CHAPTER 1 — THE FUTURE OF NUCLEAR POWER — OVERVIEW AND CONCLUSIONS

The generation of electricity from fossil fuels, notably natural gas and coal, is a major and growing contributor to the emission of carbon dioxide – a greenhouse gas that contributes significantly to global warming. We share the scientific consensus that these emissions must be reduced and believe that the U.S. will eventually join with other nations in the effort to do so.

At least for the next few decades, there are only a few realistic options for reducing carbon dioxide emissions from electricity generation:

- increase efficiency in electricity generation and use;
- expand use of renewable energy sources such as wind, solar, biomass, and geothermal;
- capture carbon dioxide emissions at fossil-fueled (especially coal) electric generating plants and permanently sequester the carbon; and
- increase use of nuclear power.

The goal of this interdisciplinary MIT study is not to predict which of these options will prevail or to argue for their comparative advantages. In *our view, it is likely that we shall need all of these options and accordingly it would be a mistake at this time to exclude any of these four options from an overall carbon emissions management strategy*. Rather we seek to explore and evaluate actions that could be taken to maintain nuclear power as one of the significant options for meeting future world energy needs at low cost and in an environmentally acceptable manner.

In our view, it would be a mistake at this time to exclude any of these four options from an overall carbon emissions management strategy.

In 2002, nuclear power supplied 20% of United States and 17% of world electricity consumption. Experts project worldwide electricity consumption will increase substantially in the coming decades, especially in the developing world, accompanying economic growth and social progress. However, official forecasts call for a mere 5% increase in nuclear electricity generating capacity worldwide by 2020 (and even this is questionable), while electricity use could grow by as much as 75%. These projections entail little new nuclear plant construction and reflect both economic considerations and growing anti-nuclear sentiment in key countries. The limited prospects for nuclear power today are attributable, ultimately, to four unresolved problems:

- *Costs: nuclear power has higher overall lifetime costs* compared to natural gas with combined cycle turbine technology (CCGT) and coal, at least in the absence of a carbon tax or an equivalent "cap and trade" mechanism for reducing carbon emissions;
- *Safety: nuclear power has perceived adverse safety, environmental, and health effects*, heightened by the 1979 Three Mile Island and 1986 Chernobyl reactor accidents, but also by accidents at fuel cycle facilities in the United States, Russia, and Japan. There is also growing concern about the safe and secure transportation of nuclear materials and the security of nuclear facilities from terrorist attack;
- *Proliferation: nuclear power entails potential security risks*, notably the possible misuse of commercial or associated nuclear facilities and operations to acquire technology or materials as a precursor to the acquisition of a nuclear weapons capability. Fuel cycles that involve the chemical reprocessing of spent fuel to separate weapons-usable plutonium and uranium enrichment technologies are of special concern, especially as nuclear power spreads around the world;
- *Waste: nuclear power has unresolved challenges in long-term management of radioactive wastes.* The United States and other countries have yet to implement final disposition of spent fuel or high level radioactive waste streams created at various stages of the nuclear fuel cycle. Since these radioactive wastes present some danger to present and future generations, the public and its elected representatives, as well as prospective investors in nuclear power plants, properly expect continuing and substantial progress towards solution to the waste disposal problem. Successful operation of the planned disposal facility at Yucca Mountain would ease, but not solve, the waste issue for the U.S. and other countries if nuclear power expands substantially.

We believe the nuclear option should be retained, precisely because it is an important carbon-free source of power.

Today, nuclear power is not an economically competitive choice. Moreover, unlike other energy technologies, nuclear power requires significant government involvement because of safety, proliferation, and waste concerns. If in the future carbon dioxide emissions carry a significant "price," however, nuclear energy could be an important — indeed vital — option for generating electricity. We do not know whether this will occur. But *we believe the nuclear option should be retained, precisely because it is an important carbon-free source of power that can potentially make a significant contribution to future electricity supply*.

To preserve the nuclear option for the future requires overcoming the four challenges described above—costs, safety, proliferation, and wastes. These challenges will escalate if a significant number of new nuclear generating plants are built in a growing number of countries. The effort to overcome these challenges, however, is justified only if nuclear power can potentially contribute significantly to reducing global warming, which entails major expansion of nuclear power. In effect, preserving the nuclear option for the future means planning for growth, as well as for a future in which nuclear energy is a competitive, safer, and more secure source of power.

To explore these issues, our study postulates a *global growth scenario* that by mid-century would see 1000 to 1500 reactors of 1000 megawatt-electric (MWe) capacity each deployed worldwide, compared to a capacity equivalent to 366 such reactors now in service. Nuclear power expansion on this scale requires U.S. leadership, continued commitment by Japan, Korea, and Taiwan, a renewal of European activity, and wider deployment of nuclear power around the world. An illustrative deployment of 1000 reactors, each 1000 MWe in size, under this scenario is given in following table.

This scenario would displace a significant amount of carbon-emitting fossil fuel generation. In 2002, carbon equivalent emission from human activity was about 6,500 million tonnes per year; these emissions will probably more than double by 2050. The 1000 GWe of nuclear power postulated here would avoid annually about 800 million tonnes of carbon equivalent if the electricity generation displaced was gas-fired and 1,800 million tonnes if the generation was coal-fired, assuming no capture and sequestration of carbon dioxide from combustion sources.

Global Growth Scenario

REGION	PROJECTED 2050 GWe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE 2000	NUCLEAR ELECTRICITY MARKET SHARE 2050
Total World	**1,000**	**17%**	**19%**
Developed world	625	23%	29%
U.S.	300		
Europe & Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWhrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

FUEL CYCLE CHOICES

A critical factor for the future of an expanded nuclear power industry is the choice of the fuel cycle — what type of fuel is used, what types of reactors "burn" the fuel, and the method of disposal of the spent fuel. This choice affects all four key problems that confront nuclear power — costs, safety, proliferation risk, and waste disposal. For this study, we examined three representative nuclear fuel cycle deployments:

We believe that the world-wide supply of uranium ore is sufficient to fuel the deployment of 1,000 reactors over the next half century.

- *conventional thermal reactors operating in a "once-through" mode*, in which discharged spent fuel is sent directly to disposal;
- *thermal reactors with reprocessing in a "closed" fuel cycle*, which means that waste products are separated from unused fissionable material that is re-cycled as fuel into reactors. This includes the fuel cycle currently used in some countries in which plutonium is separated from spent fuel, fabricated into a mixed plutonium and uranium oxide fuel, and recycled to reactors for one pass[1];
- *fast reactors[2] with reprocessing in a balanced "closed" fuel cycle*, which means thermal reactors operated world-wide in "once-through" mode and a balanced number of fast reactors that destroy the actinides separated from thermal reactor spent fuel. The fast reactors, reprocessing, and fuel fabrication facilities would be co-located in secure nuclear energy "parks" in industrial countries.

Closed fuel cycles extend fuel supplies. The viability of the once-through alternative in a global growth scenario depends upon the amount of uranium resource that is available at economically attractive prices. *We believe that the world-wide supply of uranium ore is sufficient to fuel the deployment of 1000 reactors over the next half century* and to maintain this level of deployment over a 40 year lifetime of this fleet. This is an important foundation of our study, based upon currently available information and the history of natural resource supply.

The result of our detailed analysis of the relative merits of these representative fuel cycles with respect to key evaluation criteria can be summarized as follows: *The once through cycle has advantages in cost, proliferation, and fuel cycle safety*, and is disadvantageous only in respect to long-term waste disposal; the

1. This fuel cycle is known as Plutonium Recycle Mixed Oxide, or PUREX/MOX.
2. A fast reactor more readily breeds fissionable isotopes-potential fuel-because it utilizes higher energy neutrons that in turn create more neutrons when absorbed by fertile elements, e.g. fissile Pu^{239} is bred from neutron absorption of U^{238} followed by beta (electron) emission from the nucleus.

two closed cycles have clear advantages only in long-term aspects of waste disposal, and disadvantages in cost, short-term waste issues, proliferation risk, and fuel cycle safety. (See Table.) Cost and waste criteria are likely to be the most crucial for determining nuclear power's future.

We have not found, and based on current knowledge do not believe it is realistic to expect, that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation.

Fuel Cycle Types and Ratings

				SAFETY	
	ECONOMICS	WASTE	PROLIFERATION	Reactor	Fuel Cycle
Once through	+	× short term – long term	+	×	+
Closed thermal	–	– short term + long term	–	×	–
Closed fast	–	– short term + long term	–	+ to –	–

+ means relatively advantageous; × means relatively neutral; – means relatively disadvantageous

This table indicates broadly the relative advantage and disadvantage among the different type of nuclear fuel cycles. It does not indicate relative standing with respect to other electricity-generating technologies, where the criteria might be quite different (for example, the nonproliferation criterion applies only to nuclear).

Our analysis leads to a significant conclusion: *The once-through fuel cycle best meets the criteria of low costs and proliferation resistance*. Closed fuel cycles may have an advantage from the point of view of long-term waste disposal and, if it ever becomes relevant, resource extension. But closed fuel cycles will be more expensive than once-through cycles, until ore resources become very scarce. This is unlikely to happen, even with significant growth in nuclear power, until at least the second half of this century, and probably considerably later still. Thus our most important recommendation is:

For the next decades, government and industry in the U.S. and elsewhere should give priority to the deployment of the once-through fuel cycle, rather than the development of more expensive closed fuel cycle technology involving reprocessing and new advanced thermal or fast reactor technologies.

This recommendation implies a major re-ordering of priorities of the U.S. Department of Energy nuclear R&D programs.

PUBLIC ATTITUDES TOWARD NUCLEAR POWER

Expanded deployment of nuclear power requires public acceptance of this energy source. Our review of survey results shows that a majority of Americans and Europeans oppose building new nuclear power plants to meet future energy needs. To understand why, we surveyed 1350 adults in the US about their attitudes toward energy in general and nuclear power in particular. Three important and unexpected results emerged from that survey:

- The U.S. public's attitudes are informed almost entirely by their perceptions of the technology, rather than by politics or by demographics such as income, education, and gender.
- The U.S. public's views on nuclear waste, safety, and costs are critical to their judgments about the future deployment of this technology. Technological improvements that lower costs and improve safety and waste problems can increase public support substantially.
- In the United States, people do not connect concern about global warming with carbon-free nuclear power. There is no difference in support for building more nuclear power plants between those who are very concerned about global warming and those who are not. Public education may help improve understanding about the link between global warming, fossil fuel usage, and the need for low-carbon energy sources.

There are two implications of these findings for our study: first, the U.S. public is unlikely to support nuclear power expansion without substantial improvements in costs and technology. Second, the carbon-free character of nuclear power, the major motivation for our study, does not appear to motivate the U.S. general public to prefer expansion of the nuclear option.

The U.S. public is unlikely to support nuclear power expansion without substantial improvements in costs and technology.

ECONOMICS

Nuclear power will succeed in the long run only if it has a lower cost than competing technologies. This is especially true as electricity markets become progressively less subject to economic regulation in many parts of the world. We constructed a model to evaluate the real cost of electricity from nuclear power versus pulverized coal plants and natural gas combined cycle plants (at various projected levels of real lifetime prices for natural gas), over their economic lives. These technologies are most widely used today and, absent a carbon tax or its equivalent, are less expensive than many renewable technologies. Our "merchant" cost model uses assumptions that commercial investors would be expected to use today, with parameters based on actual experience rather than engineering estimates of what might be achieved under ideal conditions; it compares the constant or "levelized" price of electricity over the life of a power plant that would be necessary to cover all operating expenses and taxes and provide an acceptable return to investors. The comparative figures given below assume 85% capacity factor and a 40-year economic life for the nuclear plant, reflect economic conditions in the U.S, and consider a range of projected improvements in nuclear cost factors. (See Table.)

Comparative Power Costs

CASE (Year 2002 $)	REAL LEVELIZED COST Cents/kWe-hr
Nuclear (LWR)	6.7
+ Reduce construction cost 25%	5.5
+ Reduce construction time 5 to 4 years	5.3
+ Further reduce O&M to 13 mills/kWe-hr	5.1
+ Reduce cost of capital to gas/coal	4.2
Pulverized Coal	4.2
CCGT[a] (low gas prices, $3.77/MCF)	3.8
CCGT (moderate gas prices, $4.42/MCF)	4.1
CCGT (high gas prices, $6.72/MCF)	5.6

a. Gas costs reflect real, levelized acquisition cost per thousand cubic feet (MCF) over the economic life of the project.

We judge the indicated cost improvements for nuclear power to be plausible, but not proven. The model results make clear why electricity produced from new nuclear power plants today is not competitive with electricity produced from coal or natural gas-fueled CCGT plants with low or moderate gas prices, unless *all* cost improvements for nuclear power are realized. The cost comparison becomes worse for nuclear if the capacity factor falls. It is also important to emphasize that the nuclear cost structure is driven by high up-front capital costs, while the natural gas cost driver is the fuel cost; coal lies in between nuclear and natural gas with respect to both fuel and capital costs.

Nuclear does become more competitive by comparison if the social cost of carbon emissions is internalized, for example through a carbon tax or an equivalent "cap and trade" system. Under the assumption that the costs of carbon emissions are imposed, the accompanying table illustrates the impact on the competitive costs for different power sources, for emission costs in the range of $50 to $200/tonne carbon. (See Table.) The ultimate cost will depend on both societal choices (such as how much carbon dioxide emission

Power Costs with Carbon Taxes

CARBON TAX CASES LEVELIZED ELECTRICITY COST cents/kWe-hr	$50/tonne C	$100/tonne C	$200/tonne C
Coal	5.4	6.6	9.0
Gas (low)	4.3	4.8	5.9
Gas (moderate)	4.7	5.2	6.2
Gas (high)	6.1	6.7	7.7

to permit) and technology developments, such as the cost and feasibility of large-scale carbon capture and long-term sequestration. Clearly, costs in the range of $100 to $200/tonne C would significantly affect the relative cost competitiveness of coal, natural gas, and nuclear electricity generation.

The carbon-free nature of nuclear power argues for government action to encourage maintenance of the nuclear option, particularly in light of the regulatory uncertainties facing the use of nuclear power and the unwillingness of investors to bear the risk of introducing a new generation of nuclear facilities with their high capital costs.

We recommend three actions to improve the economic viability of nuclear power:

The government should cost share for site banking for a number of plants, certification of new plant designs by the Nuclear Regulatory Commission, and combined construction and operating licenses for plants built immediately or in the future; we support U.S. Department of Energy initiatives on these subjects.

The government should recognize nuclear as carbon-free and include new nuclear plants as an eligible option in any federal or state mandatory renewable energy portfolio (i.e., a "carbon-free" portfolio) standard.

The government should provide a modest subsidy for a small set of "first mover" commercial nuclear plants to demonstrate cost and regulatory feasibility in the form of a production tax credit.

We propose a production tax credit of up to $200 per kWe of the construction cost of up to 10 "first mover" plants. This benefit might be paid out at about 1.7 cents per kWe-hr, over a year and a half of full-power plant operation. We prefer the production tax credit mechanism because it offers the greatest incentive for projects to be completed and because it can be extended to other carbon free electricity technologies, for example renewables, (wind currently enjoys a 1.7 cents per kWe-hr tax credit for ten years) and coal with carbon capture and sequestration. The credit of 1.7 cents per kWe- hr is equivalent to a credit of $70 per avoided metric ton of carbon if the electricity were to have come from coal plants (or $160 from natural gas plants). Of course, the carbon emission reduction would then continue without public assistance for the plant life (perhaps 60 years for nuclear). If no new nuclear plant is built, the government will not pay a subsidy.

These actions will be effective in stimulating additional investment in nuclear generating capacity if, and only if, the industry can live up to its own expectations of being able to reduce considerably capital costs for new plants.

Advanced fuel cycles add considerably to the cost of nuclear electricity. We considered reprocessing and one-pass fuel recycle with current technology, and found the fuel cost, including waste storage and disposal charges, to be about 4.5 times the fuel cost of the once-through cycle. Thus use of advanced fuel cycles imposes a significant economic penalty on nuclear power.

SAFETY

We believe the safety standard for the global growth scenario should maintain today's standard of less than one serious release of radioactivity accident for 50 years from all fuel cycle activity. This standard implies a ten-fold reduction in the expected frequency of serious reactor core accidents, from 10^{-4}/reactor year to 10^{-5}/reactor year. This reactor safety standard should be possible to achieve in new light water reactor plants that make use of advanced safety designs. International adherence to such a standard is important, because an accident in any country will influence public attitudes everywhere. The extent to which nuclear facilities should be hardened to possible terrorist attack has yet to be resolved.

We do not believe there is a nuclear plant design that is totally risk free. In part, this is due to technical possibilities; in part due to workforce issues. Safe operation requires effective regulation, a management committed to safety, and a skilled work force.

The high temperature gas-cooled reactor is an interesting candidate for reactor research and development because there is already some experience with this system, although not all of it is favorable. This reactor design offers safety advantages because the high heat capacity of the core and fuel offers longer response times and precludes excessive temperatures that might lead to release of fission products; it also has an advantage compared to light water reactors in terms of proliferation resistance.

These actions will be effective in stimulating additional investment in nuclear generating capacity if, and only if, the industry can live up to its own expectations of being able to reduce considerably overnight capital costs for new plants.

Because of the accidents at Three Mile Island in 1979 and Chernobyl in 1986, a great deal of attention has focused on reactor safety. However, the safety record of reprocessing plants is not good, and there has been little safety analysis of fuel cycle facilities using, for example, the probabilistic risk assessment method. More work is needed here.

Our principal recommendation on safety is:

The government should, as part of its near-term R&D program, develop more fully the capabilities to analyze life-cycle health and safety impacts of fuel cycle facilities and focus reactor development on options that can achieve enhanced safety standards and are deployable within a couple of decades.

WASTE MANAGEMENT

The management and disposal of high-level radioactive spent fuel from the nuclear fuel cycle is one of the most intractable problems facing the nuclear power industry throughout the world. No country has yet successfully implemented a system for disposing of this waste. We concur with the many independent expert reviews that have concluded that geologic repositories will be capable of safely isolating the waste from the biosphere. However, implementation of this method is a highly demanding task that will place great stress on operating, regulatory, and political institutions.

We do not believe a convincing case can be made, on the basis of waste management considerations alone, that the benefits of advanced, closed fuel cycles will outweigh the attendant safety, environmental, and security risks and economic costs.

For fifteen years the U.S. high-level waste management program has focused almost exclusively on the proposed repository site at Yucca Mountain in Nevada. Although the successful commissioning of the Yucca Mountain repository would be a significant step towards the secure disposal of nuclear waste, we believe that a broader, strategically balanced nuclear waste program is needed to prepare the way for a possible major expansion of the nuclear power sector in the U.S. and overseas.

The global growth scenario, based on the once-through fuel cycle, would require multiple disposal facilities by the year 2050. To dispose of the spent fuel from a steady state deployment of one thousand 1 GWe reactors of the light water type, new repository capacity equal to the nominal storage capacity of Yucca Mountain would have to be created somewhere in the world every three to four years. This requirement, along with the desire to reduce long-term risks from the waste, prompts interest in advanced, closed fuel cycles.

These schemes would separate or partition plutonium and other actinides — and possibly certain fission products — from the spent fuel and transmute them into shorter-lived and more benign species. The goals would be to reduce the thermal load from radioactive decay of the waste on the repository, thereby increasing its storage capacity, and to shorten the time for which the waste must be isolated from the biosphere.

We have analyzed the waste management implications of both once-through and closed fuel cycles, taking into account each stage of the fuel cycle and the risks of radiation exposure in both the short and long-term. *We do not believe that a convincing case can be made on the basis of waste management considerations alone that the benefits of partitioning and transmutation will outweigh the attendant safety, environmental, and security risks and economic 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 assessments, but the incremental costs and short-term safety and environmental risks would have to be greatly reduced relative to current expectations and experience.

We further conclude that waste management strategies in the once-through fuel cycle are potentially available that could yield long-term risk reductions at least as great as those claimed for waste partitioning and transmutation, with fewer short-term risks and lower development and deployment costs. These include both incremental improvements to the current mainstream mined repositories approach and more far-reaching innovations such as deep borehole disposal. Finally, replacing the current ad hoc approach to spent fuel storage at reactor sites with an explicit strategy to store spent fuel for a period of several decades will create additional flexibility in the waste management system.

Our principal recommendations on waste management are:

The DOE should augment its current focus on Yucca Mountain with a balanced long-term waste management R&D program.

A research program should be launched to determine the viability of geologic disposal in deep boreholes within a decade.

A network of centralized facilities for storing spent fuel for several decades should be established in the U.S. and internationally.

NONPROLIFERATION

Nuclear power should not expand unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small. We believe that nuclear power can expand as envisioned in our global growth scenario with acceptable incremental proliferation risk, provided that reasonable safeguards are adopted and that deployment of reprocessing and enrichment are restricted. The international community 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). Responsible governments must control, to the extent possible, the know-how relevant to produce and process either highly enriched uranium (enrichment technology) or plutonium.

Three issues are of particular concern: existing stocks of *separated* plutonium around the world that are directly usable for weapons; nuclear facilities, for example in Russia, with inadequate controls; and transfer of technology, especially enrichment and reprocessing technology, that brings nations closer to a nuclear weapons capability. The proliferation risk of the global growth scenario is underlined by the likelihood that use of nuclear power would be introduced and expanded in many countries in different security circumstances.

Nuclear power should not expand unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small.

An international response is required to reduce the proliferation risk. The response should:

- re-appraise and strengthen the institutional underpinnings of the IAEA safeguards regime in the near term, including sanctions;
- guide nuclear fuel cycle development in ways that reinforce shared nonproliferation objectives.

Accordingly, we recommend:

The International Atomic Energy Agency (IAEA) should focus overwhelmingly on its safeguards function and should be given the authority to carry out inspections beyond declared facilities to suspected illicit facilities;

Greater attention must be given to the proliferation risks at the front end of the fuel cycle from enrichment technologies;

IAEA safeguards should move to an approach based on continuous materials protection, control and accounting using surveillance and containment systems, both in facilities and during transportation, and should implement safeguards in a risk-based framework keyed to fuel cycle activity;

Fuel cycle analysis, research, development, and demonstration efforts must include explicit analysis of proliferation risks and measures defined to minimize proliferation risks;

International spent fuel storage has significant nonproliferation benefits for the growth scenario and should be negotiated promptly and implemented over the next decade.

ANALYSIS, RESEARCH, DEVELOPMENT, AND DEMONSTRATION PROGRAM

The U.S. Department of Energy (DOE) analysis, research, development, and demonstration (ARD&D) program should support the technology path leading to the global growth scenario and include diverse activities that balance risk and time scales, in pursuit of the strategic objective of preserving the nuclear option. *For technical, economic, safety, and public acceptance reasons, the highest priority in fuel cycle ARD&D, deserving first call on available funds, lies with efforts that enable robust deployment of the once-through fuel cycle*. The current DOE program does not have this focus.

Every industry in the United States develops basic analytical models and tools such as spreadsheets that allow firms, investors, policy makers, and regulators to understand how changes in the parameters of a process will affect the performance and cost of that process. But we have been struck throughout our study by the absence of such models and simulation tools that permit in-depth, quantitative analysis of trade-offs between different reactor and fuel cycle choices, with respect to all key criteria. The analysis we have seen is based on point designs and does not incorporate information about the cost and performance of operating commercial nuclear facilities. Such modeling and analysis under a wide variety of scenarios, for both open and closed fuel cycles, will be useful to the industry and investors, as well as to international discussions about the desirability about different fuel cycle paths.

We call on the Department of Energy, perhaps in collaboration with other countries, to establish a major project for the modeling, analysis, and simulation of commercial nuclear power systems — The Nuclear System Modeling Project. This project should provide a foundation for the accumulation of information about how variations in the operation of plants and other parts of the fuel cycle affect costs, safety, waste, and proliferation resistance characteristics. The models and analysis should be based on real engineering data and, wherever possible, practical experience. This project is technically demanding and will require many years and considerable resources to be carried out successfully.

For technical, economic, safety, and public acceptance reasons, the highest priority in fuel cycle R&D, deserving first call on available funds, lies with efforts that enable robust deployment of the once-through fuel cycle.

We believe that development of advanced nuclear technologies — either fast reactors or advanced fuel cycles employing reprocessing – should await the results of the *Nuclear System Modeling Project* we have proposed above. Our analysis makes clear that there is ample time for the project to compile the necessary engineering and economic analyses and data before undertaking expensive development programs, even if the project should take a decade to complete. Expensive programs that plan for the development or deployment of commercial reprocessing based on any existing advanced fuel cycle technologies are simply not justified on the basis of cost, or the unproven safety, proliferation risk, and waste properties of a closed cycle compared to the once-through cycle. Reactor concept evaluation should be part of the Nuclear System Modeling Project.

On the other hand, we support a modest laboratory scale research and analysis program on *new* separation methods and associated fuel forms, with the objective of learning about approaches that emphasize lower cost and more proliferation resistance. These data can be important inputs to advanced fuel cycle analysis and simulation and thus help prioritize future development programs.

The modeling project's research and analysis effort should only encompass technology pathways that do not produce weapons-usable material during normal operation (for example, by leaving some uranium, fission products, and/or minor actinides with the recycled plutonium). *The closed fuel cycle currently practiced in Western Europe and Japan, known as PUREX/MOX, does not meet this criterion*. There are advanced closed fuel cycle concepts involving combinations of reactor, fuel form, and separations technology that satisfy these conditions and, with appropriate institutional arrangements, can have significantly better proliferation resistance than the PUREX/MOX fuel cycle, and perhaps approach that of the open fuel cycle. Accordingly, the governments of nuclear supplier countries should discourage other nations from developing and deploying the PUREX/MOX fuel cycle.

Government R&D support for advanced design LWRs and for the High Temperature Gas Reactor (HTGR) is justified because these are the two reactor types that are most likely to play a role in any nuclear expansion. R&D support for advanced design LWRs should focus on measures that reduce construction and operating cost. Because the High Temperature Gas Reactor (HTGR) has potential advantages with respect to safety, proliferation resistance, modularity and efficiency, government research and limited development support to resolve key uncertainties, for example, the performance of HTGR fuel forms in reactors and gas power conversion cycle components, is warranted.

Waste management also calls for a significant, and redirected, ARD&D program. The DOE waste program, understandably, has been singularly focused for the past several years on the Yucca Mountain project. We believe DOE must broaden its waste R&D effort or run the risk of being unable to rigorously defend its choices for waste disposal sites. More attention needs to be given to the characterization of waste forms and engineered barriers, followed by development and testing of engineered barrier systems. We believe deep boreholes, as an alternative to mined repositories, should be aggressively pursued. These issues are inherently of international interest in the growth scenario and should be pursued in such a context.

The closed fuel cycle currently practiced in Western Europe and Japan, known as PUREX/MOX, does not meet this nonproliferation criterion.

There is opportunity for international cooperation in this ARD&D program on safety, waste, and the Nuclear System Modeling Project. A particularly pertinent effort is the development, deployment, and operation of a word wide materials protection, control, and accounting tracking system. There is no currently suitable international organization for this development task. A possible approach lies with the G-8 as a guiding body.

Our global growth scenario envisions an open fuel cycle architecture at least until mid-century or so, with the advanced closed fuel cycles possibly deployed later, but only if significant improvements are realized through research. The principal driver of this conclusion is our judgment that natural uranium ore is available at reasonable prices to support the open cycle at least to late in the century in a scenario of substantial expansion. This gives the open cycle clear economic advantage with proliferation resistance an important additional feature. The DOE should undertake a global uranium resource evaluation program to determine with greater confidence the uranium resource base around the world.

Accordingly, we recommend:

The U.S. Department of Energy should focus its R&D program on the once-through fuel cycle;

The U.S. Department of Energy should establish a Nuclear System Modeling project to carryout the analysis, research, simulation, and collection of engineering data needed to evaluate all fuel cycles from the viewpoint of cost, safety, waste management, and proliferation resistance;

The U.S. Department of Energy should undertake an international uranium resource evaluation program;

The U.S. Department of Energy should broaden its waste management R&D program;

The U.S. Department of Energy should support R&D that reduces Light Water Reactor (LWR) costs and for development of the HTGR for electricity application.

We believe that the ARD&D program proposed here is aligned with the strategic objective of enabling a credible growth scenario over the next several decades. Such a ARD&D program requires incremental budgets of almost $400 million per year over the next 5 years, and at least $460 million per year for the 5-10 year period.

Chapter 2 — Background and Purpose of This Study

In 2000 nuclear power produced about 17% of the world's electricity from 442 commercial reactors in 31 countries. The United States has the largest deployment, with 104 operating reactors producing 20% of the country's electricity, followed by France, Japan, Germany, Russia, and South Korea. The reliability of these plants has improved considerably in recent years (for example, capacity factors of U.S. nuclear reactors have achieved 90%), and many will have their originally expected operating lives extended significantly. Nuclear power is clearly an important source of electricity in the United States and the world.

If current policies continue, however, nuclear power is likely to decline gradually and conceivably disappear in this century from the world's electricity supply portfolio. We believe removing nuclear power as a supply option would be a mistake at this time. The primary reason is that nuclear power is an important source of electricity that does not rely on fossil fuel and hence does not produce greenhouse gas emissions. This is the primary motivation for our examination for an inter-connected set of issues that will challenge nations individually and collectively over the next century. The issues are:

- reducing atmospheric pollution and emissions of greenhouse gases;
- meeting dramatically increased energy, and especially electricity, demand throughout the industrialized and developing world; and
- assuring security and minimizing conflict associated with energy supply.

Our study undertakes to:

- describe the characteristics of a nuclear power infrastructure that would make a significant contribution to reducing CO_2 emissions;
- identify the issues that must be addressed if nuclear power is to make a contribution on this scale; and
- outline the needed program of analysis, research, development, and demonstration.

GLOBAL WARMING

Most developed countries are in the early stages of implementing policies to stabilize and ultimately reduce greenhouse gas emissions and the attendant global warming. The scientific consensus about the risks of further significant increases in atmospheric greenhouse gas concentrations grows steadily stronger and more widely endorsed. This consensus underlies a strong impetus for governmental actions that prepare the ground for meeting possibly stringent CO_2 emission constraints in the decades ahead, specifically global emission levels comparable to or below those of today, despite a considerable increase in energy production and use. Developing countries will need to limit the growth of greenhouse gas emissions while their energy consumption increases dramatically. For example, if atmospheric concentration of CO_2 is not allowed to exceed twice its pre-industrial value, then CO_2 emissions in the 21st century will need to be held to half the cumulative total expected under a "business as usual" trajectory,[1] and the annual emission rate would eventually need to fall well below the 2000 value. While our focus is on global warming because of its overwhelming international implications, we recognize that reduction in other emissions from fossil fuel combustion would have important regional and local benefits for clean air.

We believe that the United States will eventually join with other developed countries in the effort to reduce greenhouse gas emissions, even if the mechanisms for doing so are uncertain for the moment. Developing countries – certainly the large ones, such as China, India, Pakistan, Brazil, and Indonesia – must ultimately be party to this effort if it is to succeed. Achieving the reductions in greenhouse gas emissions likely to be required will be a major technical and economic challenge to both developed and developing countries that will persist for many decades into the future.

The power sector contributes about a third of greenhouse gas emissions worldwide. The Energy Information Administration (EIA) of the U.S. Department of Energy projects that, in the absence of CO_2-control policies and technologies, electricity's share of global emissions of greenhouse gases (CO_2 and others) will climb to over 40% by 2020. In the United States, almost 90% of the carbon emissions from electricity generation come from coal-fired generation, even though this accounts for only 52% of the electricity. (About 29% of United States electricity comes from carbon-free nuclear and renewables-based generation; about 19% comes from natural-gas-fired and oil-fired generation, but both of these fuels release less carbon per kilowatt-hour than coal-fired generation does.)

There are few realistic options to reduce significantly carbon emissions from electricity generation (besides lowering standards of living):

- increased efficiency in electricity end-use and generation;
- increased use of renewable energy technologies (e.g., wind, solar, biomass, and geothermal);
- introduction of carbon capture and sequestration at fossil-fueled (especially coal) power plants on a massive scale; and
- increased use of nuclear fission power reactors (and possibly fusion at a later date).

As we have argued in Chapter 1, *our view is that it would be a mistake to exclude at this time any of these four basic options as a possibly important part of an overall carbon emissions management strategy*. Each of the options presents technical, economic, environmental, political, and human behavioral issues that make their ultimate market penetration uncertain.

Nuclear power is a special case, however. If current trends continue, nuclear power will gradually decrease and perhaps even disappear as part of the global energy portfolio, thus failing to make any long-term contribution to reducing greenhouse gas emissions. Few nuclear power plants are under construction worldwide, and of those, most are being built in a small number of developing countries or developed countries in East Asia.[2] In most developed countries, the use of nuclear power is not expected to expand and, in many of these countries, including the United States, nuclear power has been explicitly excluded from policies to stabilize and reduce carbon emissions (e.g., direct and tax subsidies for renewable energy and energy conservation, high mandated purchase prices for renewable energy, renewable energy portfolio standards). In Britain, nuclear power plants pay a "carbon tax," even though they have essentially no CO_2 emissions. We believe that a more objective approach will have a better chance at meeting the global warming challenge. Indeed, it is likely that our energy future will exploit *all* of the four options to one degree or another. This study addresses the issues associated with maintaining the nuclear power option.

ELECTRICITY DEMAND

The U.S. National Academy of Engineering named electrification as the premier engineering achievement of the twentieth century[3]. This is a remarkable statement for the century of lasers, computers, airplanes, and other ubiquitous and important technologies and is indicative of the extraordinary impact of electricity in improving the quality of people's lives. Accordingly, it should not be surprising that global electricity use is expected to increase dramatically in the years ahead, even taking into account improvements in end use efficiency. Growth in electricity use is expected especially in developing countries, as they strive to meet basic needs and to modernize and industrialize their economies.

The U.S. Department of Energy's EIA projects a 75% increase in global electricity use in two decades, from 2000 to 2020. By mid-century, a threefold increase or more is credible and, indeed, expected. Table 2.1 gives the growth rate for electricity use in different regions of the world as anticipated in the EIA "business-as-usual" projections to the year 2020.[4]

There is a strong correlation between electricity consumption per capita and the United Nations "human development index" (HDI), which combines indicators of health, education, and economic prosperity.[5] Industrialized countries have an HDI above 0.9 (on a scale of 0 to 1) and per capita energy consumption above 4000 kWe-hrs.

Large developing countries, such as China, India, Pakistan, and Indonesia, are well below the industrialized country HDI and aspire to advance by rapid economic growth. Overall, energy consumption per capita in the developing world is currently less than a fifth of that in the developed world. Unless provided with assistance or incentives, these developing nations are likely to seek the lowest cost supply alternatives that can meet their growing industrial and consumer demand for electricity. This prospect clearly raises the specter of substantially increased greenhouse gas emissions, since coal is likely to be an economic choice for many developing countries, e.g. China and India. *How these developing countries meet their electricity demand is of central interest to the discussion of global warming, since over time their choices will influence global emissions levels more than measures taken by the developed world*. Greater electricity consumption is desirable because it accompanies social and economic advance, but we want the electricity production to take place in an economic and environmentally acceptable manner.

The attractiveness of nuclear power as an option will be determined by many country-specific factors. To understand how much nuclear power would be needed to make a significant contribution to reducing CO_2 emissions by 2050, and where it might be deployed, we present, in Appendix 2, a simple scenario for electricity growth over the next fifty years. The scenario is not based on economic forecasting, but on a model of what electricity growth could be as countries attempt to raise individual living standards to acceptable levels within credible growth constraints. The model assumes a modest 1%/year annual growth in per capita electricity consumption for developed countries and a growth rate for developing countries that takes them to 4000 kWe-hrs/person/year in 2050 (i.e., we determine the growth rate as an outcome). Population projections are those currently provided by the United Nations. The one additional constraint in the scenario is that the annual growth rate in total electricity production for any country is capped at 4.7%; this is one half percent above EIA's projected electricity growth rate for the developing world overall up to 2020. Sustaining a 4.7%/year growth rate for fifty years yields a factor of ten increase; although within the realm of possibility with appropriate policies and sufficient resource investment, this cap on total growth represents a very ambitious target for any individual developing country. Within this scenario, global electricity production is slightly below the EIA reference in 2020 and about a factor of three greater in 2050 than it is today. The implications of this scenario for four categories of nations are described below.

Table 2.1 Anticipated Growth of Electricity (billion kWe-h)[4]

REGION (billion kWe-h)	1999	2020	GROWTH RATE %
Industrialized	7,500	10,900	1.8
(US)	3,200	4,800	1.9
FSU	1,500	2,100	1.8
Developing	3,900	9,200	4.2
Total World	12,800	22,200	2.7

Developed countries. Among the major developed countries, the United States is unique in having a projected large increase in population and a concomitant large increase in total electricity demand. If the global deployment of nuclear power is to grow substantially by mid-century, the United States almost certainly must be a major participant. Nuclear power growth is unlikely to be very large in other key developed countries, such as Japan (with an anticipated population decline) or France (with a stable population and a power sector already dominated by nuclear power).

More advanced developing countries. Countries such as China, Brazil, Mexico, and Iran can reach the 4000 kWe-hrs/person/year benchmark with annual growth rates of electricity consumption in the 2%-3% range. Although improved business, regulatory, financial, political, and other conditions may be needed, these countries would likely be very important for an expanded nuclear power scenario. By 2050, they will have large urban populations (above 85%), an important factor favoring the introduction of large base load plants. This model is, of course, subject to country-specific caveats; for example, Iran has abundant natural gas supplies, so its pursuit of nuclear power logically raises proliferation concerns. Collectively, countries in this group have relatively little nuclear power today but could turn to nuclear power to meet a fraction of their future electricity supply needs, as South Korea has done.

Less advanced developing countries. Countries such as India, Pakistan, Indonesia, Philippines, and Vietnam (with a combined projected population of 2.5 billion in 2050) may, with considerable progress in their political, legal, financial, and regulatory regimes and an associated increase in domestic and foreign investment in their energy sectors, reach 2000-3000 kWe-hrs/person/year by mid-century. This will be a tall order. Nuclear power may account for part of the dramatic increase in electricity supply called for in these countries (India is an exception in that it already has fourteen units), but pursuing such a capital- and management-intensive technology will prove challenging. In many cases, proliferation concern – the concern that the commercial nuclear fuel cycle will be used as a source of materials and/or technology that will lead to proliferation of nuclear weapons – will accompany development of substantial nuclear technology infrastructures.

Least advanced developing countries. Many large developing countries, with a particular concentration in Africa, cannot come close to the per capita benchmark within economically credible scenarios. These countries are not good candidates for nuclear power, barring an unforeseen breakthrough in technology and capital requirements.

In sum, electricity utilization is likely to increase significantly worldwide over the next half-century, requiring a major investment in both replacement and expansion of generating capacity. Much of the expansion will take place in the developing world. Selected developed countries will be central to a major increase in nuclear power, but large parts of the developing world are unlikely participants. If developing nations do adopt nuclear power, all nations of the world will have an interest in how these countries regulate their nuclear enterprise with respect to reactor and fuel cycle safety, transportation of nuclear materials, waste disposal, and especially proliferation safeguards.

SECURITY

Yet another reason for thinking about the nuclear option — national security — is not new. The dependence of the developed world on oil from the Middle East, an unstable region of the world, has long presented a risk to the economies of the United States and other countries that depend on imported oil, such as Japan, Germany, and France. The United States' dependence is linked principally to fuel for the transportation sector, but many other countries rely on oil for significant power generation. Nuclear power offers one option for reducing this dependence.

Within the time horizon addressed in this study, however, the national security implications of expanded nuclear power may be even more significant with respect to natural gas, which displays the same lack of geographic correlation between supply and demand that has defined the geopolitical landscape for oil. It is likely that many nations, including the United States, may import large quantities of LNG or liquids from gas, produced from stranded gas in diverse regions of the world.

There is another national security dimension to nuclear power. Combating nuclear proliferation is one of our most important foreign policy objectives. There is no doubt about the great risk to the security of the United States and the rest of the world that the spread of nuclear weapons to other states and perhaps non-state actors would bring. So there is a major security interest in how all aspects of nuclear commerce develop around the world. For example, the extensive U.S. "Cooperative Threat Reduction program,"[6] provides assistance to Russia for the purpose of improving their efforts to protect their nuclear weapons and nuclear explosive materials against theft.[7] On the other hand, there is considerable tension between the United States and Russia created by Russian assistance to Iran on commercial nuclear power, especially since Iran is awash in natural gas.

Indeed, it is worth recalling that the unresolved nuclear fuel cycle "schism" of the 1970s between the United States and its European and Japanese allies stemmed from nonproliferation concerns. In the Ford and Carter administrations, the United States stopped the recycling of plutonium in commercial reactors because of proliferation risks associated with a "plutonium economy." The hope that others would emulate this policy was not realized, as energy resource-poor countries, such as France and Japan, evaluated the balance of risks differently. As countries look to shape today's nuclear fuel cycle policy and R&D decisions in the context of the world environmental, economic development, and security needs of the next fifty years, finding a common path among the G-8 and others can itself contribute significantly to managing proliferation concerns. The expansion of nuclear power, should it occur, will raise proliferation concerns that call for ongoing American engagement in nuclear fuel cycle issues independent of nuclear power's level of contribution to domestic electricity generation.

THE CHALLENGES OF NUCLEAR POWER EXPANSION

Despite the strong rationale for reducing greenhouse gas emissions that contribute to global warming, for meeting increasing demand for electricity, and for improving the national security aspects of energy supply, the EIA's "business-as-usual" projection for nuclear power indicates a mere 5% increase in 2020, even as world electricity use increases by 75%. After 2020, if significant investments are not made, nuclear power supply would decline as existing reactors are retired. EIA projects significant increases in nuclear generated electricity in China, Japan, and South Korea, largely offsetting decreases in the United States and Western Europe. In the United States, the last nuclear plant order was in 1979. There is considerable anti-nuclear sentiment in Europe: Belgium, Germany, the Netherlands, and Sweden are officially committed to phasing out nuclear power gradually; and there is public opposition to nuclear power in Japan and Taiwan. To be sure, several countries are still on a path to construct new operating units — South Korea, Finland, India, and Russia are examples — and China may yet commit to substantial new nuclear plant construction.

There are several reasons why nuclear power has not met the expectations for capacity growth projected several decades ago. One factor is that the public perception of nuclear energy is unfavorable, in part due to concern about effects of radiation that the public associates with nuclear energy. More importantly, the adverse impression derives from real and unique problems presented by this technology. These problems are:

Unfavorable economics. Most operating nuclear plants are economical to operate when costs going forward are considered, i.e. when sunk capital and construction costs are ignored. However, new plants appear to be more expensive than alternate sources of base load generation, notably coal and natural gas fired electricity generation, when both capital and operating costs are taken into account.

Coal plants have capital costs intermediate between those of gas and nuclear. Even with SO_2 and NO_x controls that meet U.S. new source performance standards, new coal plants are widely perceived to be less costly than nuclear plants. However, if CO_2 emissions were in the future to become subject to control and a significant "price" placed on emissions, the relative economics could become much more favorable to nuclear power.

Perceived adverse safety, environmental, and health effects. After the 1979 accident at Three Mile Island in Harrisburg, Pennsylvania and the 1986 accident at Chernobyl in the Soviet Union, public concern about reactor safety increased substantially. The 1999 accident at the Tokai-

Mura plant underscored safety concerns about the nuclear fuel cycle outside of the reactor. There is also concern about transportation of nuclear materials, and waste management. The September 11, 2001 terrorist attack on the World Trade Center and the Pentagon have heightened concerns about the vulnerability of nuclear power stations and other facilities, especially spent fuel storage pools, to terrorist attack. There is concern about radiation exposure of citizens and workers from activities of the industry despite good regulation and health records. There are significant environmental impacts, ranging from long-term waste disposal to the handling and disposal of toxic chemical wastes associated with the nuclear fuel cycle.

Proliferation. The possibility exists that nations wishing to acquire or enhance a nuclear weapons capability will use commercial nuclear power as a source of technological know-how or nuclear weapons usable material, notably plutonium. Although this has not proved to be the preferred pathway to nuclear weapons capability, the possession of a complete nuclear fuel cycle, including enrichment, fuel fabrication, reactor operation, and reprocessing, certainly moves any nation closer to obtaining such a capability. The key step for achieving nuclear weapons capability is acquisition of sufficient weapons-usable fissionable material, either high-enriched uranium or plutonium. Unfortunately, reprocessing of spent fuel for the fuel cycle operation in Europe, Russia, and Japan has led to the accumulation of about 200 tonnes of separated plutonium. The associated risks have been viewed with increased alarm since the 9/11 events that demonstrated the reach of international terrorism. Radiation exposure from spent fuel that is not reprocessed is a strong, but not certain, barrier to theft and misuse.

Difficulty of waste management. There are many radioactive waste streams created in various parts of the nuclear fuel cycle. What deservedly receives the most attention is the high level waste containing the fission products and/or transuranic (TRU) elements created during energy generation. The spent fuel from nuclear reactors contains radioactive material that presents health and environmental risks that persist for tens of thousands of years. At present, no nation has successfully demonstrated a disposal system for these nuclear wastes. On the other hand, Finland has decided on a path to manage spent fuel, and the United States has decided to proceed with licensing of Yucca Mountain as a geological repository. At the same time, many of the discussions surrounding alternative reactors and fuel cycles are motivated by a desire to reduce high-level waste management challenges.

The potential impact on the public from safety or waste management failure and the link to nuclear explosives technology are unique to nuclear energy among energy supply options. These characteristics and the fact that nuclear is more costly, make it impossible today to make a credible case for the immediate expanded use of nuclear power.

Inevitably, there will be a high degree of government involvement in nuclear power, even in market economies, to regulate safety, waste, and proliferation risk. This is, in itself, another challenge for nuclear power. There is considerable variation in how different countries approach the issues of safety, proliferation, and waste management. This often complicates the role of governments in setting international rules – especially for preventing proliferation, but also for safety and waste management – that serve common interests. Poor safeguarding of nuclear materials or facilities in any nation could result in acquisition of nuclear explosives by a rogue state or terrorist group for use in another nation. The Chernobyl accident demonstrated the potential for radioactivity to spread across borders and thus the importance of uniformly high safety standards and advanced safety technologies (such as western reactor containment designs).

Nuclear power's value as a carbon-free electricity supply technology has also generally not been recognized in government policies. Government policies have focused on targeting renewable energy resources and end-use efficiency improvements through a combination of direct subsidies, tax subsidies, renewable energy portfolio standards, appliance efficiency standards, and other "second best" mechanisms to promote carbon-free supply technologies and to reduce electricity demand. Nuclear power has generally been excluded from these programs. While the European Union will introduce a carbon dioxide emissions trading system in a few years, countries have not yet turned to broad policies to internalize the social costs of carbon emissions that would provide incentives for investment in all carbon free electricity supply or energy efficiency technologies, including nuclear power. Thus nuclear power does not compete on a level playing field and, from this perspective, is presently being discriminated against in policies designed to respond to the challenge of reducing carbon dioxide emissions.

Given these difficulties, it is fair to ask whether nuclear energy can ever recapture its attractiveness as a major energy supply option. However, this is not the question we seek to address. The answer to such a question necessarily depends on how societies and technology evolve (economic growth, electricity demand, fuel prices, environmental constraints, premium attached to energy security, the cost of alternatives such as renewables, new technologies such as fusion).

The difficulties facing nuclear power should not, at this time, rule it out as one of a small number of options that may be attractive to exercise in the future, as countries develop responses to the energy and environmental challenges of this century. *We believe that it is important for governments to adopt policies that enable the full range of significant options available. Nuclear is one of those options.* Whether it is an option that will eventually be exercised will depend on many unknown contingencies.

Given the difficulties that confront nuclear power, the effort required to overcome them is justified only if nuclear power potentially can make a significant impact on the major challenges of global warming, electric supply, and security. That is, for nuclear power to merit strategic focus and sustaining actions on the part of government , there must also be a commitment to significant expansion of nuclear power that will sustain and perhaps modestly increase its share of global electricity generation, even as use of electricity multiplies.

NOTES

1. T.M.L. Wigley, "Stabilization of greenhouse gas concentrations," in *U.S. policy on climate change: What next,?* Aspen Institute, Washington D.C., 2002.
2. In 2003, five new units are expected to come into operation: one in the Czech Republic, two in China, and two in South Korea. An additional 18 plants are under construction worldwide, primarily in China, Taiwan, India, Japan, and South Korea.
3. National Academy of Engineering website http://www.greatachievments.org/
4. U.S. Department of Energy, Energy Information Administration (EIS) International Energy Outlook 2002.
5. S. G. Benka, "The Energy Challenges," Physics Today (April 2002) p. 38.
6. This is the Nunn-Lugar-Domenici program. See " DOE's non-proliferation programs with Russia," Co- chairs Howard Baker and Lloyd Cutler, January 10, 2001, The Secretary of Energy Advisory Board, U.S. DOE.
7. For a recent report card, see M. Bunn, A. Wier, and J.P. Holdren, "*Controlling nuclear warheads and materials,*" Nuclear Threat Initiative, Washington, D.C., March 2003.

Chapter 3 — Outline of the Study

Our study makes two assumptions: First, as discussed in Chapter 1, that *nuclear energy is an important energy supply option for the future, but that exercising the option for significant deployment requires that the four significant challenges — cost, safety, waste, and proliferation — must be addressed and overcome*. Second, as discussed in Chapter 2, *that the public and private sectors can justify devoting the resources necessary to overcome these four challenges only if there is some reasonable possibility for major benefit to society* from having this option available in the future.

Therefore, we must consider large-scale deployment of nuclear power as a possible outcome and understand fully the ramifications of turning to nuclear power to provide a significant source of non-carbon electricity supply. From a public policy perspective, the scenarios that merit analysis are either a large-scale deployment or a phase-out of nuclear power over the next half-century. We stress that our approach is to evaluate expansion of nuclear energy as an *option* possibly needed in the future to meet a significant fraction of world electricity demand while addressing global environmental challenges. We are *not* declaring a specific goal for a particular time. Our evaluation criteria are:

- favorable economics;
- effective waste disposal;
- high proliferation resistance; and
- safe operation of all aspects of the fuel cycle.

To undertake this evaluation we need to establish a point of reference for nuclear deployment that might be realized 50 years from now. To set this point of reference, we stipulate as the basis of a scenario that *nuclear energy will retain or increase its current share of electricity generation at mid-century*.[1] The projected growth rate of electricity over a half century period is uncertain. The average rate of growth will depend importantly on several variables, notably the rate of economic growth and the price of electricity. A range of possibilities[2] is presented in Table 3.1.

Table 3.1 Alternative Reference Points for Nuclear Deployment in 2050 in GWe for Different Assumptions about Electricity Growth Rates and Nuclear Market Share[a]

	ALTERNATIVE AVERAGE ELECTRICITY GROWTH RATES 2000–2050 %		
NUCLEAR GENERATION MARKET SHARE %	1.5	2.0	2.5
17	650	838	1,060
20	770	970	1,235
25	880	1,235	1,545

a. We assume the global average capacity factor increases from 75% to 85%.

We adopt 1000 to 1500 GWe as the mid-century reference point range for our study. This is large enough to reveal the challenges that need to be faced to enable the large-scale deployment of nuclear energy. Our analysis and conclusions concerning what we refer to as the global growth scenario, as described in Chapter 1, would not change significantly if this number of deployed reactors were somewhat higher, nor if the time period to reach full operational deployment were extended. We have examined the rate of deployment that would need to occur for a deployment in the range of 1000 to 1500 GWe and note that it is unlikely to proceed in a linear manner; for the next ten to fifteen years, deployment is likely to be slow, and therefore the rate would necessarily accelerate dur-

Table 3.2 Global Growth Scenario

REGION	PROJECTED 2050 GWe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE 2000	2050
Total World	1,000	17%	19%
Developed world	625	23%	29%
U.S.	300		
Europe and Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWe-hrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

ing the expansion period. The implied construction rate near the mid-century endpoint of the global growth scenario would be challenging and exceed any rate previously achieved.

The pattern of deployment of nuclear power around the world is also important, especially from the viewpoint of assessing the risks of proliferation. Table 3.2 indicates how 1000 1000MWe (or equivalent smaller reactors) might be distributed around the world in the time period 2030 to 2050. Although this illustrative deployment is highly speculative, it provides a concrete instance of how the global growth scenario might be realized.

Nuclear power expansion on this scale is not likely to happen without United States leadership. It also requires continued European commitment and the initiation or expansion of nuclear power programs in many developing countries around the world. If nuclear deployment on the scale of the global growth scenario were to occur, however, it would avoid a significant amount of carbon dioxide emissions, largely by displacing carbon emitting fossil fuel generation. Today, carbon equivalent emission from human activity totals about 6,500 million metric tonnes per year. This value will probably more than double by 2050, depending on the assumptions made. The 1000 GWe of nuclear power assumed in the global growth scenario would avoid about 800 million tonnes of carbon equivalent if the electricity generation displaced was gas-fired and 1,800 million tonnes of carbon equivalent, if the generation was coal-fired, (assuming no capture and sequestration of CO_2 combustion product). *Thus, the 1000 GWe nuclear program has the potential of displacing 15 - 25% of the anticipated growth in anthropogenic carbon emissions*. In 2050, deployment of 1000 Gwe of nuclear power would generate about 20% of worldwide electricity production, if electricity production grows at 2% per year. Evidently, the global growth scenario would have nuclear power generating significant amounts of electricity that would otherwise likely be generated by fossil fuels.

FUTURE STRUCTURE OF THE NUCLEAR INDUSTRY

Significant expansion of nuclear power has implications for the structure of its supporting nuclear industry infrastructure. In an unregulated economy comprised of private business firms competing in the marketplace, market forces determine the organization and structure of the firms that design, construct, and operate nuclear power plants and supporting fuel cycle facilities. However, because nuclear technology involves significant public issues of safety, waste management, and proliferation, the government has a responsibility to ensure that whatever industry structure develops will facilitate, rather than impede, attention to these issues. The intersection of these public issues and free market operations cannot be handled through minor government regulation, as is possible in some other industries. An additional layer of government involvement stems from the traditional structure of electric utilities as vertically integrated monopolies. Government intervention has been necessary to ensure that the operations of the electric utility industry are efficient and that other public objectives for electricity supply are achieved. We do not today know how the nuclear industry will evolve but we mention issues that we believe are an important determinant of the future success of nuclear power.

The tension between public responsibility and private market operation has been present since the beginning of commercial nuclear power. In the U.S., the assumption was that any private utility was in principle capable of owning and operating a nuclear power plant and should be allowed to do so under appropriate government supervision with regard to safety. Several other countries have followed this route, notably Japan and Germany. In other countries, such as Russia and China, nuclear power has been entirely the responsibility of the central government. Elsewhere the pattern has been mixed. In France, all nuclear plants have been operated by a single state-owned utility, Electricite de France. Similar arrangements have applied in South Korea and Taiwan. In Spain and Sweden a small number of investor-owned utilities have built and operated nuclear power plants.

No arrangement has proved free of tension. In many countries with state-owned electric power monopolies, there has been a move towards privatization and increased competition, while in the U.S. it is widely recognized that in the current environment, small investor-owned utilities operating a single nuclear power plant are more likely to encounter operational problems and to experience higher generating costs.

We do not believe that a single organizational model for nuclear power will be applicable throughout the world. We do believe that industrial organization is an important consideration for the future expansion of nuclear power. To oversimplify, too much government involvement is likely to make nuclear power expensive and uncompetitive, and too little government involvement risks safety, waste, and proliferation problems. International cooperation is also critical for the effective management of these public issues, especially proliferation. Thus, the industrial structure in each country must be compatible with whatever international norms are adopted

The structure of the nuclear industry is also important because of its influence on innovation, productivity, and performance. A necessary condition for the expanded nuclear deployment postulated in the global growth scenario is that nuclear power plants and other nuclear facilities be designed, built, and operated to expectation. This performance, in turn, depends upon sound technological choices, high quality design and construction, and the availability of competent construction project management teams, craft labor, and operating and maintenance personnel. Moreover, the growth of capability in all these categories must occur in the context of a deployment schedule that will be highly uncertain. These are all matters of industrial organization that are critical to the prospects for the expansion of nuclear power but do not happen automatically. Nor is it clear that governments are sufficiently agile or wise to adopt policies that will encourage the proper sequencing of industrial capabilities and needs.

OUTLINE OF THE STUDY

In conducting this study, our first step was to define the character of the global growth scenario, i.e., the nature and size of the fuel cycle necessary for it to function. The results are discussed in Chapter 4.

Our second step was to answer the question: “Is such a mid-century scenario technically, economically and politically credible?” We do this by evaluating how well the global growth scenario can meet the four challenges of cost, safety, waste disposal, and proliferation risk. This is undertaken in Chapters 5 through 8.

Our third step was to consider public attitudes to an expanded nuclear future. Chapter 9 reports on the result of an Internet-based poll that we conducted and its implications.

Our fourth step was to make recommendations that would retain the nuclear option. These recommendations, presented in Part 2 of the report, addresses both domestic and international issues and includes both technical and institutional measures. We identify organizational changes that we believe would increase the chance of success of the effort and decrease the cost. The technical measures involve a sustained and disciplined program of analysis, research, development, and demonstration of various aspects of the nuclear enterprise. We do not seek to establish rigid goals or a fixed timetable for the technical program. The pace of the program should be determined by its technical success in the context of the world energy and environmental outlook. We anticipate that the cost of the technical program would be borne by other countries, as well as by the United States.

This study approach is conditioned by the belief that the nuclear power option makes sense only if possible deployment is quite large, since no small deployment can make a significant contribution to dealing with the greenhouse gas problem. Support for keeping the nuclear power option open will therefore depend on convincing the public and their elected representatives that large-scale deployment can overcome the four challenges. *We believe that establishing a vision for a possible large- scale deployment of nuclear energy that is both technically and politically credible is a necessary condition for gaining public support*. Indeed it is misleading to focus on small increases in nuclear capacity justified by significant CO_2 reduction. Furthermore, small deployments ignore or do not face squarely the challenges that must be overcome for nuclear energy to become a significant contributor to controlling CO_2 emissions.

It will take sustained effort to accomplish the necessary technical and institutional steps needed to make nuclear an attractive energy option. Given the expected evolution of worldwide energy supply and demand, however, we believe there is time to undertake this work . We do not believe that nuclear energy will go forward without such a comprehensive approach. The construction of a few reactors in the short term and a technology driven R&D program is not sufficient. Although R&D is a vital ingredient, a comprehensive program should address all four of the key criteria in order to create a clear and sound vision of the energy future. A similarly broad approach should be applied to all energy supply and end-use efficiency technologies under consideration. A policy directed to a single solution is inadequate. We also recognize that the deployed nuclear fuel cycle will not simply "jump" to a new reality. But, we believe the evolution will be guided by a clear picture of where we are headed and how we will get there.

NOTES

1. Some advocate hydrogen production as an objective for nuclear power. To be economical hydrogen produced by electrolysis of water depends on low cost nuclear power. Hydrogen can also be produced by high temperature thermal cracking with heat provided by a nuclear reactor. This approach is presently highly speculative. Our belief is that if nuclear proves to be an economical choice for electricity production, it *may* prove to be interesting for hydrogen production, whether the production is through electrolysis or high temperature thermal splitting of water. However, if nuclear is not an economical choice for electricity production, it is most unlikely to be used for large-scale production of hydrogen.
2. For example, the EIA projects worldwide electricity growth rate of 2.7% for the period 2000-2020. If we project that this growth rate continues [See Table 3.1.] through mid-century and recognize that about 350 GWe nuclear capacity is currently deployed worldwide (in over 400 units), then the mid-century point of reference for nuclear maintaining its market share is 1325 GWe of deployment in 2050. This deployment might correspond to 1325 reactors, each with capacity of 1000 MWe or more units of smaller rated capacity. There are higher and lower projections of world electricity use. The MIT Emissions Prediction and Policy Analysis (EPPA) project projects an average growth rate between 1995 and 2004 of 1.8% that gives a nuclear deployment of 950 Gwe in 2050, assuming nuclear power retains its market share. If we assume the EIA 2.7% growth rate to 2020 and the lower MIT EPPA 1.8% growth rate between 2020 and 2050, the calculated number is 1164 GWe of nuclear power in 2050.