Energy Economics 31 (2009) 627–634

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Cost analysis of the US spent nuclear fuel reprocessing facility

E.A. Schneider [a,1], M.R. Deinert [a,*,1], K.B. Cady [b]

[a] Department of Mechanical Engineering, University of Texas, Austin TX, United States
[b] Department of Theoretical and Applied Mechanics, Cornell University, Ithaca NY, United States

ARTICLE INFO

Article history:
Received 16 November 2007
Received in revised form 19 December 2008
Accepted 19 December 2008
Available online 15 January 2009

Keywords:
Nuclear fuel cycle
Spent nuclear fuel
Reprocessing
Energy economics

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

* Corresponding author.
E-mail address: mdeinert@mail.utexas.edu (M.R. Deinert).
[1] The first two authors contributed equally to this paper.
[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).

0140-9883/$ – see front matter
doi:10.1016/j.eneco.2008.12.011

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:

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

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 $R_0 = 365.25\,\alpha\eta P_0 / \text{BU}$ 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).