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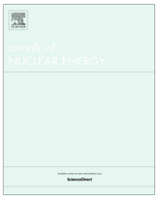

Shortening transmutation time by using the molten salt reactor

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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 $\mathrm{MWd/kg_{HM}}$ 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

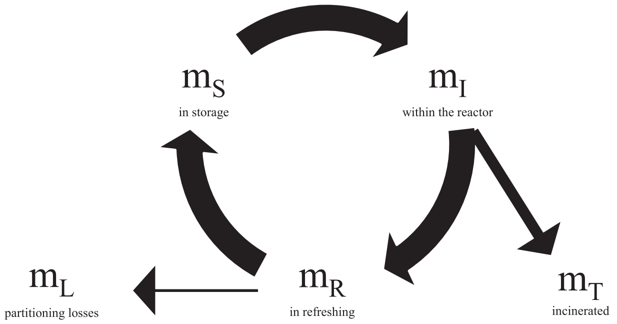

Fig. 1. Scheme of the material flow represented by material sectors.

$$m_s(t) = m_s(t-1) - m_I(t-1)/CL + m_I(t-1-t_R) \ast \epsilon_P \ast (1-\epsilon_T)/CL + (m_I(t-1) - m_I(t)) \tag{1}$$

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

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

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 $\mathrm{MW_{th}d}$ 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

$$m_R(t) = m_R(t-1) + m_I(t-1) \ast (1-\epsilon_T) \ast \epsilon_P/CL - m_I(t-1-t_R) \ast (1-\epsilon_T) \ast \epsilon_P/CL \tag{3}$$

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