pu cycle the soft spectrum of fluoride salts results in a bigger share of higher Pu nuclides. In chloride salt their production is lower. The lowest share of higher Pu nuclides is presented for the chloride salt based breed-and-burn case. The permanent removal of the fuel salt from the core assures that higher Ac nuclides cannot accumulate as in the closed cycle. The Pu/U ratio is 0.19 in a closed cycle and only 0.15 in the breed-and-burn cycle.

TABLE 2. Ratio between atomic concentrations of selected Ac nuclides or groups in the fuel salt.

Th-U cycle				U-Pu cycle			
Salt Cycle	Fluorides Closed	Chlorides Closed	Chlorides Open B&B	Salt Cycle	Fluorides Closed	Chlorides Closed	Chlorides Open B&B
U / Th	0.19	0.12	-	Pu / U	0.28	0.19	0.15
^{233}U / ^{232}Th	0.13	0.10	-	^{239}Pu / ^{238}U	0.14	0.12	0.10
(U-^{233}U) / ^{233}U	0.45	0.25	-	(Pu-^{239}Pu) / ^{239}Pu	0.98	0.66	0.44
Higher than U / ^{233}U	0.45	0.79	-	Higher than Pu / ^{239}Pu	0.11	0.07	0.04
Fissile / Fertile	0.14	0.10	-	Fissile / Fertile	0.14	0.12	0.10

4. FUEL TAP REACTOR CONCEPT CHARACTERICATION

4.4. Irradiation of initial actinides load

Initial fuel load proposed for the Fuel tap reactor concept representing the 40 % molar of the salt is uranium enriched to 10.7% [22]. In the initial simulation, this fuel was irradiated with presence and absence of different treatments, where the cycle time of case 10 from Table. 1 was used in the last simulation:

1) No treatment at all
2) Gaseous FPs removal
3) Gaseous and metallic FPs removal
4) Gaseous and metallic FPs removal and salt removal (fuel tap)

In all these cases the overall mass of Ac and FPs in the core was kept constant. In the first case, it is actually not really necessary; however, in the other three cases the removed mass of FPs and Ac is replaced by ^{238}U. The initial Ac load in the core is almost 329 tons. Since the power is only 3GW$_{th}$ the positive reactivity excess can be maintained for tens or hundreds years of irradiation. The cycle time selected in the fourth case for salt removal is 142 EFPY (Effective Full Power Years). The cycle time and achieved burnup would differ if the power or the salt volume should be altered. Left FIG. 4 shows that the fuel with no treatment can be irradiated for 60 EFPY before it becomes subcritical. The removal of gaseous FPs prolongs the irradiation by 20 EFPY. However, when also the removal of metallic or actually non-soluble FPs is activated, 300 EFPY irradiation with slightly positive reactivity excess is possible. The fourth case provides infinite irradiation time in the actual breed-and-burn mode. In right FIG. 4 the same k_{eff} values are shown as a function of the FPs share in the active core in FIMA %. This share usually represents a burnup; however, it is not the case in MSRs, where FPs and Ac are continuously removed or added to the core and it will be discussed in detail later. From right FIG. 4 it can be seen that the FPs share in case of full processing with salt removal does not exceed 13 FIMA % for the simulated case with cycle time of 142 EFPY. The figure can be used to estimate also the reactivity weight for gaseous, metallic and soluble FPs. Blue curve represents the weight of all FPs together and reaches FPs share of 20 FIMA %. Removal of gaseous FPs (orange curve) increases the relative share of metallic and soluble FPs and crosses criticality already at 18 FIMA %. Yellow curve dominated by soluble FPs crosses criticality at 27 FIMA %. Accordingly, the relative reactivity weight of metallic FPs is the highest and their removal is thus most important. Grey curve is biased by the simultaneous Ac removal and could not be thus used for FPs weight estimation.

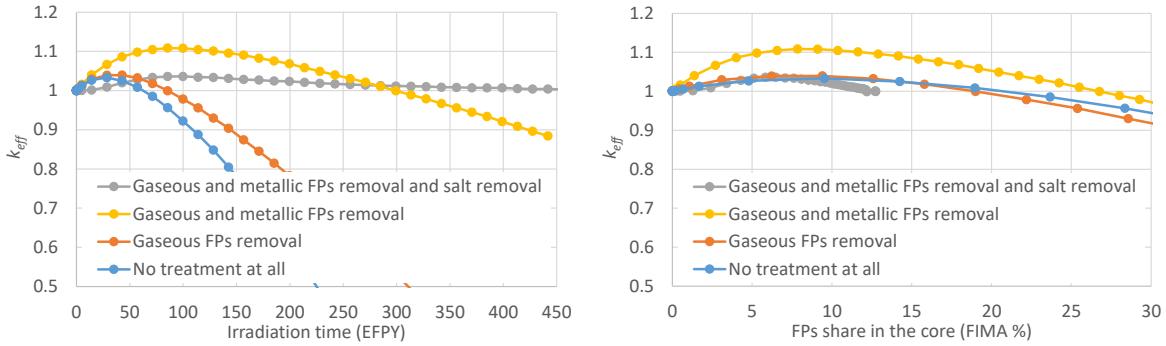

FIG. 4. Explicit irradiation of the initial fuel composition with four different treatments.

4.5. Fuel salt removal rate in the breed-and-burn fuel cycle

As the label “Fuel tap reactor” [22] states, the fuel salt is removed from the reactor with well-defined rate and replaced by salt with solely fertile ^{238}U. The fissile ^{239}Pu must firstly be created by ^{238}U transmutation before it fuels the reactor. Correspondingly, it is called breed-and-burn mode. There are three paths of elements removal from the core: gaseous FPs removal, metallic FPs filtration and fuel salt removal (tap). The impact of cycle time on the core criticality was analysed for several combinations of these removal methods. It is obvious from FIG. 5 that intensive FPs removal through filtration or gas removal will be necessary to reach criticality and enable the operation in breed-and-burn mode. Hypothetically, if all FPs would be removed through filtration or as a gas, fuel salt removal from the core would be not necessary and closed fuel cycle and open breed-and-burn cycle would become the same [28].

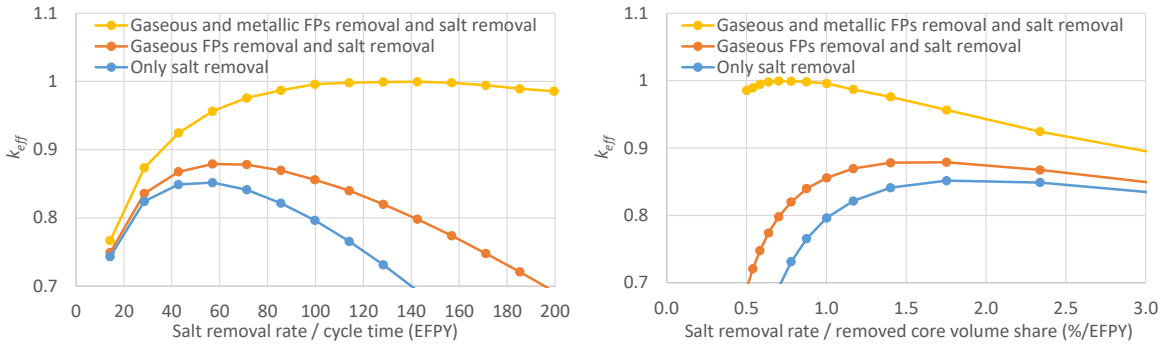

FIG. 5. Dependency of k_{eff} on salt removal rate represented by cycle time (left) and removed salt share (right) and on presence or absence of other FPs removal methods (degassing and filtering).

The core of Fuel tap reactor is just critical for salt removal rates corresponding to cycle time of 120-160 EFPY. Therefore the case with cycle time of 142 EFPY was selected in previous irradiation simulation. Each cycle time corresponds to different volume of salt removed per year. Accordingly, 0.7% of the salt in core is removed per year with cycle time of 142 EFPY. Each removal rate also results in different burnup of the fuel. Since the liquid fuel is homogenized in the reactor and since some FPs are removed from the fuel, classical definition of burnup as a share of FPs in the discharged fuel does not provide the right values. Furthermore, burnup can be defined as the balance between discharged and loaded fuel or as the balance between all Ac in the system and all FPs in the system. These two definitions leads to different results and the former correspond to the later only in equilibrium state after very long irradiation, at which the importance of initial Ac load get smeared. The dependency of burnup on the cycle time and irradiation time is presented in FIG. 6. For all cases, the initial Ac load in the core becomes unimportant with increased irradiation time when equilibrium burnup is approached. This burnup can be obtained also from the balance between fresh loaded salt and spent discharged salt.

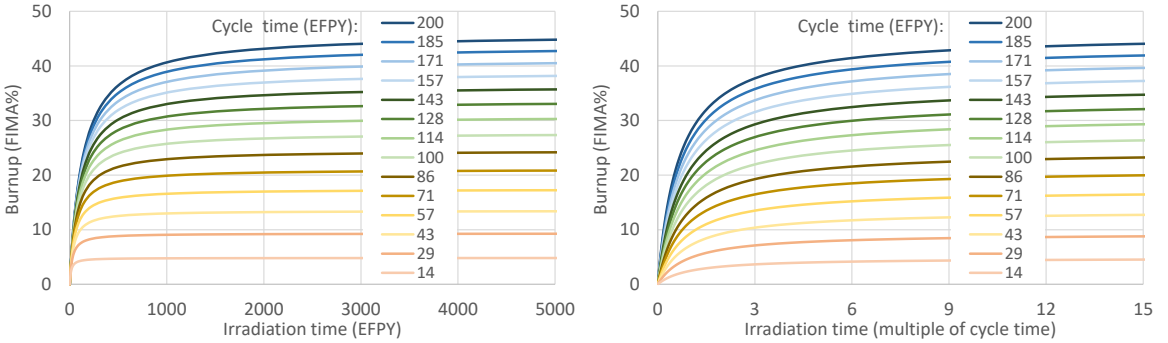

FIG. 6. Evolution of burnup defined as a balance of all Ac and all FPs in the system for different cycle times as a function of irradiation time (left) and of multiple of cycle time (right).

Based on FIG. 6 the Fuel tap reactor with cycle time of 142 EFPY achieves equilibrium burnup of 36.4 FIMA %. However, after one cycle time (see left FIG. 6) it is only 21 FIMA %. Hence, breed-and-burn reactors should be operated for at least multiple of their cycle time to achieve high burnup.

4.6. Transition from initial to equilibrium fuel

Based on left FIG. 4, the reactivity evolution is smooth during the transition between the fresh fuel based on enriched uranium and the equilibrium fuel composition roughly presented in Table. 2. To provide additional insight the major fuel components are presented in FIG. 7. The overall mass of Ac and FPs is staying constant as postulated. The initial Ac mass is reduced by the build-up of FPs share. Similarly, the U mass is decreased by Pu build-up. Obviously, the initial ^{235}U load is swiftly reduced and in less than one cycle time it is completely burned inclusive its daughter product ^{236}U. The share of higher Ac nuclides is very low due to the continuous fuel removal and the ^{239}Pu nuclide is thus accompanied predominantly with ^{240}Pu.

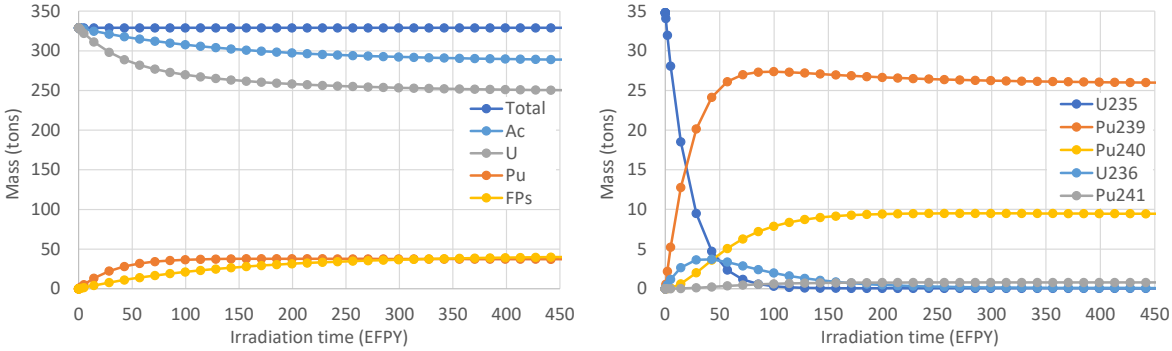

FIG. 7. Mass evolution of selected fuel salt components; total corresponds to sum of Ac and FPs masses.

The plutonium vector in the fuel discharged from a breed-and-burn reactor has according to Table 2 and FIG. 7 higher share of fissile isotopes than the respective plutonium vector form a reactor operated in the closed cycle. At the same time, since the fuel is homogeneously mixed in the core and since only single-salt layout without blankets was analysed, the discharged salt from the reactor correspond to the average fuel composition. Once it is accumulated, the discharges salt can be used for another reactor start up. In this study the salt volume outside of the core was neglected; however, the cycle time generally corresponds to the doubling time. Accordingly, in 142 EFPY the volume of discharged salt will be equal to the volume of the core. Hence, one initial reactor started by enriched uranium, will produce each 142 EFPY fuel for additional rector. This cycle time, or actually doubling time can be shorter for reactors with smaller salt volume or bigger power see FIG. 3 or [7].

The possibility to start new and new reactors opens a question how much high level waste the breed-and-burn reactor produces. To certain perspective the waste is zero. At least if the new reactors are wished. However, it represent kind of Ponzi scheme and soon or later the fuel may be declared as a waste. In that case, the synthetic Ac amount originated per unit of produced energy will be higher for breed-and-burn reactor than for closed cycle breeder. At the same time, similarly like for the closed fuel cycle the plutonium discharged from breed-and-burn reactor can be recycled and reused in a U-Pu breeder or as an initial fuel for Th-U breeder.

5. SUMMARY

MCFRs are promising alternative to MSFRs. They provide very hard neutron spectrum and good neutron economy. Hence, MCFRs can be operated as a breeder in the closed U-Pu and Th-U cycle or as a breed-and-burn reactor in open U-Pu fuel cycle. This high fuel cycle performance is, nonetheless, accompanied by unfavourable fuel salt transparency for neutrons and may result in bulky cores. Therefore, the critical core size and the achievable burnup were the two main objectives of this study.

In this paper, some new and several previous simulations by the EQL0D procedure were combined. The routine was used in all cases to obtain the equilibrium state for either closed fuel cycle or for open breed-and-burn cycle. Both these cycles represent sustainable option how to utilize natural uranium. Its utilization can reach up 95% in closed cycle with recycling and up to 36% in open breed-and-burn cycle without recycling.

The results show that breeding in homogeneous MCFRs is possible in both Th-U and U-Pu closed cycles. However, the Th-U cycle provides much lower k_{inf} and results in a much bigger core when compared to MSFR. The MCFR core size in closed U-Pu cycle is comparable to MSFR core operated in the Th-U cycle. The tight neutron economy of the breed-and-burn cycle causes that the cores are much larger. Increased size reduces neutron leakage and compensates for the absence of fissile Pu recycling after its reduction through salt removal. Both the stabilized Pu and FPs shares in the core deepens on the salt removal rate. It seems that optimal rate should result in 33-36 FIMA % burnup. It should be mentioned here that there are at least two different definition of burnup for any MSRs. The respective cycle time length depends on actinides load and core power. In the case of Fuel tap concept it is around 142 EFPY. It corresponds also to doubling time. The option to operate MCFR in open breed-and-burn cycle mode is, however, conditioned by the presence of gaseous and metallic FPs removal. Furthermore, as for many other reactors with large migration area the core size is directly competing with achievable burnup.

In general, homogeneous MCFRs are interesting alternative to MSFRs and the breed-and-burn mode can postpone the need of fuel recycling by centuries. The performance of heterogeneous fast MSR was not an objective of this paper, because of their design complexity and inferior neutron balance.

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