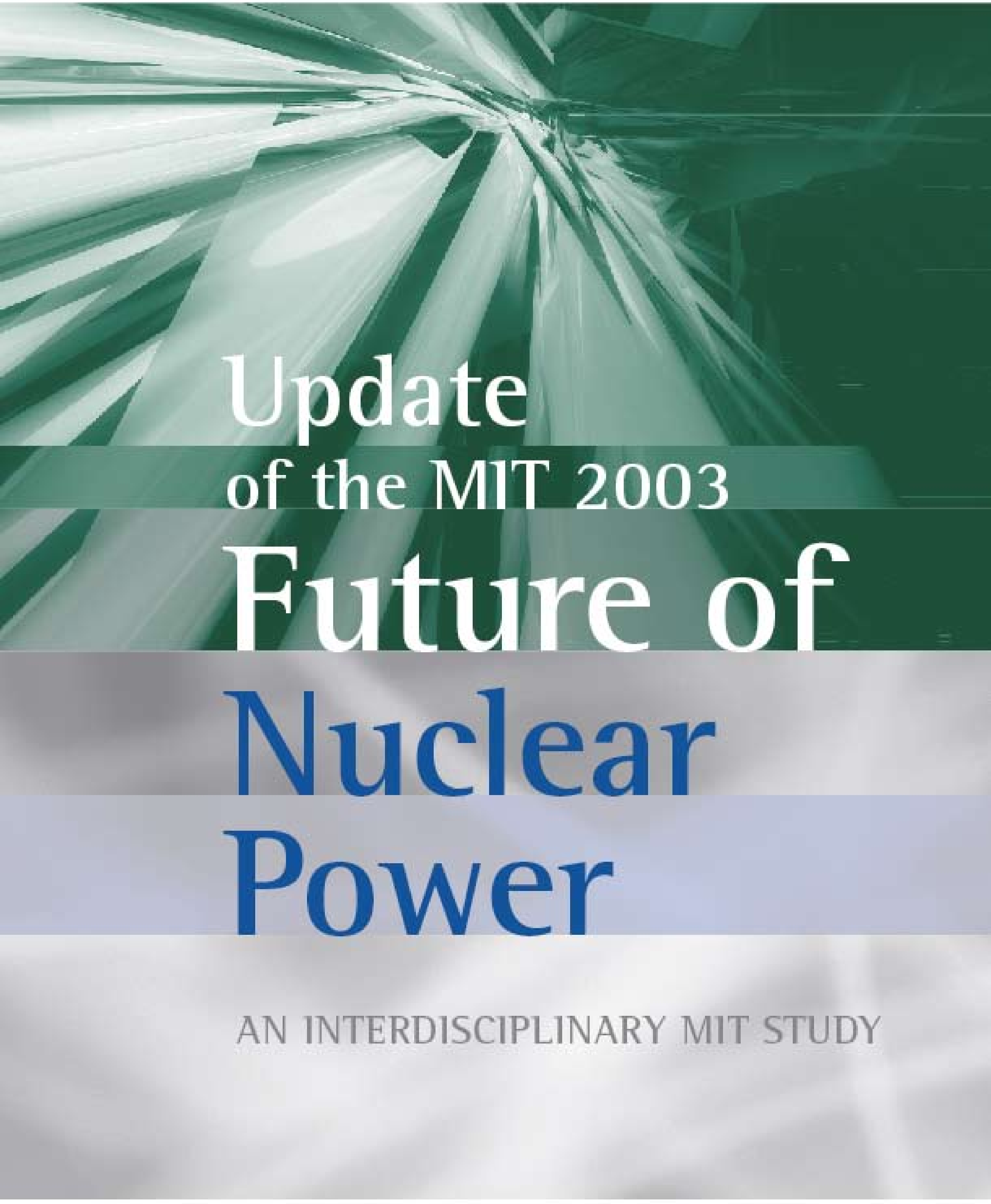

Update
of the MIT 2003
Future of Nuclear Power

AN INTERDISCIPLINARY MIT STUDY

Update of the MIT 2003

Future of Nuclear Power

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Update of the MIT 2003 Future of Nuclear Power Study

In 2003 a group of MIT faculty issued a study on *The Future of Nuclear Power.*[1] The study was motivated by growing concern about global warming and the urgency of developing and deploying electricity generating technologies that do not emit CO_2 or other greenhouse gases (GHG). The study addressed the steps needed in the near term in order to enable nuclear power to be a viable marketplace option at a time and at a scale that could materially mitigate climate change risks. In this context, the study explicitly assessed the challenges of a scenario in which nuclear power capacity expands from approximately 100 GWe in the United States in 2000 to 300 GWe at mid-century (from 340 to 1000 GWe globally), thereby enabling an increase in nuclear power's approximately 20% share of U.S. electricity generation to about 30% (from 16% to 20% globally).

The important challenges examined were (1) cost, (2) safety, (3) waste management, and (4) proliferation risk. In addition, the report examined technology opportunities and needs, and offered recommendations for research, development, and demonstration.

The 2003 MIT study on *The Future of Nuclear Power*, supported by the Alfred P. Sloan Foundation, has had a significant impact on the public debate both in the United States and abroad and the study has influenced both legislation by the U.S. Congress and the U.S. Department of Energy's (DOE) nuclear energy R&D program.

This report presents an update on the 2003 study. Almost six years have passed since the report was issued, a new administration in Washington is formulating its energy policy, and, most importantly, concern about the energy future remains high. We review what has changed from 2003 to today with respect to the challenges facing nuclear power mentioned above. A second purpose of this Update is to provide context for a new MIT study, currently underway, on *The Future of the Nuclear Fuel Cycle*, which will examine the pros and cons of alternative fuel cycle strategies, the readiness of the technologies needed for them, and the implications for near-term policies.

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[1] Massachusetts Institute of Technology, The Future of Nuclear Power: an Interdisciplinary Study (2003). Available at: http://web.mit.edu/nuclearpower/

SUMMARY FINDING OF CHANGES SINCE THE 2003 REPORT

Concern with avoiding the adverse consequences of climate change has increased significantly in the past five years[2]. The United States has not adopted a comprehensive climate change policy, although President Obama is pledged to do so. Nor has an agreement been reached with the emerging rapidly-growing economies such as China, India, Indonesia, and Mexico, about when and how they will adopt greenhouse gas emission constraints. With global greenhouse gas emissions projected to continue to increase, there is added urgency both to achieve greater energy efficiency and to pursue all measures to develop and deploy carbon free energy sources.

> *"The sober warning is that if more is not done, nuclear power will diminish as a practical and timely option for deployment at a scale that would constitute a material contribution to climate change risk mitigation."*

Nuclear power, fossil fuel use accompanied by carbon dioxide capture and sequestration, and renewable energy technologies (wind, biomass, geothermal, hydro and solar) are important options for achieving electricity production with small carbon footprints. Since the 2003 report, interest in using electricity for plug-in hybrids and electric cars to replace motor gasoline has increased, thus placing an even greater importance on exploiting the use of carbon-free electricity generating technologies. At the same time, as discussed in the MIT report *The Future of Coal*[3], little progress has been made in the United States in demonstrating the viability of fossil fuel use with carbon capture and sequestration—a major "carbon-free" alternative to nuclear energy for base-load electricity.

With regard to nuclear power, while there has been some progress since 2003, increased deployment of nuclear power has been slow both in the United States and globally, in relation to the illustrative scenario examined in the 2003 report. While the intent to build new plants has been made public in several countries, there are only few firm commitments outside of Asia, in particular China, India, and Korea, to construction projects at this time. Even if all the announced plans for new nuclear power plant construction are realized, the total will be well behind that needed for reaching a thousand gigawatts of new capacity worldwide by 2050. In the U.S., only one shutdown reactor has been refurbished and restarted and one previously ordered, but never completed reactor, is now being completed. <u>No new nuclear units have started construction.</u>

In sum, compared to 2003, the motivation to make more use of nuclear power is greater, and more rapid progress is needed in enabling the option of nuclear power expansion to play a role in meeting the global warming challenge. The sober warning is that if more is not done, nuclear power will diminish as a practical and timely option for deployment at a scale that would constitute a material contribution to climate change risk mitigation.

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[2] Summary for Policymakers. Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (2007)

[3] http://web.mit.edu/coal/

1. STATUS OF NUCLEAR POWER DEPLOYMENT

Today, there are about 44 plants under construction[4] around the world in 12 countries, principally China, India, Korea, and Russia. There are no new plants under construction in the United States.[5] The slow pace of this deployment means that the mid-century scenario of 1000 GWe of operating nuclear power around the globe and 300 GWe in the United States is less likely than when it was considered in the 2003 study.[6]

In the United States, nevertheless, there have been a series of developments that could enable new nuclear deployment in the future:

The performance of the 104 U.S. nuclear plants since 2003 has been excellent. The total number of kWh produced by the reactors has steadily increased over those five years. The fleet-averaged capacity factor since 2003 has been maintained at about 90%.[7]

Extended operating licenses. Nuclear reactors typically have initial operating licenses from the Nuclear Regulatory Commission for 40 years. The earlier trend to obtain license extensions to operate existing nuclear reactors an additional 20 years (total of 60 years) has continued with the expectation that almost all reactors will have license extensions. The NRC has granted 51 license extensions to date with 19 such renewals granted between January 2003 and February 2008.[8] Furthermore, modest power uprates have been granted in that period, adding about 1.5 GWe to the licensed capacity.

Changes in the NRC regulations in the 1990s created a new approach to reactor licensing that included a design certification process, site banking, and combined construction and operation licensing. The Energy Policy Act of 2005 authorized DOE to share the cost with selected applicants submitting licenses to the NRC to help test this new licensing approach — all actions that are consistent with recommendations of the 2003 report.

Seventeen applications [9] for combined construction and operating licenses for 26 reactors have been submitted to the NRC. Preliminary work required before construction is underway for many of these plants such as design, licensing applications development, and procurement of long-lead items. However financing and firm commitment to construction remains ahead. Authority to proceed will undoubtedly be slowed by the current dismal economic situation. Several European countries have announced plans for new reactors while several other European countries are reevaluating their stance on nuclear power plant construction and phase out.[10]

Public acceptance for nuclear power Extension of the public attitudes research carried out in 2003 reinforces a trend towards greater public acceptance of nuclear power.[11]

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[4] Forty four plants under construction: China (11), Russia (8), India (6), Korea (5), Bulgaria (2), Taiwan (2), Ukraine (2), Japan (2), Argentina (1), Finland (1) France (1), Iran (1), Pakistan (1), and the United States (1).

[5] However, since 2003 one shutdown reactor (Browns Ferry I) has been refurbished and restarted and one partly complete reactor (Watts Bar 2) is now being completed.

[6] The 2007 IEO suggests that nuclear power will grow 1.3%/year worldwide, but that optimistic forecast remains below the 2003 Study mid-century scenario.

[7] http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/v19/sr1350v19.pdf

[8] http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/license-renewal-bg.html

[9] http://www.nrc.gov/reactors/new-reactors/new-licensing-files/expected-new-rx-applications.pdf

[10] Sweden and Italy have announced reversals of their prohibitions on new nuclear plant construction. France, Finland, and Great Britain have announced plans for added nuclear power plants. Plants are under construction in France and Finland.

[11] http://www.gallup.com/poll/117025/Support-Nuclear-Energy-Inches-New-High.aspx and http://web.mit.edu/canes/pdfs/nes-008.pdf

2. UPDATING NUCLEAR GENERATION ECONOMICS

The 2003 report found that "In deregulated markets, nuclear power is not now cost competitive with coal and natural gas. However, plausible reductions by industry in capital cost, operation and maintenance costs and construction time could reduce the gap. Carbon emission credits, if enacted by government, can give nuclear power a cost advantage." The situation remains the same today. While the U.S. nuclear industry has continued to demonstrate improved operating performance, there remains significant uncertainty about the capital costs, and the cost of its financing, which are the main components of the cost of electricity from new nuclear plants.

Since 2003 construction costs for all types of large-scale engineered projects have escalated dramatically. The estimated cost of constructing a nuclear power plant has increased at a rate of 15% per year heading into the current economic downturn. This is based both on the cost of actual builds in Japan and Korea and on the projected cost of new plants planned for in the United States. Capital costs for both coal and natural gas have increased as well, although not by as much. The cost of natural gas and coal that peaked sharply is now receding. Taken together, these escalating costs leave the situation close to where it was in 2003. The following table updates the cost estimates presented in the 2003 study:[12]

Table 1: Costs of Electric Generation Alternatives

			LCOE		
	Overnight Cost	Fuel Cost	Base Case	w/ carbon charge \$25/ tCO_2	w/ same cost of capital
	\$/kW	\$/mmBtu	¢/kWh	¢/kWh	¢/kWh
	[A]	[B]	[C]	[D]	[E]
MIT (2003)					
\$2002					
[1] Nuclear	2,000	0.47	6.7		5.5
[2] Coal	1,300	1.20	4.3	6.4	
[3] Gas	500	3.50	4.1	5.1	
Update					
\$2007					
[4] Nuclear	4,000	0.67	8.4		6.6
[5] Coal	2,300	2.60	6.2	8.3	
[6] Gas	850	7.00	6.5	7.4	

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[12] The capital cost estimates do not take into account any possible prospective change to the cost of capital as a result of the current financial crisis or the recent drop in commodity prices for construction materials. Du, Yangbo and John E. Parsons, Update on the Cost of Nuclear Power, MIT Center for Energy and Environmental Policy Research Working Paper 09-004; http://web.mit.edu/ceepr/www/publications/workingpapers.html

Notes:

[1A], [2A], and [3A] See MIT (2003), Table 5.3, p. 43.

[1B] See MIT (2003) Appendix 5, Table A-5.A4.

[2B], and [3B] See MIT (2003), Table 5.3, p. 43.

[1C], [2C], and [3C] See MIT (2003), Table 5.1, p. 42, Base Case, 40-year. "Gas (moderate)" case is reported here, which was \$3.50 escalated at 1.5% real, equivalent to \$4.42 levelized real over 40 years.

[1D], [2D], and [3D] See MIT (2003), Table 5.1, p. 42, Carbon Tax Cases, 40-year. We translate results quoted in \$/tC into results in \$/t CO_2.

[1E] See MIT (2003), Table 5.1, p. 42, Reduce Nuclear Costs Cases. The table shows results stepwise for changing 3 assumptions, with the reduction of the cost of capital being the last step. We give the result for just reducing the cost of capital to be equivalent to coal and gas, without the other 2 assumptions being varied.

[4A], [5A], and [6A] From Du and Parsons (2009) Update on the Cost of Nuclear Power.

[4B] Calculated using the methodology in MIT (2003), Appendix 5 and the following inputs: \$80/kgHM for natural uranium, \$160/SWU, and \$6/kgHM for yellow cake conversion and \$250/kgHM for fabrication of uranium-oxide fuel. We derive an optimum tails assay of 0.24%, an initial uranium feed of 9.08 kgU and a requirement of 6.99 SWUs, assuming a burn-up of 50 MWd/kgHM. We assume this fuel cost escalates at 0.5% per annum, which means the average real price over the 40 years of delivery is \$0.76/mmBtu.

[5B] We assume a coal feed with 12,500Btu/lb, so that this fuel cost translates to \$65/short ton delivered in 2007 dollars. We assume this fuel cost escalates at 0.5% per annum, which means the average real price over the 40 years of delivery is \$2.94/mvmBtu or \$73.42/short ton delivered.

[6B] We assume this fuel cost escalates at 0.5% per annum, which means the average real price over the 40 years of delivery is \$7.91/mmBtu.

[4C], [5C] and [6C] Assumptions made in this calculation are described fully in the Du and Parsons (2009) Update on the Cost of Nuclear Power. For all types of generation we assume a 40 year operation and 85% capacity factor. Nuclear heat rate is 10,400 as in the MIT (2003) study. Both coal and natural gas heat rates are improved relative to MIT (2003): coal is 8,870 and gas is 6,800. We assume a general inflation rate of 3%, real escalation of O&M costs of 1%, and a tax rate of 37%. Nuclear is financed at 50% debt, with a debt cost of capital of 8% and an equity cost of capital of 15%. Coal and gas are financed with 60% debt, a debt cost of capital of 8% and an equity cost of capital of 12%. Nuclear construction has a 5 year schedule, coal construction has a 4 year schedule, and gas has a 2 year schedule. Nuclear and gas apply the MACRS 15-year depreciation schedule, while coal applies the 20-year MACRS schedule.

[4D], [5D] and [6D] As in the MIT (2003) study, the carbon intensity assumed for coal is 25.8 kg-C/mmBtu, and for gas is 14.5.

[4E] Recalculates [4C] setting the assumed debt fraction and the equity rate for nuclear to match coal and gas, i.e., a 60% debt fraction and a cost of equity of 12%.

The nuclear costs are driven by high up-front capital costs. In contrast, for natural gas the cost driver is fuel cost. Coal lies in-between.

The track record for the construction costs of nuclear plants completed in the U.S. during the 1980s and early 1990s was poor. Actual costs were far higher than had been projected. Construction schedules experienced long delays, which, together with increases in interest rates at the time, resulted in high financing charges. New regulatory requirements also contributed to the cost increases, and in some instances, the public controversy over nuclear power contributed to some of the construction delays and cost overruns. However, while the plants in Korea and Japan continue to be built on schedule, some of the recent construction cost and schedule experience, such as with the plant under construction in Finland, has not been encouraging. Whether the lessons learned from the past have been factored into the construction of future plants has yet to be seen. These factors have a significant impact on the risk facing investors financing a new build.

For this reason, the 2003 report applied a higher weighted cost of capital to the construction of a new nuclear plant (10%) than to the construction of a new coal or new natural gas plant (7.8%).

Lowering or eliminating this risk-premium makes a significant contribution to making nuclear competitive. With the risk premium and without a carbon emission charge, nuclear is more expensive than either coal (without sequestration) or natural gas (at 7$/MBTU). If this risk premium can be eliminated, nuclear life cycle cost decreases from 8.4¢ /kWe-h to 6.6 ¢/kWe-h and becomes competitive with coal and natural gas, even in the absence of carbon emission charge.

The 2003 report found that capital cost reductions and construction time reductions were plausible, but not yet proven – this judgment is unchanged today. The challenge facing the U.S. nuclear industry lies in turning plausible reductions in capital costs and construction schedules into reality. Will designs truly be standardized, or will site-specific changes defeat the effort to drive down the cost of producing multiple plants? Will the licensing process function without costly delays, or will the time to first power be extended, adding significant financing costs? Will construction proceed on schedule and without large cost overruns? The first few U.S. plants will be a critical test for all parties involved. The risk premium will be eliminated only by demonstrated performance.

3. GOVERNMENT INCENTIVES AND REGULATIONS

Both government and industry have their part to play in lowering this risk premium. The 2003 report advocated limited government assistance for "first mover" nuclear plant projects. Three principles underpinned the proposed government assistance: First, financial assistance for nuclear should be comparable to assistance extended to other low-carbon electricity generation technologies, for example wind, geothermal, and solar. Second, an appropriate degree of risk should remain with the private sector so as to motivate cost and schedule discipline. Third, government assistance should be limited to the first mover cohort without the expectation of longer-term assistance. That is, different power generation technologies should compete based on economics in a world where CO_2 emissions are priced, and where technologies are not mandated by required quotas for certain types of generation.

The Energy Policy Act of 2005 authorized assistance for new nuclear plant construction including loan guarantees, insurance against delays not caused by the utility, and production tax credits for the first 6 GWe of new plants. However, implementation of the first mover assistance program as proposed in the 2003 study has not yet been effective in moving utilities to make firm reactor construction commitments for three reasons.

First, the DOE has not moved expeditiously to issue the regulations and implement the federal loan guarantee program.

Second, since 2003, emphasis has been placed on renewable portfolio standards (RPS), adopted by many states and proposed at the federal level, as the mechanism for encouraging carbon-free and renewable technologies. RPS require that utilities obtain a certain fraction of their electricity from low-carbon electricity sources. Unfortunately, most RPS programs exclude two important low-carbon technologies, nuclear and coal with CO_2 sequestration, confusing the objective of reducing carbon emissions with encouraging renewable energy in electricity generation.

> *"However, implementation of the first mover assistance program as proposed in the 2003 study has not yet been effective in moving utilities to make firm reactor construction commitments for three reasons."*

If such RPS remain in place and a carbon emission tax or cap and trade system is implemented in parallel, inefficiencies may result. The RPS requires utilities to adopt technologies, for example wind, rather than select the most economic method to achieve lower carbon emissions. As a consequence, the emission permit prices in the parallel cap and trade system will be lower than prices without a RPS, possibly inhibiting the introduction of low-carbon technologies not included in the RPS.

Third, in a change from 2003, the nuclear industry facing increased cost estimates is arguing that more assistance is needed to demonstrate the economic viability of nuclear. While some modification of the "first mover" program is likely necessary because of the impact of the financial crisis on capital markets, the justification for government "first-mover" assistance is to demonstrate technical performance, cost, and environmental acceptability, not to extend a government subsidy for nuclear (or any other energy technology) indefinitely into the future. Consequently, any expansion of such a federal program should have limited duration. If the purpose of an expanded program is to correct for a market imperfection, in this case the external costs of global warming, the most efficient mechanism is either a carbon emission tax or a cap-and-trade system. An ironic consequence of a parallel RPS could be a call to extend subsidies to nuclear and coal with carbon capture/sequestration because of a poorly crafted policy for efficiently reducing carbon emissions.

4. SAFETY

Parallel with the improved operations has been an excellent safety record. Reliability and safety are coupled because (1) reliable operations avoid challenges to the safety systems and (2) the maintenance and operating practices required for reliable operations are generally the same required for safety. Nuclear power displays by far the highest capacity factor among all generation technologies, providing about 20% of U.S. electricity supply with about 10% of the installed capacity. <u>The judgment of the 2003 study that new light water reactor plants, properly operated, meet strenuous safety standards discussed in the 2003 report is unchanged.</u>

"An ironic consequence of a parallel RPS could be a call to extend subsidies to nuclear and coal with carbon capture/sequestration because of a poorly crafted policy for efficiently reducing carbon emissions."

5. WASTE MANAGEMENT

The 2003 study emphasized the importance of making progress on waste management in the United States.

Interim storage of spent fuel

The 2003 study conclusion "an explicit strategy to store spent fuel for a period of several decades will create additional flexibility in the waste management system" remains valid today. While dry cask spent fuel storage (SFS) has been implemented on a large scale at reactor sites, starting in 1986 and continued since 2003, no federal operated away-from-reactor surface, or near surface, spent fuel storage sites have been opened since they are not permitted by the Nuclear Waste Policy Act of 1987 until the Yucca Mountain repository is licensed.[13]

Geological Disposal of SNF

Following the requirements of the Nuclear Waste Policy Act, the DOE submitted a license application for the Yucca Mountain repository in 2008. Congress mandated and is providing the funding for the NRC to complete a license review. The new administration has stated that Yucca Mountain is no longer an option for nuclear waste disposal. There is no plan for high-level wastes; but the administration has committed to a comprehensive review of waste management. In conclusion, the progress on high-level waste disposal has not been positive.

The U.S. Environmental Protection Agency has developed the repository standard for protection of public health and safety. After decades of debate and lawsuits, it appears that the standard is generally accepted which is significant progress.

The 2003 study urged a broadening of the DOE waste management program for Yucca Mountain to other potential mined repository disposal sites and to other potential technologies such as bore-hole disposal. The 2003 study recommended that the U.S. should undertake a significant R&D program for long-term integrated waste management that includes improved repository performance (such as alternative engineered barriers) and examination of alternatives. The central concern was that the federal programs have had a narrow focus and have not explored an adequate range of technical options.

The need remains for a broader program that creates an understanding of the range of waste management options, is coupled with fuel cycle modeling, and provides a basis for robust long-term waste management policies. This is a central objective of the ongoing *MIT Nuclear Fuel Cycle Study*. It should be noted that both open and closed fuel cycles require the geological disposal of some radioactive waste.

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[13] A private fuel storage facility has been issued an NRC license but has not been built.

6. FUEL CYCLE ISSUES

Uranium resource availability

Long-term fuel cycle and nonproliferation policy considerations depend upon the future availability and costs of natural uranium ore. The 2003 study argued that uranium was not likely to be a constraint in the development of a very large nuclear enterprise using a once-through fuel cycle for this century. The last domestic[14] and international[15] resource evaluation programs were completed in the early 1980s. Since then there have been major advances in our understanding of uranium geology. Because of the importance of uranium resources in future decisions, the 2003 study recommended undertaking a significant global uranium resource evaluation program to increase the global confidence in uranium resource assessment. No such program has been initiated.

Since the 2003 MIT report, the OECD/IAEA has published its most recent (2007) "Red Book" update[16] on uranium resources, production and demand. Also noteworthy is the 2006 publication of a retrospective review[17] of the last forty years of Red Book issues. In brief, resources are rising faster than consumption. Table 2 shows Red Book identified resources, undiscovered resources, and the number of reactor years of fuel provided by those resources. Based on the total projected Red Book resources recoverable at a cost less than $130/kg (2006$) of about 13 million metric tons (hence about an 80 year supply for 800 reactors), most commentators conclude that a half century of unimpeded growth is possible, especially since resources costing several hundred dollars per kilogram (not estimated in the Red Book) would also be economically usable. Using a probabilistic resources versus cost model to extend Red Book data, we estimate an order of magnitude larger resources at a tolerable doubling of prices. Since 2003, the spot price for natural uranium spiked due to a variety of factors, including the temporary shutdown of major producing mines and the management of uranium inventories. However, this does not appear to reflect the underlying resource economic reality indicated above.

This reinforces the observation in the 2003 MIT study that "We believe that the world-wide supply of uranium ore is sufficient to fuel the deployment of 1000 reactors over the next half century."

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[14] U.S. Department of Energy, National Uranium Resource Evaluation (NURE) Program Final Report, GJBX-42(83), (1983).

[15] OECD, Nuclear Energy Agency, International Atomic Energy Agency, *World Uranium Geology and Resource Potential, International Uranium Resources Evaluation*, Miller Freeman, San Francisco, CA (1980).

[16] Uranium 2007: Resources, Production and Demand, OECD NEA No. 6345, 2008 (Red Book)

[17] Forty Years of Uranium Resources, Production and Demand in Perspective, 2006, "The Red Book Retrospective," OECD, NEA No. 6096, 2006

Table 2. World Uranium "Red Book" Resources and Implied reactor years of operation[1]

Resource Class	United States	World
Identified Resources		
Metric tons	339,000	5,469,000
Number of 1-GWe Reactor Years @ 200 MT/GWe-yr	1,700	27,000
Undiscovered Resources		
Metric tons	2,131,000	7,567,000
Number of 1-GWe Reactor Years @ 200 MT/GWe-yr	10,700	37,800

[1] Cumulative resources extractable at costs <130 $/kg U. For about 30 years resource estimates have remained constant or grown at <$130/kg U in current dollars without adjusting for inflation. In effect, the resource base in inflation adjusted dollars has grown.

Uranium enrichment

Since 2003 there have been major changes in uranium enrichment with gas centrifuge technology now replacing gaseous diffusion technology in the U.S. and Europe. In the United States one gas-centrifuge plant is starting up, two other centrifuge plants are being planned, and work is underway for an advanced laser enrichment plant. Enrichment capacity is not a constraint on a larger nuclear enterprise.[18]

Reprocessing and recycle

A decision to adopt a closed fuel cycle, with reprocessing SNF and recycling the fissile plutonium and uranium into reactors for power and transmutation of long-lived actinides, depends on three factors (1) economics, (2) impact on waste management, and (3) nonproliferation considerations.[19]

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[18] Louisiana Enrichment Services centrifuge plant in New Mexico is in startup. Areva and U.S. Enrichment Corporation have announced plans for centrifuge enrichment plants respectively in Idaho and Ohio. General Electric-Hitachi is operating a pilot laser enrichment plant and plans for a commercial plant in North Carolina

[19] The 2003 study unfortunately did not point out that decisions on adopting a closed fuel cycle or a once-through fuel cycle would vary from country to country and that there is a significant difference between continuing with a specific program and committing to a new program. In addition to reprocessing facilities in Russia and China, there are three large facilities to reprocess commercial SNF plus smaller facilities in India. Since 2003, the La Hague facility in France continues its record of reliable operations and processes SNF for several other countries. There have been operational difficulties at the British Sellafield plant. The Japanese are in the process of starting up their reprocessing plant at Rokkasho-Mura, which appears to have cost over $25B for an 800 tonne/year reprocessing capability, a high cost relative to the costs of earlier facilities.

(1) The conclusion of the 2003 study with respect to economics is generally accepted: given the assumptions about uranium resource availability and new plant deployment rates, the cost of recycle is unfavorable compared to a once-through cycle, but, the cost differential is small relative to the total cost of nuclear power generation.

(2) With respect to reprocessing and waste management, the 2003 study concluded "We do not believe 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 considerations and economic costs."

There is no basis to change that conclusion today. A major task for the ongoing nuclear fuel cycle study is to assess economic, waste management, and nonproliferation factors in the relative attractiveness of an open versus a closed fuel cycle, in the long-term, likely greater than half a century in the future.

"With respect to reprocessing and waste management, the 2003 study concluded 'We do not believe 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 considerations and economic costs.' There is no basis to change that conclusion today."

7. NON-PROLIFERATION

It is widely agreed that expansion of commercial nuclear power must occur with an acceptable low risk of transfer of nuclear material or technology that could move a nation to, or close to, acquiring a nuclear weapons capability or of making weapons-usable fissionable material available to subnational groups. The most sensitive elements of the fuel cycle are enrichment and reprocessing. In the case of enrichment, fuel enriched from natural abundance 0.7% U-235 to the commercial level of 4 to 5% must undergo further isotope separation to reach the "highly enriched level," normally taken to be >20% for U-235, necessary for nuclear devices. On the other hand, reprocessing, as practiced today in the PUREX (Plutonium and Uranium Recovery by Extraction) process, chemically separates plutonium from irradiated fuel and the separated plutonium (at the isotopic mixtures obtained from conversion of U-238 in normal reactor burn-up) is readily usable in weapons. Today, there are about 270 tonnes of separated plutonium from reprocessing of commercial nuclear fuel around the world.

The 2003 study emphasized that the expansion in global nuclear deployment envisioned in the mid-century scenario could include a significant number of emerging countries (where electricity growth is expected to be most rapid) becoming users of nuclear power. Forty countries have expressed interest in nuclear power in recent years and over 20 countries are actively considering nuclear power programs.[20] Many of these countries are located in regions of political instability, thus underlining the importance of separating potentially sensitive fuel cycle technology – front-end enrichment and back-end spent fuel management – from power reactor operations.

The 2003 study proposed that nuclear supplier states, roughly the G-8,[21] offer fuel cycle services to new user states on attractive terms in order to slow the process of additional states, especially new users with only a few reactors, building enrichment and reprocessing facilities. Other groups have made similar proposals and, since 2003, the Bush Administration took a leadership role in advancing this approach, leading, for example, to the Nonproliferation statement at the G-8 Gleneagles, Scotland summit on July 8, 2005.[22] This is a significant advance in international nonproliferation policy since the 2003 study.

Another positive development is the initiative taken by the International Atomic Energy Agency, supported by private organizations such as the Nuclear Threat Initiative and then by several countries (including the United States and the Persian Gulf states), to establish a nuclear fuel bank. The fuel bank is intended to provide security of nuclear fuel supply, so that countries have less reason to pursue enrichment or reprocessing facilities.

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[20] http://www.iaea.org/Publications/Booklets/NuclearPower/np08.pdf

[21] The G-8 countries are Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, and the United States.

[22] Available at: http://www.g7.utoronto.ca/summit/2005gleneagles/nonprolif.pdf

However, the G-8 initiative on providing fuel cycle services remains untried. Since 2003 there have been three unrealized opportunities where the G-8 nuclear fuel cycle initiative could have been helpful: (1) Russia leasing fuel to Iran for the Bushehr reactors now under construction, (2) United States convincing Brazil to abandon its plans for its new Resende enrichment plant, and (3) Using the U.S.-India agreement to encourage India to scale back its plans for PUREX fuel reprocessing. Iran's enrichment program is the centerpiece for international concern about use of the nuclear power fuel cycle to reach nuclear weapons "threshold" status.

"The G-8 initiative on providing fuel cycle services remains untried."

Since 2004, the DOE developed the Global Nuclear Energy Partnership (GNEP), a framework that encompasses its domestic and international R&D activities on advanced fuel cycles. Internationally, the purpose was to limit the spread of enrichment and reprocessing technologies through an arrangement of supplier and user countries. Domestically the purpose was to develop technology for a closed fuel cycle: the ultimate vision includes separation of spent nuclear fuel into multiple streams, fabrication of advanced fuel containing uranium, plutonium, and minor actinides, production of electricity, and destruction of the actinides in fast reactors. The objective is to achieve a closed fuel cycle that extends uranium resources, reduces long-lived isotopes in waste, and is proliferation resistant.

Whatever the merits of this closed-fuel cycle vision, it will be more expensive than today's once through fuel cycle, and involve a multi-billion dollar federal R&D and demonstration effort over several decades. Initially DOE undertook an R&D program to explore fuel cycle options. DOE then launched the GNEP program that included deployment of closed fuel cycle facilities. The unfortunate feature of GNEP is a premature move to reprocessing commercial reactor spent fuel, signaling exactly the opposite to the restraint on reprocessing being urged for new nuclear power users. Congressional doubts about the wisdom of quick deployment of reprocessing technology led to a reassessment of the GNEP effort. A key objective of the ongoing MIT Nuclear Fuel Cycle study is to provide analysis to assess the cost, benefits, and timing of different fuel cycles.

"The unfortunate feature of GNEP is a premature move to reprocessing commercial reactor spent fuel, signaling exactly the opposite to the restraint on reprocessing being urged for new nuclear power users."

8. TECHNOLOGY OPPORTUNITIES AND R&D NEEDS

The 2003 *Future of Nuclear Power* study included judgments about nuclear technology needs and recommendations for DOE's nuclear RD&D program. The 2003 study emphasized the importance of focusing on technologies relevant to near term nuclear power opportunities and avoiding large-scale demonstration and development projects for advanced fuel cycles and reactors that would not be commercialized for many decades. Comments on developments related to some technology findings and recommendations in the 2003 study follow:

(a) **Reactor technologies** The 2003 study recommended focusing on light water reactors and some R&D on the high temperature gas reactor (HTGR) because of its potential for greater safety and efficiency of operation. In contrast, the DOE has placed emphasis on fourth generation reactors (GenIV) suitable for breeding, transmutation, and production of hydrogen. The GenIV program does include HTGR R&D at a level of funding of $74 million as requested by the President for FY08. The focus is on demonstrating a high temperature reactor, suitable for providing electricity and high quality process heat for CO_2–free hydrogen production and other process heat applications. Significant progress has been made in fuel development which is the basis for HTGR enhanced safety, enhanced efficiency, and the high temperature capability. The changes in direction are a result of expressions of interest by the chemical and refinery industries; in contrast, the 2003 report emphasized the importance of demonstrating HTGR technology for commercial power applications. In the request for 2009, the DOE budget started an LWR Technology development program, which will partially examine issues of extending the life to 80 years and partially improve the power output of future LWRs. This program is expected to grow to a level of $50M per year.

(b) **Fuel cycle R&D** The 2003 study recommended lab-scale research on new separation technologies at a modest scale. Initially, the DOE program through the Advanced Fuel Cycle Initiative adopted this strategy. However, with the adoption of the GNEP program the emphasis was on near-term deployment that implied using near-term advances of existing technology and large-scale demonstration projects.

(c) **Modeling and simulation** The 2003 study emphasized the need for greater analytic capability to explore different nuclear fuel cycle scenarios based on realistic cost estimates and engineering data acquired at the process development unit scale. The DOE program has moved in this direction but much remains to be done.

(d) **International uranium resource assessment** Reliable estimates of the supply of natural uranium ore are important for estimating the economics of closed versus open fuel cycles and the timing when a transition to a closed fuel cycle might be desirable. As reported, the DOE has not launched such a project.

(e) **Waste management** The 2003 study urged that the DOE broaden its waste program beyond its almost exclusive focus on the Yucca Mountain Project to include a range of waste management alternatives. The 2003 study also emphasized the need for modeling to improve understanding of waste management and the entire fuel cycle life. The DOE has not moved significantly in this direction since 2003.

(f) **Fissile material protection, control, and accounting** (MPC&A) The 2003 study noted the need to develop MPC&A systems that would be suitable for use internationally so as to reduce the risk of material diversion from commercial fuel cycle facilities.

In total, the 2003 study recommended growing the annual nuclear R&D funding to approximately $450 million in the designated areas. The DOE nuclear budget has grown to that level but the distribution of new funds is not well aligned with the needs highlighted in the recommendations of the 2003 study.

CONCLUSIONS

The central premise of the 2003 *MIT Study on the Future of Nuclear Power* was that the importance of reducing greenhouse gas emissions, in order to mitigate global warming, justified reevaluating the role of nuclear power in the country's energy future. The 2003 study identified the challenges to greater deployment and argued that the key need was to design, build, and operate a few first-of-a-kind nuclear plants with government assistance, to demonstrate to the public, political leaders, and investors the technical performance, cost, and environmental acceptability of the technology. After five years, no new plants are under construction in the United States and insufficient progress has been made on waste management. The current assistance program put into place by the 2005 EPACT has not yet been effective and needs to be improved. The sober warning is that if more is not done, nuclear power will diminish as a practical and timely option for deployment at a scale that would constitute a material contribution to climate change risk mitigation.

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