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A moderated target design for minor actinide transmutation in sodium-cooled fast reactor

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ABSTRACT

This paper presents a moderated target assembly design study for minor actinide (MA) transmutation in the first-stage sodium-cooled fast reactor (FR) to reduce the amount of MA to be sent to the second-stage accelerator driven system (ADS) in a two-stage FR/ADS fuel cycle option. In order to minimize the local power peaking problem induced by moderated target assemblies, the target assemblies were loaded in the reflector region. Using MA-40Zr target composition and $ZrH_{1.6}$ moderator, an optimum MA target assembly design was developed to maximize the MA destruction within the practical thermal design limits on the cladding inner wall temperature. Long-lived fission product pins were used as thermal neutron filters to reduce the local power peaking in the adjacent fuel assemblies due to the thermal neutron leakage from the moderated target assembly. The performance characteristics of the FR with moderated target assemblies were evaluated by performing detailed neutronics and thermal-hydraulics analyses. Analysis results showed that the use of MA target assemblies reduces the amount of MA to be sent to ADS by a factor of six without deteriorating safety characteristics. As a result, the electricity sharing of ADS in a nuclear park composed of FRs and ADSs was reduced to 0.3% from 1.9%.

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1. Introduction

The Office of Fuel Cycle Technologies of the Department of Energy's Office of Nuclear Energy conducted an Evaluation and Screening (E&S) study to identify potentially promising fuel cycle options aiming at providing substantial improvements as compared to the current fuel cycle in United States, including both benefits and challenges for development (Wigeland et al., 2014). In the E&S study, a comprehensive set of fuel cycle options were represented by an associated set of fuel cycle evaluation groups (EGs), and promising EGs were identified with simultaneous consideration of key fuel cycle characteristics such as continuous recycle of actinide elements, fast neutron spectrum reactors, critical reactors, high internal conversion, and no uranium enrichment required once steady-state conditions are established. However, only a representative fuel cycle option was identified and analyzed for each EG in the E&S study, and hence the remaining fuel cycle options are still to be analyzed.

In order to provide supporting information for the E&S study, a two-stage, fast-spectrum fuel cycle option has recently been proposed aiming at enhancing the natural resource utilization and reducing the nuclear waste to be sent to the geological repository (Lin et al., 2016a,b). The first-stage is a sodium-cooled fast reactor (FR) fuel cycle and the second-stage is a sodium-cooled accelerator driven system (ADS) cycle. Design studies were performed for the FR core (Lin et al., 2015, 2016a,b) and the ADS blanket (Lin et al., 2016a,b). The first-stage FR starts with low-enriched uranium (LEU) fuels, but it can be operated without supporting LEU fuels at equilibrium cycle. U-10Zr and U-Pu-10Zr metal alloy fuels are used as the startup and recycled fuels, respectively. A heterogeneous recycling strategy in which minor actinides (MA) are separated from the driver fuels was adopted because the addition of MA into driver fuels would make fuel handing more difficult due to the intense radiation emissions and heat (NEA, 2012). Plutonium and uranium are co-extracted from the discharged fuels of FR and recycled back into the FR. On the other hand, the recovered MA is sent to the second-stage ADS blanket directly. The second-stage ADS burns the MA recovered from the first-stage FRs in an inert matrix fuel form. The discharged fuels of ADS are reprocessed, and all the recovered heavy metal (HM) is recycled back into the ADS along with the MA from the first-stage FR. All fission products from discharged fuels and the separation and fabrication losses of HMs are sent to the geological repository. Fuel cycle analysis results showed that the proposed two-stage fast spectrum fuel

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cycle option could increase the efficiency of natural resource utilization and reduce the nuclear waste to be sent to the geological repository, compared to the conventional two-stage fuel cycle options based on thermal and fast spectrum systems (Lin et al., 2016a,b).

According to the E&S study (Wigeland et al., 2014), the use of critical reactors lowers overall costs as compared to ADS. In addition, a high risk in operation of ADS needs to be considered when ADS is employed. Therefore, it is highly desirable to minimize the required number of ADSs in the proposed two-stage fuel cycle option. The number of ADSs in the second-stage can be minimized by reducing the amount of MA sent to the second-stage ADS through partial incineration of MA in the first-stage FR. The major MA nuclides in the discharged fuels of FR are Np-237 and Am-241 (Lin et al., 2016a,b), which have relatively small fission-to-absorption cross section ratios in the fast energy range and large thermal capture cross sections (Waltar et al., 2012). These properties of MA suggest that a promising option for incinerating MA in the first-stage FR is to convert Np-237 and Am-241 first into fissile nuclides by neutron capture reactions in moderated target assemblies (NEA, 2012) and then burn the resulting fissile nuclides by fission reactions.

The purpose of this work is to develop an optimum design for the moderated MA target assembly to be used in the first-stage FR and to assess the performance of the proposed two-stage FR/ADS fuel cycle option with the MA target assemblies in the first-stage FR. The design goal of the MA target assembly is to maximize the MA destruction while staying within the imposed thermal design constraints. A significant concern with the utilization of moderator materials in FR is the possibility for localized power peaking either inside the target or in adjacent fuel assemblies (NEA, 2012). Therefore, the optimum moderator fraction in the target assembly needs to be determined in such a way that the MA transmutation performance is maximized while satisfying the peak linear power limits derived from the constraints on the fuel and cladding temperatures. To mitigate the local power peaking problem, the target assemblies can be loaded in the core periphery and long-lived fission product (LLFP) target pins can be used as the thermal neutron filter to reduce the thermal neutron leakage from a target assembly to the neighboring fuel assemblies (Yang et al., 2004). In addition, the impacts of the moderated target assemblies on the safety parameters such as sodium void worth and Doppler coefficient need to be assessed.

This paper presents the developed MA target design and the associated performance of the proposed two-stage fast-spectrum fuel cycle option. This paper is organized as follows. Section 2 presents the optimum MA target design along with the design approaches and constraints. Section 3 discusses the core performance parameters of the first-stage FR with the moderated MA targets. Section 4 describes the fuel cycle performance of the two-stage FR/ADS fuel cycle option with the moderated targets in the first-stage FR. Finally, conclusions are summarized in Section 5.

2. Moderated minor actinide target design

Fig. 1 shows the radial core layout of the 1000 MWt sodium-cooled fast reactor concept developed for the proposed two-stage fuel cycle option (Lin et al., 2015, 2016a,b). The core consists of 186 drivers, 114 reflectors, 66 radial shields, 9 primary control and 4 secondary control assemblies. The cycle length is 18 months with an assumed capacity factor of 90%. It was decided to load MA target assemblies in the reflector region in order to minimize the local power peaking problem induced by moderated target assemblies. An optimum design for the moderated MA target assembly was developed aiming at maximizing the MA transmutation performance while satisfying all the imposed thermal design constraints. The optimal fuel to moderator ratio in the target assembly was determined through parametric studies following the selection of moderating material and MA target composition. This section discusses the selection of moderator and fuel materials, the computational methods and design constraints, and the resulting moderated target design obtained from parametric studies.

2.1. Selection of moderator and target materials

To transmute the Np-237 and Am-241 nuclides effectively, a proper moderating material and MA target composition must be selected. The two most important criteria for the moderating material are a high slowing-down power, which makes the number of collisions required to thermalize neutrons small, and a high slowing-down ratio, which yields a high thermal neutron flux. In considering the MA fuel composition, the important parameters to consider include the thermal conductivity, melting temperature, material density, fabrication cost, and compatibility with materials in the surrounding environment (sodium coolant).

After examining several moderating materials including graphite, zirconium-hydride, zirconium-deutride, yttrium hydride, and cerium hydride, zirconium-hydride was selected as the moderator of the MA target based on its high moderating capability and extensive irradiation experience in TRIGA reactors (IAEA, 2011). Furthermore, zirconium-hydride has relatively high thermal conductivity and decomposition temperature. The stoichiometry for zirconium hydride of 1.6 (i.e., $ZrH_{1.6}$) was selected because it is stable up to a temperature of at least 1000 °C (Moore and Young, 1968).

To take the advantage of the demonstrated performance of metal fuels, the MA-containing metal alloy fuel was selected as the MA target material. The MA fuel composition was chosen to be MA-40Zr under the assumption that it would have similar properties as the Pu-40Zr and Pu-MA-40Zr fuels. Metal fuel samples of Pu-40Zr, Pu-12Am-40Zr and Pu-10Am-10Np-40Zr were irradiated in the Advanced Test Reactor and included in the Advanced Fuel Cycle irradiation test series to evaluate the effects caused by the existence of MAs (Carmack and Pasamehmetoglu, 2008; IAEA, 2010). Recent experimental results showed that the major irradiation performance variables of the metal fuel samples are similar to those of U-Zr and U-Pu-Zr fuels (Carmack and Pasamehmetoglu, 2008; IAEA, 2010), which are the startup and recycled fuel types of the first-stage FR of the two-stage fuel cycle option, respectively.

For the target assembly configuration, a heterogeneous lattice of MA-40Zr target pins and $ZrH_{1.6}$ moderator pins was selected instead of mixing the target and moderator materials. Separate target and moderator pins would make easier fabrication and reprocessing and allow a higher linear power. The thermal neutron leakage from the target assembly to the neighboring fuel assemblies is reduced by replacing some MA target pins with thermal neutron filter pins. In order to reduce the amount of LLFP to be sent to the repository, LLFP is used as the thermal neutron filter.

2.2. Design constraints

The increased moderation in the MA target assembly results in an increased power peaking in the adjacent fuel assemblies and the moderated target assemblies themselves when a significant amount of MAs is converted into fissile nuclides. As a result, the moderator volume fraction in the target assembly is limited by the peak linear power limit on the adjacent fuel assemblies (drivers) and the moderated MA target assemblies. Since the linear power in the target assembly is proportional to the irradiation time (i.e., the core residence time of a target assembly), the target irradiation time is also constrained.

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