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AN ECONOMIC ANALYSIS OF A LIGHT AND HEAVY WATER MODERATED REACTOR SYNERGY: BURNING AMERICIUM USING RECYCLED URANIUM

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AN ECONOMIC ANALYSIS OF A LIGHT AND HEAVY WATER MODERATED REACTOR SYNERGY: BURNING AMERICIUM USING RECYCLED URANIUM

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An economic analysis is presented for a proposed synergistic system between two nuclear utilities, one operating light water reactors (LWR) and another running a fleet of heavy water moderated reactors (HWR). Americium is partitioned from LWR spent nuclear fuel (SNF) to be transmuted in HWRs, with a consequent averted disposal cost to the LWR operator. In return, reprocessed uranium (RU) is supplied to the HWRs in sufficient quantities to support their operation both as power generators and americium burners. Two simplifying assumptions have been made. First, that the economic value of RU is a linear function of the cost of fresh natural uranium (NU), and second, that plutonium recycling for a third utility running a mixed oxide (MOX) fuelled reactor fleet is already taking place, so that the extra cost of americium recycling is manageable. We conclude that, in order for this scenario to be economically attractive to the LWR operator, the averted disposal cost due to partitioning americium from LWR spent fuel must exceed $214/kg, comparable to estimates of the permanent disposal cost of the high level waste (HLW) from reprocessing spent LWR fuel.

I. INTRODUCTION

Studies [1] 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). Due to their low intrinsic production of americium, heavy water moderated reactors (HWR) could potentially be used to transmute americium, and because of the high neutron economy, the reprocessed uranium (RU) from spent LWR fuel is of sufficiently high quality to support HWR operation, even with the increased absorption of the americium, without loss of exit burnup. Assuming a clear net benefit (the fuel) to the HWR operator ('Utility H'), the purpose of this work is to determine the economic conditions under which it is attractive for the LWR operator ('Utility L') to forgo the use of the RU, and incur the extra cost of americium separation from the SNF, to lower their SNF disposal cost.

Americium isotopes, and in particular Am-241, are a significant contributor to the decay heat of SNF and a potential limiting factor to repository capacity. Americium isotopes are produced in uranium fuels via a process of multiple neutron captures and beta decays. The critical step is the creation of Pu-241, whose beta decay creates Am-241 in the fuel. Pu-241 is more concentrated in LWR SNF, principally because the residence time of the fuel is much longer in LWRs than in HWRs (~4 years vs. ~280 days). The decay of Pu-241 continues to produce Am-241 in the fuel outside the reactor during cooling while awaiting P&T.

The half life of Am-241 is inconveniently long, at 432 years, to allow it to decay to insignificance before disposal. While a fast reactor could fission Am-241 from LWR SNF, this technology requires further development to become commercially viable. A third option is to denature it by re-exposing it to a neutron flux in a thermal reactor. In the scenario to be considered here, it is assumed that Utility L has an operational reprocessing plant where LWR SNF is reprocessed to extract the plutonium to make mixed oxide (MOX) fuel to be used in another fleet of reactors. The extra expenses incurred by Utility L would therefore be: the addition of an extra processing step to partition americium, the cost of shipping americium to Utility H, and the loss of the value of the RU as a slightly enriched feedstock for new LWR 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 reactor design changes, and changes to fuel handling procedures to accommodate the radioactive fresh fuel. The benefit to Utility H would be the averted cost of purchasing natural uranium (NU) fuel for their reactors. In this paper it is assumed without analysis 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 have not been considered in establishing the desirability of this scenario.

LWR operators currently have large amounts of spent fuel in storage from decades of nuclear power generation. For example, there is approximately 67,000 tons of spent LWR fuel in the United States alone [2]. The proposed P&T strategy could significantly increase the capacity (e.g. per GWe of nuclear power produced) of a geologic repository required to store this SNF. Therefore, the scenario analyzed here involves spent LWR fuel that is an

approximation of SNF that has been in storage for decades.

II. PHYSICS OF AMERICIUM TRANSMUTATION

HWRs have been designed to optimize neutron economy, allowing the use natural uranium as fuel. This characteristic enables HWRs to achieve even higher energy extraction (burnup) from the RU recovered from LWR SNF, as this normally contains a concentration of U-235 greater than that found in natural uranium. Alternatively, the extra fissile content of RU could be used, as is assumed here, to recover the same burnup as NU and, in addition, expose Am-241 and Am-243 (mixed into the RU during fuel fabrication) to a high neutron fluence in order to transmute as much of it as possible thereby removing it from the waste stream.

Thermal neutron absorption by Am-241 and Am-243 leads to fissile nuclides (such as Am-242m, Cm-243, Cm-245 and Pu-239), whose subsequent fission creates isotopes that are less problematic for waste disposal and, in particular, considerably shorter-lived than the americiums. Other curium isotopes created would be Cm-242 and Cm-244[1], both of which decay relatively rapidly by α emission to Pu-238 and Pu-240 respectively. The relatively short irradiation time in the HWR fuel cycle suppresses the creation of higher mass curium isotopes (Cm-246 and above), which are considerably radiotoxic and long-lived and would cause difficulty for long-term disposal. The end result of americium irradiation, then, would be a reduced actinide mass dominated by even-mass plutoniums. This waste would be more straightforward to dispose of than the initial Am-241/Am-243.

Lattice physics calculations of fuel depletion were performed by the neutron transport code WIMS-AECL v.3.1.2.1 [3] with an ENDF/B-VII based library [4]. The bundle geometry was a typical advanced fuel cycle bundle containing 43 fuel elements in four rings, with the center and inner elements being larger than the intermediate and outer elements [5]. The central element was a non-fuel dysprosium/zirconia element designed to reduce coolant-void reactivity in accident scenarios. The WIMS-AECL code was used to simulate a bundle running at a constant power typical of an HWR (32 W/g IHE[2]) from fresh composition to its exit burnup under conditions of no leakage until the time-integrated k_∞ (an estimate of the average excess neutron production of the all the bundles in the reactor, each at a different burnup step along the single-bundle history) fell to 1.03. This value corresponds to a neutron leakage of 3% and is typical of an HWR operating in a configuration without the use of reactivity and flux control devices. For a given RU composition, the initial concentration of americium isotopes in the fuel was adjusted until the exit burnup corresponded to a burnup of 7500 MWd/tonne IHE– a typical burnup for natural uranium fuel.

The Am-241 and Am-243 remaining in the HWR SNF was ~25% and ~80% respectively of the initial amount, depending on the concentration in the initial fuel. This americium residue is assumed to be disposed of with the HWR fuel bundle.

III. ECONOMIC ANALYSIS FORMULATION

The formulation of the problem presented here is based on the formulas given in Appendix A.1.2 in [6]. Specifically, the formulation is based on the net cost of recycling LWR spent fuel without americium partitioning and transmutation per kg of spent fuel, C_{rr} ($/kg HE). If Utility L partitions the americium from its spent fuel and sends it along with some RU to Utility H, then the net cost becomes C_{cr} ($/kg HE):

$$C_{cr} = C_{rr} + M_{cU} C_{rU} + C_{sAm} \frac{M_{Am}}{x_{Am}} - C_{dAm} \frac{M_{Am}}{x_{Am}}, \quad (1)$$

where

- HE is the heavy element content of spent nuclear fuel that is reprocessed,
- M_{cU} is the amount of RU (kg/kg HE) that Utility L sends to Utility H,
- C_{rU} is the value ($/kgU) of reprocessed uranium to Utility L,
- C_{sAm} is the cost ($/kg HE) of separating americium from spent LWR fuel,
- M_{Am} is the mass of americium (kg/kg HE) that Utility L sends to Utility H,
- C_{dAm} is the disposal cost ($/kg HE) that is averted due to partitioning americium from the other elements in the high level waste (HLW) from reprocessing LWR spent fuel, and
- x_{Am} is the concentration of Am-241 in spent LWR fuel at the time of reprocessing.

The negative term in equation (1) represents the economic benefit to Utility L in the form of the reduction in disposal costs due to the partitioning and transmutation of americium relative to the direct disposal of americium and other actinides in a geological repository. The cost of partitioning americium from LWR fuel is given per mass of spent LWR fuel, therefore, the denominators in (1) convert the mass of Am-241 into an equivalent mass of spent LWR fuel with the given amount of Am-241. This also permits the distinction between spent LWR fuels with different concentrations of Am in this analysis.

[1] Cm-244 has a half life of 18.1 years, but this is short enough that it can be treated like a fission product and allowed to decay away before disposal.
[2] Initial Heavy Elements

Partitioning and transmuting Am-241 in HWR reactors is economically acceptable to Utility L if the costs of partitioning and transmuting the Am are less than the costs from the reference cycle ($C_{cr} < C_{rr}$), which means that the following condition must be satisfied in order for the transmutation option to be economically acceptable:

$$\left(C_{sAm} - C_{dAm}\right)\frac{M_{Am}}{x_{Am}} + M_{cU}C_{rU} < 0 \qquad (2)$$

In addition to this condition, a sufficient amount of RU must be sent to Utility H to transmute M_{Am} of Am-241. The relationship between M_{cU} and M_{Am} is:

$$M_{cU} = \alpha_{cU}^{Am} M_{Am}, \qquad (3)$$

where the value of α_{cU}^{Am} is determined by the HWR reactor requirements for transmuting Am-241 using RU with a given enrichment. A difficulty in evaluating the condition in (2) is due to the lack of an estimate of C_{dAm}, the reduction in geological disposal costs due to transmuting americium, in the literature. Also, the improvement in repository performance due to transmuting americium depends on the properties of the repository sites, which may vary between geographical regions [1]. Therefore, the economic acceptability of this P&T scenario is presented with respect to the minimum averted disposal cost C_{dAm}^{*} for which this scenario is economically acceptable. Substituting (3) into (2), C_{dAm}^{*} is computed as shown in (4). If the savings in disposal costs achieved by Utility L exceed C_{dAm}^{*}, then the P&T scenario is considered economically beneficial to Utility L.

$$C_{dAm}^{*} = C_{sAm} + x_{Am}\alpha_{cU}^{Am}C_{rU} \qquad (4)$$

IV. DATA

This section presents the values used for the parameters required for the computation of C^{*}_{dAm}.

The cost parameters used in this study are based on estimates used in an OECD NEA report [7] on advanced nuclear fuel cycles and waste management. This is the only known report that provides an estimate of the cost of partitioning americium from spent nuclear fuel. In this NEA report, an advanced Purex process is described that partitions the uranium, plutonium and americium in spent LWR fuel into separate products, the most likely cost of which is \$1000/kg HE[3], \$200/kg HE more than the purex process that leaves americium in the HLW stream. The lower and upper bounds on the cost of partitioning americium are given as \$0 and \$400/kg HE, respectively. Note that this report was published in the year 2006, 7 years ago, therefore estimates of these values may have changed in that time due to improved knowledge of the partitioning process.

Another parameter that is required in this analysis is the cost of natural uranium. The cost of natural uranium to a utility is dependent on market forces which can cause sudden large changes. For example, the spot price of natural uranium rose from approximately \$20/kg U in the year 2000 to nearly \$300/kg U in 2007, and then fell to \$100/kg U in 2012 [8]. Therefore it is assumed that the lower and upper bounds on the cost of natural uranium are \$20 and \$300/kg U respectively.

The other parameters that are required in this analysis are x_{Am}, the concentration of Am-241 in spent LWR fuel, and α_{cU}^{Am}, which governs the amount of RU required to be mixed with americium in the HWR fuel. These parameters depend on the exit burnup, and time since discharge of the LWR fuel. In this study, it is assumed that Utility L would like to reprocess its legacy spent fuel that is low burnup, 33 MWd/kg HE with 0.9242 wt.% U-235 and 0.4088 wt.% U-236 [9], and has been in storage for 30 years on average. In this case α_{cU}^{Am} is 578 kgU/kg Am, and x_{Am} is $1.08\text{x}10^{-3}$ kg Am/kg HE.

V. THE VALUE OF REPROCESSED URANIUM

According to (4), the economic acceptability of transmuting Am-241 produced in LWRs in Utility L using HWR reactors in Utility H depends on the value (to Utility L) of the RU that Utility L must also send to Utility H. Currently RU is considered a waste product, and demand for RU is too low for a functioning market. In this work, we have assumed that, in the future, recycling of RU into nuclear fuel will be widespread. Some possibilities for its re-use are: to be mixed with Pu and recycled as MOX fuel for converted LWRs, to be mixed with DU and sold as natural-uranium equivalent (NUE) fuel to HWRs, or to be used as a feedstock for re-enrichment into LWR fuel. Because the world is currently dominated by LWRs running a once-through fuel cycle, and will be for many decades, we have assumed for the purpose of analysis that the value of RU will be based on this last option.

The cost of enriched fuel from a feed with cost C_F (\$/kg), ignoring all losses and finance charges, is (from [6], eqn. A.10):

$$C_{LEU} = R(F)(C_F + C_{Fc}) + S(R)C_{Fs} + C_{Ff}, \qquad (5)$$

where R is the product to feed mass ratio (which depends on the product enrichment and tails assay), S is the number of separative work units (SWU) required to

[3] U.S. dollars

achieve R, and C_{Fc}, C_{Fs} and C_{Ff} are the costs of conversion, a single SWU, and fuel fabrication respectively. These last three costs will be slightly higher when using an RU feed as opposed to an NU feed because of the extra costs of handling radioactive U-236. R is also a function of the tails assay, and the tails assay is optimized depending on R, so equation (5) can only be solved iteratively. After making appropriate choices for C_{Fc}, C_{Fs} and C_{Ff}, for F = NU and F = RU, the value of RU is defined as that value of C_{rU} which makes C_{LEU} the same for a NU feed as for an RU feed.

It was assumed that the target enrichment was for an LEU fuel equivalent to that in the original reactor. The presence of U-236 in the RU requires that the target enrichment be slightly higher when it comprises the feedstock. A quality factor for spent fuel is defined as $Q = 1 - 0.21[E_{U-236}/E_{U-235}]$. The required LEU enrichment is E_{LEU}*(NU feedstock)/Q*. Q is then applied to the spent fuel enrichment, to generate a 'spent fuel quality':

$$Q_{SF} = Q*E_{U\text{-}235} = E_{U\text{-}235} - 0.21E_{U\text{-}236}. \qquad (6)$$

Equation (5) was solved numerically, assuming the choices made for manufacturing costs (for natural uranium and reprocessed uranium) in ref. [6], and five different RU feedstocks, to get C_{rU} when C_U = \$20, \$90, or \$300. The results, each labeled by the quality of the initial RU (Q_{SF}), are shown in Table 1.

Table 1: Cost of RU as a Function of NU and Q_{SF}

Original Fuel % U-235 and Burnup	'Quality' of Spent Fuel Q_{SF}	Cost of NU (/kg)		
		\$20	\$90	\$300
		Cost of RU (/kg)		
3.05% 27 MWd/kg	0.8534%	\$24	\$116	\$378
3.25% 33 MWd/kg	0.8384%	\$21	\$111	\$367
4.10% 47 MWd/kg	0.7504%	\$8	\$82	\$303
3.70% 43 MWd/kg	0.6974%	\$0	\$66	\$267
4.40% 53 MWd/kg	0.6891%	\$0	\$63	\$261

The cost of RU is quite linear with the cost of NU for any given RU, and both the slope and intercept of the RU/NU relationship are linear with the constructed RU Quality Q_{SF}. This double linearity can be expressed as:

$$C_{rU} = (208.04*Q_{SF} - 0.5129)C_U + \$12759*Q_{SF} - \$108.72 \qquad (7)$$

Equation (7) is within \$2 of the cost of RU in Table 1 for all cases except the lowest quality fuels and the highest NU costs (bottom right corner of Table 1), where it is within \$5.

VI. RESULTS

Given the data in the previous section, and the economic formulation in Section III, Utility L could estimate how much of the disposal cost of HLW must minimally be averted due to partitioning americium in order for this scenario to be economically beneficial. Also, since the cost of partitioning americium from spent LWR fuel, and the cost of natural uranium are highly uncertain, Utility L could also examine how changes in these costs affect the economics of this scenario.

The 33 MWd/kg burnup fuel under consideration corresponds to the second row of Table 1. The quality of the fuel is 0.8384% and equation (7) simplifies to:

$$C_{rU} = 1.23*C_U - \$2. \qquad (8)$$

As indicated by Eq. (4), and shown in Fig. 1, the relationship between the minimum averted disposal cost, C^*_{dAm}, and the cost of natural uranium, C_U, is linear. If the cost of partitioning americium, C_{sAm}, is \$200/kg HE, then in order for Utility L to benefit economically the averted disposal costs, C_{dAm}, must exceed \$214/kg HE. The higher the cost of natural uranium, the higher C_{dAm} must be in order for Utility L to benefit economically. If natural uranium costs \$300/kg U then the averted disposal cost would have to exceed \$420/kg HE.

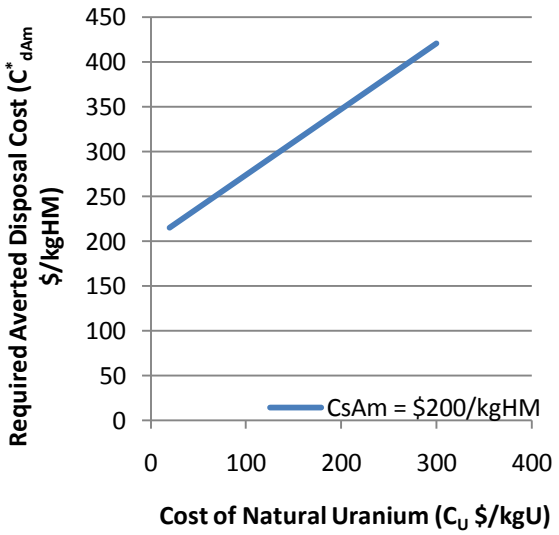

Fig. 1. Required averted disposal cost of spent LWR fuel versus the cost of natural uranium for C_{sAm} = \$200/kg HE.

The relationship between C^*_{dAm} and C_{sAm} is also linear as shown in Fig. 2. In order for Utility L to benefit economically from this scenario, the averted disposal

costs may have to exceed \$600/kg HE if C_U and C_{sAm} are both near their respective upper bounds, whereas it would have to exceed \$14/kg HE if they are both near their respective lower bounds.

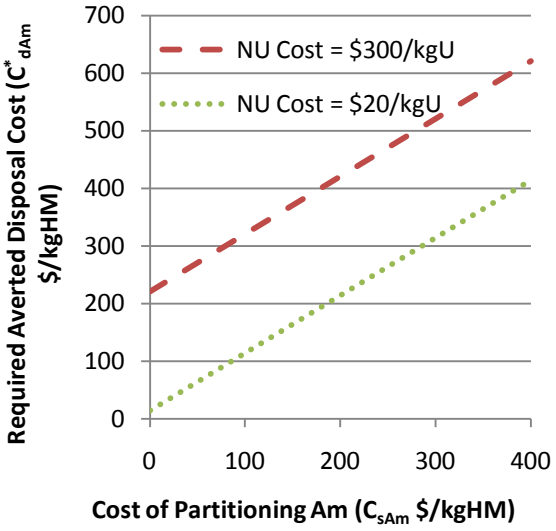

Fig. 2. Averted disposal cost versus the cost of partitioning americium.

VII. DISCUSSION

A noteworthy omission in this cost analysis is the additional cost of transporting reprocessed uranium and americium from a reprocessing plant to a HWR fuel fabrication plant. This additional cost depends on many factors. One such factor is the distance that the RU and americium must be transported in order to get from a reprocessing plant to a HWR fuel fabrication plant. In the reference scenario, on the other hand, Utility L would have to transport its RU to an enrichment plant, and the HLW, including americium, to the geological disposal site. Another factor is how removing americium from the HLW affects the cost of transporting HLW to the disposal site.

The results presented in the previous section show that the economic acceptability of the P&T scenario for Utility L gets worse as the cost of natural uranium increases. This is because re-enriching RU to be used as LWR fuel reduces the amount of NU that is needed for a given amount of energy that is generated. Therefore, re-enriching RU becomes more attractive to Utility L as the cost of NU increases. Conversely, a decrease in the cost of NU would decrease the net gain of this scenario for Utility H since replacing NU with free RU and americium will result in fewer savings.

The averted HLW disposal costs due to this P&T scenario must be less than the disposal cost of HLW without partitioning americium. According to the reference case in [6], the disposal cost of HLW is \$200/kg HE. If this estimate is accurate, then the cost of partitioning americium from spent LWR fuel should be less than \$200/kg HE in order for this P&T scenario to be economically acceptable to Utility L.

The market value of RU may turn out to be quite different than the estimate given in this analysis. According to Eq (4), the effect that the value of RU has on C^*_{dAm} depends on the ratio of RU to Am that is sent to Utility H, multiplied by the concentration of americium in the spent LWR fuel. For the RU considered in this analysis, a change in the value of RU by ±\$1/kgU results in a ±\$0.62 /kg HE change in C^*_{dAm}.

VIII. CONCLUSIONS

A synergistic scenario has been proposed in this study where americium produced in LWRs operated by Utility L is transmuted using HWRs operated by Utility H, where Utility L also sends Utility H the reprocessed uranium required to transmute the Am-241. In order for such a scenario to be economically beneficial to Utility L, the averted disposal costs due to transmuting Am-241 should exceed \$214/kg HE, assuming that the cost of partitioning americium from spent LWR fuel is \$200/kg HE. The averted disposal costs might need to be as high as \$600/kg HE due to increased costs of natural uranium and of partitioning of americium.

The cost of partitioning americium from spent LWR fuel has a large effect on whether Utility L will benefit economically from the proposed scenario. If the cost of partitioning americium indeed renders the proposed scenario uneconomical to Utility L, then Utility H may be willing to accept americium and curium, along with RU, from Utility L. A future study could be carried out to determine whether this alternative scenario would be beneficial to Utility H.

Finally, the value of the RU considered in this analysis has a smaller effect on whether Utility L will benefit economically from the proposed scenario, where a ±\$1/kgU change in the value of RU will result in a ±\$0.62/kg HE change in the minimum required disposal costs.

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