THE ECONOMICS OF REPROCESSING VERSUS DIRECT DISPOSAL OF SPENT NUCLEAR FUEL

FUEL CYCLE AND MANAGEMENT

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MATTHEW BUNN and JOHN P. HOLDREN *Harvard University*
John F. Kennedy School of Government, Cambridge, Massachusetts 02138

STEVE FETTER* *University of Maryland*
School of Public Policy, College Park, Maryland 20742-1821

BOB VAN DER ZWAAN *Harvard University*
John F. Kennedy School of Government, Cambridge, Massachusetts 02138 and
Energy research Centre of the Netherlands, P.O. Box 37154, 1030 AD, Amsterdam,
The Netherlands

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We assess the economics of reprocessing versus direct disposal of spent fuel. The uranium price at which reprocessing spent fuel from light water reactors (LWRs) and recycling the resulting plutonium and uranium in LWRs would become economic is estimated for a range of reprocessing prices and other fuel cycle costs. The contribution of both fuel cycle options to the cost of electricity is also estimated. A similar analysis is performed to compare fast neutron reactors (FRs) with LWRs. We review available information about various fuel cycle costs, as well as the quantities of uranium likely to be recoverable at a range of future prices. We conclude that the once-through LWR fuel cycle is likely to remain significantly cheaper than recycling in either LWRs or FRs for at least the next 50 yr, even with substantial growth in nuclear power.

I. INTRODUCTION

The best approach to managing spent fuel from nuclear power reactors has been debated for decades—whether it is better to dispose of it directly in geologic repositories or reprocess it to recover and recycle the plutonium and uranium. These debates have become more salient as increasing accumulations of both spent nuclear fuel and separated plutonium from reprocessing generate concern worldwide. Countries that have chosen to reprocess are facing high costs and political controversies, while many that have chosen not to reprocess are facing obstacles to providing adequate spent-fuel storage. No country has yet opened a geologic repository for either spent nuclear fuel or high-level waste (HLW) from reprocessing. Proposals to separate and transmute not only plutonium and uranium, but other long-lived radioactive materials as well, have gained increasing attention.

Cost is an important element in this debate. Economics is not the only factor affecting decisions concerning reprocessing today—the inertia of fuel cycle plans and contracts initiated long ago, hopes that plutonium recycling will contribute to energy security, lack of adequate spent-fuel storage, environmental and proliferation concerns, and other factors also play critical roles. But economics is not unimportant, particularly in a nuclear industry facing an increasingly competitive environment and where fuel cycle costs are among the few that reactor operators can control.

There is general agreement that at today's low uranium and enrichment prices, reprocessing and recycling is more expensive than direct disposal of spent fuel.[1–3] The debate is over the magnitude of the difference and how long it is likely to persist. Advocates of reprocessing argue that the premium is small today and will soon disappear as uranium becomes scarce and increases in price.[4] Here, we argue that the margin is wide and likely to persist for many decades to come.

These issues are increasingly important as a number of countries face major decisions about future management of their spent fuel. In the United States in particular,

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*E-mail: sfetter@umd.edu

16the U.S. Department of Energy (DOE) plans to spend several hundred million dollars over the next several years on research and development related to reprocessing in the Advanced Fuel Cycle Initiative.[5]

We proceed as follows. First, we compare the costs of direct disposal versus reprocessing and recycling in light water reactors (LWRs) by calculating the "breakeven" uranium price—the price of uranium at which the cost of electricity would be the same for both options—for various reprocessing prices and other fuel cycle prices and parameters. We focus on the breakeven uranium price because the prospect that rising uranium prices would make reprocessing economic has been a prominent feature of arguments made by advocates of reprocessing. We also perform a sensitivity analysis and calculate the contribution of these fuel cycle options to the cost of electricity. Second, we repeat this analysis to compare the costs of direct disposal with LWRs to reprocessing and recycling in fast neutron reactors (FRs). Third, we review the history of uranium prices, estimates of uranium resources recoverable at a given price, and scenarios of uranium consumption under the direct disposal option to assess when reprocessing and recycling in LWRs or FRs might become economically attractive. Finally, we discuss the impact of fuel cycle choices on repository requirements.

Where possible, we base our estimates on historical market prices for fuel cycle services. Where markets are not well developed, as is the case for reprocessing and mixed-oxide (MOX) fuel fabrication, our estimates are based on the best available information on facility construction and operation costs. Unless otherwise noted, prices and costs have been converted to 2003 U.S. dollars using market exchange rates and U.S. gross domestic product deflators.

II. DIRECT DISPOSAL VERSUS REPROCESSING IN LWRs

We adopt the viewpoint of an LWR operator that has discharged spent fuel and is deciding which option is less expensive: direct disposal or reprocessing. With direct disposal, the reactor operator would have to pay the costs of (a) interim storage of the spent fuel and (b) transport to a repository site and disposal of the spent fuel (possibly including conditioning prior to disposal). With the reprocessing option, the reactor operator would have to pay the costs of (a) transport to the reprocessing plant and reprocessing of the spent fuel and (b) disposal of reprocessing wastes.[a] The plutonium and uranium recovered during reprocessing can be used to fabricate MOX fuel, reducing requirements for fresh low-enriched uranium (LEU) fuel.

The value of the recovered plutonium and uranium is the value of the fuels that can be made from these materials minus the costs of fuel fabrication. Because fuels made with recovered plutonium and uranium would substitute for LEU fuels, their value is determined by the price of LEU fuel with the same design burnup, which in turn depends on the price of uranium. The uranium price at which the net present cost of the two fuel cycles is equal is the breakeven price, given notionally by

$$\begin{aligned}
\begin{bmatrix}\text{cost of interim storage }+\\ \text{disposal of spent fuel}\end{bmatrix}
&= \begin{bmatrix}\text{cost of reprocessing }+\\ \text{disposal of wastes}\end{bmatrix}\\
&\quad + \begin{bmatrix}\text{cost of producing LWR fuel}\\ \text{using recovered Pu, U}\end{bmatrix}\\
&\quad - \begin{bmatrix}\text{cost of equivalent}\\ \text{LEU fuel}\end{bmatrix} . \qquad (1)
\end{aligned}$$

Of course, many factors enter into a complete calculation—carrying charges on the cost of the material during its processing and use, fuel burnup, the isotopic composition of the recovered uranium and plutonium and the resulting plutonium concentrations or uranium enrichment levels required to achieve a given design burnup, the amount of uranium and enrichment work used to produce a kilogram of LEU at a given uranium price, and so on. The equations we have used to calculate the breakeven uranium price and the cost of electricity, which take these and other factors into account, are fully documented in Ref. 6 and have been implemented in spreadsheets that we have made publicly available.[7]

II.A. Breakeven Prices and Difference in Cost of Electricity

Figure 1 shows the breakeven uranium price as a function of the price of reprocessing [including transportation of fuel to the reprocessing plant, short-term storage of spent fuel and plutonium, treatment and disposal of low-level waste (LLW) and intermediate-level waste (ILW), and interim storage of HLW]. Table I gives central estimates of various parameters in this calculation as well as estimates that reflect best and worst cases for reprocessing. These estimates are discussed in more detail below.

The solid central line in Fig. 1 shows the breakeven uranium price using the central estimates given in Table I for other fuel cycle prices and parameters. The dotted lines labeled "Monte Carlo" show the result of a calculation in which the values of other parameters are selected randomly from independent normal distributions with 5th and 95th percentiles defined by the low and

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[a] There may be additional costs associated with storing, safeguarding, and transporting plutonium and MOX fuel, licensing MOX use in reactors, and changes in fuel management. We ignore these additional costs, an assumption favorable to the recycle approach.

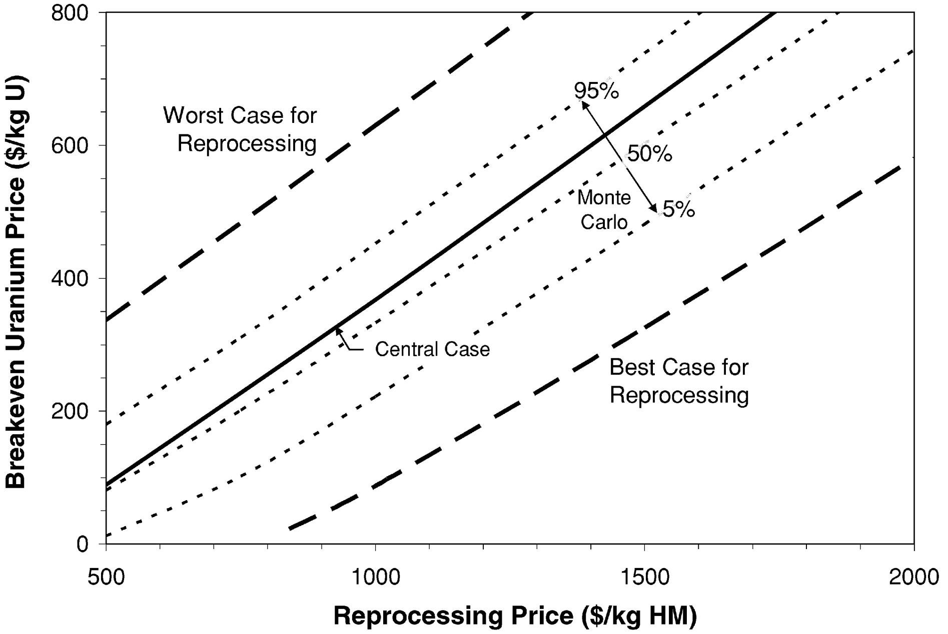

Fig. 1. Breakeven uranium price as a function of reprocessing price, for various sets of assumptions about other fuel cycle prices and parameters (see Table I).

TABLE I

Estimates of Fuel Cycle Costs and Other Parameters and Sensitivity Analysis for the Breakeven Uranium Price for Direct Disposal Versus Reprocessing and Recycling in LWRs, for a Reprocessing Price of $1000/kg HM

	Parameter Value[a]			Breakeven Uranium Price (Central = $368/kg U)		Change Compared to Central
Parameter	Low	Central	High	Low	High	
Disposal cost difference ($/kg HM)	300	200	100	298	438	±70
MOX fuel fabrication ($/kg HM)	700	1500	2300	302	434	±66
Interim fuel storage ($/kg HM)	300	200	100	310	425	±57
Enrichment ($/SWU)	150	100	50	338	404	−29 +36
Spent-fuel burnup (MWd/kg HM)	33	43	43	313	368	−54
Fresh-fuel burnup (MWd/kg HM)	53	43	43	350	368	−18
Laser enrichment	Yes	No	No	329	368	−39
Discount rate (% yr, real)	8	5	2	353	380	−15 +13
LEU fuel fabrication ($/kg HM)	350	250	150	359	376	±8
Premium for recovered uranium						
Conversion ($/kg U)	5	15	25	362	373	±5
Enrichment ($/SWU)	0	5	10	364	371	±3
Fuel fabrication ($/kg HM)	0	10	20	367	369	±1
Conversion ($/kg U)	8	6	4	367	369	±1

[a]Low = best case for reprocessing; high = worst case for reprocessing.

high values given in Table I. The outer dashed lines represent the result of setting *all* the parameters equal to those we selected as either the best or the worst case for reprocessing.

For a reprocessing price of $1000/kg heavy metal (HM), the breakeven uranium price is about $370/kg U for central estimates of the other parameters. This is roughly eight times the current uranium price and a level at which the available uranium resources would likely be sufficient to sustain a once-through fuel cycle for 100 yr or more, even with substantial growth (see below). Even the lower boundary of the Monte Carlo calculation represents a breakeven uranium price of about $220/kg U for a $1000/kg HM reprocessing price. The reason that uranium prices must increase so much to reach breakeven is that the cost of purchasing uranium is a small fraction of the overall fuel cost in the once-through fuel cycle.

Table II shows the results of breakeven calculations for selected cost parameters, holding the uranium price at $50/kg U and setting other costs equal to the central values listed in Table I. If the uranium price is $50/kg U, the reprocessing price would have to be reduced to below $420/kg HM in order for reprocessing to be cost-effective. Achieving such a low reprocessing price would be an extraordinary challenge, particularly for privately owned facilities, which must pay both taxes and higher costs of money on invested capital.

TABLE II

Breakeven Prices of Selected Parameters for Direct Disposal Versus Reprocessing and Recycling in LWRs, Assuming a Uranium Price of $50/kg U and Central Values for Other Parameters

Parameter	Central Estimate	Breakeven Value	Breakeven: Central
Disposal cost difference ($/kg HM)	200	630	3.2
Interim spent-fuel storage ($/kg HM)	200	780	3.9
Enrichment ($/SWU)	100	1200	12
Reprocessing ($/kg HM)	1000	420	0.42
Uranium ($/kg U)	50	370	7.4

Table I also gives the change in the breakeven uranium price when each of the parameters is varied from our central estimate to the worst- and best-case estimates. The parameters that have the largest impact on the breakeven uranium price are reprocessing price, difference between the disposal costs for spent fuel and HLW, MOX fuel fabrication price, and the cost of interim storage of spent fuel.

Figure 2 shows the additional electricity cost associated with reprocessing and recycling, compared to direct disposal of spent fuel, as a function of uranium price, for several reprocessing prices, with other fuel cycle cost parameters set at their central estimates. At a

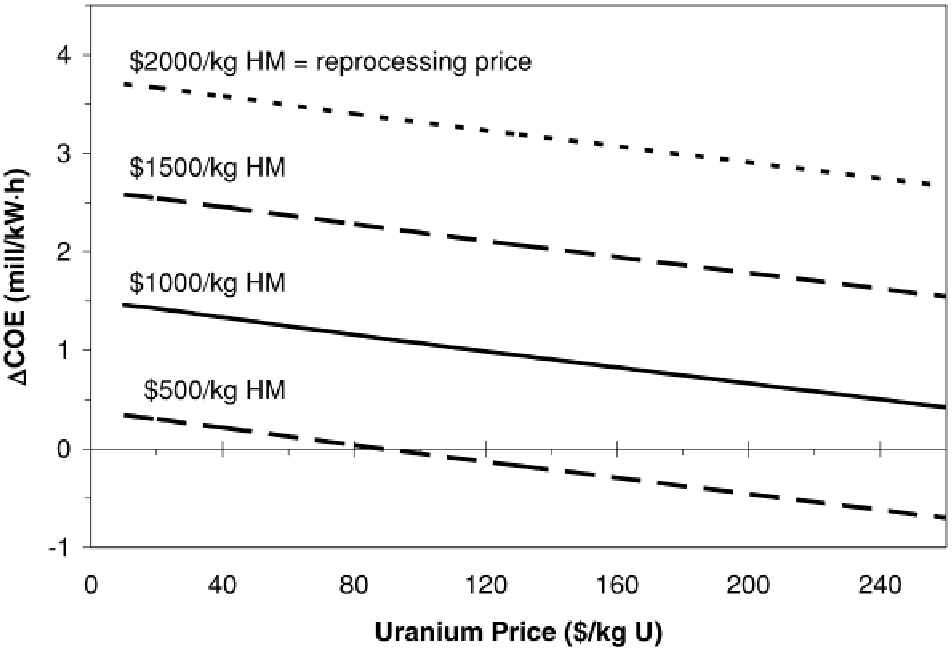

Fig. 2. The additional cost of electricity (ΔCOE, mill/kW·h) for the reprocessing-recycle option, for reprocessing prices of $500, $1000, $1500, and $2000/kg HM, compared to the cost of electricity for the direct disposal option, as a function of the price of uranium ($/kg U).

reprocessing price of \$1000/kg HM and a uranium price of \$50/kg U, reprocessing increases the cost of electricity by 1.3 mill/kW·h, or about \$10 million/yr for a typical 1-GW(electric) LWR. If the reprocessing price is \$1500/kg HM, the cost penalty would rise to ~2.4 mill/kW·h.

II.B. Reprocessing Price

Unlike markets for uranium and enrichment services, for which published prices are widely available, virtually all aspects of the economics of reprocessing are considered proprietary information. Our estimates are therefore based on the limited information that is available from the reprocessors, other studies, and press reports. Only two companies outside the former Soviet Union operate large commercial reprocessing plants today: COGEMA, now part of the Areva group, which operates the UP2 and UP3 plants in France; and British Nuclear Fuels Limited (BNFL), which operates the Thermal Oxide Reprocessing Plant (THORP) in the United Kingdom. More is known about the costs at THORP because of the extended debates that have surrounded that facility.

THORP cost some \$5.9 billion to build.[8] While there has been considerable controversy over its reprocessing capacity (arising from its frequent failure to meet targets), we will assume 800 tonnes HM/yr. BNFL has not disclosed THORP's operating costs but stated that a similar plant would cost some \$560 million/yr to operate.[2] BNFL subsequently asked for additional payments from customers to cover higher-than-expected capital and operating costs.[9] Nevertheless, to be conservative, we will rely on this early BNFL estimate.

Both THORP and the UP3 plant were built with very favorable financing arrangements—pay-ahead contracts from utility customers paid essentially the entire capital cost over a 10-yr "base-load" period. Recovering a capital cost of \$5.9 billion over 10 yr (without interest) would contribute \$740/kg HM to the reprocessing cost. Including operational costs of \$700/kg HM, start-up costs equal to 1 yr of operational costs, and refurbishment and decommissioning costs of \$100/kg HM, the total reprocessing cost is about \$1800/kg HM. Indeed, BNFL figures (adjusted for inflation) indicate that base-load contracts amounted to about \$2300/kg HM (Ref. 8), which is consistent with expected costs plus a fee of ~25%.

The cost of reprocessing at new facilities with capital and operating costs comparable to THORP would depend crucially on how they were financed. Using the financing assumptions given in Ref. 10, a government-owned facility would have a total reprocessing cost of about \$1350/kg HM; a private facility with a guaranteed rate of return like that which pertains to regulated utilities would have a cost of roughly \$2000/kg HM; and a private facility with no guaranteed rate of return would have a cost of more than \$3100/kg HM—all for the same capital and operating costs estimated for THORP.

Costs and base-load contract prices for the UP3 plant, built at roughly the same time to meet essentially the same market, have been reported to be generally similar to those for THORP, though much less detail is available. Costs for the most recent large reprocessing plant, the Rokkasho-Mura plant nearing completion in Japan, have been much higher. The capital cost of the Rokkasho-Mura plant is now expected to be roughly \$18 billion, and the operations cost is expected to be more than \$1.4 billion/yr (Ref. 11)—both about three times the THORP costs.

Post-base-load contracts for THORP and UP3 were reportedly concluded in 1989 to 1990 at prices in the range of \$1000 to \$1500/kg HM (Refs. 2, 3, 8, 12, and 13). More recently, prices offered for new reprocessing contracts have reportedly fallen to \$600 to \$900/kg HM (Ref. 13), representing the operational cost plus a small profit. These low prices are only possible because recovery of capital is no longer included and therefore do not represent sustainable prices for reprocessing services.

In short, the \$1000/kg HM reprocessing price we have used as our central estimate is quite conservative. For facilities with capital and operating costs comparable to THORP, costs in this range could only be achieved for facilities whose capital cost has already been paid off or that are government financed. If, as seems likely, financing for future plants would have to be raised on private capital markets, a price of \$1000/kg HM would require more than a 50% reduction in the capital and operating costs even for entities with a guaranteed government-regulated rate of return.

Can the cost of reprocessing be reduced substantially? The Plutonium Redox Extraction (PUREX) process used in existing facilities has been perfected over more than five decades. While refinements are possible (and ongoing), it seems unlikely that dramatic cost reductions could be achieved using this or similar technologies. Although some argue that costs could be reduced using the experience gained from existing plants, very substantial reductions would be needed just to get to our assumed \$1000/kg HM cost, even for government-financed facilities and especially for the more likely future case of privately financed facilities. Moreover, increasingly stringent environmental and safety regulations will put countervailing pressures on costs. According to a recent report to the French government, building a new plant similar to UP3 would cost \$6 billion—the same as the original plant.[14]

A wide range of alternative chemical separations processes have been proposed over the years. Recently, attention has focused on electrometallurgical processing or "pyroprocessing." A 1996 review by a committee of the National Academy of Sciences, however, concluded that the cost estimates provided in studies of the processes in the mid-1990s were "inexplicably low," that "it is by no means certain that pyroprocessing will prove more economical than aqueous processing," and that the costs of current plants such as THORP and UP3 "provide the most reliable basis for estimating the costs of future plants."[10] More recently, official reviews have concluded that such techniques are likely to be substantially more expensive than traditional aqueous reprocessing, with a nominal estimate of \$2000/kg HM (2.5 times higher than their nominal estimate of \$800/kg HM for traditional reprocessing) in two of the most recent analyses.[15,16]

In short, while future technological developments hold some promise, it does not appear likely that within the next few decades the cost of reprocessing, including payback of capital costs of facilities (likely at commercial costs of money), will be reduced to prices that would allow reprocessing to compete economically with uranium at prices likely to pertain for most of this century. Indeed, it is possible that costs could increase—as suggested by the remarkable increase in cost of Rokkasho-Mura compared to THORP and UP3—driven by the costs of meeting more stringent environmental and safety requirements.

II.C. Waste Disposal Cost Difference

The next most important parameter is the savings resulting from treatment and disposal of reprocessing wastes as compared with direct disposal of spent fuel. Permanent geologic disposal of spent fuel and HLW has not been demonstrated, and approaches to waste disposal vary considerably from country to country, making cost estimates highly uncertain.[17]

The U.S. geologic disposal program has prepared the most detailed public analyses of any program in the world. The most recent cost estimate for the U.S. repository program is \$57.5 billion (in 2000 dollars), of which \$41.8 billion is for the disposal of 83 800 tonnes HM of civilian spent fuel.[18] This is financed by charging utilities a fee of 1 mill/kW·h, which is equivalent to about \$370/kg HM at the time of discharge.[b] With interest, this fee is expected to be sufficient to fund the full costs of transport to the repository, encapsulation, and disposal of the spent fuel, including all future repository construction and operations costs.[19]

Cost estimates produced by other countries for the disposal of spent fuel are roughly comparable. Sweden, for example, released a cost estimate in 1998 of \$300 to \$350/kg HM (Ref. 20). While it remains possible that these total cost estimates will continue to grow in the future, \$400/kg HM at time of discharge is a reasonable benchmark for total disposal cost of spent fuel. Thus, our central estimate of \$200/kg HM for the cost difference implies that reprocessing would reduce waste disposal costs by 50%.

Spent fuel and HLW differ in a number of ways that could affect disposal costs. The most important characteristics are the heat, volume, and mass of the waste and the number of waste packages to be handled.

The heat output from waste packages determines how close to each other they can be placed while remaining within the repository's design temperature constraints. Thirty yr after discharge, the heat output from the vitrified HLW is ~70% of the heat output of the original spent fuel—and the heat output of the HLW declines more rapidly than that of the spent fuel thereafter.[10,17] This reduction in heat output at 30 yr may offer even greater packing efficiencies, as the spaces between HLW packages could be left empty at first, while additional canisters were emplaced for the next 60 yr, during which time another fourfold reduction in heat output would take place. New waste packages could then be put between the first canisters emplaced, while remaining within the original heat limits. Although a similar strategy could be pursued with spent fuel, it does not offer as dramatic a benefit because spent fuel cools more slowly than HLW.

Waste volume and mass affects waste package and transportation costs. The volume of vitrified HLW waste is roughly one-quarter the volume of the original spent fuel; including packaging for geologic disposal, the total volume per kilogram of original HM ranges from roughly equal to half as large for the HLW. Hence, reprocessing might reduce volume-related costs by as much as 50%.

Some costs increase with the number of items handled—fuel assemblies or HLW canisters to be loaded into waste packages, waste packages to be emplaced, and the like. A NIREX study estimated that each HLW waste package would hold two canisters of HLW, each containing HLW from the reprocessing of 1.2 tonnes HM of spent fuel.[21] Thus, there would be 0.8 HLW canisters and 0.4 waste packages/tonne HM for the reprocessing option, compared to 2.2 fuel assemblies and 0.54 waste packages/tonne HM for direct disposal, for an overall reduction in item-related costs of ~30% (Ref. 22).

We can get a rough idea for how much reprocessing might reduce waste disposal cost by dividing costs into components that are affected by various waste disposal characteristics and assigning notional reduction factors for the disposal of HLW rather than spent fuel. In the case of the U.S. Yucca Mountain repository, heat-related costs (repository construction and drip shield) amount to 19% of total program costs; those related to volume, mass, or number of items (repository emplacement operations and monitoring, waste package fabrication, and transportation) are 53%; and other costs (siting, licensing, design, and engineering) contribute 28% (Ref. 18). We assign a fourfold reduction factor for heat-related costs and costs not related to waste form (corresponding to a potential fourfold increase in the amount of fuel that could be emplaced in the repository) and a twofold reduction factor for costs related to volume, mass, or number of items.

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[b] In 2003 dollars, assuming a burnup of 43 000 MWd/tonne HM, a net efficiency of 33%, a core residence time of 4 yr, and discounting at a real rate of 0.05/yr.

The previous discussion does not include the management and disposal of ILW and LLW from reprocessing. BNFL has permission from the British government to address the cost of LLW disposal through "substitution"—adding a small amount of HLW to the amounts sent back to customers instead of returning the LLW. BNFL hopes to get similar permission for ILW, and if this were granted, the total amount of HLW returned to each customer would be ~20% higher than the amount generated by reprocessing of that customer's spent fuel.[6] If the reprocessors are required to return all ILW and LLW, costs of management of these wastes would be higher. We therefore assume that total disposal costs are 20% greater than the cost of HLW disposal alone. Applying this and the factors listed above results in an overall cost reduction of 55% due to disposal of reprocessing wastes rather than spent fuel, which corresponds well with our central estimate of $200/kg HM for the cost savings due to reprocessing. Given the large uncertainties in such estimates, we have used a range from a difference of $100 to $300/kg HM.

A 1993 Organization for Economic Cooperation and Development–Nuclear Energy Agency (NEA) study[17] compared the estimated repository costs for many countries (considering only encapsulation and disposal costs) and found that the weighted average cost was 57% less for disposal of HLW compared to spent fuel. A recent French study offers substantially lower figures for disposal costs ($80/kg HM for HLW and $130/kg HM for spent LEU fuel),[1] but the percentage reduction for reprocessing (40%) is roughly in line with our central estimate (50%). A recent review of future fuel cycle options by a group advising the DOE estimated a cost of $200/kg HM for disposal of HLW compared with $300/kg HM for spent fuel,[16] consistent with the low end of our range for the cost difference. An NEA review of transmutation technologies also provided estimates that are consistent with the low end of our range.[c]

We have assumed that spent MOX fuel is not reprocessed and that the disposal costs are equal for spent MOX and LEU fuels of equal burnup. Most countries that now recycle plutonium do so only once because of the buildup of undesirable isotopes in spent MOX fuel. The heat output of spent MOX fuel is much higher than that of spent LEU fuel—2.2 versus 0.7 W/kg HM 50 yr after discharge, for a burnup of 43 MWd/kg HM (Ref. 23). The greater heat output of spent MOX fuel should result in substantially higher disposal costs. If, for example, disposal of spent MOX fuel costs $400/kg HM more than spent LEU (twice the central value of $400/kg HM for LEU), the breakeven uranium price would increase by $26/kg U. If, on the other hand, spent MOX fuel is reprocessed and the recovered plutonium is used in a "self-generated recycle" mode, the total heat output from the HLW from that fuel cycle is higher, per unit of electricity generated, than that of the once-through cycle for the first 50 yr after discharge from the reactor,[24] negating much of the cost advantage for disposal of HLW compared to spent fuel.

II.D. MOX Fuel Fabrication Price

The principal cost in using recovered plutonium is the price of fuel fabrication. Like reprocessing, fabricating MOX fuel is expensive because it requires large, capital-intensive facilities and highly trained personnel. It is substantially more expensive than fabricating LEU fuel primarily because of the safety requirements resulting from the much higher radiotoxicity of plutonium and also because of the greater safeguards and security requirements when handling weapons-usable material. As with reprocessing, the industry is dominated by a small number of firms (COGEMA, BNFL, and Belgonucléaire), and virtually no official information on costs and prices is publicly available.

Again, because of the public controversies surrounding it, most is known about BNFL's Sellafield MOX Plant (SMP), designed for a capacity of 120 tonnes HM/yr. SMP is officially estimated to have cost $540 million[25]; when the cost of financing over the prolonged construction period and the subsequent delays in gaining approval are included, the cost increases to about $750 million.[8] Similarly, Siemens' 120 tonnes HM/yr plant at Hanau, Germany, which was built but never operated, reportedly cost roughly $750 million.[26] In 1993, the DOE estimated that the overnight cost of building a facility with a capacity of 100 tonnes HM/yr in the United States would be $440 million, or about $550 million in 2003 dollars.[27]

Current estimates for new plants in Japan and the United States are substantially higher. The overnight cost of building a MOX plant in the United States for disposition of excess weapons plutonium is currently estimated at more than $1 billion (not counting more than $300 million in research and development and precapital expenses and another $500 million for contingencies).[28] A portion of the cost of this facility will go to removing gallium and other impurities from weapons plutonium before it is fabricated into MOX fuel, but even if this represented 30% of the total, the remaining overnight cost would be $700 million. Similarly, the Rokkasho MOX Plant in Japan, with a planned capacity of 130 tonnes HM/yr, is expected to cost roughly $1 billion.

Operating costs at existing MOX plants have not been published. One group has estimated the operating costs of SMP at roughly $50 million/yr (Ref. 29). This is

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[c] The central estimates in Ref. 15 were $400 000/m^3 for HLW conditioning and disposal and $210 000/m^3 for spent fuel. Converting these to tons of original spent fuel using a relatively low estimate of 0.8 m^3/tonne HM for HLW and a relatively high estimate of 2 m^3/tonne HM for spent fuel, we have $320/kg HM for HLW and $420/kg HM, or a disposal cost difference of $100/kg HM.

consistent with an analysis that concluded that operations costs in a facility of this kind would amount to \$560/kg HM (Ref. 30); with the low end of an NEA estimate that the operating costs of such facilities are in the range of 10 to 25% of their capital costs[15]; and with annual operating costs (including an annuity for decommissioning) of \$76 million/yr estimated in the 1993 DOE study.[27] The operating costs for the planned U.S. MOX plant are expected to be in the range of \$100 million/yr (Ref. 28), which would be consistent with the earlier DOE estimate if 30% of the operating cost goes to purification of weapons plutonium.

If a plant with the reported capital cost of SMP and a \$560/kg HM operating cost succeeded in producing 100 tonnes HM/yr throughout a 30-yr life, the fabrication cost (with assumptions similar to those above for reprocessing plants) for a government-financed facility would be about \$1000/kg HM; for a regulated private facility with a guaranteed rate of return, \$1500/kg HM; and for a private facility with no guaranteed rate of return, \$2100/kg HM. Transport of MOX fuel is a significant extra cost that must be added to these figures.[30]

These costs apply for large fabrication campaigns of fuel of the same design. When a customer needs only a modest amount of MOX fuel, using different design parameters from those used by other customers, throughput suffers and per-kilogram costs increase substantially. Per-kilogram costs also increase if demand is not sufficient to keep the plant fully booked.

MOX fabrication prices, like costs, are not publicly divulged. For essentially all of the 1980s and 1990s, demand was higher than supply and prices were higher than one would expect based on the costs given above. One review indicates that in the 1980s prices were \$1900 to \$2400/kg HM, while in the 1990s they were \$2100 to \$2700/kg HM (Ref. 13). A DOE survey of fabricators in 1993 reported a range of offers centering on \$1850/kg HM (Ref. 27). Eléctricité de France enjoys lower prices of about \$1200/kg HM, as it buys very large quantities of a standard product and has a special relationship with COGEMA and its MELOX plant.[1,31] German and Swiss utilities, on the other hand, report much higher prices, in the range of \$3000 to \$4000/kg HM, which reflect their smaller purchases and the fact that much of their fuel has been fabricated in smaller, less automated plants.[3,32] With SMP now open and the supply of MOX fabrication services likely outstripping demand, prices may fall significantly—although MOX fabrication firms will still have substantial leverage to demand high prices because the only alternative for utilities with separated plutonium is to pay for plutonium storage at rates determined by the same firms.

MOX fuel fabrication is less mature than PUREX reprocessing, leaving more room for further technical improvement and cost reduction in the future. As one recent review put it, "new plants would benefit greatly from the extensive experience gained during the last decades, thereby allowing them to simplify the plants, decrease their size, and reduce maintenance requirements."[15] If, however, the focus remains on pellet-based fuels, manufacturing each pellet to stringent standards will continue to be an expensive process, and there may be limits to the scope for cost reductions. Modern MOX fabrication facilities are already highly automated and designed to minimize maintenance. Moreover, as with reprocessing, there may be trends that would increase per-kilogram costs over time—including not only increasing demands for more stringent safety and security precautions (a substantial factor driving the cost of the planned U.S. MOX plant), but also customer demands to fabricate fuels with higher design burnup, using plutonium recovered from higher-burnup spent fuel or plutonium that has been stored for long periods and therefore has higher americium content.

There may also be opportunities for new technologies that could simplify plutonium fuel fabrication and reduce cost, such as "vibropak" fuels, in which the plutonium and uranium powders are packed into the fuel pins by vibration, with no pellet manufacturing required. Further development is required to determine whether such approaches can offer substantial MOX fuel cost reductions and whether they can be used in existing LWRs or only in reactors designed for their use.

Overall, our central estimate of \$1500/kg HM is low with respect to recent prices but reasonable for a future world in which supply and demand is balanced and prices more closely reflect production costs. Our \$700/kg HM lower bound would require either very substantial technological innovation or sales from facilities whose capital costs are already amortized and which therefore do not reflect a long-run sustainable cost for providing the service. The \$2300/kg HM upper bound is in the range of prices already charged at existing facilities and could reflect future prices if societal and customer demands drive costs higher in the future.

In many cases, there are additional costs to a reactor operator associated with using MOX rather than LEU fuel, which, to be conservative, we have not included in this analysis. First, MOX fuel is often licensed to lower burnups than LEU fuel, which would require reactor operators to shut down for refueling more often. Second, because fresh MOX fuel contains weapons-usable plutonium, it requires more security than would fresh LEU fuel, often imposing additional costs. (In some cases fresh MOX fuel is simply placed with spent fuel at the reactor site, without any additional facilities or security arrangements, on the assumption that it would be difficult and dangerous for attackers to remove it from the pool.) Third, in a number of countries there are substantial political concerns over the use of MOX and additional licensing requirements for reactors wishing to use both MOX and LEU fuels. Hence, the value of MOX fuel (if there were an open market allowing utilities to choose their fuels) would not be equal to that of LEU fuel of equal design burnup, as is assumed here. In the case of the U.S. program for disposition of excess weapons plutonium, for example, persuading U.S. utilities to use MOX fuel required offering it at a price some 40% below the price of LEU fuel of equivalent energy value[33]—equivalent to increasing the net fabrication price for the MOX fuel by several hundred dollars per kilogram. Fourth, we have assumed a reprocessing and recycling system that is operating efficiently and in balance, so that there are no charges for storing plutonium or for removing americium. Commercial rates for these services are estimated at $1000 to $2000/kg·yr for storage and $10 000 to $28 000/kg for americium removal.[15] Including several years of plutonium storage and one round of americium removal would increase the effective cost of MOX fabrication by $1000 to $3000/kg HM and would increase the breakeven uranium price by $80 to $250/kg U.

II.E. Cost of Interim Spent-Fuel Storage

For reactor operators who choose reprocessing, interim storage of spent fuel for decades is not required. Interim storage generally is required for direct disposal, however, as repositories are not expected to be available for several decades. We have therefore included interim storage as an extra cost for the direct disposal fuel cycle, although new reactors are being built with pools able to accommodate storage of all the fuel they will generate in their lifetime, reducing or eliminating this extra storage cost. Costs of interim storage can vary significantly depending on the technology chosen, whether fuel is to be transported to a centralized site or kept at reactor sites (and, if at a reactor site, whether the reactor is operating), whether taxes or other payments must be made to local, regional, or national governments, and the like.

Dry-cask storage is a well-established technology for storing spent fuel for decades with minimal operating costs. In the United States, total up-front costs to establish a new dry storage facility at a reactor site (which are largely fixed regardless of the amount of spent fuel to be stored) are estimated at roughly $10 million.[34,35] Costs to purchase and load the casks—including labor, consumables, and decommissioning—are estimated at $70 to $90/kg HM (Ref. 34). The principal operating costs are providing the security and safety monitoring needed to maintain the Nuclear Regulatory Commission license for the facility. For storage sites colocated with operating reactors, many of these costs can be charged to the reactor operation, and the net additional operating costs are estimated to be about $800 000 yr (largely independent of the amount of spent fuel to be stored).[34] Total costs for 40 yr of dry-cask storage of 1000 tonnes HM at an operating reactor site in the United States would be in the range of $100 to $120/kg HM (with operational costs discounted at 3%/yr).

For storage at shutdown reactors or independent sites, the costs of maintaining the license, including security and safety personnel, must be attributed entirely to the storage facility, making its operational cost substantially higher. For shutdown reactors with all their spent fuel in dry storage, operating costs are estimated to be $3.3 to $4.4 million/yr (Refs. 34 and 35). Total cost for 40 yr of storage in this case would range from $150 to $200/kg HM. A large centralized facility could spread these operations costs over a larger amount of spent fuel, but there would be additional up-front costs for transportation to the centralized site.

Somewhat higher costs have been estimated in Japan; in a 1998 study, total discounted costs for 40 yr of storage in a 5000-tonne centralized dry-cask facility were estimated at $280/kg HM (Ref. 36). These costs do not include benefits that may be paid to the local community to build public acceptance and gain government approval, which could in some cases be substantial.

We have chosen $200/kg HM as our central estimate of interim-storage costs, which is comparable to the discounted cost of independent dry-cask storage in the United States at small facilities. The lower estimate of $100/kg HM is close to the current cost of at-reactor dry-cask storage in the United States, while the upper limit of $300/kg HM may represent the cost at independent facilities, including payments to nearby communities.

II.F. Other Fuel Cycle Prices and Parameters

Other factors—enrichment and LEU fuel fabrication prices, premiums for the use of recovered uranium, fuel burnup, and discount rate—are less important when comparing the economics of direct disposal versus reprocessing and recycling in thermal reactors.

Long-term contract prices for enrichment services fell from earlier levels of more than $100/separative work unit (SWU) (in then-year dollars) to $85/SWU by late 1999, only to increase back to some $110/SWU in 2001 (Ref. 37). The gap between long-term and spot SWU prices has declined substantially; in the first half of 2004, the spot price in the United States was about $110/SWU (Ref. 38). One projection in mid-2003 suggested that SWU prices in long-term contracts would likely remain in the range of $105/SWU for a few years and then rise slightly toward the end of the decade.[39] Production costs of gas-centrifuge enrichment are below $80/SWU and can be expected to decrease as the next generation of centrifuges is installed.[13] The NEA has estimated that enrichment prices in the short to medium term will be in the range of $80 to $120/SWU; over the longer term, the NEA reports that new facilities using advanced processes might reduce costs to $50/SWU (Ref. 40). We have chosen a central estimate of $100/SWU, with a high of $150/SWU and a low of $50/SWU, allowing a somewhat broader range of possibilities.

The NEA projects LEU fabrication prices in the short to medium term at \$200 to \$300/kg HM (Ref. 40). A previous survey by a National Academy of Sciences committee chose a central estimate of \$250/kg HM (Ref. 27). This central estimate is somewhat higher than recent prices in the U.S. market but somewhat lower than most prices in the European market.[41] We have chosen a central estimate of \$250/kg HM, with a low of \$150/kg HM and a high of \$350/kg HM, again allowing a somewhat broader range of possibilities than the NEA projections. The technology of LEU fuel fabrication is mature and the safety and health impacts modest, so it appears unlikely that this price will change substantially in the future.

Uranium recovered from reprocessing contains undesirable isotopes such as ^{232}U (whose radioactive daughter products emit penetrating gamma rays) and ^{236}U (which is a neutron absorber, increasing the enrichment required to achieve a given design burnup). Because of the higher radioactivity of recovered uranium, firms charge higher prices for its conversion, enrichment, and fabrication. If natural uranium is cheap, recovered uranium has no value at all. Indeed, most utilities have not bothered to recycle recovered uranium, and the vast majority of all the uranium recovered from the reprocessing of LWR fuel remains in storage. Market estimates of the relevant premiums are therefore somewhat uncertain.[13] We have chosen central estimates of \$15/kg U for conversion, \$5 for enrichment, and \$10 for fuel fabrication.[15] Recovered uranium would become more valuable if laser isotope enrichment is commercialized because laser enrichment would remove the undesirable isotopes.

Conversion of uranium from U_3O_8 to UF_6 for enrichment is a minor cost element. We have chosen a central estimate of \$6/kg U, with a range of \$4 to \$8/kg U. The NEA projects conversion prices in the short to medium term in the range of \$3 to \$8/kg U, nearly identical to our range.[40]

Recycle becomes less attractive economically as the burnup of the reprocessed spent fuel increases because the isotopic quality of the recovered plutonium and uranium declines.[42] On the other hand, increased design burnup of the fresh fuel makes recycle more attractive because the additional enrichment required makes LEU relatively more expensive.[27] We have taken, as our best case for reprocessing, the fabrication of MOX with a design burnup of 53 MWd/kg HM using plutonium recovered from spent fuel with a burnup of 33 MWd/kg HM. Our central and worst-case estimates have spent- and fresh-fuel burnups of 43 MWd/kg HM.

All fuel cycle services are discounted to the time of fuel discharge. We use a central value of 0.05/yr for the real discount rate, which is roughly the debt rate available to a regulated utility with a guaranteed rate of return. We adopt a range of 0.02 to 0.08/yr, which has a modest effect on our calculations. The geologic disposal cost difference is the net present value at the time of fuel discharge.

III. DIRECT DISPOSAL IN LWRs VERSUS RECYCLE IN FRs

From the dawn of the nuclear age, the nuclear industry believed that uranium was relatively scarce and that the number of reactors would grow rapidly, leading to rapidly rising uranium prices. Hence, the industry projected that there would be a rapid transition from LWRs, which rely heavily on fissioning the rare ^{235}U isotope, to FRs, which more efficiently transform ^{238}U into plutonium that is either fissioned in place or recycled via fuel reprocessing. The recycling of plutonium in LWRs was seen only as a temporary expedient until the transition to primary reliance on FRs began.

The transition to FRs has taken much longer than once expected. Uranium has turned out to be abundant and cheap, nuclear energy has grown much more slowly than expected, and FRs have been more expensive and problematic than anticipated. As a result, only Russia, India, and Japan still have near-term plans for commercializing FRs. Russia is the only country that operates a commercial-scale FR (the BN-600); construction of a slightly larger plant, the BN-800, has recently resumed after having been largely on hold since the 1980s. The United States, France, Britain, Germany, and other countries have terminated FR commercialization efforts, though in a number of countries longer-term research and development continues. More recently, as part of efforts to develop advanced systems for a possible future resurgence of nuclear energy, FRs have again received increased attention as a long-term option.[43]

III.A. Breakeven Prices and Difference in Cost of Electricity

At what uranium price would recycling in FRs become economical? To answer this question we must account not only for differences in fuel cycle costs but also for the fact that the capital costs of FRs and LWRs may be different. (We have assumed for the sake of simplicity that the nonfuel operations and maintenance costs of LWRs and FRs would be the same; this is a generous assumption, as studies have suggested that FRs would have higher nonfuel operations and maintenance costs.[44,45]) The estimated capital costs of sodium-cooled FRs have typically been up to 50% higher than those of LWRs. As with reprocessing and MOX fuel fabrication plants, we explore three different financing arrangements for this additional capital cost, appropriate for facilities owned by a government, by a regulated utility, and by an unregulated electricity producer.

Figure 3 gives the breakeven uranium price as a function of the difference in capital cost between LWRs and

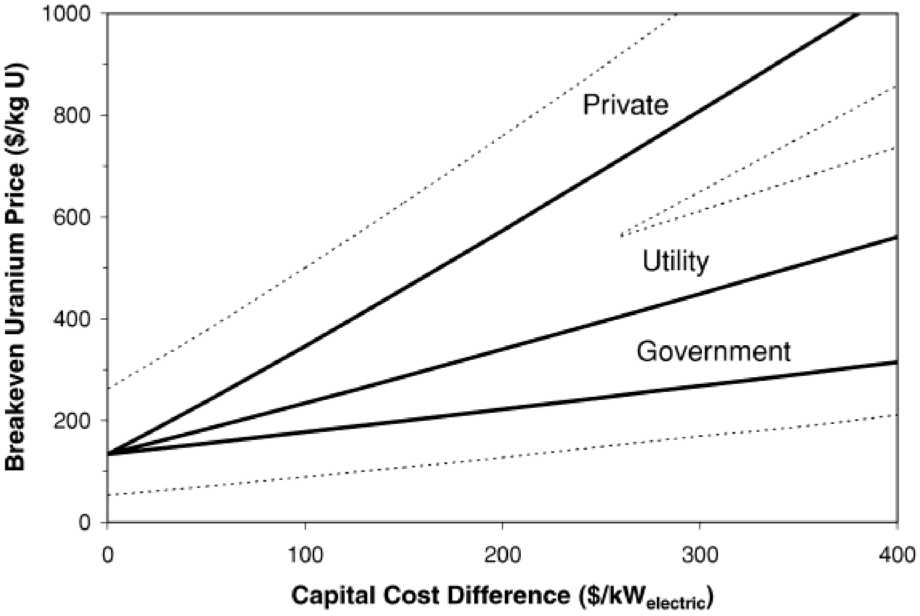

Fig. 3. Breakeven uranium price for LWR with direct disposal and FR, as a function of capital cost difference, for reactors financed by government, a regulated utility, and a private electricity producer, for central values of other parameters (see Table IV).

FRs for the three financing arrangements. The characteristics of the generic FR are given in Table III. Table IV gives our central, low, and high estimates for the various cost parameters used to produce these graphs, along with the sensitivity of the outcome to changes in each parameter. The dotted lines in Fig. 3 represent the results of a Monte Carlo calculation in which these parameters are selected randomly from independent normal distributions with the 5th and 95th percentiles defined by the low and high values given in Table IV.

TABLE III

Characteristics of the Generic FR*

Parameter	Low	Central	High
Breeding ratio	1.0	1.12	1.25
Annual blanket loading (kg HM/MW(electric)·yr)	19.0	25.5	31.9
Annual core loading (kg HM/MW(electric)·yr)		11.5	
Residence time of core elements (yr)		3.0	
Residence time of blanket elements (yr)		3.2	
Plutonium fraction in core		0.246	
Makeup fraction in blanket		0.024	
Efficiency (net MW(electric)/MW(thermal))		0.38	

*Reference 16.

We have chosen the reactor owned by a regulated utility with a guaranteed rate of return as the reference case for the sensitivity analysis in Table IV. This may be a generous assumption given the global trend toward increased reliance on privatized power plants operating in competitive electricity markets. While there remain some major countries where power plants are built and operated by a government-owned monopoly, this is not likely to be the case in most countries that will have to consider the choice between once-through LWRs and FRs with recycling.

As shown in Fig. 3 and Table IV for the case of a utility-owned reactor, if the capital cost of FRs is $200/kW(electric) greater than that of LWRs and other parameters are held at their central values, FRs with recycling would not be economic unless the price of uranium rose to more than $340/kg U—similar to our central estimate of the breakeven price for recycle in LWRs. Differences in capital cost between FRs and LWRs are less important for government-owned facilities and more important for a private venture; for a capital cost difference of $200/kW(electric), the breakeven uranium price ranges from $220/kg U for the former to $570/kg U for the latter. Even if the capital cost of FRs is equal to that of LWRs (in which case the type of financing is irrelevant to the comparison), the breakeven uranium price under the same assumptions is $130/kg U—a price that is unlikely to be seen for decades.

One assumption we have made in these calculations should be noted. Because there are currently hundreds of

TABLE IV

Estimates of Fuel Cycle Costs and Other Parameters and Sensitivity Analysis for the Breakeven Uranium Price for Direct Disposal in LWRs Versus Reprocessing and Recycling in FRs, for Reactors Owned by a Regulated Utility

Parameter	Parameter Value			Breakeven Uranium Price (Central = $340/kg U)		Change Compared to Central
	Low	Central	High	Low	High	
Capital cost difference [$/kW(electric)]	0	200	400	134	560	−205 +221
Reactor owner	Government	Utility	Private	222	574	−118 +234
Reprocessing cost ($/kg HM)	500	1000	2000	255	516	−85 +176
Enrichment ($/SWU)	150	100	50	282	415	−58 +75
FR core fabrication ($/kg HM)	700	1500	2300	286	394	±54
FR breeding ratio	1.0	1.12	1.25	294	386	±46
Geological disposal cost difference ($/kg HM)	300	200	100	322	358	±18
LEU burnup (MWd/kg HM)	43	53	53	322	340	−17
Construction time (yr)	3	6	9	326	355	±15
FR blanket fabrication ($/kg HM)	150	250	350	325	355	±15
LEU fuel fabrication ($/kg HM)	350	250	150	327	353	±13
Capacity factor (%)	90	85	80	328	353	±13
Preoperating, contingency costs (%)	5	10	15	330	350	±10
Interim spent-fuel storage ($/kg HM)	300	200	100	332	348	±8
Conversion ($/kg U)	8	6	4	338	342	±2
DU ($/kg)	6	6	Uranium price	340	341	+1

tons of separated plutonium in storage, we have assigned zero cost to the plutonium needed for the initial FR core. Past analyses have assumed that the cost of reprocessing LWR fuel to recover plutonium for the initial core would be charged to the cost of the FR, with the cost capitalized over the life of the reactor.[46,47] This assumption may be more accurate because if FRs are deployed in numbers large enough to make a substantial contribution to world electricity demand, existing stockpiles of separated plutonium will not be sufficient to start them up, and reprocessing of spent LWR fuel to provide the necessary plutonium would be needed. If the cost of reprocessing LWR fuel was $1000/kg HM and each kilogram of LWR fuel provided ~10 g of plutonium, the cost of start-up plutonium would be $100 000/kg; accounting for savings in interim spent-fuel storage and waste disposal costs ($200/kg HM each) and the value of the recovered uranium (of order $300/kg U by the time FRs might be competitive), the net cost would be on the order of $30 000/kg. In that case, the plutonium for the start-up fuel (the initial core plus one-third core for the first refueling) would add $340/kW(electric) to the cost of the FR. [Highly enriched uranium (HEU) could be used for the initial core, but the cost would be even higher.[d]] The cost of the start-up plutonium could be offset somewhat by the sale of excess plutonium generated during the operation of the reactor; this would reduce the net plutonium cost to about $200/kW(electric).[e] Thus, even if other FR capital costs are reduced to those of LWRs, the uranium breakeven price would still be at our central

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[d] The start-up core and initial reload would require 46 kg/MW(electric) of HEU with an enrichment of ~25% ^{235}U. Assuming uranium, conversion, and enrichment prices of $50/kg U, $6/kg U, and $100/SWU, respectively, the cost would be $8300/kg of HEU, equivalent to $380/kW(electric). Using the breakeven price of uranium in our reference case ($340/kg U) would increase these costs to $22 000/kg and $1000/kW(electric).

[e] With a breeding ratio of 1.25 the FR produces surplus plutonium at a rate of 0.3 kg/MW(electric)·yr; assuming a value of $30 000/kg and a discount rate of 0.05/yr over 30 yr, and taking into account the plutonium recovered from the final core, the net present value at start-up of the surplus plutonium is $130/kW(electric).

TABLE V

Breakeven Prices of Selected Parameters for Direct Disposal in LWRs Versus Reprocessing and Recycling in FRs, Assuming a Regulated Utility Owner, a Uranium Price of $50/kg U, and Central Values for Other Parameters

Parameter	Central Estimate	Breakeven Value	Breakeven: Central
Capital cost difference [$/kW(electric)]	200	−95	
Disposal cost difference ($/kg HM)	200	3400	17
Interim spent-fuel storage ($/kg HM)	200	4100	21
Enrichment ($/SWU)	100	570	5.7
Reprocessing ($/kg HM)	1000	<0	
Uranium ($/kg U)	50	340	6.8

estimate of about $340/kg U for our central values of other parameters.

Table V gives breakeven values of several other price parameters for the case of a regulated utility owner assuming a uranium price of $50/kg U and central values for other parameters. Note that reductions in the price of reprocessing alone cannot make FRs economic so long as the FRs remain $200/kW(electric) more expensive than LWRs.

Figure 4 shows the difference between the cost of electricity from FRs with recycling and LWRs operating on a once-through cycle, as a function of the price of uranium, for differences in capital cost ranging from $0 to $400/kW(electric), assuming utility-owned reactors and other parameters set at their central values. The electricity price for FRs will remain significantly higher than that for LWRs operating on a once-through cycle until the uranium price increases to at least several times its current level—a development that is not likely to occur for many decades to come.

This overall finding is broadly consistent with other recent studies. An NEA assessment found that the cost of electricity from FRs with recycle of plutonium and minor actinides would be 50% higher than from LWRs operating on a once-through cycle.[15] The Generation IV Fuel Cycle Crosscut Group examined the fuel cycle contribution to electricity costs for different types of nuclear energy mixes throughout the 21st century, during which time they projected uranium prices to increase dramatically. Despite those projected increases (and despite looking only at fuel cycle costs and therefore not including any increased capital cost of FRs), the costs for all the mixes that included FRs remained higher throughout the century than the price for electricity from once-through LWRs (Ref. 16). Similarly, a mid-1990s study by a committee of the National Academy of Sciences concluded that the electricity cost of FRs would be substantially higher than that of once-through LWRs until uranium reached a price of well over $250/kg U (in 1992 dollars),

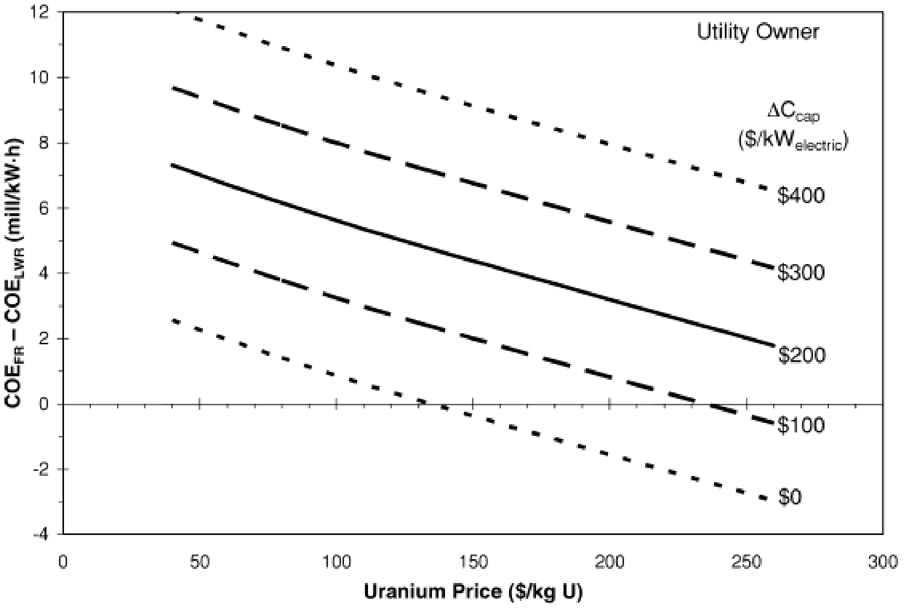

Fig. 4. The difference in the cost of electricity between an FR with recycling and an LWR with direct disposal as a function of the price of uranium, for differences in the initial capital cost of $0, $100, $200, $300, and $400/kW(electric), assuming utility ownership.

even if reprocessing costs for LWR fuel and FR fuel were at the lower bounds given here.[10]

III.B. Capital Cost Difference and Related Factors

The most sensitive parameters in this analysis are the difference in capital cost between FRs and LWRs and the financing arrangements for capital costs. We have assumed a central value of $200/kW(electric) for the difference in capital cost, with a range of $0 to $400/kw(electric). This range reflects past experience and peer-reviewed estimates for the additional capital cost of FRs and the expectation that there would be further progress in bringing FR costs down.

The most recent FR designs in the United States and Western Europe were expected to be significantly more expensive than LWRs. The capital cost of the U.S. Advanced Liquid Metal Reactor (ALMR) was estimated in the mid-1990s, shortly before the program's termination, to be 20 to 30% higher than that of advanced LWRs (a difference of $500 to $740/kW(electric) in 2003 dollars).[27] Similarly, the European Fast Reactor (EFR), after major reductions in various elements of capital cost compared to earlier designs, was expected to have a capital cost in series production 20 to 30% higher than that of a comparable LWR (Refs. 45 and 48). Russia's minister of atomic energy recently acknowledged that "life has proved that a VVER-1000 reactor [a modern Russian LWR] is one-and-a-half times cheaper than a BN [fast neutron] reactor . . . [LWRs] are cheaper, safer, and economically more viable."[49]

Some FR designers argue, however, that recent developments would make it possible to build FRs at a cost no higher than that of LWRs (Ref. 50), and the Japanese FR program, among others, has set capital cost equality with LWRs as an explicit goal.[51,52] New FR concepts, such as lead-cooled and gas-cooled systems, are hoped by their advocates to have lower capital costs than traditional sodium-cooled FRs (Ref. 43). The economic features of these concepts remain undemonstrated, however, and new thermal reactors are hoped by *their* advocates to have significantly lower capital costs than traditional LWRs.

Recent estimates of the cost of LWRs cover a broad range. Those based on actual experience tend to be more than $2000/kW(electric) (Ref. 53). Estimates for future construction from independent assessments are in the range of $1500 to $2000/kW(electric) (Refs. 15 and 54), while reactor vendors project overnight capital costs of $1000 to $1500/kW(electric) (Ref. 55). If the LWRs that would compete with future FRs had a capital cost of $1500/kW(electric), a capital cost difference of $0 to $400/kW(electric) would correspond to a 0 to 27% premium for FRs—the high end comparable to that estimated in the most recently designed commercial systems and the low end representing success in efforts to equalize capital costs. Our range is substantially more generous to FRs than that adopted in the most recent NEA assessment, whose nominal estimate for future FRs was $400/kW(electric) higher than future LWRs, with a range of $150 to $900/kW(electric) higher.[15]

As noted earlier, we used three different sets of assumptions about the financing for capital costs, corresponding to facilities owned by government, a regulated utility, and a private venture. Our financing assumptions are identical to those in Ref. 10 and result in fixed charge rates of 0.058, 0.123, and 0.208/yr, respectively. Construction time (which is assumed to be the same for both types of reactor) enters into the calculation due to the interest paid on capital during construction; we use a central value of 6 yr with a range of 3 to 9 yr and real average costs of money of 0.04, 0.064, and 0.139/yr for government, utility, and private venture, respectively. Finally, preoperating costs and contingency funds are usually proportional to capital cost; we have assumed central values equal to 10% of overnight capital cost for both preoperating costs and contingency funds, for both types of reactors, with a range of 5 to 15%.

III.C. Reprocessing and Fuel Fabrication Prices

The breakeven uranium price is also sensitive to the reprocessing price for FR fuel. For simplicity, we have chosen a central estimate for both the core and blanket fuel of $1000/kg HM, with a range of $500 to $2000/kg HM—the same as for reprocessing LWR fuel. This is a generous assumption, as reprocessing costs for higher-burnup FR fuels with much higher plutonium content generally will be significantly higher. The recent NEA review, for example, posited a range of $1000 to $2000 to $2500/kg HM for core fuel and $900 to $1500 to $2500/kg HM for blanket fuel reprocessing (low-central-high values).[15] The $500/kg HM lower bound of our range is intended to cover the possibility of substantial technological advance in the future. Our high value of $2000/kg HM is by no means an upper bound on the price of FR reprocessing, but if reprocessing turns out to be more expensive, then there is little hope that uranium will reach the corresponding breakeven price in the foreseeable future.

We have assumed a central estimate for FR core fuel fabrication price of $1500/kg HM, with a range of $700 to $2300/kg HM. As with reprocessing, this is the same as for MOX fuel fabrication price in the LWR recycling case. This also is generous because FR core fuel will have much higher plutonium content and design burnup, which generally implies a higher fabrication cost. This price range is approximately equal to that employed in the recent NEA analysis for FRs using MOX fuels.[15] For metal fuels, where the NEA study assumed minor actinides would also be recycled with the plutonium, they envisioned that core fuel fabrication would be more expensive (because of the extra cost of handling the more radioactive minor actinides), with a range of $1400 to $2600 to $5000/kg HM.

We assume that the price of blanket fuel fabrication is about the same as the price of LEU fuel fabrication for LWRs—a central value of $250/kg HM, with a range of $150 to $350/kg HM. This range appears again to be generous to the FR, as it is a factor of 2 lower than that used in the recent NEA assessment.[15]

Future FR systems, such as some of those envisioned in the Generation IV initiative, might involve substantially different fueling approaches, such as liquid fuels that would not require fabrication. Such approaches could have lower costs, but an accurate assessment will have to await further development of these technologies.

III.D. Other Prices and Parameters

We assume a central value of $200/kg HM for the difference between the disposal cost for spent LWR fuel and for HLW resulting from the reprocessing of FR fuel, with a range of $100 to $300/kg HM. This is the same range used in Sec. II.C, which again is generous to FRs, as one would expect that HLW from higher-burnup FR core fuel would have higher activity and volume, increasing disposal costs. (This factor is compensated for, however, by the fact that we have chosen the same cost of disposal for wastes from reprocessing the blanket fuel, which will have low burnup, and the core fuel, which will have high burnup.)

We assume a nominal FR breeding ratio of 1.125, with a range of 1.0 to 1.25. Electricity price increases with breeding ratio in our model because more blanket material must be reprocessed each year. This result is an artifact of assigning a zero cost to the initial core fuel—and to excess plutonium produced by FRs. If start-up fuel was assigned a substantial value, then higher breeding ratios could be more economical (but, as explained earlier, FRs would be less competitive with once-through LWRs).

After the initial core and first reload, FRs would only require depleted uranium (DU) to replace uranium that fissioned, was transformed into plutonium, or was lost in processing. Many thousands of tons of DU already exist in the stored waste from uranium enrichment plants. As long as uranium demand is driven by LWRs, there will be little use for this DU, and its price will be low. We therefore assume a central DU price of $6/kg U—the price of converting the material from uranium hexafluoride. However, once uranium prices increase to the point that FRs become competitive, those holding stocks of DU may begin to assign a significant value to it. When demand for uranium begins to be dominated by FRs and stocks of DU begin to be drawn down, the price of DU should approach the price of natural uranium because DU and natural uranium are almost perfect substitutes for use in breeder blankets. Even with such a high upper bound, DU price has virtually no effect on the economics of FRs.

IV. URANIUM PRICES AND RESOURCES

In the previous analysis we have calculated the breakeven uranium price—the price that would make reprocessing and recycling in LWRs or FRs economically competitive with LWRs operating on a once-through fuel cycle. In this section we review past and estimated future uranium prices, estimates of the amount of uranium that is ultimately recoverable at a given price, and scenarios of uranium consumption during the next century. We conclude that the uranium price will probably remain below the breakeven prices calculated in our previous reference cases for the next 100 yr and that reprocessing and recycling in both LWRs and FRs will remain uneconomic for the foreseeable future, barring dramatic reductions in the price of reprocessing and the fabrication of plutonium fuels, and, in the case of FRs, capital cost.

Figure 5 shows selected uranium prices during the last 30 yr. The real price paid by U.S. reactor operators (the weighted average of deliveries under long- and short-term contracts) fell from a high of $190/kg U in 1982 to about $28/kg U in 2002 (in 2003 dollars)[56]; prices in Europe were somewhat higher.[57] The spot market price for uranium has been considerably more volatile, falling from a high of $300/kg U in 1977 to a low of $20/kg U in 2000; the spot price of $44/kg U in March 2004 was the highest in 15 yr and appeared still to be headed upward.[38]

The nuclear enthusiasm of the 1960s and 1970s, together with the rapid growth in electricity demand that was expected at that time, led utilities to order large numbers of reactors; expectations of a correspondingly rapid increase in uranium consumption led to the large price spike in the late 1970s. But the lower growth of electricity demand following the oil price shocks of the 1970s, coupled with the increase in nuclear costs and controversies following the Three Mile Island accident in 1979, led to the cancellation of most of these reactor orders, greatly reducing projected uranium demand and bringing the price back down. During much of the 1990s, world uranium production was well below world consumption, as governments and utilities reduced their inventories (because of their increased confidence in the availability of uranium when they needed it); this additional supply from inventory sales (including the U.S.-Russian HEU Purchase Agreement) reduced prices to a level below that necessary for production to equal consumption. In the last few years, however, there have been concerns about when these inventory supplies would run out and whether mine production could increase quickly enough to meet demand. As a result, uranium price has gone up significantly. Given the availability of large quantities of uranium recoverable (once the relevant mines are brought online) at prices in the range of $40 to $50/kg U, it appears unlikely that the price would rise above that level for any sustained period over the next few decades (though temporary fluctuations during periods

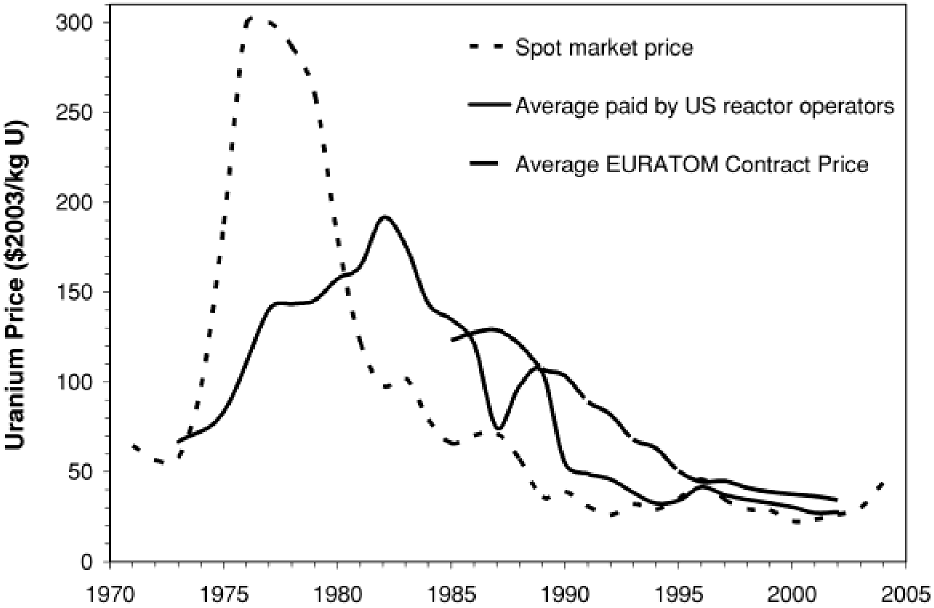

Fig. 5. Uranium prices from 1971 to 2004 (Refs. 38, 56, and 57).

when new mines have not yet come online to meet increased demand are likely).

Longer-term price predictions are notoriously difficult. Classical economic theory suggests that the price of nonrenewable resources should rise steadily over time, as the fixed available stock grows scarcer and more costly resources have to be used. But this model fails to take into account the ongoing discovery of additional resources and the development of improved technologies for identifying and extracting resources.[58] The amount of a mineral that can be recovered at a given cost of extraction can increase if technological improvements and discoveries of additional resources outpace the depletion of known deposits. This has, in fact, been the pattern throughout the last century for most minerals: Real prices have fallen even while rates of consumption have increased. The history of copper production is illustrative: As a result of improved technology, the real price declined by a factor of 3.8 from 1900 to 2000 despite a 25-fold increase in demand[59] and a decline in the average ore grade from 2 to 0.85% (Ref. 60). There is little reason to expect that uranium prices, which have been following a similar trend, will reverse course and begin increasing steadily until far more of the available resource has been consumed than will be the case in the next few decades.

The most commonly cited estimates of uranium resources are those in the "Red Book."[61] The 2001 Red Book estimates that total world "conventional" resources available at less than $130/kg U amount to 16.2 million tonnes U (the sum of "reasonably assured resources," "estimated additional resources," and "speculative resources"). If already-mined inventories are included, the total rises to 17.1 million tonnes U (Ref. 62). An international meeting sponsored by the International Atomic Energy Agency in 2000 concluded that total resources available in this category likely amount to 20 million tonnes U (Ref. 63).

Several points should be made about the Red Book estimates. First, many countries do not report resources in the lower-confidence and higher-cost categories. For example, Australia, which has some of the world's largest uranium resources, does not bother to estimate "speculative" resources because its better-characterized resources are so large already.

Second, this estimate is limited to "conventional" resources—that is, deposits where the uranium ore is rich enough to justify mining at the indicated price. In some cases, however, it may be attractive to produce uranium as a by-product. For example, ores with uranium concentrations as low as 4.5 ppm—less than twice the average abundance in the Earth's crust—have been recovered as by-products from copper mines, at costs of less than $50/ kg U (Ref. 64). An additional 22 million tonnes U are estimated to be available in phosphate deposits worldwide (though at very low concentrations), and a significant fraction of this may ultimately be recovered as global demand for fertilizer continues to rise.

Third, low uranium prices over the last two decades virtually eliminated incentives for uranium exploration. Consequently, there are almost certainly large quantities of still-undiscovered uranium that are not included in the Red Book estimates—particularly in the higher-cost categories. Modest investments have led in recent years to dramatic increases in estimates of available resources. In early 2001, for example, the Canadian firm Cameco increased its estimate of the uranium available at its

McArthur River mine by more than 50% (Ref. 65). In short, despite the inclusion of "speculative resources" in the 17.1 million tonnes U figure, there is a very high probability that the amount of uranium that will ultimately prove recoverable at or below \$130/kg U will be significantly greater.

Another way to approach the problem is to estimate the shape of the supply curve as a function of price. Based on geologic relationships, which indicate that exponentially larger resources are available at lower ore grades, it seems likely that the relationship between price and resources is roughly exponential. According to one industry observer, "a doubling of price from present levels could be expected to create about a tenfold increase in measured resources."[66] If we assume, very conservatively, that the 2.1 million tonnes U of known resources reported in the 2001 Red Book as recoverable at \$40/kg U represent all resources that will ever be recoverable at that price, then the total uranium resource R (million tonnes uranium) recoverable at price p (dollars per kilogram of uranium) is given by

$$R = 2.1\left(\frac{p}{40}\right)^{\varepsilon} , \tag{2}$$

where ε is the long-term price elasticity of supply. If a doubling of price leads to a tenfold increase in resources, $\varepsilon = 3.32$. By this crude estimate, more than 100 million tonnes U would be available at \$130/kg U. If the amount of uranium available at \$40/kg U is >2.1 million tonnes U, as seems very likely, then estimates of resource availability at higher prices would be proportionately greater as well.

One of the few serious attempts to estimate how much uranium is likely to be available worldwide concluded that a tenfold reduction in ore concentration is associated with a 300-fold increase in available resources.[67] If a doubling in price results in a tenfold increase in supply, this implies that a doubling in price would make economical the exploitation of ores with uranium concentrations 2.5 times lower. This seems plausible because not all extraction costs scale in direct proportion to the amount of ore mined and processed per ton of uranium recovered. If, at the other extreme, we assume that costs are inversely proportional to ore grade (as might be true at very low concentrations, when total costs became dominated by the amount of material mined and processed), then $\varepsilon = 2.48$, and ~40 million tonnes U would be available at \$130/kg U. More recently, the Generation IV Fuel Cycle Crosscut Group judged that ε might be as low as 2.35 (Ref. 16), which would give 34 million tonnes U available at \$130/kg U. Extrapolating to still higher prices, 170 to 500 million tonnes U would be available at \$260/kg U. These estimates are summarized in Table VI.

At the extreme of low-grade resources is the 4500 million tonnes U dissolved in the world's oceans at a concentration of 3 ppb. The recovery of this uranium has been demonstrated using adsorbents. Early approaches involved pumping seawater through the adsorbent; a pilot plant operated in Japan for 2 yr, but the pumping required more energy than would be provided by the recovered uranium, and this approach was abandoned.[68] More recent approaches rely on ocean currents to move seawater through fixed arrays of adsorbents, with a ship collecting the uranium-bearing adsorbents for onboard processing or delivery to a shore-based processing facility. Rough cost estimates have varied from \$100/kg U to more than \$1000/kg U; the 2001 Red Book chose \$300/kg U as representative of current thinking. If uranium could be recovered from seawater at costs below the breakeven cost for reprocessing and recycling, the use of plutonium fuels could be deferred for many centuries.

Setting aside the question of seawater uranium, if the previous estimates of terrestrial resource availability are matched to estimates of future uranium consumption on a once-through fuel cycle, it is clear that uranium prices will not rise anywhere close to our central estimates of the breakeven price for reprocessing and recycling in LWRs or FRs for many decades to come. In a study of future energy scenarios in 1998, the World Energy Council and the International Institute for Applied Systems Analysis outlined six scenarios for future energy supply, covering a wide range of assumptions about population and economic growth,

TABLE VI

Estimates of Uranium Resources Ultimately Recoverable at \$80, \$130, and \$260/kg U, Assuming 2.1 million tonnes U Ultimately Recoverable at \$40/kg U

Source	Long-term Elasticity of Supply, ϵ	R (million tonnes uranium) for p less than or equal to		
		\$80/kg U	\$130/kg U	\$260/kg U
Uranium Information Centre[66]	3.32	21	105	500
Deffeyes and MacGregor[67]	2.48	12	40	220
Generation IV group[16]	2.35	11	34	170

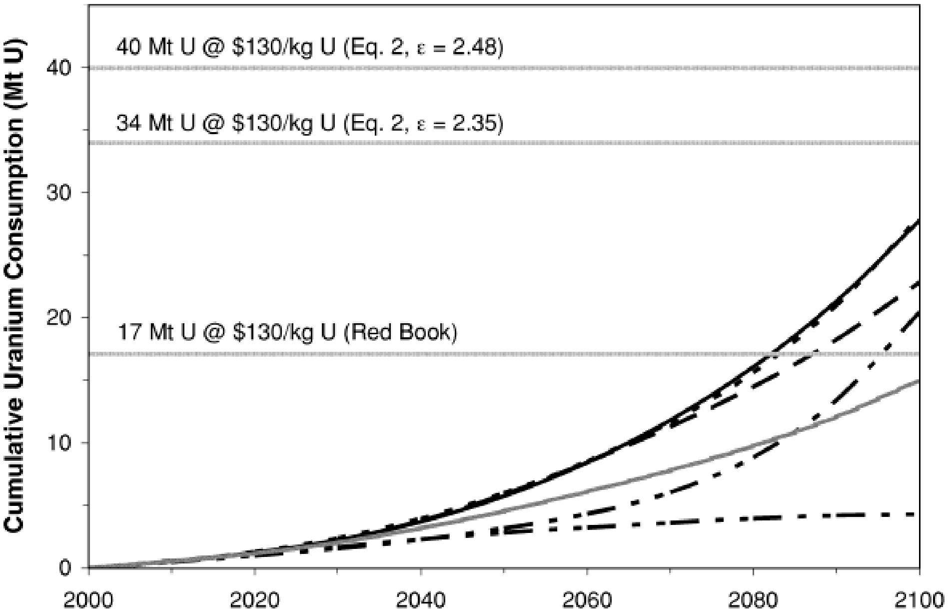

Fig. 6. Scenarios of cumulative uranium consumption, assuming a once-through fuel cycle with an average uranium requirement of 19 tonnes U/TW·h, and estimates of ultimately recoverable uranium resources at $130/kg U. Scenarios of nuclear electricity production taken from Ref. 69, normalized to 2434 TW·h in 2000.

resources, and technology.[69] Figure 6 shows cumulative uranium consumption in these scenarios, assuming that nuclear electricity is produced entirely by LWRs operating on a once-through cycle with an average uranium requirement of 19 tonnes U/TW·h.[f] Also shown are estimates of uranium resources available at prices of $130/kg U or less. Based on these scenarios, it seems very likely that uranium resources will continue to be available at substantially below the breakeven price for reprocessing at $1000/kg HM throughout the 21st century.

V. IMPACT ON REPOSITORY REQUIREMENTS

In recent years, some have argued that repository space is the most pressing constraint on the expansion of nuclear power. This argument is one of the principal drivers of the U.S. Advanced Nuclear Fuel Cycle Initiative. The DOE argues that existing U.S. reactors, discharging nearly 2000 tonnes HM/yr of spent fuel, will fill the 63 000 tonnes HM legislative capacity limit for the Yucca Mountain repository by 2015 and the "theoretical maximum" capacity of 120 000 tonnes HM by ~2050 (if the current level of nuclear capacity were retained).[70] Reprocessing the fuel and separating and transmuting the heat-generating radionuclides, it is argued, could make a second repository unnecessary, even if U.S. nuclear energy generation grows substantially in the future.

Several points should be made concerning this argument. First, it applies only to the United States. Only the United States has chosen a repository site with fixed boundaries, whose capacity cannot be increased indefinitely by digging more tunnels. Other countries are examining sites in huge areas of rock, clay, or salt, where the waste from centuries of nuclear electricity generation could be emplaced at a single site.

Second, traditional approaches to reprocessing and recycling do not lead to reductions in the amount of repository space required per unit of electricity generated. As discussed earlier, the required repository volume is determined by heat output of the wastes, and if plutonium is recycled in existing LWRs, the resulting buildup of heat-generating minor actinides means that the total waste heat per unit of electricity generated is higher than for direct disposal of spent nuclear fuel. To avoid the need for an additional U.S. repository, it would be necessary to separate, recycle as fuel, and transmute all the major long-lived heat-generating radionuclides. If we assume, as recent international reviews do, a higher reprocessing cost for these kinds of separations than the central

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[f] Assumes an average burnup of 50 MWd/kg HM, a net efficiency of 35%, and fuel enrichment and tails assays of 4.2 and 0.2% ^{235}U. [A tails assay of 0.2% would minimize cost when uranium price is ~1.3 times enrichment price (e.g., $130/kg U for $100/SWU).] The use of higher burnups, lower tails assays, and other reactor systems could reduce uranium consumption in a once-through cycle to as little as 12 tonnes U/TW·h (e.g., a pebble-bed reactor with burnup of 100 MWd/kg HM, an efficiency of 46%, and enrichment and tails assays of 8 and 0.1%).

estimate for traditional reprocessing used in the text, a higher fabrication cost (given the need for remote handling) for the fuel, and a transmutation reactor or accelerator capital cost $200/kW(electric) higher than that of comparably advanced once-through systems, then separations and transmutation would not be economic until the cost of spent-fuel disposal reached some $3000/kg HM, nearly ten times current estimates.[6]

Third, the argument is based on the assumption that it would be less difficult to gain public acceptance and licensing approval for complex and expensive spent-fuel separation and transmutation facilities than for a second repository. This assumption is likely wrong. Reprocessing of spent fuel has been fiercely opposed by a substantial section of the interested public in the United States for decades. The health and safety risks to current generations from a separations and transmutation approach would be greater than those associated with direct geologic disposal of spent fuel.

Fourth, the argument is also based on the assumption that, many decades in the future when repository space has become scarce and reactor operators are willing to pay a significant price for it, it will still not be possible to ship spent fuel from one country to another for disposal. If, in fact, repository capacity does become scarce in the future, reactor operators will likely be willing to pay a price for spent-fuel disposal well above the cost of providing the service. It seems likely that if the willingness to pay gets high enough, the opportunity for profit will motivate some country with an indefinitely expandable repository to overcome the political obstacles that have blocked international storage and disposal of spent fuel in the past.

Premature decisions based on early estimates of unproven technology can be very costly. Given the availability of proven, low-cost dry-cask storage technology that can store spent fuel safely for decades, there is no rush to resolve these debates.

VI. CONCLUSIONS

At a reprocessing price of $1000/kg HM and with our other central estimates for the key fuel cycle parameters, reprocessing and recycling plutonium in existing LWRs will be more expensive than direct disposal of spent fuel until the uranium price reaches more than $370/kg U—a price that is not likely to be seen for many decades, if then.

At a uranium price of $50/kg U (somewhat higher than current prices), reprocessing and recycling at a reprocessing price of $1000/kg HM would increase the cost of nuclear electricity by 1.3 mill/kW·h. Since the total back-end cost for the direct disposal is in the range of 1.5 mill/kW·h, this represents more than an 80% increase in the costs attributable to spent-fuel management (after taking account of appropriate credits or charges for recovered plutonium and uranium from reprocessing).

These figures for the breakeven uranium price and the contribution to the cost of electricity are conservative. The central estimate of the reprocessing price, $1000/kg HM, is substantially below the cost that would pertain in privately financed facilities with costs and capacities identical to the large (and largely not privately financed) commercial facilities now in operation. The central estimate of the MOX fuel fabrication price, $1500/kg HM, is significantly below the price actually offered to most utilities in the 1980s and 1990s. No charges were included for storage of separated plutonium or removal of americium, or for additional security, licensing, or shutdown expenses for the use of plutonium fuels in existing reactors. A full charge for 40 yr of interim storage in dry casks was included for all fuel going to direct disposal even though new reactors are being built with storage capacity for their lifetime fuel generation. The costs of geological disposal of spent MOX fuel were assumed to be equal to that of spent LEU fuel despite the substantially higher heat output of spent MOX fuel.

Reprocessing and recycling plutonium in FRs with an additional capital cost of $200/kW(electric) compared to new LWRs will not be economically competitive with a once-through cycle in LWRs until the price of uranium reaches some $340/kg U, given our central estimates of the other parameters. Even if the capital cost of new FRs could be reduced to equal that of new LWRs, recycling in FRs would not be economic until the uranium price reached $140/kg U.

At a uranium price of $50/kg U, electricity from a plutonium-recycling FR with an additional capital cost of $200/kW(electric), and with our central estimates of the other parameters, would cost more than 7 mill/kW·h more than electricity from a once-through LWR. Even if the additional capital cost could be eliminated, the extra electricity cost would be more than 2 mill/kW·h.

As with reprocessing and recycling in LWRs, these estimates are conservative. We have assumed no cost for start-up plutonium, no additional cost for reprocessing or fabricating higher-plutonium-content FR fuel (compared to LWR fuel), and no additional operations and maintenance costs for FRs compared to LWRs. Costs for the more complex chemical separation processes and more difficult fuel fabrication processes needed for more complete separation and transmutation of nuclear wastes have been estimated in recent studies to be substantially higher than those estimated here for traditional reprocessing and recycling. The extra electricity cost would be even higher if these approaches were pursued.

World resources of uranium likely to be economically recoverable in future decades at prices below the breakeven uranium price amount to several tens or even hundreds of millions of tons, enough to fuel a growing nuclear enterprise using a once-through fuel cycle throughout the century.

Limits on repository space are not a persuasive reason to pursue reprocessing. Traditional approaches to reprocessing and recycling would not help, in any case; a complex of separations and transmutation facilities would be necessary. It is unlikely to be easier to gain approval and acceptance for building separation and transmutation facilities rather than for repository expansion or building a new repository. Reactor operators probably would be willing to pay substantially more for direct disposal of spent fuel in order to avoid expensive separation and transmutation, which would increase incentives for states or other countries to accept the spent fuel.

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