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An economic analysis of reactor synergy: Transmuting light water reactor produced americium in heavy water moderated reactors

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ABSTRACT

An economic analysis is presented of a proposed synergy between two nuclear utilities, Utility L that owns light water reactors (LWR) and Utility H that owns heavy water moderated reactors (HWR). Americium is partitioned from LWR spent fuel produced by Utility L and then transmuted in HWRs operated by Utility H. Additionally, reprocessed uranium (RU) from spent LWR fuel is used as fuel for the HWRs to transmute the americium. The analysis is based on the estimated value of RU to Utility L if it is re-enriched using centrifuges and used as LWR fuel, and the estimated cost to Utility L of partitioning americium from spent LWR fuel. In order for this scenario to be economically acceptable to Utility L, the averted disposal cost due to partitioning americium from LWR spent fuel most likely must exceed $230/kg heavy metals in spent nuclear fuel. A sensitivity analysis shows that the cost of partitioning americium from spent LWR fuel has the greatest effect on this value, followed by the cost of natural uranium. During steady state operations, a single HWR should be able to transmute all of the Am-241 from approximately five LWRs using RU from just those reactors as fuel.

1. Introduction

Studies have shown that the partitioning and transmutation (P&T) of americium will improve the performance of geologic repositories for spent nuclear fuel (SNF) from light water reactors (LWR) (Organisation for Economic Co-operation and Development – Nuclear Energy Agency, 2011). It is typically assumed that, following partitioning, minor actinides will be dispositioned by inclusion in fast reactor fuel, but the U.S. experience in the production of super transuranic nuclides (above curium) from americium is that the process is highly inefficient due to the presence of fissile isotopes (Am-242m, Cm-243, Cm-245) in the capture path (Collins et al., 2012). In thermal reactors, the cross section for the fission of these isotopes is much larger than in fast reactors, and the overall minor actinide transmutation efficiency of thermal and fast reactors is comparable. Due to their high neutron economy and highly thermal spectra, heavy water moderated reactors (HWR) may be expected to be particularly efficient as transmutation engines, and this current work builds on previous comparisons of LWRs and HWRs with respect to transmutation efficiency (Hyland et al., 2009) and the potential of HWRs to transmute an unseparated lanthanum, curium and lanthanide stream (Hyland et al., 2011). The purpose of this work is to determine a condition in which a utility owning a fleet of LWRs would economically benefit from separating americium from spent fuel (SF), then transmuting americium in HWRs using RU from spent LWR fuel to provide the extra fissile material to support the process.

Americium-241 is a significant contributor to the decay heat of SNF, and a potential limiting factor to repository capacity. Americium isotopes are produced in enriched uranium fuels via a process of multiple neutron captures and beta decays. Some of the major pathways are shown in Fig. 1. Am-241 is produced mainly by β^- decay of Pu-241 with a 14.29 year half life and hence is created in only small amounts during irradiation, albeit in larger amounts in LWRs than HWRs because of the longer residence time in the former ($\sim$4 years vs. <1 year). The ground state of Am-242 has a short half life of 16.02 h, decaying by either electron capture or β^- decay, and only insignificant quantities are found in SNF. Because of the Pu-241 decay, the critical parameter in the creation of Am-241 in SNF is the amount of time the fuel is in storage outside of the reactor while awaiting P&T. Storage times of between 5 and 30 years are usually envisioned. Longer storage times allow the fission products to decay, allowing easier handling, but lose the value of Pu-241 in the reprocessed MOX fuel.

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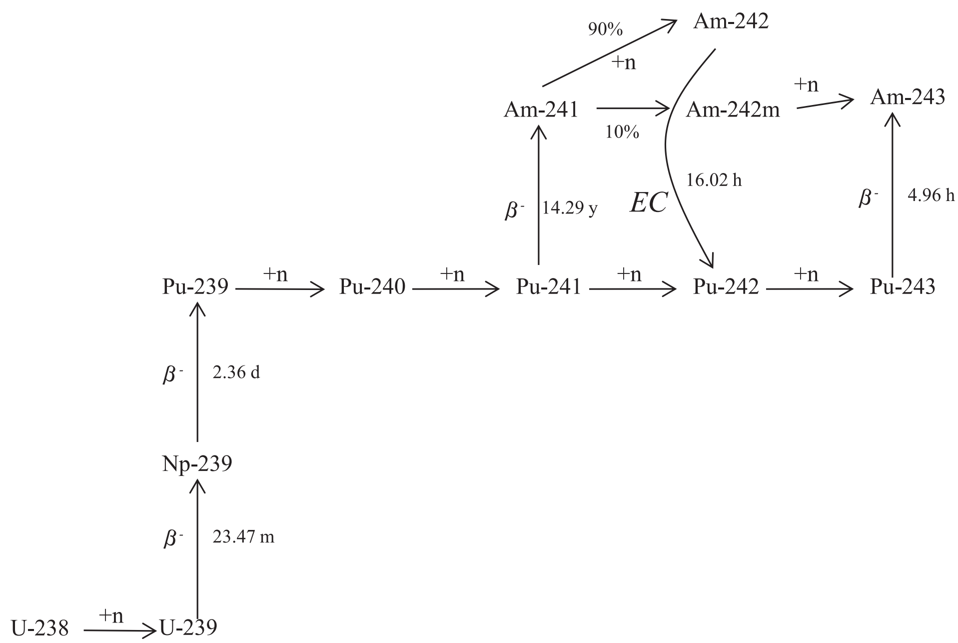

Fig. 1. Production of americium isotopes in a nuclear reactor. Only reactions and decays that lead to americium are shown.

Heavy water moderated reactors have been designed to optimize for neutron economy, allowing them to use natural uranium as fuel. This characteristic may enable HWRs to achieve even higher energy extraction (burnup) from the RU recovered from LWR SNF as this contains amounts of U-235 greater than that found in natural uranium. This additional burnup is tempered by the presence of U-236, a neutron absorber, in the RU.

If americium is partitioned from spent nuclear fuel, one option is to mix it with the reprocessed uranium also separated from LWR SNF and fabricate fuel for HWRs. This study considers fuel which can be taken to the same burnup as natural uranium in an HWR. The irradiation of Am-241 in an HWR will transmute it into other nuclides, mitigating its heat production in geological disposal repositories. This document presents an economic analysis of this P&T scenario, describing the economic conditions under which such a synergy between two nuclear utilities (L, which operates an LWR fleet, and H, which operates an HWR fleet) will be mutually beneficial.

In the scenario under consideration, Utility L is assumed to have already implemented a nuclear fuel cycle where spent LWR fuel is reprocessed to extract the plutonium to make mixed oxide (MOX) fuel (for example, as is currently in use in France). Assuming the use of the industrially common solvent–solvent extraction 'PUREX' process, lanthanides, americium, curium and many fission products are separated and treated as a waste product. In particular, the difficulty of separating americium from curium, which have similar valances, is well known. Some recent work, however, indicates that this might be done (Laidler, 2006; Modolo et al., 2008; Organisation for Economic Co-operation and Development – Nuclear Energy Agency, 2005). The extra expenses incurred by Utility L would therefore be those of partitioning and shipment of americium from the PUREX waste product and the loss of the value of the RU, assuming that RU would otherwise be used as feedstock for enrichment plants making new fuel. The benefit to Utility L would be the averted disposal cost of the americium. The extra expenses incurred by Utility H would be any required upgrades to their fuel handling procedures and equipment due to the extra radioactivity of the fuel, while the benefits to Utility H would be the averted cost of purchasing NU fuel for their reactors. It is assumed that the HWRs can use Am/RU fuel with no design changes to the reactor. In this paper it is assumed that the net benefit to Utility H would be positive, and the conditions under which the net benefit to Utility L would be positive are analyzed. Non-economic factors, such as political and environmental considerations, are not explicitly taken into account in establishing the desirability of this scenario.

2. Physics of transmuting americium in a HWR

HWR reactors, designed to use the low-fissile content natural uranium fuel, can easily be adapted to use other highly absorbing fuels that may be part of advanced fuel cycles. In particular, various kinds of RU, with burnups between 27 GWd/t IHE[1] and 53 GWd/t IHE, were examined in this paper and found to have sufficient extra U-235 for useful americium burning, even tempered by the extra absorption of U-236 inevitably produced from capture on U-235 during irradiation. Multiple neutron absorption in Am-241 and Am-243 leads to fissile isotopes (Pu-239, Cm-243 and Cm-245 as seen in Fig. 2), whose subsequent fission creates small amounts of fission products, although this will not be a major factor due to the short residence time and low burnup (7.5 GWd/t IHE) of this fuel in an HWR. More probable is the creation of actinides having much longer half lives (like Am-243), or much shorter half lives (like Pu-238, Cm-242, Cm-244) which decay by α emission to Pu-238 and Pu-240 over relatively short timescales (162.8 d and 18.1 y respectively), and therefore do not represent significant disposal problems (at least as Cm isotopes) in a repository. (Cm-244 is a significant neutron emitter. The handling problems associated with this isotope, which may be significant, are not investigated here.) The residence time of fuel in an HWR is insufficient to create significant quantities of the problematic heavy, long-lived curium of mass 246 and higher, and as mentioned earlier; it is also insufficient to create significant quantities of americium from U-238 by the processes shown in Fig. 1.

The physics calculations of fuel depletion were performed by the neutron transport code WIMS-AECL v.3.1.2.1 (Altiparmakov,

[1] IHE is initial heavy elements.