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by

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We analyze the levelized cost of electricity (LCOE) for three different fuel cycles: a Once-Through Cycle, in which the spent fuel is sent for disposal after one use in a reactor, a Twice-Through Cycle, in which the spent fuel is recycled for a second use in a light water reactor after which the spent fuel is sent for disposal, and a Fast Reactor Recycle in which all of the transuranics are repeatedly recycled in fast reactors. We carefully define the LCOE and provide a simple solution method that involves simultaneously calculating the value of the recycled materials, whether plutonium or the transuranics. We parameterize our formulas and calculate the LCOEs. Earlier reports do not provide general formulas and solution methods for calculating the LCOE. We contrast our methodology with the definitions and solution methods employed in various prior reports, and we compare our parameter inputs and resulting LCOEs. For example, we show that the 'equilibrium cost' of fast reactor systems as calculated in other studies exaggerates the LCOE. Our calculations show that, based on current estimates of the costs for the various activities, recycling increases the LCOE by between 1.7 and 2.8 mills/kWh. This is an approximately 20-34% increase in the fuel cycle cost of the Once-Through Cycle, which we estimate at 8.28 mill/kWh. This is an approximately 2-4% increase in the total LCOE of the Once-Through Cycle, which we estimate at 75.32 mill/kWh. For the Twice-Through Cycle, the separated plutonium has a negative value, meaning that a reactor will have to be paid to take the recycled plutonium. For the Fast Reactor Cycle, the separated transuranics have a negative value, meaning that a fast reactor will have to be paid to take the transuranics.

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INTRODUCTION

We analyze the levelized cost of electricity (LCOE) for three different fuel cycles:

- the traditional, Once-Through Cycle, in which the spent fuel is not recycled, but sent for disposal in a geologic repository,
- a Twice-Through Cycle, in which the plutonium and uranium extracted from the spent fuel from the first pass in a light water reactor are used in a second pass through a light water reactor, after which the spent fuel is sent for disposal in a geologic repository, and
- a Fast Reactor Recycle system, in which the spent fuel from the first pass in a light water reactor is followed by a repeated recycling of all of the transuranics through a fast reactor.

We compare the LCOEs for both recycle systems against the LCOE for the traditional, Once-Through Cycle.

The three cycles we analyze are similar to the cycles discussed in the MIT (2003) *Future of Nuclear Power* study with the labels "option 1", "option 2" and "option 3", respectively. A complete description of each cycle is contained in Guerin and Kazimi (2009). The Once-Through Cycle is similar to what is practiced in the US today, although the US has postponed implementing its geologic disposal plans in the face of political and technical disputes. The Twice-Through Cycle is similar to the system used in France, up to the disposition of the spent fuel from the second pass. We assume that at the end of the first pass through a light water reactor, the PUREX process is used to separate the spent uranium oxide (UOX) fuel into three streams: uranium, plutonium and a waste stream containing the fission products, minor actinides and impurities. After a period of storage, the waste stream is sent for disposal in a geologic repository. The uranium is used for fabrication of fresh UOX fuel and the plutonium is used, together with depleted uranium, for fabrication of mixed oxide fuel (MOX) for reuse in a light water reactor. In France,

the MOX fuel, once spent, is kept in interim storage pending future resolution of its disposition which may include further recycling. In the Twice-Through Cycle that we evaluate the spent MOX fuel is not recycled, but sent for disposal in a geologic repository. The Fast Reactor Recycle system begins with a first pass of UOX through the traditional light water reactor. At the end of this first pass, the TRUEX process is used to separate the spent UOX fuel into three streams: uranium, the transuranics, and a waste stream made up of the fission products together with impurities. After a period of storage, the waste stream is sent for disposal in a geologic repository. The uranium can be enriched and used for fabrication of fresh UOX fuel for reuse in a light water reactor. The transuranics are blended with depleted uranium to produce a metallic fuel for a fast reactor. The fast reactor can be designed to produce new fissile transuranics at a rate that exceeds or falls short of its rate of consumption by the neutron chain reaction, i.e. the fast reactors can operate as either a breeder or a burner, respectively. At the end of each pass through a fast reactor, pyroprocessing is used to separate the spent fuel into two streams: a mixture of uranium and transuranics, and a waste stream containing the fission products and impurities. After a period of storage, the waste stream is sent for disposal in a geologic repository. The mixture of uranium and transuranics can be refabricated into fresh fuel for another fast reactor. This cycle is not currently practiced at an industrial scale anywhere in the globe, although it is widely studied as a potentially valuable option for the future.

A number of criteria are relevant to policy makers selecting across these cycles, including issues of proliferation, the safety of disposal, the security of the fuel supply and public acceptance. Our analysis focuses only on one criteria, economics, and reduces it to

a single measure, the LCOE. We provide this measure as one contribution to a more comprehensive discussion of the many criteria relevant for a policy choice. If a cycle is preferred on a number of non-economic criteria, but the LCOE is higher, then the higher LCOE can be thought of as the price paid to purchase the non-economic benefits of the chosen cycle.

The estimated LCOEs also provide a useful measure of where things stand today. With that in hand, research efforts can be usefully targeted to the most important components that need to be reduced in order to make a switch to a new cycle economically feasible in the future.

In section 2 of this paper we develop the methodology for calculating a LCOE for different cycles. In the case of systems with recycling, this involves understanding the coupling between the different reactors through which the fuel passes over time. We show how this coupling implies a value for the fuel elements that are passed from one reactor to another: the plutonium in the Twice-Through Cycle, and the transuranics in the Fast Reactor Recycle. In section 3, we detail our parameter assumptions and calculate the component elements of the LCOE for each cycle. We also derive the implied value of plutonium and transuranics. In section 4, we compare methodology, our input parameters, and our results to those of other studies. A list of all of the variables used is provided after the references.

In calculating the LCOE from alternative generating technologies, one often assumes that all costs are constant in real terms. This need not be the case.[1] Indeed, the

[1] For example, the MIT (2003) study of *The Future of Nuclear Power* assumes different rates of inflation for maintenance capital expenditures, operating costs, fuel costs and electricity when calculating its LCOEs for a nuclear power plant. For those interested in exploring the implementation under these assumptions,

assumption about the real rate of escalation in the various components of costs is a critical consideration for studies of the economics of the nuclear fuel cycle. One of the key arguments in favor of recycling is concern that the scarcity of the raw materials relative to the exponentially growing demand for electricity will drive the price of the fuel to escalate more rapidly than the general inflation rate. To our knowledge, there are no studies of the comparative LCOE of different fuel cycles that explicitly incorporate a changing price of uranium through time. In this paper we continue this tradition and assume that real prices for all cost elements are constant. Our assumption that real prices are constant is critical for the way that we allocate costs across components of a cycle that follow one another in time.[2]

2. METHODOLOGY

The Levelized Cost of Electricity in the Once-Through Fuel Cycle

Calculating the levelized cost of electricity (LCOE) for the traditional, Once-Through Cycle is a relatively straightforward application of the usual formula:

$$\ell_1 = \frac{\int_0^T C_t\, e^{-Rt}\, dt}{\int_0^T Q_t\, e^{-Rt}\, dt}, \qquad (1)$$

where C_t denotes the full set of realized costs for all dates $t \in [0,T]$, Q_t denotes the time profile of electricity produced for all dates $t \in [0,T]$, and R denotes the continuously

see the spreadsheet accompanying Du and Parsons (2009), available on-line at: http://web.mit.edu/ceepr/www/publications/workingpapers.html.

[2] In a companion paper, De Roo and Parsons (2009), we develop some of the methodology necessary to solve the problem in the more general case where the real cost of the various inputs need not be constant over time.

compounded discount rate. The costs include all costs from the purchase of the raw ore, the fabrication of the fuel, construction and operation of the nuclear reactor, and finally the disposal of the spent fuel. In most calculations, the time horizon used, T, appears to be the life of a single reactor. In fact, the costs of disposal are incurred long after the life of the reactor, but these have been recalculated so that they are represented as a charge incurred either during the life of the reactor or shortly after the spent fuel is unloaded. So long as all costs are accounted for and present valued in a consistent fashion, it is immaterial what reference time frame is employed. In this paper, it will be convenient to think of the time horizon, T, as being defined by the time that a unit of fuel is resident in a reactor together with buffers at the loading and unloading when the relevant fabrication and interim storage operations occur.

We write the levelized cost of electricity from fuel cycle #1 as the sum of four elements:

$$\ell_1 = f_1 + k_1 + m_1 + d_1, \tag{2}$$

where f_1 is the cost associated with the front-end of the fuel cycle, including the raw ore, conversion, enrichment and fabrication, k_1 is the capital charge for the light water reactor, m_1 is the operating and maintenance charge for the light water reactor, and d_1 is the cost associated with the back-end of the fuel cycle, i.e., disposal, including any above-ground storage and final geologic sequestration. All four cost components are represented as a charge per kWh levied as the electricity is produced. Each charge is calculated to be sufficient, in present value terms, to cover the actual respective cash flows for each activity at the time the cash flow is incurred. For later comparison purposes, it will be

useful to write the front-end cost as the sum of the cost of raw uranium, u_1, and the sum of the enrichment, conversion, and fabrication costs, b_1, with $f_1 = u_1 + b_1$.

The Levelized Cost of Electricity Formula in the Twice Through Cycle

The LCOE for the Twice-Through Cycle can be written as a sum of the various costs incurred as the fuel passes first through one reactor, is reprocessed and then passes through a second reactor:

$$\ell_2 = \frac{\int_{A_1}^{B_1} C_{1t}\, e^{-Rt}\, dt + \int_{A_2}^{B_2} C_{2t}\, e^{-Rt}\, dt}{\int_{A_1}^{B_1} Q_{1t}\, e^{-Rt}\, dt + \int_{A_2}^{B_2} Q_{2t}\, e^{-Rt}\, dt}, \tag{3}$$

where the subscript 1 denotes the first pass with fresh UOX fuel and the subscript 2 denotes the second pass with MOX fuel, A_1 and B_1 denote the start and end dates for the first pass, C_{1t} denotes the full set of realized costs in the first pass at date t, and Q_{1t} denotes the time profile of electricity produced in the first pass at date t, and the same variables marked with subscript 2 denote the same things for the second pass through a light water reactor with the MOX fuel. The full set of realized costs will include the costs of reprocessing the fuel at the end of the first pass, including any storage costs, the costs of disposing of any separated waste stream that will not be passed along to the second reactor, the costs of fabricating the MOX fuel from the plutonium that is passed along from the first reactor to the second, and the cost of disposing of the spent MOX at the conclusion of the second pass.

As we define equation (3), it does not include any assessment of the value of the recovered plutonium passed from one cycle to another, since the cost to one cycle would be exactly cancelled out in the equation as a credit to the other cycle. However, we do

incorporate a credit in the first pass for the reprocessed uranium that is recovered. The value of the reprocessed uranium can be derived from the value of fresh uranium and the differential cost for fabrication into equivalent UOX fuel.

It is arbitrary whether the costs of reprocessing and MOX fuel fabrication are assigned to the first or to the second reactor, since the definition of the LCOE depends only upon the total costs for the complete pair of passes. We choose to assign these costs to the first reactor, but this does not impact any of the results, only the form in which they are presented.

The Price of Plutonium

Although the value of the plutonium passed from one reactor to another does not appear in equation (3), the equation is obviously unaffected if we attribute a value to the plutonium. Writing q for the quantity of plutonium separated out from the spent UOX fuel and p as the attributed price for the plutonium, equation (3) is rewritten as:

$$\ell_2 = \frac{\int_{A_1}^{B_1} C_{1t}\, e^{-Rt}\, dt + q\, p\, e^{-RB_1} - q\, p\, e^{-RB_1} + \int_{A_2}^{B_2} C_{2t}\, e^{-Rt}\, dt}{\int_{A_1}^{B_1} Q_{1t}\, e^{-Rt}\, dt + \int_{A_2}^{B_2} Q_{2t}\, e^{-Rt}\, dt}. \qquad (4)$$

We can use this attributed price to decompose the levelized cost calculation for the cycle as a whole into separate levelized costs for each pass through a reactor:

$$\ell_{2,1} = \frac{\left(\int_{A_1}^{B_1} C_{1t} e^{-Rt}\, dt + q\, p\, e^{-RB_1} \right)}{\int_{A_1}^{B_1} Q_{1t} e^{-Rt}\, dt}, \qquad (5)$$

and,

$$\ell_{2,2} = \frac{\left(-q\,p\,e^{-RB_1} + \int_{A_2}^{B_2} C_{2t} e^{-Rt}\,dt \right)}{\int_{A_2}^{B_2} Q_{2t} e^{-Rt}\,dt} \tag{6}$$

Of course, an arbitrary attributed value for the plutonium produces an arbitrary pair of LCOEs. Changing the value attributed to the plutonium leaves equation (4) unchanged, but changes (5) and (6). In order for the attributed value to be meaningful, we require that the LCOE for each pass be the same as the LCOE calculated for the entire cycle:

$$\ell_2 = \ell_{2,1}(p) = \ell_{2,2}(p). \tag{7}$$

The Components of the LCOE

We write each of the two levelized costs as the sum of the same four components used in the Once-Through Cycle:

$$\ell_{2,1}(p) = f_{2,1} + k_{2,1} + m_{2,1} + d_{2,1}(p), \tag{8}$$

$$\ell_{2,2}(p) = f_{2,2}(p) + k_{2,2} + m_{2,2} + d_{2,2}, \tag{9}$$

where by definition, $f_{2,1}=f_1$, $k_{2,1}=k_1$ and $m_{2,1}=m_1$. We also assume that $k_{2,2}=k_{2,1}$ and $m_{2,2}=m_{2,1}$, although in general this need not be the case. The cost of disposal for the first reactor in the Twice-Through Cycle is:

$$d_{2,1}(p) = s_{2,1} + w_{2,1} - u_{2,1B} - z_{2,1}(p), \tag{10}$$

where $s_{2,1}$ is the levelized reprocessing cost, $w_{2,1}$ is the levelized cost of disposal of the separated high level waste stream, $u_{2,1B}$ is the levelized credit for the recovered reprocessed uranium, and $z_{2,1}$ is the levelized attributed value of the separated plutonium. The front-end fuel costs for the second reactor will reflect the cost of purchase of the

plutonium, the cost of purchase of depleted uranium and the cost of fabricating the MOX fuel:

$$f_{2,2}(p) = u_{2,2} + z_{2,2}(p) + b_{2,2}\,. \tag{11}$$

The back-end cost of the second reactor does not depend on the value of separated plutonium, but is equal to the fixed interim storage and the disposal costs for spent MOX.

Note that the value of the recovered plutonium from the first reactor must equal the value of the plutonium input to the second reactor, when measured in absolute dollars. However, in equations (10) and (11) the terms $z_{2,1}(p)$ and $z_{2,2}(p)$ report these respective values measured per unit of electricity produced during the fuel's occupation of the respective cores, and so $z_{2,1}(p) \neq z_{2,2}(p)$. Instead, we have:

$$\frac{z_{2,2}(p)}{z_{2,1}(p)} = \frac{\int_{A_1}^{B_1} Q_{1t} e^{-Rt}\,dt}{\int_{A_2}^{B_2} Q_{2t} e^{-Rt}\,dt}\,. \tag{12}$$

We now rewrite equation (7) using the notation from equations (8) and (9),

$$\ell_{2,1}(p) = f_{2,1} + k_{2,1} + m_{2,1} + d_{2,1}(p) = f_{2,2}(p) + k_{2,2} + m_{2,2} + d_{2,2} = \ell_{2,2}(p),$$

or, more expansively, using equations (10) and (11),

$$\begin{aligned}\ell_{2,1}(p) &= f_{2,1} + k_{2,1} + m_{2,1} + s_{2,1} + w_{2,1} - u_{2,1} - z_{2,1}(p) \\ &= u_{2,2} + z_{2,2}(p) + b_{2,2} + k_{2,2} + m_{2,2} + d_{2,2} = \ell_{2,2}(p).\end{aligned} \tag{13}$$

Given our assumptions that the pair of reactors have the same capital and operating costs, this reduces to:

$$f_{2,1} + d_{2,1}(p) = f_{2,2}(p) + d_{2,2}\,, \tag{14}$$

or,

$$f_{2,1} + s_{2,1} + w_{2,1} - u_{2,1} - z_{2,1}(p) = u_{2,2} + z_{2,2}(p) + b_{2,2} + d_{2,2}\,. \tag{15}$$

Solving (15) gives us the unique attributed value of plutonium satisfying (7). Using this value, equations (8) and (9) give us the levelized cost for this twice through cycle.

There is no a priori constraint on the sign of the price of the recovered plutonium. It may be positive or negative. If it is positive, then the recovered plutonium is an asset for which the second reactor is willing to pay money. If it is negative, then the recovered plutonium is a liability and the second reactor has to be compensated for accepting it. The payment made to the second reactor is the first reactor's contribution to the ultimate disposal cost. For example, increasing the cost of MOX disposal drives down the plutonium price, increasing the amount the first reactor must pay. Although the second reactor is the point of payment for the cost of disposing of the spent MOX, the cost of disposal should be understood to be borne by both reactors.

The Levelized Cost of Electricity Formula for Fast Reactor Recycling

A General Formula

In recycling of spent fuel through fast reactors, the process of passing along a portion of the original fuel to the next reactor is repeated ad infinitum. A truly complete LCOE calculation requires a full accounting of the infinite chain of costs incurred as the packet of fuel moves from one reactor to the next:

$$\ell_3 = \frac{\sum_{j=1}^{\infty}\left[\int_{A_j}^{B_j} C_{jt}\, e^{-Rt}\, dt\right]}{\sum_{j=1}^{\infty}\left[\int_{A_j}^{B_j} Q_{jt}\, e^{-Rt}\, dt\right]}, \tag{16}$$

where j indexes the pass through a reactor, with j=1 referring to the initial pass through the light water reactor, and j=2,3,4… referring to the subsequent passes through fast reactors, A_j denotes the start date for pass j, B_j denotes the end date, C_{jt} denotes the full set of realized costs in pass j at date t, and Q_{jt} denotes the time profile of electricity produced in pass j at date t. The full set of realized costs will include the costs of reprocessing the fuel at the end of each cycle, including any storage costs, the costs of disposing of any separated waste stream that will not be passed along to the next reactor, and the costs of fabricating fuel for the next pass using the reprocessed spent fuel from the last pass.

As we define equation (16), it does not include any assessment of the value of the transuranics passed from one cycle to another, since the cost to one cycle would be exactly cancelled out in the equation as a credit to the other cycle. As before, we do incorporate a credit in the first pass for the reprocessed uranium that is recovered. We also incorporate a credit in subsequent passes for the depleted uranium that is mixed with the transuranics. This cost of depleted uranium is given in our assumptions.

A proper representation of the chain of costs in a full actinide recycling system is actually very complex. Each pass through a reactor changes the isotopic composition of the fuel. In particular, the vector of uranium and transuranic elements is changing with each pass, only gradually approaching an equilibrium vector. The isotopic composition determines the neutronic behavior which must be taken into account in fabricating the new fuel at each stage, changing the costs at each pass. A proper calculation of the levelized cost for the cycle as a whole must account for the complete profile of these changing costs through time, requiring a unique assessment of C_{jt} for each j.

A Simplified Formula

The levelized cost formula in equation (16) can be greatly simplified if we assume that the vector of transuranics is constant through all of the fast reactor cycles, as if the equilibrium vector were reached at the extraction of the transuranics from the light water reactor. We then assume that all of the various costs at each fast reactor cycle scale according to the transuranics mass ratio, q_{j+1}/q_j, which measures the quantity of the transuranics exiting the cycle relative to the quantity entering the cycle. This ratio is linked to but different from the conversion ratio by which fast reactors are usually labeled.[3] Under this constant transuranics vector assumption, the present value of the costs at each pass through a fast reactor is a simple scaling of the costs at the first pass in fast reactors, with the scaling factor being $\alpha^{j-2} = \left(\frac{q_2}{q_1} e^{-R(B_2 - B_1)} \right)^{j-2}$. Consequently, the infinite chain of distinct cost calculations can be reduced to one involving only two cycles with different cost elements:

$$\ell_3 = \frac{\int_{A_1}^{B_1} C_{1t} e^{-Rt} dt + \sum_{j=2}^{\infty} \alpha^{j-2} \left(\int_{A_2}^{B_2} C_{2t} e^{-Rt} dt \right)}{\int_{A_1}^{B_1} Q_{1t} e^{-Rt} dt + \sum_{j=2}^{\infty} \alpha^{j-2} \left(\int_{A_2}^{B_2} Q_{2t} e^{-Rt} dt \right)}.$$

This, in turn, collapses to,

$$\ell_3 = \frac{\int_{A_1}^{B_1} C_{1t} e^{-Rt} dt + \frac{1}{1-\alpha} \int_{A_2}^{B_2} C_{2t} e^{-Rt} dt}{\int_{A_1}^{B_1} Q_{1t} e^{-Rt} dt + \frac{1}{1-\alpha} \int_{A_2}^{B_2} Q_{2t} e^{-Rt} dt}. \quad (17)$$

[3] The conversion ratio is the ratio of the rate of production of new fissile transuranics to the rate of fissile transuranics consumption by the neutron chain reaction. At equilibrium, if the transuranics mass ratio is equal to one, then the conversion ratio is also equal to one. Around this point, the two ratios move together, with the conversion ratio having a greater amplitude than the transuranics mass ratio.

Given the large uncertainties involved in estimating major elements of the total cost for the recycle technology, this approximation seems reasonable.

The Price of Transuranics

Paralleling our earlier solution for an attributed price of plutonium, we now derive an attributed value for the transuranics passed from one cycle to another.[4] Writing q_j for the quantity of transuranics separated out from pass j and p_j as the attributed price of these transuranics, the general equation for the LCOE, equation (16), becomes:

$$\ell_3 = \frac{\int_{A_1}^{B_1} C_{1t}\, e^{-Rt}\, dt - q_1 p_1 e^{-RB_1} + \sum_{j=2}^{\infty}\left[q_{j-1} p_{j-1} e^{-RB_{j-1}} + \int_{A_j}^{B_j} C_{jt}\, e^{-Rt}\, dt - q_j p_j e^{-RB_j} \right]}{\sum_{j=1}^{\infty}\left[\int_{A_j}^{B_j} Q_{jt}\, e^{-Rt}\, dt \right]}. \qquad (18)$$

We can use this attributed price of transuranics to decompose the levelized cost calculation into a sequence of individual levelized cost of electricity calculations for each component step in the full cycle:

$$\ell_{3,1}(p_1) = \frac{\left(\int_{A_1}^{B_1} C_{1t} e^{-Rt} dt - q_1 p_1 e^{-RB_1} \right)}{\int_{A_1}^{B_1} Q_{1t} e^{-Rt} dt}, \qquad (19)$$

and,

[4] In fact, it is not really the transuranics that are exchanged from one step of the cycle to another, but more generally, a mix of transuranics and depleted uranium. Hence we should consider a price for the mix. But since at each step, the new fuel can be obtained by addition of depleted uranium or transuranics to the mix, we can show that the value of the mix is equal to the value of its separated elements. In our calculations, the price of depleted uranium is given as an input parameter. Therefore, we can extract and reason with a price for the transuranics alone.

$$\ell_{3,j}\left(p_{j-1}, p_j\right) = \frac{\left(q_{j-1} p_{j-1} e^{-RB_{j-1}} + \int_{A_j}^{B_j} C_{j,t} e^{-Rt} dt - q_j p_j e^{-RB_j} \right)}{\int_{A_j}^{B_j} Q_{jt} e^{-Rt} dt}, \text{ for } j = 2, 3, \ldots . \quad (20)$$

We require that:

$$\ell_3 = \ell_{3,1}\left(p_1\right) = \ell_{3,j}\left(p_{j-1}, p_j\right), \text{ for } j = 2, 3, \ldots . \quad (21)$$

The decomposition shown in equation (19) and (20) and satisfying equation (21) is feasible under a minimal set of conditions. For example, if we assume that the mix of uranium and transuranics reaches its equilibrium after a finite number of steps, *i*, then solving for the LCOE and transuranics prices can be represented as the solution to the following set of equations shown in matrix form:

$$\left[\begin{array}{c|ccc} \int_{A_1}^{B_1} Q_{1t} e^{-Rt} dt & q_1 e^{-RB_1} & 0 & 0 \\ \vdots & \ddots & \ddots & 0 \\ \int_{A_i}^{B_i} Q_{it} e^{-Rt} dt & 0 & -q_{i-1} e^{-RB_{i-1}} & q_i e^{-RB_i} \\ \hline \int_{A_{i+1}}^{B_{i+1}} Q_{i+1t} e^{-Rt} dt & 0 & 0 & -q_i e^{-RB_i} + q_{i+1} e^{-RB_{i+1}} \end{array}\right] \left[\begin{array}{c} \ell_3 \\ p_1 \\ \vdots \\ p_i \end{array}\right]$$

$$= \left[\begin{array}{c} \int_{A_1}^{B_1} C_{1t} e^{-Rt} dt \\ \vdots \\ \int_{A_i}^{B_i} C_{it} e^{-Rt} dt \\ \int_{A_{i+1}}^{B_{i+1}} C_{i+1t} e^{-Rt} dt \end{array}\right] \quad (22)$$

For all practical reactors, $0 < q_j$ for all j and $q_j < q_{j-1} e^{R(B_j - B_{j-1})}$ for all $j>i$, so that the matrix is invertible and there exists one unique solution for the set of prices attributable to the set of transuranic vectors passed at each cycle. [5,6]

This decomposition of the LCOE can also be done in the simpler case represented by equation (17). Rewriting equation (17) with our attribution of a price to the single vector of transuranics passed from one cycle to the next, we have:

$$\ell_3 = \frac{\left[\int_{A_1}^{B_1} C_{1t} e^{-Rt}\,dt - q_1 p_1 e^{-RB_1} + \frac{1}{1-\alpha}\left(q_1 p_1 e^{-RB_1} + \int_{A_2}^{B_2} C_{2t} e^{-Rt}\,dt - \alpha q_1 p_1 e^{-RB_1}\right)\right]}{\left[\int_{A_1}^{B_1} Q_{1t} e^{-Rt}\,dt + \frac{1}{1-\alpha}\int_{A_2}^{B_2} Q_{2t} e^{-Rt}\,dt\right]}. \qquad (23)$$

This is decomposed into a LCOE for the initial pass—through a light water reactor—and a LCOE for the succeeding pass—through a fast reactor, with the price for the transuranics being determined by the requirement that these two LCOEs be identical:

$$\ell_{3,L}(p) = \frac{\left(\int_{A_1}^{B_1} C_{1t} e^{-Rt}\,dt - q_1 p\, e^{-RB_1}\right)}{\int_{A_1}^{B_1} Q_{1t} e^{-Rt}\,dt}, \qquad (24)$$

[5] At equilibrium, for all $j>i$ $\left[\int_{A_j}^{B_j} Q_{jt} e^{-Rt}\,dt,\ -q_{j-1} e^{-RB_{j-1}} + q_j e^{-RB_j},\ \int_{A_j}^{B_j} C_{jt} e^{-Rt}\,dt\right]$ is proportional to $\left[\int_{A_{i+1}}^{B_{i+1}} Q_{i+1t} e^{-Rt}\,dt,\ -q_i e^{-RB_i} + q_{i+1} e^{-RB_{i+1}},\ \int_{A_{i+1}}^{B_{i+1}} C_{i+1t} e^{-Rt}\,dt\right]$, Therefore $\forall j > i, (\ell_{2,j} = \ell_{2,i}) \Leftrightarrow (p_j = p_i)$

[6] For a reactor with a fuel cycle length of 10 years and a discount rate of 7%, these inequalities imply that the transuranics mass ratio, MR, be 0<MR<1.97. In practice, the highest conversion ratios and the corresponding mass ratios do not exceed 1.5.

$$\ell_{3,F}(p)=\frac{\left(q_1 p e^{-RB_{j-1}} + \int_{A_2}^{B_2} C_{2t} e^{-Rt}\,dt - \alpha\, q_1 p e^{-RB_j}\right)}{\int_{A_2}^{B_2} Q_{2t} e^{-Rt}\,dt}, \tag{25}$$

and,

$$\ell_3 = \ell_{3,L}(p) = \ell_{3,F}(p). \tag{26}$$

The Components of the LCOE

We represent each of these two levelized costs as the sum of the same four elements discussed for the Once-Through and the Twice-Through Cycles:

$$\ell_{3,L}(p) = f_{3,L} + k_{3,L} + m_{3,L} + d_{3,L}(p), \tag{27}$$

$$\ell_{3,F}(p) = f_{3,F}(p) + k_{3,F} + m_{3,F} + d_{3,F}(p). \tag{28}$$

In our Fast Reactor Recycle, the initial pass through the light water reactor is the same as in the Once-Through Cycle, up to disposal. Therefore, $f_{3,L} = f_1$, $k_{3,L} = k_1$ and $m_{3,L} = m_1$, while $d_{3,L} \neq d_1$. In the Once-Through Cycle, d_1 is the costs of interim storage and geologic disposal. In the Fast Reactor Recycle, $d_{3,L}$ is the sum of the cost of reprocessing, the cost of disposing of the high level waste stream separated out in the reprocessing, less the value of the recovered reprocessed uranium stream, and less the value of the recovered transuranics:

$$d_{3,L}(p) = s_{3,L} + w_{3,L} - u_{3,L} - z_{3,L}(p), \tag{29}$$

where $u_{3,L}$ is the levelized value of the reprocessed uranium recovered from the light water reactor spent fuel and $z_{3,L}(p)$ is the levelized value of the separated transuranics.[7] In

[7] We specify the cost of reprocessing as being paid as a back-end expense of the pass producing the spent fuel that is reprocessed. It could just as easily have been paid as a front-end expense of the succeeding pass that uses the separated product as a fuel. For the final LCOE number, and the determination of the

fuel cycle #3, the front-end fuel costs for the fast reactor is the sum of the cost of the depleted uranium required, the cost of the transuranics, and the cost of fabrication:

$$f_{3,F}(p) = u_{3,FA} + z_{3,F}(p) + b_{3,F}\,. \tag{30}$$

where u_{3FA} is the levelized value of the depleted uranium contained in the fast reactor fuel, $z_{3F}(p)$ is the levelized value of the transuranics contained in the fast reactor fuel, and b_{3F} is the cost of fabricating the fast reactor fuel.

The cost of disposing of the spent fuel from the fast reactor is:

$$d_{3F}(p) = s_{3F} + w_{3F} - u_{3FB} - \alpha\, z_{3F}(p), \tag{31}$$

where $u_{3,FB}$ is the levelized price of depleted uranium recovered from the fast reactor spent fuel and $z_{3,F}(p)$ is the levelized value of the separated transuranics.

The attributed price of the transuranics, p, is the free parameter that allows us to set the two LCOEs in equations (27) and (28) equal to one another so as to satisfy equation (26):

$$\ell_{3,L}(p) = f_{3,L} + k_{3,L} + m_{3,L} + d_{3,L}(p) = f_{3,F}(p) + k_{3,F} + m_{3,F} + d_{3,F}(p) = \ell_{3,F}(p),$$

or, more expansively, p solves:

$$\begin{aligned}\ell_{3,L}(p) &= f_{3,L} + k_{3,L} + m_{3,L} + s_{3,L} + w_{3,L} - u_{3,LB} - z_{3,L}(p) \\ &= u_{3,FA} + z_{3,F}(p) + b_{3,F} + k_{3,F} + m_{3,F} + s_{3,F} + w_{3,F} - u_{3,FB} - \alpha\, z_{3,F}(p) = \ell_{3,F}(p).\end{aligned} \tag{32}$$

Solving (32) gives us the unique attributed value of transuranics satisfying (26) which allows us to calculate (27) and (28).[8]

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transuranics price, the assignment is irrelevant, since the numerator of equation (17) uses the total costs over all passes, not the allocated cost for a single pass. Changing the allocation changes the elements building up (27) and (28). However, our condition (26) forces (27) and (28) to be equal to (17). The equilibrium value of the spent fuel, whether expressed as a package or in terms of its constituent elements, will simply be adjusted to reflect whether it is the buyer or the seller who must incur the reprocessing cost.

[8] The price of reprocessed uranium is determined by the price of raw uranium, also assumed constant through time, and the relative cost of producing uranium-oxide fuel from raw or from reprocessed uranium.

As with the previous cycle, there is no a priori constraint on the sign of the price of the recovered transuranics. If it is positive, then the separated transuranics are an asset for which the fast reactor is willing to pay money. If it is negative, then the separated transuranics are a liability and the fast reactor has to be compensated for accepting them.

3. PARAMETERIZATION AND SOLUTION

The main parameter assumptions we make are displayed in Table 1. All figures are denominated in 2007 dollars.

For the front-end fuel services we assume a price of natural uranium of $80/kgU, a cost of depleted uranium of $10/kgU, a cost of conversion of $10/kgHM, a cost of enrichment of $160/SWU, and a cost of fabrication of UOX fuel of $250/kgHM. For reprocessed uranium, we assume a premium for the cost of conversion of 200%, for the cost of enrichment of 10%, and for the cost of fabrication of 7%. In the Appendix, we derive from these figures a price of reprocessed uranium of $108.40/kgHM. We assume that the cost of fabrication of MOX fuel is $2,400/kgHM and the cost of fabrication of fast reactor fuel is also $2,400/kgHM.

For the reactor costs, we assume that the overnight capital cost for a light water reactor is $4,000/kWe, per Du and Parsons (2009). Both the capital and the non-fuel O&M costs are independent of whether the light water reactor burns UOX or MOX fuel. We assume that a fast reactor has a 20% cost premium, both for capital and for non-fuel O&M costs. We assume that both types of reactors operate at an 85% capacity factor.

This enters into the calculation of the levelized cost, but is derived explicitly beforehand. It is independent of the levelized cost of either component of the cycle, and need not be solved for implicitly by equating the two levelized costs.

For reprocessing, we assume that the cost of using the PUREX process for the spent UOX fuel is $1,600/kgHM, that the cost of using the TRUEX process for the spent UOX fuel is also $1,600/kgHM, and that the cost of pyroprocessing the spent fast reactor fuel is $3,200/kgHM.

When spent fuel is to be sent for geologic disposal, we assume that it is first stored above ground in dry casks for some number of years. The cost of this storage is $200/kgiHM, whether for spent UOX or for spent MOX fuel. This value is measured at the time of discharge from the reactor storage pools, which is 5 years after unloading. The cost of geologic disposal of spent UOX fuel is $463/kgiHM, measured at the time of unloading. This is equivalent to the statutory 1 mill/kWh fee. For spent MOX fuel, we assume a cost of geologic disposal of $3,086/kgiHM, based on the densification factor given in BCG (2006).

We calculate a cost of geologic disposal of the separated fission products from the TRUEX process using a densification factor of 2.5 as provided by Shropshire et al. (2008), so that the cost is $185/kgiHM. Measured in terms of the fission products contained in the initial heavy metal, this translates to a cost of $3,590/kgFP. We use this cost per unit of fission products to set the cost of disposal of the high level waste from the pyroprocessing of fast reactor fuel and this translates to a cost of $281/kgiHM. Although the cost of disposing of the high level waste from the PUREX process should be higher per unit of fission products due to the presence of minor actinides, for these calculations we nevertheless assume the same cost of $185/kgiHM.

We apply an annually compounded discount rate of r=7%, which is equivalent to a continuously compounded discount rate, R=ln(1+r)=6.8%. Since we apply this 7%

discount rate to full project cash flows, independent of any explicit evaluation of financing structure and debt levels, the tax shield benefits of debt must be reflected through the choice of the discount rate, and therefore this figure should be evaluated as a Weighted Average Cost of Capital (WACC) when making comparisons to other sources.

In the paragraphs that follow we show how these parameter values are used to implement the LCOE calculations for each cycle, describing as we proceed any additional assumptions being made. We first calculate the LCOE for the Once-Through Cycle. Second, we set up the equations for the Twice-Through Cycle, then solve for the attributed value of plutonium, and finally calculate the cycle LCOE. Third, we set up the equations for the fast reactor recycle, then solve for the attributed value of transuranics, and finally calculate the cycle LCOE. Following this complete section, we provide a comparison of our parameter assumptions with those made in other studies as well as a comparison of our results with the results of other studies.

Once-Through Cycle

For our light water reactor, we assume a thermal efficiency of 33%, a burn-up of 50 MWd/kgHM, an average capacity factor of 85% and a fuel cycle length of 1.5 years. Therefore, the core will require a mass of UOX fuel containing M_L=84.7 MTHM/GWe. The fuel core is composed of 3 batches, with each batch of fuel resident for 4.5 years. With these assumptions, each kgHM of UOX fuel has the effective electricity generating capacity of 10.04 kWe. This leads us to calculate the following present value factor for the electricity produced by this 1 kg of UOX fuel:

$$\psi_L = 10.04 \int_0^{4.5} 8{,}766\, e^{-Rt}\, dt\,,$$

where 8,766 is the number of hours in a year. We will also need the corresponding present value factor for the electricity produced by the full mass of fuel, M_L, making up the entire core for its 60 years of operation:

$$\phi_L = 10.04\, M_L \int_0^{60} 8{,}766\, e^{-Rt}\, dt\,.$$

We construct our up-front fuel costs from the following underlying assumptions. We assume 0.2% loss at each stage of conversion, enrichment and fabrication. Therefore, in order to have 1 kgHM of UOX fuel we require 10.05 kgHM of fresh uranium ore (yellowcake), which is converted into 10.03 kgHM of uranium hexafluoride. By the optimization described in the Appendix, our cost assumptions imply 6.37 SWU to reach the enrichment of 4.5% of U235 in the UOX fuel. This yields us the following discounted cash flow representation of the front-end fuel costs:

$$u_1 = \left(\frac{(\$80/\text{kgHM})(10.05\,\text{kgHM})}{(1+r)^{-2}} \right) \Big/ \Psi_L = 2.70 \text{ mill/kWh},$$

$$b_1 = \left(\frac{(\$10/\text{kgHM})(10.03\,\text{kgHM})}{(1+r)^{-1.5}} \right.$$

$$\left. + \frac{(\$160/\text{SWU})(6.37\,\text{SWU})}{(1+r)^{-1}} + \frac{(\$250/\text{kgHM})(1\,\text{kgHM})}{(1+r)^{-0.5}} \right) \Big/ \psi_L = 4.28 \text{ mill/kWh},$$

so that

$$f_1 = u_1 + b_1 = 6.97 \text{ mill/kWh}.$$

In addition to following Du and Parsons (2009) for the overnight capital cost, we follow their assumptions for the annual incremental capital cost of \$40 million/GWe, the \$700 million/GWe decommissioning cost, the construction schedule, depreciation

schedule and the tax rate. However, we assume a 60 year life for the reactor. Therefore, the capital charge per unit of electricity is given by:

$$k_1 = \left(\$4{,}000/\text{kW} \times \left[\frac{9.5\%}{(1+r)^{-4}} + \frac{25\%}{(1+r)^{-3}} + \frac{31\%}{(1+r)^{-2}} + \frac{25\%}{(1+r)^{-1}} + 9.5\% \right] \right.$$

$$\left. - \$4{,}000/\text{kW} \times \sum_{t=1}^{16} \frac{D_t \tau}{(1+r)^t} + \sum_{t=1}^{60} \frac{\$40/\text{kW}\,(1-\tau)}{(1+r)^t} + \frac{\$700/\text{kW}\,(1-\tau)}{(1+r)^{60}} \right) \times 1\,\text{GW} \Big/ \phi_L (1-\tau),$$

where D_t denotes the MACRS depreciation schedule and τ the tax rate. Evaluating the equation gives us:

$$k_1 = 59.30 \text{ mill/kWh.}$$

We also assume the operating and maintenance cost schedule used in Du and Parsons (2009), giving us:

$$m_1 = \left(\sum_{t=1}^{60} \frac{\$56.44/\text{kW}}{(1+r)^t} \times 1\,\text{GW} \Big/ \phi_L \right) + 0.42 \text{ mill/kWh,}$$

so that

$$m_1 = 7.74 \text{ mill/kWh.}$$

We assume that the spent UOX fuel is stored first in a cooling pond for 5 years, but the cost for this storage is generally included in the reactor capital and operating cost figures, and so this charge is not separately itemized here. Currently, upon leaving the cooling pond, the spent fuel is stored above-ground in dry casks, awaiting ultimate disposal in a geologic repository. Because of political disputes surrounding the repository plan, the envisioned system is not in operation. This makes any firm statement about the costs of a specific disposal strategy tentative, pending political resolution and therefore the selection of the actual timing and engineering parameters of the system. We assume a

system will include some period of above-ground storage in dry casks and ultimate disposal in a geologic repository similar in cost to Yucca Mountain as currently designed.

Using the parameters specified earlier, we have:

$$d_1 = \left(\frac{\$200}{(1+r)^{9.5}} \Big/ \psi_L \right) + 1 \text{ mill/kWh},$$

so that

$$d_1 = 1.31 \text{ mill/kWh}.$$

Pulling together these results into one equation, we have that the LCOE for the Once-Through Cycle is:

$$\ell_1 = f_1 + k_1 + m_1 + d_1$$

$$= 6.97+59.30+7.74+1.31$$

$$= 75.32 \text{ mill/kWh}.$$

Table 2 lists these results.

Figure 1 graphs the LCOE with a breakdown into three categories, (i) capital cost, k_1, (ii) operating and maintenance costs, m_1, and (iii) total fuel cycle costs, front- and back-end combined, f_1+d_1. The largest component is the capital cost which accounts for 79% of the total LCOE. O&M costs account for 10%. The total fuel cycle cost contribution is 11%, made up of 9% from the front-end and 2% from the back-end.

The Twice-Through Cycle

The First Reactor and Reprocessing

For the first reactor in the cycle, the front-end fuel costs are exactly the same as for the Once-Through Cycle, $f_{2,1}$= f_1=6.97. The capital and O&M costs are the same, too:

$k_{2,1}=k_1=59.30$, $m_{2,1}=m_1=7.74$. The total cost of disposal in a system with recycling is composed of the cost of PUREX reprocessing which produces the separated streams, the cost of disposal for the high level waste stream, and the value attributed to the stream of separated plutonium and uranium.

The cost of reprocessing is,

$$s_{2,1} = \frac{(\$1{,}600 / \text{kgiHM})}{(1+r)^{9.5}} \Big/ \psi_L = 2.46 \text{ mill/kWh.}$$

Our cost for the waste stream from reprocessed light water reactor spent fuel is:

$$w_{2,1} = \frac{(\$185\,(1+r)^5 / \text{kgiHM})}{(1+r)^{9.5}} \Big/ \psi_L = 0.40 \text{ mill/kWh.}$$

Each 1kg of initial spent UOX leads to the separation of 0.93kg of reprocessed uranium valued at \$108.4/kgRU, therefore

$$u_{2,1B} = \frac{(\$108.4 / \text{kgRU})(0.93\,\text{kgRU} / \text{kgiHM})}{(1+r)^{10.5}} \Big/ \psi_L = 0.15 \text{ mill/kWh.}$$

Finally, 1kg of spent UOX leads to the separation of 0.011kg of plutonium, therefore

$$z_{2,1}(p) = \frac{p\,(0.011\,\text{kg})}{(1+r)^{10.5}} \Big/ \psi_L = 1.65\ 10^{-5}\,p \text{ mill/kWh,}$$

where the price of plutonium, p, is denominated in \$/kgHM.

The Second Reactor Fueled With MOX

The fuel cost for the second reactor include the price of purchasing the plutonium (from the first pass), the cost of purchasing depleted uranium and the cost of MOX fabrication. We assume 0.2% loss at the fabrication stage, and a fuel designed to sustain a 50MWd/kgHM. The corresponding composition should be 91.3% by weight depleted

uranium and 8.7% plutonium coming from spent UOX fuel produced by a 50MWd/kgHM burnup. We assume 2 years between plutonium separation and its use in a light water reactor, such that it contains 1.6% of americium. Having assumed that the MOX assemblies are designed to sustain the same burnup as UOX under the same conditions in the same type of reactors, we apply the same present value factor, ψ_L, previously introduced for the light water reactor burning UOX fuel. This yields us the following discounted cash flow representation of the front-end fuel costs:

$$u_{2,2} = \frac{(\$10/\text{kgHM})(0.915\,\text{kgHM})}{(1+r)^{-1}} \Big/ \psi_L = 0.03 \text{ mill/kWh},$$

$$z_{2,2}(p) = \frac{p\,(0.0875\,\text{kgHM})}{(1+r)^{-1}} \Big/ \psi_L = 2.74\ 10^{-4}\, p \text{ mill/kWh},$$

and,

$$b_{2,2} = \frac{(\$2{,}400/\text{kgHM})(1\,\text{kgHM})}{(1+r)^{-0.5}} \Big/ \psi_L = 7.27 \text{ mill/kWh}.$$

We assume that for the second reactor cycle the capital and O&M costs are the same as for the first reactor: $k_{2,2}= k_{2,1}=k_1=59.30$, $m_{2,2}= m_{2,1}=m_1=7.74$.

For the second reactor, the back-end cost reflects only the cost of storage and geologic disposal of the MOX:

$$d_{2,2} = \frac{\$200}{(1+r)^{9.5}} \Big/ \psi_L + \frac{1}{0.15}, = 6.97 \text{ mill/kWh}.$$

The Value of Plutonium and the LCOE for the Twice-Through Cycle

We can now solve for the attributed value of plutonium using equation (15) with the values above inserted:

$$6.97 + \left(2.46 + 0.40 - 0.15 - 1.65\times10^{-5}\, p\right) = \left(0.03 + 2.74\times10^{-4}\, p + 7.27\right) + 6.97\,.$$

We find that $p = -15{,}775$ \$/kgHM, so that,

$$z_{2,1}(p) = -0.26 \text{ mill/kWh},$$

$$d_{2,1}(p) = 2.98 \text{ mill/kWh},$$

$$z_{2,2}(p) = -4.32 \text{ mill/kWh},$$

and,

$$f_{2,2}(p) = 2.98 \text{ mill/kWh}.$$

Then, equations (8) and (9) give,

$$\ell_{2,1} = \ell_{2,2} = 76.99 \text{ mill/kWh}.$$

Table 2 lists these results.

Figure 1 shows the LCOE for this Twice-Through Cycle with a breakdown into the three categories of capital cost, O&M costs, and total fuel cycle costs, front- and back-end combined. The figure shows two separate bars for the cycle. The first bar in the pair is the breakdown of costs for the first reactor in the cycle, and the second bar is the breakdown for the second reactor in the cycle. For the first reactor, the capital cost accounts for 77% of the total LCOE, while O&M costs account for 10%. The total fuel cycle cost contribution is 13%, made up of 9% from the front-end and 4% from the back-end. For the second reactor, the fraction accounted for by the capital and O&M costs is the same as for the first reactor. The total fuel cycle cost contribution is 9%, made up of 4% from the front-end and 9% from the back-end.

The Fast Reactor Recycle

The LWR Reactor and Reprocessing of UOX

For the first reactor in the cycle, the front-end fuel costs are exactly the same as for the Once-Through Cycle, $f_{3,1}=f_1=6.97$. The capital and O&M costs are the same, too: $k_{3,1}=k_1=59.30$, $m_{3,1}=m_1=7.74$. The total cost of disposal is composed of the cost of TRUEX reprocessing which produces the separated streams, the cost of disposal for the high level waste stream, and the value attributed to the stream of separated transuranics and uranium.

The cost of reprocessing is,

$$s_{3,L} = \frac{(\$1{,}600/\text{kgiHM})}{(1+r)^{9.5}} \Big/ \psi_L = 2.46 \text{ mill/kWh.}$$

Our cost for the waste stream from reprocessed light water reactor spent fuel is:

$$w_{3,L} = \frac{(\$185\,(1+r)^5/\text{kgiHM})}{(1+r)^{9.5}} \Big/ \psi_L = 0.40 \text{ mill/kWh.}$$

Each 1kg of initial spent UOX leads to the separation of 0.93kg of reprocessed uranium valued at \$108.4/kgRU, therefore

$$u_{3,LB} = \frac{(\$108.4/\text{kgRU})(0.93\,\text{kgRU/kgiHM})}{(1+r)^{10.5}} \Big/ \psi_L = 0.15 \text{ mill/kWh.}$$

Finally, 1kg of spent UOX fuel leads to the separation of 0.013kg of transuranics, therefore

$$z_{3,L}(p) = \frac{p\,(0.013\,\text{kg})}{(1+r)^{10.5}} \Big/ \psi_L = 1.85\ 10^{-5}\,p \text{ mill/kWh,}$$

where the price of transuranics, p, is denominated in \$/kgHM.

The Fast Reactors and Reprocessing of Fast Reactor Fuel

For our fast reactor, we assume a thermal efficiency of 41%, a burn-up of 73 MWd/kgHM, an average capacity factor of 85% and a fuel cycle length of 1.2 years. Therefore, the core will require a mass of fuel containing M_F=43.4 MTHM/GWe. With a core composed of 5 batches, each batch of fuel is resident for 3.51 cycles on average, 66% staying for 3.6 years and 34% for 5.4 years depending on its place in the core. We add the assumption that a unit of fuel's production of energy is independent of its place in the core.[9] With these assumptions, each kgHM of fast reactor fuel has the average generation capacity of 19.57 effective kW. This leads us to calculate the following present value factor which can be used to levelize any cost measured at the initial loading date of the fuel:

$$\psi_F = 19.57\left(0.66\int_0^{3.6} 8{,}766\, e^{-Rt}\,dt + 0.34\int_0^{5.4} 8{,}766\, e^{-Rt}\,dt\right).$$

The fuel cost for the fast reactor must include the price of purchasing the transuranics (for the first pass in a fast reactor) or the uranium/transuranics mix (for all subsequent passes), the cost of purchasing the necessary depleted uranium and the cost of fabrication. We assume 0.2% loss at the fabrication stage, and a fuel designed to sustain a 73MWd/kgHM burn-up in metallic form in a fast reactor with conversion ratio of 1. At equilibrium the fuel should have a composition, c_{ZF}, that is 13.9% transuranics on average for each batch, and 86.1% of depleted uranium. If the source material for the fuel is reprocessed fast reactor fuel, then the depleted uranium will already be mixed together with the transuranics. Otherwise, it will be separately sourced as a by-product from a

[9] As a consequence, fuel staying longer in the core would have a higher burn-up, and consequently a different composition. We however assume that all fuel coming out has the same average composition, in the same way that we assumed that all fuel coming in has the same average composition.

uranium enrichment plant. This yields us the following discounted cash flow representation of the front-end fuel costs:

$$u_{3,FA} = \left(\frac{(\$10/\text{kgHM})(0.861\,\text{kgHM})}{(1+r)^{-1}} \right) \Big/ \psi_F = 0.01 \text{ mill/kWh},$$

$$z_{3,F}(p) = \left(\frac{p\,(0.139\,\text{kgHM})}{(1+r)^{-1}} \right) \Big/ \psi_F = 2.39\ 10^{-4}\, p \text{ mill/kWh},$$

and,

$$b_{3,F} = \left(\frac{(\$2{,}400/\text{kgHM})(1\,\text{kgHM})}{(1+r)^{-0.5}} \right) \Big/ \psi_F = 3.99 \text{ mill/kWh},$$

where p is denominated in \$/kgHM.

We assume that the fast reactor capital and operating costs are 20% higher than the comparable costs for the light water reactor. Given the same 60 years lifetime and 85% capacity factor, we directly have,

$$k_{3,F} = 1.2k_1 = 71.16 \text{ mill/kWh, and,}$$

$$m_{3,F} = 1.2\ m_1 = 9.29 \text{ mill/kWh.}$$

The cost of reprocessing spent fuel from the fast reactors using pyroprocessing is,

$$s_{3,F} = \left(\$3{,}200/\text{kgiHM} \times \left(\frac{0.66}{(1+r)^{8.6}} + \frac{0.34}{(1+r)^{10.4}} \right) \right) \Big/ \psi_F = 2.77 \text{ mill/kWh.}$$

We calculate the cost of disposing of spent fast reactor fuel based on the 7.8% fission products it contains, so that,

$$w_{3,F} = \left(\$5{,}222/\text{kgFP} \times \left(\frac{0.66}{(1+r)^{8.6}} + \frac{0.34}{(1+r)^{10.4}} \right) \times 0.078\,\text{kgFP/kgiHM} \right) \Big/ \psi_F$$

$$= 0.34 \text{ mill/kWh.}$$

Each 1kg of initial spent fast reactor fuel leads to the separation of 0.78kg of depleted uranium, therefore

$$u_{3,FB} = (\$10/\text{kgDU})\left(0.78\,\text{kgDU/kgiHM} \times \left(\frac{0.66}{(1+r)^{9.6}} + \frac{0.34}{(1+r)^{11.4}} \right) \right) \Big/ \psi_F$$

$$= 0.01 \text{ mill/kWh.}$$

Finally, 1kg of spent fast reactor fuel leads to the separation of 0.140kg of transuranics, and therefore

$$\alpha = \frac{0.140}{0.139}\left(\frac{0.66}{(1+r)^{8.6}} + \frac{0.34}{(1+r)^{10.4}} \right) = 0.437,$$

so that,

$$\alpha\, z_{3,F}(p) = 1.13\ 10^{-4}\, p \text{ mill/kWh.}$$

The Value of Transuranics and the LCOE for the Fast Reactor Recycle

We can now solve for the value of transuranics and complete the LCOE calculation, by solving equation (32) with the values above inserted:

$$6.97 + 59.30 + 7.74 + \left(2.46 + 0.40 - 0.15 - 1.85 \times 10^{-5}\, p\right)$$

$$= \left(0.01 + 2.39 \times 10^{-4}\, p + 3.99\right) + 71.16 + 9.29 + \left(2.77 + 0.34 - 0.01 - 1.13 \times 10^{-4}\, p\right)$$

We find that $p = -74{,}704$ \$/kgHM, so that finally

$$z_{3,L}(p) = -1.38 \text{ mill/kWh,}$$

$$d_{3,L}(p) = 4.10 \text{ mill/kWh,}$$

$$z_{3,F}(p) = -17.89 \text{ mill/kWh,}$$

$$f_{3,F}(p) = -13.88 \text{ mill/kWh}$$

$$\alpha\, z_{3,F}(p) = -8.45 \text{ mill/kWh,}$$

and.

$$d_{3,F}(p) = 11.55 \text{ mill/kWh.}$$

Inserting these values back into equation (32) or into equations (27) and (28) gives,

$$\ell_3 = \ell_{3,L} = \ell_{3,F} = 78.11 \text{ mill/kWh}$$

Table 2 lists these results.

Figure 1 shows the LCOE for this Fast Reactor Recycle with a breakdown into the three categories of capital cost, O&M costs, and total fuel cycle costs, front- and back-end combined. The figure shows two separate bars for the cycle. The first bar in the pair is the breakdown of costs for the light water reactor in the cycle, and the second bar is the breakdown for a fast reactor in the cycle. For the light water reactor, the capital cost accounts for 76% of the total LCOE, while O&M costs account for 10%. The total fuel cycle cost contribution is 13%, made up of 9% from the front-end and 5% from the back-end. For a fast reactor, the capital cost accounts for 91% of the total LCOE, while O&M costs account for 12%. The total fuel cycle cost contribution is −3%, made up of −18% from the front-end and 15% from the back-end.

To this point, the Fast Reactor Recycle system that we studied used a conversion ratio of 1. We repeated our calculations for a burner system with a conversion ratio of 0.5 and for a breeder system with a conversion ratio of 1.2. For each system some adjustments need to be made in some of the input parameters, especially those relating to the fabrication of the fuel and the cost of disposal of high level wastes, as well as changes to the cycle lengths. The LCOE's for all three Fast Reactor Recycle systems are shown together in Table 3. The results are also shown in Figure 2. The notes to Table 3 discuss changes to the input parameters. The lower the conversion ratio, the lower the

transuranics mass ratio, the lower the LCOE. The burner system with a conversion ratio of 0.5 has a LCOE of 77.39 mill/kWh, which is less than a 1 mill/kWh improvement over the 78.11 mill/kWh for the system with a conversion ratio of 1. The breeder system with a conversion ratio of 1.2 has a LCOE of 78.51 mill/kWh, which is less than a 1 mill/kWh more expensive than the 78.11 mill/kWh for the system with a conversion ratio of 1.

The Relative LCOE Across Fuel Cycles

Given our parameter selections, recycling increases the total LCOE, regardless of which form of recycling is used.

The LCOE for the Twice-Through Cycle is 1.67 mill/kWh greater than the LCOE for the Once-Through Cycle, a 2.2% increase. Relative to just the fuel cycle costs in the Once-Through Cycle, which are 8.28 mill/kWh, this is a 20% increase. Relative to the cost of disposal, which is 1.31 mill/kWh, this is a 128% increase.

The LCOE for the Fast Reactor Recycle is 2.79 mill/kWh greater than the LCOE for the Once-Through Cycle, a 3.7% increase. Relative to just the fuel cycle costs in the Once-Through Cycle, this is a 34% increase. Relative to the cost of disposal, this is a 214% increase.

Table 4 shows these results.

What does recycling do to the portion of the LCOE that is the fuel cycle? This seems like a straightforward question, but on examination the issues are more troublesome than first supposed, and such a simple comparison is likely to be uninformative at best and misleading at worst. In the Once-Through Cycle, the sum of the front- and back-end fuel cycle costs is 8.28 mill/kWh. In the Twice-Through Cycle, this sum is 9.95 mill/kWh. In the Fast Reactor Recycle, this cost depends upon which reactor

we are examining. For the light water reactor, the sum of the front- and back-end fuel cycle costs is 11.07 mill/kWh. For the fast reactor, the sum is -2.34 mill/kWh. The fast reactor apparently has a negative fuel cycle cost! This is due to the high value paid by the light water reactor to the fast reactor for taking its wastes, its transuranics. This upfront payment more than compensates the fast reactor for the high costs of fuel fabrication and the ultimate charge it must pay for passing along its own wastes, its own transuranics. But by focusing only on the cost components that are somewhat arbitrarily grouped together as the fuel-cycle components, we overlook a key cost of the fuel cycle which is the high capital and operating costs for the fast reactor itself. The fast reactor in this system is operating like a sort of "waste incinerator". Some of the high capital costs of the fast reactor are being charged back to the light water reactor as a price for disposing of the light water reactor's wastes. These capital costs are, in an economic sense, part of the fuel cycle costs. This highlights the caution with which a comparison of any subset of the cost components across fuel cycles should be made.

The Negative Value to Transuranics

In the Twice-Through Cycle, the price of plutonium we derive is negative. In the Fast Reactor Recycle, the price of the transuranics is negative. This has implications for the feasible commercial organization of a system with recycling. What it means is that the next reactor in the system must be paid to take the separated plutonium or the separated transuranics.

In the Twice-Through Cycle, if the second reactor is not paid to take the separated plutonium, then its costs of producing electricity will be greater than the costs for the first reactor. Assuming that at any point in time there will be both types of reactors operating

in the system—reactors burning UOX fuel and reactors burning MOX fuel, and assuming that the reactors are selling their electricity into a common marketplace with a single price for electricity, then it is not commercially viable for one type of reactor to have higher costs than the other type of reactor. Unless reactors are paid to take the separated plutonium, reactors will prefer to fabricate their fuel from uranium rather than from plutonium. A competitive market in fresh fuel, spent fuel and separated components would drive the price of the spent UOX fuel and the plutonium down below zero. Even if the prices are not set in a competitive market, a system in which one type of reactor is producing electricity at a higher cost than another type of reactor will come under pressure to somehow spread the burden beyond the customer base of the reactors with the higher cost. This could be done through subsidies of various sorts.

Our calculations are premised on the implicit assumption that one or the other fuel cycle is chosen. This is very likely to be the case in that the government's regulatory authority on disposal of wastes ultimately shapes which cycle is allowed. We do not put the alternative cycles into direct competition with one another, although one could imagine such a system. For example, the government could establish a set of regulations for disposal of spent fuel, unseparated, as well as regulations for the disposal of the high level waste from separation, leaving power generation companies to decide whether they wished to recycle fuel or not,. In our current calculation, we require that the LCOE for a reactor using MOX fuel equal the LCOE for the reactor using UOX fuel, but with both reactors being a part of the single recycle system. For the Twice-Through Cycle, that is $\ell_{2,2}(p) = \ell_{2,1}(p)$. For the Fast Reactor Recycle, that is $\ell_{3,F}(p) = \ell_{3,L}(p)$. If the recycling system were to co-exist with a non-recycling system, then that would impose the

condition that $\ell_{2,2}(\hat{p}) = \ell_1$ for the Twice-Through Cycle and, $\ell_{3,F}(\breve{p}) = \ell_1$ for the Fast Reactor Recycle. In both cases, that would imply different equilibrium values for the price of the separated elements, whether plutonium or transuranics. For the parameters we selected, in which the Once-Through Cycle is the cheapest cycle, the price of plutonium would have to be even more negative in order for the reactor using the recycle fuel to have the same costs, and the price of the transuranics would have to be even more negative, too.

4. COMPARISON TO OTHER STUDIES

Methodology

To our knowledge, the LCOE formulas derived here for the two systems with recycling have not been used in other reports. Before looking at how others have approached the problem, it is worth revisiting a couple of key features of our own solutions. In the case of the Twice-Through Cycle, the formula defining the LCOE is equation (3). In the case of the Fast Reactor Recycle, the formula defining the LCOE, in the simplified problem, is equation (17). Note two things about each of these formulas: (i) the LCOE is defined solely with respect to the costs of the cycle at hand, and not in terms of the LCOE of another cycle such as the Once-Through Cycle, and (ii) the LCOE is defined independently of the value attributed to the recycled resource that is passed from one reactor to another—plutonium in the case of the Twice-Through Cycle and the transuranics in the case of the Fast Reactor Recycle.

Having defined the pair of LCOEs with these properties, we then provide for a convenient solution method that involves attributing a value to the recycled resource.

This solution method involves the *simultaneous* derivation of the LCOE together with the attributed value of the resource being recycled. In the case of the Twice-Through Cycle, this is done by solving the system defined by equations (5)-(7). In the case of the simplified version of the Fast Reactor Recycle, this is done by solving the system defined by equations (24)-(26). Although we chose to attribute a value to the recycled resource, this was only a tool for conveniently solving equations (3) and (17), respectively. We could have solved each of them without ever attributing a value to the recycled resource. The attributed value does not determine the LCOE, but rather the LCOE determines the unique attributed value.

Studies of the Twice-Through Cycle have adopted a variant of this approach that avoids the simultaneous solution of the LCOE and the value of the recycled resource. For example, Bunn et al. (2003) and the NEA (1994) begin by finding the value for the recycled plutonium that sets the LCOE for the other reactor using MOX fuel equal to the LCOE for the Once-Through Cycle. They then use this attributed value for the recycled plutonium to derive the LCOE for the first reactor in the recycling system, the reactor that sends its spent UOX fuel to be reprocessed. In our notation, they begin by finding a $\hat{p}$ that solves $\ell_{2,2}(\hat{p}) = \ell_1$, and they then define the LCOE of the Twice-Through Cycle as $\ell_2 \equiv \ell_{2,1}(\hat{p})$.[10] Note that in this methodology it will generally be the case that $\ell_{2,1}(\hat{p}) \neq \ell_{2,2}(\hat{p})$, which also implies that their derived LCOE for recycling will not match the LCOE definition provided in our equation (3). Moreover, using this methodology, it is impossible to define the LCOE of the recycling system independently

[10] Both the NEA (1994) and Bunn et al. (2003) assume away the differential cost of disposing of spent MOX fuel as compared to the cost of disposing of spent UOX fuel.

of the LCOE for the Once-Through Cycle. This is odd. In every other mundane application of the LCOE methodology, the LCOE for a given technology is defined independently of the LCOE of any other technology, not on some relative basis.

Studies of a Fast Reactor Recycle system typically adopt an entirely different approach known as the 'equilibrium cost'. For example, this is employed in EPRI (2007) and Shropshire et al. (2009). EPRI (2007) never provides a mathematical definition of this concept. However, it describes it as being based on the condition that "all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached an equilibrium" (p. 4-1). Our LCOE definition requires no such condition, so clearly the two concepts are different. Our conjecture is that the EPRI figure is calculated by summing up all of the costs incurred at a point in time, and that this is rationalized on the premise that the system has reached a point in which the profile of costs is replicated period-by-period thereafter. The Advanced Fuel Cycle Initiative costs reported in Shropshire et al. (2006) are based on a similar equilibrium structure that the authors acknowledge "does not include dynamic conditions such as start-up, ramp-down, end-of-life conditions, intermittent or long-term storage strategies, transportation, or the reactor costs." This appears to be the methodology employed in Shropshire et al. (2009).

The equilibrium cost does not correspond to a levelized cost. The levelized cost concept is meant to reflect the price a producer would need to charge in order to recoup all costs, including start-up and wind-down costs. Disregarding these costs would be analogous to calculating the net present value of an investment project disregarding any working capital necessary to begin the project and disregarding any future liabilities incurred while operating. Profit making businesses reject such cost measures. In contrast,

our definition of LCOE as embodied in equations (3) and (17) captures all start-up and wind-down costs.

One way to understand the difference between our definition of the LCOE and the equilibrium cost concept is with respect to the dimension of time. Equations (3) and (17) construct a profile of electricity production *through time*. They follow a unit of fuel as it passes through one reactor, is unloaded, reprocessed and then fed into another reactor. As with all levelized cost calculations, equations (3) and (17) generate a kind of average cost. In the Twice-Through Cycle, equation (3) generates an average of (i) the costs incurred in burning UOX fuel in a first pass through a light water reactor, and (ii) the costs incurred in burning MOX fuel in a second pass through a light water reactor. The weights in the averaging calculation are determined by (i) the relative quantity of electricity produced by 1 kg of UOX in the first reactor as compared against the quantity of electricity produced by the plutonium extracted from that 1 kg of UOX when it is fabricated into MOX fuel and burned in the second reactor, and (ii) the present value weights that adjust the respective values of these two quantities of electricity and the associated cost expenditures. In the Fast Reactor Recycle, equation (17) generates an average of (i) the costs incurred in burning UOX fuel in a first pass through a light water reactor, and (ii) the costs incurred in burning transuranics in an infinite sequence of succeeding fast reactors. The weights in the averaging calculation are determined by (i) the relative quantity of electricity produced by 1 kg of UOX in the first reactor as compared against the quantity of electricity produced by the transuranics extracted from that 1 kg of UOX when it is fabricated into fast reactor fuel and burned in the infinite

sequence of fast reactors, and (ii) the present value weights that adjust the respective values of these two quantities of electricity and the associated cost expenditures.

Note that the relative weights are set once and for all by each technology. The resulting LCOE is entirely independent of the aggregate profile of electricity consumption and the fraction of the profile currently being generated by one or the other reactor type. In an economy with a constant demand for electricity being served by the Fast Reactor Recycle technology, there will be an initial stage of construction of light water reactors, followed by the growth of fast reactors. The fraction of electricity generated by light water reactors will start high and gradually decline. However, the LCOE will be constant through time. This property of equations (3) and (17) holds for any profile of electricity demand that can be served by one or the other technology.[11]

In contrast, the equilibrium cost concept calculates the cost *at a single moment in time*. The concept requires that we find the equilibrium profile of reactors in the recycling system precisely because the instantaneous measured system-wide costs will vary as one selects different points in time along the historical trajectory defined by the recycling technology. The true LCOE is an average of all of these instantaneous system-wide costs. But the equilibrium cost concept does not calculate this average, and instead focuses on the cost at one single point in the historical trajectory.

In general, for sensible parameters, the equilibrium cost measure will exaggerate the costs of a fast reactor cycle with full actinide recycling as compared against the once-through cycle. This is because the fast reactor recycle system involves a delayed

[11] For a more thorough investigation into this property of the LCOE under different aggregate demand profiles, see De Roo and Parsons (2009). We abstract here from problems that follow from discreteness in the construction of individual reactor units. This is a second order problem that a systems analysis model is well suited to tackle. See for example, Busquim et al. (2008). We also abstract from the problem of a potentially declining demand profile and the depreciation of installed capital.

realization of costs relative to the once-through cycle. A portion of the costs required to operate the light water reactor that begins the system are incurred by the operators of the fast reactors as they manage the stream of transuranics inherited from the initial light water reactor. Our LCOE measure levelizes these costs across the full time profile of electricity generated by the system. The equilibrium cost measure does not, and so it exaggerates the cost of the Fast Reactor Recycle system, assigning costs incurred to produce earlier units of electricity to that subset of units of electricity generated by the fast reactor.

The equilibrium cost measure appears to be attractive because it avoids attributing any value to the recycled transuranics. But avoiding this attribution is exactly what causes the equilibrium cost measure to deviate from a proper levelized cost. It is the attributed value of the transuranics that serves, in our equations (24)-(26) to levelize the costs properly across the units of electricity produced by all of the reactors, both light water and fast reactors. The Fast Reactor Recycle system involves delaying the realization of some of the costs of the initial light water reactor. The negative value of the transuranics is what allows this unrealized cost to be attributed back to the electricity produced by the light water reactor.

Bunn et al. (2003) also employ an equilibrium cost measure when they determine the LCOE for their Fast Reactor Recycle, although they do not call it that. To calculate their number, they begin by focusing their attention on the special case in which the transuranics mass ratio assures that the levelized cost of the transuranics entering and leaving the fast reactor are the same: $z_{3F}(p)=\alpha\, z_{3F}(p)$, which means that $\alpha=1$ and therefore the transuranics mass ratio exactly equals the time value of money for the duration of a

single full pass through a fast reactor, inclusive of reprocessing time, $q_2/q_1 = e^{R(B_2-B_1)} > 0$. This finesse appears to make it possible to solve for $\ell_{3F}(p)$ independent of p, and they use this value as the definition of the LCOE for the cycle, $\ell_3 \equiv \ell_{3F}$.[12] This gives the same result as an equilibrium cost measure because (i) their condition implies that the conversion ratio is greater than 1, and (ii) when the conversion ratio is greater than 1, the limiting steady-state is one populated only by fast reactors, so that an equilibrium cost calculation is the realized costs on the fast reactors, without any accounting for the value of the transuranics passed from the light water reactor to the fast reactors.

The last alternative methodology we should mention is the one used in BCG (2006). They focus exclusively on comparing the disposal costs of the first reactor in the Twice-Through Cycle against the disposal cost for the reactor in the Once-Through Cycle: $d_{2,1}(p)$ vs. d_1. Since $f_{2,1}=f_1$, $k_{2,1}=k_1$, and $m_{2,1}=m_1$, it follows that $\ell_{21}(p)-\ell_1=d_{2,1}(p)-d_1$, i.e. the difference in levelized costs equals the difference in disposal costs so that their focus is locally similar to ours. The uncommon step in their methodology is to avoid making a definitive decision about the ultimate disposition of the spent MOX fuel, and the corresponding cost. They argue that the spent MOX fuel will not be sent to a geologic repository since that cost is too high, and they suggest several recycling strategies. However, they never cost any of these strategies fully through to a final disposition of the spent fuel, or they never determine a full cost for infinite recycling. Therefore, they never directly define an expected cost for the contingent

[12] This is an interesting finesse, but clearly not an appropriate definition of the LCOE for the Fast Reactor Recycle. This is clear simply from the fact that the finesse is not generalizeable. It can only be applied for conversion ratios sufficiently greater than 1. The method provides no LCOE for Fast Reactor Recycles with conversion ratios slightly greater than 1, equal to 1 or less than 1.

disposition of the spent MOX fuel. This would seem to pose an insurmountable hurdle in arriving at a definite LCOE for the cycle, leaving a key parameter input, $d_{2,2}$, undefined. Their solution is to assign a cost of managing the spent MOX fuel that is equal to the cost of managing the spent UOX fuel, i.e., $d_{22}(p)=d_{2,1}(p)$, although this begs the question of what value to attribute to the plutonium, p. Some method for determining this value is required. Presumably they apply the same condition that we employ: $\ell_{21}(p)=\ell_{22}(p)$. There is no foundation for setting the cost of managing the spent MOX fuel this way. It does not account for the major technical differences between spent UOX and spent MOX, nor for the disposal of the ultimate streams of waste coming from spent MOX recycling. Absent more detailed investigation of the possible scenarios, this is just a bald assumption.[13]

Parameterization

In addition to listing the parameters we used in our calculations, Table 1 also lists the comparable parameter values used in these other studies. The following paragraphs provide some additional information and commentary on the comparisons that are evident in the table.

Front-end Fuel Cost Parameters

For fabrication of MOX fuel, our $2,400/kgHM figure is comparable to the $1,500/kgHM figure used by Bunn et al. (2003) inflated by 12% per annum between 2003 and 2007. The figure from Bunn et al. (2003) was based on the little available

[13] BCG (2006) claims that it would make no sense to dispose of the spent MOX. Instead, they imply, the fuel would be held in storage for possible use in a future reactor cycle benefiting from the plutonium. But the value or cost of this is explored in only a limited fashion. De Roo (2009) provides a rigorous option-theoretic analysis of the contingent value of the spent MOX held in storage, and finds savings compared to traditional deterministic valuations, albeit not enough to make MOX more attractive than interim storage.

information there exists on (i) the realized cost of existing MOX plants at the date of publication, (ii) prices historically offered for MOX fabrication services, and some estimated costs for new plants. BCG (2006) provide a combined cost for reprocessing and fabrication, which, inclusive of transportation to the reprocessing plant, comes to $705/kgHM. In Table 1 we have allocated this cost as $896/kgHM for fabrication of MOX and $597/kgHM for reprocessing.[14] The combined figure derives from Areva's proprietary estimates for a new reprocessing process called COEX, and is reconciled against historical costs in France based on presumed process improvements and rationalizations of operations. EPRI (2007) assume a cost of MOX fuel fabrication of $1,250/kgHM. No justification is given, except to say it is not at odds with the figures in Bunn et al. (2003), MIT (2003) and others; however, no adjustment for inflation was made. Shropshire et al. (2009) assume a cost for MOX fuel fabrication of $1,950/kgHM.

Bunn et al. (2003) set the cost of fabricating fast reactor fuel equal to the $1,500/kgHM cost for fabrication of MOX fuel, although they point to studies indicating that the cost of fabricating fast reactor fuel would be twice the cost of fabricating MOX fuel.[15] This is because they are only concerned with establishing that the breakeven uranium cost necessary to justify a shift to recycling is very high, and even with this lowball $1,500/kgHM figure, their point is made. EPRI (2007) assume a cost of fabricating fast reactor fuel that is slightly more than twice the cost of fabricating MOX fuel. Shropshire et al. (2009) provide a combined cost for reprocessing and fuel fabrication of fast reactor fuel. This combined cost is $5,000/kgHM, is slightly lower than

[14] The allocated figures add up to more than $705/kgHM since there is a shifting from measurement in terms of kg of UOX spent fuel, and kg of new MOX fuel fabricated representing 0.12 kg of the spent UOX fuel.

[15] Since the fast reactor system Bunn et al. (2003) evaluate has a blanket fuel containing no transuranics, they assume the blanket fuel can be fabricated at the same cost as UOX fuel.

our combined cost, adjusted for the timing of payments. In Table 1 we have allocated this cost as $2,100/kgHM for fabrication of fast reactor fuel and $2,900/kgHM for pyroprocessing of fast reactor spent fuel.

Reactor Cost Parameters

The large discrepancy between our estimate of the overnight capital cost for light water reactors and the estimates of others is probably the significant inflation in overnight costs that occurred between 2003 and 2008. In the years immediately preceding 2003, costs for the various inputs to reactor construction did not change much. But in the years between 2003 and 2008, costs rose precipitously each year. Du and Parsons (2009) document this change. An estimate that had been at $2,000/kWe measured in 2002 dollars rose by 15% per annum to $4,000/kWe measured in 2007 dollars. It is unclear why INL (2009) continues to report a low figure of $2,300/kWe.

We employ an 85% capacity factor for light water reactors. Some studies, such as INL (2009) and EPRI (2007) employ a 90% capacity factor. This is sometimes rationalized based upon the recent improved performance of US reactors. But the relevant statistic is lifetime capacity factors, and there is no justification in the history of reactor performance to set this at 90%.

The overnight capital cost for fast reactors is a major factor in determining the cost of fast reactor recycling. However, only a few fast reactors have ever been built, and most of these for experimental purposes, any estimate of the cost of a fast reactor is highly speculative. The NEA (2002-not shown in Table 1) uses a central estimate of $2,100/kW, denominated in year 2000 dollars, which is a 24% premium to their central estimate for the overnight capital cost of a light water reactor of $1,700/kW. Bunn et al.

(2003), relying on a history of estimates that places the cost of fast reactors at between 10 and 50% more than light water reactors, use a central premium of $200/kW, which is a 13% of their $1,500/kW central estimate for the overnight capital cost of a light water reactor. EPRI (2007) assumes that the cost of the fast reactor is 20% more than the cost of a light water reactor. Shropshire et al. (2009) use a central estimate of $2,900/kW, which is a 26% premium to their central estimate for the overnight capital cost of a light water reactor of $2,300/kW. All studies apply a premium, but there is little foundation for the specific choice.

A number of studies apply slightly higher O&M costs to fast reactors and a slightly lower capacity factor to fast reactors, possibly due to the different fuel loading schedules. EPRI (2007) scales the O&M charge to the original capital cost of the plant, so that the O&M charge would be 20% more for a fast reactor as compared to a light water reactor. Shropshire et al. (2009) set the fixed and variable non-fuel O&M costs for a fast reactor at 6% and 11% more, respectively, yielding a total O&M cost premium of 5%. Just as with the capital cost premium, the reader should appreciate how speculative these parameter choices are.

Reprocessing Cost Parameters

There is significant historical experience with the costs of reprocessing spent UOX fuel by the PUREX process. Unfortunately, reliable data on costs can be difficult to obtain. Focus is given to what can be gleaned of the costs of constructing and operating the French UP2 and UP3 plants at La Hague, the UK's THORP plant and the recently constructed Rokkasho-Mura plant in Japan. Bunn et al. (2003) use this data to assert that a reprocessing cost above $2,000/kgHM would be required if these plants were financed

and operated on a commercial basis, even were they guaranteed a regulated rate of return. Bunn et al. (2003) then choose to employ $1,000 as a conservative (low ball) figure which serves their purpose of finding a conservative minimum price of uranium necessary to justify reprocessing on the ground of resource savings. EPRI (2007) use a central value of $1,000/kgHM for the PUREX process. Shropshire et al. (2008) review the same data as Bunn et al. (2003) with the addition of updated information on Rokkasho-Mura and acknowledge that the realized costs for existing reprocessing plants, if financed and operated by private investors would require a charge greater than $1,000/kgHM, and in the case of Rokkasho-Mura a charge greater than $2,000/kgHM. Shropshire et al. (2009) report a figure of $1,320/kgHM for comparable reprocessing, but this figure is exclusive of the transportation, storage and vitrification services normally included in the price. Based upon private correspondence, we add $700/kgHM to produce an all-in comparable cost of $2,020/kgHM. Our $1,600/kgHM figure, denominated in 2007 dollars, equates to a 12% annual inflation from the Bunn et al. (2003) $1,000/kgHM figure that was denominated in 2003 dollars, and seems conservative. The BCG (2006) figure of $600/kgHM for reprocessing, based on Areva's data, is an outlier on the low side.[16,17]

[16] BCG (2006) uses a 2,500 MTHM facility as reference (close to the present annual US spent fuel production), while most other studies base their calculations on an 800 MTHM facility (on which most of the data is available). This scaling up along with technical optimization is claimed to yield a 3 fold decrease of reprocessing costs.

[17] In addition to data on the cost of building and operating reprocessing plants, one can look to the terms at which reprocessing services are offered. For example, in 2007 the French firm AREVA, which operates the UP2 and UP3 plants, announced that it had signed a contract to reprocess 235 tons of spent fuel from Italian plants at a price of more than €250 million—see AREVA press release for May 9, 2007. This would be slightly above €1,000/kgHM and slightly below $1,500/kgHM at the contemporaneous market exchange rate. Of course, commercially negotiated prices may be above or below the price required to recover the full cost of reprocessing depending upon a number of factors. In addition, the schedule of deliveries, payments and other commercial terms make hazardous this calculation of a levelized reprocessing cost based on the data in the press release.

Estimates for the reprocessing cost for other processes that separate out all of the transuranics from spent UOX fuel, such as TRUEX, or processes for reprocessing fast reactor fuel, such as pyroprocessing, are not based on specific historical experience with these processes at scale. Instead, some extrapolation from the costs of PUREX based upon knowledge of the key differences in the processes is required. Bunn et al. (2003) make no estimate for the cost of reprocessing spent UOX fuel in preparation for use in a fast reactor system, and neither does BCG (2006). EPRI (2007) use a central value of $1,000/kgHM for the UREX process that would be comparable to our TRUEX process, which is the same cost they estimate for the PUREX process. Shropshire et al. (2009) report a figure of $1,000/kgHM for UREX+ reprocessing, exclusive of the transportation, storage and vitrification services. We add $700/kgHM to produce an all-in comparable cost of $1,700/kgHM.

For the reprocessing of fast reactor fuel, Bunn et al. (2003) acknowledge that the cost is likely to be much more, but simply apply the same $1,000/kgHM figure used for the PUREX process as a low ball estimate, since the true costs would be higher and for their purposes they were satisfied to produce a minimum cost figure. EPRI (2007) use a central value of $2,750/kgHM for the cost of pyroprocessing used for spent fast reactor fuel, more than double their estimated cost for the PUREX process. Shropshire et al. (2009) apply a combined fabrication and reprocessing figure of $5,000/kgHM. In Table 1 we have allocated that figure across the two activities to show a cost of $2,900 for reprocessing alone.

Waste Disposal Cost Parameters

The final set of parameter estimates are the costs of interim storage and the geologic disposal of the wastes. For the Once-Through and Twice-Through cycles, we assume that the cost of 5 years of storage of the spent fuel in pools is contained in the reactor capital and O&M costs, while the follow-on cost of above-ground interim storage of the spent UOX and spent MOX fuel is additive to the cost of disposal in a geologic repository. For all reprocessed materials, we assume that the cost of interim storage of the streams are included in the cost of reprocessing. The various cost estimates for above-ground interim storage of spent fuel are driven primarily by the cost of the containers, and only modestly by the operating cost paid through time.

Our assumption of the cost of disposal in a geologic repository is equal to the 1 mill/kWh statutory fee given fuel with the burn-up we assume. The question arises whether that is a good estimate of the true cost of disposal. An answer can be had by referring to the US DOE's report on the historical and projected costs for the Yucca Mountain Repository—see OCRWM (2008). Using our 7% discount rate, we estimate a total cost for levelized across the electricity production associated with the waste to be stored at 0.93 mill/kWh in 2007 dollars, which is just below the figure we use. Our assumption is roughly comparable to those made by others. For the cost of geologic disposal of spent UOX fuel, Bunn et al. (2003) applies a central charge of $400/kgiHM, paid at discharge for 43 MWd/kgHM burnup. Our figure is approximately 10% higher, which is accounted for both by the difference in burnup assumptions and by the fact that our estimates are in 2007 dollars while the Bunn et al. (2003) estimate is denominated in 2003 dollars. Using slightly earlier US DOE figures, BCG (2006) arrives at a figure of

$375/kgiHM. The small difference with our calculation is that they employ the statutory discount rate of 3%, while we employ a risk-adjusted discount rate. In addition, BCG (2006) makes some different assumptions about the schedule for sending the spent fuel to the repository. EPRI (2007) report their cost assumptions per cubic meter of space required, but the information necessary to translate that into comparable units is not available. Shropshire (2009) uses a central value of $1,000/kgiHM. However, it is not clear whether this charge is paid at the time of unloading or some other point in time.

Because of the higher heat load, disposal of spent MOX will be more expensive than disposal of spent UOX. BCG (2006) estimates a density factor for MOX disposal relative to UOX disposal of 0.15, so that their estimate for the cost of disposal of UOX of $340/kgiHM (excl. of transport costs) rises to $2,240/kgiHM for MOX (excl. of transport costs).[18] Table 1 shows this pair of costs inclusive of transportation as $375/kgiHM and $2,295/kgiHM, respectively. We apply this same densification factor of 0.15 to our UOX disposal cost of $463/kgiHM and arrive at a MOX disposal cost of $3,086/kgiHM. Bunn et al. (2003) apply the same cost for MOX disposal as for UOX disposal, but this is consistent with their general practice of lowballing the estimate of elements of recycling costs.

The final fuel cycle parameters to compare are the cost estimates for disposal of the high level waste stream from each of the separation processes. Bunn et al. (2003) estimate that the costs of disposing of the high level waste from PUREX reprocessing would be reduced by a factor of 2.2 relative to the cost of disposing of the spent UOX

[18] BCG (2006) reports this as the densification factor in the counterfactual where spent MOX is sent to a geological repository. However, they assert that this yields such a high cost that this is not the right choice for a cycle producing spent MOX fuel. They never explicitly define the ultimate fate for spent MOX fuel, and never fully detail the future costs associated with handling the legacy of spent MOX fuel.

fuel. They round this to a factor of 2 in setting their high level waste disposal cost at $200/kgiHM. They treat the cost of disposing of high level waste from a fast reactor as the same as the cost of disposing of high level waste from a light water reactor using the PUREX process. They are silent on the cost of disposing of high level waste from a light water reactor using a TRUEX or similar process that removes the minor actinides from the waste stream. Shropshire et al. (2009) assume a densification factor of 2.5 in setting the cost for disposing of high level wastes from reprocessed light water reactor fuel, yielding a $400/kgiHM cost of disposal of the high level waste from their process that is comparable to TRUEX.

Discount Rate

For all of the fuel cycle calculations, the choice of a discount rate is central. Du and Parsons (2009), following on MIT (2003) used a base case nominal WACC for nuclear power plants of 10%, which, given the 3% inflation rate, translates to a real WACC of 6.8%. For coal- and natural gas-fired power plants they used a nominal WACC of 7.8%, which translates to a real WACC of 4.7%. Both of these costs of capital were intended to reflect the costs borne by an investor-owned company operating in a merchant (deregulated) environment. The difference between the WACC for nuclear and the WACC for coal- and natural-gas fired power plants in Du and Parsons (2009) represents a risk-premium being charged for new nuclear plants given the risks and uncertainties associated with a restart of this industry in the U.S.

Bunn et al. (2003) used a central value of 5%, which is supposed to correspond to the rate applicable to an investor-owned utility operating in a rate-of-return regulatory environment. They apply an 8% high value, which is supposed to correspond to the rate

applicable to an investor-owned utility operating in a merchant environment, and a 4% low value, which is supposed to correspond to the rate applicable to a government-owned operation. For their reference case, BCG (2006) employed a 3% discount rate, with a range extending from 2% to 4%. EPRI (2007) reports the many inputs that would go into deriving a discount rate, but instead of reporting a discount rate, they report a related capital charge factor and do not reveal their methodology. Shropshire et al. (2009) use a central real discount rate of 7.5% and examine a low scenario and a high scenario ranging from 5% to 10%.

Many sources, including Bunn et al. (2003), BCG (2006), EPRI (2007), and Shropshire et al. (2008) and (2009), also report a case with a very low rate that is supposed to correspond to the case of government owned operations. Many of these sources suggest that this low rate reflects the financing cost savings from factors like the fact that government owned operations would not be subject to certain taxes and that the interest rate on government debt is less than the rate paid on corporate debt. These factors do not reflect any real cost savings from government ownership, but rather a shifting of costs to other entities so that the cost is not attributed to the nuclear operations.

Results

Table 4 shows the incremental LCOE for the Twice-Through Cycle and for the Fast Reactor Recycle with different conversion ratios, using the LCOE of the Once-Through Cycle as the baseline. The table shows both our results and the incremental LCOE as reported in Bunn et al. (2003), BCG (2006), EPRI (2007) and Shropshire et al. (2009), for those cycles and conversion ratios each source reported. For each source we display only the central value reported for each type of cycle, as each source considers a

variety of cases or variations in parameters. Table 4 also shows the incremental LCOE measured as a percent of (i) the total LCOE of the Once-Through Cycle, ℓ_1, (ii) the total fuel cycle costs in the Once-Through Cycle, f_1+d_1, and (iii) the back-end fuel cycle costs in the Once-Through Cycle, d_1. We display each of these different percentage metrics because each of the metrics is highlighted in at least one of the reports we cite.

For the Twice-Through Cycle, Bunn et al. (2003) calculate that the LCOE increases by 1.3 mills/kWh and report that "this represents more than an 80% increase in the costs attributable to spent fuel management..." BCG (2006) finds an increase in disposal costs of $20/kgiHM, which we translate to approximately 0.07 mills/kWh. They compare this to the total disposal cost in the Once-Through Cycle of $500/kgiHM, giving a 4% increase in back-end costs. EPRI (2007) find an increase in the LCOE of 0.73 mills/kWh, which they report is a 1% increase in the total LCOE. Our figure of a 1.35 mill/kWh increase in LCOE is close to the Bunn et al. (2003) result and nearly double the EPRI (2007) result. Of course, the low figure from BCG (2006) is an outlier that results from both their aggressive assumption about driving down the cost of recycling and fuel fabrication, and their peculiar assumptions about the value of the liability associated with spent MOX fuel.

For the Fast Reactor Recycle, Bunn et al. (2003) calculate that the LCOE increases by 7 mills/kWh. This represents more than a 400% increase in the costs attributable to spent fuel management. As we noted in our discussion of methodology, Bunn et al. (2003) implicitly assume a conversion ratio that is greater than 1, although they are not explicit about the value. We compare their results to the 3.19 mill/kWh increase in LCOE we obtain for our breeder reactor with a 1.2 conversion ratio. Our cost

increase is less than one-half of theirs. This is surprising since on a number of different parameters for the fast reactor system we choose parameter values that imply higher costs. Bunn et al. (2003) had deliberately lowballed their parameter estimates for the fast reactor cycle. The major factor in the difference between our result and their result is the different definition of the LCOE as discussed in the methodology section above. Bunn et al. are implicitly calculating the equilibrium cost in a system with a conversion ratio greater than one. This equilibrium cost ignores the costs of the light water reactor component of the cycle, and calculates the cost from the fast reactor portion of the cycle with no credit given for the transuranics first passed along to the fast reactor. Since the fast reactors are more expensive, and since the credits for the transuranics first passed along to the fast reactor are essential to lowering its cost, this equilibrium cost will be much greater than the LCOE for the cycle.

EPRI (2007) find an increase in the LCOE of 2.37 mills/kWh, which they report is a 4% increase in the total LCOE. This is very comparable to our result, despite the difference in our definitions of the LCOE.

Shropshire et al. (2009) calculate an increase in the LCOE of 5.97 for a burner reactor, which is a 14% increase over the LCOE for the Once-Through Cycle. This is substantially higher than our result for a burner reactor. They calculate an increase in the LCOE of 15.20 mill/kWh for a self-sustaining fast reactor system, which is much, much greater than our 2.79 mill/kWh increase. The higher differential for Shropshire et al. (2009) are probably due to their higher capital cost premium and lower capacity factor assumptions for the fast reactor. The higher differential is also probably due to their use of the equilibrium cost concept as opposed to our definition of the LCOE. The impact of

the methodological difference becomes more significant as the conversion ratio approaches 1.

CONCLUSION

We analyze the levelized cost of electricity (LCOE) for three different fuel cycles: the traditional, Once-Through Cycle, in which the spent fuel is not recycled, but sent for disposal in a geologic repository; a Twice-Through Cycle, in which the plutonium and uranium extracted from the spent fuel from the first pass in a light water reactor are used in a second pass through a light water reactor, after which the spent fuel is sent for disposal in a geologic repository, and a Fast Reactor Recycle system, in which the spent fuel from the first pass in a light water reactor is followed by a repeated recycling of all of the transuranics through a fast reactor. We compare the LCOEs for both recycle systems against the LCOE for the traditional, Once-Through Cycle.

One contribution of our work is a clear definition of the LCOE that is consistent across fuel cycles. Our definition is also consistent with the way the LCOE is defined for non-nuclear generating technologies. To date, the literature has not employed a consistent definition, and a few of the commonly used definitions are not consistent with the way that the LCOE is defined for non-nuclear generating technologies. Our definition of the LCOE is independent of any value ascribed to the recycled materials, whether plutonium or transuranics. Nevertheless, we show that it is convenient to derive a value for these materials as one step in the calculation of the LCOE for a system with recycling. We show how this attributed value should be derived in a manner consistent with the meaning of a levelized cost for a given technology. The method we employ helps to make

the analysis more transparent than is commonly the case in the literature. We show how our definition relates to each of the other definitions used in studies of different cycles.

One widely used definition for fast reactor cycles is the 'equilibrium cost'. This concept requires the definition of a steady-state distribution of reactors – the ratio of fast reactors to light water reactors – and other activities. It totals all of the costs realized in the steady-state. We show how this concept differs from our definition of the LCOE and why it is inconsistent with the way the LCOE is commonly defined for other technologies. In general, for sensible parameters, the equilibrium cost measure will exaggerate the costs of a fast reactor cycle with full actinide recycling as compared against the once-through cycle. This is because the fast reactor recycle system involves a delayed realization of costs relative to the once-through cycle.

We parameterize our formulas and calculate the LCOEs. Based on current estimates of the costs for the various activities, recycling increases the LCOE by between 1.7 and 2.8 mills/kWh. This is an approximately 20-34% increase in the fuel cycle cost of the Once-Through Cycle, which we estimate at 8.28 mill/kWh. This is an approximately 2-4% increase in the total LCOE of the Once-Through Cycle, which we estimate at 75.32 mill/kWh. For the Twice-Through Cycle, the separated plutonium has a negative value, meaning that a reactor will have to be paid to take the recycled plutonium. For the Fast Reactor Cycle, the separated transuranics have a negative value, meaning that fast reactors will have to be paid to receive the transuranics (or the fuel that contains them) if they are to sell their electricity at prices comparable to the electricity being sold by light water reactors in the system.

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APPENDIX

Enrichment

To release a certain energy, i.e. to reach a certain burnup, uranium has to be enriched beforehand in its only fissile isotope: ^{235}U. This required concentration increases with the target burnup. Simulation of a PWR core shows that the necessary enrichment for a UOX fuel made from natural uranium is 4.5% for 50 MWd/kgHM.

However, UOX fuel can also be made from reprocessed uranium. If this uranium were used to fabricate UOX and enriched to the same percentage, it would not be able to reach the same burnup. The reason is that irradiation of the UOX in the core produces a synthetic isotope, ^{236}U, a neutron absorber, which is extracted together with the reprocessed uranium by the aqueous reprocessing. Therefore, a higher enrichment of the reprocessed uranium in ^{235}U must be reached, to compensate for this absorber. Similarly to Bunn et al. (2003), we use the following formula: [19]

$$x_{rp} = \frac{x_p}{1 - 0.21\frac{x_{r236}}{x_{rf}}}$$

where x_{rp} is the equivalent enrichment, where x_p is the regular enrichment, x_{r236} is the concentration of the reprocessed uranium in ^{236}U, and x_{rf} is the concentration of the reprocessed uranium in ^{235}U. In our reference case, spent and cooled UOX from natural uranium contains 1.02% of ^{235}U and 0.62% of ^{236}U. Therefore, the resulting enrichment target for reprocessed uranium is 5.16%.

[19] Rearranged from *Plutonium Fuel: An Assessment* (NEA, 1989), p.129

Once the proper enrichment is determined, whether for natural or reprocessed uranium, there are many ways to produce such a fuel. Indeed, you can extract most of the ^{235}U present in a small quantity of uranium, or just a little of the ^{235}U present in a bigger amount of uranium. This problem can be formulated in terms of finding the enrichment of the tails, which leads to the minimal cost of fabrication. The resulting enrichment does not depend on the product enrichment, but solely on the feed enrichment and on the relative cost of uranium to separative work units.[20] In our reference, we find a 0.29% enrichment of the tails for natural uranium and 0.39% for reprocessed uranium.

Value of Reprocessed Uranium

We make the simplifying assumption that once enriched and fabricated into new fuel, UOX from reprocessed uranium has the same exact properties as UOX from natural uranium. Therefore, the value of reprocessed uranium is the price such that a UOX assembly fabricated from either natural or reprocessed uranium have the same cost.

1kgHM of UOX from natural uranium is fabricated from 10.05 kgHM of ore, of which 10.03 kgHM are converted and enriched, using 6.37 SWU, and leading to a final cost of $ 2,428 /kgHM at time of loading into the reactor.

In a similar way, to make 1 kgHM of UOX from reprocessed uranium uses 7.44 kgHM of reprocessed uranium, of which 7.43 is converted and enriched using 4.93 SWU and also leading to a final cost of $ 2,428 /kgHM at time of loading.

[20] As a consequence, solving for the value of reprocessed uranium leads to an implicit equation, which must be solved numerically, see De Roo (2009).

List of Variables

Once-Through Cycle

ℓ_1	LCOE for the Once-Through Cycle; $\ell_1 = f_1 + k_1 + m_1 + d_1$
f_1	front-end fuel cost, levelized in mill/kWh; $f_1 = u_1 + b_1$
k_1	reactor capital cost, inclusive of future maintenance, capital expenditures and decommissioning costs, levelized in mill/kWh;
m_1	non-fuel operating and maintenance cost, levelized in mill/kWh;
d_1	cost of disposal of spent UOX fuel, including the cost of interim storage and geologic repository, levelized in mill/kWh;
u_1	cost of the raw uranium, levelized in mill/kWh;
b_1	enrichment, conversion and fabrication cost for UOX, levelized in mill/kWh;
Ψ_L	present value factor for the electricity produced by 1 kg of UOX fuel during a single loading of 4.5 years;
M_L	full core mass of a 1GWe thermal reactor;
ϕ_L	present value factor for the electricity produced by the full mass of UOX fuel in the core, M_L, during the course of the full 60 year life of the reactor;

Twice-Through Cycle

ℓ_2	LCOE for the Twice-Through Cycle;
$\ell_{2,1}(p)$	LCOE for the first reactor in the cycle, i.e, the reactor burning fresh fuel and sending its spent fuel for reprocessing; this is a function of the value attributed to the separated plutonium, p; $\ell_{2,1}(p) = f_{2,1} + k_{2,1} + m_{2,1} + d_{2,1}(p)$
$f_{2,1}$	front-end fuel cost for the first reactor in the cycle, levelized in mill/kWh; $f_{2,1} = u_{2,1A} + b_{2,1}$
$k_{2,1}$	reactor capital cost for the first reactor in the cycle, levelized in mill/kWh;
$m_{2,1}$	non-fuel operating and maintenance cost for the first reactor in the cycle, levelized in mill/kWh;
$d_{2,1}(p)$	cost of disposal of spent fuel, including the cost of reprocessing, disposal of high level wastes and credits for the separated uranium and plutonium, levelized in mill/kWh; $d_{2,1}(p) = s_{2,1} + w_{2,1} - u_{2,1B} - z_{2,1}(p)$
$u_{2,1A}$	cost of the raw uranium, levelized in mill/kWh;
$b_{2,1}$	enrichment, conversion and fabrication cost for UOX, levelized in mill/kWh;
$s_{2,1}$	reprocessing cost, inclusive of interim storage for the separated streams and of low and intermediate-level waste disposal, levelized in mill/kWh;
$w_{2,1}$	high level waste disposal cost, levelized in mill/kWh;
$u_{2,1B}$	credit for the separated uranium, levelized in mill/kWh;
$z_{2,1}(p)$	credit for the separated plutonium, levelized in mill/kWh;

List of Variables (cont.)

Twice-Through Recycle (cont.)

$\ell_{2,2}(p)$ LCOE for the second reactor in the cycle, i.e, the reactor burning recycled fuel; this is a function of the value attributed to the separated plutonium, *p;*

$$\ell_{2,2}(p) = f_{2,2}(p) + k_{2,2} + m_{2,2} + d_{2,2}$$

$f_{2,2}(p)$ front-end fuel cost for the first reactor in the cycle, levelized in mill/kWh; this is a function of the value attributed to the separated plutonium, *p*, used to fabricate the fuel;

$$f_{2,2}(p) = u_{2,2} + z_{2,2}(p) + b_{2,2}$$

$k_{2,2}$ reactor capital cost for the second reactor in the cycle, levelized in mill/kWh;

$m_{2,2}$ non-fuel operating and maintenance cost for the second reactor in the cycle, levelized in mill/kWh;

$d_{2,2}$ cost of disposal of spent MOX fuel, levelized in mill/kWh;

$u_{2,2}$ cost of purchasing depleted uranium used in fabricated the recycled fuel, levelized in mill/kWh;

$z_{2,2}(p)$ cost of purchasing the separated plutonium used for fabricating the recycled fuel, levelized in mill/kWh;

$b_{2,2}$ cost of fabricating the recycled fuel, levelized in mill/kWh;

p value attributed to the separated plutonium, levelized in mill/kWh; variable is solved for in deriving the two LCOEs, $\ell_{2,1}(p)$ and $\ell_{2,2}(p)$;

Fast Reactor Recycle

ℓ_3 LCOE for the Fast Reactor Recycle;

$\ell_{3,L}(p)$ LCOE for the light water reactor in the cycle; this is a function of the value attributed to the separated transuranics, *p*;

$$\ell_{3,L}(p) = f_{3,L} + k_{3,L} + m_{3,L} + d_{3,L}(p)$$

$f_{3,L}$ front-end fuel cost for the light water reactor in the cycle, levelized in mill/kWh;

$$f_{3,L} = u_{3,LA} + b_{3,L}$$

$k_{3,L}$ reactor capital cost for the light water reactor in the cycle, levelized in mill/kWh;

$m_{3,L}$ non-fuel operating and maintenance cost for the light water reactor in the cycle, levelized in mill/kWh;

$d_{3,L}(p)$ cost of disposal of spent fuel, including the cost of reprocessing, disposal of high level wastes and credits for the separated transuranics and uranium mix, levelized in mill/kWh;

$$d_{3,L}(p) = s_{3,L} + w_{3,L} - u_{3,LB} - z_{3,L}(p)$$

$u_{3,LA}$ cost of the raw uranium, levelized in mill/kWh;

$b_{3,L}$ enrichment, conversion and fabrication cost for UOX, levelized in mill/kWh;

$s_{3,L}$ reprocessing cost, levelized in mill/kWh;

$w_{3,L}$ high level waste disposal cost, levelized in mill/kWh;

List of Variables (cont.)

Fast Reactor Recycle (cont.)

$u_{3,LB}$ credit for the separated uranium, levelized in mill/kWh;

$z_{3,L}(p)$ credit for the separated transuranics, levelized in mill/kWh;

$\ell_{3,F}(p)$ LCOE for a fast reactor in the cycle; this is a function of the value attributed to the separated transuranics, *p*, used to fabricate the fuel;
$\ell_{3,F}(p) = f_{3,F}(p) + k_{3,F} + m_{3,F} + d_{3,F}(p)$

$f_{3,F}(p)$ front-end fuel cost for a fast reactor in the cycle, levelized in mill/kWh; this is a function of the value attributed to the separated tranuranics, *p*, used to fabricate the fuel;
$f_{3,F}(p) = u_{3,FA} + z_{3,F}(p) + b_{3,F}$

$k_{3,F}$ reactor capital cost for a fast reactor in the cycle, levelized in mill/kWh;

$m_{3,F}$ non-fuel operating and maintenance cost for a fast reactor in the cycle, levelized in mill/kWh;

$d_{3,F}(p)$ cost of disposal of spent fuel, including the cost of reprocessing, disposal of high level wastes and credits for the separated transuranics and uranium mix, levelized in mill/kWh;
$d_{3,F}(p) = s_{3,F} + w_{3,F} - u_{3,FB} - \alpha\, z_{3,F}(p)$

$u_{3,FA}$ cost of purchasing depleted uranium used in fabricated the fast reactor fuel, levelized in mill/kWh;

$z_{3,F}(p)$ cost of purchasing the separated transuranics used for fabricating the fast reactor fuel, levelized in mill/kWh;

$b_{3,F}$ cost of fabricating the fast reactor fuel, levelized in mill/kWh;

$s_{3,F}$ reprocessing cost for fast reactor fuel, inclusive of interim storage for the separated streams and of low and intermediate-level waste disposal, levelized in mill/kWh;

$w_{3,F}$ high level waste disposal cost, levelized in mill/kWh;

$u_{3,FB}$ credit for the separated uranium, levelized in mill/kWh;

$z_{3,F}(p)$ credit for the separated transuranics, levelized in mill/kWh;

α the TRU mass ratio (i.e. the ratio of the mass of TRU in fast reactor spent fuel to the mass of TRU in fresh fuel) adjusted for the present value difference between when the fuel is initially loaded and when it is next loaded;
$\alpha = (q_2/q_1)\, e^{-R(B_2 - B_1)}$, where q_2/q_1 is the TRU mass ratio, B_1 is the date of loading of the fuel into the first fast reactor and B_2 is the date of loading of the recycled transuranics from the first fast reactor into a second fast reactor; R is the continuously compounded annual rate of interest;

p value attributed to the separated transuranics, levelized in mill/kWh; variable is solved for in deriving the two LCOEs, $\ell_{3,L}(p)$ and $\ell_{3,F}(p)$;

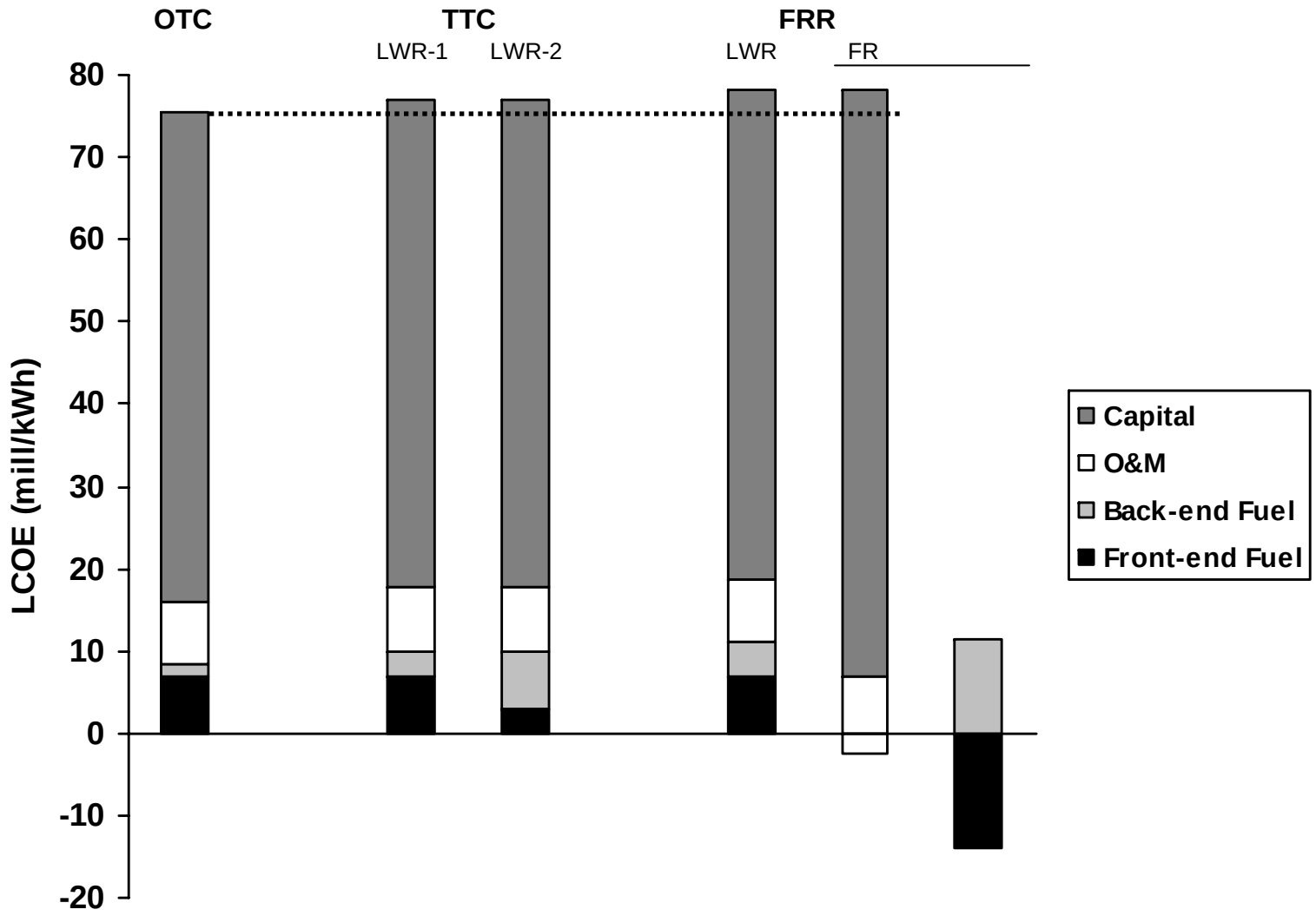

Figure 1. LCOEs for Alternative Cycles, by Component.

The graph displays the LCOE figures from Table 2. The first bar shows the LCOE, by component, for the Once-Through Cycle. The second and third bars show the two LCOEs for the Twice-Through Cycle: the left-hand bar is the LCOE for the first pass reactor, while the right-hand bar is the LCOE for the second pass reactor. The fourth, fifth and sixth bars show the LCOEs for the Fast Reactor Recycle: the left-hand bar is the LCOE for the light water reactor, while the center and right-hand bar show the LCOE for a fast reactor. The total fuel cycle cost for the fast reactor is negative, so that the total LCOE is less than the sum of the reactor capital and O&M costs, as seen in the center bar. The right-hand bar shows the two fuel cycle cost components, one negative and the other positive.

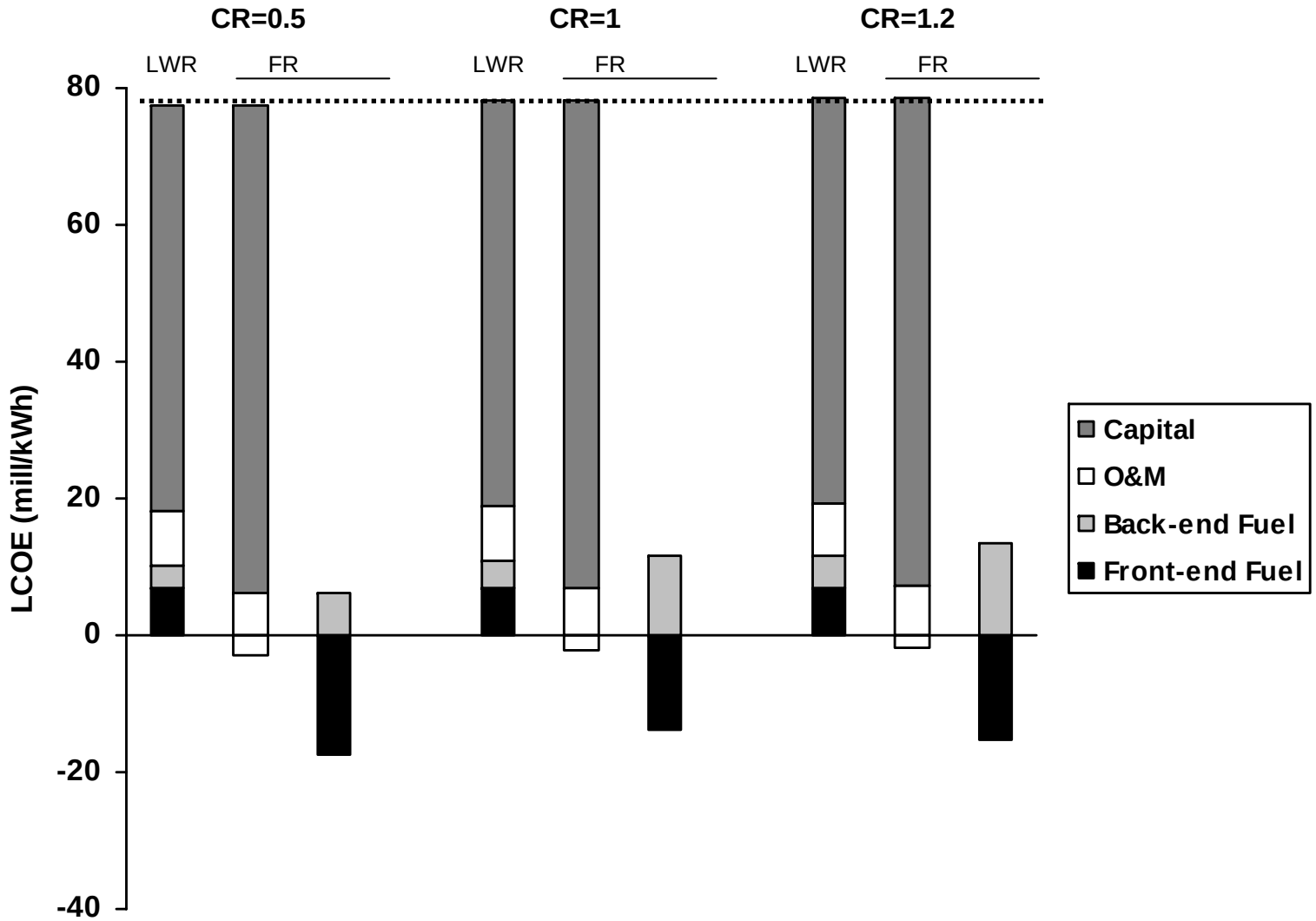

Figure 2. LCOEs in a Fast Reactor Recycle for Alternative Conversion Ratios.

The graph displays the LCOE figures from Table 3. In each set of three bars, the left-hand bar in the set is the LCOE for the light water reactor, while the center and right-hand bar show the LCOE for a fast reactor. The total fuel cycle cost for the fast reactor is negative, so that the total LCOE is less than the sum of the reactor capital and O&M costs, as seen in the center bar for each set. The right-hand bar shows the two fuel cycle cost components, one negative and the other positive.

Table 1
Input Parameter Assumptions

			This Paper	Comparison to others:			
				Shropshire (2009)	EPRI (2007)	BCG (2006)	Bunn (2003)
			[A]	[B]	[C]	[D]	[E]
	Front-end Fuel Costs						
[1]	Natural Uranium	$/kgHM	80	60	260	80	50
[2]	Depleted Uranium	$/kgHM	10	10	260		6
[3]	Conversion of Natural U	$/kgHM	10	10	15	12	6
[4]	Enrichment of Natural U	$/SWU	160	105	140	110	100
[5]	Fabrication of UOX from Natural U	$/kgHM	250	240	250	200	250
[6]	Conversion of Repr. U		200%				250%
[7]	Enrichment of Repr. U		10%				5%
[8]	Fabrication of UOX from Repr U		7%			7%	4%
[9]	Fabrication of MOX	$/kgHM	2,400	1,950	1,250	900	1,500
[10]	Fabrication of FR fuel	$/kgHM	2,400	2,100	2,600	n/a	1,500
	Reactor Costs						
[11]	LWR Capital (overnight)	$/kWe	4,000	2,300	2,500		1,500
[12]	LWR Capacity Factor		85%	90%	90%		85%
[13]	FR Capital premium		20%	26%	20%		13%
[14]	FR O&M premium		20%	5%	20%		
[15]	FR Capacity Factor		85%	82%	85%		85%
	Reprocessing Cost						
[16]	UOX, PUREX	$/kgHM	1,600	2,020	1,000	600	1,000
[17]	UOX, UREX+ or TRUEX	$/kgHM	1,600	1,700	1,000		n/a
[18]	FR fuel, pyroprocessing	$/kgHM	3,200	2,900	2,750		1,000
	Waste Costs						
[19]	Interim Storage of UOX	$/kgiHM	200	120	150	150	200
[20]	Interim Storage of MOX	$/kgiHM	200	120	300	n/a	200
[21]	Disposal of Spent UOX	$/kgiHM	463	1,000	n/a	375	400
[22]	Disposal of Spent MOX	$/kgiHM	3,086		n/a	2,295	400
[23]	Disposal of HLW from UOX (PUREX)	$/kgiHM	185		n/a	96	200
		d. factor			n/a	3.9	2.0
		$/kgFP			n/a		n/a
[24]	Disposal of HLW from UOX (TRUEX)	$/kgiHM	185	400	n/a		n/a
[25]	Disposal of HLW from FR	$/kgiHM	281		n/a		200
[26]	Discount Rate (real)		7.0%	7.5%	n/a	3%	5%

Table 1 (continued)
Input Parameter Assumptions

Notes:

[A] Figures are in 2007 dollars.

[16]-[18] Reprocessing costs are inclusive of storage, transportation and vitrification.

[21]-[25] Disposal costs are inclusive of transportation and packaging.

[21] Equal to the 1 mill/kWh statutory fee given our burn-up assumptions. Approx. equal to the historical plus forecasted cost of Yucca Mountain charged on a kWh basis independent of burn-up, using our discount rate.

[22] =[21]/0.15. The 0.15 densification factor applied is based on BCG (2006) figures; approx. equal to [C-21]/[C/22]. Discrepency arises due to addition of transportation costs after accounting for the densification factor.

[23] = [24].

[24] = [21]/2.5. The 2.5 densification factor applied is based on Shropshire et al. (2008) and (2009).

[25] = ([24]/5.146%)*7.8%. I.e., cost is based on the cost of disposal of the HLW from TRUEX measured per kg fission products, multiplied times the quantity of fission products in the fast reactor spent fuel.

[B] Figures are in 2008 dollars.

[10] Shropshire et al. provides a combined cost for reprocessing plus fabrication equal to $5,000/kgHM. We allocate the combined cost to the two separate line items, [10] and [18], in the proportion they are allocated in our parameter assumptions, column [A].

[16] Shropshire et al. provides an estimate of $1,320/kgHM for its F1+. This does not include other costs normally included with reprocessing, such as transportation, storage and vitrification. These other services are separately itemized in other modules of Shropshire et al. (2009), but not necessarily on a kgHM basis, making the total amount difficult to compile. Based on private correspondence, we add $700/kgHM for these costs.

[17] Shropshire et al. provides an estimate of $1,000/kgHM for its F1-1. This does not include other costs normally included with reprocessing, such as transportation, storage and vitrification. These other services are separately itemized in other modules of Shropshire et al. (2009), but not necessarily on a kgHM basis, making the total amount difficult to compile. Based on private correspondence, we add $700/kgHM for these costs.

[18] Shropshire et al. provides a combined cost for reprocessing plus fabrication equal to $5,000/kgHM. We allocate the combined cost to the two separate line items, [10] and [18], in the proportion they are allocated in our parameter assumptions, column [A].

[24] = [21]/2.5. Shropshire (2009) reports both the factor 2.5 and the result measured as a charge measured in kg fission products.

[C] Figures are in 2007 dollars.

[21-25] EPRI reports costs per cubic meter. Translation to our units requires additional information about heat content and other inputs that are not available to us.

[26] EPRI provides the component elements of a discount rate calculation, but report the results as a capital charge.

[D] Figures are in 2005 dollars.

[9] BCG provides a combined cost for reprocessing plus fabrication of $630/kg, and a $75 cost for transportation to the reprocessing plant, yielding a total combined cost of $705. We allocate the combined cost to the two separate line items based upon the proportion they are allocated in our parameter assumptions, column [A]. It is necessary to take into account the denomination in terms of kg UOX and kg MOX. BCG assumes 0.12 kg MOX for every 1 kg UOX. Therefore, the formula for fabrication is [9]=((630+75)*(0.12*2,400)/(0.12*2,400+1,600))/0.12.

[16] BCG provides a combined cost for reprocessing plus fabrication of $630/kg, and a $75 cost for transportation to the reprocessing plant, yielding a total combined cost of $705. We allocate the combined cost to the two separate line items based upon the proportion they are allocated in our parameter assumptions, column [A]. It is necessary to take into account the denomination in terms of kg UOX and kg MOX. BCG assumes 0.12 kg MOX for every 1 kg UOX. Therefore, the formula for reprocessing is [16]=(630+75)*(1,600)/(0.12*2,400+1,600).

[20] No separate cost for the interim storage of MOX appears in the report.

[21] Inclusive of the transportation cost.

[22] Inclusive of the transportation cost.

[23] Inclusive of the transportation cost. The undiscounted transportation cost is shown for the separate items of transport for reprocessing and transport for the repository. For the discounted cost only a combined figure is shown. We interpolate to get the separate discounted cost items.

[E] Figures are in 2003 dollars.

[10] Not a best estimate, but a lowball figure set equal to the cost of MOX fabrication in order to provide a conservative estimate of recycling costs. Also, this is the cost for the fuel in the core. Bunn et al. assume a blanket fuel without any transuranics and therefore a lower cost of fabrication. Since our fast reactor fuel contains transuranics in both components, for comparison we cite here only the cost for fabricating the core fuel.

[17] Bunn et al. do not examine a coupled LWR/FR system, but rather a self-sustaining system of fast reactors assuming an initial stock of free plutonium. Therefore there are no explicit costs for reprocessing LWR fuel into FR fuel.

[22] Setting MOX disposal cost equal to UOX disposal cost is meant to be a conservative figure and not a best estimate.

[18] Not a best estimate, but a lowball figure set equal to the cost of PUREX reprocessing in order to provide a conservative estimate of recycling costs.

[24] Bunn et al. do not examine a coupled LWR/FR system, but rather a self-sustaining system of fast reactors assuming an initial stock of free plutonium. Therefore there are no explicit costs for disposing of HLW from reprocessing LWR fuel into FR fuel.

Table 2
Outputs: LCOE by Components + Price of Plutonium and Price of Transuranics

		Once-Through Cycle (mill/kWh) [A]		Twice-Through Cycle (mill/kWh) [B]		Fast Reactor Recycle (mill/kWh) [C]	
[1]	Front-end Fuel Cycle	f_1	6.97	$f_{2,1}$	6.97	$f_{3,L}$	6.97
[2]	Raw Uranium	u_1 2.70		$u_{2,1A}$ 2.70		$u_{3,LA}$ 2.70	
[3]	Fabrication	b_1 4.28		$b_{2,1}$ 4.28		$b_{3,L}$ 4.28	
[4]	Capital Charge	k_1	59.30	$k_{2,1}$	59.30	$k_{3,L}$	59.30
[5]	O&M Costs (non-fuel)	m_1	7.74	$m_{2,1}$	7.74	$m_{3,L}$	7.74
[6]	Disposal Cost	d_1	1.31	$d_{2,1}$	2.98	$d_{3,L}$	4.10
[7]	Reprocessing			$s_{2,1}$ 2.46		$s_{3,L}$ 2.46	
[8]	HLW Disposal			$w_{2,1}$ 0.40		$w_{3,L}$ 0.40	
[9]	Reprocessed Uranium			$u_{2,1B}$ 0.15		$u_{3,LB}$ 0.15	
[10]	Plutonium/TRUs			$z_{2,1}$ -0.26		$z_{3,L}$ -1.38	
[11]	LCOE Total	ℓ_1	75.32	$\ell_{2,1}$	76.99	$\ell_{3,L}$	78.11
[12]	Front-end Fuel Cycle			$f_{2,2}$	2.98	$f_{3,F}$	-13.88
[13]	Depleted Uranium			$u_{2,2}$ 0.03		$u_{3,FA}$ 0.01	
[14]	Plutonium/TRUs			$z_{2,2}$ -4.33		$z_{3,F}$ -17.89	
[15]	Fabrication			$b_{2,2}$ 7.27		$b_{3,F}$ 3.99	
[16]	Capital Charge			$k_{2,2}$	59.30	$k_{3,F}$	71.16
[17]	O&M Costs (non-fuel)			$m_{2,2}$	7.74	$m_{3,F}$	9.29
[18]	Disposal Cost			$d_{2,2}$	6.97	$d_{3,F}$	11.55
[19]	Reprocessing					$s_{3,F}$ 2.77	
[20]	HLW Disposal					$w_{3,F}$ 0.34	
[21]	Depleted Uranium					$u_{3,FB}$ 0.01	
[22]	TRUs					$\alpha\, z_{3,F}$ -8.45	
[23]	LCOE Total			$\ell_{2,2}$	76.99	$\ell_{3,F}$	78.11
[24]	Price of Plutonium, $/kgHM			p -15,777			
[25]	Price of TRU, $/kgHM					p -74,704	

Notes:

[A]
- [1]=[2]+[3]
- [11]=[1]+[4]+[5]+[6]

[B]
- [1]=[2]+[3]
- [6]=[7]+[8]-[9]-[10]
- [11]=[1]+[4]+[5]+[6]
- [12]=[13]+[14]
- [23]=[12]+[16]+[17]+[18]
- [24] chosen to set [23]=[11]

[C] The conversion ratio = 1.
- [1]=[2]+[3]
- [6]=[7]+[8]-[9]-[10]
- [11]=[1]+[4]+[5]+[6]
- [12]=[13]+[14]
- [18]=[19]+[20]-[21]-[22]
- [23]=[12]+[16]+[17]+[18]
- [25] chosen to set [23]=[11]

Table 3
Fast Reactor Recycle LCOEs for Different Conversion Ratios

			CR=0.5 (mill/kWh) [A]		CR=1 (mill/kWh) [B]		CR=1.2 (mill/kWh) [C]	
[1]	Front-end Fuel Cycle	$f_{3,L}$		6.97		6.97		6.97
[2]	Raw Uranium	$u_{3,LA}$	2.70		2.70		2.70	
[3]	Fabrication	$b_{3,L}$	4.28		4.28		4.28	
[4]	Capital Charge	$k_{3,L}$		59.30		59.30		59.30
[5]	O&M Costs (non-fuel)	$m_{3,L}$		7.74		7.74		7.74
[6]	Disposal Cost	$d_{3,L}$		3.38		4.10		4.49
[7]	Reprocessing	$s_{3,L}$	2.46		2.46		2.46	
[8]	HLW Disposal	$w_{3,L}$	0.40		0.40		0.40	
[9]	Reprocessed Uranium	$u_{3,LB}$	0.15		0.15		0.15	
[10]	Plutonium/TRUs	$z_{3,L}$	-0.66		-1.38		-1.77	
[11]	LCOE Total	$\ell_{3,L}$		77.39		78.11		78.51
[12]	Front-end Fuel Cycle	$f_{3,F}$		-17.32		-13.88		-15.33
[13]	Depleted Uranium	$u_{3,FA}$	0.01		0.01		0.02	
[14]	Plutonium/TRUs	$z_{3,F}$	-11.37		-17.89		-21.07	
[15]	Fabrication	$b_{3,F}$	2.22		3.99		5.71	
[16]	Capital Charge	$k_{3,F}$		71.16		71.16		71.16
[17]	O&M Costs (non-fuel)	$m_{3,F}$		9.29		9.29		9.29
[18]	Disposal Cost	$d_{3,F}$		6.09		11.55		13.39
[19]	Reprocessing	$s_{3,F}$	1.51		2.77		3.35	
[20]	HLW Disposal	$w_{3,F}$	0.34		0.34		0.30	
[21]	Depleted Uranium	$u_{3,FB}$	0.00		0.01		0.01	
[22]	TRUs	$\alpha z_{3,F}$	-4.24		-8.45		-9.75	
[23]	LCOE Total	$\ell_{3,F}$		77.39		78.11		78.51
[24]	Price of TRU, $/kgHM	p	-35,677		-74,704		-95,912	

Notes:

Except as otherwise noted, all input parameters are as shown in Table 1. The notes below discuss the adjustments that must be accounted for as the conversion ratio is changed.

As the CR increases, the burnup per kgHM decreases. We have 132, 73 and 55 MWd/kgHM for CR=0.5, 1 and 1.2, respectively. We keep the cost of fabrication and reprocessing, measured in $/kgHM, constant. Consequently, the cost measured in $/kWh will increase as the CR increases. Arguably, the higher CR means a lower TRU concentration in the fuel and therefore a possibly lower fabrication cost measured in $/kgHM.

As the CR increases, the cycle length also increases. The average residence time in the reactor is 4.4, 4.2 and 6.7 for CR=0.5, 1 and 1.2, respectively. One consequence of these residence times is that although the ratio of burnup to fission products is fairly constant, the timing of the realization of the disposal cost varies. This explains line [18] above.

We keep the cost of disposal of the separated waste from the fast reactor fuel constant in $/kgFP. This means a varying cost when measured in $/kgHM of initial heavy metal.

Table 4
Increase in LCOE Relative to the Once-Through Cycle

		This Paper	Comparison to others:			
			Shropshire (2009)	EPRI (2007)	BCG (2006)	Bunn (2003)
		[A]	[B]	[C]	[D]	[E]
Twice-Through Cycle						
[1]	mills/kWh	1.67		0.73	0.07	1.30
[2]	% of total LCOE in OTC, ℓ_1	2.2%		1%	–	–
[3]	% of total fuel cycle costs in OTC, f_1+d_1	20%		–	–	–
[4]	% of back-end fuel cycle costs in OTC, d_1	128%		–	4%	80%
Fast Reactor Recycle						
Burner, CR<1						
[5]	mills/kWh	2.07	5.97	2.37		
[6]	% of total LCOE in OTC, ℓ_1	3%	14%	4%		
[7]	% of total fuel cycle costs in OTC, f_1+d_1	25%	92%	–		
[8]	% of back-end fuel cycle costs in OTC, d_1	158%	226%	–		
Self-Sustaining, CR=1						
[9]	mills/kWh	2.79	15.20			
[10]	% of total LCOE in OTC, ℓ_1	3.7%	36%			
[11]	% of total fuel cycle costs in OTC, f_1+d_1	34%	233%			
[12]	% of back-end fuel cycle costs in OTC, d_1	214%	575%			
Breeder, CR>1						
[13]	mills/kWh	3.19				7.00
[14]	% of total LCOE in OTC, ℓ_1	4%				–
[15]	% of total fuel cycle costs in OTC, f_1+d_1	38%				–
[16]	% of back-end fuel cycle costs in OTC, d_1	244%				466%

Notes:

[A-5]: For our burner reactor, we use a conversion ratio of 0.5.

[B-5]: Based on Shropshire et al. (2009) scenario for a burner reactor with a conversion ratio of 0.5.

[C-5]: EPRI (2007) is not explicit about which conversion ratio is assumed, except that since it studies a stead-state that includes light water reactors, it must be a ratio less than 1.

[A-13]: For our breeder reactor, we use a conversion ratio of 1.2.

[E-13]: Bunn et al. (2003) is not explicit about which conversion ratio is assumed, except that it must be a ratio greater than 1 and exactly large enough so that the present value adjusted transuranics mass ratio, α, equals 1.