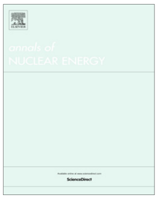
Annals of Nuclear Energy 71 (2014) 230–236

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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



Economic analysis of two nuclear fuel cycle options

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ARTICLE INFO

Article history:
Received 11 February 2014
Received in revised form 3 April 2014
Accepted 5 April 2014
Available online 3 May 2014

Keywords:
Nuclear fuel cycle option
LFCC
Material flows
Economics analysis
Breakeven price
Sensitivity

ABSTRACT

There are two major nuclear fuel cycle options in the world: the once-through cycle (OTC) option and the closed fuel cycle (CFC) option which consists of the thermal reactor recycle (TRR) and the fast reactor recycle (FRR). Presently, the TRR option has been industrially implemented in some European countries while the FRR option is still under development internationally. In this paper, the economic analysis of OTC and TRR options was carried out using levelized fuel cycle cost (LFCC). The two options were analyzed by calculating the equilibrium material flows as well as the economic costs of the overall fuel cycle components. The LFCCs of the two options were obtained as follows: OTC $\$5.94 \pm 0.67$ mills/kW h and TRR $\$6.13 \pm 0.55$ mills/kW h. Taking all uncertainties into considerations, the two options' costs were in the same range. In addition, the sensitivity analysis was made to figure out the breakeven uranium price (\$112/kgHM), at which uranium price from OTC was economically competitive to TRR option slightly. Under the most possible international circumstance, it indicates a decreasing breakeven uranium price in future, which means TRR option would be more economical than OTC option.

1. Introduction

Since the industrial revolution, the large scale use of fossil fuels has generated a huge amount of greenhouse gases accumulated in the atmosphere, resulting in serious global warming. As a low carbon energy, nuclear energy has made significant contributions in reducing carbon emission globally over past 50 years. However, the utilization of nuclear energy inevitably results in the generation of spent fuels and other nuclear wastes. Different countries may treat spent fuels in different ways. The economics of nuclear fuel cycle plays, with no doubt, a significant role for policy makers.

There are two main strategies of the nuclear fuel cycle already industrially implemented in the world (Deutch, 2009). One is the once-through cycle (OTC option), which features that spent UOX assemblies unloaded from reactors are directly disposed of after decades of cooling. The other option is the thermal reactor recycle using MOX fuel (TRR option). The scheme is that the spent UOX assemblies are sent to reprocessing plants to extract uranium and plutonium. The recovered uranium is stored for later use and plutonium is sent to fabricate MOX fuel for recycling. The high level liquid waste containing fission products and minor actinides is vitrified for final disposal. Then the MOX assemblies are reloaded in thermal reactors again. The spent MOX fuels will be interim stored for several decades and ultimate disposed without separation.

Arguments on the choice of fuel cycle options have never stopped. A large number of papers and reports have been published with different results. Matthew Bunn's group (Bunn et al., 2003) in Harvard University, and J.M. Deutch's group (Deutch, 2009) in Massachusetts Institute of Technology, arrived at their conclusions that the OTC option was superior to the TRR option based on the economics analysis on different nuclear fuel cycle options. While the economics analysis also conducted by Won Il Ko's group (Ko and Gao, 2012) in the Korea Atomic Energy Research Institute, and the NEA's expert group (OECD/NEA, 1994) in Europe, suggested that the TRR option was competitive with the OTC option for there was a negligibly small difference in terms of overall cost.

More and more nuclear power plants will be deployed in the future (World Nuclear Association, reactors facts, 2014). In order to manage the nuclear fuel cycle to make nuclear power be used economically, the suitable nuclear fuel cycle option should be analyzed by the means of the economic calculations. In this paper, the methodology would produce separate levelized economic nuclear fuel costs which could be used to determine the economical fuel cycle options. A typical PWR's (pressure water reactor) standard model was developed to calculate the equilibrium results of

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http://dx.doi.org/10.1016/j.anucene.2014.04.005
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material flows in two different nuclear fuel cycle options. The economics equations were formulated by the material flows, the specific unit costs of overall fuel cycle components and the lag and lead time of each option step. The Monte Carlo simulation was used in this methodology to get the statistical results with deviations. The economics results were obtained and the sensitivity analysis on the uranium breakeven price was discussed. The real uranium price with its future trends and the sensitive uranium breakeven price influenced from various factors were taken into account.

2. Material flows of different nuclear fuel cycle options

2.1. Different nuclear fuel cycle alternatives

The two nuclear cycle options employ the same front-end processes, such as mining, milling, conversion, enrichment and the fuel fabrication. The material flows would be different in the back-end processes: interim storage, spent fuel reprocessing, MOX fuel fabrication and nuclear waste ultimate disposal, etc.

OTC and TRR option schemes has been discussed in Section 1, the material flows were calculated from the equilibrium models based on these two options. The equilibrium model focused on the assumption that the whole nuclear fuel cycle system is in a steady state and that the material flows as well as electricity production through the fuel cycle is in an ideal equilibrium state. The equilibrium model enables a clear and direct comparison to alternative fuel cycle material flows.

2.2. The material flows calculation

More than half of the nuclear reactors (271 of 436) in the world are PWRs (World Nuclear Association, power reactors, 2014), in this paper it is reasonable to assume a simplified model for a typical PWR for each fuel cycle option (Table 1; Deutch, 2009). The annual requirement of the fuels was calculated based on the parameters of the typical PWRs.

Table 1
Characteristics of the reference reactors.

Parameters of the reference power plants	PWR
Thermal power (GWt)	2.966
Thermal efficiency (%)	33.7
Electrical power (GWe)	1.00
Capacity factor (%)	0.90
Cycle length (EFPD*)(day)	500
Average number of batches	3
Average irradiation time (EFPD*)	1500
Discharge burn up (GWd/kgHM)	0.050
*EFPD: effective full power days	

See reference Deutch (2009).

$$\text{Annual requirement (tHW/year)} = M = \frac{Q}{B_d} = \frac{P_e * \mathrm{CF} * 365}{\eta * B_d} \qquad (1)$$

where Q, B_d, P_e, CF, η are the annual reactor heat (GWd/a), thermal efficiency (%), electrical power (GWe) of a PWR, capacity factor (%) and discharge burn up (GWd/kgHM), respectively.

In order to evaluate unit material flow, we calculated the equilibrium model based on a PWR with electricity power (P_e) of 1.00 GWe operating for a whole year (365 days). Based on the average parameters of the fuel composition (Table 2; Deutch, 2009), the process of two spent nuclear fuel cycle options were designed, and the equilibrium material flows were obtained. Especially in TRR option, plutonium is not thought of as suitable for continuous recycling in thermal reactors. Its numbered non-fissile plutonium isotopes and higher actinides with the extended irradiation of plutonium will complicate the handling of the fuel and degrade the nuclear reactivity of the fuel (Deutch, 2009). Figs. 1a and 1b schematically describe the two fuel cycle options with the equilibrium material flows calculated.

Finally, the results of different nuclear fuel cycle options based on the equilibrium material flows model are listed (Table 3).

3. Economic data of different nuclear fuel cycle options

It should be mentioned that the capital cost as well as operation and maintenance cost are not included in this study as they are fixed cost and the capital cost could largely induce the uncertainty of the fuel cycle cost. This method is also acknowledged by the previous studies (Deutch, 2009; Bunn et al., 2003; OECD/NEA, 1994; Ko and Gao, 2012).

3.1. Estimates of the specific unit cost

The unit costs of each fuel cycle components were presented in 2013 US dollars. Because of the fluctuations in the world market, a wide range (indicated by low bound, high bound) of each unit cost was introduced to reflect the uncertainties.

Most reliable data, such as uranium prices, enrichment prices and conversion prices, are readily available. However, the information of commercial reprocessing or MOX fuel fabrication plants are limited. Some estimations based on published literature data from BNFL or COGEMA (now part of the Areva group in France) are taken in the paper with a reasonable range of uncertainty.

Table 2
Average UOX/MOX fuel compositions.

Capacity factor = 90%								
OTC option			TRR option					
Material flows (tHM/GWe/Year)								
	Load	After cooling	Load			After cooling		
			MOX	UOX	Total	MOX	UOX	Total
FP	0	1.006	0	0	0	0.293	0.703	0.996
U	19.500	18.244	5.220	13.667	18.887	5.041	12.79	17.83
(^{235}U)	(0.825)	(0.150)	(0.013)	(0.615)				
MA	0	0.025	0.008	0	0.008	0.040	0.020	0.060
Pu	0	0.225	0.491	0	0.491	0.343	0.157	0.500
TRU	0	0.250	0.499	0	0.499	0.383	0.177	0.560
HM	19.500	18.494	5.719	13.667	19.386	5.425	12.96	18.39
Total	19.500	19.500	5.719	13.667	19.386	5.719	13.67	19.39

FP: fission products, MA: minor actinides and TRU: transuranic elements. See reference Deutch (2009).