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 $200/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.*

I. 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) [1]. Due to their high neutron economy, heavy water moderated reactors (HWR) could potentially be used to transmute americium using reprocessed uranium (RU) from spent LWR fuel. The purpose of this work is to determine under what conditions a utility that owns a fleet of LWRs would economically benefit from transmuting americium in HWRs.

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. The ground state of Am-242 has a short half life of 16.02 hours, decaying by either electron capture or β^- decay, and only insignificant quantities are found in SNF. The creation of the heavier plutonium isotopes (Pu-240 and higher) and of the americium and curium isotopes occurs more frequently in LWRs (over HWRs) due to the relatively long irradiation period in LWRs (~ 4 years vs. < 1 year in HWRs). The critical step in the creation of americium isotopes, and of Am-241 in particular, is the Pu-241 decay, which will occur in the reactor, in the approximate 5 year cooling period during which SNF will be kept in storage at the reactor site, and during subsequent cooling while awaiting P&T. One method of transmuting Am-241 is to irradiate it in a heavy water moderated reactor.

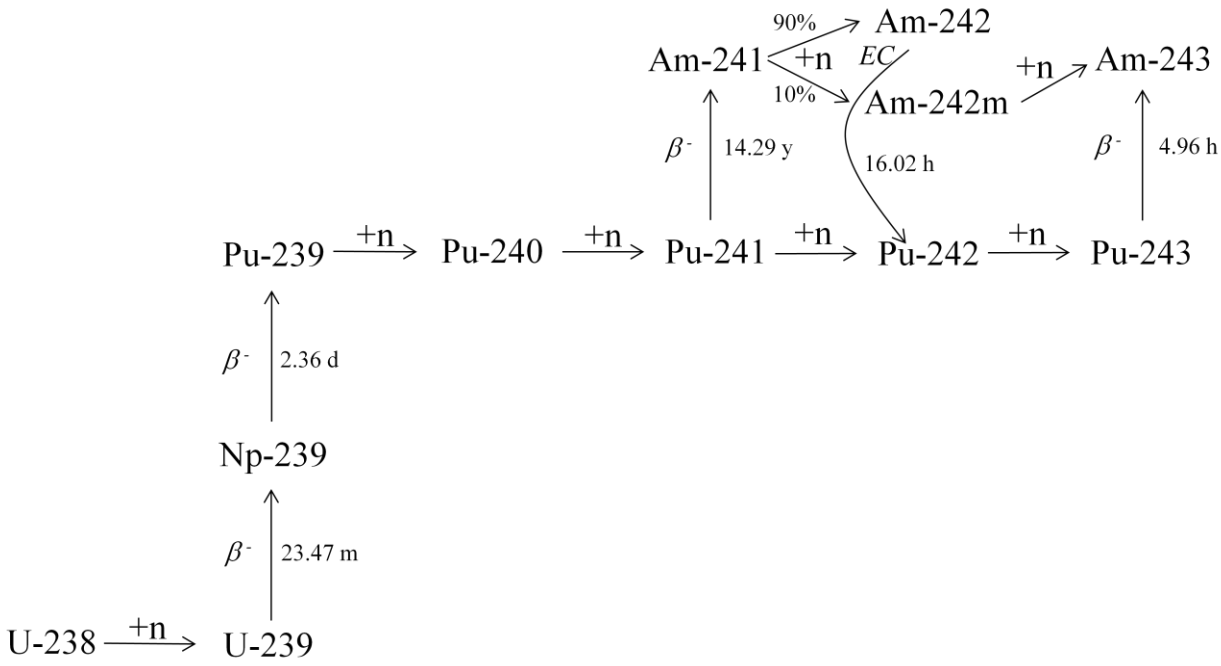


Fig. 1. Production of americium isotopes in a nuclear reactor. Only reactions and decays that lead to americium are shown.

Heavy water moderated reactors have been designed to optimize for neutron economy, allowing them to use natural uranium as fuel. This characteristic enables 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.

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). The extra expenses incurred by Utility L would therefore be those of partitioning and shipment of americium (on top of those for separation and shipment of plutonium) 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.

II. 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, the extra U-235 content of RU is sufficient to support the loss of some neutrons to absorption in Am-241 and Am-243 mixed into the fresh fuel after extraction from LWR SNF. Neutron absorption in Am-241 and Am-243 leads to fissile isotopes (Fig. 2), whose subsequent fissioning leads to less problematic and shorter-lived fission products, and to actinides having much longer, or much shorter half lives. Even mass isotopes of curium are created through beta-decay of even-mass Am isotopes (242m and 244), while odd-mass curium isotopes are created through subsequent neutron absorption. This extra step, plus the fact that the odd mass curiums are fissile, guarantees that the final fuel composition will be predominately the even-mass isotopes Cm-242 and Cm-244. However, these 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. The residence time of fuel in an HWR is insufficient to create significant quantities of the problematic heavy, long-lived curiums of weight 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.

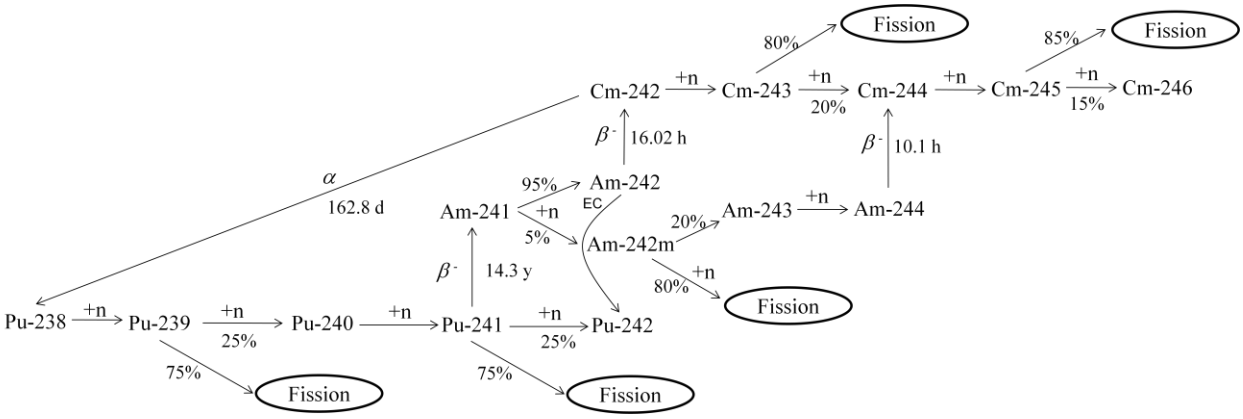


Fig. 2. The transmutation of americium. The branching ratios are based on thermal neutron cross section data from [2].

The 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 of neutron cross sections [4]. The type of bundle analyzed 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 burnup of bundles at a constant power typical of an HWR (32 W/g IHM[1]) until the integrated, burnup weighted k_∞ fell to 1.03, indicating that the fuel had reached exit burnup. For a burnup calculation, the burnup weighted k_∞ is an estimate of the k_∞ of an

[1] IHM is initial heavy metals.

infinite lattice of fuel bundles with a distribution of burnups from 0 to the current burnup (i.e. of an infinite online-refueled reactor with an equilibrium burnup distribution). A neutron leakage of 3% is possible from an HWR operating in a configuration without the use of reactivity devices for spatial flux adjustment. By adjusting the initial concentration of americium isotopes in the fuel, the exit burnup point was adjusted until it corresponded to a burnup of 7500 MWd/tonne – a typical exit burnup for natural uranium fuel.

Fairly high destruction rates of the americium isotopes in an HWR were observed, ~75 wt.% of the initial Am-241 and ~20 wt.% of the initial Am-243, depending on the amount added initially.

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} ($/kgHM)[2]:

$$C_{rr} = C_r + C_{dh} - M_{Pu}C_{Pu} - M_{rU}C_{rU}.$$

Where

- HM is the heavy metal content of spent nuclear fuel that is sent for reprocessing,
- C_r is the cost ($/kgHM) of separating uranium and plutonium from spent LWR fuel,
- C_{dh} is the cost ($/kgHM) of geological disposal of high level wastes,
- M_{Pu} is the mass (kg/kgHM) of plutonium recovered per mass of spent fuel,
- C_{Pu} is the estimated value ($/kg) of recovered plutonium,
- M_{rU} is the mass of reprocessed uranium (kg/kgHM) per mass of spent fuel, and
- C_{rU} is the estimated value ($/kg) of reprocessed uranium (RU).

The purpose of partitioning and transmuting americium is to reduce the cost of geological disposal. Therefore, define the following:

- C_{dAm} is the reduction in geological disposal cost ($/kgHM), relative to the direct disposal of americium and the other actinides, per unit mass of spent LWR fuel from which the americium is transmuted in HWRs, and
- M_{Am} is the mass of americium that is transmuted per mass of spent LWR fuel (kg/kgHM).

With respect to Utility L, the costs associated with transmuting Am-241 in HWR reactors depend on:

- the cost of partitioning americium from spent fuel C_{sAm} ($/kgHM)[3],
- the amount of RU, M_{cU} (kg/kgHM), that must be used in the HWR reactor to transmute M_{Am} of Am-241,

[2] Factors that account for the difference in time that each cost is incurred are omitted here for clarity.

[3] Note that C_{sAm} is assumed to include all costs associated with separating americium from spent fuel (including capital, operating, and waste disposal costs), and transportation to the HWR reactors.

- the estimated value of RU, and
- x_{Am}, the concentration of Am-241 in spent LWR fuel at the time of reprocessing.

The net cost of recycling LWR spent fuel, including americium partitioning and averted disposal costs, C_{cr} (\$/kgHM) is:

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

The negative term in (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.

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:

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

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

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

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 acceptable to Utility L.

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

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 Am-241 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 (5) is the SR such that all of the Am-241 produced by each LWR is transmuted in a HWR assuming a sufficient supply of RU. The RU SR (6) is the support ratio such that all of the RU produced by each LWR is burned in a HWR.

$$R_{Am} = \frac{\frac{F_{HWR}}{T_{HWR}\alpha_{cU}^{Am}}}{\frac{x_{Am}F_{LWR}}{T_{LWR}}} \quad (5)$$

$$R_{RU} = \frac{\frac{F_{HWR}}{T_{HWR}}}{\frac{x_{RU}F_{LWR}}{T_{LWR}}} \quad (6)$$

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 reprocessed spent 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 Am-241 that Utility L produces in the steady state with LWR produced RU.

IV. THE VALUE OF REPROCESSED URANIUM

According to (2), the economic acceptability of transmuting Am-241 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 reprocessed uranium (RU) to Utility L depends on how reprocessed uranium can be used in a LWR reactor to produce power [7]. According to [8], RU can be used in LWR by re-enriching to make LEU, or it can be combined with plutonium to make MOX fuel.

Due to the inability of current enrichment techniques to separate U-236 from U-235, the LWR fuel manufactured from the enrichment of RU to make the enriched reprocessed uranium (ERU) would require a higher concentration of U-235 than enriched natural uranium (ENU) for a similar burnup design, due to the neutron absorption by U-236 in RU [6]. Enriching RU to an equivalent enrichment of ENU may require U-235 enrichments greater than 5 wt.%. Since most fuel handling facilities are neither licensed nor designed for fuel with enrichment greater than 5 wt.% [9], change in licensing or upgrading of these facilities may be required. Like ENU, manufacturing ERU also requires conversion and fuel fabrication, the costs of which are higher than for ENU due to additional complications of handling RU [10].

In this report, 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. Sections IVA and IVB describe the use of RU in MOX, and the blending of RU ENU, respectively, and why these options are unsuitable for estimating the value of RU at this time. Section IVC describes the enrichment of RU using centrifuges and presents the equations used to estimate the value of RU.

IVA. REPROCESSED URANIUM BASED MOX

In addition to RU, another product of reprocessing spent LWR fuel is plutonium. As with U-235, Pu-239 and Pu-241 are fissile [11]. Plutonium containing high enough quantities of these isotopes can be

combined with depleted uranium in MOX fuel and irradiated in LWRs [12]. There are no published data or experience with the use of RU in MOX fuel. Also, two reports on potential uses of RU do not consider its use in MOX [9,13]. Therefore, there is not enough information available to estimate the value of RU if it is to be used in MOX fuel. It also should be noted that this option was not considered by Baumgärtner [9] because the great expense of MOX fabrication made it important to maximize the amount of plutonium per MOX fuel assembly.

IVB. BLENDING WITH HIGHER ENRICHED URANIUM

The enrichment of RU by blending it with higher enriched uranium was performed by OAO Mashinostroitelny Zavod [9] to make use of an existing inventory of highly enriched uranium (HEU). The benefit of blending RU with ENU is a reduction in the concentration of U-236 in ERU and, consequently, a reduction in the enrichment of ERU required for a given equivalent enrichment of ENU. If no inventories of higher enriched uranium are available, then ENU with higher enrichment could be made specifically for this purpose, although this process incurs the additional cost of NU feed, conversion, and enrichment, and would create significant non-proliferation concerns. The enrichment of NU specifically for blending with RU has not been implemented for the purpose of generating electricity.

IVC. ENRICHMENT USING CENTRIFUGES

The enrichment of RU using centrifuges has been carried out by COGEMA's UP2 plant, and the resulting fuel has been used in LWRs [9]. The cost of enriching RU is higher than for NU due to additional complications of handling RU [14], and the concentration of U-236 in ERU is greater than in RU due to the inability of centrifuges to separate U-236 from U-235.

Bunn et al. [6] 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.

$$C_{lwr} = \frac{1}{1-f_{lf}}\left[\frac{R}{1-f_s}\left(\frac{C_u}{(1-f_c)(1+i)^{t_u}} + \frac{C_c}{(1+i)^{t_c}}\right) + \frac{SC_s}{(1+i)^{t_s}}\right] + \frac{C_{lf}}{(1+i)^{t_f}} \quad (7)$$

$$C_{rlwr} = \frac{1}{1-f_{rlf}}\left[\frac{R_r}{1-f_s}\left(\frac{C_{rU}}{(1-f_c)(1+i)^{t_u}} + \frac{C_{rc}}{(1+i)^{t_c}}\right) + \frac{S_r C_{rs}}{(1+i)^{t_s}}\right] + \frac{C_{rlf}}{(1+i)^{t_f}} \quad (8)$$

The parameters in (7) and (8) are defined in Table I and Table II.

Table I: 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 ratio	R	R_r
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 II: Definitions of the enrichment formulas and parameters for producing ENU and ERU.

ENU	ERU
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 U-236 in RU
$R = \frac{x_p - x_t}{x_f - x_t}$	$R = \frac{x_{rp} - x_{rt}}{x_{rf} - x_{rt}}$
$S = V(x_p) - V(x_t) - R[V(x_f) - V(x_t)]$	$S_r = V(x_{rp}) - V(x_{rt}) - R[V(x_{rf}) - V(x_{rt})]$
	$x_{rp} = \frac{x_{rp} - x_{rt}}{x_{rf} - x_{rt}}$

$$V(x) = (2x - 1)\ln\frac{x}{1 - x}$$

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 ERU 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.

V. DATA

This section presents the values used for the parameters required for the computation of C_{rU}. The parameters can be categorized as cost, enrichment, and process parameters.

VA. COST ESTIMATES

The cost estimates used in this paper are based on estimates used in an OECD NEA report[15] 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. These cost estimates are shown in Table III. The analysis presented here also requires the cost estimates associated with manufacturing LWR fuel from RU, estimates that are not included in [15]. Therefore, the cost estimates used in this paper are based on the estimates made by Bunn et al. [6], which are presented as the costs of manufacturing LWR fuel from NU plus premiums for handling RU.

Table IV shows the estimated differences in costs between making LWR fuel from RU and making LWR fuel from NU that are used in this paper.

Table III: The cost estimates of making LWR fuel from Nu, and of partitioning americium from spent LWR fuel [15].

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

Mode[4]	50	5	100	250	200
Max	80	8	120	300	400

Table IV: Estimates of the difference in costs of making LWR fuel from RU and making LWR fuel from NU [6].

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

Table V shows the time at which each cost is paid for relative to the time at which C_{sAm} is paid, and the discount rate used to levelize each cost.

Table V: The time (years) at which each cost is paid relative to C_{sAm}, and the discount rate used to levelize each cost [6].

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
0	0.5	1	1.5	5%

VB. FUEL PARAMETERS

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 VI for 5 year decayed material and Table VII for 30 year decayed material. The sources for these data are varied. The 3.25 wt.%, 3.7 wt.% and 4.4 wt.% materials are from OECD NEA [11]. The Am-242m and Am-243 fractions are not given in that report, so nominal values based on LWR SNF in OECD NEA [16] were used and decayed 5 and 30 years to obtain roughly 72 wt.%: 0 wt.%: 28 wt.% (Am-241:Am-242m:Am243) and 85 wt.%: 0 wt.%: 15 wt.%, respectively. The ATM-104 data is a simulation [17] of a sample of a fuel element taken from near the end of the 14x14 LWR fuel assembly validation case [18]. The final RU enrichment, Pu-241 and Am-241 concentrations, were within 5% of measured values. The Takahama data is a simulation[5] of a 17x17 assembly PWR validation case [19] in which the final predicted RU enrichment was within 1%. The Am-241 and Am-243 exit SNF concentrations were predicted about 15% high in this simulation, but after five years 80% of the Am-241 present in LWR SNF, for fuel with a typical LWR power history, is due to Pu-241 decay. Since Pu-241 levels were predicted to be within 1% of those measured, the Am-241 levels predicted will be within 5% of the true values.

Table VI: LWR 5-year decayed spent fuel compositions.

Initial Enrichment Wt.%	Burnup (MWd_t/kg IHM)	RU Composition Wt.%	Wt.% Am-241/HM in RU	Am Composition Wt.%	Source
3.05%	27.35	U-235: 0.9338% U-236: 0.3846%	0.0267%	Am-241: 82.79% Am-242m: 0.32%	[17]

[4] The mode is the most probable value.
[5] Unpublished work using the same techniques as in [16].

		U-238: 98.6817%		Am-243: 16.89%	
3.25%	33	U-235: 0.9242% U-236: 0.4088% U-238: 98.6670%	0.0325%	Am-241: 72% Am-242m: 0 Am-243: 28%	[11]
3.70%	43	U-235: 0.8043% U-236: 0.5090% U-238: 98.6866%	0.0413%	Am-241: 72% Am-242m: 0 Am-243: 28%	[11]
4.10%	47	U-235: 0.8769% U-236: 0.6027% U-238: 98.5203%	0.0464%	Am-241: 66.7% Am-242m: 0.2% Am-243: 33.1%	Takahama
4.40%	53	U-235: 0.8228% U-236: 0.6363% U-238: 98.5409%	0.0480%	Am-241: 72% Am-242m: 0 Am-243: 28%	[11]

Table VII: LWR 30-year decayed spent fuel compositions

Initial Enrichment Wt.%	Burnup (MWd_t/kg IHM)	RU Composition Wt.%	Wt.% Am-241/HM in RU	Am Composition Wt.%	Source
3.05%	27.35	U-235: 0.9342% U-236: 0.3851% U-238: 98.6808%	0.0780%	Am-241: 93.4% Am-242m: 0.1% Am-243: 6.5%	[17]
3.25%	33	U-235: 0.9242% U-236: 0.4088% U-238: 98.6670%	0.1080%	Am-241: 85% Am-242m: 0 Am-243: 15%	[16]
3.70%	43	U-235: 0.8043% U-236: 0.5090% U-238: 98.6866%	0.1340%	Am-241: 85% Am-242m: 0 Am-243: 15%	[16]
4.10%	47	U-235: 0.8775% U-236: 0.6035% U-238: 98.5191%	0.1450%	Am-241: 86.2% Am-242m: 0.1% Am-243: 13.7%	Takahama
4.40%	53	U-235: 0.8228% U-236: 0.6363% U-238: 98.5409%	0.1550%	Am-241: 85% Am-242m: 0 Am-243: 15%	[16]

The enrichment of NU (x_{rf}) is assumed to be 0.711 wt.%. Table VIII shows the mass of RU that Utility L will have to send to Utility H to transmute each kilogram of Am-241, α_{cU}^{Am}, and the wt. percent of RU in spent LWR fuel (x_{RU}).

Table VIII: The minimum mass (kg) of RU required to transmute 1 kg of Am-241 in a HWR (α_{cU}^{Am}), and the wt. percent RU in spent LWR fuel (x_{RU}).

Decay Time (years)		27.35 MWd_t/kg IHM	33 MWd_t/kg IHM	43 MWd_t/kg IHM	47 MWd_t/kg IHM	53 MWd_t/kg IHM
5	α_{cU}^{Am}	549 kg	613 kg	1471 kg	833 kg	1220 kg
	x_{RU}	99.26%	98.78%	98.80%	98.72%	98.77%
30	α_{cU}^{Am}	532 kg	578 kg	1333 kg	813 kg	1136 kg
	x_{RU}	99.11%	99.08%	99.26%	98.64%	98.73%

VC. PROCESS PARAMETERS

The values of the fractional losses of each stage of manufacturing LWR fuel are shown in Table IX.

Table IX: The fractional losses of manufacturing LWR fuel [6].

Conversion, f_c	Separation, f_s	Fabrication of ENU f_{lf}	Fabrication of ERU f_{rlf}
0.005	0.005	0.005	0.01

VI. 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 (4) presented in Section III and the data presented in Section V. This section also presents an estimate of the number of LWRs that could be supported by a HWR in the scenario.

Fig. 3 shows the minimum required averted disposal cost, C^*_{dAm}, for the scenario to be economically acceptable for each RU enrichment and each storage duration, given the modes of the cost parameters. Any values of RU enrichment, x_{rf}, and averted disposal cost, C_{dAm}, that lie above a given line correspond to the Am transmutation scenario being economically acceptable for Utility L. Recall that C^*_{dAm} is the averted disposal cost per unit mass of spent LWR fuel. The storage of LWR spent fuel for an additional 25 years prior to reprocessing results in increased values of C^*_{dAm} by at least \$15/kgHM, for each amount of U-235 in RU that is considered here. This is due to the larger amount of Am in spent fuel that is stored for a longer period of time, which is in turn due to the decay of Pu-241. 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 U-235 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 Am in an HWR (therefore Utility L is required to give away less of its valuable RU stocks), and the reduction in the amount of Am in LWR spent fuel with lower burnup. In the case that the spent fuel is stored for 30 years, C^*_{dAm} varies from a minimum of \$225 to a maximum of \$250/kgHM, whereas storage for 5 years results in a variation between \$208 and \$217/kgHM.

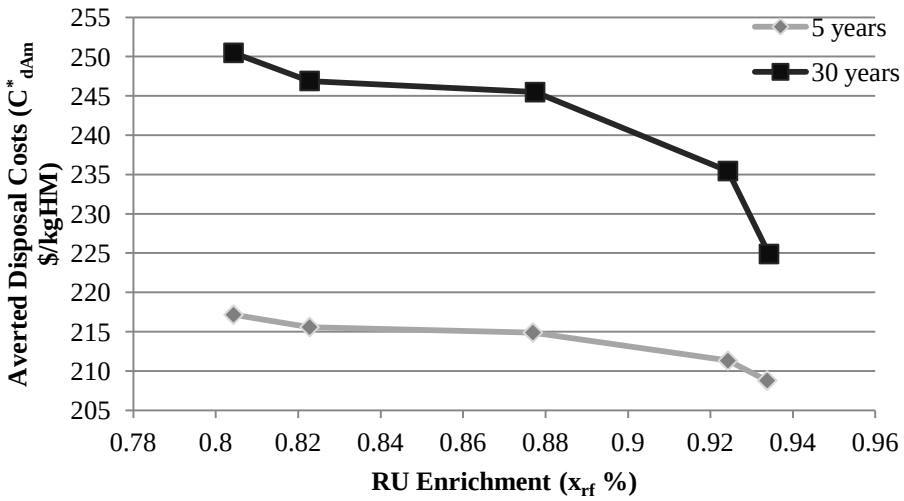


Fig. 3: The value of C^*_{dAm} given the modes of the cost parameters and each storage duration.

There are uncertainties in the various fuel cycle costs, therefore a sensitivity analysis was performed to determine how each cost parameter and the U-235 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 modes. For this sensitivity analysis, the mode of U-235 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}.

Fig. 4 shows C^*_{dAm} for the minimum and maximum of each parameter, indicated as the percent parameter change from its mode. The economics of the P&T scenario are most sensitive to the additional cost of partitioning americium from spent LWR fuel. This is due to the large difference between the mode, and the extreme costs. The minimum and maximum partitioning costs are 100% less and 100% more than the mode cost, respectively. If there is no additional cost to partition americium then the averted disposal cost should be around $15/kgHM and $46/kgHM, or more for fuel that is stored for 5 and 30 years, respectively. If the additional cost is $400/kgHM (the maximum value from the literature) then the averted disposal cost should be around $415/kgHM and $446/kgHM, 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/kgHM and $208/kgHM or more for fuel that is stored for 5 and 30 years, respectively. If the cost of uranium increases to $80/kg then the averted disposal costs should be around $228/kgHM and $283/kgHM, respectively. This is assuming that if RU is not used to transmute Am-241 then it will be enriched using centrifuges and fabricated into LWR fuel. C^*_{dAm} is relatively insensitive to the other fuel cycle parameters. The complete numerical results can be found in Table XI in Appendix A.

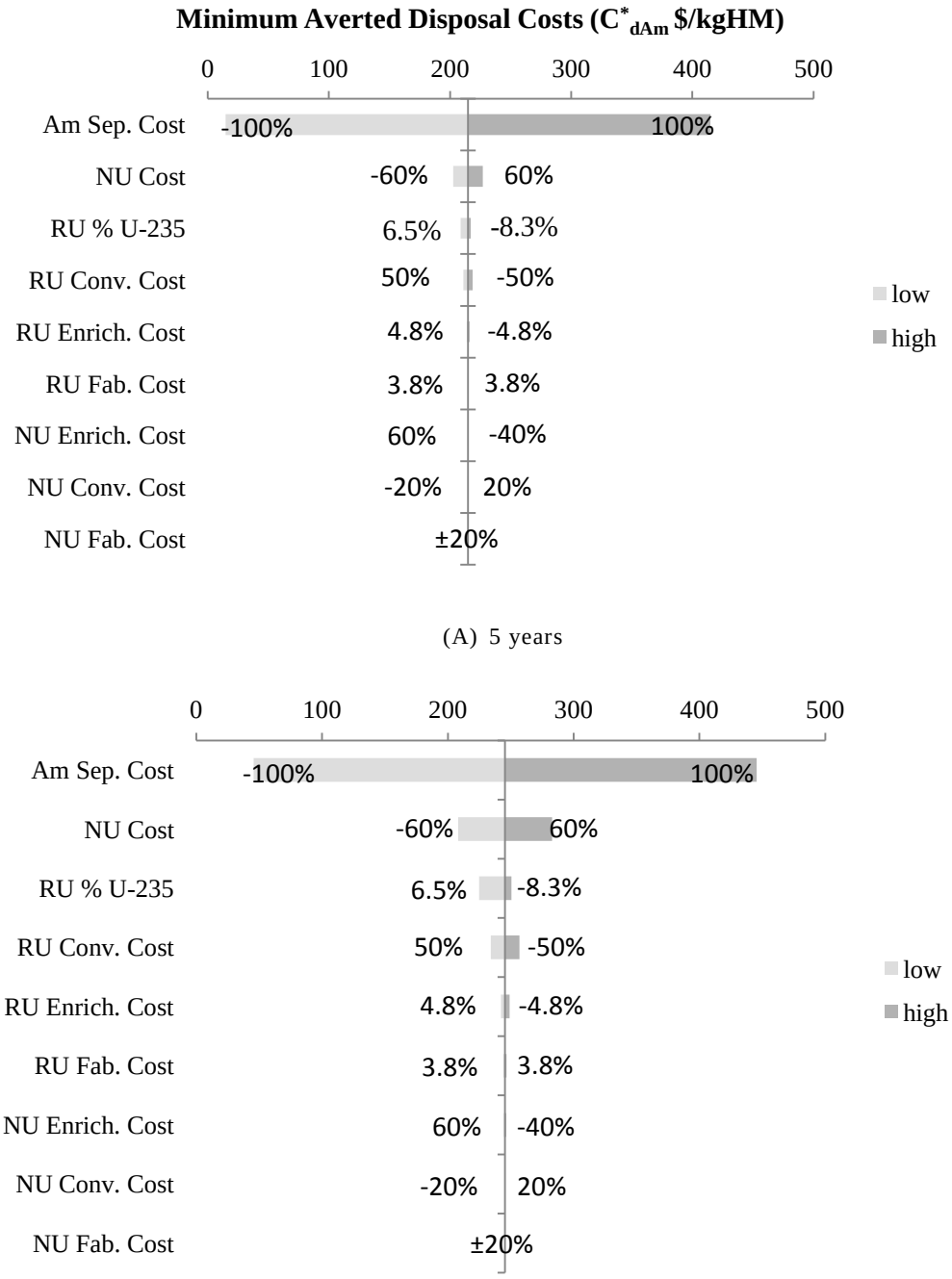
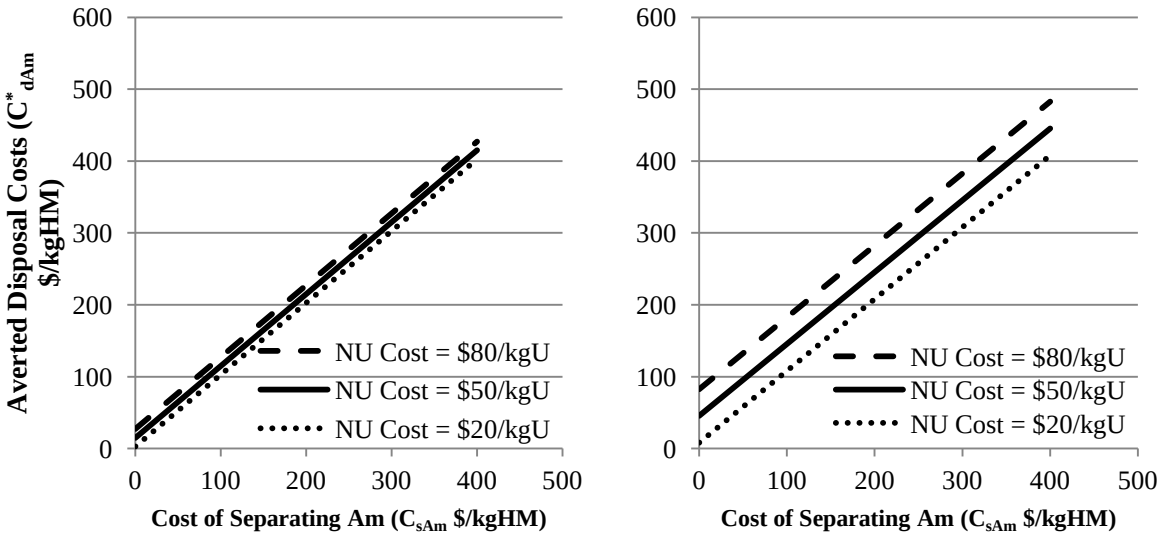


Fig. 4: The values of C^*_{dAm} for the minimum and maximum of each parameter, and each storage duration. Each parameter is also labeled with the percent change between its mode, and its minimum and maximum, respectively.

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. 5. This relationship is also shown for each of the minimum, mode, and maximum cost of natural uranium.



(A) 5 years (B) 30 years

Fig. 5: C^*_{dAm} versus C_{sAm} for each storage duration, and for the minimum, mode, and maximum cost of NU. All other parameters are set to their modes.

If Utility L and Utility H agree to implement the Am transmuting scenario, then it would be useful to know, in the steady state, the ratio of LWRs to HWRs such that all of the Am-241 is transmuted using RU. This is referred to as the support ratio (SR). In order to estimate the SR, the following assumptions are used:

1. each LWR produces approximately 1 Gigawatt (GW) of electricity (3 GW thermal power),
2. each HWR produces approximately 0.7 GW of electricity (2.1 GW thermal power),
3. a full fuel core load for each LWR and HWR is 80,000 kg IHM and 88,000 kg IHM, respectively;
4. each LWR and HWR takes three years [11] and 2/3 years, respectively, to burn a full core load;
5. the LWR spent fuel is stored for five years prior to reprocessing.

Based on these assumptions, the estimated SRs for transmuting Am-241 and burning RU are shown in Table X. In order for Utility H to transmute all of the Am-241 from Utility L using only RU from Utility L, then Utility L should have 4 or fewer LWRs per HWR for 27.35 MWd_t/kgHM LWR burnup, and 5 or fewer LWRs per HWR for the other LWR burnups. The support ratio is limited by the availability of RU, not Am. 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 Am content), in the LWR SNF.

Table X: The Am-241 and RU support ratios for each fuel burnup.

Burnup (MWd_t/kgIHM)	27.35	33	43	47	53
Am Support Ratio (R_{Am})	33	24	8	12	8
RU Support Ratio (R_{RU})	4	5	5	5	5

DISCUSSION

The decision by Utility L on whether to pursue this P&T scenario depends foremost on the effect that partitioning and transmuting americium from the other high level waste products has on the performance of any proposed, or operating, geological disposal facilities where its high level wastes may be deposited. The greater the improvement in repository performance is, the greater the economic incentive. The results show that, given the averted disposal cost, the cost of separating americium from the other minor actinides is the most important factor when it comes to whether this P&T scenario is economically acceptable to Utility L. The relationship between the partitioning cost and the minimum averted disposal costs, shown in Fig. 5, indicates what the maximum partitioning cost should be for a given averted disposal cost. This could be treated as a target cost when developing the americium partitioning process.

The results presented in the previous section also 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.

VII. CONCLUSION

A synergistic scenario has been proposed in this study where Am-241 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 Am-241. In order for such a scenario to be economically acceptable to Utility L, the averted disposal costs due to transmuting Am-241 should most likely exceed \$210/kgHM and \$225/kgHM for spent fuel that has been burned for 27.35 MWd_t/kgHM 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 MWd_t/kgHM, the averted disposal costs must exceed \$217/kgHM and \$250/kgHM for spent fuel that has been stored for 5 and 30 years, respectively.

The economics of this scenario are most sensitive to the additional cost of partitioning americium from spent LWR fuel, where increasing costs present an increased burden to Utility L. Another parameter that significantly affects the economics of this scenario is the cost of natural uranium, assuming that if RU is not used to transmute Am-241 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.

For the steady-state fuel cycle, Utility L should have no more than 4 or 5 LWRs for each HWR in Utility H, depending on the LWR burnup, in order to transmute all of the Am-241 from 5-year old spent LWR fuel with the RU extracted from this spent fuel.

Ultimately, the question of the economic acceptability of this P&T scenario to Utility L cannot be answered until the resulting averted disposal costs are estimated, and the estimate of the cost of partitioning americium from the other high level wastes is improved based on experience.

For future work, there are some possible variations to this P&T scenario that could be analyzed:

- if RU is considered a liability to Utility L (not re-enriched) and therefore it has a negative value that depends on its storage and disposal costs;
- at what cost of NU does this scenario become unacceptable to Utility H;
- under what conditions would a utility that operates both LWRs and HWRs find it economically acceptable to partition and transmute americium from LWR fuel in HWRs.

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A. NUMERICAL RESULTS

Table XI: The minimum averted disposal cost (C^*_{dAm} \$/kgHM) for each burnup, each storage time, and the mode, minimum, and maximum of each cost parameter.

Table IV.

Storage Time (years)		**27.35 MWd_t/kgHM**	**33 MWd_t/kgHM**	**43 MWd_t/kgHM**	**47 MWd_t/kgHM**	**53 MWd_t/kgHM**
5	Min C_{sAm}	208.79	211.32	217.16	214.89	215.59
	Max C_{sAm}	8.79	11.32	17.16	14.89	15.59
	Min C_u	408.79	411.32	417.16	414.89	415.59
	Max C_u	202.96	203.62	200.41	202.64	199.84
	Min C_c	214.44	218.81	234.25	227.13	231.72
	Max C_c	208.70	211.22	217.24	214.85	215.69
	Min C_s	208.92	211.47	217.04	214.95	215.44
	Max C_s	208.40	210.84	217.11	214.55	215.61
	Min C_{lf}	209.14	211.75	217.18	215.18	215.54
	Max C_{lf}	208.79	211.32	217.16	214.89	215.59
	Min C_{rc}	208.79	211.32	217.16	214.89	215.59
	Max C_{rc}	210.21	213.26	223.06	218.64	221.27
	Min C_{rs}	207.36	209.38	211.26	211.14	209.90
	Max C_{rs}	209.20	211.90	218.80	216.04	217.25
	Min C_{rlf}	208.39	210.76	215.59	213.79	214.01
	Max C_{rlf}	209.06	211.65	217.81	215.31	216.09
30	Min C_{sAm}	224.88	235.44	250.48	245.36	246.90
	Max C_{sAm}	24.88	35.44	50.48	45.36	46.90
	Min C_u	424.88	435.44	450.48	445.36	446.90
	Max C_u	208.38	211.35	201.20	208.02	199.52
	Min C_c	240.88	258.88	300.76	282.65	295.45
	Max C_c	224.64	235.12	250.72	245.23	247.21
	Min C_s	225.24	235.92	250.13	245.55	246.45
	Max C_s	223.77	233.94	250.33	244.33	246.96
	Min C_{lf}	225.89	236.79	250.54	246.24	246.77
	Max C_{lf}	224.88	235.44	250.48	245.36	246.90
	Min C_{rc}	224.88	235.44	250.48	245.36	246.90
	Max C_{rc}	228.91	241.50	267.83	256.81	264.01
	Min C_{rs}	220.85	229.38	233.13	233.91	229.80

	Max C_{rs}	226.06	237.25	255.30	248.87	251.90
	Min C_{rlf}	223.75	233.70	245.87	242.00	242.14
	Max C_{rlf}	225.64	236.48	252.38	246.63	248.43