Science and Global Security, 14:183–211, 2006

ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929880600993139

Nuclear Fission

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The potential role of nuclear fission to meet increased future energy demand while reducing greenhouse gas emissions and controlling nuclear proliferation is assessed. The World Energy Council projection for an environmentally driven future is used, which projects deployment of nearly 3 TW(e) of nuclear generation by 2100, with concurrent reduction of global CO_2 emissions to one-third of present levels. We simulate three scenarios based on this demand curve that rely on evolutionary and advanced systems of reactors. The scenarios differ only in fuel cycle choice between once-through, transmutation, and breeding. We show that the cost of nuclear power will likely remain a minimum using the once through fuel cycle, which, we argue, also minimizes proliferation risks. The other two fuel cycle choices have the benefits of decreased waste production and increased uranium resource utilization, but these come at a price that is probably not acceptable unless the cost of repository space increases dramatically, or the cost of building advanced transmuting or breeding reactors can be reduced to a level lower than that of constructing new plants with contemporary technology. The importance of choice of discount rate in allocating resources to advanced nuclear technologies is discussed. The linkage of fuel cycle choice with the international non-proliferation regime is emphasized.

INTRODUCTION

If the UN Framework Convention on Climate Change (UNFCCC)[1] were ultimately successful it would result in an international carbon-abatement regime that enables a shift in energy supply to sources that do not emit CO_2.[2–4] Of the countries that are party to the UNFCCC, two with the lowest emissions of carbon dioxide per unit of gross domestic product are Japan and France, the two countries with the greatest commitments to nuclear energy. While the "developed" world currently is the greatest source of CO_2 emissions, economic growth, and therefore energy demand growth, is expected to occur over the next century

Received 31 August 2005; accepted 20 April 2006.
We are grateful for helpful comments from at least six reviewers, including Richard Garwin, Hal Feiveson, and four others who remain anonymous. This was published under LANL authorization number LA-UR-03–8526.
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in developing countries such as India and China. International encouragement of carbon-free energy growth in such nations would entail subsidy in order to minimize cost impacts on the poorest nations. Nuclear fission could be used (in theory) to avoid all atmospheric CO_2 increases over the next century.[5–13]

However, under the existing regime, based on the Non-Proliferation Treaty (NPT) and its safeguards provisions, nuclear power may expand in some countries but not in others. The United States, France, and Japan, for example, could use nuclear energy to reduce their carbon emissions. This system may work to the advantage of countries that already have an advanced nuclear infrastructure, but it is not greatly expandable. Nuclear growth would be so small that essentially the entire carbon-abatement problem would continue to exist for the world as a whole.

Nuclear power can play a major role in reducing greenhouse gas emissions only if inclusion of nuclear energy in future UNFCCC agreements can be configured so as to strengthen the UNFCCC, the nonproliferation regime, and international nuclear safety standards.

As viewed by the developing world, the UNFCCC has many drawbacks.[14] However, subsidizing nuclear energy can be an inducement for developing nations to join the regime if they are interested in nuclear energy (India may be such a case). However, there would be worldwide dissatisfaction with nuclear energy if there was an accident as a result of poor regulation combined with poor design choices, regardless of where an accident was to occur. Blaming the recipient nation is not a recourse. Safety standards must be universal.

Nuclear proliferation is assumed by many to be positively correlated with nuclear energy growth. Recent nuclear crises have involved North Korea,[15] Iran,[16] and the proliferation "ring" headed by the Pakistani A. Q. Khan.[17] Terrorist acquisition of nuclear explosives, "the ultimate preventable catastrophe," is of the highest concern.[18] Because of these legitimate worries, nuclear power is thought by many to be unacceptable as a technology for mitigating future carbon emissions.

Most nuclear power growth until now, however, has not led to weapons and most weapons acquisition paths do not involve nuclear power. An alternative and more realistic thought process[19] is to accept that future nuclear technology diffusion throughout the world is an inevitable consequence of the universal knowledge that nuclear fission can be used for weapons and power. Attempting to stop nuclear power growth therefore does not necessarily lead to any slowing of nuclear proliferation. In taking this second track, we see the challenges mainly to be in slowing of demand for weapons, limiting the availability of nuclear materials to rogue actors, and in increasing the incentives for all actors to comply with international norms.[20]

Peaceful nuclear energy has been used for decades by the United States and other countries as a "carrot" for reinforcing norms. For example, the December 2003 renunciation of nuclear and chemical weapons by Libya was the result of years of negotiations, the desire of Libyan President Qaddafi to lift sanctions on his country, and fear of a U.S. preemptive military strike. Qaddafi later said he wanted the United States and other Western nations to reward him for his decision by providing Libya with nuclear technology for civilian uses.[21] This type of anti-correlation between nuclear power and weapons must be a long-term goal for the incorporation of nuclear power into the UNFCCC.

A renewal in nuclear energy growth has seemed unlikely until recently because there have been few economic incentives in place for the use of nuclear energy to abate carbon emissions, and a lack of public support for nuclear energy in many of the richer nations. There have been some recent indications of a changing trend in both situations, at least in the United States.[22] We predicate our hypothesis of a renewal in demand for nuclear power on both of these situations continuing to improve dramatically, along with progress in nuclear non-proliferation and environmental treaties.

In the United States, the recently launched Global Nuclear Energy Partnership (GNEP) aims to provide a paradigm for the growth of nuclear energy in the United States and the world. This program sets forth a seven-point set of objectives that together outline a specific vision for the future of nuclear energy, one that relies on advanced technologies currently in the initial stages of development. For instance, the GNEP calls for "developing and deploying new nuclear recycling technologies [and]... designing Advanced Burner Reactors that would produce energy from recycled nuclear fuel.[23]" The GNEP plan also seeks to support proliferation-resistant nuclear power in developing countries via a fuel services program and RD&D efforts geared toward small-scale reactors. This proposal has inspired our effort to compare and contrast nuclear futures based on evolutionary technologies to the GNEP vision of rapid deployment of advanced but unproven reactors and fuel cycle facilities.

The main issue is whether nuclear energy, in its evolutionary or revolutionary guises, can compete economically in the field of choices available in the future. We therefore attempt to assess the cost of electricity from nuclear power in terms of cents per kilowatt hour, and whether it can be reduced by varying the nuclear fuel cycle. An even-handed approach is to use the existing cost data available from the Organization for Economic Co-operation and Development (OECD) and an energy demand curve already available from the World Energy Council and the International Institute for Applied Systems Analysis (WEC/IIASA).[24]

WEC/IIASA[25] presents a number of scenario-based projections of aggregate energy demand and energy demand by generation technology. Of their six scenarios, three exhibit roughly equivalent nuclear shares of primary energy consumption[26]; however, they assume strongly varying energy economic landscapes as well as nuclear fuel cycle technology options. In the WEC/IIASA high-growth scenario A3, both economic growth and technological progress are assumed strong across all regional and technological groupings. Especially vigorous advances are postulated in nuclear and renewable technologies for this case. The middle course scenario B reflects more modest progress with persistent inter-regional cleavages. Energy demand growth and technological progress are weaker than in case A3, leading the authors to refer to this scenario as the "muddling through" option. Finally, the ecologically driven case C2 postulates a strong focus upon energy efficiency, technology and resource transfer, and a carbon control policy that reduces emissions to 2 GtC/yr by 2100 (1/3 of today's level). With respect to nuclear power, this case assumes that next-generation nuclear technologies attain public acceptance and that small, self-contained modular facilities would facilitate market entry in the developing world.

We base our calculations on the nuclear power growth rates from the ecologically driven case. Our study adds depth to the WEC/IIASA results through use of a simplified version of a nuclear energy and fuel cycle simulation model[27] that builds reactors to meet demand and computes the costs and nuclear materials flows associated with their operation. We consider three technology mixes that could meet the demand function presented in WEC/IIASA. These feature the "once through" fuel cycle, fast neutron spectrum transmuting reactors, and plutonium breeders, respectively. The simulation results allow development of a much more exact understanding of the ramifications of options predicted by optimization tools such as IIASA's MESSAGE-III[28] and the National Energy Modeling System[29] used by the US DOE. The results presented herein are not predictive, but rather descriptive of a set of plausible scenarios.

THE COMPETITIVENESS OF NUCLEAR ECONOMICS

"Cost will not be an obstacle to the use of atom-fueled electricity. The only official word so far on cost is an estimate of 8 mills per kWh. It was submitted by R. C. Tolman, scientific adviser of the US delegate to the international committee on control of atomic energy. This figure is some 30% higher than the cost of coal-generated power in areas where coal is plentiful." This quote is from the March 8, 1947 issue of *Business Week*.[30]

The International Atomic Energy Agency (IAEA) recently estimated that the cost of electricity using the new advanced light water reactors (LWR) would be 4.9 cents per kilowatt-hour Operations and maintenance costs are predicted to be 0.5 cents per kWh (lower than experience) and fuel costs 0.8 cents per kWh. Computed carbon abatement costs are $57 per ton of emitted carbon versus coal.[31]

A more rigorous study by the OECD[32] catalogued its results by separating construction and operation costs. Capital charges for the construction are generally higher than operating costs. There is a wide range in each of the costs depending on the country and plant design. Variations in labor and regulatory costs range between $1,500/kWe and $2,500/kWe for plant construction costs, not including interest charges during construction. With a 5 year construction time at a 10 percent discount rate, the range of total capital costs is $2,000–$3,100/kWe. This translates into capital charges during operation of between 2.8–5.1 cents per kWh of electricity produced. Operations, maintenance, and fuel costs, lumped together by the OECD as "operation costs," show large variations from country-to-country and from plant-to-plant.

Collecting all of these costs, it appears that, depending on the country, the current projected cost of nuclear power ranges from an optimistic 4.0 to a pessimistic 8.7 cents/kWh. The 1947 estimate of 6.4 cents is at the midpoint.

Much of the emphasis of nuclear power reactor research and development is to lower the construction and operation costs. Many of the reactors that could be deployed in, say 20 years from now, may have 30 percent lower costs than those discussed here. More dramatic cost savings beyond this may be considered unrealistic for technology at this stage of maturity.

QUALITATIVE DESCRIPTION OF FUEL CYCLE EVOLUTION

Three different fuel cycle scenarios are described here: direct disposal of spent fuel in geological media ("once-through"), transmutation, and breeding.

The once-through fuel cycle relies on uranium-burning, open fuel cycle. This involves construction of evolutionary versions of today's light water reactors. Waste, consisting of the spent fuel discharged from these facilities, would be emplaced in a stable geologic medium. Additional engineered facilities similar to Yucca Mountain could be built; alternatively other methods of disposal such as deep boreholes may become available.

Partitioning and transmutation (or simply "transmutation") is a waste treatment process in which certain long-lived radionuclides are partitioned (separated) from high level waste and transmuted by further irradiation. This, in theory, converts the longer-lived radionuclides into shorter lived ones, or ones that are stable. Transmutation has been the object of much research, but it has not been practiced to date.

Transmutation, if added to the current once-through fuel cycle, would add three stages to the direct disposal method. First, the spent fuel is chopped, crushed, and dissolved separating streams of radioactive species. These streams (such as one stream for plutonium, one for neptunium, one for ^{99}Tc, etc.) are made into fuel elements that can be irradiated in a special reactor. Lastly, the special reactor is operated for an extended period to burn-up or transmute these species into less troublesome ones from a waste-disposal perspective.

The perceived benefit is that transmutation makes final disposal simpler by reducing the number, size, and costs of repositories. Elimination of ^{237}Np would make the performance of the repository in the time frame between 100,000 and

1,000,000 years better defined.[33] Alternatively, the species ^{129}I, ^{14}C, and ^{99}Tc can be made into special waste forms, such as alloys, rendering them insoluble in water. These species, especially the ^{99}Tc, are important contributors to the projected releases from the repository in the 1,000 to 100,000 year time frame. Special transmutation facilities for these species are also an option.[34] The only other long-lived radioactive species that would go to the repository would be species such as ^{59}Ni, ^{93}Zr, and some other species that are not soluble in water.

For a geological repository, the maximum capacity for safe operation is governed by the time-dependent decay heat production of the emplaced waste. If all the transuranic species (TRU; primarily neptunium, plutonium, americium, curium) are removed from the waste, reductions in the long-term heat load borne by the repository would allow it to hold the waste output from several times as many GW-years of operation versus direct disposal of spent fuel. It is estimated that the capacity would be enhanced by a factor of 2.7 –4,[35] whereas the long-term safeguarding requirements for the repository would be reduced.[36] If plutonium *only* is recycled in conventional water-cooled reactors, capacity would not be enhanced because of the build-up of high-heat-producing TRU isotopes. In fact, even the fourfold benefit quoted earlier cannot be achieved using conventional reactors alone. Some heat producing isotopes (e.g., americium-241) have a negative effect on the chain reaction in a water-cooled reactor and can only be transmuted to a limited extent. Therefore, recycling and transmutation in water-cooled reactors of the type in use today cannot increase repository capacity by more than a factor of two.[37]

Reactor concepts that would not suffer from this limitation exist, notably the sodium, lead, and high temperature helium-cooled reactors being developed as part of the DOE's Generation-IV initiative.[38] These reactors could eventually transmute all of the TRU into fission products, although this would require a sustained, long-term nuclear fuel reprocessing and recycling campaign. When the TRU species are removed from the waste and eliminated as a heat production burden, the fission product isotopes ^{90}Sr and ^{137}Cs reduce repository capacity. To achieve further benefit, the period of forced ventilation must be extended to timescales on the order of centuries,[39] or these fission products must also be removed from the waste. If these isotopes are partitioned, the repository's capacity would increase further, as the heat production of the remaining isotopes would be a factor of 40 to 80 less than un-reprocessed spent fuel. This achievement, the ultimate goal of the transmutation strategy, would remove the waste heat generation limitation upon repository capacity. However, this benefit cannot fully be achieved unless the ^{137}Cs and ^{90}Sr are isolated in another storage medium for a period of time. Moreover, to achieve the large reduction mentioned earlier, the reprocessing of fast reactor spent fuel must achieve 99.99% separation efficiency for transuranics.[40]

Several technical hurdles must be overcome before transmutation or other completely closed fuel cycles could work as planned. Using current technology, many reprocessing byproducts are packaged as waste that must also be consigned to a repository; hence, the waste volume would be reduced by perhaps a factor of two. Therefore, several new chemical separations processes must be developed and brought to an industrial scale before transmutation becomes strongly beneficial.[41,42] Only at that point could waste disposal cost and capacity requirement reductions be achieved. Also, transmutation would likely increase the amount of low-level waste produced per unit of electricity.[43]

Although significant capital investment is required for this option, the main advantage is that it could minimize the mass and volume of material that must be isolated from the environment per unit of electricity produced. Significant benefits would be realized if final disposal costs become much higher than currently projected.

The third option, breeding, is similar to transmutation. A certain number of reactors in the fleet would employ a fast spectrum and be designed to transmute ^{238}U or ^{232}Th into plutonium or ^{233}U, respectively. Through reprocessing and recycling, this new fuel could be used to fuel many other reactors without the need for uranium mining. Three fast reactor concepts that are suitable for plutonium breeding are being funded under Generation IV initiative. In the future, liquid metal reactors (LMRs) or other advanced fission technologies that recycle fissile material internally may be improved to the point where they could be widely deployed. Systems that replace the LWR could, for instance, employ a once-through fuel cycle with a core lifetime equal to the reactor lifetime and the system completely sealed. There are additional breeding and conversion concepts as well.[44–47]

QUANTITATIVE STUDY OF FUEL CYCLE EVOLUTION

The objective of this section is to simulate the evolution of nuclear energy under the three divergent fuel cycle strategies: once-through, fast-spectrum transmutation, and plutonium breeding. The latter two rely on one of the Generation-IV reactors concepts; to first order, any of the reactors mentioned in the previous section could do the job. The simulations quantify tradeoffs inherent in the strategies. One such tradeoff is the positive correlation between the amount of TRU requiring storage or disposal (negative environmental and repository impacts) and the quantity of TRU being transported, separated, made into fuel, or otherwise rendered more vulnerable to diversion or proliferation-related activity than is the case for TRU ensconced in spent fuel. Another is the widely expected cost penalty, at least in the near term, following deployment of a “closed” fuel cycle option. For a given strategy, our simulation model can build reactors to meet time-dependent demand. It cannot, however, determine the demand; therefore as mentioned in the introduction we utilize the demand curves calculated by the WEC/IIASA.

Utilizing the WEC/IIASA nuclear energy demand function, for our three scenarios—once-through, transmutation, and breeding—we rely on the literature for guidance in choosing availability dates for reactor technologies as well as the time dependent makeup of the reactor fleet. Our model computes material balance parameters such as spent nuclear fuel inventories (tons of initial heavy metal, tIHM) and inventories of plutonium and the minor actinides. We compute the time-dependent material balances shown in our figures using a simple set of rules. The rules take the form of throughput transfer functions for each facility type being considered. For instance, in a uranium oxide (UOX) fueled LWR, we assume that each kilogram of uranium fuel releases 60 MWd of thermal energy during its four year residence time in the reactor. Upon discharge, the spent fuel composition is 0.9249 kg of uranium, 0.0119 kg of plutonium, 0.0016 kg of minor actinides, and 0.0616 kg of fission products (FP).

This is the rule that describes all UOX LWRs in the fleet. Similar rules exist for the other reactor types we consider: some of them contain plutonium and/or minor actinides as inputs. Some additional information is required to complete this picture, for instance the enrichment level of the uranium, the process (e.g., fuel fabrication, reprocessing) holdup times, the thermal-to electric efficiency of the plant. Nonetheless, the simulation model merely balances the books each year, adding spent fuel containing U, Pu, MA, and FP to the global SF inventory and withdrawing it, if called for, to be reprocessed. One constraint serves to limit the rate at which certain types of reactors—those using the Pu and MA discharged by other reactors as fuel—may be built. If the nuclear electricity demand function calls for a new reactor to be constructed, the simulation model will not construct a reactor of this type if, at some point during the time horizon, the stock of Pu and MA bearing fuel available for reprocessing would drop below zero. A uranium burning reactor is built in its stead.

Additional detail regarding our simulation model, including the rule base governing all reactor types, may be found in the Appendix.

Figure 1 shows the time evolution of two key nuclear fuel cycle indicators, spent nuclear fuel inventory and actinide mass, assuming growth in world nuclear generation capacity as described and adopting the once-through fuel cycle. The initial conditions for the scenarios were specified by current realities. The worldwide spent fuel inventory stood at 154,000 tons as of 2000,[48] at this time world civil plutonium stocks were 1,270 tons.[49] The year 2000 reactor fleet reflects current world realities and includes a number of MOX-burning LWRs. From 2000 to 2010, growth is met by constructing LWRs. Both LWRs and high temperature gas cooled reactors (HTGRs) are assumed to enter the market after that; the HTGR market share is consistent with the demands of an emerging hydrogen economy.[50] All newly constructed facilities are given a 50 year lifetime. The system-wide nuclear fuel inventory is divided into two categories. Spent fuel in long-term storage represents fuel that has been out of the reactor long enough to be considered safe for reprocessing or repository disposal. The

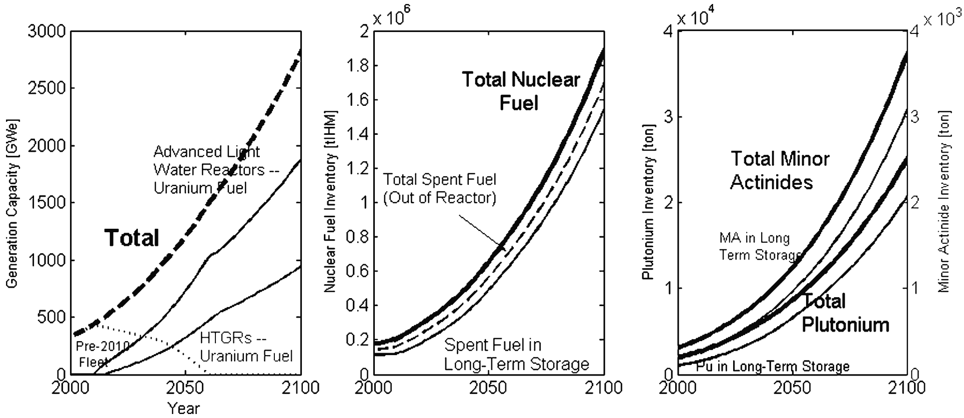

Figure 1: Once-Through, Uranium Based Nuclear Future. Advanced LWRs are assumed most competitive for electricity production, HTGRs for hydrogen production. Inventories of plutonium and the hot, radioactive minor actinides—tracked for their impact upon repository disposal—increase. Inventories in long-term storage represent materials that have cooled sufficiently to be moved from at-reactor cooling. Large inventories in long-term storage, then, represent a significant demand for engineered storage and/or geologic disposal.

remainder of the fuel is being fabricated, being burned in a reactor, or in short-term cooling storage to allow for hazardous short-lived radioactive isotopes to decay.

In Figure 1, TRU inventories are accounted for in the right-most box. The same distinction between materials unused but available for disposal or reprocessing and those in active use is made. Curves are shown for plutonium, of interest for its residual energy content as well as its potential for diversion by proliferators, and the minor actinides (MA). The minor actinides, primarily neptunium, americium and curium, pose significant radiation hazards as was discussed earlier in the Quantitative Study of Fuel Cycle Evolution. In any scenario involving nuclear growth, the quantity of these materials in the fuel cycle will increase with time. However, by 2100 large quantities of these materials would require disposal, as evidenced by the unbounded growth of inventories in long-term storage.

A transmutation-based strategy, similar to those under study in the Advanced Fuel Cycle Initiative, is illustrated in Figure 2. Uranium burning reactors continue to supply the bulk of the power, but a small number of reactors dedicated to burning the actinides not used in the uranium burning facilities are also constructed. In this illustration, these actinides pass through a mixed oxide (MOX) burning LWR, where they are partially consumed, before being sent to a fast spectrum reactor for complete transmutation. This burner reactor has a conversion ratio (CR) of 0.25, meaning that for every atom of Pu or MA created through nuclear reactions in its core, four such atoms are consumed through

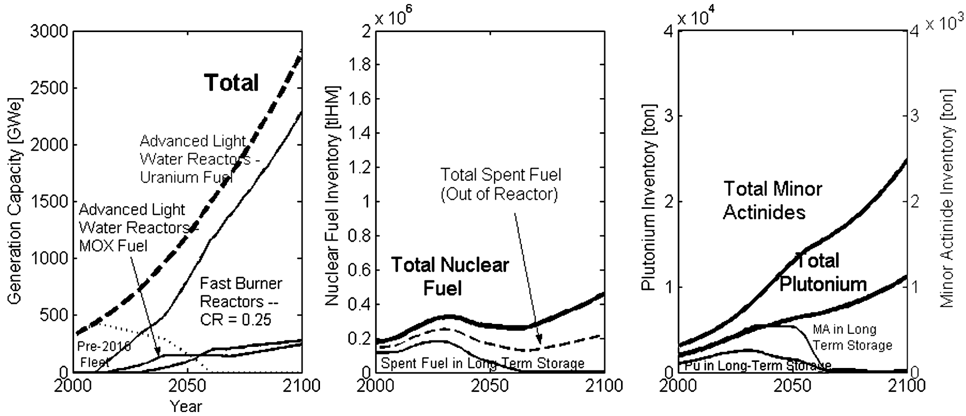

Figure 2: Transmuter-Supported Nuclear Future. LWRs burning MOX fuel, followed by fast-spectrum burner reactors, are deployed with the aim of quickly reducing long-term storage requirements to zero. LWRs operating with uranium fuel continue to supply the bulk of the energy demand. System-wide TRU inventories are suppressed compared to once-through; however, in a growing nuclear economy the TRU mass circulating through the fuel cycle will always increase over the long term.

fission.[51] This design was used by the US Advanced Fuel Cycle Initiative in its scenario studies.[52] The reactor mix deployed is geared toward minimizing out-of-reactor storage of materials; it is consistent with that reported in more detailed studies.[53,54] The right-most box shows that this strategy can reduce the amount of TRU material requiring disposal to essentially zero.

In the scenario illustrated by Figure 3 it is assumed that fast spectrum reactors become more economically attractive than current water reactor designs. Hence, instead of just a few such facilities being deployed for waste management

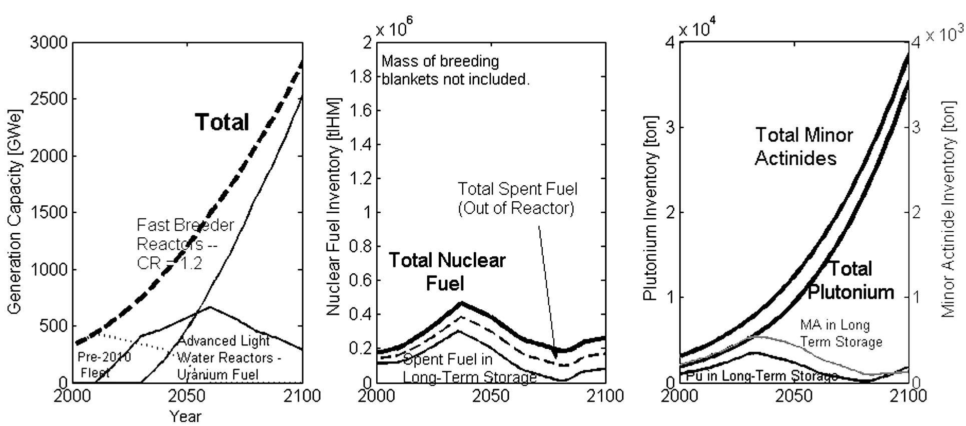

Figure 3: Breeder-Based Nuclear Future. Fast spectrum breeder reactors meet essentially all demand by 2100. Breeders are assumed to require an initial inventory of plutonium to start up; hence, plutonium stocks affect the rate of breeder deployment.

purposes, the entire fleet would eventually be replaced.[56] In this case, the fast reactors being deployed would be breeders rather than burners: with a conversion ratio (CR) of greater than 1, they create more fuel than they consume. The facilities illustrated here, with a CR of 1.2, breed sufficient fuel to double the size of the fast reactor fleet every 35 years. The fraction of nuclear generation capacity supplied by breeders is consistent with "nominal" projections as reported by EPRI.[57] This strategy also eliminates the large-scale need for TRU disposal. However, the system-wide plutonium inventory is nearly triple that of the transmutation oriented scenario by 2100.

The CR does not vary with year in the scenario presented. However, it is anticipated that the fleet of reactors would be "tunable," by alterations to the fuel configuration, for anticipated plutonium demand. When demand saturates, breeding would be decreased. A steady-state could be achieved with a CR value of one. The fleet of reactors could eventually be retired by using a CR value less than one, making them net burners of TRU species. A rapid shut-down of the reactor fleet, in contrast, would once raise the issue of disposal of thousands of tons of TRU species, which would be costly and problematic.

Numerous studies have shown that, given current and short-term forecasted cost data for the various technologies, the "once-through" uranium-only strategy incorporating eventual repository disposal of waste exhibits superior economics. This leads to a question: What must transpire for the fast-reactor based strategies described earlier to become competitive with the once-through scenario?

Beginning from estimates for present and near-future costs, it is possible to identify changes in market conditions or technological progress that would cause these strategies to become attractive when compared to the once-through case. The unit cost values, discounting scheme, reactor capital cost amortization and other aspects of our cost calculation follow the methodology of the 1994[55] and 2002 OECD studies,[58] as well as the Massachusetts Institute of Technology (M.I.T) study[5] These studies focused on busbar costs for electricity delivered by evolutionary and advanced reactors; further details of our cost assessment methodology may be found in the Appendix. Four top-level unit costs are identified as critical decision variables. These are the fixed costs associated with a fast-spectrum facility, the uranium resource cost, reprocessing, and disposal costs. OECD reference values for these technologies, given in year 2000 dollars, are $2,100/kWe of capacity for the fast reactor construction cost, $30/kg U for ore, $800/kg of initial heavy metal (IHM) in fuel for uranium oxide spent fuel reprocessing costs,[59] and $500/kgIHM for repository disposal.[60]

In the OECD study, as well as in the results presented here, the cost of electricity (COE) varied with fuel cycle strategy, but generally fell within the range 3.5 to 5.5 cents/kWh(e). This range is optimistic when compared to current nuclear electricity costs of 4 to 8 cents/kWh, or even the projections of the M.I.T

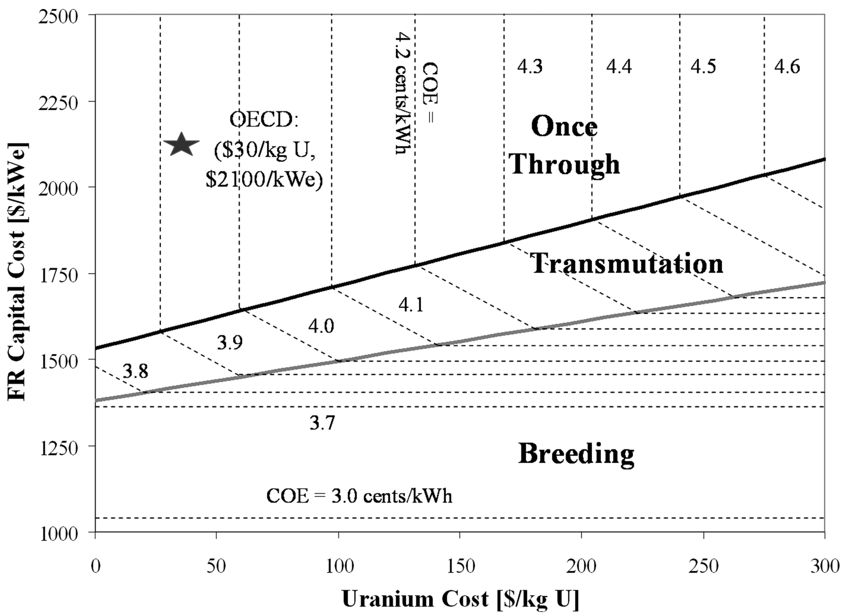

Figure 4: Cost of Electricity as a Function of Fast Reactor Capital and Uranium Costs. Transmutation and breeding, employing progressively larger fractions of advanced generation technologies, become competitive only if construction costs for these technologies decrease by 25%. Holding all other costs constant, uranium prices would need to increase by 1000% before advanced fuel cycles become competitive.

study.[5] It reflects optimistic projections for capital plant construction times (four years), reduced barriers to acquisition of capital (8 to 10 percent fixed charge rate), and bullish expectations for overnight reactor construction costs.

Figure 4 illustrates the sensitivity of the cost of electricity (COE) to fast reactor construction and uranium resource costs. In this figure, the cost space regions in which each of the three options offers the least-cost alternative is displayed. The dotted lines are isocost curves; these vary in slope between scenarios, as the dependence of each option on the unit costs is different. For instance, the once through option does not depend on fast reactor capital costs at all; therefore, the isocost lines for this scenario are vertical. The reactors in breeding-based economy, on the other hand, are all of the fast spectrum type. A fleet composed entirely of these reactors relies only on already-existing inventories of depleted uranium. This "top-up" fuel replaces uranium that has been transmuted to plutonium. Therefore, the breeding-only scenario depends on the fast reactor (FR) cost but not the natural uranium cost, and its isocost lines are horizontal. Transmutation is an intermediate case; the bulk of power-producing reactors are LWRs using enriched uranium fuel, but fast reactors are also present. The heavy lines describe the locus of breakeven points between regions in which one option is uniquely cheapest.

At present, FRs are projected by OECD and M.I.T. to cost 25percent more to construct than LWRs. These costs must be significantly reduced to values 10percent lower than the LWR construction cost before either transmutation or breeding becomes an option that markets are likely to select. This is because other costs associated with a reprocessing-oriented fuel cycle are greater than those of direct disposal.

The relative insensitivity of COE to resource costs can be seen in Figure 4. Even an unlikely tenfold increase in the ore cost would only increase COE by 20 percent: from 3.91 to 4.66 cents/kWh. This would still leave once-through as the most attractive option. In fact, such an increase would, in the long run, have an even smaller effect on the COE because the U-235 content of tails in the enrichment process can be adjusted. As the market for enrichment services adapts to higher demand, utilities could partially compensate for higher ore costs by reducing the enrichment of tails and obtaining more product per unit ore purchased. In this study, we assume a fixed tails enrichment of 0.30 percent, and we do not undertake this exercise in optimization.

If the spent nuclear fuel (SNF) disposal cost, rather than the resource cost, is varied Figure 5 would lead one to arrive at a similar conclusion. Holding

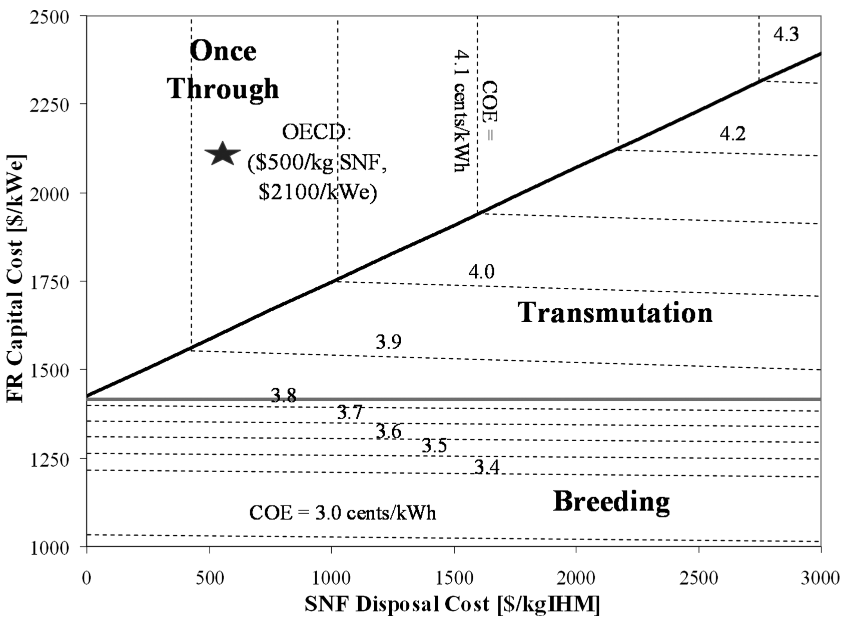

Figure 5: Cost of Electricity as a Function of FR Capital and SNF Disposal Costs. A four-fold increase in waste disposal costs, to which advanced fuel cycles are less sensitive than once-through, would result in breakeven between the transmuting and once through economies. A more probable breakeven case would follow from marginal reductions in fast reactor capital costs coupled with marginal increases in disposal costs.

other costs constant, only if disposal costs were higher by a factor of four would transmutation be cheaper than once-through.

The OECD reference SNF disposal cost may have a high degree of uncertainty, as large-scale geologic disposal of SNF has not been achieved. In fact, the Department of Energy's own fee adequacy assessments for Yucca Mountain have increased, in constant year 2000 dollars, from $34.4 bn in 1980 to $60.1 bn in 2000.[61] An independent assessment commissioned by the state of Nevada in 1998 computed a cost of $57.6 bn.[62]

Another factor influencing net disposal costs is the time for which SNF must be stored prior to disposal. Some above-ground storage time is desirable to allow time for fuel to cool. The cost assessments here assume 12 year surface cooling for LWR SNF prior to disposal. Additional storage of SNF at dispersed surface facilities, especially if unplanned, would affect the results.

The OECD reference data point in Figure 6 assumes timely disposal of SNF in a facility that conforms to the 1 mill/kWh cost target. Nonetheless, recent experiences confirm that the earlier uncertainties are not great enough to drive utilities or governments toward transmutation or breeding. Figure 6 also illustrates that reductions in reprocessing costs are not alone sufficient to drive the nuclear economy toward a transmutation- or breeding-based future. The OECD estimate for a reprocessing contract cost for UOX SNF of $800/kg is

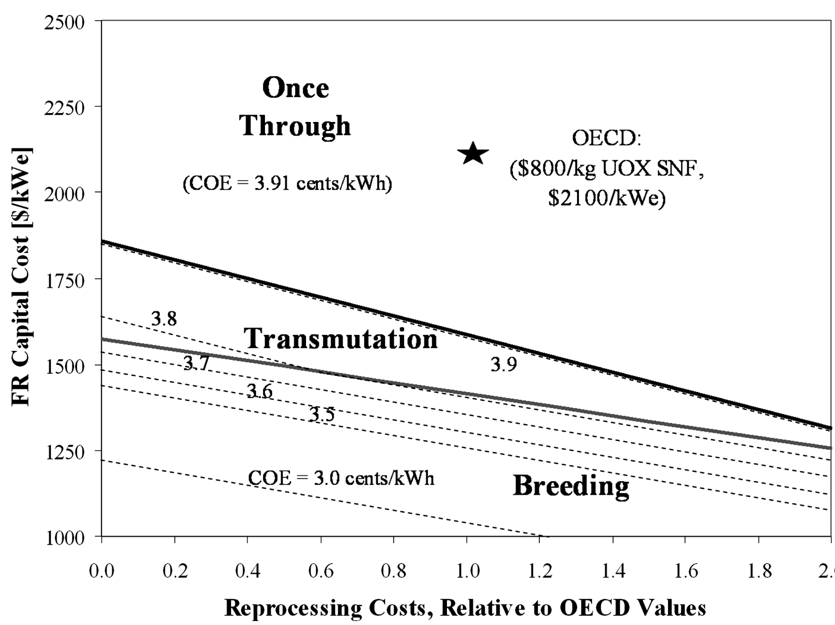

Figure 6: Cost of Electricity as a Function of FR Capital and Reprocessing Costs. Both LWR and FR fuel reprocessing costs are varied from OECD reference values. Reprocessing represents too small a contribution to the cost of electricity for advances in this area alone to lead to breakeven between once-through and recycling-oriented nuclear economies.

based on La Hague experience. This estimate is also subject to uncertainty. The OECD drew on recent experiences at the UP3 expansion to La Hague in France and Thorp in Britain, where construction costs amounted to 8,200 and 6,400 per kg/year of capacity, respectively,[63] as well as allusions to reported service contract prices, to arrive at their estimate.[64]

The following list summarizes possible catalysts for market adoption of advanced—transmuting or breeding—fuel cycles in preference to once-through. The order is chosen according to estimated decreasing likelihood of occurrence.

1. FR capital costs decrease by 20–30 percent through learning and economy of scale effects. This could be spurred by deployment of government-sponsored transmutation programs or through aggressive pursuance of Generation-IV concepts.
2. The cost of repository deployment proves to exceed reference values given earlier by a factor of four. Given that large-scale spent fuel disposal has not yet been demonstrated, this possibility cannot be dismissed.
3. Fuel handling costs (reprocessing and fabrication) for closed cycles substantially improve from reference values. The improvements needed from reference values are quite large for this mature technology.
4. The cost of uranium ore increases by roughly an order of magnitude, to about $300/kg (comparable to the estimated cost of extracting uranium from seawater).[65] The likelihood of such a price being reached appears remote.[66,67]

A combination of these factors would be more likely to occur than any one transpiring in isolation. Given that the fuel cycle changes described earlier are universally of large magnitude, though, a decrease in FR capital costs to levels close to those of LWRs appears to be mandatory. The conditions under which transmutation is the optimal choice are always intermediate to once-through and breeding. Therefore, it is plausible to expect this fuel cycle, which deploys many of the same facilities as a breeding economy but on a smaller scale, to enter the market first. This hypothesis assumes evolutionary rather than radical change in the technologies; given the maturity of our understanding of fission reactors this assumption is probably a good one.

Other less quantifiable factors will influence the deployability of the "advanced" technologies. A sociological analysis has been applied in characterizing the strategies adopted by nations and like-minded supranational groupings with respect to nuclear energy.[68] Hierarchical societies, those characterized by high acceptance of formal central control and compliance with technical elites, were more likely to favor fuel cycles placing higher reliance on advanced technologies. Examples of such societies include France, Japan, and perhaps the emerging Asian economies. It is entirely possible that specific nations or regional groupings might follow trajectories along the lines of each of the three scenarios depicted earlier, a state of affairs that is arguably already being realized. One variable parameter in economic calculations that will impact the technology path is the discount rate.

Effect of Discount Rate

The merits of an R&D pathway leading to deployment of an economically viable closed fuel cycle will depend on the discount rate. Decisions affecting waste disposal have often been cited, along with global warming policies, as being intergenerational in nature and thus amenable to cost-benefit analysis using social rates of discount. Smith[69] recommends applying the risk free rate of return, whereas Nordhaus[70] chose 6 percent/year and Cline[71] adopted values ranging from 1.5—5 percent. Arrow[72] quotes figures in the 3–4 percent range, whereas the Office of Management and Budget typically applies a 7 percent discount rate regardless of generational issues.

Hence, cost-benefit analysis offers guidance that is colored by a somewhat-arbitrary choice of discount rate. Presently, cost-benefit analysis is being employed by Japan Nuclear Cycle Development Institute[73] (JNC) to guide R&D policy development for large-scale deployment of fast-spectrum facilities. This study considers a Japanese nuclear economy ultimately consisting of 70 GWe of fast breeder reactor (FBR) capacity. The benefits of FBR deployment, consisting primarily of reduced electricity costs and mitigation of resource importation requirements, are weighed against the R&D costs associated with bringing this project to fruition—Yen 50 bn/year ($500 M/year) over the period 2000—2030.[74] The analysis found that ". . . a several fold benefit will be derived from FR cycle R&D investment." However, it was observed that significant uncertainty connected with the future benefits of such a system remains. At least one other consideration must be addressed: the discount rate used in such efforts must be subject to sensitivity analysis.

The analysis employed a 2 percent discount rate. At this level, the present value (all figures below given in year 2000 dollars) of a fixed-size benefit commencing in 2030 and continuing indefinitely would need to be $11.2 bn for a $500 M/year expenditure during 2000–2030 to be justified. This corresponds to an annual benefit of $397 M/year beginning in 2030. JNC forecast a much larger benefit, in excess of $1 bn/year. However, if the discount rate chosen were 7 percent rather than 2 percent, one might reach a quite different conclusion regarding the cost effectiveness of the research. With a 7 percent discount rate, the $ 397 M/year benefit commencing in 2030 would be worth only $798 M when discounted to the year 2000. Obtaining this benefit would, in turn, justify the expenditure of merely $64 M/year over the period extending from 2000 to 2030. These differing discount rates, both painstakingly justified in the literature, arrive at R&D expenditures that differ by a factor of eight. One can imagine the difficulty of allocating limited R&D resources in such a climate.

An options-based model that internalizes risk and recognizes that R&D efforts often serve as hedges against one another would be a better analysis tool in these circumstances.

PROLIFERATION IN THE GROWTH SCENARIOS

Three types of proliferation threats (linked to nuclear power), epitomized by cases from recent history, are identified here. The threats are national subterfuge, national breakout, and sub-national acquisition of material for nuclear explosives. Some means for reducing these threats are described.

Subterfuge occurs when a nation undergoes an ambitious program for nuclear materials production capacity ostensibly for peaceful purpose, while secretly planning to use the infrastructure for weapons. The production of plutonium by India, Israel, and North Korea are examples of this deception, as are the examples of production of uranium by Pakistan and Iran. Only India, of these countries, has a serious peaceful nuclear program in addition to its weapons program.

Breakout occurs when a county converts part of its civilian nuclear infrastructure into a weapons infrastructure in a time of crisis or after a political change. A country that has an un-exercised option to do this could be called a "nuclear abstainer." There are at least a dozen of them, and they have had a remarkable track record of having never produced a weapon.[75] This observation seems to contradict the worst fears of the early arms control advocates, that proliferation would be limited only by technological availability. In fact, the period of strongest growth of nuclear power worldwide, during the late 1970s through the 1980s, saw a slowing-down in weapons proliferation.[76] The abstainers simply have found that it is easier and cheaper not to build weapons. Some may depend on an alliance with a nuclear weapon state as the primary deterrent to nuclear threats. This would paradoxically imply that there *should* be some nuclear weapon states in order to control proliferation. The continued existence of the abstainer club will also depend on a continuation and strengthening of the international arms control regime.[77] There are few technological barriers to breakout by the abstainers; the barriers are political and economic. The key to reducing incentives for breakout is to reduce the perceived nuclear threat by other nations.

A comprehensive regional or international agreement can help alleviate tensions. In the case of Japan and South Korea, the threat is posed by a resource-poor developing country, North Korea (DPRK), that needs an increased energy supply. In 1994 these two countries agreed to pay for nuclear power plant construction in DPRK as an emergency measure to placate the DPRK leadership and continue the process of improving relations between the three countries and the United States. Under a nuclear expansion as described in this article, power reactors would be provided to developing nations in a fashion similar to the Agreed Framework with DPRK. The recipient must freeze and ultimately abandon its un-safeguarded nuclear path in order to receive the power reactors. Comprehensive, full-scope IAEA safeguards are to be put into place. Such agreements would also remove any possible cover story for a nation to develop a dual-use reactor program: the agreements can be engineered to reduce both subterfuge and breakout potential. While the once-through fuel cycle as currently practiced may be suitable for such an agreement, some of the technologies involved in the transmutation and breeder fuel cycle seem to be more problematic.

Technological decisions made in the generation of nuclear electricity can impact terrorist or sub-national use of nuclear weapons. Configuring the nuclear fuel cycle to make theft by terrorists or criminal organizations as difficult as possible is independent of any perceived threat of national diversion of fissile materials to weapons purposes. For this reason alone, discouraging the production of any separated weapons-usable fissile material should be undertaken worldwide as part of the nuclear expansion. High priority should be given to universal enforcement of rigid physical security measures of countries over their nuclear materials. But the world cannot rely solely on institutional measures such as armed-guards to protect fissile materials, because the problem of social disorder tends to arise in every part of the world at one time or another. For example, although Japan and France are two of the most stable countries in the world, some portions of these countries were in chaos during some of the years of the last century. Discouragement of stockpiling weapon-usable material in any country is insurance against such chaos.[78]

THE REGIME

Mohamed ElBaradei, the Director of the International Atomic Energy Agency (IAEA), has called for greater adherence to the "Additional Protocol," which allows more intrusive IAEA inspections. He suggested that there should be no provision for withdrawal from the Non-Proliferation Treaty, and that there be an international treaty controlling exports of nuclear technology.[79] He also has made several proposals for a new nonproliferation framework; separated plutonium and HEU will only be produced under multilateral control, existing HEU facilities will be converted as much as possible to LEU, all new nuclear facilities shall be proliferation-resistant, multinational spent fuel storage and disposal facilities be negotiated, a Fissile Material Cutoff Treaty (FMCT) be created.

Transmutation and breeding facilities, using current technology, under the IAEA director's proposals would only exist under international control. The reason to disallow these facilities under national control is not that they necessarily present a proliferation risk in a given country, for example, France, which may even be a weapon state already. The main reason to disallow national facilities is to flag such facilities as being potentially part of a weapon infrastructure, thereby defining a nation (such as DPRK) who constructs one of these facilities as a rogue. Internationalization would presumably lead to greater uniformity of fissile protection measures, to prevent the availability of fissile materials to sub-national groups in unstable nations. A regime like that proposed by ElBaradei is more easily envisioned with a universal acceptance of a once-through fuel cycle.

Although a once-through fuel cycle requires a more limited set of fuel cycle facilities. these, under ElBaradei's plan, would likely also have to be under international control, or have technological barriers to prevent reconfiguration for HEU production. Recent experience with Iran has alerted the world that it may be challenging to monitor these national facilities. Future laser enrichment facilities may be even more easily hidden.

ElBaradai's proposals, taken alone, do not offer a path forward. However, Deutch et al.[80] recently proposed an initiative that would provide guarantees and incentives to states complying with the proposals. The proposal, called the Assured Nuclear Fuel Services Initiative (ANFSI), is targeted at these "user states," nations not possessing enrichment, reprocessing or other fuel cycle facilities but deploying or wishing to deploy reactors. The user states would obtain, for the lifetime of each reactor, guaranteed access to nuclear fuel and guaranteed removal of spent fuel. These services would be provided, at market price, by a few designated "fuel cycle states." In return, the "user state" would guarantee that it not obtain an enrichment facility or other fuel cycle technologies. Clearly, most "user states," as small-scale consumers of nuclear energy, would find the cost per unit energy of developing and deploying their own fuel cycle facilities to be higher than price obtained from "fuel cycle states" with well-developed, large-scale infrastructures.

From our economic analysis of fuel cycle options, it is clear that the ANFSI need only begin with the open fuel cycle. The "fuel cycle states" would provide LEU fuel and take back the spent fuel only. Unless the economics change drastically, the lack of supplier facilities supporting the reprocessing-based fuel cycles would not damage the growth of nuclear power.

The ANFSI would be subject to the same criticism as the Non-Proliferation Treaty, that it would be discriminatory, rather than having no distinction between the parties.[81] The NPT specifically recognizes only five countries as possessing nuclear weapons legitimately. Hence India will probably never become a signatory to the NPT and would likewise not join the ANFSI without major changes in the international arms control and security regime.[82] The Kyoto treaty is also seen as discriminatory, because the developed world can better afford to implement expensive alternative energy technologies to reduce carbon emissions whereas developing nations cannot. The leaders of the developing nations feel that they must expand the use of fossil fuels to grow economically and allow a better material life for their people. For this reason India is not likely to become a signatory to the Kyoto treaty or any UNFCCC treaty that follows in the near term.

CONCLUSIONS

The early economic forecast predicting 6.4 cents per kilowatt-hour for nuclear electricity has proven to be remarkably accurate, although departures of plus or minus 2 cents or worse have been experienced. The plus or minus follows from country-specific structural differences in the regulatory burden and labor costs.

It is reassuring that a carbon-free energy source, with minimal air pollution or land use requirements, exists today and can be scaled to future needs. Our scenarios, which are congruous with WEC/IIASA energy growth scenarios, predict that the cost of nuclear electricity will probably not change dramatically with future fuel cycle choice or with increasing demand. Slow, continuous unit-based learning can be expected to reduce nuclear costs only slightly in the future. Only a radical new reactor type that is substantially cheaper than existing LWR plants can significantly improve the competitiveness of nuclear energy among carbon-abating energy technologies.

The detailed calculations presented in this article show that transmutation or breeding fuel cycles are unlikely to become economically preferential to the once-through fuel cycle. Briefly, the most feasible prospect for transmutation or breeding to become competitive with the once-through fuel cycle is for the capital cost of fast reactors to become 20–30 percent cheaper than present-day expert projections indicate, becoming less expensive than light-water reactors. This would only occur after significant government investment in research and development, and the investment would not be guaranteed to pay for itself. Furthermore, the discounting schemes employed by some nations to justify R&D budgets appear to be somewhat arbitrary and may favor greater-than-necessary expenditures.

Another breakpoint in the fuel cycle tradeoff, which is more unlikely, would be if the cost of repository space becomes a factor of a few higher than the current expectation. This would have the adverse effect of making nuclear power *in all cases* less competitive against non-nuclear alternatives. Other potential future developments that could affect the tradeoff, such as a dramatic lowering of reprocessing costs or a dramatic increase in the cost of uranium ore, are highly unlikely.

A nuclear power expansion as described here could only occur within a greatly strengthened institutional framework. The once-through fuel cycle seems to be more readily consistent with such a framework. Some would argue that the level of international cooperation needed to control nuclear proliferation is too large an undertaking to allow the expansion of nuclear power. However, abandoning nuclear energy in the United States or in the EU would not stop proliferation and probably would not even slow it down. Instead, we have an opportunity to develop a new integrated global carbon control regime. Peaceful nuclear energy would be an incentive for the regime.

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82. A truly non-discriminatory nuclear regime would probably require first the complete abolition of nuclear weapons. Certain ("safe") nuclear functions could be allowed for nations, whereas others ("dangerous") disallowed, as was once proposed in 1946 under the Acheson/Lilienthal plan. An international agency would control the all functions that are seen as dangerous for proliferation. The power reactors in existence today would all have been considered "dangerous" under the 1946 plan, which of course was never implemented.

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Appendix: Methodology for Cost and Material Balance Results

The MATLAB™-based model used to evaluate the scenarios herein is VEGAS. VEGAS propagates reactor fleets through time by evaluating facility material balances and economics on a quasi-equilibrium basis for each year of forecasting. Facility material balances are externally specified, with uranium, plutonium, minor actinides, and fission products being tracked.

VEGAS constructs reactor fleets based on an exogenously supplied demand for nuclear energy. If facility retirements or demand increases necessitate the additional capacity, VEGAS allocates it from a suite of available technologies based on material availability and position in the process chain. For instance, if LWRs burning UOX and/or MOX as well as fast-spectrum burners drawing on spent MOX fuel as feed are available, VEGAS first attempts to construct a fast spectrum facility. If sufficient spent MOX proves not to be available to support this facility for its entire lifetime, the order is cancelled and a LWR is built. This LWR burns MOX if enough UOX SNF is available—whether the LWR is full or partial core MOX is also specified in the scenario definition. If UOX SNF is not available for reprocessing in a given year, the LWR burns entirely UOX fuel. This methodology ensures that, within the limits of certain constraints (e.g., capacity of a reprocessing or fuel fabrication facility) the deployment of transmuting facilities is optimized.

For an individual facility, materials throughput is computed by a simple mass balance. If facility thermal power is P [MWt], fuel discharge burnup is B [MWd/kg], and the availability is α [percent of days during which power is being produced], the mass M [kg] of material charged and discharged in a given year is, on average, M = 365 alpha P/B. The composition of this material is specified by mass fractions at input and output. The mass fractions are given in Table A1; data are drawn from the open literature[52,58,83]

This approach is highly aggregated in nature: it collects plutonium and the minor actinides from all sources into a single lump of material. The isotopic composition of plutonium discharged from LWRs is very different from that of Pu discharged from fast burner reactors. Although this difference was respected in the derivation of the material balances underpinning the description of each reactor type, information at the isotopic level is not preserved in our model. This approach is not uncommon and has been utilized in nuclear energy systems codes developed by the US DOE.[84]

Economic assessments are carried out using the levelized cost methodology presented in a 1994 OECD study of the economics of nuclear fuel cycles.[55] Where this methodology is incomplete in the treatment of capital costs, an approach based on the 2003 M.I.T study[5] is used. Reactor capital costs are amortized over the facility lifetime, while fixed operations and maintenance costs are assessed in proportion to the capital expense, simulated by augmenting the fixed charged rate for capital cost assessment by 4 percent. For the fuel cycle, front end costs are discounted to the time at which electricity is generated. The fixed charge rate used for evaluating reactor and front end charges was 11 percent. Back end costs are paid for through a sinking fund with the rate of return assumed to be at risk-free levels—2 percent in this study. Table 2A summarizes the major unit costs, lead and lag times used in the cost assessment. In the table, negative numbers indicate lead times (prior to fuel charge), whereas positive numbers are lag times (after fuel discharge). For back end processes where reprocessing takes place, lag times are dependent on the time T* at which reprocessing occurs.

The data given in Table A2 are given in year 2000 dollars; they are drawn from the most recent publicly available study.[58] Even at this highly aggregated level, no clear consensus exists in the literature for the cost of technologies and facilities, especially those involving fast reactors. Variations in the material balances and the assessment methodology lead to small differences in the COE between this work and the 2002 OECD study. For instance, for the once through case the OECD predicts a COE of 3.80 cents/kWh whereas this study arrives at 3.93 cents/kWh.

Table A1: Material balance and operational parameters for reactor facilities.

Quantity	Unit	Legacy LWR SF	LWR-UOX	LWR-MOX	HTGR-UOX	FR (CR 0.25)	FR (BR 1.2)[1]
Availability	—	—	0.9	0.9	0.9	0.9	0.9
Burnup	[MWd/kg]	33	60	60	130	180	123
Thermal Efficiency[2]	[MWe (gross)/ MWt]	—	0.36	0.36	0.48	0.42	0.42
Fuel Res. Time	[yr]	—	6	6	3	4	4
Min. Cool Time	[yr]	—	5	5	4	3	3
Nat. Uranium	[kgU /kgIHM]	—	10.0	0.9	36.2	0	0
SWU	[SWU/ kgIHM]	—	6.2	0	28.5	0	0
U at Charge	[kg/kgIHM]	1.0000	1.0000	0.8780	1.0000	0.4250	4.0000
Pu at Charge	[kg/kgIHM]	0	0	0.1140	0	0.5190	0.2290
MA at Charge[3]	[kg/kgIHM]	0	0	0.0080	0	0.0560	0.0150
U at Discharge	[kg/kgIHM]	0.9560	0.9247	0.8509	0.8440	0.3860	3.9150
Pu at Discharge	[kg/kgIHM]	0.0090	0.0119	0.0762	0.0230	0.3670	0.2740
MA at Discharge[4]	[kg/kgIHM]	0.0008	0.0016	0.0122	0.0050	0.0430	0.0150

[1] For the fast breeder reactor, mass flow inputs and outputs reflect blanket as well as driver material. There are 3 kg of blanket per kg of driver.
[2] Electric power to the grid is also adjusted to account for recirculating power. This was chosen to be 2% for all facilities.
[3] MA content at charge includes retained neptunium for MOX reactors. For the CR 0.25 fast burner, to account for variations in feed stemming from the changing composition of the LWR fleet, the MA content was allowed to vary from the reference values given here with Pu content being held fixed.
[4] discharge Pu and MA values are adjusted to reflect expected average decay times.

Table A2: Costs and lead/lag times.

Item	Lead/lag time [yr]	UOX fueled LWRs	MOX fueled LWRs	HTGRs	Fast reactors
Capital cost ($/kWe)	−4[1]	1700	1700	1700	2100
Natural Uranium ($/kg U)	−2.5		30		
Enrichment ($/SWU)	−2		90		
Fuel fabrication ($/kg IHM)	−1	250	1100	250	3000
Fuel transport ($/kg IHM)	Note[2]		50		
SF cooling storage ($/kg IHM)	2		100		
Reprocessing ($/kg IHM)	T*	800	2000	800	4000
SF disposal ($/kg IHM)	12	500	N/A	500	N/A
HLW vitrification ($/kg HLW)	T*		580		
HLW disposal ($/kg HLW)	T* + 2		1000		

[1]Given in years prior to the beginning of power production.
[2]Transport costs are accessed 0.5 years prior to fuel charge and again immediately prior to reprocessing or disposal.