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Cost analysis of the US spent nuclear fuel reprocessing facility

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ABSTRACT

The US Department of Energy is actively seeking ways in which to delay or obviate the need for additional nuclear waste repositories beyond Yucca Mountain. All of the realistic approaches require the reprocessing of spent nuclear fuel. However, the US currently lacks the infrastructure to do this and the costs of building and operating the required facilities are poorly established. Recent studies have also suggested that there is a financial advantage to delaying the deployment of such facilities. We consider a system of government owned reprocessing plants, each with a 40 year service life, that would reprocess spent nuclear fuel generated between 2010 and 2100. Using published data for the component costs, and a social discount rate appropriate for intergenerational analyses, we establish the unit cost for reprocessing and show that it increases slightly if deployment of infrastructure is delayed by a decade. The analysis indicates that achieving higher spent fuel discharge burnup is the most important pathway to reducing the overall cost of reprocessing. The analysis also suggests that a nuclear power production fee would be a way for the US government to recover the costs in a manner that is relatively insensitive to discount and nuclear power growth rates.

1. Introduction

Nuclear power accounts for 20% of the electricity production in the United States and concerns over global warming and energy independence have rekindled calls for an increase in its use (National energy policy, 2001). The current US fleet of light–water reactors (LWRs) produces around 2000 tonnes of spent fuel (SF) heavy metal each year all of which is destined for interment at Yucca Mountain along with the existing inventory of stockpiled SF. However, at current production rates the expected capacity of this repository will be met by 2010 (Richter et al., 2002; Schneider et al., 2003; Xu et al., 2005). While appropriate engineering could increase the amount of SF that can be stored safely at Yucca Mountain, it is unlikely that the repository could handle more SF than that anticipated from the LWRs that are in operation today[2] (Richter et al., 2002; Schneider et al., 2003). Because of this, a 1987 amendment to the US Nuclear Waste Policy Act mandates the Secretary of Energy to report on a site for a second repository by 2010 (Nuclear Waste Policy Amendments Act, 1987). However, the difficulties encountered with opening Yucca Mountain have led the US Department of Energy (DOE) to seek strategies that would significantly delay, or even eliminate, the need for further geological disposal sites. For this reason it is prudent to consider the costs of reprocessing SF produced at 2010.

The capacity of Yucca Mountain is limited by the thermal and radiological output of the materials that will be interred (DOE, 2005a). Because of this, considerable attention has been given to developing methods for transmuting the long lived radioisotopes that are contained in LWR SF into more benign or shorter lived forms. All of the plausible methods for doing this involve recycling these isotopes through a nuclear reactor. Depending on the technologies that will be employed for this purpose, the capacity of Yucca Mountain (or a repository of similar design) could be extended by orders of magnitude (Richter et al., 2002). Central to this approach is the ability to reprocess LWR SF in order to extract the requisite isotopes for recycle. At present, the US has no facilities that are capable of doing this on an industrial scale and a number of recent reports suggest that it would be advantageous to delay construction of such facilities for economic reasons (e.g. Anolabehere et al., 2003).

Reprocessing facilities built in the US will very likely be financed and operated by the federal government (National Research Council, 1996, pp 430). As a result, the US congress has mandated that a significant benefit must be achievable from reprocessing based fuel cycles by 2100 in order for federally funded R&D to continue. In response the DOE has set a goal of achieving sustained recycle of transuranics by 2100 and this will require that all SF discharged between 2010 and 2100 be reprocessed. The cost of doing this is poorly understood and depends on the times at which the required infrastructure is built, becomes operational, the time at which reprocessing of SF must be completed, as well as the time at which associated facilities are decommissioned. Until the required facilities are

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[2] Much of the current US reactor fleet is expected to receive license extensions allowing them to operate beyond their original life times. However, none are expected to be in operation after 2045 (Schneider et al., 2003).

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in place, the inventory of SF, and the required interim storage capacity, will continue to increase as will the capacity of the required reprocessing facilities. Reprocessing costs are therefore a function of their deployment time: the sooner the facilities are put in place, the smaller they can be, but the higher the discounted value of their capital expenditures and the longer that they incur operational expenses.

The present contribution analyses the minimum cost of opening, operating and decommissioning a US governmental facility that would reprocess spent nuclear fuel, discharged between 2010 and 2100, under a best case scenario in which all facilities operate at 100% capacity with no private financing required. The costing model depends on the time at which infrastructure is deployed, intergenerational discount rate, demand growth for nuclear power, plant life, spent fuel burnup (i.e. amount of energy that is liberated from a unit mass of nuclear fuel) and the unit costs associated with reprocessing and decommissioning.

2. Reprocessing cost: overview

In order to calculate the total system cost we assume that SF will be produced by a fleet of uranium fueled LWRs and that all SF generated between 2010 and 2100 will be reprocessed[3]. We assume that construction of the first reprocessing plant, and related interim storage facilities, begins in 2010 with construction of subsequent plants beginning at 40 year intervals thereafter. Experience suggests that the time, ΔT_C {yr}, required for construction of a reprocessing facility is typically 10 years (National Research Council, 1996, pp 422). We assume that a plant is finished at time T_R {yr}. Each facility will be sized to reprocess all SF generated during the 40 year interval that follows the start of its construction. A backlog of SF will accumulate between the date, T_0, when a reprocessing plant's construction begins and the date, T_R, at which it is complete. This requires that adequate interim storage capacity be built. We assume that one plant is always in operation, and construction of the next reprocessing facility begins 10 years prior to the shutdown of its predecessor. Fig. 1 summarizes the timelines considered in this study. The overall cost of reprocessing SF generated between 2010 and 2100 is then given by sum of the component costs:

$$C_{Total} = C_R + C_R^{OM} + C_S + C_S^{OM} + C_D. \tag{1}$$

Here C_R is the capital cost of the reprocessing plants, C_R^{OM}, is the cost of operations and maintenance cost for the plants, C_S, is the capital cost of the interim SF storage facilities, C_S^{OM}, is the operations and maintenance cost of the interim storage facilities and C_D is the cost of decommissioning the reprocessing and related facilities.

2.1. Reprocessing cost data

Cost data for the reprocessing plant were taken from the National Research Council (1996, 413–443) which provides estimated (and realized) costs for construction, operation and maintenance for the THORP, and UP3 and Rokkasho reprocessing facilities[4]. Operations and maintenance (O&M) charges reported in the National Research Council study were derived from British Nuclear Fuels estimates of the costs avoided by not operating THORP for one year.

The capital cost, C_0 {\$}, for a reprocessing plant with annual capacity M_0 of 900 {tonnes/yr} is given in National Research Council (1996, pp 424) and is based on values reported for THORP, which operates a PUREX process. Since the US is proposing to build larger facilities, it will be necessary to account for potential economies of scale. Therefore, we estimate the capital cost, C_R, of a hypothetical facility with capacity M_R using a cost/capacity scaling factor:

$$C_R / C_0 = (M_R / M_0)^{\gamma} \tag{2}$$

where γ is typically between 0.6 and 1.0. Treatment of decades worth of US SF will require a plant (or several modular plants) with a total annual capacity of some thousands of tonnes of heavy metal (HM) per year, even if the growth in nuclear power production remains low. Recent work suggests that economies of scale are important for plants of small to intermediate capacity, and that a value of $\gamma = 0.9$ for large plants is reasonable (Haire, 2003). We assume that no significant economies of scale exist for expansion of a medium to large scale reprocessing facility and take $\gamma = 1.0$, implying that a reprocessing plant's construction costs scale in a one to one manner with its capacity and we impose the same assumption on its operations and maintenance costs. An optimistic ($\gamma = 0.8$) scaling factor is considered as a perturbation.

The SF production rate {kgHM/yr} is given by $R_0 = 365.25\,\alpha\eta P_0 / \mathrm{BU}$ where P_0 is the reactor fleet's thermal output {MW}, η its thermal efficiency, α its capacity factor, and its burnup, BU, is the amount of energy that is liberated by its fuel per unit of heavy metal {MWd/kgHM}. We take as representative values those from the current US reactor fleet and assume a burnup of 52 {MWd/kgHM}. This latter value is higher than that of the current reactor fleet and leads to an SF production rate, R_0, of 1800 tonnes {HM/yr} instead of the 2000 tonnes {HM/yr} applicable today. However, burnup has historically increased over time and the value of 52 {MWd/kgHM} represents a likely average between 2010 and 2100. We assume that nuclear power will maintain its share of overall energy production and therefore increase at the rate of 1.8% per year (DOE, 2005b, pp 17) and we consider other growth scenarios as perturbations.

Data on SF storage costs were drawn from a 1994 International Atomic Energy Agency (IAEA) study (International Atomic energy Agency, 1994). The figures used here are the average of those provided for storage facilities in four European countries. The IAEA study provides construction plus annual fixed and variable O&M charges and given the modularity of interim storage capacity we assume that its unit costs are independent of the amount of fuel being stored. Data on discounted and undiscounted decommissioning costs for the reprocessing plant and related facilities are taken from estimates given by the British Nuclear Decommissioning Authority for the THORP facility and we assume that these costs scale in a one to one manner with plant size. The undiscounted decommissioning costs are reported in (NDA, 2005; OECD/NEA, 1994, annex 3) and give values that are within 20% of one another when adjusted for inflation and we take those from the latter (and more recent) study. All unit costs were adjusted to 2006 USD using a gross domestic product deflator.

Table 1 gives a summary of the relevant unit cost data and time points needed to determine the cost of reprocessing US SF produced between 2010 and 2100.

2.2. Cost calculations

To derive the overall cost of reprocessing SF generated between T_0 (the date after which SF is to be reprocessed by a given facility) and T_E (the date on which the last shipment of SF enters the respective interim storage facility) we calculate the capital and O&M costs for the reprocessing plant and interim storage facilities discounted to time $T = 2010$[5]. For the sake of simplicity we use continuous discounting and we employ a continuous model for the demand growth rate of

[3] The inventory of civilian SF was 47,023 tHM as of December 31, 2001 (EIA, 2002). At the current production rate of 2000 tHM/yr the 63,000 tHM capacity of Yucca Mountain will be met in ~2010.

[4] The Rokkasho cost estimate given in this study was a forecast that, in the end, proved to be optimistic.

[5] Executive Order 12866 requires that comparisons of the costs and benefits of US legislation be done with discounted values and we employ that convention here (Executive order 12866, 1993).

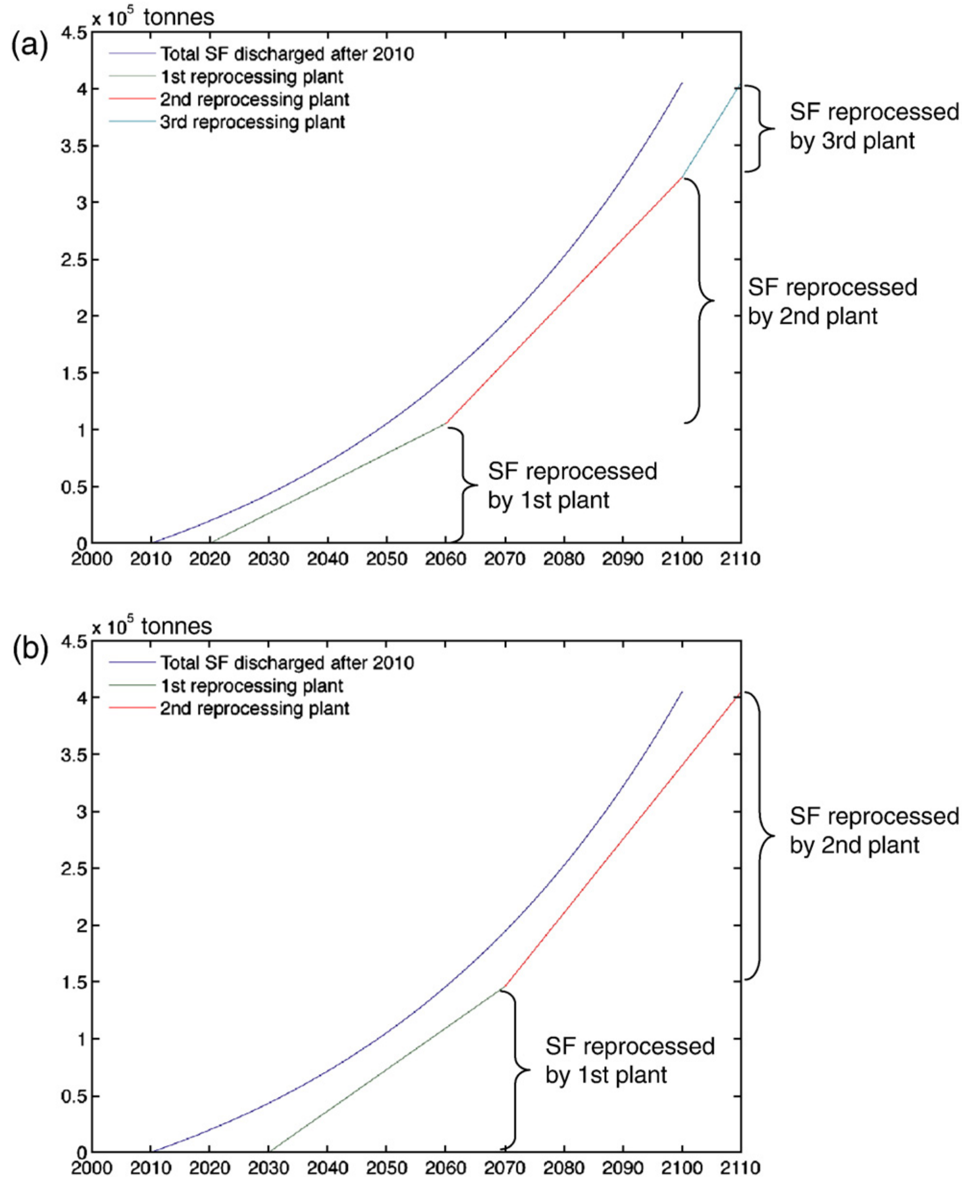

Fig. 1. Spent fuel discharged and reprocessed over time. (a) Reprocessing comes online in 2020. In order to reprocess all SF discharged between 2010 and 2100 three plants with a design life of 40 years will be needed. The first plant will reprocess SF discharged between 2010 and 2050, the second SF discharged between 2050 and 2090 and the third SF discharged between 2090 and 2100. Each plant has a 10 year lag on the SF is it intended to reprocess. Only 10 years of the third plants design life is required. (b) Reprocessing comes online in 2030. In this case only two reprocessing plants will be needed to handle SF discharged between 2010 and 2100, however both of those facilities will have to be larger than the first two in (a). The first facility handles SF discharged between 2010 and 2060 and the second SF discharged between 2060 and 2100. In both cases (a) and (b) reprocessing of SF discharged between 2010 and 2100 is completed in 2110.

nuclear power. The total inventory, I, of SF generated over a time period extending from T_0 to T_E is then given by:

$$I = \int_{T_0}^{T_E} R_0 e^{gt}\, dt = \frac{R_0}{g}\left[e^{gT_E} - e^{gT_0}\right] \tag{3}$$

where g is the growth rate {1/yr}, Fig. 2.

For the purpose of this study we size reprocessing plants by assuming that they operate at full capacity and handle all SF generated between T_0 and T_E. If reprocessing comes online in year T_R and the plant operates until year T_T its separations capacity, M_R {tHM/yr} is:

$$M_R = I/(T_T - T_R). \tag{4}$$

where I is the SF accumulation evaluated over the time period for which that reprocessing plant is responsible. Fig. 2 summarizes the mass flow rates of SF to and from a storage facility.

2.2.1. Reprocessing plant capital cost

We make the simplifying assumption that a single reprocessing plant takes ΔT_C years to build and comes online at time T_R. Using Eqs. (2)–(4), and assuming that the capital cost is incurred uniformly over each year of construction, the discounted capital cost of the plant is given by:

$$C_R = \int_{T_R - \Delta T_C}^{T_R} \frac{C_{R0} M_0}{\Delta T_C}\left(\frac{M_R}{M_0}\right)^{\gamma} e^{-rt}\, dt, \tag{5}$$

which gives:

$$C_R = C_{R0} M_0 \left(\frac{M_R}{M_0}\right)^{\gamma} \frac{\left(e^{-r(T_R - \Delta T_C)} - e^{-rT_R}\right)}{r\Delta T_C}. \tag{6}$$

Here C_{R0} is the reference construction cost, Table 1. By contrast, the undiscounted capital cost of the plant is merely equal to the total cash outlay for its construction and is given by: $C_R = C_{R0} M_R (M_R/M_0)^{\gamma} \Delta T_C$.

Table 1
Parameters for determining the cost of reprocessing SF.

Var	Units	Definition	Value	Ref
g	1/yr	Annual nuclear power growth rate	0.018	a
R_O	tHM/yr	SF discharge rate at T_0	1800	See text
P_0	GW(e)	Electric power output in 2010	100	b
α	–	Power plant capacity factor for LWR fleet	0.9	b
η	–	Thermal efficiency of reactor fleet	0.34	–
M_0	tHM/yr	Reprocessing capacity of reference plant	900	e
γ	–	Reprocessing plant scaling factor	1.0	See text
C_{R0}	$/tHM/yr	Capital cost per unit reprocessing capacity for reference plant, 1992 $	$6.8*10^6$	c
C_{R0}^{OM}	$/yr/tHM/yr	Annual plant O&M cost per unit of reprocessing capacity, 1992 $.	$0.49*10^6$	d
ΔT_c	yr	Reprocessing plant construction time	10	e
C_{S0}^{OM}	$/tHM/yr	O&M cost for interim SF storage per unit of storage, 1994 $	$5*10^3$	f
C_{S0}	$/tHM	Capital cost for interim SF storage per unit of storage, 1994 $	$0.25*10^6$	f
C_{D0}	GB/tHM/yr	Cost of decommissioning the reprocessing facility, 2005 GB ($r=0$)	$1.47*10^6$	g
		Cost of decommissioning the reprocessing facility, 2005 GB ($r=0.02$)	$0.75*10^6$	
r	1/yr	Intergenerational discount rate	0.02	h
□□□	–	Conversion factor GB—>$, 2005	0.55	i
CF94	–	Inflation factor for 1994–>2006 $	1.221	j
CF92	–	Inflation factor for 1992–>2006 $	1.275	j
CF05	–	Inflation factor for 2005–>2006 $	1.015	j

Relevant unit cost data needed to determine the overall cost of reprocessing US SF generated between 2010 and 2100. The reprocessing facility OM_{R0} is comprised of the cost of operating the facility and an annual facility refurbishment cost of 1% of the facilities capital cost per year. The design life of the THORP facility, on which the capital and O&M costs are based, was reported as 27–30 yrs in (National Research Council, 1996, pp 413–446; OECD/NEA, 1994, annex 3). However the 1994 OECD/NEA study suggests that a design life of 40 year is possible for the same cost rates and this is the basis used here. The capital, O&M and decommissioning costs for the reprocessing facility were reported as costs for the THORP facility and where put on a per unit capacity basis here by dividing by the 900 tHM/yr capacity of that facility. Nuclear power production in 2010 was derived by applying the 1.8% demand growth rate to the 90 GW(e) output given for 2004 (EIA, 2005).
a (DOE, 2005b, pp 17).
b (EIA, 2005), see caption.
c (National Research Council, 1996, pp 424).
d (National Research Council, 1996, pp 432).
e (National Research Council, 1996, pp 422).
f (International Atomic energy Agency, 1994).
g (NDA, 2005).
h (Arrow, 1999).
i Historical currency exchange rates, broadly available.
j (GPO, 2005, Table 10.1).

2.2.2. Reprocessing plant O&M

We assume that the reprocessing plants run at full capacity, M_R, from T_R to T_T. The total O&M cost is then the cumulative discounted annual O&M cost:

$$C_R^{OM} = \int_{T_R}^{T_T} \left(C_{R0}^{OM}\right) M_0 \left(\frac{M_R}{M_0}\right)^{\gamma} e^{-rt}\, dt \tag{7}$$

where we have made use Eq. (2) to scale the O&M cost for the reprocessing plant. Here C_{R0}^{OM} is the reference operations and maintenance cost, Table 1. We assume that C_{R0}^{OM} includes the cost of interim storage of reprocessing plant waste. Note that the capacity, M_R of the second and third (if needed) plants is larger than the first. Performing the integration we get:

$$C_R^{OM} = \left(C_{R0}^{OM}\right) M_0 \left(\frac{M_R}{M_0}\right)^{\gamma} \frac{e^{-rT_R} - e^{-rT_T}}{r}. \tag{8}$$

The undiscounted O&M cost for the reprocessing plant is equal to the total cash outlay for O&M during the interval $[T_R,T_T]$ and is given by: $C_R^{OM} = C_{R0}^{OM} M_R (M_R/M_0)^{\gamma} (T_T - T_R)$.

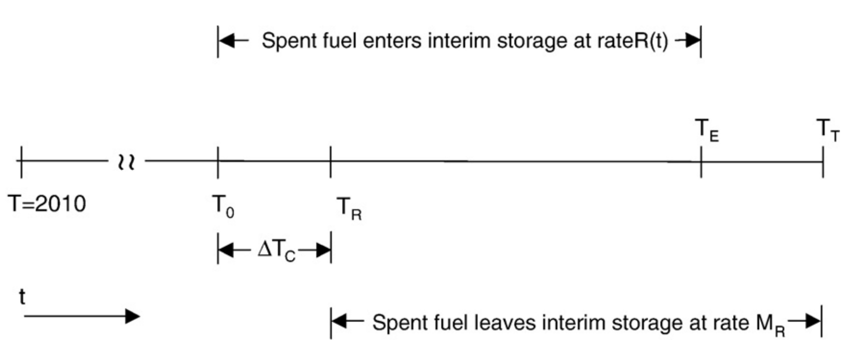

Fig. 2. Storage facility spent fuel mass flows. Between T_0 and T_E SF will enter each reprocessing plant's storage facility at the rate $R = R_0\, e^{gt}$ {kgHM/yr}, where g {1/yr} is the growth rate in the demand for nuclear power and t is time. Between T_R and T_T SF will leave the storage facility at a rate $M_R = I/(T_T - T_R)$ {kgHM/yr}, , where I {kg} is given by Eq. (3). The mass of SF in storage goes to zero at T_T. Construction of a given reprocessing plant begins in T_0, takes ΔT_C years, and is complete in T_R. The facility will operate until T_T. For the first plant in the base case $T_0 = 2010$, $T_R = 2020$, $T_E = 2050$ and $T_T = 2060$ with subsequent plants beginning construction at 40 year intervals thereafter.

Table 2
Costs of reprocessing system components {mills/kWh(e)}.

Component	Reference cost	10 year delay cost
Reprocessing plant construction	0.664	0.650
Reprocessing plant O&M	1.136	1.112
Storage capacity construction	0.174	0.242
Storage O&M	0.096	0.128
Reprocessing plant decommissioning	0.033	0.032
Total	2.103	2.163

The discounted costs for the reference case with and without a 10-year delay in the time at which reprocessing becomes available are shown. The time by which all reprocessing of SF generated between 2010 and 2100 is the same in both cases, i.e. 2110. As can be seen, there is virtually no difference in the overall cost per kWh(e) of reprocessing.

2.2.3. Storage facility capital cost

Spent fuel produced after T_0 will be stored in one or more dedicated facilities while it awaits reprocessing, which could be onsite at the reactors or within a dedicated facility at the reprocessing plant. The storage capacity will depend on nuclear power production at T_0 and its demand growth rate thereafter. Because SF will continue to accumulate until the first separations facility comes online, the amount of storage capacity needed will also depend on the time that separations commence, T_R. We assume that storage capacity is built as SF is discharged from the LWR fleet. The unit construction cost, C_{S0} {\$/kgHM}, for the facility is assumed to include the purchase of reusable casks or containers for immobilizing the SF while in storage and the construction time is assumed to be short. The total discounted capital cost for storage capacity is then given by:

$$C_S = \int_{T_0}^{T_R} C_{S0}\, R_0 e^{gt}\, e^{-rt}\, dt, \tag{9}$$

which gives:

$$C_S = \frac{C_{S0}\, R_0}{g-r}\left[e^{(g-r)T_R} - e^{(g-r)T_0}\right]. \tag{10}$$

The undiscounted capital cost for the SF storage facility is equal to the total cash outlay for its construction during the interval $[T_0,T_R]$ and is given by: $C_S = C_{S0}R_0(e^{gTR} - e^{gT0})/g$.

2.2.4. Spent fuel storage facility O&M

We assess the annual charge OM_{ST} {\$/kgHM/yr} for SF while it resides in the storage facility. The undiscounted total O&M cost is proportional to the time dependent inventory of unreprocessed SF. The cumulative, discounted, O&M cost may be written as:

$$C_S^{OM} = \int_{T_0}^{T_T} \left(C_{S0}^{OM}\right) I(t) e^{-rt} dt \tag{11}$$

where $I(t)$ is the SF inventory in storage at time t. Eq. (11) can be written in terms of three time intervals:

$$C_S^{OM} = \left(C_{S0}^{OM}\right)\left[\int_{T_0}^{T_R} I(t)e^{-rt}dt + \int_{T_R}^{T_E} I(t)e^{-rt}dt + \int_{T_E}^{T_T} I(t)e^{-rt}dt\right]. \tag{12}$$

Appendix A gives $I(t)$ during each of the relevant intervals. Completing the integrations we get:

$$C_S^{OM} = C_{S0}^{OM}\Big[\frac{R_0}{g}\Big(\frac{\left(e^{(g-r)T_E} - e^{(g-r)T_0}\right)}{g-r} + e^{gT_0}\frac{e^{-rT_E} - e^{-rT_0}}{r}\Big) + I(T_E)\frac{\left(e^{-rT_E} - e^{-rT_T}\right)}{r} + M_R\frac{T_R\left(e^{-rT_R} - e^{-rT_E}\right) + T_E\left(e^{-rT_E} - e^{-rT_T}\right)}{r} + \frac{M_R}{r^2}\left(e^{-rT_T}(rT_T+1) - e^{-rT_R}(rT_R+1)\right)\Big] \tag{13}$$

which applies when $g \neq r$ and $r \neq 0$, see Appendix. The undiscounted O&M cost for the SF storage can be easily obtained by setting $r = 0$ in Eq. (12) and substituting the values of $I(t)$ given in the Appendix.

2.2.5. Reprocessing plant decommissioning costs

Discounted decommissioning costs for the THORP facilities were reported in NDA (2005; OECD/NEA, 1994, annex 3) and give similar values when adjusted for inflation. The former study indicates that the reprocessing facility would be operated for 27 years followed by passive safe storage for 20 years and a seven year decommissioning period thereafter. However, only the total decommissioning cost discounted to T_0 was reported, not the decommissioning cash outlays during this period.

In order to adjust the costs reported in NDA (2005; OECD/NEA, 1994, annex 3) to a plant with a life other than 27 years we observe that the discounted cost is equal to the sum of the required cash outlays discounted to T_T with the result then discounted to T_0. Assuming that decommissioning costs scale with plant size in a one to one manner the discounted cost of decommissioning is then:

$$C_D = (M_R / M_0) C_{D0}\, e^{-r\Delta t}. \tag{14}$$

Here C_{D0} is the decommissioning cost of the THORP plant and Δt is the difference between the 27 year plant life given in OECD/NEA (1994, annex 3) and the actual plant life plus the time between the start of decommissioning and $T = 0$.

2.2.6. Reprocessing cost per kWh(e)

The sum of Eqs. (6), (8), (10), (13) and (14) gives the total discounted cost incurred from building, operating and decommissioning the SF interim storage and reprocessing facilities. Costs associated with fuel cycles are more typically given in terms of mills/kWh(e) rather than aggregate dollars, where a mill is equal to \$ 0.001. To make the conversion, we compute the electricity E produced by the reactor fleet {kWh(e)} during the interval $[T = 2010, T = 2100]$, discounted at the same rate r as was applied to the costs:

$$E = \alpha P_0 \int_{T_{2010}}^{T_{2100}} e^{(g-r)t}\, dt. \tag{15}$$

With the proper unit conversion factor of (8766 h/yr)(1e6 kW/GW) applied, Eq. (15) gives:

$$E = \alpha P_0 \frac{e^{(g-r)T_{2100}} - e^{(g-r)T_{2010}}}{g-r}\, \frac{8766 \cdot 10^6 \text{ kW hr}}{\text{GW yr}}. \tag{16}$$

When the discount rate is zero this reduces to $E = \alpha P_0\, [(e^{gT\mathrm{final}} - 1)/g]\, 8766 * 10^6$ kWh/GWyr.

3. Results and discussion

The US DOE has set a goal of achieving sustained recycle of transuranics by the year 2100, and this requires that all SF discharged between 2010 and 2100 be reprocessed. The model developed here provides a method for assessing the minimum cost of building and operating the required infrastructure and can be considered to be a best case estimate in which all facilities are government owned, operate at 100% capacity and no private financing is required.

Table 3
Reprocessing plant capacities.

Base case	Capacity {tHM/yr}	Delayed case	Capacity {tHM/yr}
1st Plant (operates 2020–60)	2636	1st Plant (operates 2030–70)	3649
2nd Plant (operates 2060–2100)	5416	2nd Plant (operates after 2070)	6484
3rd Plant (operates after 2100)	11,126		

Reprocessing plant capacities for the reference case where reprocessing begins in 2020 and for a ten year delay where reprocessing begins in 2030. Only 25% of the third plant's design life, and 75% of its capacity, are needed in the base case to reprocess the SF generated between 2090 and 2100.

Table 4
Sensitivity of reprocessing cost to changes in selected parameters.

Alternate scenario	Input(s) changed	Cost {mill/kWh(e)}	Change from base case {%}
Base case	–	2.103	–
Delay reprocessing by 10 years	$T_R=2020$ $T_E=2040$ $T_T=2050$ (fixed)	2.163	+2.8
Less optimistic LWR burnup assumption	$R_0=2000$ {tHM/yr} } ⇒ burnup = 47 {MWd/kgHM}	2.344	+12
Plant life of 30 years	$T_R=2020$ $T_E=2030$ $T_T=2040$	2.392	+14
Less optimistic LWR burnup assumption, plant life of 30 years	$T_R=2020$ $T_E=2030$ $T_T=2040$ $R_0=2000$ {tHM/yr}	2.658	+26
Optimistic cost/capacity scaling exponent	$\gamma=0.8$	1.639	−22
Low (0.5%) growth in LWR fleet	$g=0.005$	2.129	+1
Aggressive (2.5%) growth in LWR fleet	$g=0.025$	2.094	−1
'Best case': improved LWR burnup; 25% decrease in costs; 0.8 plant cost scaling factor	$R_0=1500$ {tHM/yr} } ⇒ burnup = 63 {MWd/kgHM}; unit costs × 0.75; $\gamma=0.8$	1.056	−50

The variation in total cost from changes in system parameters is given in mills/kWh(e) for eight potential deviations from the base case.

When no discounting is employed, an earlier start will always lead to a cheaper system since it reduces the amount and duration of interim SF storage that is required. A nonzero discount rate results in near term costs being weighted more heavily than those occurring in the future. The large expenditures for construction of the separations plant and addition of storage capacity occur early in the period of interest, while most of the revenue from energy production comes after these costs have been met. Therefore, increasing the discount rate can at times *increase* the discounted system cost per mills/kWh (e). Note that it is inappropriate to use a financial discount rate (typically 5%–10% above inflation) as such instruments are meant to capture the cost of money in the short term. For intergenerational calculations of type discussed here, a social discount rate is more appropriate as it better captures economic growth plus the marginal rate of GNP substitution (a measure of the decreasing rate of utility gain from increases in income). The use of an intergenerational discount rate is also required for comparison of the costs and benefits of potential US legislation on projects of the length considered here (Executive order 12866, 1993), and would be required for any strategy intended to extend the capacity of Yucca Mountain. A typical value for this discount rate is 2% above inflation in the US (Arrow, 1999) which is close to the 40 year average of the 30 year US treasury note which is 2.6% (DOE, 2002).

Table 2 gives the discounted costs of reprocessing system components needed to reprocess SF generated between 2010 and 2100. Table 3 gives the sizes of the respective reprocessing plants. As can be seen, for the reference values given in Table 1, delaying the deployment of the separations facility by ten years would increase the discounted costs by around 2.5%. This occurs entirely because of increased storage costs.

The discharge burnup of LWR SF has a strong effect on reprocessing system costs. The results in Table 4 show that a decrease in discharge burnup from 52 to 47 {MWd/kgHM} leads to an 11% increase in overall cost, which results from the extra need for reprocessing capacity and storage. It is known that cost savings can be obtained on the front end of the fuel cycle by increasing discharge burnup, but the marginal savings decrease with increasing burnup. As a result, utilities might not perceive any real benefit to increasing burnup past 50–60 {MWd/kgHM}. However, the cost reductions that can accrue on the back end of the fuel cycle at higher burnups are large. Therefore, it is reasonable to place

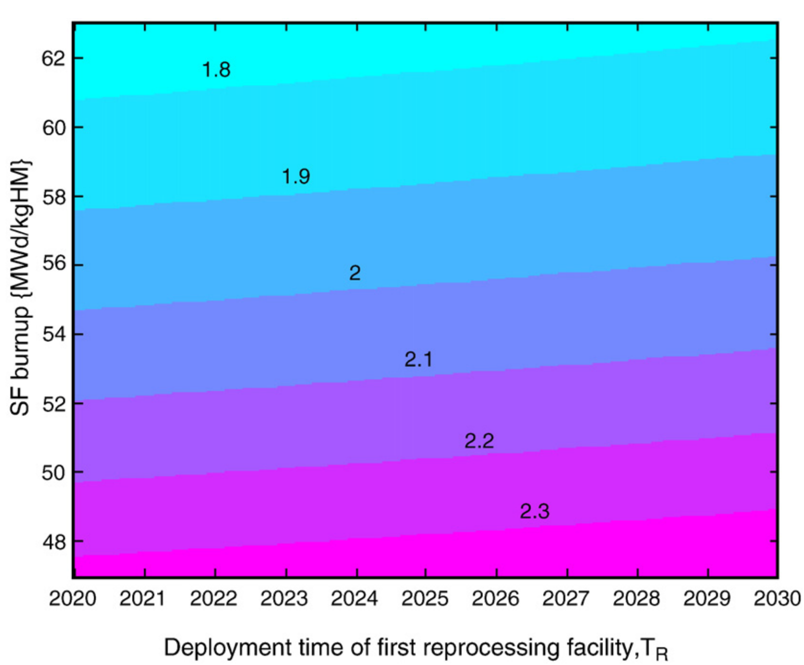

Fig. 3. Life cycle cost {mills/kWh(e)} -vs- SF burnup and deployment time. The total cost of SF reprocessing and storage is shown as a function of the date that reprocessing comes online and SF discharge burnup. The figure corresponds to the case where the first reprocessing comes online in $2020 \le T_R < 2030$ and three plants are required to reprocess all SF generated between 2010 and 2100. As can seen, the total life cycle cost of reprocessing increases slightly as deployment time is pushed back.

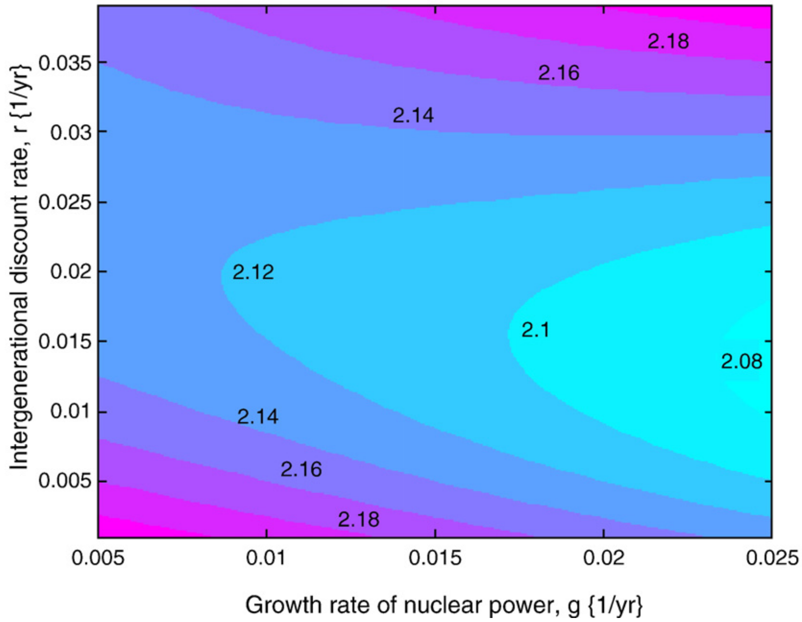

Fig. 4. Life cycle cost {mills/kWh(e)} -vs- discount rate and growth rate. The discounted reprocessing systems cost is shown as a function of the growth rate of nuclear power and intergenerational discount rate. The cost represents the mills/kWh(e) that utilities would need to pay in order to cover the cost of reprocessing LWR SF generated between 2010 and 2100.

strong emphasis on continued progress toward higher burnups. Fig. 3 shows the sensitivity of the system cost to variations in SF discharge burnup and the year at which reprocessing begins.

The results in Table 4 show that the reprocessing cost/kWh(e) is not strongly affected by either the nuclear power growth rate *g* or the discount rate *r*. In fact, when the discount rate is set to zero, only the storage cost depends on *g*. At intergenerational discount rates, a stronger nuclear growth rate translates into a slightly lower cost per unit energy owing to the larger amount of electricity being generated relative to the discounted cost of reprocessing. The relationship between cost, nuclear growth rate, *g*, and social discount rate, *r*, is shown in Fig. 4. Fig. 5 shows the variation in reprocessing cost with the nuclear power growth rate and LWR discharge burnup. These results suggest that if the US government were to recover costs through a mills/kgHM fee, the back end cost would be relatively stable against changes in discount and nuclear power growth rates.

The economic life of a reprocessing facility has a strong effect on the total discounted cost of reprocessing. If plant life is decreased from 40 to 30 years, the discounted systems cost of the first reprocessing facility rises from \$622/kgHM to \$760/kgHM, a gain of 22%. These reprocessing

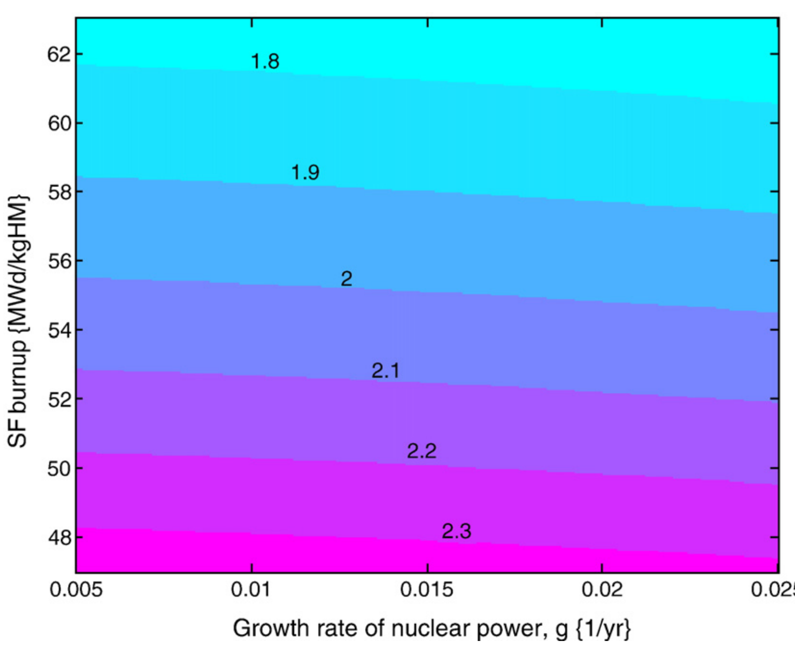

Fig. 5. Life cycle cost {mills/kWh(e)} -vs- SF burnup and growth rate. The discounted reprocessing systems cost is shown as a function of the nuclear power growth rate and LWR discharge burnup. The cost represents the mills/kWh(e) that utilities would need to pay in order to cover the cost of reprocessing LWR SF generated between 2010 and 2100.

costs, for the base case, are about 25% below those that have been reported for the THORP facility when adjusted for inflation (National Research Council, 1996, pp 413–446)[6]. However, the THORP facility operated as a commercial enterprise, whereas the figures given here represent "at cost" reprocessing which would be necessarily lower.

The reference construction and operation costs in Table 1 were taken from the literature. They represent present realities or, in some cases, best estimates of what it would cost to deploy a system in the near future. It is reasonable to expect improvements, though efforts to capture or estimate this are always controversial. Since the mill/kWh(e) cost is linear in the individual construction and O&M unit costs, readers not agreeing with these costs may scale the results based upon the cost breakdown presented in Tables 2 and 4. The burnup value given in Table 1 assumes better LWR performance than is currently available, however discharge burnup has increased substantially over time and continued improvement is likely, especially if incentives are put in place. The value given in Table 1 represents a reasonable average during the time period from 2010 to 2100. The cost calculations performed here assumed that a reprocessing facility would operate at full capacity. However, experience has shown that this is rarely the case and it is more likely that the reprocessing plant capacity factor will increase over time (as it has with nuclear power plants) as people have learned to operate them efficiently. The effect that such 'learning' has on reprocessing economics should be investigated in future studies.

The type of reactor fleet used to burn the long lived isotopes recycled from LWR SF has not been addressed in this study, neither were SF disposal costs, the geopolitical implications of reprocessing and the price dynamics of making uranium fuel. We emphasize that these factors will have a significant impact on the overall cost of the nuclear fuel cycle and hence play a role in the decision to whether or not to reprocess. Since advanced reactors will generate revenue through electricity production they should, in principle, pay for their own construction and operation. The effect that different reactor technologies would have on fuel cycle costs, the stockpiling and accessibility of proliferation sensitive materials, and the overall need for reprocessing capacity should be assessed in future work. The effect of uncertainty in unit cost data was also not considered here and should be the subject of future studies as well.

4. Conclusions

- The cost impact of delaying the deployment of a reprocessing facility was found to be minor. Postponing deployment by ten years, from 2020 to 2030, increase the discounted reprocessing system costs by 2.5%, which is in contrast to the conventional thinking that delaying the deployment of reprocessing infrastructure will reduce its discounted cost. Previous cost estimates have used a relatively high time value of money, whereas an intergenerational discount rate of about 2% more accurately reflects the long-term, sustained nature of the SF disposition effort.
- The discounted systems cost of the first reprocessing facility is $622/kgHM and $760/kgHM for plants with 40 with a 30 year service lives, respectively. These reprocessing costs are about 25% below those that have been reported for the THORP facility when adjusted for inflation. However, the THORP facility operated as a commercial enterprise, whereas the figures given here represent "at cost" reprocessing in which all facilities operated at 100% capacity and no private financing was needed.
- The back end system cost, in mills/kWh(e), is not strongly dependent on either the nuclear power growth nor the discount rates. Within the space of growth rate between 0.5% and 2.5% per year and the discount rate between 0.005 and 4.0% the cost of reprocessing, in mills/kWh(e), varies by less than 15%.
- The discharge burnup of LWR fuel was found to strongly affect the reprocessing system costs. In fact, the systems cost is almost directly proportional to discharge burnup, with a 10% increase in fuel burnup leading to a slightly greater than 10% cost savings. This results because better energy extraction per unit mass of fuel leads to fewer tons of fuel being discharged per year and a smaller infrastructure for all aspects of the back end systems.
- Regardless of deployment scenario, it will be difficult to attain a back-end cost that could be covered by the 1 mill/kWh(e) charge currently being charged to utilities. To achieve such a low cost, fuel discharge burnup would have to increase considerably and construction and operating costs would need to be improved from the levels achieved at La Hague and THORP.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.eneco.2008.12.011.

References

Anolabehere, S., Deutch, J., Driscoll, J., Holdren, P.E., Joskow, P.L., Lester, R.K., Moniz, E.J., Todreas, N.E., Beckjord, E.S., 2003. The future of nuclear power. MIT, Boston MA.
Arrow, K., 1999. Discounting, morality, and gaming. In: Prtney, P.R., Weyant, J.P. (Eds.), Discounting and intergenerational equity. RFF Press, Washington DC. pp.
DOE, 2002. Nuclear waste fund fee adequacy: An assessment. DOE, Office of Civilian Radioactive Waste Management, Washington DC. DEO/RW-0534.
DOE, 2005a. The path to sustainable nuclear energy, basic and applied research opportunities for advanced fuel cycles. Department of Energy, Washington DC. September.
DOE, 2005b. Report to Congress. Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary, Department of Energy, Office of Nuclear Energy, Science and Technology, May 2005.
EIA, 2002. Energy Information Agency, Detailed United States spent nuclear fuel data as of December 31, 2001. http://www.eia.doe.gov/cneaf/nuclear/spent_fuel/ussnfdata.html.
EIA, 2005. Energy Information Agency, Nuclear power plant operations. http://www.eia.doe.gov/emeu/aer/txt/ptb0902.html.
Executive order 12866, 1993. www.thewhitehouse.gov.
GPO, 2005. Budget of the United States Government: Historical tables fiscal year 2005. http://www.gpoaccess.gov/usbudget/fy05/hist.html.
Haire, J., 2003. Nuclear fuel reprocessing costs. Proceedings of Proceedings of Advances in Nuclear Fuel Management III, Hilton Head, SC.
International Atomic energy Agency, 1994. Cost analysis methodology for spent fuel storage. IAEA, p. 361.
National energy policy, 2001. The White House. Washington DC.
National Research Council, 1996. Nuclear Waste: Technologies for separation and transmutation, ed. National Academy Press, Washington DC.
NDA, 2005. Sellafield: decommissioning and termination category summary. Nuclear Decommissioning Authority, 2005/06 Lifecycle baseline rev A Issue 2 25-11-2005 - 35.13 Sellafield.
Nuclear Waste Policy Amendments Act, Public Law No. 100–203. 101 Stat. 1330, 1987.
OECD/NEA, 1994. The economics of the nuclear fuel cycle, OECD/NEA, Paris.
Richter, B., Hoffman, D.C., Mtingwa, S.K., Omberg, R.P., Pillon, S., Rempe, J.L., 2002. Report of the Advanced Nuclear Transformation Technology Subcommittee of the Nuclear Energy Research Advisory Committee. Department of Energy, Washington DC.
Schneider, E.A., Bathke, C.G., Demuth, S., James, M.R., 2003. Transient simulation of light water reactor recycle strategies in the United States. Proceedings of Proceedings of Global 2003, New Orleans LA.
Xu, Z.W., Kazimi, M.S., Driscoll, M.J., 2005. Impact of high burnup on PWR spent fuel characteristics. Nuclear Science and Engineering 151, 261–273.

[6] The THORP facility was reported to have charged $670/kgHM for reprocessing of German SF in 1993 USD.