Chapter 4 — Fuel Cycles

The description of a possible global growth scenario for nuclear power with 1000 or so GWe deployed worldwide must begin with some specification of the nuclear fuel cycles that will be in operation. The nuclear fuel cycle refers to all activities that occur in the production of nuclear energy.

It is important to emphasize that producing nuclear energy requires more than a nuclear reactor steam supply system and the associated turbine-generator equipment required to produce electricity from the heat created by nuclear fission. The process includes ore mining, enrichment, fuel fabrication, waste management and disposal, and finally decontamination and decommissioning of facilities. All steps in the process must be specified, because each involves different technical, economic, safety, and environmental consequences. A vast number of different fuel cycles appear in the literature,[1] and many have been utilized to one degree or another. We review the operating characteristics of a number of these fuel cycles, summarized in Appendix 4.

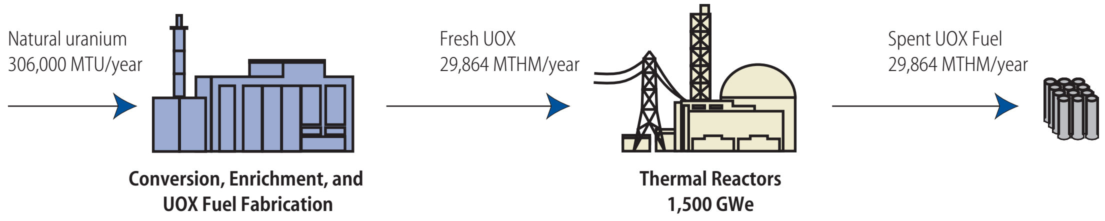
In this report, our concern is not with the description of the technical details of each fuel cycle. Rather, we stress the importance of aligning the different fuel cycle options with the global growth scenario criteria that we have specified in the last section: cost, safety, nonproliferation, and waste. This is by no means an easy task, because objective quantitative measures are not obvious, there are great uncertainties, and it is difficult to harmonize technical and institutional features. Moreover, different fuel cycles will meet the four different objectives differently, and therefore the selection of one over the other will inevitably be a matter of judgment. All too often, advocates of a particular reactor type or fuel cycle are selective in emphasizing criteria that have led them to propose a particular candidate. We believe that detailed and thorough analysis is needed to properly evaluate the many fuel cycle alternatives.

We do not believe that a new technical configuration exists that meets all the criteria we have set forth, e.g. there is not a technical ‘silver bullet’ that will satisfy each of the criteria. Accordingly, the choice of the best technical path requires a judgment balancing the characteristics of a particular fuel cycle against how well it meets the criteria we have adopted.

Our analysis separates fuel cycles into two classes: “open” and “closed.” In the open or once-through fuel cycle, the spent fuel discharged from the reactor is treated as waste. See Figure 4.1. In the closed fuel cycle today, the spent fuel discharged from the reactor is *reprocessed*, and the products are partitioned into uranium (U) and plutonium (Pu) suitable for fabrication into oxide fuel or mixed oxide fuel (MOX) for recycle back into a reactor. See Figure 4.2. The rest of the spent fuel is treated as high-level waste (HLW). In the future, closed fuel cycles could include use of a dedicated reactor that would be used to transmute selected isotopes that have been separated from spent fuel. See Figure 4.3. The dedicated reactor also may be used as a breeder to produce new fissile fuel by neutron absorption at a rate that exceeds the consumption of fissile fuel by the neutron chain reaction.[2] In such fuel cycles the waste stream will contain less actinides,[3] which will signifi-

Figure 4.1 Open Fuel Cycle: Once-Through Fuel — Projected to 2050

Current Burnup: 50 GWD/MTIHM:



High Burnup: 100 GWD/MTIHM:

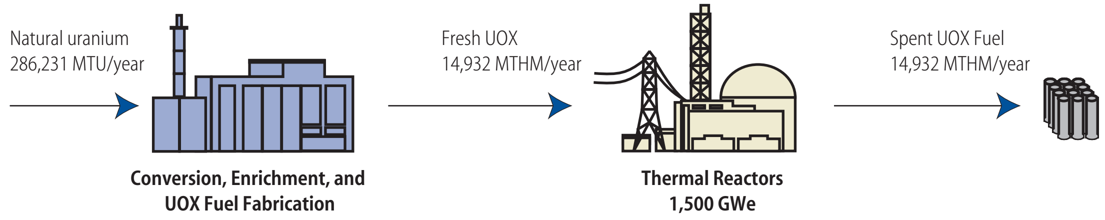


Figure 4.2 Closed Fuel Cycle: Plutonium Recycle (MOX option - one recycle) — Projected to 2050

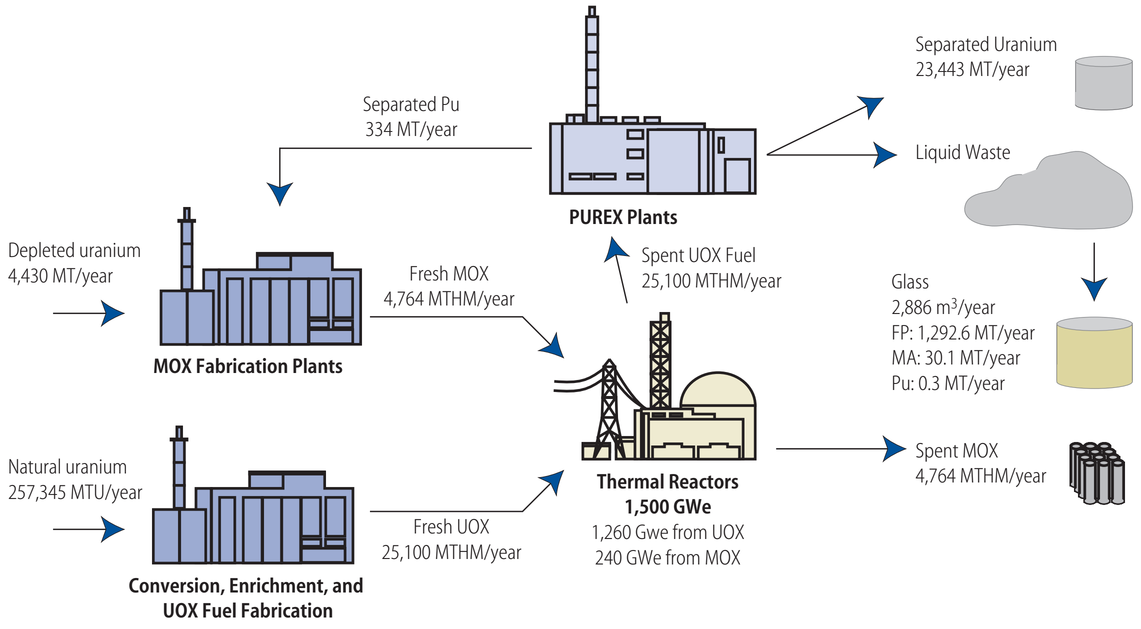
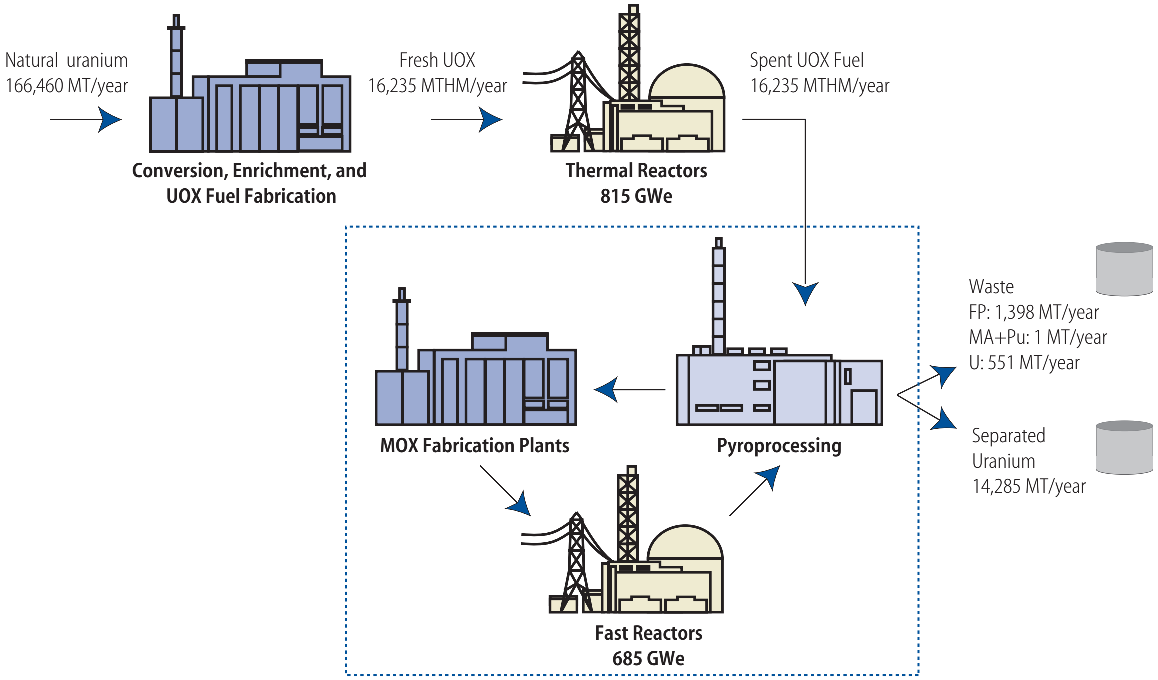


Figure 4.3 Closed Fuel Cycle: Full Actinide Recycle — Projected to 2050



cantly reduce the long-term radioactivity of the nuclear waste.[4]

In general, we expect the once-through fuel cycle to have an advantage in terms of cost and proliferation resistance (since there is no reprocessing and separation of actinides), compared to the closed cycle. Closed cycles have an advantage over the once-through cycle in terms of resource utilization (since the recycled actinides reduce the requirement for enriched uranium), which in the limit of very high ore prices would be more economical. Some argue that closed cycles also have an advantage for long-term waste disposal, since long-lived actinides can be separated from the fission products and transmuted in a reactor. Our analysis below focused on these key comparisons.

Both once-through and closed cycles can operate on U or Th fuel and can involve different reactor types, e.g., Light Water Reactors (LWRs), Heavy Water Reactors (HWRs), Supercritical water reactors (SCWRs), High Temperature and very High Temperature Gas Cooled Reactors (HTGRs), Liquid Metal and Gas Fast Reactors (LMFRs and GFRs), or Molten Salt Reactors (MSR) of various sizes. Today, almost all deployed reactors are of the LWR type. The introduction of new reactors or fuel cycles will require considerable development resources and some period of operating experience before initial deployment.

The fuel cycle characteristics of the current worldwide deployment of nuclear power (with the exception of three operating liquid metal fast breeder plants[5]) are summarized in Table 4.1. At present, plants employing the once-though enriched uranium oxide (UOX) fuel have a total capacity of about 325 GWe of electricity. In addition there are plants burning reprocessed mixed Pu and U oxide fuel (MOX) in reactors with a total capacity of about 27 GWe.[6] Current plans call for only one recycle of the fuel. Table 4.1 gives the annual material flows for the entire fleet of reactors.

The proposed mid-century deployment under the global growth scenario of this study is

Table 4.1 Fuel Cycle Characteristics of Current Plants[a]

	U FEED 10^3 MT/YR	HLW DISCHARGED YR^{-1}	Pu DISCHARGED MT/YR	SEPARATED Pu INVENTORY MT
UOX Plants 325 GWe	66.340	Spent UOX: 6471 MTIHM	Discharged: 89.7	—
MOX Plants 27 GWe	3.675	Spent MOX: 179 MTIHM Glass[b]: 109 m^3 Process Waste: 330 m^3	Consumed: 12.6 Discharged: 8.8	6.3[c]

a. Initial enrichment 4.5%, tails assay 0.3%, discharge burnup 50GWd/MTIHM, thermal efficiency 33%, capacity factor 90%. Values on a per GWe basis are given in appendix 4.
b. Requires reprocessing of 944 MTIHM spent UOX per year (0.6 La Hague equivalents). Borosilicate glass contains: 48.6 MT FP, 1.1 MT Pu+MA.
c. Separated Pu storage time is assumed to be 6 months. See Brogli, Krakowski, "Degree of Sustainability of Various Nuclear Fuel Cycles," Paul Scherrer Institut, August 2002.

achieved either by exclusive use of the once-through cycle with current LWRs (option one) or by plutonium recycle (where all the spent UOX but none of the spent MOX is reprocessed) with current LWRs (option two). Under both of these options, material flows increase significantly, as presented in Table 4.2.

The once-through fuel cycle is a technically credible option, assuming there is sufficient uranium ore available at reasonable cost to support a deployment of this size. Note that the single-pass[7] thermal reprocessing option uses almost as much U ore as the once-through system. Furthermore, if there is adequate ore supply at reasonable prices, then the single-pass recycle option will not be economically attractive compared to the once through option as Appendix 4.1 discusses.

As indicated in Table 4.2, the thermal recycle option does have an advantage in producing less material requiring permanent waste disposal, but this is balanced by greater transuranic (TRU)[8] waste produced during reprocessing. Furthermore, the fission product

Table 4.2 Fuel Cycle Characteristics Projected to Mid-Century

	1500 GWE FLEET PER YEAR IN 2051			
	U FEED 10^3 MT/YEAR	**HLW DISCHARGED YEAR^{-1}**	**Pu DISCHARGED MT/YEAR**	**SEPARATED Pu INVENTORY MT**
Scenario 1 Once-through 1500 GWe	306	Spent UOX: 29 864 MTIHM	Discharged: 397	—
Scenario 2 Thermal Recycle[d] UOX Plants: 780 GWe MOX Plants: 720 GWe	257	Glass a: 2886 m^3 Process Waste: 8785 m^3 Spent MOX: 4764 MTIHM	Discharged: 233	167[e]
	FLEET CUMULATIVE, FROM 352GWE IN 2002 TO 1500 GWE IN 2051			
	U FEED 10^6 MT	**HLW DISCHARGED**	**Pu DISCHARGED 10^3 MT**	—
Scenario 1 Once-through 1500 GWe	9.45	Spent UOX: 922·10^3 MTIHM (13.2 YMEs[c])	Discharged: 12.0	—
Scenario 2 Thermal Recycle[d] UOX Plants: 780 GWe MOX Plants: 720 GWe	8.18	Spent UOX: 147·10^3 MTIHM Spent MOX: 124·10^3 MTIHM Glass[b]: 75·103 m^3 Process Waste: 228·103 m^3	Discharged: 8.0	—

a. Requires reprocessing of 26 335 MTIHM spent UOX per year (14 La Hague equivalents). Borosilicate glass contains: 1292.6 MT FP, 30 MT MA, 0.3 MT Pu.
b. Requires reprocessing of 651·10^3 MTIHM spent UOX. Borosilicate glass contains: 33.5·10^3 MT FP, 781 MT MA, 8.7 MT Pu.
c. YME : Yucca Mountain Equivalent (70 000 MTIHM).
d. MOX Plants have 2/3 of the core loaded with UOX and 1/3 loaded with MOX. Hence, 540 GWe is generated from UOX, and 240 GWe is generated from MOX.
e. Separated Pu storage time is assumed to be 6 months. See Brogli, Krakowski, "Degree of Sustainability of Various Nuclear Fuel Cycles," Paul Scherrer Institut, August 2002.

Table 4.3 Global Growth Scenario — Fuel Cycle Parameter comparison. Annual Amounts for 1500 GWe Deployment[a]
See Appendix 4 for fuel cycle calculations.

	OPTION 1A ONCE THROUGH LOW BURN UP	OPTION 1B ONCE THROUGH HIGH BURN UP	OPTION 3 LWR + FAST REACTOR[b]	
			LWR	Fast reactor
Capacity, GWe	1,500	1,500	815	685
Enrichment, %	4.5	8.2	4.5	25
Burn up, GWd/MTIHM	50	100	50	120
Uranium ore				
per year, 10^3 MT/yr	306	286	166	
cumulative, 10^6 MT	9.45	8.76	5.96	
Spent or repr. Fuel				
per year, 10^3 MTIHM/yr	29.9	14.9	Repr.: 20.9 (12.3 LHE[c])	
cumulative, 10^3 MTIHM	922 (13.7 YME)	516 (7.4 YME)	Spent : 4.1 YMEs	
HLW, MT/yr	Not applicable	Not applicable	FP: 1398; MA+Pu: 1.0	
Pu, MT/yr	397	294	0.7 (repr. losses)	
Waste decay heat[d]				
W/GWeY (100 yrs)	$1.1\cdot10^4$	$1.1\cdot10^4$	$2.8\cdot10^3$	
Waste ingestion hazard				
m^3/GWeY (1,000 yrs)	$6.9\cdot10^{11}$	$5.3\cdot10^{11}$	$2.2\cdot10^7$	

a. Thermal efficiency 33% for LWRs and 40% for FRs, capacity factor 90%, enrichment tails assay 0.3%. Capacity is assumed to increase linearly. Fast reactors start deployment in 15 years.

b. Intended as generic fast reactor; data from ANL IFR.

c. LHE means La Hague equivalent (1,700 MTHM/year)

d. The decay heat and radiotoxicity are computed from and MCODE/ORIGEN run and expressed on a per GWe-y basis to establish a fair comparison between the various fuel cycles. The decay heat and radiotoxicity per unit mass can be obtained by dividing by the mass of spent fuel discharged per GWe-y. The spent fuel discharge for option 1A is 22.1 MTIHM/y, giving a decay heat at 100 years of 5.0·102 W/MTIHM and a radiotoxicity at 1000 years of 3.1·1010 m3/MTIHM, as shown in Figures 7.2 and 7.3.

inventory is essentially the same. Most important, the thermal recycle case has a large amount of Pu separated each year.[9] The separated plutonium inventory required for option two is 167 metric tons. A nuclear weapon of significant yield can comfortably be made with less than 10kg of Pu, so this amount represents the potential for thousands of nuclear weapons. Thus, the once-through thermal recycle scenario will not be a reasonable mid-century state, so long as U ore is available at reasonable prices. If ore prices were to become very high, the one-pass thermal recycle option would potentially be attractive, but under those conditions, a fuel cycle that includes reactors that transmute actinides must then be considered (option 3). Single-pass thermal recycle is not an attractive approach for nuclear energy for the next half century.

In option 3 we consider a *fully closed fuel cycle*. This fuel cycle is exactly balanced so the number of fast reactors deployed is sufficient to burn all the actinides produced in once through thermal reactors. Only the fast reactor fuel is reprocessed, presumably in a developed country and a 'secure' energy park; the thermal reactors operating on a once-through cycle, can be located anywhere. This configuration has proliferation advantage over the situation considered in option two, as discussed in Chapter 8. *It is important to note that this balanced closed fuel cycle is entirely different from breeder fast reactor fuel cycles where net plutonium produced in fast reactors is made into MOX fuel to be burned in thermal reactors*. In the closed fuel cycle we considered, the fast reactor burns plutonium and actinides created in the thermal reactor.

In Table 4.3, we describe three illustrative deployments of 1500 reactors each with rated capacity of 1000 MWe, in order to give a more concrete impression of what the global growth scenario might look like. Option one is expanded and option two is replaced by a fully closed fuel cycle. The three options are:

- *Base line*. 1000 MWe LWRs operating on a oncethrough fuel cycle with today's typical characteristics. (Option 1A);
- *Advanced once-through* LWRs , perhaps with some smaller, modular HTGR nuclear systems, with higher fuel burnup characteristics that better meet the four objectives. (Option 1B);
- *Fast reactors* deployed in developed countries with a balanced closed fuel cycle. Reprocessing, fuel fabrication, and fast reactor burners are co-located in secure nuclear energy "parks." In the developing world, the deployment is largely once-through LWR fuel cycle (Option 3).

AVAILABILITY OF URANIUM RESOURCES

How long will the uranium ore resource base be sufficient to support large-scale deployment of nuclear power without reprocessing and/or breeding?[10] Present data suggests the required resource base will be available at an affordable cost for a very long time. Estimates of both known and undiscovered uranium resources at various recovery costs are given in the NEA/IAEA "Red Book"[11]. For example, according to the latest edition of the Red Book, known resources[12] recoverable at costs < $80/kgU and < $130/kgU are approximately 3 and 4 million tonnes of uranium, respectively. However, the amount of known resources depends on the intensity of the exploration effort, mining costs, and the price of uranium. Thus, any predictions of the future availability of uranium that are based on current mining costs, prices and geological knowledge are likely to be extremely conservative.

For example, according to the Australian Uranium Information Center, a doubling of the uranium price from its current value of about $30/kgU could be expected to create about a ten-fold increase in known resources recoverable at costs < $80/kgU[13] i.e., from about 3 to 30 million tonnes. By comparison, a fleet of 1500 1000 MWe reactors operating for 50 years requires about 15 million tonnes of uranium (306,000 MTU/yr as indicated in Table 4.2), using conventional assumptions about burn-up and enrichment.

Moreover, there are good reasons to believe that even as demand increases the price of uranium will remain relatively low: the history of all extractive metal industries, e.g., copper, indicates that increasing demand stimulates the development of new mining technology that greatly decreases the cost of recovering additional ore. Finally, since the cost of uranium represents only a small fraction of the busbar cost of nuclear electricity, even large increases in the former — as may be required to recover the very large quantities of uranium contained at low concentrations in both terrestrial deposits and seawater — may not substantially increase the latter.[14] In sum, we conclude that resource utilization is not a pressing reason for proceeding to reprocessing and breeding for many years to come.

NOTES

1. See, for example, OECD Nuclear Energy Agency, Trends in the Nuclear Fuel Cycle ISBN 92-64-19664-1 (2001) and Nuclear Science Committee "Summary of the workshop on advanced reactors with innovative fuel," October 1998, NEA/NSC/DOC(99)2.
2. Several nations have explored breeder reactors, notably the U.S., France, Russia, Japan, and India.
3. Minor actinides are Americium (Am),Neptunium (Np), and Curium (Cm).
4. There are still other options, such as using an accelerator to produce neutrons in a sub-critical assembly.
5. The three surviving developmental breeder reactors are Phenix in France, Monju in Japan, and BN600 in Russia.
6. The MOX fueled plants are currently operating with only about a third of their core loaded as MOX fuel; the balance is UOX fuel. Hence only about 9 GWe are being generated in these reactors from the MOX fuel
7. Single pass recycle means that a discharged fuel batch is reprocessed once only.
8. TRU here refers to the U.S. definition: low-level waste contaminated with transuranic elements.
9. Due to process holding time, the actual amount of separated Pu inventory could be several or more years' worth of separations.
10. For additional details, see Appendix 5-E and Marvin Miller, *Uranium resources and the future of nuclear power,* Lecture notes, MIT, Spring 2001; for copies contact marvmiller@mit.edu.
11. Uranium resources, production, and demand ("The Red Book"), OECD Nuclear Energy Agency and International Atomic Energy Agency, 2001.
12. Such resources are also known as measured resources and reserves.
13. Uranium Information Center, "Nuclear Electricity", 6th edition, Chapter 3 (2000). Available on the web at http:www.uic.com.au/ne3.htm.
14. For example, recent research in Japan indicates that uranium in seawater — present in concentration of 3.3 ppb — might be recovered at costs in the range of $300–$500/kg.

Chapter 5 — Nuclear Power Economics

Investments in commercial nuclear generating facilities will only be forthcoming if investors expect the cost of producing electricity using nuclear power will be lower than the risk-adjusted costs associated with alternative electric generation technologies. Since nuclear power plants have relatively high capital costs and very low marginal operating costs, nuclear energy will compete with alternative electricity generation sources for “baseload” (high load factor) operation. We recognize that over the next 50 years some significant but uncertain fraction of incremental electricity supplies will come from renewable energy sources (e.g. wind) either because these sources are less costly than alternatives or because government policies (e.g. production tax credits, high mandated purchase prices, and renewable energy portfolio standards) or consumer choice favor renewable energy investments. Despite the efforts to promote renewable energy options, however, it is likely that a large fraction of the incremental and replacement investments in electric generating capacity needed to balance supply and demand over the next 50 years will, in the absence of a nuclear generation option, rely on fossil-fuels — primarily natural gas or coal. This is particularly likely in developing countries experiencing rapid growth in income and electricity consumption. Accordingly, we focus on the costs of nuclear power compared to these fossil fuel generating alternatives in base-load applications.

Any analysis of the costs of nuclear power must take into account a number of important considerations. First, all of the nuclear power plants operating today were developed by state-owned or regulated investor-owned vertically-integrated utility monopolies.[1] Many developed countries and an increasing number of developing countries are in the process of moving away from an electric industry structure built upon vertically integrated regulated monopolies to an industry structure that relies primarily on competitive generation power plant investors. We assume that in the future nuclear power will have to compete with alternative generating technologies in competitive wholesale markets — as merchant plants.[2] These changes in the structure of the electric power sector have important implications for investment in generating capacity. Under traditional industry and regulatory arrangements, many of the risks associated with construction costs, operating performance, fuel price changes, and other factors were borne by consumers rather than suppliers.[3] The insulation of investors from many of these risks necessarily had significant effects on the cost of capital they used to evaluate alternative generation options and on whether and how they took extreme contingencies into account. Specifically, the process reduced the cost of capital and led investors to give less weight to regulatory (e.g. construction and operating licenses) and construction cost uncertainty, operating performance uncertainties and uncertainties associated with future oil, gas and coal prices than if they had to bear these cost and performance risks.

In a competitive generation market it is investors rather than consumers who must bear the risk of uncertainties associated with obtaining construction and operating permits, construction costs and operating performance. While some of the risks associated with uncertainties about the future market value of electricity can be shifted to electricity marketers and consumers through forward contracts, some market risk and all construction cost, operating cost and performance risks will continue to be held by power plant investors.[4] Thus, the shift to a competitive electricity market regime necessarily leads investors to favor less capital-intensive and shorter construction lead-time investments, other things equal.[5] It may also lead investors to favor investments that have a natural "hedge" against market price volatility, other things equal.[6]

Second, the construction costs of nuclear plants completed during the 1980s and early 1990s in the United States and in most of Europe were very high — and much higher than predicted today by the few utilities now building nuclear plants and by the nuclear industry generally. The reasons for the poor historical construction cost experience are not well understood and have not been studied carefully. The realized historical construction costs reflected a combination of regulatory delays, redesign requirements, construction management and quality control problems. Moreover, construction on few new nuclear power plants has been started and completed anywhere in the world in the last decade. The information available about the true costs of building nuclear plants in recent years is also limited. Accordingly, the future construction costs of building a large fleet of nuclear power plants is necessarily uncertain, though the specter of high construction costs has been a major factor leading to very little credible commercial interest in investments in new nuclear plants. Finally, while average U.S. nuclear plant availability has increased steadily during the 1990s to a high of 90% in 2001, many nuclear plants struggled with low availabilities for many years and the life-cycle availability of the fleet of nuclear plants (especially taking account of plants that were closed early) is much less than 90%.[7] In addition, the average operation and maintenance costs of U.S. nuclear plants (including fuel) were over $20/MWh during the 1990s (though average O&M costs had fallen to about $18/MWe-hr and the lowest cost quartile of plants to about $13/MWe-hr by 2001)[8], rather than the $10/MWe-hr often assumed in many paper engineering cost studies.

Third, even if an investment in nuclear power looked attractive on a spreadsheet, investors must confront the regulatory and political challenges associated with obtaining a license to build and operate a plant on a specific site. In the past, disputes about licensing, local opposition, cooling water source and discharge requirements, etc., have delayed construction and completion of nuclear plants. Many planned plants, some of which had incurred considerable development costs, were cancelled. Delays and "dry-hole" costs are especially burdensome for investors in a competitive electricity market.

With these considerations in mind, we now proceed to examine the relative costs of new nuclear power plants, pulverized coal plants, and combined-cycle gas turbine (CCGT) plants in base-load operations in the United States.[9] The analysis is not designed to produce precise estimates, but rather a "reasonable" range of estimates under a number of different assumptions reflecting uncertainties about future construction and operating costs. Similar analysis for Europe and especially Japan and Korea would be somewhat more favorable to nuclear, since gas and coal costs are typically higher than in the United States.

We start with a "base case" that examines the levelized *real* life-cycle costs of nuclear, coal, and CCGT generating technology using assumptions that we believe commercial investors would be expected to use today to evaluate the costs of the alternative generation options. The levelized cost is the constant real wholesale price of electricity that meets a private investor's financing cost, debt repayment, income tax, and associated cash flow constraints.

The base case assumes that non-fuel O&M costs can be reduced by about 25% compared to the recent operating cost experience of the average nuclear plant operating in the U.S. in the last few years. This puts the total O&M costs (including fuel) at about 15 mills/kWe-hr. We include this reduction in O&M costs in the base case because we expect that operators of new nuclear plants in a competitive wholesale electricity market environment will have to demonstrate better than average performance to investors. The 15 mill O&M cost value is consistent with the performance of existing plants that fall in the second lowest cost quartile of operating nuclear plants.[10] (The assumptions underlying the base case are listed in Table 5.3 and illustrative cash flows produced by our financial model are provided in Appendix 5.)

We then examine how the real levelized cost of nuclear generated electricity changes as we allow for *additional* cost improvements. First, we assume that construction costs can be reduced by 25% from the base case levels to more closely match optimistic but plausible forecasts. Second, we examine how life-cycle costs are further reduced by a one-year reduction in construction time. Third, we examine the effects of reducing financing costs to a level comparable to what we assume for gas and coal generating units as a consequence of, for example, reducing regulatory risks and commercial risks associated with uncertainties about construction and operating costs that presently burden nuclear compared to fossil-fueled alternatives. This reduction in financial risk might result from an effective commercial demonstration program of the type that we discuss further in Part II. Finally, we examine how the relative costs of coal and CCGT generation are affected by placing a "price" on carbon emissions, through carbon taxes, the introduction of a carbon emissions cap and trade program, or equivalent mechanism to price carbon emissions to internalize their social costs into investment decisions in a way that treats all supply options on an equivalent basis. We consider carbon prices in a range that brackets current estimates of the costs of carbon sequestration (capture, transport and storage). The latter analysis provides a framework for assessing the option value of nuclear power if and when the United States adopts a program to stabilize and then reduce carbon emissions.

The levelized cost of electric generating plants has typically been calculated under the assumption that their regulated utility owners recover their costs using traditional regulated utility cost of service cost recovery rules. Investments were recovered over a 40 year period and debt and equity were repaid in equal proportions over this lengthy period at the utility's cost of capital, which reflected the risk reducing effects of regulation. Moreover, the calculations typically provided levelized *nominal* cost values rather than levelized *real* cost values, obscuring the effects of inflation and making capital intensive technologies look more costly relative to alternatives than they really were.

We do not believe that these traditional levelized cost models based on regulated utility cost recovery principles provide a good description of how merchant plants will be financed in the future by private investors. Accordingly, we have developed and utilized an alternative model that provides flexibility to specify more realistic debt repayment obligations and associated cash flow constraints, as well as the costs of debt and equity and income tax obligations that a private firm would assign to individual projects with specific risk attributes, while accounting for corporate income taxes, tax depreciation and the tax shield on interest payments. We refer to this as the Merchant Cash Flow model. We have relied primarily on simulation results using this model under assumptions of both a 25-year and 40-year capital recovery period and 85% and 75% lifetime capacity factors.

BASE CASE

The base case reflects reasonable estimates of the current perceived costs of building and operating the three generating alternatives in 2002 U.S. dollars. The overnight capital cost for nuclear in the base case is $2000/kWe. As discussed in Appendix 5, this value is consistent with estimates made by the U.S. Energy

Information Administration (EIA), estimates reported by other countries to the OECD, and recent nuclear plant construction experience abroad. We have not relied on construction cost data for U.S. plants completed in the late 1980s and early 1990s; if we had, the average overnight construction cost in 2002 U.S. dollars would have been much higher. We are aware that some vendors and some potential investors in new nuclear plants believe that they can achieve much lower construction costs. We consider significant construction cost reductions in our discussion of improvements in nuclear costs.[11]

As previously discussed, our base case assumes that O&M costs are 15 mills/kWe-hr, which is lower than the recent experience for the average nuclear plant and is consistent with the recent performance of plants in the second lowest cost quartile of operating nuclear plants in the U.S. The O&M costs of plants in the lowest cost quartile (best performers) are about 13 mills/kWe-hr. We consider this to represent the potential for further cost improvements for a fleet of new nuclear plants but we do not believe that investors will assume that all plants will achieve the O&M cost levels of the best performers.

The construction costs assumed for CCGT and coal plants are in line with experience and EIA estimates. The construction cost of the coal plant is assumed to reflect NOx and SO_2 controls as required to meet current New Source Performance Standards. There are four cases presented for the CCGT plants: (1) a low gas price case that starts with gas prices at \$3.50/MMBtu which rise at a real rate of 0.5% over 40 years (real levelized cost of \$3.77/MMbtu over 40 years); (2) a moderate gas price case with gas prices starting at \$3.50/MMBtu as well, but rising at a real rate of 1.5% per year over 40 years (real levelized cost of \$4.42 over 40 years); (3) high gas price case that starts at \$4.50/MMbtu and rises at a real rate of 2.5% per year (real levelized cost of \$6.72/Mmbtu over 40 years). (4) The fourth CCGT case reflects high gas prices and an advanced CCGT design with a (roughly) 10% improvement in its heat rate. The base case results for 25 and 40-year economic lives and 85% capacity factor are reported in Table 5.1 and the equivalent results for a 75% lifetime capacity factor are reported in Table 5.2. The assumptions for the cases are given in Table 5.3. The discussion that follows is based on the 85% capacity factor simulations since the basic results don't change very much when we assume the lower capacity factor.

The base case results suggest that nuclear power is much more costly than the coal and gas alternatives even in the high gas price cases. In the low gas price case, CCGT is cheaper than coal. In the moderate gas price case, total life-cycle coal and gas costs are quite close together, though we should recognize that there are regions of the country with below average coal costs where coal would be less costly than gas and vice versa. Under the high gas price assumption, coal beats gas by a significant amount. (We have not tried to account for the relative difficulties of siting coal and gas plants.) We discuss potential future carbon emissions regulations separately below.

This suggests that high natural gas prices will eventually lead investors to switch to coal rather than to nuclear under the base case assumptions as nuclear appears to be so much more costly than coal and U.S. coal supplies are very elastic in the long run so that significant increases in coal demand will not lead to significant increases in long term coal prices. In countries with less favorable access to coal, the gap would be smaller, but 2.5 cents/kWe-hr is too large a gap for nuclear to beat coal in many areas of the world under the base case assumptions (absent additional restrictions on emissions of carbon dioxide from coal plants which we examine separately below).

The bottom line is that with current expectations about nuclear power plant construction costs, operating cost and regulatory uncertainties, it is extremely unlikely that nuclear power will be the technology of choice for merchant plant investors in regions where suppliers have access to natural gas or coal resources. It is just too expensive. In countries that rely on state owned enterprises that are willing and able to shift cost risks to consumers to reduce the cost of capital, or to subsidize financing costs directly, and which face high gas and coal costs, it is possible that nuclear power could be perceived to be an economical choice.[12]

IMPROVEMENTS IN NUCLEAR COSTS

We next examine how the cost of electricity generated by nuclear power plants would change, if effective actions can be taken to reduce nuclear electric generation costs in several different ways. First, we assume that construction costs can be reduced by 25%. This brings the construction costs of a nuclear plant to a level more in line with what the nuclear industry believes is feasible in the medium term under the right conditions.[13] While this reduces the levelized cost of nuclear electricity considerably, it is still not competitive with gas or coal for any of the base cases. Reducing construction time from 5 years to 4 years reduces the levelized cost further, but not to a level that would make it competitive with fossil fuels. However, if regulatory, construction and operating cost uncertainties could be resolved, and the nuclear plant could be financed under the same terms and conditions (cost of capital) as a coal or gas plant, then the costs of nuclear power become very competitive with the costs of CCGTs in a high gas price world and only slightly more costly than pulverized coal plants, assuming that comparable improvements in the costs of building coal plants are not also achieved. If nuclear plant operators could reduce O&M costs by another 2 mills to 13 mills/kWe-hr, consistent with the best performers in the industry, nuclear's total cost would match the cost of coal and the cost of CCGT in the moderate and high gas price cases. However, nuclear does not have a meaningful economic advantage over coal.

These results suggest that with significant improvements in the costs of building, operating, and financing nuclear power plants, and continued excellent operating performance (85% capacity factor), nuclear power could be quite competitive with natural gas if gas prices turn out to be higher than what most analysts now appear to believe and would be only slightly more costly than coal within the range of assumptions identified.[14]

The cost improvements we project are plausible but unproven. It should be emphasized, that the cost improvements required to make nuclear power competitive with coal are significant: 25% reduction in construction costs; greater than a 25% reduction in non-fuel O&M costs compared to recent historical experience (reflected in the base case), reducing the construction time from 5 years (already optimistic) to 4 years, and achieving an investment environment in which nuclear power plants can be financed under the same terms and conditions as can coal plants. Moreover, under what we consider to be optimistic, but plausible assumptions, nuclear is never less costly than coal.

CARBON "TAXES"

From a societal cost perspective, all external social costs of electricity generation should be reflected in the price. Here we consider the cost of CO_2 emissions and not other externalities; for example we ignore the costs of other air pollutants from fossil fuel combustion and nuclear proliferation and waste issues (except for including the costs of new coal plants to meet new source performance standards). Nuclear looks more attractive when the cost of CO_2 emissions is taken into account. Unlike gas and coal-fired plants, nuclear plants produce no carbon dioxide during operation and do not contribute to global climate change. Accordingly, it is natural to explore what the comparative social cost of nuclear power would be, if carbon emissions were "priced" to reflect the marginal cost of achieving global carbon emissions stabilization and reduction targets.[15] Future United States policies regarding carbon emissions are uncertain at the present time.

Table 5.1 Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (85% capacity factor)

Base Case	25-YEAR	40-YEAR
Nuclear	7.0	6.7
Coal	4.4	4.2
Gas (low)	3.8	3.8
Gas (moderate)	4.1	4.1
Gas (high)	5.3	5.6
Gas (high) Advanced	4.9	5.1
Reduce Nuclear Costs Cases		
Reduce construction costs (25%).	5.8	5.5
Reduce construction time by 12 months	5.6	5.3
Reduce cost of capital to be equivalent to coal and gas	4.7	4.4

Carbon Tax Cases (25/40 year)	$50/tC	$100/tC	$200/tC
Coal	5.6/5.4	6.8/6.6	9.2/9.0
Gas (low)	4.3/4.3	4.9/4.8	5.9/5.9
Gas (moderate)	4.6/4.7	5.1/5.2	6.2/6.2
Gas (high)	5.8/6.1	6.4/6.7	7.4/7.7
Gas (high) advanced	5.3/5.6	5.8/6.0	6.7/7.0

Table 5.2 Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (75% capacity factor)

Base Case	25-YEAR	40-YEAR
Nuclear	7.9	7.5
Coal	4.8	4.6
Gas (low)	4.0	3.9
Gas (moderate)	4.2	4.3
Gas (high)	5.5	5.7
Gas (high) advanced	5.0	5.2
Reduce Nuclear Costs Cases		
Reduce construction costs (25%)	6.5	6.2
Reduce construction time by 12 months	6.2	6.0
Reduce cost of capital to be equivalent to coal and gas	5.2	4.9

Carbon Tax Cases (25/40 year)	$50/tC	$100/tC	$200/tC
Coal	6.0/5.8	7.2/7.0	9.6/9.4
Gas (low)	4.5/4.4	5.0/5.0	6.0/6.0
Gas (moderate)	4.7/4.8	5.3/5.3	6.3/6.4
Gas (high)	6.0/6.3	6.5/6.8	7.5/7.8
Gas (high) advanced	5.5/5.7	5.9/6.2	6.8/7.1

By examining the relative economics of nuclear power under different assumptions about future social valuations for reducing carbon emissions, we can get a feeling for the option value of nuclear generation in a world with carbon emissions restrictions of various severities.

To examine this question we have recalculated the costs of the fossil-fueled generation alternatives to reflect a carbon tax of $50/tC, $100/tC, and $200/tC. The lower value is consistent with an EPA estimate of the cost of reducing U.S. CO_2 emissions by about 1 billion metric tons per year.[16] The $100/tC and $200/tC values bracket the range of values that appear in the literature regarding the costs of carbon sequestration, recognizing that there is enormous uncertainty about the costs of deploying CO_2 capture, transport, and storage on a large scale. These hypothetical taxes should be thought of as a range of “backstop” marginal costs for reducing carbon emissions to meet aggressive global emissions goals. These results are reported in Table 5.1 and 5.2, as well.

With carbon taxes in the $50/tC range, nuclear is not economical under the base case assumptions. If nuclear costs can be reduced to reflect all of the cost-reduction specifications discussed earlier, nuclear would be less costly than coal and less costly than gas in the high gas price cases. It is roughly competitive with gas in the low and moderate price gas cases. With carbon taxes in the $100/tC to $200/tC range, nuclear power would be an economical base load option compared to coal under the base case assumptions, but would still be more costly than gas except in the high gas price case. However, nuclear would be significantly less costly than all of the alternatives with carbon prices at this level, if all of the cost reduction specifications discussed earlier could be achieved.

The last conclusion ignores one important consideration. With carbon taxes at these high levels, it could become economical to deploy a generating technology involving the gasification of coal, its combustion in a CCGT (IGCC), and the sequestration of carbon dioxide produced in the process. The potential cost savings from this technology compared to conventional pulverized coal plants arises from (a) the use of relatively inexpensive coal to produce syngas (mostly CO and H_2) (b) the higher thermal efficiency of CCGT, and more economical capture of CO_2. Depending on the economics of this technology, coal could play a larger competitive role in a world with high carbon taxes than might be suggested by Tables 5.1 and 5.2. We observe as well, that from an environmental perspective, the world looks very different if there are abundant supplies of cheap natural gas, than if natural gas supplies are scarcer and significantly more expensive than many recent projections imply.

Table 5.3 Base Case Assumptions

Nuclear	
Overnight cost:	$2000/kWe
O&M cost:	1.5 cents/kWh (includes fuel)
O&M real escalation rate:	1.0%/year
Construction period:	5 years
Capacity factor:	85%/75%
Financing:	
Equity: 15% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income Tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 50%	
Debt: 50%	
Project economic life:	40 years/25 years
Coal	
Overnight cost:	$1300/kWe
Fuel Cost:	$1.20/MMbtu
Real fuel cost escalation:	0.5% per year
Heat rate (bus bar):	9300 BTU/klWh
Construction period:	4 years
Capacity factor:	85%/75%
Financing:	
Equity: 12% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income Tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 40%	
Debt: 60%	
Project economic life:	40 years/25 years
Gas CCGT	
Overnight cost:	$500/kWe
Initial fuel cost:	
Low: $3.50/MMbtu ($3.77/MMbtu real levelized over 40 years)	
Moderate: $3.50/MMbtu ($4.42/MMbtu real levelized over 40 years)	
High: $4.50/MMbtu ($6.72/MMbtu real levelized over 40 years)	
Real fuel cost escalation:	
Low: 0.5% per year	
Moderate: 1.5% per year	
High: 2.5% per year	
Heat rate:	7200 BTU/kWh
Advanced:	6400 BTU/kWh
Construction period:	2 years
Capacity factor:	85%/75%
Financing:	
Equity: 12% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 40%	
Debt: 60%	
Project economic life:	40 years/25 years

INTERNATIONAL PERSPECTIVE ON COST OF ELECTRICITY

The methodology followed above is pertinent to an electricity generation market that is unregulated, a situation that the United States is moving toward, as are several other countries. An additional advantage to describing deregulated market situations is that the methodology properly focuses on the true economic cost of electricity generating alternatives. There are however many nations that do not enjoy an unregulated generating market and are unlikely to adopt deregulation for some time to come. In many of these countries electricity generation is run directly or indirectly by the government and significant subsidies are provided to generating facilities. The electricity "cost" in these countries is not transparent and leads to a different political attitude toward investment decisions because consumers enjoy subsidized prices. The result is a misallocation of resources and over the long-run one can expect that political and economic forces will call for change. These non-market situations are encountered in Europe, e.g. Electricite de France, although there is a strong move to deregulation in the EU and in developing countries that frequently have state run power companies. Importantly, the costs of advanced fuel cycle technologies such as PUREX reprocessing and MOX fabrication are heavily subsidized reflecting political rather than economic decision making.

COST OF ADVANCED FUEL CYCLES.

We have not undertaken as complete analysis for the costs of advanced fuel cycles as we have for the open fuel cycle. We have however examined in some detail the cost of the closed fuel cycle with single pass PUREX/MOX relative to the open cycle. This analysis is reported in the Appendix 5.D.

The fuel cycle cost model presented in Appendix 5.D shows that the closed cycle PUREX/MOX option fuel costs are roughly 4 times greater than for the open cycle, using estimated costs under U.S. conditions. The closed cycle can be shown to be competitive with the once-through option only if the price of uranium is high and if optimistic assumptions are made regarding the cost of reprocessing, MOX fabrication, and high level waste disposal. As explained in Appendix 5.D, the effect of the increased MOX fuel cycle cost on the cost of electricity depends upon the percentage of MOX fuel in the entire fleet if fuel costs are blended.

The case is often advanced that disposing of reprocessed high level waste will be less expensive than disposing of spent fuel directly. But there can be little confidence today in any estimate of such cost savings, especially if disposal of non-high-level waste contaminated with significant quantities of long-lived transuranic radionuclides (TRU waste) associated with recycle facilities and operations is taken into account. Furthermore, our cost model shows that even if the cost of disposing of reprocessed high-level waste were zero, the basic conclusion that reprocessing is uneconomic would not change.

It should be noted that the cost increment associated with reprocessing and thermal recycle is small relative to the total cost of nuclear electricity generation. In addition, the uncertainty in any estimate of fuel cycle costs is extremely large.

NOTES

1. Though in the United States and the United Kingdom some nuclear plants were subsequently sold or transferred to merchant generating companies.
2. Merchant plants sell their output under short, medium and longer term supply contracts negotiated competitively with distribution companies, wholesale and retail marketers. The power plant developers take on permitting, development, construction cost and operating performance risks but may transfer some or all risks associated with market price volatility to buyers (for a price) through the terms of their contracts.
3. It is often assumed that regulated monopolies were subject to "cost-plus" regulation which insulated utilities from all of these risks. This is an extreme and inaccurate characterization of the regulatory process, at least in the United States. (P.L. Joskow and R. Schmalensee, "Incentive Regulation for Electric Utilities," *Yale Journal on Regulation*, 1986; P.L. Joskow, "Deregulation and Regulatory Reform in the U.S. Electric Power Sector," in *Deregulation of Network Industries: The Next Steps* (S. Peltzman and Clifford Winston, eds.), Brookings Press, 2000). Several U.S. utilities were faced with significant cost disallowances associated with nuclear power plants they completed or abandoned, a result inconsistent with pure cost-plus regulation. Nevertheless, it is clear that a large fraction of these cost and market risks were shifted to consumers from investors when the industry was governed by regulated monopolies.
4. The current state of electricity restructuring and competition in the United States and Europe has made it difficult for suppliers to obtain forward contracts for the power they produce. We believe that this chaotic situation is unsustainable and that a mature competitive power market will make it possible for power suppliers to enter into forward contracts with intermediaries. However, these contracts will not generally be like the 30-year contracts that emerged under regulation which obligated wholesale purchasers (e.g. municipal utilities) to pay for all of the costs of a power plant in return for any power it happened to produce. In a competitive market the contracts will be for specified delivery obligations at a specified price (or price formula), will tend to be much shorter (e.g. 5-year contract portfolios), and will place cost and operating performance risk on the generator not on the customer.

5. Oversimplifying, these effects can be thought of as an increase in the cost of capital faced by investors.
6. For example, in areas of the United States where the wholesale market tends to clear with conventional gas or oil-fired power plants on the margin, spot market clearing prices will move up and down with the price of natural gas and oil. A combined cycle gas turbine (CCGT) that also burns natural gas, but with a heat rate 35% lower on average than those of the marginal gas plants that clear the market (e.g. 11,000 BTU/kWh), will always run underneath the market clearing price of electricity. Whatever the price of gas, the CCGT is always in the money and will be economical to run under these circumstances. If gas prices go up, the CCGT will be more profitable, and if they go down it will be less profitable, but the volatility in profits with respect to changes in gas prices will be lower than that for coal or nuclear plants.
7. In 2000, the capacity factors for the nuclear plants in France were 76%, for those in Japan 79%, and for those in South Korea, 91%. Ideally, we would look at availability data, but except for France where nuclear accounts for such a large share of electricity supply that some plants must by cycled up and down, nuclear units are generally run full out when they are available (Source: Calculated from data on EIA web site.)
8. These numbers underestimate the true O&M costs of nuclear plants because they exclude administrative and general operating costs that are typically captured elsewhere in utility income statements. These overhead costs probably add another 20% to nuclear O&M costs. We do not consider these additional costs here because they are also excluded from the O&M costs for competing technologies. In a competitive power market, however, generating plants must earn enough revenues to cover these overhead costs as well as their direct capital and O&M costs.
9. That is, we are not considering competition between new nuclear plants and *existing* coal and gas plants (whose construction costs are now sunk costs). We recognize there may be economical opportunities to increase the capacity of some existing nuclear plants and to extend their commercial lives. We do not consider these opportunities here.
10. The reduced non-fuel O&M costs assumed are about 10 mills/kWh in the base case and compare favorably to 9 mills/kWh assumed by TVA (90% capacity factor) in its recent evaluation of the restart of Browns Ferry Unit #1.
11. Of course, in a competitive wholesale electricity market investors are free to act on such expectations by making financial commitments to build new nuclear plants. About 150,000 MWe of new generating capacity has been built in the U.S. in the last five years, most of it owned by merchant investors and most of it fueled by natural gas and none of it nuclear. See Paul L. Joskow, "The Difficult Transition to Competitive Electricity Markets in the U.S.," May 2003
12. We have seen some analyses that assume that nuclear plants will be financed with 100% government-backed debt, pay no income or property taxes, and have very long repayment schedules. One can make the costs of nuclear power look lower this way, but it simply hides the true costs and risks of the projects which have effectively been transferred to consumers and taxpayers.
13. This brings the nuclear plant cost down to $1500/kW. This is roughly the cost used in the analysis of the costs of a new nuclear power plant in Finland at current exchange rates. (However, the Finnish analysis assumes that the plant can be financed with 100% debt at a 5% real interest rate and would pay no income taxes). Note, however, that TVA estimates that the costs of *refurbishing* a mothballed unit at Browns Ferry will cost about $1300/kWe, and that recent Japanese experience is closer to the $2000/kWe base case assumption. TVA's analysis of the costs of refurbishing the Browns Ferry unit assume that the project can be financed with 100% debt at an interest rate 80 basis points above 10-year treasury notes and would pay no taxes.
14. Obviously, there is some set of assumptions that will make nuclear cheaper than coal. However, they basically require driving the construction costs and construction time profile to be roughly equivalent to those of a coal unit. We also have not assumed any improvements in construction costs or heat rates for coal units associated with advanced coal plant designs.
15. We have modeled the carbon "price" as a carbon dioxide emissions tax. However, the intention is to simulate any policies that give nuclear power "credit" relative to fossil fuel alternatives for producing no CO_2.
16. "Summary and Analysis of McCain-Leiberman 'Climate Stewardship Act of 2003'," William Pizer and Raymond Kopp, Resources for the Future, January 28, 2003.

Chapter 6 — Safety

Safe operations of the entire nuclear fuel cycle are a paramount concern. In this chapter we address reactor safety, the continuing availability of trained personnel for nuclear operations, the threat of terrorist attack, and nuclear fuel cycle safety, including nuclear fuel reprocessing plants.

There are about 100 nuclear power plants in the U. S., and over 400 in the world, mostly light water reactors (LWRs). With the benefit of experience and improved plant designs going into service, performance has improved over time to unit capacity factors[1] of 90% and higher in the U.S.[2] The means of improvement include independent peer review and the feedback of operating experience at reactor fleets worldwide, so that all operators become aware of mishaps that occur, and the commitment of plant owners and managements to the development of safety culture within the organizations that operate nuclear power plants. These actions and initiatives in training and qualification of reactor operators that have been implemented by organizations of plant owners[3] are major factors in the performance improvements. Experience also includes three serious reactor accidents[4] and several fuel cycle facility accidents.[5]

A number of events have occurred at reactors that were headed for an accident but stopped short. Such an event[6] came to light during an inspection of the Davis-Besse reactor vessel head in March, 2002, during reactor shutdown. The inspection disclosed a large cavity in the vessel head next to one of the reactor control rod drive mechanisms, caused by boric acid leakage and corrosion. The cavity seriously jeopardized reactor vessel integrity. Fortunately, the fault was discovered before restart of the reactor. This event discloses a failure on the part of the plant owners to respond to earlier indications of an issue and to look for problems in an early stage at their plant. It is still an open question whether the average performers in the industry have yet incorporated an effective safety culture into their conduct of business. The U.S. Nuclear Regulatory Commission shares responsibility in the matter, as it accepted delay of scheduled surveillance and inspection of vital primary system components. A major nuclear power initiative will not gain public confidence, if such failures occur.

With regard to the mandate of the Nuclear Regulatory Commission for safety of nuclear plants in the U. S., the Davis-Besse incident also raises questions about whether nuclear reactor safety goals are compatible with the transition to competitive electricity markets. On the one hand some observers suggest that unregulated generators will be more concerned with maximizing plant output and less willing to close plants for safety inspections and corrective actions where necessary. On the other hand, owners groups have long stated that nuclear plant operation conducted to ensure a high level of safety is also economically beneficial. Further, nuclear plant accident costs are not financially attractive for plant owners. While there may be some accident costs that are not fully internalized into decisions made by individual nuclear plant owners, the owner of a plant that has a serious accident would face very significant adverse financial consequences, as was the case of General Public Utilities after the accident at Three Mile Island Unit 2. We believe it is important to maintain the principle that the primary responsibility for safe operation of nuclear plants rests with the plant owners and operators, as the generation segment of the electric power industry is deregulated, and that the Nuclear Regulatory Commission should adapt its inspection activities, reporting requirements, and enforcement actions to reflect the new incentives created by competitive generation markets.

REACTOR SAFETY

The global growth scenario considered in this report is a three-fold increase in the world nuclear fleet capacity by 2050. The goal, of course, should be to carry out this large expansion without increasing the frequency of serious accidents. We believe this can be accomplished by means of both evolutionary and new technologies focused on LWRs.

Three major reasons for reducing the frequency of serious accidents are: first, and foremost, they are a threat to public health. Reactor core damage has the potential to release radioactivity to air and groundwater. Second, an accident destroys capital assets. Loss of a plant costs billions of dollars and could restrict electrical generating capacity in the locality until replacement, thereby adding to the economic loss. Third, a serious accident erodes public confidence in nuclear generation, with possible consequences of operating plant shutdowns, and/or moratoria on new construction.

What is the expected frequency of accidents today with the currently operating nuclear plants? There are two ways to determine the frequency of accidents: historical experience and Probabilistic Risk Assessment.[7] Since the beginning of commercial nuclear power in 1957, more than 100 LWR plants have been built and operated in the U.S., with a total experience of 2679 reactor-years through 2002. During this time, there has been one reactor core damage accident at Three Mile Island Unit 2. The core damage frequency of U.S. reactors is therefore 1 in 2679 reactor-years on average.

Probabilistic Risk Assessment (PRA) identifies possible failures that can occur in the reactor, e.g., pipe breaks or loss-of-reactor coolant flow, then traces the sequences of events that follow, and finally determines the likelihood of their leading to core damage. PRA includes both internal events and external events, i.e., natural disasters. Expert opinion using PRA considers the best estimate of core damage frequency to be about 1 in 10,000 reactor-years for nuclear plants in the United States. Although safety technology has improved greatly with experience, remaining uncertainties in PRA methods and data bases make it prudent to keep actual historical risk experience in mind when making judgments about safety.

With regard to implementation of the global growth scenario during the period 2005-2055, both the historical and the PRA data show an unacceptable accident frequency. The expected number of core damage accidents during the scenario with current technology[8] would be 4. We believe that the number of accidents expected during this period should be 1 or less, which would be comparable with the safety of the current world LWR fleet. A larger number poses potential significant public health risks and, as already noted, would destroy public confidence. We believe a ten-fold reduction in the likelihood of a serious reactor accident,[9] i.e., a core damage frequency of 1 in 100,000 reactor- years is a desirable goal and is also possible, based on claims of advanced LWR designers, that we believe plausible. In fact, advanced LWR designers claim that their plant designs already meet this goal, with even further reduction possible. If these claims and other plant improvements and cost reductions are verified, advanced LWRs will be in a very good position to drive a large share of the global growth scenario market.

For future LWR development, we recommend implementation of designs that use a combination of passive and active features in order to enhance reliability of plant safety systems. Passive systems utilize stored energy for pumping, either by means of pressurized tanks or by gravity acting on water in elevated tanks. They substitute for motor-driven pumps ultimately driven by emergency diesel generators, and can thereby remove the risk of failure of diesels to start when needed, i.e., during a station blackout.

Additional gains may come with the introduction of High-Temperature Gas Reactors (HTGRs). In principle the HTGR may be superior to the LWR in its ability to retain fission products in a loss-of- coolant accident, because of fuel form and because core temperatures can be kept sufficiently low due to low power density design and high heat capacity of the core, if RD&D validates this feature. Two HTGR plants of small capacity and modular design are under development for eventual commercial application.

We describe briefly deployment for the global growth scenario, first for LWRs, and then for HTGRs. Because of the experience base, construction of certified LWR designs at approved sites could begin within the year or two required for contractual arrangements, limited primarily by retooling of a dormant industry, and obtaining regulatory approvals under new licensing procedures. In order to build the global growth scenario capacity of 1000 GWe in 50 years, an average rate of construction of 20 to 25 plants[10] per year would be required, with greater numbers in later years. For historical comparison, LWR actual worldwide construction totaled about 400 plants over 25 years, for an average of 16 plants completed per year. Doubling the past rate of construction for this scenario is not an unreasonable projection, but remains a challenge, because plant construction time must also be reduced in order to reduce plant capital cost.

LWR experience does not exclude entry of the HTGR into the marketplace. However, it does focus attention on the lead times and costs associated with its development and the need for operating experience before commitment of capital investment and the large manufacturing expansion required to carry it out.

We believe that the lead time to carry out RD&D requirements for HTGR licensing, and at least several years of operation by one or more demonstration plants, will add up to 15 to 20 years before rapid, commercial deployment can be expected. Given this lead time, we expect that two thirds or more of the fleet through 2050 will be LWRs.

It is possible with success at every turn that HTGR deployment could make up as much as one third of the global growth scenario. The uncertainties in this projection are large, however, and a range of HTGR penetration from very small to a high of one third is realistic. We note that the plant capacity of the two HTGR concepts is in the range of 125-350 MWe, i.e., substantially smaller than LWR plants. This is a very attractive feature of HTGRs, if cost targets are met. Depending on the market shares of the two HTGR concepts, about 4 plants would be required to equal the output of a 1000 MWe LWR. If HTGR plants were to capture one third of the mid-century scenario, there would be about twice as many HTGRs as LWRs in 2050.

TRAINING AND QUALIFICATION OF PLANT MANAGEMENT AND STAFF

Realization of the mid-century scenario has important implications for safety, and especially in training and qualification of people competent to manage and operate the plants safely, including the supporting infrastructure necessary for maintenance, repair, refueling, and spent fuel management. Development of competent managers and identification of effective management processes is a critical element in achieving safe and economic nuclear power plant operations. For developed countries that now operate nuclear plants, these tasks require attention to the rejuvenation of the entire workforce.[11]

For developing countries, however, this challenge is much greater, because of the lack of workers in the many skills required in nuclear power plant construction, operations, and maintenance. The workforce must be trained and grow from a small or negligible base. There are two main models for realization of the necessary growth: first, "do it yourself," and second, the commercial mode of importing goods and services. The first takes time and is subject to error in the process of learning. The second is expensive in the long run and fails to create skills and provide jobs at home. The best path for most developing countries is likely to be some combination of the two models that yields both competence and jobs.

TERRORIST ATTACK ON NUCLEAR INSTALLATIONS

Terrorists have demonstrated their ability to inflict catastrophic damage. Nuclear facilities as potential targets have not escaped notice. On the one hand experts have concluded that civil works and security provisions make nuclear plants hard targets. On the other hand, the hazards are on a scale previously considered to be extremely rare in evaluation of severe reactor accidents. The question is what new security measures, if any, are appropriate? We believe there is no simple, one-size-fits-all answer. It depends on many factors including threat evaluation, plant location, facility design, and government security resources and practices.

Nuclear plant safety is a good starting point for the evaluation of security risk. What we conclude about plants also applies to other fuel cycle facilities. Nuclear plant safety has considered natural external events, such as earthquakes, tornadoes, floods, and hurricanes. Terrorist attack by fire or explosion is analogous to external natural events in its implication for damage and release of radioactivity. The strength of containment buildings and structures presents a major obstacle and hardened target for attack. The Electric Power Research Institute[12] carried out an evaluation of aircraft crash and NPP structural strength, concluding that U.S. containments would not be breached. The U.S. NRC is performing its own evaluation, including structural testing at Sandia National Laboratory, not yet complete.

A broad survey and evaluation of hazards and protective actions is in order to make decisions on adequate protection. Such a survey must begin by identifying possible modes of attack and vulnerabilities associated with designs and locations. It must also identify the cost effectiveness of a range of security options for new designs, old plants near decommissioning, and plants in mid-life. There is also a need for sharing information with governments of countries and supporting institutions that will undertake nuclear power programs in order to provide effective intelligence and security.

NUCLEAR FUEL CYCLE SAFETY

Realization of the global growth scenario entails construction and operation of many fuel cycle facilities around the world, such as those described in Chapter IV, and also the facilities and repositories associated with waste management. There are varying degrees of risk to public safety associated with these facilities, and therefore a need for systematic evaluation of risk on a consistent basis that takes into account evaluations performed heretofore on individual fuel cycle facilities.

The need for such an evaluation is especially important in the case of reprocessing plants. The United States does not have any commercial reprocessing plants. France, the United Kingdom and Japan have reprocessing plants in operation, based on aqueous PUREX separations technology and improvements to it over many years. Pyro-reprocessing and dry reprocessing R&D has been done with no commercial application as yet. Aqueous separation plants have high inventories of fission products, as well as fissile material of work in process, and many waste streams. Future improvements in separation technology may be capable of reducing radioactive material inventories, measured as a fraction of annual throughput, but inventories will continue to be large, because of the large annual product required, if and when reprocessing comes into wider commercial use many years in the future.

We are concerned about the safety of reprocessing plants,[13] because of large radioactive material inventories, and because the record of accidents, such as the waste tank explosion at Chelyabinsk in the FSU, the Hanford waste tank leakages in the United States and the discharges to the environment at the Sellafield plant in the United Kingdom. Releases due to explosion or fire can be sudden and widespread. Although releases due to leakage may take place slowly, they can have serious long-term public health consequences, if they are not promptly brought under control. Although the hazards of reprocessing plants differ from those of reactors, the concepts and methods and practices of reactor safety are broadly applicable to assuring the safety of reprocessing plants. We do not see the need for commercial reprocessing in the global growth scenario, but we believe the subject requires careful study,[14] and action, if and when reprocessing becomes necessary.

NOTES

1. Capacity factor is the ratio of actual annual plant electrical production and maximum annual production capability.
2. While worldwide capacity factors (around 75%) are lower than those recently achieved in the U.S., a similar trend of improved capacity factors is observed outside of the U.S. as well.
3. The Institute of Nuclear Power Operations in the U.S. and the World Association of Nuclear Operators worldwide.
4. Windscale, UK, gas-cooled reactor, graphite combustion due to graphite stored heat release, with limited release of radioactivity, 1952; TMI 2, PWR, loss-of-coolant, 20% core meltdown, and small release, 1979; Chernobyl, graphite-moderated, water-cooled reactor, reactivity accident with large external release of radioactivity and health effects, 1986.
5. Chelyabinsk, FSU, reprocessing waste explosion, (1957); Hanford, Washington State, waste storage tank leakage, (1970-); Sellafield, UK, reprocessing waste discharges into ocean, (1995-), Tokai-Mura, Japan, nuclear criticality incident in fuel fabrication, (1999). We know of no complete inventory of reprocessing accidents; such a survey is needed.
6. A similar event was discovered at a French nuclear power plant in 1991.
7. Three important references are: Reactor Safety Study, WASH 1400, U.S. Nuclear Regulatory Commission, October 1975; Severe Accident Risks, NUREG-1150, U.S. NRC, December 1990; and Individual Plant Examination Program, NUREG-1560, U.S. NRC, December 1997.
8. The number of core damage accidents expected is the product of the CDF and the reactor-years of experience. We assume a CDF of 10-4 and 40,000 reactor-years experience during the period of 2005 to 2055: the product is 4 accidents. The Safety Appendix 6 explains the relevant data in more detail.
9. Potentially large release of radioactivity from fuel accompanies core damage. Public health and safety depends on the ability of the reactor containment to prevent leakage of radioactivity to the environment. If containment fails, there would be a large, early release (LER) and exposure of people for some distance beyond the plant site boundary, with the amount of exposure depending on accident severity and weather conditions. The probability of containment failure, given core damage, is about 0.1. Hence the frequency of a LER is 1 in 1,000,000 years. LER is defined in U.S. NRC Regulatory Guide 1.174.
10. We expect individual plant capacities in the range of 600-1500 MWe. In developed countries the average plant capacity is expected to be about 1000 MWe, with a smaller average capacity in developing countries.
11. The workforce has been aging for more than ten years due to lack of new plant orders and decline of industrial activity.
12. Deterring Terrorism - Aircraft Crash Impact Analyses Demonstrate Nuclear Power Plant's Structural Strength; EPRI Study, Nuclear Energy Institute website, www.nei.org, December 2002.
13. A brief comparison of reprocessing plants with reactors shows that the historical accident frequency of reprocessing plants is much larger than reactors: three of the more significant accidents are cited in footnote 5. Furthermore, the number of reprocessing plant-years of operation is many fewer that in the case of reactors. Therefore the accident frequency of reprocessing plants is much higher.
14. We are not aware of PRA analyses of fuel cycle facilities; one exception is: *Status report on the EPRI fuel cycle accident risk assessment*, prepared by SAIC for EPRI report number NP-1128, July 1979.

Chapter 7 — Spent Fuel/High-Level Waste Management

The management and disposal of radioactive waste from the nuclear fuel cycle is one of the most difficult problems currently facing the nuclear power industry. Today, more than forty years after the first commercial nuclear power plant entered service, no country has yet succeeded in disposing of high-level nuclear waste – the longest-lived, most highly radioactive, and most technologically challenging of the waste streams generated by the nuclear industry.[1]

In most countries, the preferred technological approach is to dispose of the waste in repositories constructed in rock formations hundreds of meters below the earth's surface. Although several experimental and pilot facilities have been built, there are no operating high-level waste repositories, and all countries have encountered difficulties with their programs. The perceived lack of progress towards successful waste disposal clearly stands as one of the primary obstacles to the expansion of nuclear power around the world. [2]

THE GOALS OF NUCLEAR WASTE MANAGEMENT AND DISPOSAL

Spent nuclear fuel discharged from nuclear reactors will remain highly radioactive for many thousands of years. The primary goal of nuclear waste management is to ensure that the health risks of exposure to radiation from this material are reduced to an acceptably low level for as long as it poses a significant hazard. Protection against the risk of malevolent intervention and misuse of the material is also necessary.

Because of the very long toxic lifetime of the waste, the primary technical challenge is that of long- term isolation. However, shorter-term risks must also be addressed. Prior to final disposition, the waste will pass through several intermediate stages or operations, including temporary storage, transportation, conditioning, packaging, and, potentially, intermediate processing and treatment steps. There are several possible choices at each stage, and the design of the overall waste management system – including the specific technical characteristics and the physical location of each stage – will importantly affect the overall level of risk and its distribution over time. For example, waste management strategies involving the separation of individual radionuclides from the spent fuel could reduce long-term exposure risks, while elevating risks in the short term. Such interdependencies attest to the importance of an integrated approach to nuclear waste management decision-making, in which the system-wide impacts of individual decisions are fully considered.

What constitutes an acceptable level of exposure risk? The U.S. Environmental Protection Agency (EPA) has stipulated that the radiation dose from all potential exposure pathways to the maximally- exposed individual living close to a waste disposal site should not exceed 15 millirems per year for the first 10,000 years after final disposition. This is about twenty times less than the dose that individuals receive annually from natural background radiation on average. EPA has translated the 15 millirem per year standard into an annual risk of developing a fatal cancer of about 1 chance in 100,000.

Different radiation exposure standards apply to operating nuclear fuel cycle facilities.

The suitability of alternative waste management schemes must ultimately be judged in relation to these fundamental safety goals. Other measures of waste management system performance are frequently cited, such as the volume or mass of waste material generated, the total inventory of radioactivity in the waste, the amount of heat it emits, its radiotoxicity, and the solubility and mobility of specific radionuclides. Each of these metrics contains useful information about the technical requirements of individual components of the waste management system. But none of these metrics is an adequate proxy for the fundamental measure of waste management system performance — that is, the risk to human health from radiation exposure in the short and long term.

THE FEASIBILITY OF GEOLOGIC DISPOSAL

As already noted, most countries with nuclear power programs have stated their intention to dispose of their high-level waste in mined repositories, hundreds of meters below the earth's surface. The concept of deep geologic disposal has been studied extensively for several decades, and there is a high level of confidence within the expert scientific and technical community that this approach is capable of safely isolating the waste from the biosphere for as long as it poses significant risks.[3] This assessment is based on: (1) an understanding of the processes and events that could transport radionuclides from the repository to the biosphere; (2) mathematical models which, when combined with information about specific sites and repository designs, enable the long-term environmental impact of repositories to be quantified; and (3) natural analog studies which help to build confidence that the analytical models can be reliably extrapolated to the very long time-scales required for waste isolation.

We concur with the view that high-level waste can safely be disposed of in geologic repositories. As discussed below, we believe there are opportunities for advances in geologic and engineering system design that can provide additional assurance regarding the long-term performance of such repositories. We note, however, that among the general public, and even among some in the technical community, there is a lack of confidence in the prospects for successful technical and organizational implementation of the geologic disposal concept. Previous missteps and failures in the waste management programs of several countries have contributed to these doubts. Some members of the public – especially those living in the vicinity of proposed repository sites – also question the fairness and integrity of the site selection process.

MEASURES TO INCREASE THE LIKELIHOOD OF SUCCESSFUL IMPLEMENTATION OF WASTE MANAGEMENT AND DISPOSAL

We have examined several possible innovations that might facilitate the successful implementation of waste management and disposal. In order to make a difference, any such measure should have to contribute significantly to one or more of the following goals:

- ☐ reduction of the risks to public health and safety and the environment from waste management and disposal activities in the short and/or long term;
- ☐ reduction of the economic costs of achieving an acceptable level of performance with respect to short and long-term risk;
- ☐ increase of public confidence in the technical and organizational effectiveness of waste management and disposal activities.

The innovations we have considered can be grouped into three categories:

- ☐ technical modifications or improvements that could be incorporated into the once-through fuel cycle;

- technical modifications or improvements requiring a closed fuel cycle;
- institutional or organizational innovations.

It is important to emphasize that each innovation must be evaluated in terms of its impact on the entire waste management system, including not only final disposal but also pre-disposal processing, transportation, and storage operations. In the following paragraphs we summarize our findings concerning each category of innovations. More detailed discussions can be found in Appendix 7.

TECHNICAL MODIFICATIONS OR IMPROVEMENTS TO SPENT FUEL MANAGEMENT IN THE ONCE-THROUGH FUEL CYCLE

Extended interim storage of spent fuel Although most spent fuel destined for direct disposal will in practice be stored above ground for many years because of the protracted process of developing high level waste repositories, storage arrangements so far have mostly been ad hoc and incremental. We believe that a period of several decades of interim storage should be incorporated into the design of the spent fuel management system as an integral part of the system architecture.[4] Such a storage capability would:

- provide greater flexibility in the event of delays in repository development;
- allow a deliberate approach to disposal and create opportunities to benefit from future advances in relevant science and technology;
- provide greater logistical flexibility, with centralized buffer storage capacity facilitating the balancing of short and long-term storage requirements, and enabling the optimization of logistics, pre- processing, and packaging operations;
- allow countries that want to keep open the option to reprocess their spent fuel to do so without actually having to reprocess;
- create additional flexibility in repository design, since the spent fuel would be older and cooler at the time of emplacement in the repository; and
- potentially reduce the total number of repositories required.

At-reactor storage will be feasible for some spent fuel, even for several decades. For the remainder, centralized storage facilities will be required. Internationally, a network of safeguarded, well protected central storage facilities will also yield important non-proliferation benefits (see Chapter 8). The siting of temporary storage facilities will likely be difficult. Although the technical issues involved are more straightforward than for geologic repositories, the task of persuading affected communities to accept such facilities may be no less challenging. Nevertheless, making provision for several decades of temporary spent fuel storage would make for a more robust waste management system overall, and could be cost-effective too, if the result was to postpone the onset of major spending on repository construction and operation.

High burnup fuel The burnup of spent fuel – the amount of energy that has been extracted from a unit of fuel at the time of its discharge from the reactor – is a design choice for reactor operators. In the past, the burnup of LWR fuel averaged about 33 MWD/kg. An increase to 100 MWD/kg is within technical reach, and even greater increases are potentially achievable.

Increasing the burnup to 100 MWD/kg would yield a threefold reduction in the volume of spent fuel to be stored, conditioned, packaged, transported, and disposed of per unit of electricity generated. The corresponding reduction in the required repository storage volume would be more modest; the individual fuel assemblies, although there would be fewer of them, would generate more decay heat and would therefore have to be spaced farther apart in the repository. The amount of plutonium and other actinides, which are the dominant contributors to the radiotoxicity of the spent fuel after the first hundred years or so, would also be reduced somewhat per unit of electricity generated. A further benefit of higher burnup is that the isotopic composition of the discharged plutonium would make it less suitable for use in nuclear explosives.[5]

It is important to note, however, that the present pricing structure for nuclear waste management services in the United States – a standard fee of one-tenth of a cent payable to the government on each kilowatt hour of nuclear electricity generated — provides no economic incentive for nuclear generators to move in the direction of higher burnup. No discount is provided for the reduced volume of spent fuel and the safety, proliferation resistance, and economic benefits associated with higher burnup.[6]

Advances in geologic repository design A geologic repository must provide protection against every plausible scenario in which radionuclides might reach the biosphere and expose the human population to dangerous doses of radiation. Of all possible pathways, the one receiving most attention involves groundwater seeping into the repository, the corrosion of the waste containers, the leaching of radionuclides into the groundwater, and the migration of the contaminated groundwater towards locations where it might be used as drinking water or for agricultural purposes. Although the details differ, all proposed repository designs adopt a 'defense in depth' approach to protecting against this scenario, relying on a combination of engineered components and natural geologic, hydrologic, and geochemical barriers to contain the radionuclides.

The engineered barriers, broadly defined to include those physical and chemical features of the near- field environment that affect the containment behavior of the waste packages, have an important role to play in the overall performance of the repository. To date there has not been an adequate technical basis for the selection and development of the engineered barriers in the context of the overall multi- barrier system.

In siting a repository, it is important to select a geochemical and hydrological environment that will ensure the lowest possible solubility and mobility of the waste radionuclides. The geochemical conditions in the repository host rock and surrounding environment strongly affect radionuclide transport behavior. For example, several long-lived radionuclides that are potentially important contributors to long-term dose, including technetium-99 and neptunium-237, are orders of magnitude less soluble in groundwater in reducing environments than under oxidizing conditions.

Alternative disposal technologies: The deep borehole approach An alternative to building geologic repositories a few hundred meters below the earth's surface is to place waste canisters in boreholes drilled into stable crystalline rock several kilometers deep. Canisters containing spent fuel or high-level waste would be lowered into the bottom section of the borehole, and the upper section – several hundred meters or more in height – would be filled with sealant materials such as clay, asphalt, or concrete. At depths of several kilometers, vast areas of crystalline basement rock are known to be extremely stable, having experienced no tectonic, volcanic or seismic activity for billions of years.

The main advantages of the deep borehole concept relative to mined geologic repositories include: (a) a much longer migration pathway from the waste location to the biosphere; (b) the low water content, low porosity and low permeability of crystalline rock at multi-kilometer depths; (c) the typically very high salinity of any water that is present (because of its higher density, the saline water could not rise convectively into an overlying layer of fresh water even if heated); and (d) the ubiquity of potentially suitable sites.

An initial screening suggests that most of the countries that are likely to employ nuclear power in our global growth scenario may have geology appropriate for deep waste boreholes. Co-location of boreholes with reactor sites is a possibility. Suitable host rock also occurs beneath the sea floor. For this reason the concept may be particularly interesting for densely populated countries like Japan, Korea, and Taiwan. Since most of the power reactors in these countries (and indeed in most countries) are located on or close to the coast, the possibility arises of constructing artificial offshore islands which would be ideal sites from which to drill beneath the seabed and which could also serve as temporary storage venues for the spent fuel, obviating the need for on-land waste transportation and storage.

The overall system cost of deep borehole disposal using conventional drilling technology is uncertain, but according to one estimate would be comparable to that of mined geologic disposal.[7] Advances in technology could reduce the cost of drilling significantly. But since drilling alone accounts for only a relatively small fraction of the overall costs, the opportunities for savings are limited. A more important economic advantage may derive from the modularity of the deep borehole concept and the more flexible siting strategy that it allows. [8]

Implementing the deep borehole scheme would require the development of a new set of standards and regulations, a time-consuming and costly process. A major consideration would be the difficulty of retrieving waste from boreholes if a problem should develop (though the greater difficulty of recovering the plutonium in the waste might also be an advantage of the borehole scheme). Current U.S. regulatory guidelines for mined repositories require a period of several decades during which the high level waste should be retrievable. This would be difficult and expensive to ensure in the case of deep boreholes, though probably not impossible. Moreover, at the great depths involved, knowledge of in situ conditions (e.g., geochemistry, stress distributions, fracturing, water flow, and the corrosion behavior of different materials) will never be as comprehensive as in shallower mined repository environments. Recovery from accidents occurring during waste emplacement – for example, stuck canisters, or a collapse of the borehole wall – is also likely to be more difficult than for corresponding events in mined repositories. Finally, despite the order of magnitude increase in the depth of waste emplacement, it is difficult to predict the impact on public opinion of a shift in siting strategy from one large central repository to scores of widely dispersed boreholes.

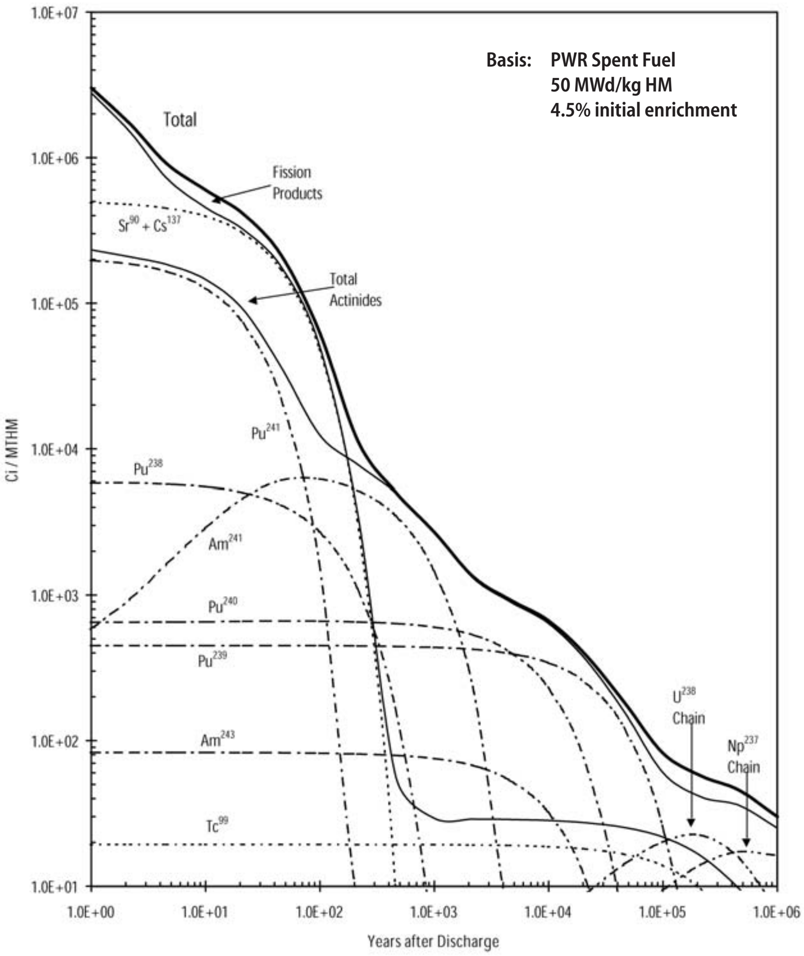
Despite these obstacles, we view the deep borehole disposal approach as a promising extension of geological disposal, with greater siting flexibility and the potential to reduce the already very low risk of long-term radiation exposure to still lower levels without incurring significant additional costs.

TECHNICAL MODIFICATIONS REQUIRING A CLOSED FUEL CYCLE

We next consider a set of waste management options involving the extraction of radionuclides from the spent fuel. The motivations for waste separation can be inferred from Figures 7.1, 7.2, and 7.3. At different times, different radionuclides are the dominant contributors to overall radioactivity and radiotoxicity and to the radioactive decay heat emitted by the fuel. Partitioning the spent fuel into separate radionuclide fractions and managing each fraction according to its particular characteristics could create additional flexibilities and new opportunities to optimize the overall waste management system. Partitioning also creates the opportunity to transmute the most troublesome radionuclides into more benign species. Thermal reactors, fast reactors, and accelerators have all been investigated as candidate transmutation devices, both individually and in combination.

Decisions about partitioning and transmutation must also consider the incremental economic costs and safety, environmental, and proliferation risks of introducing the additional fuel cycle stages and facilities necessary for the task.[9] These activities will be a source of additional risk to those working in the plants, as well as the general public, and will also generate con-

Figure 7.1 Radioactivity profile of spent fuel (curies/MTHM)



siderable volumes of non-high- level waste contaminated with significant quantities of transuranics. Much of this waste, because of its long toxic lifetime, will ultimately need to be disposed of in high-level waste repositories. Moreover, even the most economical partitioning and transmutation schemes are likely to add significantly to the cost of the once-through fuel cycle.[10]

We first consider the option of waste partitioning alone, and then the combination of partitioning and transmutation.

Waste partitioning Two fission products, strontium-90 and cesium-137, each with half-lives of about 30 years, account for the bulk of the radioactivity and decay heat in spent fuel starting a few years after discharge and for the next several decades. Thereafter, the actinides as a group become the dominant contributors to decay heat and radiotoxicity, with different actinides dominating at different times.

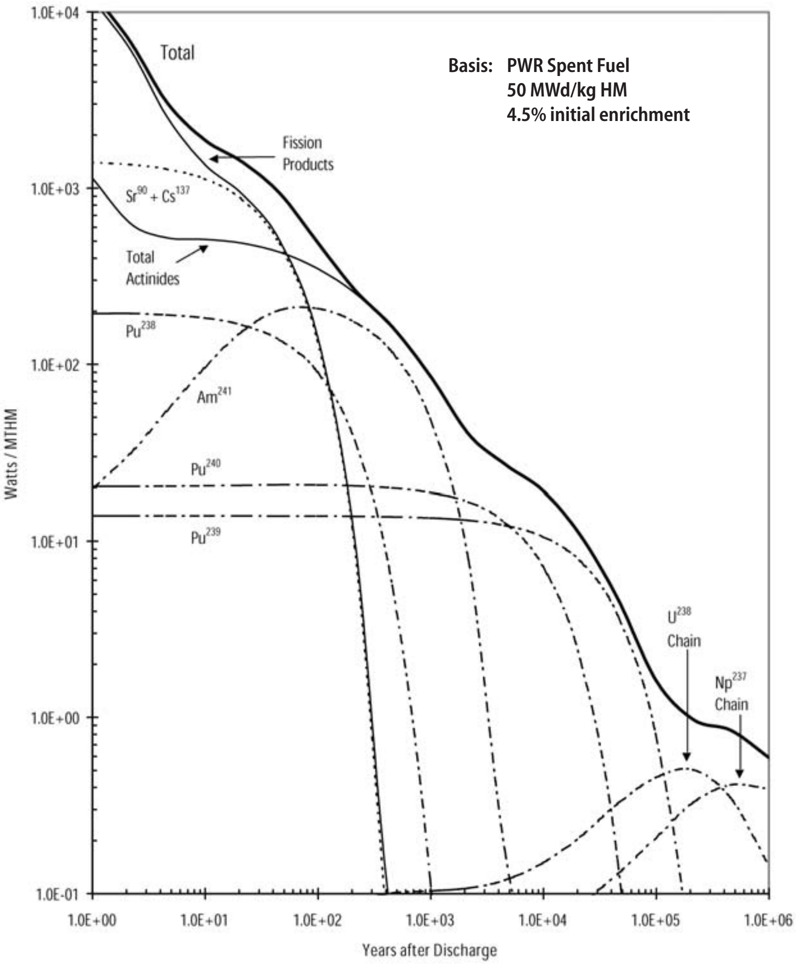
Extracting the high-heat-emitting fission product radionuclides from the spent fuel and storing them separately would allow the remainder of the radionuclides to occupy a more compact volume in a geologic repository, perhaps even reducing the total number of repositories required. It should be noted, however, that a similar result could be achieved without the need for separation by storing the spent fuel for several decades to allow the fission products to decay. In this case, moreover, there would be no need for a separate storage facility for the partitioned strontium-90 and cesium-137, which would have to be isolated from the biosphere for several hundred years before radioactive decay would render them harmless.

An alternative strategy would be to partition the uranium, plutonium and the other actinides from the spent fuel. If actinide partitioning were implemented in conjunction with interim waste storage for long enough to allow the strontium-90 and cesium-137 to decay significantly before repository emplacement, the effective storage capacity of a given repository could be increased many-fold. But the partitioned actinides would still have to be stored in a separate repository (or alternatively in deep boreholes). Moreover, by separating the actinides from the more radioactive fission products, the radiation barrier against unauthorized recovery of weapons-usable plutonium would be reduced relative to the case of intact spent fuel, at least for a century or so.

The case for partitioning the spent fuel and separately storing the different radionuclide fractions does not seem persuasive, especially given the additional costs and near-term environmental and safety risks associated with partitioning operations.

Waste partitioning and transmutation Waste partitioning strategies potentially become more attractive when combined with transmutation. There are three principal motivations for partitioning/transmutation schemes. First, if the long-lived isotopes in the waste could be extracted and destroyed, many more locations might become suitable candidates to host a repository for the remaining material. Indeed, if *all* of the long-lived radionuclides could be removed and destroyed, a disposal strategy relying solely on engineered structures for radionuclide containment might become feasible. The actinides, which as a group dominate the radiotoxicity of the spent fuel after about 100 years (see Figure 7.3), are usually cited as the prime candidates for partitioning and transmutation. However, performance assessments of the proposed repository sites at Yucca Mountain and at Olkiluoto in Finland show that long-lived fission products, such as technetium-99 and iodine-129, are more important than most actinides as sources of long-term exposure risk.[11] Partitioning and transmutation studies have yet to show that these fission products can be dealt with effectively. Even for the actinides, the technology is not yet available to remove these isotopes from all fuel cycle waste streams, and complete elimination of these isotopes from secondary, as well as primary waste streams, is unlikely ever to be attractive on economic grounds.

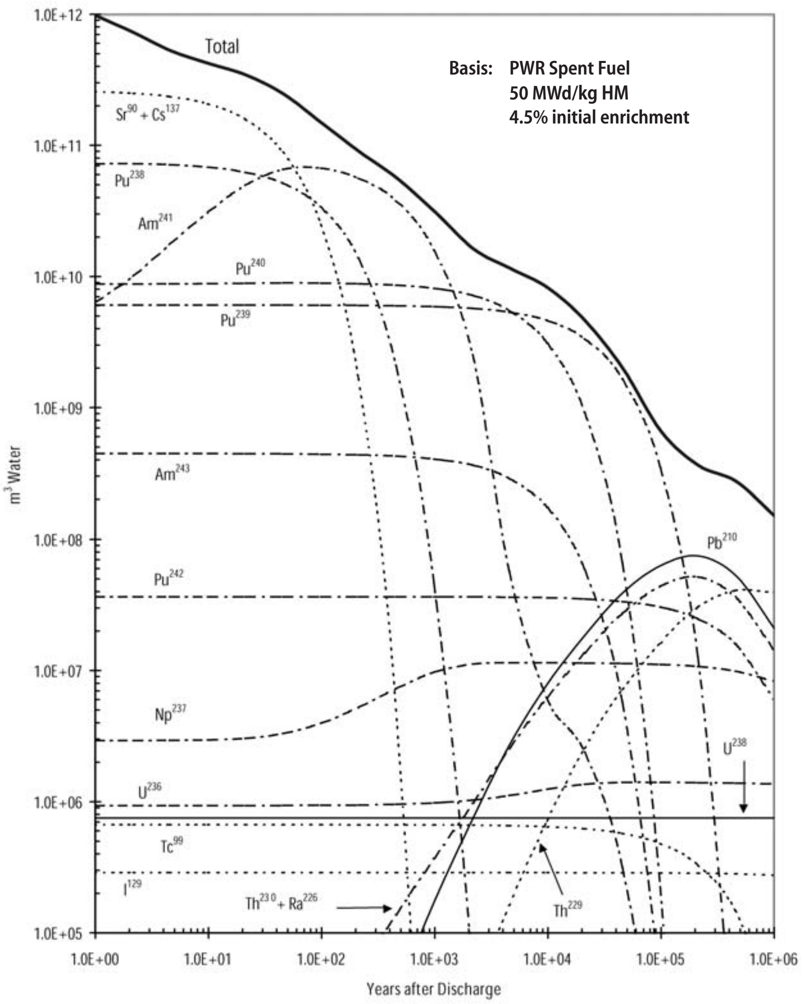
Figure 7.2 Decay Heat Profile of Spent Fuel



A second motivation for partitioning and transmutation is to reduce the thermal load on the repository, thereby increasing its storage capacity. As Figure 7.2 shows, after 60–70 years, the actinides are the dominant contributors to waste heating. As previously noted, actinide partitioning and transmutation, combined with a period of several decades of interim storage prior to final disposal of the residual waste, could increase the effective storage capacity of a given repository several-fold. Given the extreme difficulty of repository siting in most countries, any reduction in the required number of repositories must be counted as a significant gain, although this would be at least partly offset by the additional difficulty of siting the necessary waste partitioning and related fuel cycle facilities. As noted above, a less costly way to increase the effective storage capacity of repositories would simply be to defer waste emplacement until more of the heat-emitting radionuclides have decayed. In some countries, moreover, especially those with relatively small nuclear programs, a single repository is likely to be able to accommodate the entire national inventory of high-level waste even without actinide partitioning.[12]

A third motivation for partitioning and transmutation is to eliminate the risk that plutonium could later be recovered from a repository and used for weapons. It is difficult to assess the significance of this result. The value today of elim-

Figure 7.3 Radiotoxicity Index for 1MT of Spent Fuel



inating the technical means for one particular type of aggressive or malevolent human behavior centuries or millennia from now, out of all possible opportunities for such behavior that may exist at that time, is a question perhaps better addressed by philosophers than engineers, political scientists, or economists. From a narrowly technical perspective the best that can be said is that, without partitioning and transmutation, the feasibility of plutonium recovery from a repository will increase with time, as the radiation barrier created by the fission products in the waste decays away.

Against these putative long-term benefits of waste partitioning and transmutation must be weighed the increased short-term health, safety, environmental, and security risks involved. All actinide partitioning and transmutation schemes currently under consideration also seem likely to add significantly to the economic cost of the nuclear fuel cycle.

The trade-off between reduced risk over very long time scales and increased risk and cost in the short term is an issue on which reasonable people can disagree. The evaluation can furthermore be expected to vary by country, reflecting the different preferences and different constraints – geological, demographic, political, economic – of different societies. *Nevertheless, taking all these factors into account, we do not believe that a convincing case can be made on the basis of waste management considerations alone that the benefits of advanced fuel cycle schemes featuring waste partitioning and transmutation will outweigh the attendant risks and costs.* Future technology developments could change the balance of expected costs, risks, and benefits. For our fundamental conclusion to change, however, not only would the expected long-term risks from geologic repositories have to be significantly higher than those indicated in current risk assessments, but the incremental costs and short-term safety and environmental risks would have to be greatly reduced relative to current expectations and experience.

Some argue that partitioning and transmutation, by reducing the toxic lifetime of the waste, could change public attitudes towards the feasibility and acceptability of nuclear waste disposal. There is no empirical evidence of which we are aware to support this view. Our own judgment is that local opposition to waste repositories or waste transportation routes would not be much influenced, even if the toxic lifetime were reduced from hundreds of thousands to hundreds of years.

Our assessment of alternative waste management strategies leads to the following important conclusion: *technical improvements to the waste management strategies in the once-through fuel cycle are potentially available that could yield benefits at least as large as those claimed for advanced* *fuel cycles featuring waste partitioning and transmutation, and with fewer short-term risks.* The most that can reasonably be expected of partitioning and transmutation schemes is to reduce the inventory of actinides in geologic repositories by perhaps two orders of magnitude.[13] Reductions of two orders of magnitude or more in long-term radiation exposure risks could potentially be achieved by siting the repositories in host environments in which chemically reducing conditions could be ensured. Moreover, deep borehole technology offers a credible prospect of risk reductions of several orders of magnitude relative to mined repositories. Neither of these options is likely to cost as much or take as long to develop and deploy as waste partitioning and transmutation schemes.

INSTITUTIONAL INNOVATIONS

Technological advances can increase the likelihood that nuclear waste disposal will be successfully implemented. But an equally important consideration is the competence of the implementing authorities. A major challenge for these authorities under our global growth scenario will be to find suitable disposal sites. A worldwide deployment of one thousand 1000 megawatt LWRs operating on the once-through fuel-cycle with today's fuel management characteristics would generate roughly three times as much spent fuel annually as does today's nuclear power plant fleet.[14] If this fuel was disposed of directly, new repository storage capacity equal to the currently planned capacity of the Yucca Mountain facility would have to be created somewhere in the world roughly every three or four years. For the United States, a three-fold increase in nuclear generating capacity would create a requirement for a Yucca Mountain equivalent of storage capacity roughly every 12 years (or every 25 years if the physical rather than the legal capacity limit of Yucca Mountain is assumed.) Even if the technical strategies discussed above succeed in reducing the demand for repository capacity, the organizational and political challenges of siting will surely be formidable.

Today the political and legal mechanisms for balancing broad national policy goals against the concerns of affected local communities in the site selection process vary widely, even among the democratic societies of the West. This diversity of approaches will surely persist, although over time, as some nations achieve success in gaining local acceptance of repositories, some international diffusion of 'best siting practices' is probable. On present evidence, these best practices seem likely to include full access to information, opportunities for broad-based and continuing local community participation in consensus-building processes, the adoption of realistic and flexible schedules, and a willingness not merely to compensate local communities for hosting facilities, but also to find ways to make them actually better off.

Another important requirement for successful waste management implementation is the effective administration of a large-scale industrial operation involving the transportation, storage, processing, packaging, and emplacement of large quantities of radioactive waste. In the United States, as a matter of law and policy, the governance and management structure of the high-level waste program has been heavily focused on the development of the Yucca Mountain project. The scientific and engineering effort has also been almost exclusively focused on the investigation of the Yucca Mountain site and the development of a repository design for that site. However, the organizational and managerial demands of repository siting – a one-time project that is by definition exploratory, developmental, and, inevitably, highly politicized – are fundamentally different from the demands of a routine-based large-scale industrial processing and logistics operation. The intense focus on the Yucca Mountain project will continue as design and licensing activities gain momentum over the next few years. *In addition, the U.S. high level waste management program will require (1) a broadly-based, long-term R&D program, and (2) a separate organization for managing the operations of the waste management system.*

Finally, we note that international cooperation in the field of high-level waste management and disposal is presently under-developed. Stronger international coordination of standards and regulations for waste transportation, storage, and disposal will be necessary in order to strengthen public confidence in the safety of these activities. There is also considerable potential for international sharing of waste storage and disposal facilities. This might not only reduce proliferation risks from the fuel cycle (as discussed in the following chapter), but could also yield significant economic and safety benefits, although formidable political obstacles will have to be overcome first.

The authors of this study wish to acknowledge the valuable research support provided by our former students, Dr. Brett Mattingly and Dr. David Freed in the preparation of this chapter.

NOTES

1. In this study we focus on spent fuel and reprocessed high-level waste, since these waste types contain most of the radioactivity generated in the nuclear power fuel cycle and pose the greatest technical and political challenges for final disposal. We also include in the discussion so-called TRU waste — non-high-level waste contaminated with significant quantities of long-lived transuranic radionuclides — which because of its longevity will likely be disposed of in the same facilities as high-level waste. Other types of nuclear waste, including low-level waste and uranium mill tailings, are generated in larger volumes in the nuclear fuel cycle but pose fewer technical challenges for disposal, although localized opposition to disposal facilities for these materials has sometimes been intense.
2. In the opinion survey commissioned for this study, almost two-thirds of respondents did not believe that nuclear waste could be safely stored for long periods.
3. According to one recent international scientific assessment, "[I]n a generic way, it can be stated with confidence that deep geologic disposal is technically feasible and does not present any particularly novel rock engineering issues. The existence of numerous potentially suitable repository sites in a variety of host rocks is also well established." (International Atomic Energy Agency, "Scientific and Technical Basis for the Geologic Disposal of Radioactive Wastes", Technical Report No. 413, IAEA, Vienna, 2003.) Another expert group, convened by the OECD's Nuclear Energy Agency, found that, "[T]here is today a broad international consensus on the technical merits of the disposal of long-lived radioactive waste in deep and stable geologic formations…. Currently, geologic disposal can be shown to have the potential to provide the required level and duration of isolation." "The Environmental and Ethical Basis of Geologic Disposal of Long-Lived Radioactive Wastes: A Collective Opinion of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency," 1995 at http://www.nea.fr/html/rwm/reports/1995/geodisp.html . Yet another recent international assessment, this time under the auspices of the U.S. National Academy of Sciences, found that, "geological disposal remains the only scientifically and technically credible long-term solution available to meet the need for safety without reliance on active management…a well-designed repository represents, after closure, a passive system containing a succession of robust safety barriers. Our present civilization designs, builds, and lives with technological facilities of much greater complexity and higher hazard potential." See National Academy of Sciences, Board on Radioactive Waste Management, *Disposition of High Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges,* National Academy Press, Washington, D.C., 2001.
4. Because of the high heat generation, spent fuel must be stored for at least five years before it can be emplaced in a geologic repository. After another 30 years, the decay heat from the fission products Cs-137 and Sr-90, the leading sources of heat during this period, will have halved. After 100 years, the contribution from these isotopes will have declined by more than 90%. At that point, the fission product radiation barrier, which until then would complicate attempts by would-be proliferators to recover plutonium from the spent fuel, will have largely dissipated, and storage in relatively accessible surface or near-surface facilities thereafter would be less desirable on non-proliferation grounds.

5. As the burnup increases, the proportion of plutonium-239 in the plutonium declines, while the proportion of Pu-238 increases. For example, an increase in the burnup of PWR fuel from 33 MWD/kg to 100 MWD/kg would result in a decline in the Pu-239 content from 65% to 53%, while the Pu-238 content would increase from 1% to about 7%. (Zhiwen Xu, Ph.D. dissertation, Department of Nuclear Engineering, M.I.T., 2003). Pu-238 is a particularly undesirable isotope in nuclear explosives because of its relatively high emission rate of spontaneous fission neutrons and decay heat. According to some specialists, a Pu- 238 content above about 6% would make plutonium essentially unusable for weapons purposes. The denaturing effect of Pu-238 would be limited to a couple of centuries, however, because of its relatively short (87-year) half-life.

6. In recent years the average burnup of LWR fuel has risen from about 33 MWD/kg to about 45–50 MWD/kg. LWR operators have taken this step for economic reasons that are largely unrelated to waste disposal; the higher-burnup fuel cycle allows the reactors to operate for longer periods between refueling, thus increasing the reactor capacity factor.

7. Weng-Sheng Kuo, Michael J. Driscoll, and Jefferson W. Tester, "Re-evaluation of the deep drillhole concept for disposing of high-level nuclear wastes," *Nuclear Science Journal*, vol. 32, no. 3, pp. 229–248, June 1995.

8. According to one recent estimate, a full-scale 4-kilometer deep borehole could be drilled and cased in less than 5 months, at a cost of about $5 million. Tim Harrison, "Very Deep Borehole: Deutag's Opinion on Boring, Canister Emplacement and Retrievability", Swedish Nuclear Fuel and Waste Management Co., R- 00-35, May 2000.

9. See, for example, National Academy of Sciences, *Nuclear Wastes: Technologies for Separation and Transmutation, Committee on Separations Technology and Transmutation Systems*, National Research Council, Washington, D.C., 1996; B.Brogli and R. A. Krakowski, "Degree of sustainability of various nuclear fuel cycles," Paul Scherrer Institut Nuclear Energy and Safety Research Department, PSI Bericht No. 02-14, August 2002.

10. The PUREX/MOX fuel cycle currently practiced in several countries is one variant of the waste partitioning/transmutation option, in which uranium and plutonium isotopes are partitioned from the spent fuel, and the separated plutonium isotopes are partially transmuted into shorter-lived fission products in light water reactors. As shown in Appendix 5D, PUREX/MOX increases the fuel cycle cost to 4.5 times the once-through fuel cycle cost, depending on various assumptions.

11. To determine which radionuclides should be the principal targets of partitioning and transmutation, it is necessary to assess the likelihood that individual radionuclides will be transported from the repository to the biosphere. This in turn is a function of the particular geochemical and hydrological characteristics of the repository environment. In the oxidizing conditions characteristic of Yucca Mountain, the dominant contributors to long-term exposure risk are neptunium-237 and technetium-99. During the first 70,000 years, technetium-99 is the leading contributor, and between 100,000 years and 1 million years, the dominant isotope is Np-237. The peak dose of about 150 millirems/year (about half the background dose) occurs after about 400,000 years. (See: *Final Environmental Impact Statement for Yucca Mountain Repository*, February 2002) In contrast, a performance assessment of the proposed Finnish repository at Olkiluoto, in crystalline rock in a chemically reducing environment, concludes that the actinides would contribute very little to long-term dose, and that the dominant contributors would be a few long-lived fission products. The projected peak dose, moreover, is three orders of magnitude lower than that at Yucca Mountain (see Vieno and Nordman, "Safety Assessment of Spent Fuel Disposal in Hastholmen, Kivetty, Olkiluoto and Romuvaara - TILA-99," POSIVA 99-07, March 1999, ISBN 951-652-062-6).

12. For the repository at Yucca Mountain, operating in the so-called higher-temperature operating mode, the total subsurface area that would be required to accommodate the legal limit of 70,000 MT of spent fuel equivalent (including 7000 MT of defense high level waste) would be 1150 acres, equivalent to a square roughly 2 kilometers along a side. U.S. Department of Energy, "Yucca Mountain Science and Engineering Report, Rev. 1", DOE/RW-0539-1, February 2002, Executive Summary, at http://www.ymp.gov/documents/ser_b/. The current fleet of U.S. reactors is expected to discharge at least 105,000 MT of spent fuel and possibly considerably more, depending on reactor operating lifetimes. The 70,000 MTHM capacity limit at Yucca Mountain was politically determined, and according to some knowledgeable observers the physical storage capability of the site would be at least twice as large.

13. Nuclear Energy Agency, *Accelerator-Driven Systems and Fast Reactors in Advanced Fuel Cycles: A Comparative Study,* OECD, 2002 (available at http://www.nea.fr/html/ndd/reports/2002/nea3109.htm.

14. If each reactor has a burn-up of 50,000 MWth-d/MTHM , a capacity factor of 0.9, and a thermal efficiency of 33%, deployment of 1000 1 Gwe reactors would result in an annual spent fuel discharge of about 20,000 metric tons per year.

Chapter 8 — Nonproliferation

Nuclear weapons proliferation has been prominent in discussions about nuclear power since its earliest days. The birth of nuclear technology that began with production of the first weapons-usable fissionable material — plutonium production in nuclear reactors and high-enriched uranium by isotope enrichment — assured that this would be so. *Today, the objective is to minimize the proliferation risks of nuclear fuel cycle operation*. We must prevent the acquisition of weapons-usable material, either by diversion (in the case of plutonium) or by misuse of fuel cycle facilities (including related facilities, such as research reactors or hot cells) and control, to the extent possible, the know-how about how to produce and process either HEU (enrichment technology) or plutonium.

This proliferation concern has led, over the last half century, to an elaborate set of international institutions and agreements, none of which have proved entirely satisfactory. The Nuclear Nonproliferation Treaty (NPT) is the foundation of the control regime, since it embodies the renunciation of nuclear weapons by all signatories except for the declared nuclear weapons states – the P-5 (the United States, Russia, the United Kingdom, France, China) — and a commitment to collaborate on developing peaceful uses of nuclear energy. However, non-signatories India and Pakistan tested nuclear weapons in 1998, and signatories, such as South Africa and North Korea, have admitted to making nuclear weapons.

The International Atomic Energy Agency (IAEA) has responsibility for verifying NPT compliance with respect to fuel cycle facilities through its negotiated safeguards agreements with NPT signatories. The IAEA's safeguard efforts, however, are seriously constrained by the scope of their authorities (as evidenced in Iraq, Iran, and North Korea during the last decade), by their allocation of resources, and by the growing divergence between responsibilities and funding. The United Nations Security Council has not yet established a procedure or shown a willingness to impose sanctions when IAEA safeguards agreements are violated. A variety of multilateral agreements, such as the Nuclear Supplier Group guidelines for export control, aim to restrict the spread of proliferation-enabling nuclear and dual-use technology. European centrifuge enrichment technology, however, is known to have contributed to weapons development elsewhere, and the US and Russia have a continuing dispute over transfer of Russian fuel cycle technologies to Iran (a NPT signatory). This is not to say that the safeguards regime has failed to restrain the spread of nuclear weapons; it almost certainly has. Nevertheless, its shortcomings raise significant questions about the wisdom of a global growth scenario that envisions a major increase in the scale and geographical distribution of nuclear power.

In addition to the risk of nuclear weapons capability spreading to other nations, the threat of acquisition of a crude nuclear explosive by a sub-national group has arisen in the aftermath of the September 11, 2001 terrorist attacks. The report of interest in nuclear devices by the terrorist Al Qaeda network especially highlights this risk. Terrorist or organized crime groups are not expected to be able to produce nuclear weapons material themselves; the concern is their direct acquisition of nuclear materials by theft or through a state sponsor. This places the spotlight on the PUREX/MOX fuel cycle as currently practiced in several countries, since the fuel cycle produces during conventional operation nuclear material that is easily made usable for a weapon. The sub-national theft risk would be exacerbated by the spread of the PUREX/MOX fuel cycle, particularly to those countries without the infrastructure for assuring stringent control and accountability.

A separate concern is the dirty bomb threat in which radioactive material (from any source, such as nuclear spent fuel or cobalt sources used in medicine and industry) is dispersed in a conventional explosive as a weapon of mass disruption. The dirty bomb threat is a very serious security concern but is not specific to the nuclear fuel cycle and will not be discussed further in the proliferation context.

It is useful to set a scale for the proliferation risk that has emerged from nuclear power operation to date. Spent fuel discharged from power reactors worldwide contains well over 1000 tonnes of plutonium. While the plutonium is protected by the intense radioactivity of the spent fuel, the PUREX chemical process most commonly used to separate the plutonium with high purity, is well known and described in the open literature. With modest nuclear infrastructure, any nation could carry out the separation at the scale needed to acquire material for several weapons. Further, the MOX fuel cycle has led to an accumulation of about 200 tonnes of separated plutonium in several European countries, Russia and Japan. This is equivalent to 25,000 weapons using the IAEA definition of 8 kg/weapon. Separated plutonium is especially attractive for theft or diversion and is fairly easily convertible to weapons use, including by those sub-national groups that have significant technical and financial resources.

The nonproliferation issues arising from the global growth scenario are brought into sharp focus by examining a plausible scenario for the deployment of 1000 GWe nuclear capacity (see Table 3.2 and Appendix 2). An important characteristic of this scenario is that much of the deployment would be expected in industrialized countries that either already have nuclear weapons, thus making materials security against theft the principal issue, or are viewed today as minimal proliferation risks. The concern about these nations' ability to provide security for nuclear material is especially elevated for Russia, whose economic difficulties have limited its effort to adopt strong material security measures; the concern applies to materials from both the weapons program and the fuel cycle,[1] which have significant inventories of separated Pu. Moreover geopolitical change, for example, in East Asia, could change the interests of some nations in acquiring nuclear capability. Japan, South Korea, and Taiwan have advanced nuclear technology infrastructures and over several decades might adjust to the emergence of China as both a nuclear weapons state and a regionally dominant economic force by seeking nuclear capability. North Korea provides a further complication to this dynamic.

The developing world might plausibly account for about a third of deployed nuclear power in the mid-century scenario. An appreciable part of this will likely be in China and India, which already have nuclear weapons and dedicated stockpile facilities and thus are not viewed as the highest risks for fuel cycle diversion. Nevertheless, dramatic growth of nuclear power in the sub-continent could be a pathway for nuclear arsenal expansion in India and Pakistan. The security of their nuclear enterprises remains of concern.

On the other hand, a number of other nations with relatively little nuclear infrastructure today, such as the Southeast Asian countries Indonesia, Philippines, Vietnam, and Thailand (with a 2050 projected combined population over 600 million) are also likely candidates for nuclear power in the global growth scenario. Iran is actively pursuing nuclear power, with Russian assistance, even though it has vast unexploited reserves of natural gas and could clearly meet its electricity needs more economically and rapidly by using this domestic resource. The United States in particular has argued that this indicates Iranian interest in acquiring a nuclear weapons capability, even though Iran is an NPT signatory and has a safeguards agreement with the IAEA in place. Recent revelation of the spread of clandestine centrifuge enrichment and heavy water technology exacerbates this concern. Thus the U.S. is arguing that cooperation with Iran on nuclear power should cease irrespective of the NPT's call for cooperation in the peaceful use of nuclear energy (Article IV). This issue has been a significant irritant in U.S.-Russia relations. Such conflicts between an underlying principle of the NPT and the aims of specific countries could become more common in the growth scenario.

The rapid global spread of industrial capacity (such as chemicals, robotic manufacturing) and of new technologies (such as advanced materials, computer-based design and simulation tools, medical isotope separation) will increasingly facilitate proliferation in developing countries that have nuclear weapons ambitions. A fuel cycle infrastructure makes easier both the activity itself and the disguising of this activity. Indeed, even an extensive nuclear fuel cycle RD&D program and associated facilities could open up significant proliferation pathways well before commercial deployment of new technologies.

We conclude that the current non-proliferation regime must be strengthened by both technical and institutional measures with particular attention to the connection between fuel cycle technology and safeguardability. Indeed, if the nonproliferation regime is not strengthened, the option of significant global expansion of nuclear power may be impossible, as various governments react to real or potential threat of nuclear weapons proliferation facilitated by fuel cycle development. The U.S. in particular should recommit itself to strengthening the IAEA and the NPT regime.

The specific technical and institutional measures called for will depend upon the fuel cycle technologies that account for growth in the global growth scenario. We have considered several representative fuel cycles: light water reactors and more advanced thermal reactors and associated fuel forms, operated in an open, once-through fuel cycle; closed cycle with Pu recycling in the PUREX/MOX fuel cycle; and closed fuel cycles based on fast reactors and actinide burning. The priority concern is accounting and control of weapon-usable material during normal operation and detection/prevention of process modification or diversion to produce or acquire such material.[2]

The open fuel cycles seek to avoid the proliferation risk of separated plutonium by requiring that the highly radioactive spent fuel be accounted for until final disposition. This defines the baseline for adequate proliferation-resistance, assuming that spent fuel is emplaced in a geological repository less than a century or so following irradiation (i.e., before the self-protection barrier is lowered excessively). However, the open fuel cycle typically requires enriched uranium fuel, so the spread of enrichment technology remains a concern.

The advanced closed fuel cycles that keep the plutonium associated with some fission products and/or minor actinides also avoid "directly usable" weapons material in normal operation, since there is a chemical separation barrier analogous to that which exists with spent fuel. Nevertheless, closed fuel cycles need strong process safeguards against misuse or diversion. However, the development and eventual deployment of closed fuel cycles in non-nuclear weapons states is a particular risk both from the viewpoint of detecting misuse of fuel cycle facilities, and spreading practical know-how in actinide science and engineering.

Greater proliferation resistance will require the adoption of technical and institutional measures appropriate to the scale and spread of the global growth scenario and responsive to both national and sub-national threats. Proliferation concerns contributed significantly to our conclusion that the open, once-through fuel cycle best meets the global growth scenario objectives, since no fissile material easily usable in a nuclear weapon appears during normal operation, and the "back end" does not have plutonium separation facilities. Enrichment facilities that could be employed for HEU production represent a risk. A variety of measures can minimize the risk: strengthened IAEA technical means to monitor material flows and assays at declared facilities; reliable supply of fresh fuel (and perhaps return of spent fuel) from a relatively small set of suppliers under appropriate safeguards; implementation of IAEA prerogatives with respect to undeclared facilities (the "Additional Protocol"); strengthened export controls on enrichment technologies and associated dual-use technologies; and utilization of national intelligence means and appropriate information sharing with respect to clandestine facility construction and operation. This is a demanding agenda, both diplomatically and in its resource needs, and calls for active effort on the part of the U.S. and other leading nuclear countries. With such an effort, the level of proliferation risk inherent in the possible expansion to 1000 GWe nuclear power by mid-century appears to us to be manageable.

It is clear that international RD&D on closed fuel cycles will continue and indeed grow over the next years, with or without U.S. participation. We believe that such work should be restricted by proliferation considerations to those fuel cycles that do not produce "direct use" nuclear materials in their operation. Current R&D planning discussions in the U.S. reflect this concern. Such fuel cycles may also have manageable proliferation risks when coupled with improved technical and institutional safeguards. However, although advanced closed fuel cycles cannot realistically by deployed for many decades, the R&D program could itself assist and provide cover for proliferants unless structured carefully from the beginning. Today, the international discussions are carried out by those principally interested in developing advanced technologies, without the needed level of engagement from those whose primary responsibility is nonproliferation. The U.S. could play a crucial role in shaping these discussions properly before major efforts are underway.

In this context, the PUREX/MOX fuel cycle is a major issue. It is the current candidate, because of experience, for near-term deployment in nations determined to pursue closed fuel cycles. However, it should be stressed that the PUREX/MOX fuel cycle is not on the "technology pathway" to the advanced fuel cycles discussed earlier (typically, the advanced fuel cycles will involve different separations technology, fuel form, and reactor). The U.S. should work with France, Britain, Russia, Japan, and others to constrain more widespread deployment of this fuel cycle, while recognizing that development of more proliferation-resistant closed fuel cycle technologies is widely viewed as a legitimate aspiration for the distant future. The associated institutional issues encompass examination of the underlying international regime embedded in the NPT/Atoms for Peace framework. All of these issues confront the fundamental question of tradeoffs of national sovereignty in the context of access to nuclear materials and technology. Such issues are intrinsically difficult and time-consuming to resolve through diplomacy, but concomitantly important for realizing the global growth scenario, while preserving international commitment to and confidence in a strong nuclear nonproliferation regime.

In summary, the global growth scenario built primarily upon the once-through thermal reactor fuel cycle would sustain an acceptable level of proliferation resistance if combined with strong safeguards and security measures and timely implementation of long term geological isolation. The PUREX/MOX fuel cycle produces separated plutonium and, given the absence of compelling reasons for its pursuit, should be strongly discouraged in the growth scenario on nonproliferation grounds. Advanced fuel cycles may achieve a reasonable degree of proliferation resistance, but their development needs constant and careful evaluation so as to minimize risk. The somewhat frayed nonproliferation regime will require serious reexamination and strengthening to face the challenge of the global growth scenario, recognizing that fuel cycle-associated proliferation would greatly reduce the attraction of expanded nuclear power as an option for addressing global energy and environmental challenges.

NOTE

1. "DOE's Nonproliferation Programs with Russia, Howard Baker and Lloyd Cutler, co-chairs, Secretary of Energy Advisory Board report, January 2001; "Controlling Nuclear Warheads and Material", M. Bunn, M. Wier, and J. Holdren, Nuclear Threat Initiative report, March 2003.
2. E. Arthur, et. al., "Uranium enrichment technologies: workshop materials," Los Alamos Report — LA-CP-03-0233, (December, 2002).

Chapter 9 — Public Attitudes and Public Understanding

There is little question that the public in the United States and elsewhere is skeptical of nuclear power. A majority of Americans simultaneously approve of the use of nuclear power, but oppose building additional nuclear power plants to meet future energy needs. Since the accident at the Three Mile Island power plant in 1979, 60 percent of the American public has opposed and 35 percent have supported construction of new nuclear power plants, although the intensity of public opposition has lessened in recent years.[1] Large majorities strongly oppose the location of a nuclear power plant within 25 miles of their home.[2] In many European countries, large majorities now oppose the use of nuclear power. Recent Eurobarometer surveys show that 40 percent of Europeans feel that their country should abandon nuclear power because it poses unacceptable risks, compared with 16 percent who feel it is "worthwhile to develop nuclear power."[3]

Why does nuclear power, or for that matter any energy source, receive or lose public confidence? There is a surprising lack of survey data in the public domain that would allow us to understand why people oppose and support specific power sources. [4] To fill that void, we have conducted a survey[5] of 1350 adults in the United States. This internet survey[6] measures public opinion about future use of energy sources, including fossil fuels, nuclear power, hydroelectricity, and solar and wind power.

Our survey showed the same level of skepticism as other surveys. Respondents in our survey, on average, preferred that the United States reduce somewhat nuclear power usage in the future. The same, however, was true of coal, the nation's largest energy source, and oil. On average, respondents wanted to keep natural gas at its current level. And, respondents strongly support a significant expansion of wind and solar power.

On what do these attitudes depend? We explored this question this question two ways. First, we performed a statistical analysis to determine which factors explain who supports nuclear power and who does not. This analysis is presented in the Chapter 9 Appendix. The results are, briefly, as follows:

- Perceived environmental harms weigh most heavily. The average person responded that nuclear power is moderately harmful to the environment, and the difference between someone who perceives nuclear power as "somewhat harmful" and "moderately harmful" is the difference between wanting to expand and wanting to reduce nuclear power in the future.
- Safety and waste are also significant factors. Those who believe that waste can be stored safely for many years express higher levels of support for building additional nuclear power plants. Those who believe that a serious accident is unlikely in the next 10 years also express higher support for nuclear power. The problem is a majority of respondents do not believe that nuclear waste can be stored safely for many years, and the typical respondent believes that a serious reactor accident is somewhat likely in the next 10 years.
- Perceived costs of nuclear power are the third most important factor. Those who

believe nuclear power is uneconomical support it less.

- ☐ Surprisingly, concern about global warming, in our survey, does not predict preferences about future use of nuclear power. There is no difference in support for expanding nuclear power between those who are very concerned about global warming and those who are not.
- ☐ Political beliefs and demographics, such as age, gender, and income, mattered relatively little, if at all.

Second, we performed an experiment within the survey to measure sensitivity of attitudes to possible changes in cost, waste, and global warming. Half of the sample was provided no information; they are the control group. The remaining half was divided into four groups. These groups were provided with information about future energy prices or about toxic waste from fossil fuels or about global warming or about all three factors (economics, pollution, and global warming). Our aim was not to increase support for nuclear power, but to see how the mix of energy sources would change with accurate information about costs, toxic waste, and global warming.

Only nuclear power showed substantially more support between the control group and the others. Those who received all three pieces of information supported nuclear power and natural gas equally, and supported nuclear power much more than coal and oil.

Information about the relative prices of energy sources produced almost all of this shift. The public perceives solar and wind to be inexpensive. When informed that solar and wind are more expensive than fossil fuels or nuclear power, survey respondents showed substantially less support for expanding solar and wind and substantially more support for nuclear power and somewhat more support for coal and oil. Information about global warming again had no effect on public attitudes toward alternative energy sources.

In our view, these survey data reveal the fundamental importance of the technology itself for public support. American public opinion toward energy is not the product of political ideology or party politics. Rather, public opposition to nuclear power in the United States is due primarily to the public reaction to the concrete problems of the technology and the industry, notably concerns over safety, toxic waste, and poor economics. It is not surprising that the public is skeptical about a technology that has over promised.

Should there be a public campaign to change perceptions about nuclear power? The evidence suggests that such a campaign may have only modest effect. Most of the change would come through education about the high price of alternative energy sources, such as solar and wind. The other possible source of change in public attitudes is the connection between global warming and fossil fuels. The typical person expresses concern about global warming, but that concern does not in turn translate into higher support for carbon free electricity sources, such as nuclear power.

The surer way to cultivate public acceptance of nuclear power, though, is through the improvement of the technology itself and choosing carefully what nuclear technology to use. Developing and deploying technology that proves uneconomical and hazardous will make the global growth scenario infeasible. Technology choices and improvements that lower the cost of nuclear power, that improve waste management and safety, and that lessen any environmental impact will substantially increase support for this power source.

NOTES

1. Eugene A. Rosa & Riley E. Dunlap, "Poll Trends: Nuclear power — three decades of public opinion" Public Opinion Quarterly, *58*, 295-324 (1994). National Science Board, Science and Engineering Indicators 2000, volume 1, page 8–19. Washington DC: National Science Foundation. Survey results vary because researchers ask different questions and in different contexts. Recent surveys range from 60 percent opposed to "building new nuclear power plants" (AP/Washington Post) to 55 percent favoring "new nuclear power plants in the future" (Nuclear Energy Industry tracking survey questionnaire, October 2002, carried out by Bisconti Research Inc). For a discussion of some of these issues and the state of public opinion, see Steve Miller "Pragmatic Concerns Fuel Nuclear Support," IEEE Spectrum, http://www.spectrum.ieee.org/WEBONLY/publicfeature/nov01/natt.html. Because existing survey data do not directly address many of the issues that motivate our inquiry, we conducted our own survey.
2. Associated Press poll conducted by ICR March 12–16 1999, N = 1015 adults nationwide. MIT Energy Survey, June, 2002, N = 1350.
3. European and Energy Matters, 1997, EUROBAROMETER 46.0, Directorate General for Energy, European Commission, February 1997.
4. Studies of particular factors have been conducted. Accidents and waste loom large in public thinking. See, for example, Ellen Peters and Paul Slovic, Journal of Applied Social Psychology, *26*, 1427-1453, (1996). Connie de Boer and Ineke Catsburg, "A Report: The Impact of Nuclear Accidents on Attitudes Toward Nuclear Energy," Public Opinion Quarterly, 52, 254-261 (1988).
5. We surveyed the United States for reasons of cost. A reliable survey of a similar size in another country performed by a reputable survey research firm was too expensive. It is our hope that this survey offers a model for studies of public attitudes toward energy use and development in other countries. The responses might be quite different. For example, Europeans are more concerned with global warming which could influence their attitudes toward nuclear energy.
6. We performed an Internet based survey because of four design advantages over the alternative methods, phone or face-to-face. First, a face-to-face survey was prohibitively costly — at least 10 times the cost of the Internet survey. Second, Internet surveys have much higher response rates than phone surveys. Knowledge Networks, the firm we employed, recruits a pool of approximately 2 million people from which it draws a random sample. Approximately 80 percent of the people sampled responded to our survey within one week. The typical phone survey with a similar cost structure has a non-response rate of around 70 percent. Third, ensuring a higher response rate in a phone survey would have increased costs substantially (approximately double). Fourth, Internet surveys are ideal for the experimental manipulations we performed. We provided information in graphics and text format, which is superior to reading text over the phone.

   The drawback of the Internet survey is that Internet users are not necessarily representative of the population. Knowledge Networks recruits a pool of potential survey respondents from the general population and develops sample weights to allow us to extrapolate to the general population. So, a college educated, high income individual receives less weight than an individual without a bachelor's degree and with modest or low income, because individuals with college educations and above average income are more common in the pool than in the population. Data analyses are performed with appropriate sample weights and controlling for demographic factors.