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Shortening transmutation time by using the molten salt reactor

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ABSTRACT

This paper investigates the duration of the Partitioning and Transmutation process for different efficiencies in the total mass reduction of high-level waste by describing the mass flow during the process. Besides the transmutation and partitioning efficiency per fuel cycle, the impact of the deployed thermal power and the refreshing time, which is the sum of cooling, reprocessing, and fabrication time, was analyzed. It was discovered that besides the transmutation efficiency the refreshing time has a significant impact on the duration. The molten salt reactor concept is proposed in order to realize this potential for shortening the time consuming P&T process.

1. Introduction

The utilization of nuclear power by fission leads to a build-up of radioactive nuclides. While most of the fission products are stable or short lived, the long-lived ones are considered as responsible for the effective dose by a direct disposal in deep geological structures (Renn, 2014; Von Lensa et al., 2008). Together with transuranic elements (TRU), they represent the high level waste (HLW). While plutonium as major part of TRU can be used nowadays as Mixed oxide (MOX) fuel (Carbajo et al., 2001; Ramirez et al., 2012), the minor actinides (MA) such as americium, curium, and neptunium are not considered as fuel for present nuclear power plants.

The further use of TRU and long-lived fission products after Partitioning (P) has been investigated for different fuel cycle strategies (Von Lensa et al., 2008; OECD, 2002; Hyland and Gihm, 2011). Due to its neutronic properties, the usage of MA in critical reactors is limited (Zhang et al., 2013). Therefore, only small MA quantities could be used in homogeneous transmutation cores. This would, however, prevent a build-up of most of the transuranic elements (Ochoa et al., 2013; Song et al., 2008; van Rooijen and Kloosterman, 2009).

A sub-critical reactor, realized by an accelerator-driven system (ADS), allows better core loading flexibility, especially to accommodate very high minor actinide inventories (Malambu et al., 2004; Artioli et al., 2008). Therefore, it is a useful option to incinerate MA efficiently, as suggested in the double-strata fuel cycle (Oigawa et al., 2011).

In conclusion, Partitioning and Transmutation (P&T) offers an opportunity to reduce the quantity of TRUs by converting it into shorter-lived fission products. This could reduce volume, decay heat, and radiotoxicity of the HLW in a long-term disposal. Maximize P&T efficiency requires a high burn-up to minimize the number of reprocessing cycles, in which losses occur. Assuming a high burn-up of 200 MWd/kg_{HM} and a mass loss of 0.1% in each reprocessing cycle, a theoretical P&T efficiency of 99.5% in mass reduction is possible (Magill et al., 2003).

The major source for losses during hydrometallurgical processing, like the PUREX process, occurs by shredding and dissolving the spent fuel rods (Head–End) (Renn, 2014, p.107). Since the molten salt reactor (MSR) is based on liquid fuel, this process step is not required leading to a short reprocessing time. Therefore, MSR, which is part of the generation IV reactor designs (Gen IV International Forum, 2013), should be of particular interest for P&T, as shown and discussed in this paper.

The potential of a high P&T efficiency has been the subject of numerous investigations (Delpech et al., 1999). Although the number of facilities for the P&T process has been mentioned in some studies, no particular attention has been paid to the duration (OECD, 2009). The reason for this might be that the benefit of P&T for final disposal has been of primary interest (Nishihara et al., 2008; González-Romero, 2011).

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The relation between the duration and the efficiency of the P&T process is analyzed in the present paper. In addition to burn-up and reprocessing losses, the refreshing time for the fuel and the deployed thermal power of the facility are considered.

In order to calculate the P&T efficiency, the mass flow within the P&T process is described by five sectors which are defined in the method section. Then, values for the parameters of the calculation are determined. Next, the influence of each parameter is studied by varying one parameter while the others are kept constant. By calculating all possible combinations for the variations, the upper and lower duration for a certain P&T efficiency is obtained. The reasons for the large variation in duration are discussed and, as a result, the molten salt reactor is introduced as a plausible solution to realize the potential of a short duration for any P&T efficiency.

2. Method

In order to calculate the duration necessary to achieve a specific P&T efficiency, the fraction of the mass which has been incinerated has to be documented. For this reason, the mass flow of the P&T process was tracked by five material sectors. According to each sector an equation describes the mass quantity over time.

In contrast to studies for a specific core or fuel design where the irradiated fuel has been recorded with isotopic resolution (Hyland and Gihm, 2011; Malambu et al., 2004), the mass in each sector was considered as sum of all elements. This means that all isotopes were incinerated equally. This simplification is a consequence of investigating not a specific core design, reactor type, or fuel composition. As a result neither the decay of radioactive isotopes nor the influence of the changing fuel composition was investigated.

Instead, all requirements for proper operation were assumed to be fulfilled and since this paper focuses on the duration, the P&T process was influenced by specific parameters only. These parameters are the transmutation and partitioning efficiency, the deployed thermal power, and the refreshing time. Further constant parameters used in the equations are the cycle length and the availability of the facilities.

Using above-mentioned parameters, five mass sectors were characterized. These sectors are the storage of manufactured nuclear fuel for use in the reactor m_s, the inventory within the reactor m_I, the fuel in the refreshing process m_R, the overall losses m_L, and the incinerated material m_T (Fig. 1). The refreshing time was defined as the time for cooling and reprocessing of the spent fuel and fabrication of new fuel assemblies.

The section for the manufactured nuclear fuel in storage was the starting point for material flow development. At time step zero it was assumed that all TRU elements are available as manufactured nuclear fuel. The development of the stored nuclear fuel $m_s(t)$ is described by

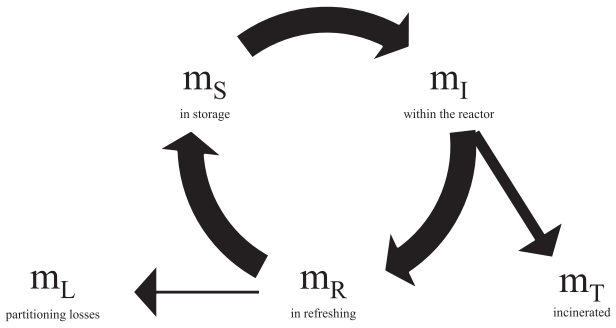

Fig. 1. Scheme of the material flow represented by material sectors.

$$m_s(t) = m_s(t-1) - m_I(t-1)/CL + m_I(t-1-t_R) * \epsilon_P * (1-\epsilon_T)/CL + (m_I(t-1) - m_I(t)) \quad (1)$$

The additional mass sections used are m_I, which represents the mass of TRU elements in the reactors, and m_R, which is the mass fed back from the refreshing process. The first term represents the mass at the previous time step. The second term describes the extraction of fuel due to cycle length (CL) in the core. CL was chosen to be four years according to previous transmutation investigations (Biss, 2014). The third term represents the recirculation from the refreshing process from mass entered into refreshing at time $t-1-t_R$. This mass is reduced by the transmutation efficiency ϵ_T and partitioning efficiency ϵ_P. The fourth and last term considers changes in the usage of the deployed power plants and therefore the change of the inventory mass of the reactor cores. For example, a reduced usage of the deployed power leads to an increase in the storage mass since the inventory mass is reduced.

This handling is based on the assumption that burn-up and cycle length remain unchanged. This means that changing fuel composition and its impact on the reactor system were compensated. This is a challenge as in fertile free fuel like it is the case for TRU fuel reactivity loss is high, which reduces the cycle length. On the other side, including fertile material would decrease the burn-up rate, but stabilize the cycle length. One strategy might be the usage of a fertile free fuel in the first stage. Reactivity loss could be compensated by an increase in the proton beam in ADS. In the second stage, a switch to another fuel composition with thorium as fertile material could ensure longer irradiation time, but decreasing transmutation efficiency for TRU elements (Biss, 2014). Technical challenges like higher neutron flux, higher neutron source in case of an ADS, the switch to another reactor core, or the reduction of the transmutation zone by replacing fuel assemblies with reflector material were not discussed, since the present paper focuses on the duration of the P&T process.

One important fact for the application of the formula is that mass sectors are changed at the beginning of the time period. For example, at time step t equals zero the reactors are loaded, but there is no mass which has been incinerated or is in the refreshing process. Therefore, m_R and m_T are zero.

The inventory mass m_I is derived by

$$m_I(t) = (P_i * AV * CL/\epsilon_T) * (uta * P_m); uta \in [0, P_i/P_m] \subset \mathbb{N} \quad (2)$$

The minimal thermal power P_m also represents the smallest possible change of the deployed thermal power P_i. AV stands for availability of the facility and was set to 0.85 (OECD, 2009, p. 48). During the burn-up time in the core, the fraction ϵ_T is incinerated by nuclear fission. Altogether, the factor within the first brackets represents the fissionable mass by using the conversion of 1 $MW_{th}d$ equals 1 g of incinerated fissile material. The second factor describes the utilization of the deployed power capacity by multiplying P_m by its integer multiple, designated uta. Since a time step describes the situation at the beginning of the time period, m_I represents the amount of fissile material in a fully loaded reactor. It should be noted again that at that point the transmutation efficiency ϵ_T corresponds to the fuel burn-up. As a consequence, this description of m_I is only valid for fertile free systems, because additional heavy metal for a breeding process is unnecessary.

The mass in the refreshing process is described by

$$m_R(t) = m_R(t-1) + m_I(t-1) * (1-\epsilon_T) * \epsilon_P/CL - m_I(t-1-t_R) * (1-\epsilon_T) * \epsilon_P/CL \quad (3)$$

The first term describes the mass that was in the refreshing process in the previous time step. Additionally, the second term adds the amount of material which went into the refreshing process at the end of the previous time step. The inventory mass from the previous

time step is taken as starting point for calculation. The fraction of $1/CL$ is replaced from the reactor in every time step. Furthermore, only fissile material is fed into the reprocessing process. Since it was assumed that all fuel assemblies have the same burn-up characteristics, the factor $(1-\epsilon_T)$ is considered to be constant for all refreshing processes. The fraction which is lost during the partitioning is immediately excluded by multiplying the term by the partitioning efficiency ϵ_P. Finally, the third term represents the recirculation into m_s after the refreshing time t_R. It describes the same situation as the second term, but at time $t-1-t_R$.

The mass which is transmuted into fission products is described by

$$m_T(t) = m_T(t-1) + m_I(t-1) * \epsilon_T/CL \tag{4}$$

In addition to the already transmuted mass $m_T(t-1)$, the mass transmuted in the previous time step is added with the second term. This is realized by multiplying the inventory mass m_I by ϵ_T/CL. The P&T efficiency ϵ_{PT} for transuranic elements is calculated by dividing m_T by the initial fissile mass.

The last mass sector represents the losses due to the refreshing process, which is the process chain of cooling and reprocessing spent fuel and fabrication of new fuel assemblies.

$$m_L(t) = m_L(t-1) + m_I(t-1)/CL * (1-\epsilon_T) * (1-\epsilon_P) \tag{5}$$

It was assumed that losses only occur during reprocessing. This process can be characterized by three steps: shredding and dissolving, separation of the elements, and fabrication of new fuel assemblies. In this paper only the overall losses were considered. There was no differentiation between different partitioning processes such us hydrometallurgical or pyro-chemical. The first term for the description of losses during P&T represents existing losses. The second term is similar to the second term of Eq. (3) and describes the mass which has been unloaded from the reactor for reprocessing. Instead of the partitioning efficiency ϵ_P, the factor $(1-\epsilon_P)$ is multiplied by this amount. Since there is no decreasing term, m_L increases monotonously and limits the P&T efficiency.

Besides the proper description of the material flow, controllability of the deployed thermal power was necessary for the simulation. As introduced in Eq. (2), *uta* allows an integer multiple of the minimal possible power P_m to be used. In each time step power can be increased or reduced. For simulation, the increase or decrease was calculated by the available mass. Reduction of used deployed power was caused by an insufficient amount of fuel needed for current power.

3. Calculation

In order to run proper simulations to estimate the duration of the partitioning and transmutation process, a set of values for the parameters described in the method section has to be chosen. The parameters transmutation efficiency ϵ_T and partitioning efficiency ϵ_P were selected on the basis of literature values. In addition to these parameters, the set of parameters for deployed thermal power and refreshing time were chosen. After input data are described in the present section, the simulation run is briefly presented leading directly to the results section.

The theoretical maximal efficiency of the partitioning and transmutation process has been calculated as 99.5% (Magill et al., 2003). This calculation has been based on a transmutation efficiency ϵ_T of 0.20 and a partitioning efficiency ϵ_P of 0.999. Both values are best case assumptions if there is a high share of minor actinides. Especially for the transmutation efficiency, the value of 0.20 has been assumed to be a reasonable limitation, which is caused by neutronic behavior like neutron flux, neutron effluences, embrittlement, or decay heat. Therefore, lower efficiencies of 0.10 and 0.15 were included in the set for the burn-up and have been achieved in special reactor designs (Artioli et al., 2008).

Even if the partitioning efficiency of 0.999 has already been established for the PUREX process (Salvatores and Palmiotti, 2011), this value is rather high for fuel containing a high share of minor actinides. Especially the transmutation of Am-241 leads to a build-up of Cm-242, which causes a high decay heat and alpha emission due to its half-life of 183 days. Furthermore, emission of neutrons, which are harder to shield, hinders reprocessing. However, these are only physical challenges. The chemical ones are those which determine the efficiency. In the case of MA separation, the difficulty lies in the chemical similarity to the lanthanides (Salvatores and Palmiotti, 2011). An overview of R&D for the pyro-chemical processes is given in Nawada and Fukuda (2005). In order to show the impact of the efficiency, a high efficiency of 0.9995 and a lower one of 0.995 were included in the set for the partitioning efficiency. Although in liquid fuel concept like in the MSR shredding, additional dissolving, and fabrication of new fuel assemblies would be redundant, there was no differentiation in the efficiency between the partitioning processes. This choice was justified by lower experience in pyro-chemical processes.

Another parameter is the thermal power deployed for the transmutation process. Besides possible economic considerations, this power was limited by the inventory mass m_I. For simulation, a deployed thermal power was assumed, which leads to a first loaded inventory of 1/3 and 1/6 of the total transuranic mass. The deployed power varies due to the fact that m_I is dependent on the transmutation efficiency (see Eq. (2)). Nevertheless, the choice of expressing the deployed power in terms of the fraction of the total inventory rather than the installed power in thermal units was due to the fact that this present paper investigates the duration of the P&T process independent of the absolute mass, which is going to be transmuted.

The refreshing time t_R is the last parameter for the calculation. It is the time for cooling and reprocessing of spent fuel and fabrication of new fuel assemblies. The cooling and reprocessing time depends on fuel type and burn-up, because they determine the level of alpha, gamma, and neutron emissions of spent fuel. A minimum cooling time of 5 years before reprocessing is currently required, followed by a fuel ageing time of 2 years before repeated irradiation in a reactor (Grouiller et al., 2003; Camarcat et al., 2011). For a fuel type with higher content of minor actinides, as in the case of spent MOX fuel, a refreshing time of 10 years has been assumed (Ishida and Sekimoto, 2010). However, a refreshing time of 3 years has been considered feasible with a cooling time of 2.5 years and a reprocessing and manufacturing time of six months (Fiorina et al., 2013). For this reason the values for the refreshing time were chosen as 3, 7, and 10 years.

Additionally to this set, a calculation was performed for a refreshing time of one year and no refreshing time at all. While no refreshing time is considered as the optimal value, the refreshing time of one year is based on the assumption to use the molten salt reactor (LeBlanc, 2010). By using liquid fuel, reprocessing is a continuous process. Helium bubbling allows a gaseous extraction of all gaseous fission products and noble metals (Delpech et al., 2009). Although the removal of most fission products and actinides is taken place off-line, the continuous reprocessing allow the reprocessing of the entire core volume within 450 days (Heuer et al., 2014). In the US ORNL–MSBR concept the reprocessing time of less than 10 days were considered to achieve better breeding performances (Robertson, 1971).

Table 1 presents an overview of all parameter sets. The duration for seven efficiencies is presented in figures in which one parameter is flexible and the other three are kept constant. This is done in order to discuss the impact of the flexible parameter.

Table 1
Set of parameters used to investigate the duration of the P&T process.

Parameter	Set of values
Transmutation efficiency	10%, 15%, 20%
Partitioning efficiency	99.50%, 99.90% 99.95%
Deployed thermal power	1/6 and 1/3 of initial transuranic mass
Refreshing time	0, 1, 3, 7, 10 years

4. Results

The transmutation of transuranic elements has been considered in studies about a sustainable nuclear fuel cycle (closed fuel cycle) (González-Romero, 2011; Camarcat et al., 2011; Fiorina et al., 2013). In these studies, the duration has not been of specific interest since a long-term use of nuclear power has been assumed. In the case of nuclear power being phased out, the duration of the transmutation of the final HLW has been investigated in principle rather than in detail. Instead, the benefit of the P&T process for a final repository has been discussed.

With the parameters described in the methods section, the present paper focuses on the duration of the P&T process, which was investigated independent of a specific reactor or fuel concept. The duration was calculated for 90 different combinations for the partitioning and transmutation process. The impact of each parameter is discussed separately in the following.

The influence of partitioning efficiency is shown in Fig. 2. Up to a transmutation of 80%, differences between partitioning efficiencies are insignificant. At 90% the duration of the two higher efficiencies is still similar while the deviation of the lowest one rises by 5 and 16 years for P&T efficiencies of 90 and 95%, respectively. P&T efficiencies higher than 95% are only possible for higher partitioning efficiencies. This is consistent with the calculation of the maximal P&T efficiency

$$\epsilon_{PT} = \frac{\epsilon_P \epsilon_T}{1 - (1 - \epsilon_T)\epsilon_P} \tag{6}$$

derived by Magill et al. (2003). The P&T efficiency ϵ_{PT} depends on the transmutation efficiency ϵ_T and the partitioning efficiency ϵ_P. For a P&T efficiency close to 1, the difference at the duration due to the partitioning efficiency becomes substantial. There, difference in the available mass between the efficiencies is found to be significant.

Furthermore, it can be seen from the Eq. (6) that also the transmutation efficiency influences the achievable P&T efficiency at a given partitioning efficiency. However, for reasons of clarity, the other parameters are kept constant while discussing one specific parameter. As a consequence, the transmutation efficiency variation is varied next.

The transmutation efficiency is one of the most important parameters for the reactor design. It is, however, difficult to achieve high burn-up levels because the irradiation causes an increasing He pressure and decay heat in the solid fuel as well as swelling or deteriorating of it. A burn-up of 200 MWd/kg_{HM} was considered as the highest value in multirecycling. This level is necessary to achieve a P&T efficiency of 99.5% as shown in Fig. 3.

Apart from the highest P&T efficiencies, the duration is almost anti-proportional to the burn-up levels. This is expected since the burn-up represents the amount incinerated per fuel cycle. As a result, duration is halved when burn-up level is doubled. Due to the refreshing time and the partitioning efficiency, however, duration for lower burn-up levels increases faster and the anti-proportional relation between different burn-up levels weakens. This makes a higher burn-up level even more desirable. Consequently, a high burn-up is not only important for realizing high P&T efficiency, but for a short P&T process as well.

Another parameter that influences the duration is the thermal power deployed at the beginning of the P&T process. As mentioned above, the power is expressed by the fraction of the loaded inventory and the total available inventory at the beginning of the P&T process. The values of 0.17 and 0.33 are quite high and were chosen to minimize duration as much as possible by this parameter. As shown in Fig. 4, the impact on duration does not seem to be appreciable. Only for lower P&T efficiencies does the influence of doubling the deployed power seem to be noteworthy. In addition, the time difference between the two cases seems to be time independent.

The reason for the low and constant impact of the deployed power is its utilization. In the case of higher deployed power, the inventory is used up after two fuel cycles. After that, refreshing time of 7 years prevents full utilization of deployed capacity. As a consequence, refreshing time is set to zero in order to maximize the period where the deployed power can be fully used (Fig. 5). As a result of this change, the reduction in the duration for a P&T efficiency of 50% is almost proportional to the ratio of deployed

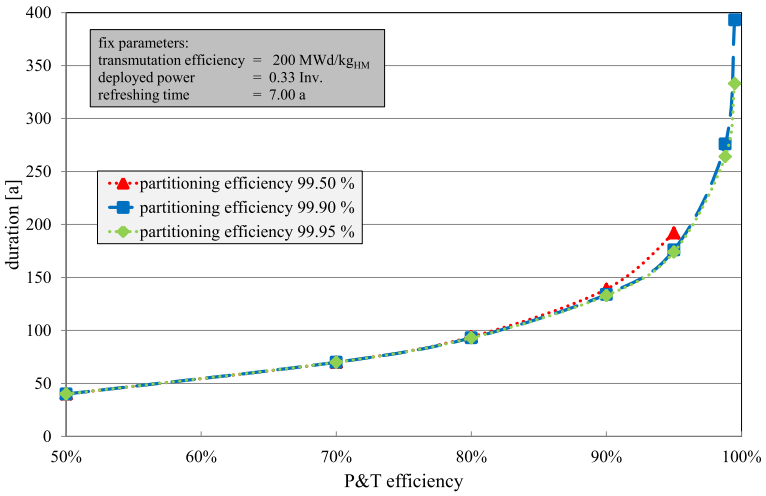

Fig. 2. Duration for achieving a certain P&T efficiency by varying the partitioning efficiency ϵ_P and maintaining values for transmutation efficiency, deployed power and refreshing time.

powers. For a P&T efficiency of 70%, the gap between the two curves increases to 42 years and remains constant for higher efficiencies. This is due the fact that the higher deployed power is only an advantage at the beginning of the process. After a few fuel cycles, utilization decreases because there is not enough fuel for full utilization. However, as long as utilization is larger than for the lower deployed power the duration of the P&T process is reduced in comparison. In case of no refreshing time, this reduction is 42 years.

The last parameter investigated is the refreshing time. It covers cooling and reprocessing of spent fuel and fabrication of new fuel assemblies. The direct influence of this parameter on the duration of the P&T process is shown in Fig. 6. Although the impact is not as great as for the transmutation efficiency, the reduction is appreciable, especially for higher P&T efficiencies.

Neglecting the impact of the refreshing time, the latter will probably increase to 10 years due to the higher burn-up and MA content. In this way, the P&T process is extended by about almost a century for a P&T efficiency of 95% in comparison to the refreshing time of 3 years. The value of 10 years for refreshing describes the business as usual scenario while the value of 3 years stands for the technically feasible refreshing time for solid fuel, according to the discussion in the calculation section.

In addition, the use of liquid fuel with on-line reprocessing could make a cooling and new fabrication of fuel assemblies unnecessary. The reprocessing time in a molten salt reactor has been estimated to be 1 year (Sheu et al., 2013), which is more a theoretical value because the reprocessing takes place continuously. With such a short refreshing time, a duration of less than 230 years for achieving a P&T efficiency of 99.5% is possible as can be seen in Fig. 7. Therefore, the refreshing time has to be considered as an important parameter in order to realize high P&T efficiencies in a shorter time. Especially for these efficiencies, the refreshing time becomes an essential factor for the duration.

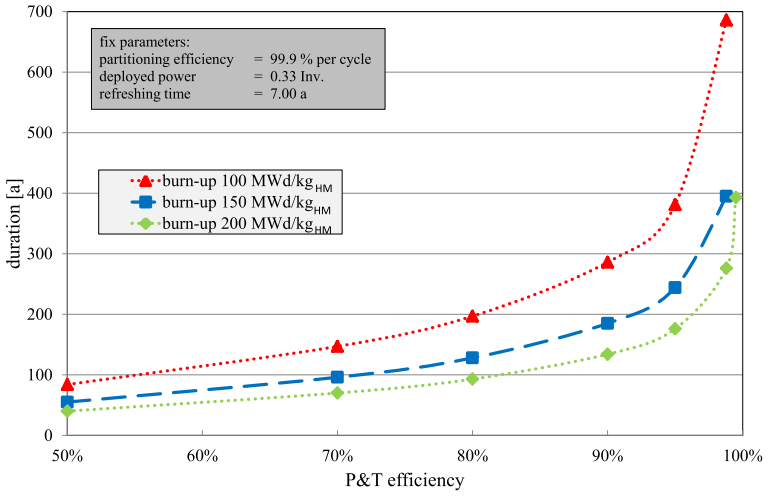

Fig. 3. Duration for achieving a certain P&T efficiency by varying the transmutation efficiency ϵ_T and maintaining values for partitioning efficiency, deployed power and refreshing time.

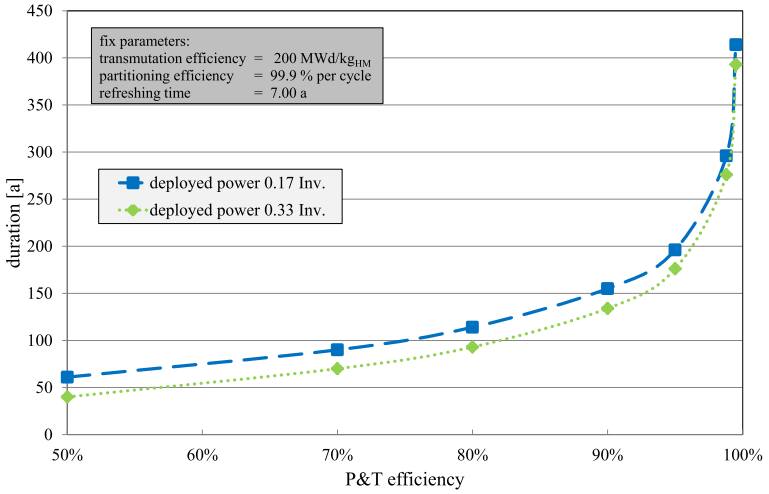

Fig. 4. Duration for achieving a certain P&T efficiency by varying the deployed power and maintaining values for transmutation and partitioning efficiency and refreshing time.

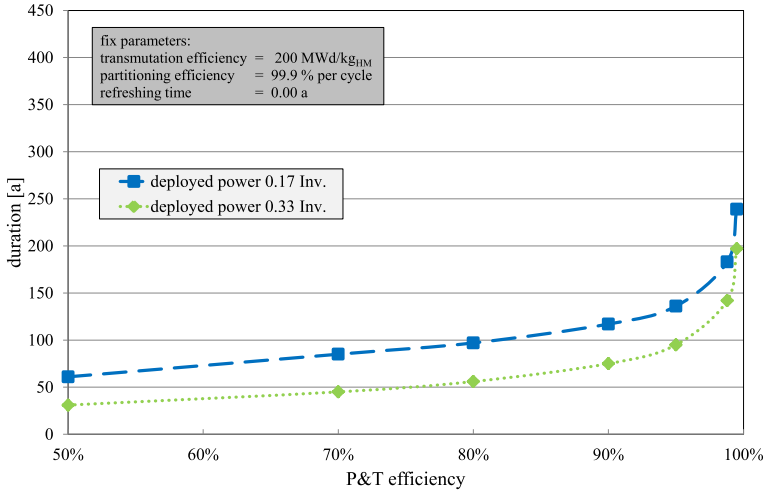

Fig. 5. Duration for achieving a certain P&T efficiency by varying the deployed power and maintaining values for transmutation efficiency and deployed power. The refreshing time is not considered.

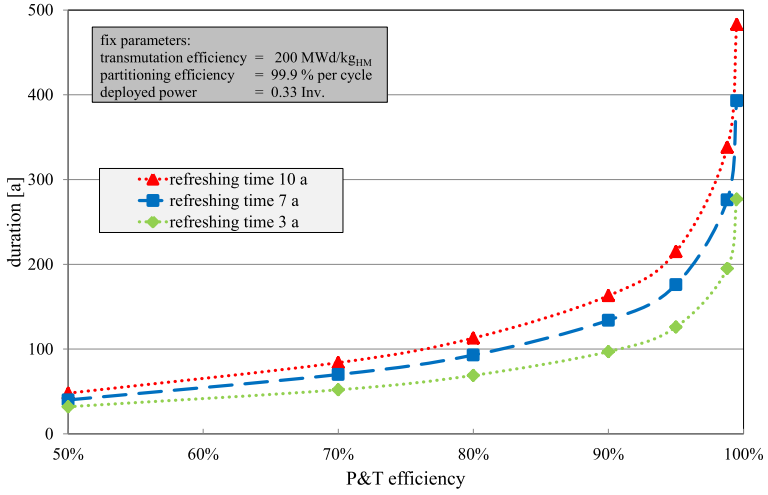

Fig. 6. Duration for achieving a certain P&T efficiency by varying the refreshing time for solid fuel and maintaining values for transmutation and partitioning efficiency and deployed power.

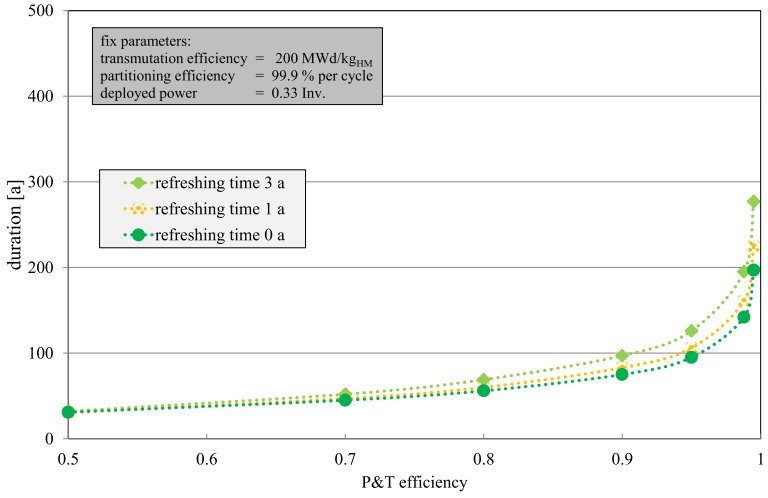

Fig. 7. Duration for achieving a certain P&T efficiency by varying the refreshing time for solid (3 years) and liquid fuel (0, 1 year) and maintaining values for transmutation and partitioning efficiency and deployed power.

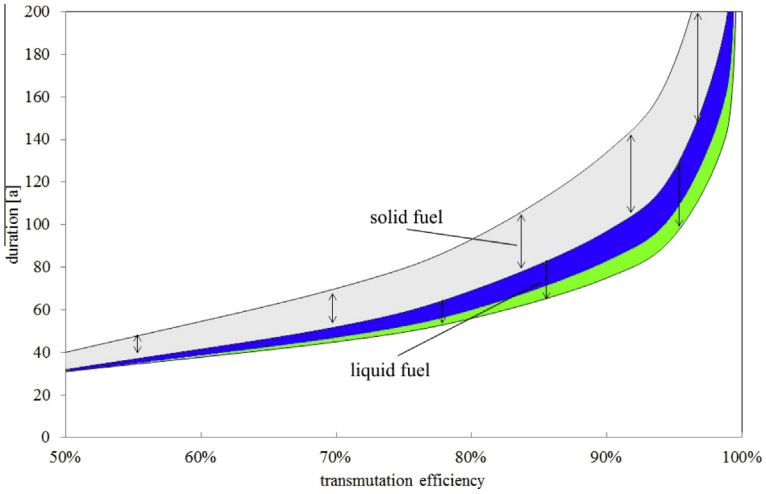

Fig. 8. Duration for achieving a certain P&T efficiency for different refreshing times and the maintained parameters burn-up (200 MWd/kg_{HM}), partitioning efficiency (99.9%), and deployed thermal power (0.33 Inv.). The refreshing time (sum of cooling, reprocessing and fabrication time) is in the range of 3–7 years for solid fuel. For liquid fuel, a refreshing time of 1 year (blue area) and none at all (green area) was considered. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

5. Discussion

In the following approximations made for the calculations are discussed. Moreover, the molten salt reactor is described in more detail because this reactor concept could be the key for a short P&T process.

One approximation was constant transmutation efficiency during the P&T process. Especially for the ambitious rate of 20% per cycle, several challenges were assumed to be solved. For starters, only fertile free fuel consisting of TRU was used. By that, a high content of plutonium would be necessary to reach criticality. The reactivity loss would be high, since no breeding of new fissile material was assumed. The transmutation of americium into plutonium might stabilize the k_{eff} but only if americium content is high enough (Artioli et al., 2008). Based on the composition of TRU, this is not the case in a phase-out scenario (Biss, 2014). Reactivity loss would make it necessary to feed new fissile material which shortens the cycle length. Conversely, the cycle length was kept constant too. Despite the cycle length, the changing plutonium vector would decrease the reactivity gained by refueling reprocessed fuel into a core. As a consequence of a constant burn-up and cycle length approximation, the calculation for a given transmutation efficiency underestimates the duration.

A solution might be the usage of ADS at beginning of P&T as a single-facility type solution because a high burn-up for TRU can be achieved per fuel cycle (OECD, 2009). By increasing proton beam, reactivity loss can be compensated to a certain extend allowing additional flexibility for ensuring the assumed conditions for burn-up and cycle length. Alternatively, the MSR could be used already in this phase because it has also high fuel flexibility regarding to fuel composition (Ignatiev et al., 2014) and additionally provide a low refreshing time. At a certain point the unfavorable remaining plutonium vector would make it necessary to switch to fuel with breeding material. In this second phase, the molten salt reactor could be used to incinerate the remaining TRU and breeding new fissile material by thorium. The usage of thorium would prevent the build up of new TRU. But also in this solution, it needs to be kept in mind that with decreasing amount of TRU in the core more and more fission taking place by the breeded material causing a longer irradiation time to achieve aspired burn-up for TRU. Avoiding of running a breeder reactor at the end limits this phase as well. Furthermore, left over of breeded U-233 has to be used abroad or the target of reducing the long term effects of TRU is corrupted.

The reason why molten salt reactor is favoured as key for shorting the P&T process lies not only in liquid fuel. Also the safety characteristics are conclusive. The continuous processing and feed in of new fissile material avoid the necessity of initial reactivity reserves (Delpech et al., 2009) and as consequence no burnable poison has to be added. Additionally, as shown for the MOSART design, the strong negative reactivity coefficient of the fuel salt temperature leads to an inherently stable reactor design for all basic transient conditions (LeBlanc, 2010; Zhang et al., 2009). Furthermore, the partitioning losses remain in the fuel. Since in reprocessing the fission products and lanthanides are extracted, losses of such elements remain in the fuel. This reduces the transmutation performance but not overall transmutation efficiency.

Despite the advantages of molten salt reactor, there are still open challenges. For instance, the pyro-chemical process needs still intensive research. Furthermore, "closed safety approaches for liquid fuel reactors in conjunction with the fuel processing has not been developed up to now " (Merk et al., 2014).

Another improvement which could be achieved in the molten salt reactor due to the unnecessary fuel change is the enhancement of the availability. This, however, would only be the case if stability of the structural material is not diminished by the influence of high temperature, high neutron irradiation, and exposition to corrosive media (Merk et al., 2014), which would lead to more frequent breaks caused by maintenance.

6. Conclusion

Partitioning and Transmutation (P&T) offers an opportunity to reduce the quantity of transuranic elements by converting it into fission products. Although decay heat and radiotoxicity would increase in the short term, on the long term P&T would reduce volume, decay heat, and radiotoxicity of long lived HLW in a long-term repository. While these aspects have been investigated extensively, duration of the P&T concept has not been considered as a significant part of the discussion. This is most likely due to the fact that P&T is seen as a part of a long-term strategy for the use of nuclear power. In the case of nuclear power being phased out, however, the duration should be considered in P&T implementation.

Therefore in the present paper, besides the transmutation and partitioning efficiency which determine the P&T efficiency, the parameters refreshing time and deployed power were additionally included in order to estimate a minimal duration. As a result of varying the parameters, the duration can be reduced significantly. In line with previous investigations, transmutation efficiency is the crucial parameter, not only for P&T efficiency but for duration as well.

In addition, it is shown that the refreshing time (sum of cooling, reprocessing, and fabrication time) is the second significant parameter for shortening the duration. It not only reduces the duration directly but also implicitly by increasing the use of a higher deployed capacity at the beginning of the P&T process.

In view of the importance of the refreshing time, the duration is illustrated in Fig. 8 with the best case values for the other parameters. There is quite significant potential for reducing the duration for solid fuel, which follows from a reduction of refreshing time from 7 to 3 years. However, only for liquid fuels a refreshing time under 1 year seems to be achievable, corresponding to a shorter duration. In case of a long-term use of nuclear power, the use of the molten salt reactor concept should strongly be considered.

Since the benefit of P&T has been characterized by different indicators for the final repository such as heat load, volume and radiotoxicity reduction, it has to be kept in mind that in this paper the P&T efficiency only describes the mass reduction. The reduction for the other indicators might be similar but not the same, especially for different periods of storage.

Furthermore, the used parameters were kept constant for the entire calculation, which is especially at the end phase of P&T an approximation. As a consequence of this approximation the calculated duration most likely underestimates the real time for the P&T process.

As a result of the findings in this paper, future work should concentrate on analyzing a proper implementation of the P&T process by considering in particular transmutation efficiency as well as the refreshing time. Additionally, the relation between P&T efficiency, duration, and costs should be investigated to develop a effective strategy for P&T. This includes number, controllability, and installed power of reactors to be built.

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