ANNEX XXVII.

A REACTOR SYNERGY: USING HWRs TO TRANSMUTE AMERICIUM FROM LWR SPENT FUEL

XXVII-1. INTRODUCTION

This contribution is an analysis of economic considerations governing a two-utility synergy in which recovered uranium, mixed with americium to make a natural uranium equivalent, is supplied from LWR spent fuel reprocessing to use in HWRs. The important factors are the cost of americium separation (on top of plutonium separation already assumed to be performed), the forgone cost to the LWR utility of americium disposal in a repository, and the forgone potential income from the potential use of reprocessed uranium (RU) for re-enrichment and re-use in LWRs. Values of these parameters for which the synergy is of a net benefit to the LWR utility are determined.

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) [XXVII-1]. It is typically assumed that, following partitioning, minor actinides will be dispositioned by inclusion in fast reactor fuel, but the very high thermal fission cross sections of ^{242m}Am, ^{243}Cm, ^{245}Cm have been shown to make the transmutation efficiency of minor actinides comparable in thermal reactors to that in fast reactors [XXVII-2]. Heavy water moderated reactors (HWR) are expected to be particularly efficient as transmutation engines due to their high neutron economy and highly thermal spectra, and this current work builds on previous comparisons of LWRs and HWRs with respect to transmutation efficiency [XXVII-3] and the potential of HWRs to transmute an unseparated lanthanum, curium and lanthanide stream [XXVII-4]. Specifically, the purpose of this work is to determine a condition in which a utility owning a fleet of LWRs (Utility L, in this discussion) would economically benefit from separating americium from spent nuclear fuel (SNF), then transmuting americium in HWRs (operated by Utility H), using reprocessed uranium (RU) from LWR SNF to provide the extra fissile material to support the process.

The important isotopes of americium are ^{241}Am, ^{242m}Am and ^{243}Am (^{242}Am having quite a short half-life and therefore being present in only trace quantities). Of these, ^{241}Am is a significant contributor to the decay heat of SNF, and is a potential limiting factor to repository capacity. Americium isotopes are produced in enriched uranium, or mixed oxide (MOX), fuels via a process of multiple neutron captures and beta decays. For ^{241}Am, the final step in its production is mainly the β^- decay of ^{241}Pu. Since this process has a 14.29 year half-life, relatively small amounts are created during irradiation (albeit much larger amounts in LWRs than HWRs because of the longer residence time, 4 years in the former vs less than 1 year, in the latter). The critical parameter in the creation of ^{241}Am in SNF is, therefore, the amount of time the fuel is in storage outside of the reactor while awaiting partitioning and transmutation (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 also result in reduced value of the reprocessed MOX fuel due to the decay of ^{241}Pu.

If americium is partitioned from SNF, 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 ^{241}Am in an HWR will transmute it into other nuclides, mitigating its heat production in geological disposal repositories. This annex includes a break-even economic analysis, and a fuel cycle system simulation analysis

XXVII-2. FUEL COMPOSITION

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 GWday/t IHE[1] and 53 GWday/t IHE, were examined in this analysis and found to have sufficient extra ^{235}U for useful americium burning, even tempered by the extra absorption of ^{236}U inevitably produced from capture on ^{235}U during irradiation in an LWR.

XXVII-2.1. Reprocessed uranium composition

Five different RU compositions, corresponding to full burnup fuel with a range of starting enrichments, were used in this study. The burnup and isotopics are summarized in Table XXVII-1 for 5 year decayed material and Table XXVII-2 for 30 year decayed material[2]. The sources for these data are varied. The 3.25 weight % (wt.%), 3.7 wt.% and 4.4 wt.% materials are from OECD NEA [XXVII-5]. The ^{242m}Am and ^{243}Am fractions are not given in that report, so a nominal ^{241}Pu, ^{241}Am, ^{243}Am composition for LWR SNF in OECD NEA [XXVII-6] was assumed and decayed for 5 and 30 years to obtain roughly 72 wt.%: 0 wt.%: 28 wt.% (^{241}Am:^{242m}Am:^{243}Am) and 85 wt.%: 0 wt.%: 15 wt.%, respectively. The ATM-104 data is a simulation [XXVII-7] of a sample of a fuel element taken from near the end of the 14x14 LWR fuel assembly validation case [XXVII-8]. The simulated final RU enrichment, ^{241}Pu and ^{241}Am concentrations were within 5% of measured values. The Takahama data is a simulation[3] of a 17x17 assembly PWR validation case [XXVII-9] in which the final predicted RU enrichment was within 1% of the measured value. The ^{241}Am and ^{243}Am exit SNF concentrations were predicted to be approximately 15% high in this simulation (relative to the validation data), but after five years decay, 80% of the ^{241}Am present in LWR SNF is due to ^{241}Pu decay. Since ^{241}Pu levels were predicted to be within 1% of those measured, the ^{241}Am levels predicted will be within 5% of the true values.

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[1] IHE is for initial heavy elements.

[2] ^{234}U is not included as it is a weak absorber and, in addition, is not always included in stated spent fuel isotopics.

[3] Unpublished work using the same techniques as in Ref. [XXVII-9].

TABLE XXVII-1. LWR 5-YEAR DECAYED SNF COMPOSITIONS

Initial Enrichment (wt.%)	Burnup (GW(th)day/t IHE)	RU Composition (wt.%)	^{241}Am/HE in RU (wt.%)	Am Composition (wt.%)	wt.% U	Source
3.05%	27.35	^{235}U: 0.9338% ^{236}U: 0.3846% ^{238}U: 98.6817%	0.0267%	^{241}Am: 82.79% ^{242m}Am: 0.32% ^{243}Am: 16.89%	96.34%	[XXVII-7]
3.25%	33	^{235}U: 0.9242% ^{236}U: 0.4088% ^{238}U: 98.6670%	0.0325%	^{241}Am: 72% ^{242m}Am: 0 ^{243}Am: 28%	95.65	[XXVII-5]
3.70%	43	^{235}U: 0.8043% ^{236}U: 0.5090% ^{238}U: 98.6866%	0.0413%	^{241}Am: 72% ^{242m}Am: 0 ^{243}Am: 28%	94.49%	[XXVII-5]
4.10%	47	^{235}U: 0.8769% ^{236}U: 0.6027% ^{238}U: 98.5203%	0.0464%	^{241}Am: 66.7% ^{242m}Am: 0.2% ^{243}Am: 33.1%	93.87%	Takahama
4.40%	53	^{235}U: 0.8228% ^{236}U: 0.6363% ^{238}U: 98.5409%	0.0480%	^{241}Am: 72% ^{242m}Am: 0 ^{243}Am: 28%	93.35%	[XXVII-5]

TABLE. XXVII-2. LWR 30-YEAR DECAYED SNF COMPOSITIONS

Initial Enrichment (wt.%)	Burnup (GW(th)day/t IHE)	RU Composition (wt.%)	^{241}Am/HE in RU (wt.%)	Am Composition (wt.%)	wt.% U	Source
3.05%	27.35	^{235}U: 0.9342% ^{236}U: 0.3851% ^{238}U: 98.6808%	0.0780%	^{241}Am: 93.4% ^{242m}Am: 0.1% ^{243}Am: 6.5%	96.34%	[XXVII-7]
3.25%	33	^{235}U: 0.9242% ^{236}U: 0.4088% ^{238}U: 98.6670%	0.1080%	^{241}Am: 85% ^{242m}Am: 0 ^{243}Am: 15%	95.65	[XXVII-6]
3.70%	43	^{235}U: 0.8043% ^{236}U: 0.5090% ^{238}U: 98.6866%	0.1340%	^{241}Am: 85% ^{242m}Am: 0 ^{243}Am: 15%	94.49%	[XXVII-6]
4.10%	47	^{235}U: 0.8775% ^{236}U: 0.6035% ^{238}U: 98.5191%	0.1450%	^{241}Am: 86.2% ^{242m}Am: 0.1% ^{243}Am: 13.7%	93.86%	Takahama
4.40%	53	^{235}U: 0.8228% ^{236}U: 0.6363% ^{238}U: 98.5409%	0.1550%	^{241}Am: 85% ^{242m}Am: 0 ^{243}Am: 15%	93.35%	[XXVII-6]

XXVII-2.2. HWR fuel composition

Multiple neutron absorptions in ^{241}Am and ^{243}Am lead to fissile isotopes such as ^{239}Pu (after α-decay of ^{242}Cm), ^{241}Pu (after α-decay of ^{244}Cm), ^{243}Cm and ^{245}Cm, whose subsequent fission creates small amounts of fission products. However, these processes will not be a

major factor in the fuel cycle considered due to the short residence time and low burnup (7.5 GWday/t IHE) of this fuel in the HWR. More probable is the creation of actinides having much longer half-lives (like ^{243}Am), or much shorter half-lives (like ^{242}Cm, ^{244}Cm) which decay by α emission to ^{238}Pu and ^{240}Pu over relatively short timescales (162.8 d and 18.1 y respectively), and therefore do not represent significant disposal problems (at least as Curium isotopes) in a repository. ^{238}Pu, with a 87.7 year half-life remains a decay heat problem in SNF, albeit over much shorter timescales than ^{241}Am. ^{244}Cm is a significant neutron emitter and may cause SNF handling problems but this will not be investigated here. The residence time of fuel with a burnup of 7.5 GWday/t in an HWR is insufficient to create significant quantities of the problematic heavy, long-lived curiums of mass 246 and higher, and is also insufficient to create significant quantities of new americium from ^{238}U.

The physics calculations of fuel depletion were performed by the neutron transport code WIMS-AECL v.3.1.2.1 [XXVII-10] with an ENDF/B-VII based library of neutron cross sections [XXVII-11]. The type of bundle analyzed was a typical HWR advanced fuel cycle bundle containing 43 fuel elements in four rings, with the center (1) and inner (7) elements being larger than the intermediate (14) and outer (21) elements [XXVII-12]. The central element was a non-fuel dysprosia/zirconia element designed to increase the reactivity safety margin reactivity in loss of coolant scenarios. The WIMS-AECL code was used to simulate the irradiation of bundles at a constant power typical of an core-averaged HWR fuel (32 W/g IHM). The initial concentration of americium in the fuel was adjusted to achieve an exit burnup of 7.5 GWday/t IHE – a typical value for natural uranium fuel. In this calculation, the exit burnup is determined when the burnup-weighted k_∞ of the fuel reaches 1.03 (corresponding to a neutron leakage of 3% which is possible for an HWR operating in a configuration without the use of reactivity devices for spatial flux adjustment).

TABLE XXVII-3. THE MINIMUM MASS ($\boldsymbol{\alpha_{cU}^{Am}}$ KG) OF RU REQUIRED TO TRANSMUTE 1 KG OF ^{241}AM IN AN HWR, THE RATIO OF RU IN SNF TO U IN INITIAL FUEL ($\boldsymbol{x_{RU}}$), AND THE AMERICIUM AND RU CONTENT OF FRESH HWR FUEL

Decay Time[4], years	Burnup, GW(th)day/t IHE	27.35	33	43	47	53
5	α_{cU}^{Am}, kg RU/kg Am	549	613	1471	833	1220
	AmO_2, wt.%	0.232	0.238	0.1	0.19	0.12
	RUO_2, wt.%	99.768	99.762	99.9	99.81	99.88
30	α_{cU}^{Am}, kg RU/kg Am	532	578	1333	813	1136
	AmO_2, wt.%	0.212	0.215	0.093	0.15	0.109
	RUO_2, wt.%	99.788	99.785	99.907	99.85	99.891

XXVII-3. ECONOMIC ANALYSIS

This section presents an economic analysis of burning LWR-produced americium in HWRs using RU, describing the economic conditions under which such a synergy between two nuclear utilities ('L' having LWRs and 'H', having HWRs) will be mutually beneficial.

In the scenario under consideration, Utility L is assumed to have already implemented a nuclear fuel cycle in which SNF is reprocessed to extract the plutonium to make mixed oxide

[4] Decay time of LWR fuel before reprocessing to remove americium.

(MOX) fuel for reuse in other LWRs (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 such a fuel cycle. Separating americium from curium isotopes, which have similar valances, is a well-known problem, although recent work indicates that this might be do-able [XXVII-13, XXVII-14 and XXVII-15]. 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[5]. 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 upgrade to their fuel handling procedures and equipment due to the extra radioactivity of the initial fuel, while the benefit to Utility H would be the averted cost of purchasing NU fuel for their reactors[6]. It is assumed that the HWRs can use americium/ RU fuel with no design changes to the reactor. In this analysis it is assumed that the net benefit to Utility H would be positive (i.e. that averted fuel costs outweigh other expenses), 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.

XXVII-3.1. Break-even analysis formulation

The formulation of the net cost to Utility L of the proposed P&T scenario is based on the formulas given in Appendix A.1.2 in [XXVII-16]. This formulation takes into account the extra cost of separating Americium from Curium (C_{sAm} \$/kgHM), and the value of RU to Utility L (C_{rU} \$/kgU), to compute the reduction in geological disposal cost due to partitioning americium from the HLW (C^*_{dAm} \$/kgHM) that must be achieved for Utility L to break-even economically if they implemented this scenario. In this formulation HM refers to the mass of LWR SNF. C^*_{dAm} is calculated using Eq. (XXVII-1), the complete derivation of which can be found in [XXVII-17].

$$C^*_{dAm} = C_{sAm} + x_{Am}\alpha^{Am}_{cU}C_{rU}. \qquad \text{(XXVII-1)}$$

In this equation x_{Am} is the wt.% of ^{241}Am in LWR spent fuel at the time of reprocessing, and α^{Am}_{cU} is the mass of RU required to transmute a given mass of ^{241}Am.

If Utility L and Utility H agree to implement the americium transmuting scenario, then it would be useful to know, in the steady state, the ratio of the number of LWRs to HWRs such that all of the ^{241}Am is transmuted using RU. This is referred to as the support ratio (SR). There are two relevant SRs in this scenario: the transmuting americium SR, and the RU SR. The transmuting americium SR (see Eq. (XXVII-2)) is the SR such that all of the ^{241}Am produced by each LWR is transmuted in a HWR assuming a sufficient supply of RU. The RU SR (see Eq. (XXVII-3)) is the support ratio such that all of the RU produced by each LWR is burned in a HWR.

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[5] Other possible uses exist, of course, and in an ideal market the value of RU would be determined by the bidder willing to pay the highest price. However, it will be relatively easy to augment the analysis with such considerations after the framework is built in this section.

[6] Of course, in a more realistic scenario it would be assumed that Utility H would acquire the fuel at some discount from the NU fuel price, but this first attempt at an economic analysis seeks only to find the conditions where Utility L could afford to provide the fuel free, maximizing the benefit to Utility H.

$$R_{Am} = \frac{\frac{F_{HWR}}{T_{HWR}(1+\alpha_{cU}^{Am})}}{\frac{x_{Am}F_{LWR}}{T_{LWR}}} \qquad \text{(XXVII-2)}$$

$$R_{RU} = \frac{\frac{F_{HWR}}{T_{HWR}(1+1/\alpha_{cU}^{Am})}}{\frac{x_{RU}F_{LWR}}{T_{LWR}}} \qquad \text{(XXVII-3)}$$

F_{HWR} and F_{LWR} are the full fuel core loads for each HWR and LWR, respectively. T_{HWR} and T_{LWR} are the times that each HWR and LWR take to burn a full core load, respectively. x_{RU} is the mass of RU per mass of U in fresh LWR fuel.

If the ratio of LWRs in Utility L to HWRs in Utility H is less than R_{Am} and R_{RU} then Utility H will be able to transmute all of the ^{241}Am that Utility L produces in the steady state with LWR produced RU.

XXVII-3.2. The value of reprocessed uranium

According to Eq. (XXVII-2) above, the economic acceptability of transmuting ^{241}Am produced in LWRs in Utility L using HWR reactors in Utility H depends on the value of the reprocessed uranium that Utility L must also send to Utility H. Since Utility L has only LWR reactors, the value of RU to Utility L depends on how reprocessed uranium can be used in a LWR reactor to produce power [XXVII-18]. Two possibilities are [XXVII-19] that RU can be used in an LWR by re-enriching it to make LEU, or it can be combined with plutonium to make a MOX fuel.

Due to the inability of current enrichment techniques to separate ^{236}U from ^{235}U efficiently, the LWR fuel manufactured from the enrichment of RU to make the enriched reprocessed uranium (E RU) would require a higher concentration of ^{235}U than enriched natural uranium (ENU) for a similar burnup design, due to the neutron absorption by ^{236}U in RU [XXVII-16].

In this analysis, the value of RU to Utility L is estimated assuming that if it is not given to Utility H then it would be enriched using centrifuges and used as LWR fuel [XXVII-16]. Bunn et al estimate the value of reprocessed uranium by equating the cost, C_{lwr}, per kilogram of LWR fuel produced from NU to the cost, C_{rlwr}, per kilogram of LWR fuel produced by enriching RU using centrifuges. They assume that RU is composed of LWR fuel that has been irradiated only once.

$$C_{lwr} = \frac{1}{1-f_{lf}}\left[\frac{R}{1-f_s}\left(\frac{C_u}{(1-f_c)(1+i)^{t_u}} + \frac{C_c}{(1+i)^{t_c}}\right) + \frac{SC_s}{(1+i)^{t_s}}\right] + \frac{C_{lf}}{(1+i)^{t_f}} \qquad \text{(XXVII-4)}$$

$$C_{rlwr} = \frac{1}{1-f_{rlf}}\left[\frac{R_r}{1-f_s}\left(\frac{C_{rU}}{(1-f_c)(1+i)^{t_u}} + \frac{C_{rc}}{(1+i)^{t_c}}\right) + \frac{S_r C_{rs}}{(1+i)^{t_s}}\right] + \frac{C_{rlf}}{(1+i)^{t_f}} \qquad \text{(XXVII-5)}$$

The parameters in Eq. (XXVII-4) and (XXVII-5) are defined in Table XXVII-4 and XXVII-5. The Value Function 'V(x)', where 'x' is the fraction of ^{235}U in total U, measures

the relative work required to create a material with ^{235}U fraction 'x' from a starting material that is 50% ^{235}U and 50% ^{238}U. V(x) is infinite for pure materials (x=0 or x=1), and 0 for uranium which is 50% ^{235}U, 50% ^{238}U.

TABLE XXVII-4. LWR FUEL COST PARAMETERS

Source		NU	RU
Costs	source material ($/kgU)	C_u	C_{rU}
	conversion ($/kgU)	C_c	C_{rc}
	enrichment ($/SWU)	C_s	C_{rs}
	fabrication ($/kgHM)	C_{lf}	C_{rlf}
Fractional material losses	conversion	f_c	f_c
	enrichment	f_s	f_s
	fabrication	f_{lf}	f_{rlf}
Enrichment parameters	separative work units	S	S_r
	feed to product mass ratio	R	R_r
	value function	V	
Levelized cost parameters	time at which source U is paid	t_u	
	time at which conversion is paid	t_c	
	time at which enrichment is paid	t_s	
	time at which fabrication is paid	t_f	
	discount rate	i	

TABLE XXVII-5. DEFINITIONS OF THE ENRICHMENT FORMULAS AND PARAMETERS FOR PRODUCING ENU AND ENRICHED RU (E RU).

ENU	E RU
x_p, x_f, and x_t are the product, feed and tails assay respectively.	x_{rp}, x_{rf}, and x_{rt} are the product, feed and tails assay respectively. x_{236} is the concentration of ^{236}U in RU
$R = \frac{x_p - x_t}{x_f - x_t}$	$R_r = \frac{x_{rp} - x_{rt}}{x_{rf} - x_{rt}}$
$S = V(x_p) - V(x_t) - R[V(x_f) - V(x_t)]$	$S_r = V(x_{rp}) - V(x_{rt}) - R[V(x_{rf}) - V(x_{rt})]$
	$x_{rp} = \frac{x_p}{1 - 0.21\mathrm{x}_{236}/\mathrm{x}_{\mathrm{rf}}}$
$V(x) = (2x - 1)\ln\frac{x}{1 - x}$	

The computation of C_{rU} is a two phase optimization problem. First, the ENU tails assay, x_t, is set to a value that minimizes C_{lwr}, and then the E RU tails assay, x_{rt}, is set to a value that maximizes C_{rU} such that C_{lwr} is equal to C_{rlwr}. Also, x_t and x_{rt} must be between zero and x_f and x_{rf}, respectively.

XXVII-3.3. Fuel cycle cost estimates

The cost estimates used in this analysis are based on estimates used in an OECD NEA report [XXVII-22] on advanced nuclear fuel cycles and waste management, and on spot prices between the years 2000 and 2013. The NEA report is used because it is the only known

source of an estimate of the cost of partitioning americium from SNF. These cost estimates are shown in Table XXVII-6. The analysis presented here also requires the cost estimates associated with manufacturing LWR fuel from RU, estimates that are not included in [XXVII-22]. Therefore, the cost estimates used in this analysis are based on the estimates made by Bunn et al. [XXVII-16], which are presented as the costs of manufacturing LWR fuel from NU plus premiums for handling RU. Table XXVII-7 shows the estimated differences in costs between making LWR fuel from RU and making LWR fuel from NU that are used in this analysis.

TABLE XXVII-6. THE COST ESTIMATES OF MAKING LWR FUEL FROM NU, AND OF PARTITIONING AMERICIUM FROM LWR SNF [XXVII-22]

Cost Parameter	Uranium, C_u, ($/kgU)	Conversion, C_c, ($/kgU)	Enrichment, C_s ($/SWU)	Fabrication, C_{lf} ($/kgIHM)	Partitioning the Am, C_{sAm} ($/kgHM)
Min	20	3	80	200	0
Ref	90	10	120	250	200
Max	300	13	160	300	400

TABLE XXVII-7. ESTIMATES OF THE DIFFERENCE IN COSTS OF MAKING LWR FUEL FROM RU AND MAKING LWR FUEL FROM NU [XXVII-16]

Incremental Cost	Conversion $C_{rc} - C_c$ ($/kgU)	Enrichment $C_{rs} - C_s$ ($/SWU)	Fabrication $C_{rlf} - C_{lf}$ ($/kgIHM)
Min	5	0	0
Ref	15	5	10
Max	25	10	20

XXVII-3.4. Economic analysis results

The economic acceptability of the P&T scenario is analyzed in terms of the minimum averted geological disposal costs (C^*_{dAm}) that must be achieved by Utility L in order for the P&T scenario to be economically equivalent to the direct disposal of americium, along with other minor actinides, in a geological repository. This is the savings in disposal cost that the utility L must realize in order to offset the additional costs associated with the new fuel cycle, and the loss of the value of the RU. C^*_{dAm} is computed using Eq. (XXVII-1) and the data presented in Sections 2 and 3.2. This section also presents an estimate of the number of LWRs that could be supported by a HWR in the scenario.

The minimum required averted disposal costs for the scenario to be economically acceptable for each RU enrichment and each storage duration, given the reference values of the cost parameters, is shown in Fig. XXVII-1. Any values of RU enrichment, x_{rf}, and averted disposal cost, C_{dAm}, that lie above a given line correspond to the americium transmutation scenario being economically acceptable for Utility L. Recall that C^*_{dAm} is the averted disposal cost per unit mass of LWR SNF. The storage of LWR SNF for an additional 25 years prior to reprocessing results in increased values of C^*_{dAm} by at least $30/kgHE for each amount of ^{235}U in RU that is considered in this study. This is due to the larger amount of americium in SNF that is stored for a longer period of time, which is in turn due to the decay of ^{241}Pu. Thus this fuel cycle will be more economically viable if the fuel can be reprocessed

and re-irradiated at shorter times after exit from the LWR. C^*_{dAm} decreases as the ^{235}U content of RU increases (which corresponds to a lower burnup of the LWR SNF) due to the reduced amount of RU that is required to transmute a given quantity of americium in an HWR (therefore Utility L is required to give away less of its valuable RU stocks), and the reduction in the amount of americium in LWR SNF with lower burnup. In the case that the SNF is stored for 30 years, C^*_{dAm} varies from a minimum of $248 to a maximum of $318/kgHE, whereas storage for 5 years results in a variation between $217 and $240/kgHE.

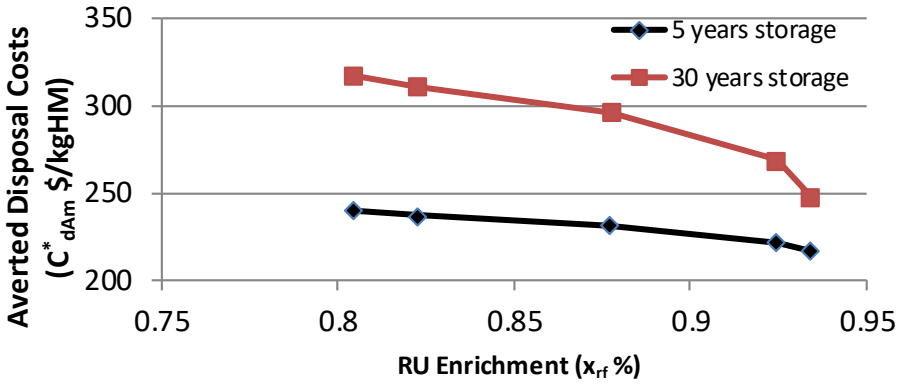
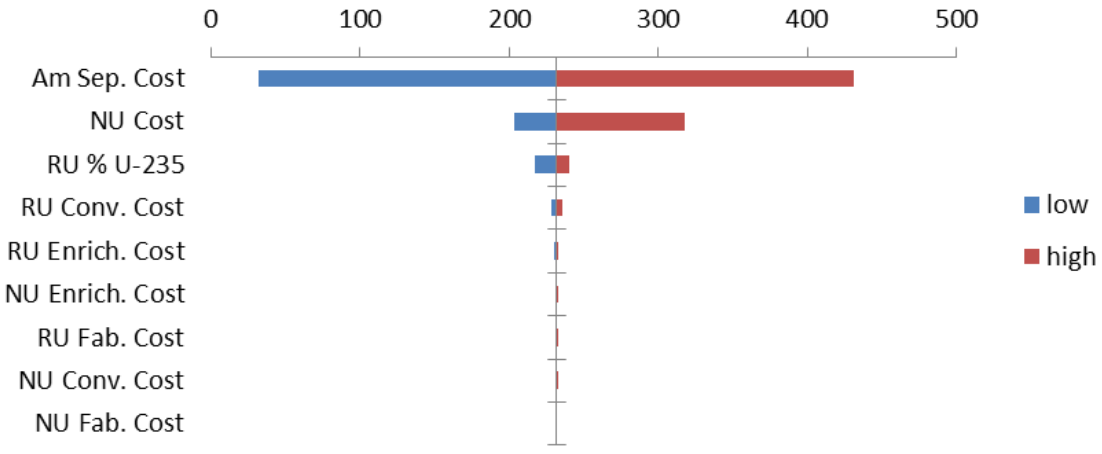


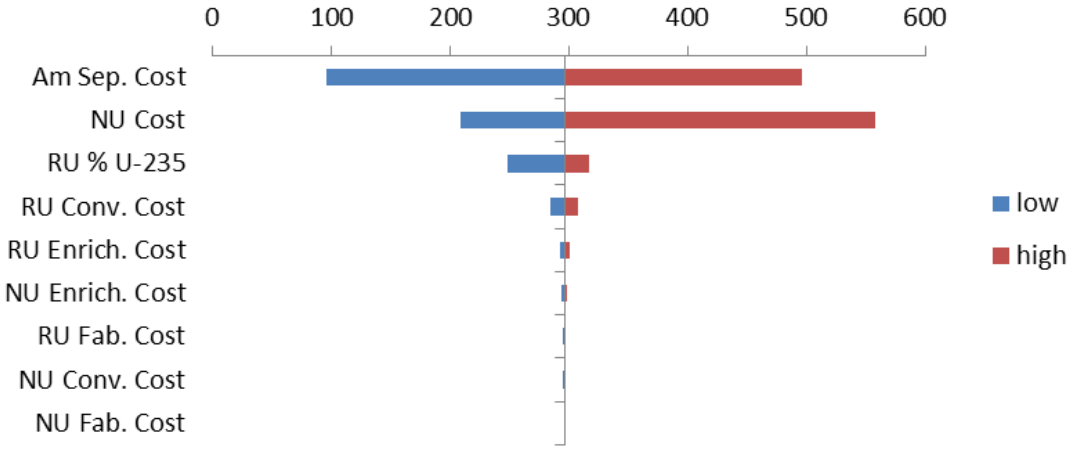
FIG. XXVII-1. The minimum required averted disposal costs of HLW given the reference values of the cost parameters and each storage duration.

There are uncertainties in the various fuel cycle costs, therefore a sensitivity analysis was performed to determine how each cost parameter and the ^{235}U content of RU affects C^*_{dAm}. For each of these parameters, the value of C^*_{dAm} is computed at its minimum and its maximum value, while all of the other parameters are held constant at their reference values. For this sensitivity analysis, the reference value of ^{235}U content in RU (x_{rf}) is assumed to be 0.8769 wt.%, because this corresponds to the median value of C^*_{dAm} over all values of x_{rf}.

Figure XXVII-2 shows C^*_{dAm} for the minimum and maximum of each parameter, indicated as the percent parameter change from its reference value. The economics of the P&T scenario are most sensitive to the additional cost of partitioning americium from LWR SNF. This is due to the large difference between the reference and the extreme costs. The minimum and maximum partitioning costs are 100% less and 100% more than the reference cost, respectively. If there is no additional cost to partition americium then the averted disposal cost should be around $32/kgHE and $97/kgHE, or more for fuel that is stored for 5 and 30 years, respectively. If the additional cost is $400/kgHE (the maximum value from the literature) then the averted disposal cost should be around $432/kgHE and $497/kgHE, respectively. Another parameter that significantly affects the economics of this scenario is the cost of natural uranium. If the cost of natural uranium drops to $20/kg then the averted disposal cost should be around $203/kgHE and $209/kgHE or more for fuel that is stored for 5 and 30 years, respectively. If the cost of uranium increases to $300/kg then the averted disposal costs should be around $317/kgHE and $558/kgHE, respectively. This is assuming that if RU is not used to transmute ^{241}Am then it will be enriched using centrifuges and fabricated into LWR fuel. C^*_{dAm} is relatively insensitive to the other fuel cycle parameters.



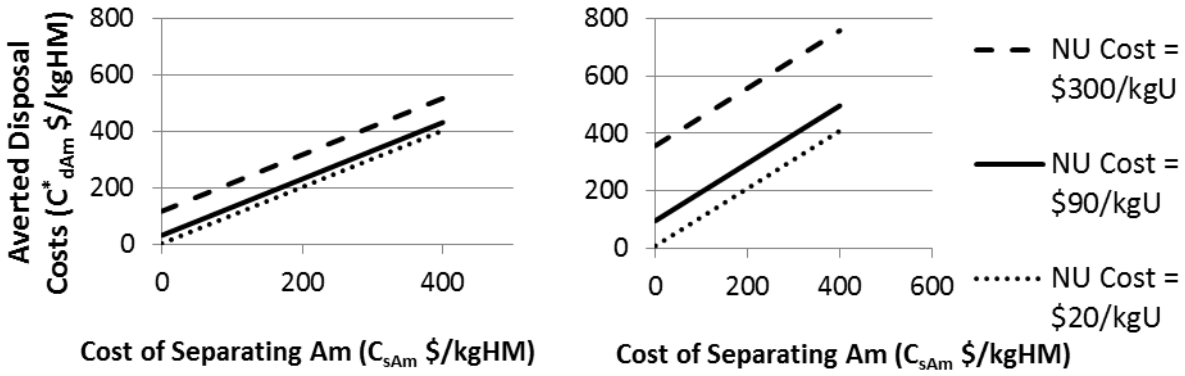
(a) *5 years*



(b) 30 years

FIG. XXVII-2. The minimum required averted disposal costs for the minimum and maximum of each parameter, and each storage duration.

Since the required averted disposal cost is most sensitive to the cost of separating americium, the relationship between these two costs are shown in Fig. XXVII-3. This relationship is also shown for each of the minimum, reference value, and maximum cost of natural uranium.



(a) 5 years (b) 30 years

FIG. XXVII-3. C^*_{dAm} versus C_{sAm} for each storage duration, and for the minimum, reference value, and maximum cost of NU. All other parameters are set to their reference values.

In order to estimate the SR for this scenario, the following assumptions are used:

1. A full fuel core load for each LWR and HWR is 80,000 kg IHE and 88,000 kg IHE, respectively.
2. Each LWR and HWR takes three years[7] [XXVII-5] and 2/3 years, respectively, to burn a full core load.
3. The LWR SNF is stored for five years prior to reprocessing.

Based on these assumptions, the estimated SRs for transmuting ^{241}Am and burning RU are shown in Table XXVII-7. In order for Utility H to transmute all of the ^{241}Am from Utility L using only RU from Utility L, then Utility L should have 5 or fewer LWRs per HWR. The support ratio is limited by the availability of RU, not americium. If another fissile component (such as LEU) were used in place of the RU, the support ratio rises to between 8 and 33 LWRs per HWR, depending on the burnup (and hence the americium content) in the LWR SNF.

TABLE XXVII-7. THE ^{241}AM AND RU SUPPORT RATIOS FOR EACH FUEL BURNUP

Burnup (GWd_t/tIHE)	27.35	33	43	47	53
Am Support Ratio (R_{Am})	33	24	8	12	8
RU Support Ratio (R_{RU})	5	5	5	5	5

XXVII-4. FUEL CYCLE SYSTEM SIMULATION ANALYSIS

This section analyzes the fuel cycle system of the proposed synergy of fuelling HWRs with reprocessed uranium and americium extracted from used LWR fuel. In this analysis the proposed synergy is compared to a non-synergistic case where the reprocessed uranium from LWRs is recycled into LWRs along with the plutonium.

[7] Note that this is a conservative assumption for the irradiation time for LWRs where longer irradiation times (~4.5 years) are common for higher fuel burnup, thus resulting in lower throughput of LWR spent fuel per year. Therefore the support ratios are likely higher than reported here.

XXVII-4.1. Scenario definitions

Each of the scenarios analyzed in this study has the following characteristics:

- The scenarios start in 2000 and end in 2110. The years 2000 to 2010 are used to allow reactors to be ordered to meet increasing demands between 2010 and 2020. The results are recorded starting in 2010.
- The global nuclear electricity demand is assumed to be the moderate case from the GAINS report [XXVII-23].
- 346 and 48 legacy LWRs and HWRs, respectively, are operating in 2010, and begin retiring in 2030 at a constant rate such that all legacy reactors are retired by 2060.
- The ratio of LWRs to HWRs is always approximately 12 to ensure that all americium is burned in the synergy scenario, as indicated by the americium support ratios in Table XXVII-7.
- Reprocessing of spent LWR fuel begins in 2030.
- Reprocessing losses = 0.1%.
- Tails from enrichment = 0.3% U-235.

In both scenarios all plutonium is recycled into LWRs as MOX fuel. In the synergy scenario the RU and americium is recycled into HWRs. Any RU not sued to fuel HWRs is stored for the duration of the scenario.

XXVII-4.2. LWR fuel and parameters

The LWRs in this analysis are assumed to have the following characteristics:

- Nominal electrical power = 1 GW(e).
- Efficiency = 33%.
- Load factor = 85%.
- Reactor lifetime = 40 years.

In both the synergy and non-synergy scenarios the LWRs are initially fuelled with 4.1% enriched uranium, with burnup of 47 GW(th)day/t and irradiation time of 3.3 years. The plutonium from LWR spent fuel is blended with depleted uranium (DU) to make MOX fuel with the following characteristics:

- 90% DU and 10% plutonium.
- 51 GW(th)day/t burnup.
- 4.5 years irradiation time.

Any RU that is not used to fuel HWRs is stored indefinitely.

XXVII-4.3. HWR fuel and parameters

The HWRs in this analysis are assumed to have the following characteristics:

- Nominal electrical power = 0.6 GW€.
- Efficiency = 33%
- Load factor = 85%.
- Reactor lifetime = 30 years.

In the non-synergy scenario the HWRs are fuelled solely with NU for a burnup of 7.5 GW(th)day/t and irradiation time of 0.8 years. In the synergy scenario RU and americium from LWR spent fuel is recycled into HWR fuel.

XXVII-4.4. Scenario model

The scenarios were implemented using the VISION model. VISION is a dynamic simulation model of the nuclear fuel cycle built on the PowerSim platform [XXVII-24]. It models the interaction of the various components of the fuel cycle, including fuel fabrication, nuclear power plants, SNF storage, SNF reprocessing, and long term disposal.

XXVII-4.5. Results

The results of synergy and non-synergy scenarios are analyzed to quantify the benefit of the synergy to Utility L with respect to high level waste, and to Utility H with respect to the savings in NU consumption. The effects of this synergy on the characteristics of fresh and irradiated HWR fuel are also analyzed. Figure XXVII-4 shows the electricity generation capacity for HWRs and LWRs in both scenarios.

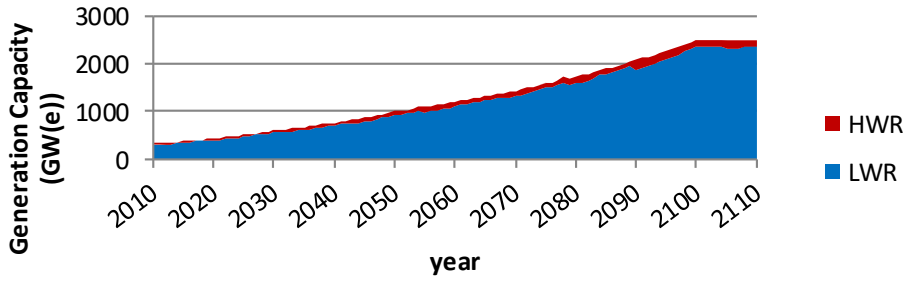
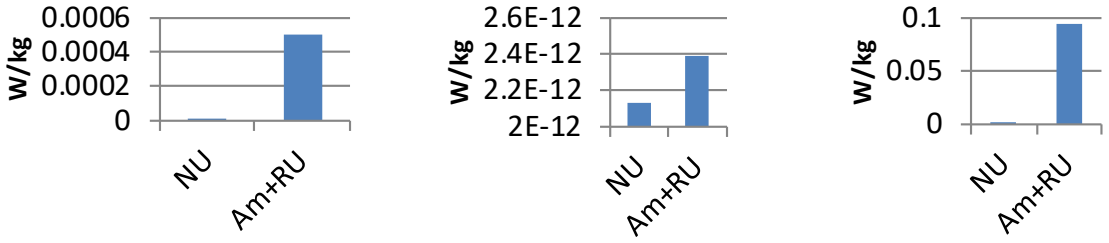


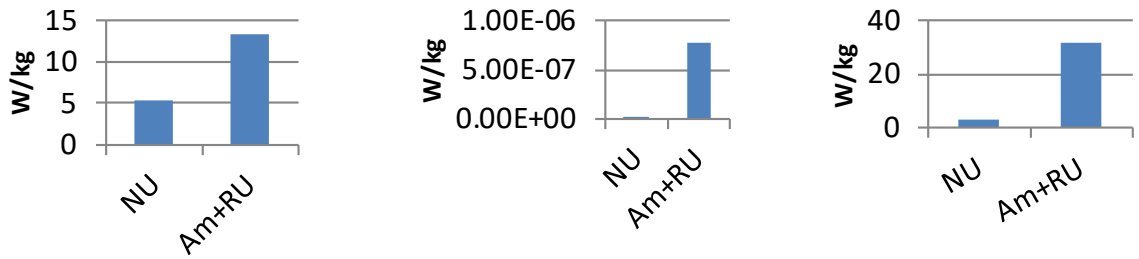
FIG. XXVII-4. The electricity generation capacity for each reactor type over the duration of the scenarios.

If Utility H accepts RU and americium from Utility L, then it must be ensured that the fresh and irradiated fuel handling facilities for HWRs are capable of handling fuel with increased gamma and neutron emissions, and decay power, as is shown in Figures XXVII-5 and XXVII-6.



(a) (b) (c)

FIG. XXVII-5. Fresh HWR fuel characteristics at discharge: (a) gamma emissions, (b) neutron emissions, (c) decay power.



(a) (b) (c)

FIG. XXVII-6. Irradiated HWR fuel characteristics at discharge: (a) gamma emissions, (b) neutron emissions, (c) decay power.

The principal benefit of synergy to Utility L is in the reduction of the long-term decay power of its high level waste. The ratios of decay power of the Am+ RU Syn to the No Syn case at various times after the scenario are shown in Fig. XXVII-7. At 1000 years after the end of the scenario the decay power of HLW from LWRs in the Am+ RU Syn case is 0.63 times the decay power in the No Syn case. The synergy case for HWRs, on the other hand, produces irradiated fuel with increased long-term decay power, which is between 1.08 and 3.2 times as much as the non-synergy case. The higher decay power of irradiated HWR fuel in the synergy case is due to the RU+Am SNF. Over the first 1000 years after discharge, this higher decay power is due to the larger amount of curium and americium in RU+Am SNF. The decay power of RU+Am SNF does not decrease as quickly as that of NU between 10 and 100 years, and 10000 and 100000 years due to the larger amount of ^{238}Pu in the RU+Am SNF at discharge. Overall, the synergy scenario would reduce the long-term decay power of irradiated fuel at 1000 years and beyond.

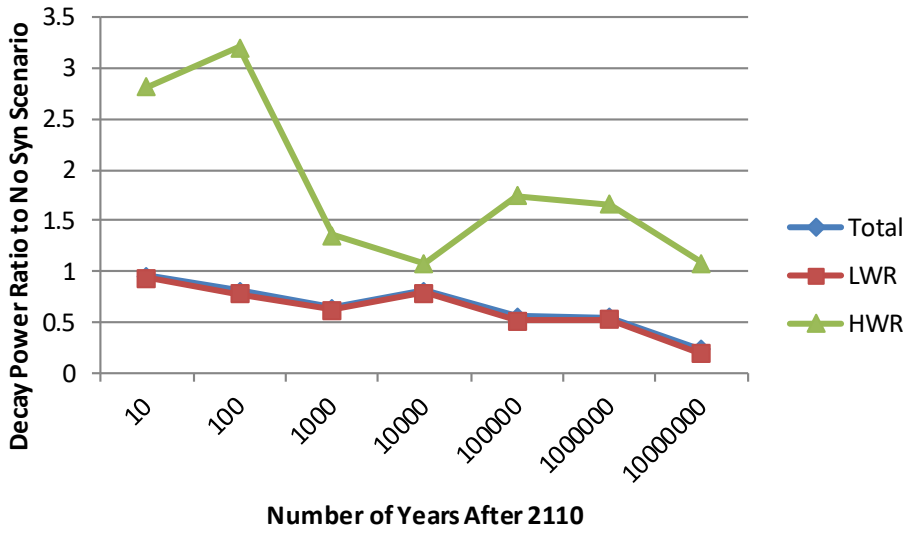


FIG. XXVII-7. The ratio of the decay power of all irradiated fuel and high level waste in the synergy scenario to the non-synergy scenario.

XXVII-5. SUMMARY

A synergy has been proposed in this study in which ^{241}Am produced in LWRs in Utility L is transmuted using HWRs in Utility H, where Utility L also sends Utility H the reprocessed uranium required to transmute the ^{241}Am.

XXVII-5.1. Economic analysis

In order for the proposed synergy to be economically acceptable to Utility L, the averted disposal costs due to transmuting ^{241}Am should most likely exceed $217/kgHM and $248/kgHM for SNF that has been burned for 27.35 GW(th)day/tHE and stored for 5 and 30 years respectively. In both cases, the averted disposal costs should be higher for higher LWR fuel burnup. For the worst case burnup of 53 GW(th)day/tHE, the averted disposal costs must exceed $240/kgHE and $317/kgHE for SNFSNF that has been stored for 5 and 30 years, respectively.

The economics of this synergy are most sensitive to the additional cost of partitioning americium from LWR SNF, where increasing costs present an increased burden to Utility L. Another parameter that significantly affects the economics of this synergy is the cost of natural uranium, assuming that if RU is not used to transmute ^{241}Am then it will be enriched using centrifuges and fabricated into LWR fuel. In this case, an increased cost of NU results in reprocessed uranium being more valuable to Utility L.

Ultimately, the question of the economic acceptability of this synergy to Utility L cannot be answered until the resulting averted disposal costs are estimated, and the uncertainty in the estimate of the cost of partitioning americium from the other high level wastes is reduced.

XXVII-5.2. Fuel cycle system simulation analysis

A fuel cycle system simulation analysis of the proposed synergy shows that the decay power of HLW for Utility L would be 0.63 times the non-synergy case at 1000 years after the scenario when compared to a non-synergy case. Beyond 100,000 years, this decay power for

the synergy is less than 0.6 times the non-synergy case. Utility H would have to cope with fresh fuel that has irradiated material with higher gamma and neutron emissions. Utility H would also have to cope with irradiated fuel with long-term decay power that is between 1.08 and 3.2 times the non-synergy case.

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