Nuclear Power Joint Fact-Finding

June 2007

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About The Keystone Center

The Keystone Center is an independent, nonprofit, public policy and education organization with a distinguished history of convening diverse stakeholders, brokering productive information exchanges, building consensus and creating applied solutions to seemingly intractable policy problems. Through a method of "Dialogue by Design," stakeholders, technical information and high-quality social and political processes are joined in a way that produces smarter and more durable solutions. We focus on three substantive areas: energy, environment and public health. More information about The Keystone Center can be found at www.keystone.org.

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Acknowledgements

The Keystone Center would like to thank the following organizations for their generous financial support of this project:

American Electric Power
Constellation Energy
Duke Energy
Entergy
Exelon
Florida Power & Light
General Electric
National Commission on Energy Policy
Nuclear Energy Institute
Pew Charitable Trusts
Southern Company

We would also like to thank the following individuals for their expert contribution to the Joint Fact-Finding:

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Photos courtesy of NEI and GE

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Endorsement

This report is designed to be an accurate portrayal of the NJFF group's discussions and joint findings. By endorsing this report, participants agree that they "generally support" the package of findings and the way the issues are described. To ensure an open and candid dialogue, participants presented their personal opinions in the Dialogue deliberations and not necessarily the official positions of their organizations. Therefore, the recommendations do not represent official government or organizational positions.

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Executive Summary

Nuclear technology is reemerging as a power generation option in the face of concerns about climate change, energy demand growth, and the relative cost of competing technologies. After more than a decade in which no new nuclear power plants were completed in the U.S., nuclear power is now the focus of considerable attention and debate. Nuclear power has long been controversial; consequently, the debate about its reemergence requires a fresh assessment of the facts about the technology, its economics and regulatory oversight, and the risks and benefits of its expansion. In the past year, the Keystone Center assembled a group of 27 individuals (see the Endorsement page for a list of Participants) with extensive experience and unique perspectives to develop a joint understanding of the "facts" and for an objective interpretation of the most credible information in areas where uncertainty persists. Participants represent diverse backgrounds and points of view—environmental and consumer advocates, the utility and nuclear power industry, non-governmental organizations, state regulators and former federal regulators, public policy analysts, and academics.

The participants consulted with a number of respected experts and conducted original analyses to answer questions they believe to be most important to an informed debate: Can we develop a reasonable range of expected costs to compare with other alternatives? How quickly can nuclear power be expanded to contribute to reducing worldwide greenhouse gas (GHG) emissions? What is the best way to manage nuclear waste? Can existing commercial nuclear facilities, as well as the next generation of nuclear reactors, be expected to operate safely and with adequate security safeguards in place? Should additional institutions or safeguards be put in place to prevent the proliferation of nuclear weapons derived from commercial fuel cycle activities?

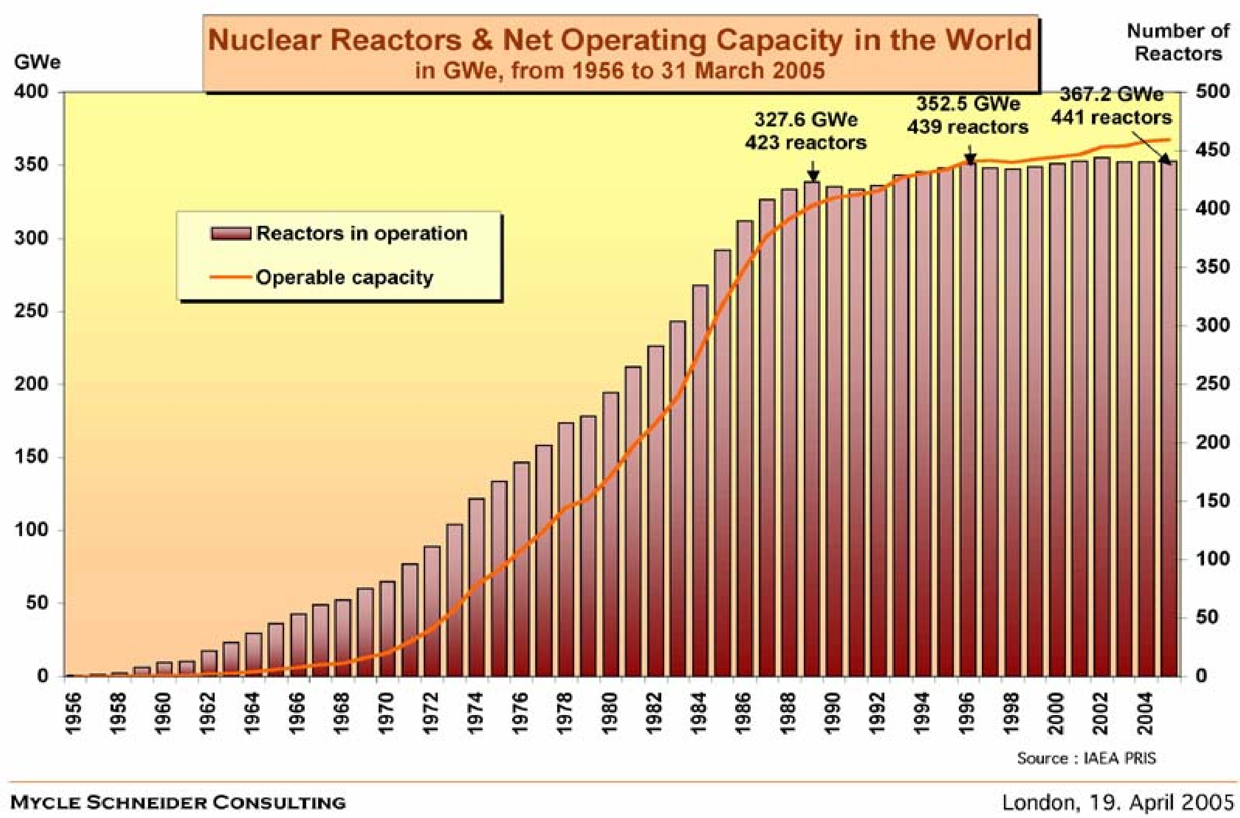
We trust that the research, expertise, and deliberations of this broad range of individuals lend strong credibility to the findings, which are intended to lay the foundation for continued discussions of the role of nuclear power in the U.S. and abroad. We expect, nonetheless, that readers will draw their own conclusions, since many of the findings are best efforts to interpret uncertainties.

EXECUTIVE SUMMARY

Nuclear Power and Climate Change Mitigation

Members of the Nuclear Power Joint Fact Finding (NJFF) reached no consensus about the likely rate of expansion for nuclear power in the world or in the U.S. over the next 50 years. Some group members thought it was unlikely that overall nuclear capacity would expand appreciably above its current levels and could decline; others thought that the nuclear industry could expand rapidly enough to fill a substantial portion of a carbon-stabilization "wedge" during the next 50 years.

To maintain the low-carbon benefits of the current 435 nuclear plants (370 GWe) around the world that will be retired over the next 50 years and to expand nuclear power's share of electricity generation would require an ambitious nuclear reactor building program. We looked at the number of nuclear power plants that would be required to displace 1 gigatonne of carbon annually from an equivalent amount of generation by new, efficient coal plants by the end of 50 years (a "carbon stabilization wedge.")[1]



Source: Mycle Schneider Consulting.

[1]Pacala and Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, 13 August 2004, Vol. 305, No. 5686. pp 968-972.

The NJFF participants agree that to build enough nuclear capacity to achieve the carbon reductions of a Pacala/Socolow wedge (1 GtC/year or 700 net GWe nuclear power; 1,070 total GWe) would require the industry to return immediately to the most rapid period of growth experienced in the past (1981-90) and sustain this rate of growth for 50 years.

This projection is more optimistic than indicated by the current announcements of proposed plant construction reported by the World Nuclear Association, is higher than the average historical growth rate during the industry's first 40 years, and represents more rapid industry growth than forecast by the Energy Information Administration for the U.S for the next 30 years.

We know that in a carbon-constrained world, in which either a substantial greenhouse gas (GHG) tax or cap and trade program is implemented, the relative economics of nuclear power (as compared to fossil-fueled power) will improve.

Climate policies enhance the position of all low-GHG sources of power, including: renewables, coal with carbon capture and sequestration, and energy efficiency investments. A broadly applied GHG tax or cap and trade program would create GHG saving alternatives in all sectors. The more stringent the climate policy (the greater the reduction target or the higher the carbon tax), the greater the relative economic advantage of nuclear and other low-GHG technologies.

Economics of Nuclear Power

The NJFF participants reviewed a number of studies that evaluated the life-cycle levelized cost of future nuclear power.[2] *We also relied on our own spreadsheet model to analyze the sensitivity of costs and price to certain factors. We found that a reasonable range for the expected levelized cost of nuclear power is between 8 and 11 cents per kilowatt-hour (kWh) delivered to the grid.*

We agreed that the most recent construction experience is the best indicator of future costs. We considered a likely range of assumptions on the critical cost factors, such as escalation of material costs, length of construction period, and capacity factor. While this value is significantly higher than many current vendor or government estimates, that is because our estimates are based on recent escalation in construction and raw material costs, which can be compounded in the future by tightness in the supply chain (availability of large forgings, skilled contractors and crews, etc.). Factors other than cost can have an acute impact on the outlook of investors, CEOs, and regulators about the potential risks and benefits of a nuclear investment, including the market structure, certainty of regulatory oversight, public perception, and the disposition of nuclear waste.

Summary of Levelized Cost (Cents/kWh)

Cost Category	Low Case	High Case
Capital Costs	4.6	6.2
Fuel	1.3	1.7
Fixed O&M	1.9	2.7
Variable O&M	0.5	0.5
Total (Levelized Cents/kWh)	8.3	11.1

[2]Levelized life-cycle cost is the total cost of a project from construction to retirement and decommissioning, expressed in present value and then spread evenly over the useful output (kWh) of the product.

The NJFF group concludes that while some companies have announced their intentions to build "merchant" nuclear power plants, it will likely be easier to finance nuclear power in states where the costs are included in the rate base with a regulated return on equity.

We also recognize that developers may face regulatory hurdles in cost-of-service states, which may make it difficult to build plants in some states. The power plant cost overruns of the 1970s and 1980s have led to a number of changes in the traditional cost-of-service regulatory framework that creates a more rigorous environment in which to consider new capital-intensive generation investments.

Safety and Security

According to the U.S. Nuclear Regulatory Commission (NRC) assessment, U.S. nuclear power plants meet the NRC's safety goal. Some NJFF participants agree with this assessment. Others believe that the methodology used cannot adequately demonstrate that the NRC safety goal is being met.

The method that the NRC currently uses to assess the safety of a nuclear power plant is a quantitative risk assessment known as Probabilistic Risk Assessment (PRA). Variations in the quality of data, models, and assumptions used at each power plant, and different perceptions about the capacity to quantify low-probability catastrophic accidents led to disagreement about the adequacy and reliability of the NRC's assessment.

On balance, commercial nuclear power plants in the U.S. are safer today than they were before the 1979 accident at Three Mile Island.

The NJFF participants reviewed a number of factors, including improvements in plant equipment and human performance, organizational and risk insights gained through experience, the implications of aging materials and components, and institutional changes in safety oversight. All participants agree that a strong safety culture is necessary to ensure the protection of public health and safety; not everyone agreed that the safety culture at all U.S. power plants is strong enough (e.g., the Davis-Besse event). The participants also did not agree on whether or not the NRC Commissioners have been consistently effective in ensuring the safe operation of current nuclear power plants.

There is agreement that, while plants have gotten safer since the Three Mile Island accident, public concern over plant security is greater today than it was before September 11, 2001. There is not agreement on whether it has been demonstrated that the security systems and procedures to protect existing reactors are sufficiently robust. In the current classification environment, it is difficult for outside entities lacking security clearances to adequately assess security measures, as well as their implementation and oversight.

NJFF participants, some with security clearances who have analyzed the Design Basis Threat (DBT) and current security measures, disagree about whether the DBT and its oversight are adequate. The DBT profiles the type, composition, and capabilities of an adversary as a basis for designing safeguards and security systems to protect against acts of radiological sabotage and to prevent the theft of special nuclear material. The details of the post-September 11th DBT are no longer available to the public; and there remains debate, even among some NRC Commissioners and staff, about how prescriptive a DBT should be.

The public ought to be able to trust both the nuclear industry and the federal agency conducting its security oversight. Transparency is a key cornerstone for public trust-building. However, when it comes to the security of nuclear power plants, full disclosure may be counter-productive.

There is agreement that the details of security measures (e.g., the number and location of guards, barriers, and alarms) should be kept classified to ensure their effectiveness. Debate continues about how much information should be made public on security measures and on related oversight by the NRC in order to instill public confidence.

Over the next two or three decades, the safety and security of the U.S. nuclear industry will largely be determined by the safety and security of existing reactors. Principal concerns for the U.S. power plants will continue to be those related to aging equipment and materials, as well as potential terrorist threats.

New reactors are expected to include advanced features that enhance both safety and security; however, existing reactors should be the focus of primary attention for improved safety and security, as they are likely to receive license extensions and for the next 30 years will outnumber new reactors.

On balance, this group has concerns about nuclear plant expansion in certain other countries that currently have significant weaknesses in legal structure (rule of law); construction practice; operating, safety, and security cultures; and regulatory oversight.

A reliable safety culture is critical to any safe commercial nuclear program, but the current safety culture varies greatly among countries. Systematic assessments of non-U.S. safety and security preparedness proved nearly impossible for the NJFF group, as there are no international standards that require countries with commercial nuclear power to meet minimum safety security standards, and current practices are generally kept classified.

Substantial changes have been made to the nuclear power plant licensing process in the last 15 years. These include moving consideration of public input toward the front of the process before significant capital expenditures are made. They also include new procedural modifications in such areas as raising contentions, cross-examination and discovery. Some members of the NJFF believe that the procedural modifications limit effective public involvement and could have a deleterious effect on safety and security.

Public involvement in the licensing process permits the opportunity to raise issues that will improve the safety of nuclear power plants and analysis of other alternatives. It also enhances the levels of transparency and trust in governmental decision-making. The NRC licensing process is the only federal forum for raising these issues, but the NJFF participants could not agree on whether or not the changes in the public participation process have overly constrained public involvement.

Waste and Reprocessing

There is consensus among the NJFF group that spent nuclear fuel must ultimately be placed in long-term disposal facilities, and that the best disposal option is a deep underground geologic repository. A consensus also exists regarding the suitable environments for geologic repositories. However, thus far, nations have yet to actually site and complete these repositories.

The NJFF participants agreed with the technical group convened by the International Atomic Energy Agency as to the desirable characteristics of a nuclear waste repository: geologic stability, low groundwater content and flow, stable geochemical or hydrochemical conditions, and good engineering properties that allow for ease of construction. Suitable geological environments for disposal exist throughout the world, including in the U.S., but each provides different combinations of desirable characteristics that must be judged on a site-specific basis.

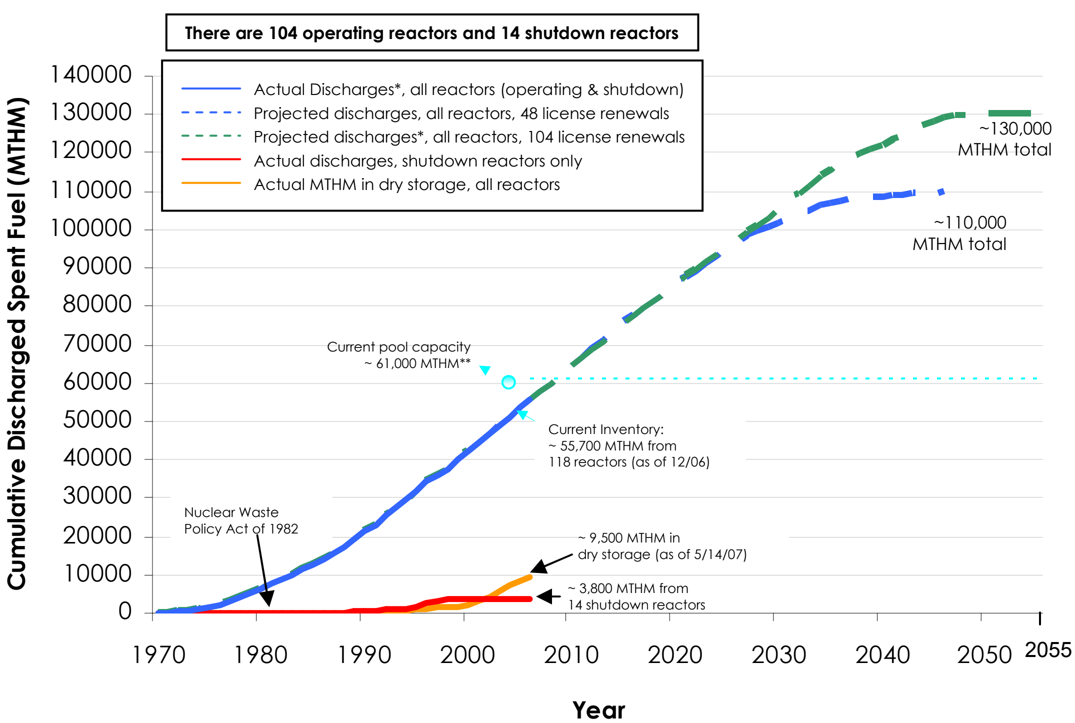
The NJFF group observes that the Yucca Mountain project has repeatedly failed to meet its own schedule. There is little confidence that currently established DOE schedules will be met. Projected delays in the commissioning of a repository mean added liability for the federal government, open-ended obligations on the part of nuclear plant owners to manage spent fuel, and additional physical and financial requirements for interim storage. Given this experience, the search for a second site or an alternative site would benefit from a different approach.

The availability of a repository in the U.S. is currently a decade behind schedule due to past and ongoing political, technical, and legal challenges. If the Yucca Mountain license application is submitted to NRC in June 2008 as currently projected, the most optimistic date for first emplacement of waste will be 2017, but more likely it will be beyond 2020. The EPA-proposed dose limit standard, which is a critical component of the licensing process, was rejected by the DC Court of Appeals in 2004. A revised final standard, which may also face legal challenges, has not been issued. To get an NRC license, DOE will have to demonstrate convincingly that it will meet the final EPA standard. The cost of completing and operating Yucca Mountain consequently remains uncertain, and continued delays, changes in design, and changes in requirements for spent fuel transportation add to the uncertainty. The NJFF participants considered but did not analyze alternative decision-making processes to those used by DOE in consideration of Yucca Mountain.

Yucca Mountain has a statutory capacity limit that is less than the amount of spent fuel expected to be produced by currently operating reactors over their licensed lifetimes. Any net expansion of U.S. nuclear power generation would require significantly greater repository capacity than currently established by law for Yucca Mountain.

The statutory capacity of Yucca Mountain is 70,000 metric tons. Congress may increase the capacity or may authorize DOE to begin the search for a second repository. Under the National Waste Policy Act, DOE must submit to Congress a proposal to do so no later than 2010. Some states legally restrict the expansion of nuclear power until a long-term solution for waste management is in place.

Historical and Projected Commercial Spent Nuclear Fuel Discharges as of May 14, 2007



Sources: * Based on actual discharge data as reported on RW-859's through 12/31/02, and projected discharges, in this case, based on 104 license renewals.
** Represents the aggregate industry pool capacity based on pool capacities provided in 2002 RW-859 (less FCR) and supplemented by utility storage plans. However, the industry is not one big pool and storage situations at individual sites differ based on pool capacities versus discharges into specific pools.

With regard to older spent fuel that must be stored on an interim basis until an operating repository is available, the NJFF participants believe that this spent fuel can be stored safely and securely in either spent fuel pools or dry casks, on-site. The NJFF group also agrees that centralized interim storage is a reasonable alternative for managing waste from decommissioned plant sites and could become cost-effective for operating reactors in the future.

Three options exist for spent fuel storage: on-site fuel pools, on-site dry cask storage systems, and centralized storage in dry casks. Although pool storage capacity is constrained at some sites, the dry storage option generally is not; however, dry cask storage incurs additional costs. Centralized dry cask storage for spent fuel currently at decommissioned plant sites may make sense, because it would allow more efficient management and oversight of the spent fuel and allow reuse of land at decommissioned plants.

There is wide agreement among the NJFF group participants that transport of spent fuel and other high-level radioactive waste is highly regulated, and that it has been safely shipped in the past. Security requirements during transport have been enhanced in response to 9/11; however, transport security will require continued vigilance. Transport of spent fuel to any repository will take many years to complete, and will require ongoing regulatory oversight.

If Yucca Mountain is licensed or centralized interim storage is permitted, the spent fuel must be transported. Total shipments of waste are expected to take 24 years to complete. Since 1965 there have been more than 2,700 relatively small shipments of spent nuclear fuel in the U.S., covering more than 1.6 million miles. Although there have been accidents in that time, there were no injuries, no breach of the containers, and no release of radioactivity. Under the NWPA disposal program, DOE and commercial carriers will plan and conduct spent fuel shipments under extensive federal regulations for rail, highway, and water modes. Interstate transportation protocols have been in place for several decades.

No commercial reprocessing of nuclear fuel is currently undertaken in the U.S. The NJFF group agrees that while reprocessing of commercial spent fuel has been pursued for several decades in Europe, overall fuel cycle economics have not supported a change in the U.S. from a "once-through" fuel cycle. Furthermore, the long-term availability of uranium at reasonable cost suggests that reprocessing of spent fuel will not be cost-effective in the foreseeable future. A closed fuel cycle with any type of separations program will still require a geologic repository for long-term management of waste streams.

Reprocessing as currently practiced is several times more expensive than a once-through fuel cycle system. Uranium prices have increased dramatically over the past 10 years, but this has not changed our fundamental conclusion that reprocessing is uneconomic. While reprocessing decreases the volume of high-level waste, a geologic repository is still needed. In addition, the volume of low- and intermediate-level wastes substantially increases with reprocessing, and these radioactive waste streams need to be disposed of in facilities that require siting and long-term management. The Global Nuclear Energy Partnership (GNEP), which includes an advanced reprocessing component, was proposed in 2006 to help expand nuclear power in the U.S. and abroad by, among other things, reducing the number of geologic repositories that would eventually be needed to sequester nuclear waste. But from a waste management perspective, there are many potential problems with the GNEP concept, including cost, technology choice, and waste streams.

Proliferation

Expansion of nuclear power in ways that substantially increase the likelihood of the spread of nuclear weapons is not acceptable.

Proliferation of nuclear weapons can occur without an expansion of the commercial nuclear power industry, but the challenges increase as the industry grows. In particular, if growth in commercial nuclear power plants also results in the construction of fuel cycle facilities in countries that do not now possess nuclear weapons, the risk of proliferation will increase. Proliferation can occur by the actions of either national governments (state actors) or non-state, possibly terrorist organizations. Weapons-grade materials can be obtained from states or non-state actors, or they can be developed by the non-nuclear weapons states using either dedicated weapons facilities or IAEA-safeguarded civilian nuclear fuel cycle facilities.

The NJFF participants agree that there are critical shortcomings in the current IAEA safeguards and that the international community has not demonstrated that the enforcement mechanisms are effective.

Today there is a collection of treaties, agreements, and commitments that are applied to peaceful uses of nuclear energy; they are designed to reduce the likelihood that special fissionable and other materials, services, equipment, facilities, and information will be used for military purposes. The International Atomic Energy Agency (IAEA) is the institution responsible for safeguarding civil nuclear activities in non-weapons states. The IAEA safeguards are currently insufficient to provide timely detection when weapon quantities of HEU and plutonium are diverted. This is because the time required to convert different forms of nuclear material to the metallic components of a nuclear explosive device are short compared to the IAEA timeliness detection goals used to define the frequency of inspections. Also, significant quantities (SQ) of nuclear material, defined by IAEA for the purpose of monitoring inventories and detecting diversion or theft of materials, are significantly greater than the amount of material needed to make a nuclear weapon without detection.

The NJFF participants agree that a principal proliferation concern is the diversion or theft of material from bulk fuel handling facilities (e.g., reprocessing, enrichment, mixed-oxide fuel fabrication, and plutonium storage facilities) to develop weapons capability.

While efforts have been made in the past to preclude non-weapons states from acquiring reprocessing or enrichment technologies, they have not always been successful. Non-weapons states can operate civilian fuel cycle facilities, particularly enrichment plants, mixed-oxide fuel fabrication facilities, and reprocessing facilities. It is relatively simple to use these technologies to produce weapons-grade material.

Growing stocks of civilian separated plutonium (250 tons and growing at a rate of 10 tons/yr) pose a significant proliferation risk and require extraordinary protection and international attention. Diversion or theft of these stocks represents a risk of weapons development by sub-national terrorist organizations. Levels of physical protection and risk vary widely from country to country.

While a number of countries have reprocessed spent fuel, few have used the separated plutonium as fuel in light-water reactors, mainly because such mixed-oxide fuel is currently more expensive than using enriched natural uranium. There are three options for dealing with the risk posed by civilian separated plutonium. First, it can be stored indefinitely. Second, the plutonium can be fabricated into mixed-oxide fuel, burned in reactors, and converted to spent fuel. Finally, the plutonium can be "diluted" by adding it to materials that would allow for permanent underground storage with low risk of criticality.

While the NJFF agrees with several premises of the GNEP, the program is not a strategy for resolving either the radioactive waste problem or the weapons proliferation problem. The NJFF group agrees with the following proliferation concerns that GNEP attempts to address:

- All grades of plutonium, regardless of the source, could be used to make nuclear explosives and must be controlled.
- Reprocessing poses a problem in non-weapons states. Widespread use of mixed-oxide fuel by both weapons states and non-weapons states is similarly troublesome.
- Even in the weapons states, plutonium must be protected, and one should not increase stocks of plutonium in separated or easily separated forms such as mixed-oxide fuel.

Estimated Quantities of Civilian Separated Plutonium by Country

Country	Civilian Pu Stock at End of 2005 (Tonnes)
Belgium	3.3 (plus 0.4 in France)
France	81.0 (30 foreign-owned)
Germany	12.5 (plus 15 in France and UK)
India	5.4
Japan	5.9 (plus 38 in France and UK)
Russia	41.0
Switzerland	<2.0 (in France and UK)
UK	105.0 (27 foreign owned plus 0.9 abroad)
Total	**250.0**

The NJFF participants believe that critical elements of the GNEP are unlikely to succeed because:

- GNEP requires the deployment of commercial-scale reprocessing plants, and a large fraction of the U.S. and global commercial reactor fleets would have to be fast reactors.
- To date, deployment of commercial reprocessing plants has proven uneconomical.
- Fast reactors have proven to be uneconomical and less reliable than conventional light-water reactors.

Although it is not its aim, the GNEP program could encourage the development of hot cells and reprocessing R&D centers in non-weapons states, as well as the training of cadres of experts in plutonium chemistry and metallurgy, all of which pose a grave proliferation risk.

Introduction

Nuclear power is reemerging as the focus of considerable attention and debate in the face of concerns about climate change, energy demand growth and the persistently high fossil fuel prices. Existing nuclear generating capacity currently contributes to meeting world-wide electricity demand while simultaneously reducing greenhouse gases (GHG) that contribute to climate change. Expanding nuclear capacity is one option among many that might do so in the future. After more than a decade in which no new nuclear power plants were completed in the U.S., stakeholders are reengaging—including companies considering building new plants, analysts evaluating costs, and public interest advocates looking at safety and risks.

Nuclear power has always been controversial. Thus, the foundation for reengagement must be an assessment of the facts—what do we know, what is uncertain, what is generally agreed to, where there are disagreements, and what the implications are for public policy. A number of uncertainties and unresolved challenges remain: Can a reasonable range of expected costs be determined in order to enable comparisons with other alternatives? How quickly can nuclear power be expanded to help mitigate climate change? What is the best way to manage the nuclear waste? Can we expect existing commercial nuclear facilities, as well as the next generation of nuclear reactors, to operate safely and with adequate security safeguards in place? Should additional institutions or safeguards be put in place to prevent the proliferation of nuclear weapons derived from commercial fuel cycle activities?

By answering these questions through a joint fact-finding process, this report is an attempt to begin to lay the foundation for an informed debate of the future of nuclear power in a carbon-constrained world.

What is a Joint Fact-Finding?

A joint fact finding allows stakeholders with different interests to uncover together information that is helpful to resolving a conflict. They identify mutually trusted, credible experts and sources of information or, in some cases, conduct new analysis to answer questions.

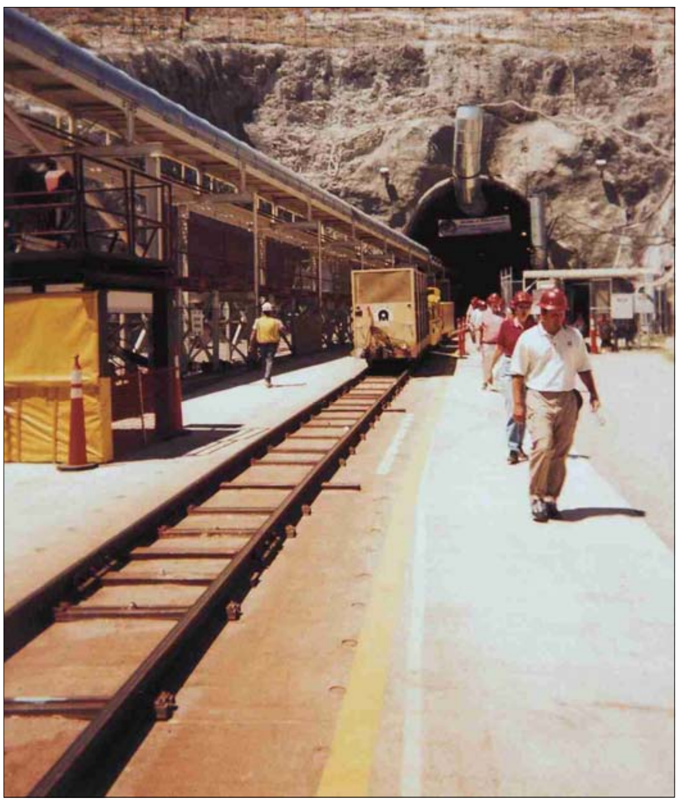
The final outcome is a common understanding of what is known, what is still uncertain, and what needs more research to help resolve the conflict or to support good policy. In the process, the parties to a joint fact finding may also build greater trust and understanding in learning how others rely on and interpret information.

Who participated?

To better understand what role nuclear power might play, The Keystone Center assembled a group of 27 individuals (see the Endorsement page for a list of Participants) with extensive experience and different perspectives on these topics. They met over the past year to develop a joint understanding of the "facts" and a common interpretation of the most credible information where uncertainty remains. The group included environmental and consumer advocates, the utility and nuclear power industry, non-governmental organizations, state regulators and former federal regulators, public policy analysts, and academics. They brought their knowledge and experience to the table, but they also entered the room with minds open to learning from others. They consulted with a number of experts on all sides of the debate. The strength of these findings rests in the agreement they found despite their different perspectives. Where the same information led to different interpretations and clear agreement was not reached, different perspectives are presented.

What issues did the NJFF cover?

The participants developed the questions that they felt were the most important to answer, but this is not intended to be a comprehensive treatise on nuclear power. We tackled the question of what the likely cost of building advanced nuclear reactors in the next 10-15 years will be. We did not attempt to do a comparative analysis of the cost of nuclear power against other low-GHG energy resources such as energy efficiency, renewable energy, and coal-fired generation with carbon capture and storage. We took on the question of how much new nuclear power capacity might be needed world - wide to make a significant contribution to reducing GHG emissions. We did not try to answer the question of how much nuclear power capacity *should* be built.



We asked and answered the questions of whether the operation of nuclear reactors is safer today than it was in the past, but we did not provide recommendations on how to assure the safe operation of plants in the future. We evaluated available information on the security of the existing and future nuclear facilities against terrorist attacks, but we chose not to make recommendations on how to solve the tension between the public desire for transparency and the real need for confidentiality. We did not examine a host of other environmental issues related to uranium mining and milling, and other nuclear fuel cycle activities.

We evaluated the current and proposed options for waste management and agreed that geological repositories are the best option. We agreed on the desirable characteristics of such a repository, but we chose not to answer the question of whether Yucca Mountain is an acceptable long-term storage site for nuclear waste from existing power plants. The group evaluated current reprocessing techniques, but did not make recommendations about whether advanced reprocessing techniques should be pursued in the future or, if so, which ones.

Finally, we identified the most urgent proliferation risks associated with current and expanded commercial nuclear facilities. We did not try to answer the question of what additional safeguards and treaties are needed to address those risks.

How should this report be used?

We hope that the research, expertise, and deliberations of this broad range of individuals will lend strong credibility to the findings. We expect nonetheless, that readers may draw their own conclusions, because many of the findings are still best efforts to interpret the uncertainties. The findings in this report should lay the foundation for continued discussions of the role of nuclear power in the U.S. and abroad. Ultimately the decisions surrounding the future of nuclear power in the U.S. and abroad will rest on choices made by industry executives and boards, state and federal regulators, government policymakers, and the public.

I. The Role of Nuclear Power in Mitigating Climate Change

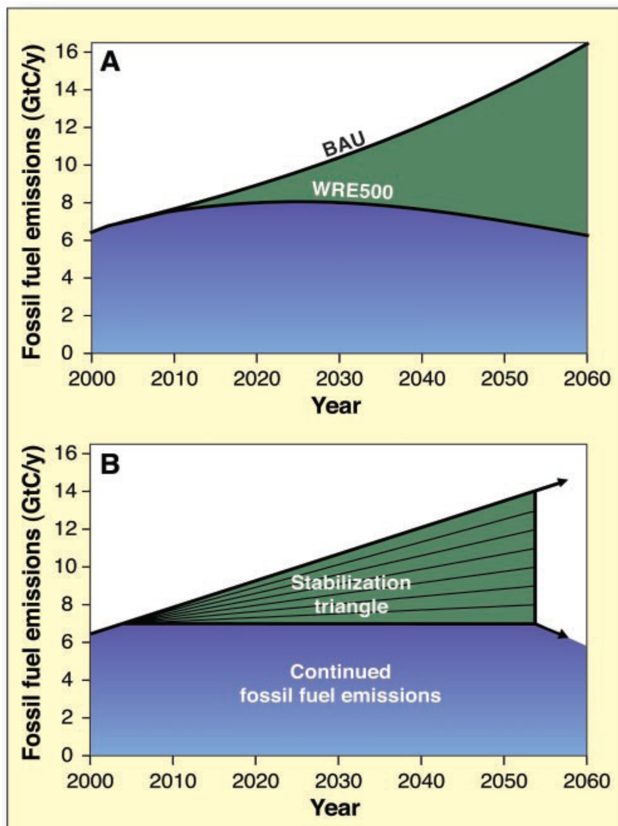
While we did not explicitly compare the costs and benefits of nuclear power to alternative low-emission technologies,[1] we did consider potential scenarios for nuclear expansion in order to better understand what role nuclear power might play in mitigating global climate change.

Members of the NJFF reached no consensus about the likely rate of expansion for nuclear power in the world or in the United States over the next 50 years. Some group members thought it was unlikely that overall nuclear capacity would expand appreciably above its current levels and could decline; others thought that the nuclear industry could expand rapidly enough to fill a substantial portion of a carbon-stabilization "wedge" during the next 50 years.

Pacala/Socolow Wedge

To demonstrate the breadth and scope of any effort required to stabilize world carbon emissions over the next 50 years, Princeton professors Stephen Pacala and Robert Socolow developed a concept they called "stabilization wedges."[2] Each wedge represents a potential reduction of one gigatonne of carbon per year (GtC/yr) at the end of 50 years; or a total of 25 gigatonnes over the 50-year period. Pacala/Socolow presented 15 possible technology wedges, not all completely independent of each other, and argued that at least seven of these wedges, or a larger number of partial wedges, would be necessary to stabilize global atmospheric CO_2 concentrations[3](see Figure 1). One of their wedges represented global expansion of nuclear capacity.

Figure 1. Pacala/Socolow Stabilization Wedge Concept



Notes, Figure 1: **BAU** is Business As Usual CO_2 emissions path for global carbon emissions as CO_2 from fossil fuel combustion and cement manufacture: 1.5% per year growth starting from 7.0 GtC/year in 2004.
WRE is a CO_2 emissions path consistent with atmospheric CO_2 stabilization at 500 ppm by 2125 akin to the Wigley, Richels, and Edmonds (WRE) family of stabilization curves.
Source: Pacala and Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, Aug. 2004.

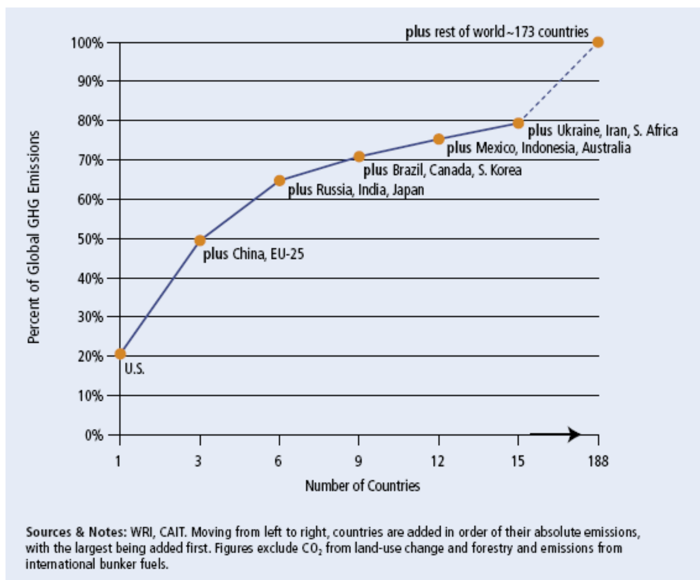
[1]All generation technologies, including nuclear power, emit some GHG when the full life cycle (uranium mining, enrichment, construction materials, and waste management) is included in the analysis. Our analysis is limited to GHG emissions from nuclear generation, not the life-cycle emissions.
[2]Pacala and Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, 13 August 2004, Vol. 305, No. 5686, pp. 968-972. Some of these wedges are interrelated (e.g., other electric sector carbon savings).
[3]Pacala/Socolow's definition of "stabilization" is a reduction of atmospheric concentrations of carbon dioxide to two times pre-industrial

In their analysis, approximately 700 gigawatts-electric (GWe)[4] of new *net* nuclear capacity would be needed globally by the mid-2050s to achieve a wedge, assuming that this capacity would displace new, highly-efficient coal generation.[5] To add 700 GWe to current nuclear capacity world-wide over the next 50 years would require completing, on average, fourteen 1,000-megawatt-electric (MWe) plants each year.

Before 2050, however, it will also be necessary to replace retiring nuclear capacity (approximately 370 GWe) or to construct another 7.4 (1,000-MWe) reactors each year over the next 50 years. If we assume that the existing nuclear fleet is replaced over that 50-year period, then 1,070 GWe (about 21.4 GWe a year) must be built world-wide in order to yield a single climate-stabilization wedge while maintaining the low-carbon benefits of existing nuclear generation. Failure to replace the existing nuclear-plant fleet with new units, other low-carbon electric generation facilities, or energy efficiency improvements would effectively create a negative half-wedge or increase total emissions by 12.5 GtC over the next half century.

U.S. emissions are about 20% of global GHG emissions today from all sectors (Figure 2).[6] The generation of electricity is responsible for one-third of all U.S.GHG emissions. This sector is the largest single source of these emissions.[7] Therefore, the U.S. share of one nuclear wedge could represent

Figure 2.
Aggregate Contribution of Major GHG-Emitting Countries



Notes, Figure 2: Moving from left to right, countries are added in order of their absolute emissions, with the highest being added first. Figures exclude CO_2 from land-use change and forestry and emissions from international bunker fuels. Source: WRI, CAIT.

[4]A gigawatt of electricity is equal to 1,000 megawatts, which is slightly greater than the average size of the nuclear plants currently operating in the U.S. but smaller than many proposed new reactors.

[5]While Pacala and Socolow assume that nuclear displaces a highly efficient coal plant (50% thermal efficiency), actual carbon displacement is a function of other resource options, growth rates, relative operating costs, and the current generating mix. To the extent that nuclear replaces less thermally efficient coal capacity or other high-emitting resources, the amount of nuclear generation needed to displace a wedge of carbon would be less; if nuclear displaces natural gas or other lower carbon emitting resources, the amount of nuclear capacity needed to displace a wedge of carbon would be greater.

[6]Baumert, K. Herzog, T., and Pershing, J. "Navigating the Numbers: Greenhouse Gas Data and International Climate Policy." 2005. The World Resources Institute: Washington, DC. Chapter 2 GHG Emissions and Trends. Available at http://pdf.wri.org/navigating_numbers_chapter2.pdf.

[7]Morgan, G., Apt, J. and Lave, L. "The U.S. Electric Power Sector and Climate Change Mitigation." June 2005. Pew Center on Global Climate Change: Arlington, VA. Available at http://www.pewclimate.org/docUploads/Electricity%5FFinal%2Epdf.

140 new GWe, plus replacement of current capacity (98 GWe), or 238 GWe. That level of expansion would require completion of about five 1,000-MWe plants per year, on average. Given the global nature of carbon emissions, however, there is no particular requirement for a retiring nuclear plant to be replaced by another in the same nation.

From our perspective, these figures are not forecasts or goals but merely calculations designed to test the cost, credibility, level-of-effort, and risks that may be encountered in global and U.S. nuclear expansion.

To meet the 700-GWe world-wide wedge plus replace the 370 GWe of existing capacity would also require substantial expansion of fuel-cycle facilities (e.g., uranium mines, mills, and enrichment plants, fuel fabrication plants, and nuclear waste repositories). The rough estimated capacity increase needed to meet fresh and spent fuel requirements for a 50-year ramp-up from 370 GWe to 1,070 GWe are:[8]

- 11-22 large enrichment plants, each yielding 4-8 million "kilogram separative work units per year" (kg SWU/y)[9] (compared to 17 existing plants);
- 18 fuel fabrication plants, each producing 1,000 tons of fuel per year (compared to 24 existing facilities world-wide); and
- 10 nuclear waste repositories the size of the statutory capacity of Yucca Mountain—713,000 tons of spent fuel.[10]

Even if nuclear power does not expand beyond its current capacity, additional facilities would be needed to support the continued operation of nuclear power plants. Appendix A lists the existing nuclear facilities around the world.

Expansion Scenarios

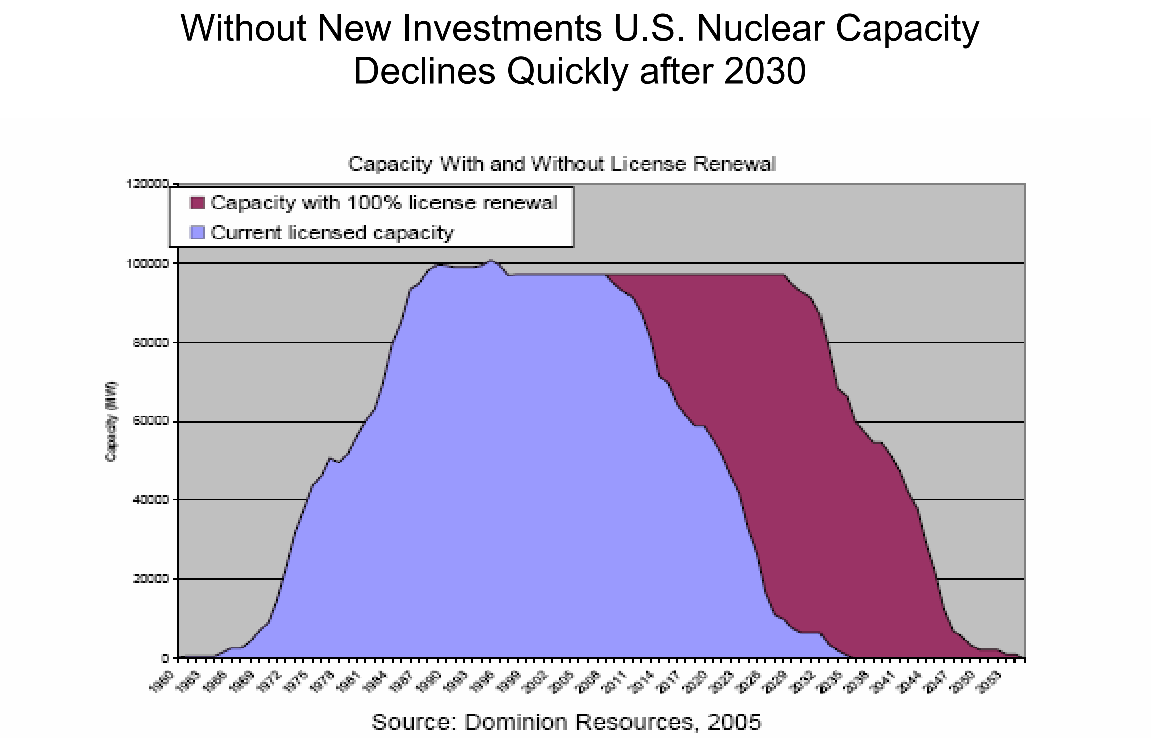
Members of the NJFF had different opinions about the *likely* expansion scenarios for nuclear power. Some members believe that it will take substantial effort to maintain the size of the existing world-wide nuclear plants and the greenhouse gas benefits in the face of retirements, while others believe that significant new capacity can be added.

Simply maintaining the current capacity of nuclear power will require a significant number of new reactors over the next 50 years. Figure 3 shows current U.S. nuclear capacity, with and without license renewal to a 60-year lifetime. It demonstrates the decline in current nuclear capacity after 2030 even with license renewals. The retirement scenario world-wide looks very similar.[11] Extending the life of current capacity delays but does not eliminate the need to replace more than about 370 GWe of generating capacity to maintain the greenhouse gas offsets provided by the current 435 nuclear power plants.

The NJFF participants looked at different sources of data on planned or proposed construction of nuclear power plants to gain greater perspective on the level of effort required to achieve a significant reduction in carbon emissions through expansion of nuclear power. Modeling forecasts are useful, but it is often difficult to reconcile the underlying reasons that forecasts differ. Historical trends give us a sense of what has been achieved in the past. Trade journal reports provide some insight into near-term constraints, but they give little guidance over a 50-year horizon. Nonetheless, this was the best information available for considering different potential levels of expansion and their climate change implications. After reviewing a variety of projects, we relied on plans for new world-wide additions compiled by the World Nuclear Association (WNA) and forecasts by the U.S.

[8] Tom Cochran, director, NRDC Nuclear Program.
[9] More modern and energy-efficient centrifuge enrichment plants are generally smaller. The proposed American Centrifuge Plant in Piketon, Ohio, has an estimated annual capacity of 3.8 million kg SWU/y.
[10] If all fuel were reprocessed, it would take approximately 36 reprocessing plants, each handling 800 tons of spent fuel per year.
[11] IAEA, Power Reactor Information System, http://www.iaea.org/programmes/a2/.

Figure 3. U.S. Nuclear Capacity, 1960-2055



Department of Energy (DOE), Energy Information Administration (EIA), for U.S. additions. We looked at historical expansion experience and, finally, reviewed industry trade journal comments on the implications of nuclear scale-up for the fuel cycle.

World Nuclear Association Projections

The WNA maintains a database of reactors that are "Operating," "Under Construction," "On Order or Planned," and "Proposed." The total amount of additional world-wide nuclear capacity over currently operating capacity in these categories is 216 GWe as shown in Table 1 below.[12] WNA does not provide information that allows us to determine when these planned and proposed units are expected to be built, but indicates that at least

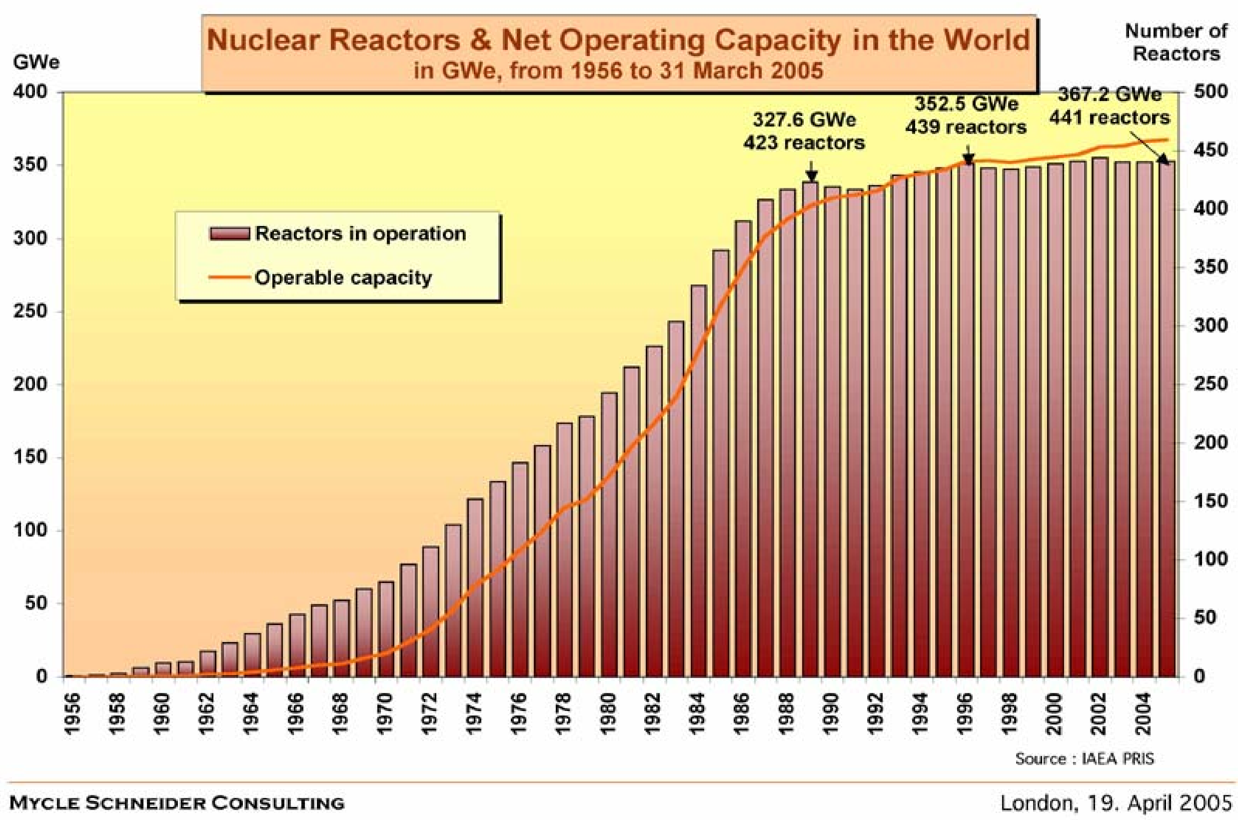
Table 1. Commercial Nuclear Power Plants, Current and Projected, in the U.S. and World-wide as of the End of 2006

	Operating		Under Construction		On Order or Planned		Proposed	
	No.	GWe	No.	GWe	No.	GWe	No.	GWe
World	435	369	28	23	64	69	158	124
U.S.	103	98.3	1	1.2	2	2.7	21	24

Source: "World Nuclear Power Reactors and Uranium Requirements," 4 January 2007, http://www.world-nuclear.org/info/reactors.html.

[12]In WNA's projections, the "On Order or Planned" category includes completion of reactors in which "construction [is] well advanced but suspended indefinitely." The "Proposed" category includes reactors that are part of a country's or national agency's long-range nuclear plans, but are "still without funding and/or approvals."

Figure 4. Nuclear Reactors and Net Operating Capacity in the World, 1956 to 31 March 2005 (GWe)



60 new reactors (in addition to approximately 30 under construction) are expected to be built in the next 15 years which would bring total nuclear capacity to 430 GWe in 2020.[13] Because most long-term planning does not extend beyond 30 years, we assumed that the proposed plants could be completed within the next 30 years.

If as we assumed, all long-term nuclear construction plans identified by WNA are fully implemented within 30 years, the equivalent average construction rate of nuclear capacity would be approximately 7.2 GWe/yr. Assuming continued expansion at this rate for another 20 years brings the total to 360 MWe, or just slightly less than what is needed to replace retiring capacity over the next 50 years. Again, this growth rate would not result in new reductions in global carbon emissions and would not correspond to any portion of a Pacala/Socolow "stabilization wedge."

Historical Growth in Global Nuclear Capacity

Another way of estimating nuclear power's potential expansion is to extrapolate from the historical performance of the industry. Figure 4 shows the historical *net* operating capacity (after retirements) and the number of nuclear power plants world-wide. Table 2 and Figure 5 display historical gross capacity additions by decade and by country over the past 55 years. As is evident in both figures, the nuclear industry went through several different phases of growth:

- During the initial start-up phase (1956-1970) nuclear capacity increased slowly from zero to approximately 17 GWe of operable capacity or about **1 GWe/year**.
- During the decade 1971-1981, nuclear capacity increased 123 GWe or **12 GWe/year.**
- During its most rapid world-wide growth (1981-1990), **20 GWe/year** of nuclear power was added.
- During the 17-year period from 1991 to 2006, the rate of new capacity slowed significantly at an average rate of **4 GWe/year.**

[13] www.world-nuclear.org/info/inf17.html.

Table 2. World Nuclear Capacity Additions Each Decade by MW

Period	MW
1951-1960	929
1961-1970	15,739
1971-1980	123,386
1981-1990	202,804
1991-2000	44,739
2001-Now	19,268

Source: International Atomic Energy Agency

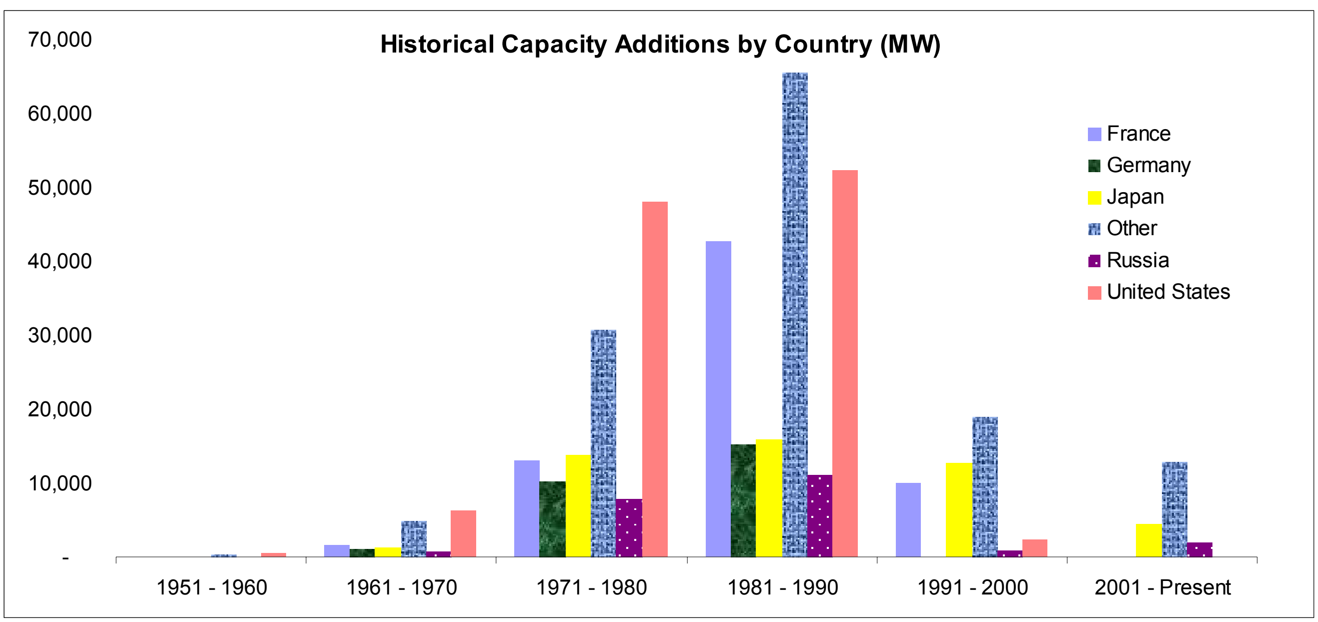
A number of factors suggest that the most aggressive level of historic capacity growth (20 GWe/year) could be achieved or exceeded in the future. For instance, future reactors are expected to have larger output per plant (10-50%), be built with advanced on-site construction methods, make greater use of modularization to reduce on-site labor constraints, rely on advances in information management to provide more efficient data sharing, and have a more competent global supply base.

However, it is not clear how quickly we can increase our industrial and labor force capacity to achieve this rate of construction or how long it can be sustained. Therefore, we also looked at average capacity expansion rate experienced from the initial era and extending through the rapid construction period ending in 1990 (approximately **8.5 GWe/year**). Projected over the next 50 years, this growth rate would add 430 GWe to global capacity or 60 GWe to *net* nuclear capacity—equal to about 9% of a carbon wedge.

Energy Information Administration U.S. Forecast

Although most of the future growth in nuclear capacity is expected to take place in Asia and India, the NJFF group also thought it was important to look at potential growth in the U.S. The EIA's *Annual Energy Outlook 2007* (AEO) presents a series of forecasts for additions to U.S. electricity generating capacity to the year 2030, based on the National Energy Modeling System (NEMS).[14] The EIA reference case forecast of electricity supply estimates an increase in U.S. net nuclear capacity from 100 GWe in 2005 to 112.6 GWe by 2030. This change includes 2.7 gigawatts of capacity expansion at existing plants, 12.5 gigawatts of new plant capacity, and 2.6 gigawatts of retirements of older units. The AEO reference case assumes that current environmental policies are maintained indefinitely, that the Energy Policy Act of 2005 (EPACT 2005) production tax incentive of 1.8 cents per kilowatthour (kWh) is implemented, and that total electricity sales increase by 41% over the period. Despite the growth in new capacity, the

Figure 5. Historical Capacity Additions by Country, 1951-2006



[14]For an overview of NEMS, see http://www.eia.doe.gov/oiaf/aeo/overview/index.html.

nuclear share of total generation falls from 19 percent in 2005 to 15 percent in 2030.[15]

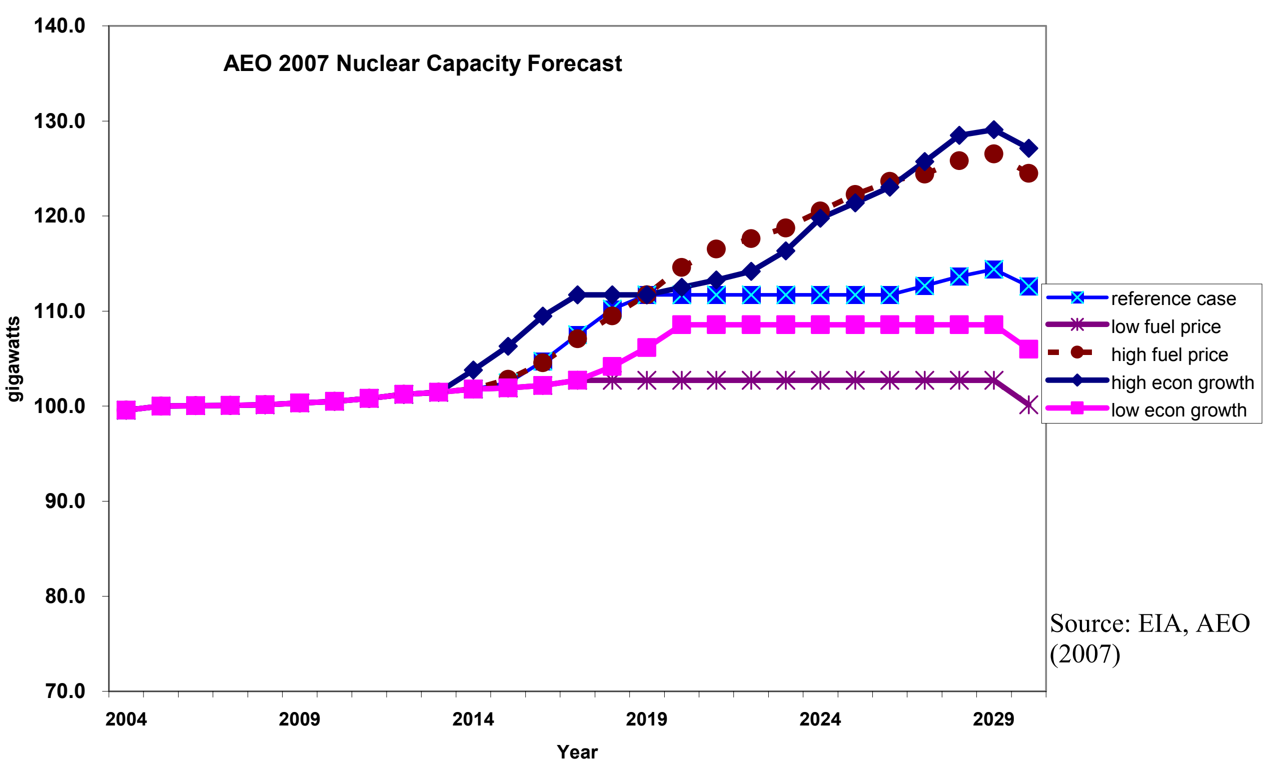
EIA also analyzed several additional scenarios, including low and high economic growth scenarios (resulting in low and high electricity demand) and low and high fossil fuel cost scenarios. As shown in Figure 6, this range of assumptions results in forecasts of growth in nuclear capacity between no new growth and 27 gigawatts. In the low fuel price scenario, natural gas prices are 10 percent lower than in the reference case and new nuclear plants are not considered economical. In the high fuel price and high economic growth cases, respectively, 24 and 27 gigawatts of new nuclear capacity are projected.

Under the reference case, new nuclear capacity additions average 0.5 GWe per year through 2030. If this growth rate continued through 2050, total new capacity in the U.S. could be 25.5 GW or about 25 new reactors by 2056. Under the high economic growth scenario, total new nuclear capacity might be as high as 53 GWe by 2056. This would not be enough new capacity to replace the 99 GWe of existing nuclear capacity that is expected to be retired over the same period.

The NJFF participants agree that to build enough nuclear capacity to achieve the carbon reductions of a Pacala/Socolow wedge (700 net GWe; 1,070 total GWe) would require the industry to return immediately to the most rapid period of growth experienced in the past (1981-90) and sustain this rate of growth for 50 years.

This is more optimistic than indicated by the current announcements reported by WNA for new plants, higher than the average historical growth rate during the first 40 years, and more rapid growth than forecast by EIA for the U.S.

Figure 6. U.S. Nuclear Power Net Capacity, 2004-2030 (Gigawatts)



Source: EIA, AEO (2007)

[15]EIA, *Annual Energy Outlook 2007*. Electricity Demand and Supply and Supporting Data.

Impact of Climate Change Policy on Expansion of Nuclear Power

We know that in a carbon-constrained world, in which either a substantial greenhouse gas (GHG) tax or cap and trade program is implemented, the relative economics of nuclear power (as compared to fossil-fueled power) will improve.

A number of different approaches have been debated or proposed in the U.S., including an economy-wide cap and trade program for GHG emissions, a sector-specific cap and trade approach, and a carbon tax. Each confers different economic advantages to nuclear power compared to fossil generation, and each alternative is more likely to be sustained over time than the "jump-start" subsidies/incentives in EPACT 2005.

Climate change mitigation policies enhance the position of all low-GHG sources of power, including renewables, coal with carbon capture and sequestration, and energy efficiency. It is also important to add that a broadly applied GHG tax or cap and trade program creates GHG saving alternatives in all sectors, not just in electricity. Consequently, nuclear power still will need to compete with other low-GHG and zero-GHG sources including non-electric sector GHG reduction options.

The specifics of the climate policy will affect exactly how much of an advantage nuclear power receives. Most importantly, the more stringent the policy (the greater the reductions required or the higher the tax), the greater the relative advantage bestowed on low-GHG generation. The Clean Air Task Force analyzed the impacts of proposed national cap and trade legislation[16] for nuclear power and concluded that electricity market price increases driven by the GHG cap and trade system would increase the economic viability of both existing and new nuclear plants and many other types of power generation that do not emit CO_2.[17] According to the recent IPCC report,[18] "Given costs relative to other supply options, nuclear power, which accounted for 16% of the electricity supply in 2005, can have an 18% share of the total electricity supply in 2030 at carbon prices up to 50 US$/t$CO_2$-eq, but safety, weapons proliferation and waste remain as constraints [4.2, 4.3, 4.4]."[19]

If a cap and trade system is enacted, all emitting sources will have to factor in the marginal costs (market price) of greenhouse gas emission allowances in their dispatch and investment decisions. Therefore, nuclear power and other low-GHG emitting power (and energy efficiency) will certainly be at an advantage. How GHG allowances are distributed could have an impact on the magnitude of this advantage. For example, if carbon dioxide allowances are auctioned, so that existing GHG emitters must pay the full price of allowances, owners of nuclear power will be in a relatively better position because owners of fossil-fired generation will see reduced profit margins.

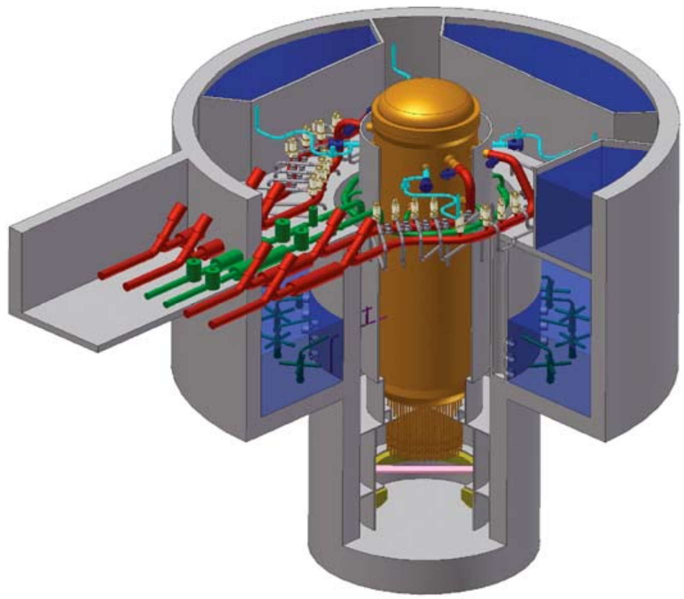
[16]Climate Stewardship Act (CSA) and the Climate Stewardship and Innovation Act (CSIA).
[17]Clean Air Task Force, "Fact Sheet: Impacts of the Climate Stewardship Act (CSA) & the Climate Stewardship and Innovation Act (CSIA) on Nuclear Power" (June 9, 2005).
[18]Intergovernmental Panel on Climate Change, Working Group III contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report; Summary for Policy Makers, May 2007.
[19]This projection is also based on generating costs between 25-75 US$/MWh (section 4.4.2), noting that the relatively low costs developed by life cycle analysis remain controversial. IPCCC Fourth Assessment Report, Chapter 4, pg. 66.

II. Economics of Nuclear Power

Introduction

Nuclear power is one option that can contribute to meeting expected U.S. and global demand for low-carbon electricity. If new nuclear reactors are to make a significant contribution to U.S. and global energy supply, they must be competitive with other alternatives. But competitiveness cannot be gauged entirely by comparing financial numbers. Utilities, vendors, the investment community, regulators, and the public base long-term investment and public policy decisions on many other factors—such as public acceptance, risk, technological change, and environmental impact—that are not amenable to either easy or sophisticated quantification. The influence of these factors varies both within the U.S. and abroad.

In the near term, the balance between competing energy resources can be shifted by various forms of government or private financial support; concerns about supply reliability and diversity; environmental impacts; ease of licensing and siting; or the willingness of utilities, vendors, consumers, investors, or regulators to take or share risks. All these issues need to be evaluated in an environment that is more competitive than when the U.S. last embarked on a major nuclear building program in the 1970s, with the electric utility industry—at least in the U.S.—facing more competitive electricity market pressures. Even in regulated markets, however, utilities must remain competitive, lest industrial customers shift production to other locations or adopt self-generation.



Graphic courtesy GE

We must also ask whether the industry can scale up quickly. A rapidly growing nuclear industry could face a number of challenges throughout the supply chain, including: acquiring reactor pressure vessels and other heavy components; availability of skilled and unskilled labor, reactor personnel, uranium supplies, enrichment services, and waste management capacity; public acceptability of streamlined licensing; and the likely disappearance of financial assistance for first-of-a-kind reactors. Which, if any, of these issues are most likely to affect cost? Answering these questions will lay the groundwork for further discussions of whether the economics of new nuclear power plants are sufficiently robust to be an important contributor to alleviating climate change.

These questions are not easy to answer. The economics of nuclear energy vary substantially across the U.S. and between the U.S. and other countries, based on differently structured electricity markets and different levels of access to alternative technologies. Public acceptability also varies.

While we did not attempt to estimate the costs and risks of other generating technologies, it is clear that utilities and their regulators do. Life-cycle cost[20] per kWh is the best way to compare new nuclear power plants with other energy choices, including energy efficiency. Because the capital and operating cost profiles of energy technologies can vary substantially, economists use discounted cash flows and levelization to achieve a degree of comparability.

To compare nuclear power with resources that avoid some or all transmission and distribution (T&D) costs (e.g., cogeneration or efficiency improvements), it is important but difficult to base the comparison on "delivered" cost. Avoided T&D costs can be significant.[21] The costs of new T&D capacity vary substantially by resource and region, but they are likely to be higher than embedded T&D costs.

While useful, this sort of analysis is mainly a screening tool. Risk may be the most important factor utilities must consider before making major investment decisions. Many take a fairly formal approach to risk analysis, examining issues that are statistically quantifiable (i.e., stochastic), such as demand and spot-market electricity prices; scenario risks, such as new carbon taxes, where numbers can be estimated, but magnitude, timing, and probability are uncertain; and paradigm risks, such as retail competition, market restructuring driven by the Federal Energy Regulatory Commission (FERC), or breakthrough economic improvements in competing generation sources, where specific impacts are very hard to assess. Utilities are also acutely sensitive to investment decisions that can lead to bond deratings, and they face competing internal demands for capital (e.g., for distribution, grid expansion, new metering technologies, etc.).

Deliverability and system integration are also important factors. For many large new resources, the cost and lead time for transmission can be larger and longer than the cost and lead time for the generating plant. After a recent joint meeting between FERC and U.S. Nuclear Regulatory Commission (NRC) officials, NRC Chairman Dale Klein reported that he was surprised that "it may take as long to site, permit, and build a new transmission line for a new plant as to site, license, and build the plant itself."[22]

The goal of evaluating the costs, benefits, and risks is not necessarily to find the lowest cost new resource, but instead to assess what portfolio of demand and supply is most robust in the face of numerous risks, uncertainties, and delivery costs (i.e., transmission), some of which can be quantified and some of which cannot.

Levelized Life-Cycle Cost of Nuclear Power in the Next 10 Years

The NJFF participants reviewed a number of studies that evaluated the life-cycle levelized cost[23] of future nuclear power. We also relied on our own model[24] to analyze the sensitivity of costs to certain factors. We found that a reasonable range for the expected levelized cost of nuclear power is between 8 and 11 cents per kWh delivered to the grid, before transmission and distribution costs, as explained in the following section.

[20]Life-cycle cost is the total cost of construction and operation over the operating life of the unit. Utilities increasingly consider externalities, such as future carbon controls, in estimating these costs.
[21]Based 1996 EIA data, the average price differential between wholesale power prices and average retail rates was 2.75 cents/kWh. The biggest share of that differential is capital recovery and labor costs for maintaining the "wires."
[22]"Supply Chain Could Slow the Path to Construction, Officials Say," *Nucleonics Week* (February 15, 2007).
[23]Levelized life-cycle cost is the total cost of a project from construction to retirement and decommissioning, expressed in present value and then spread evenly over the useful output (kWh) of the product.
[24]Several spreadsheet models were used to calculate nuclear capital cost, fuel-cycle cost, and lifetime levelized cost. The details are documented in Appendix B.

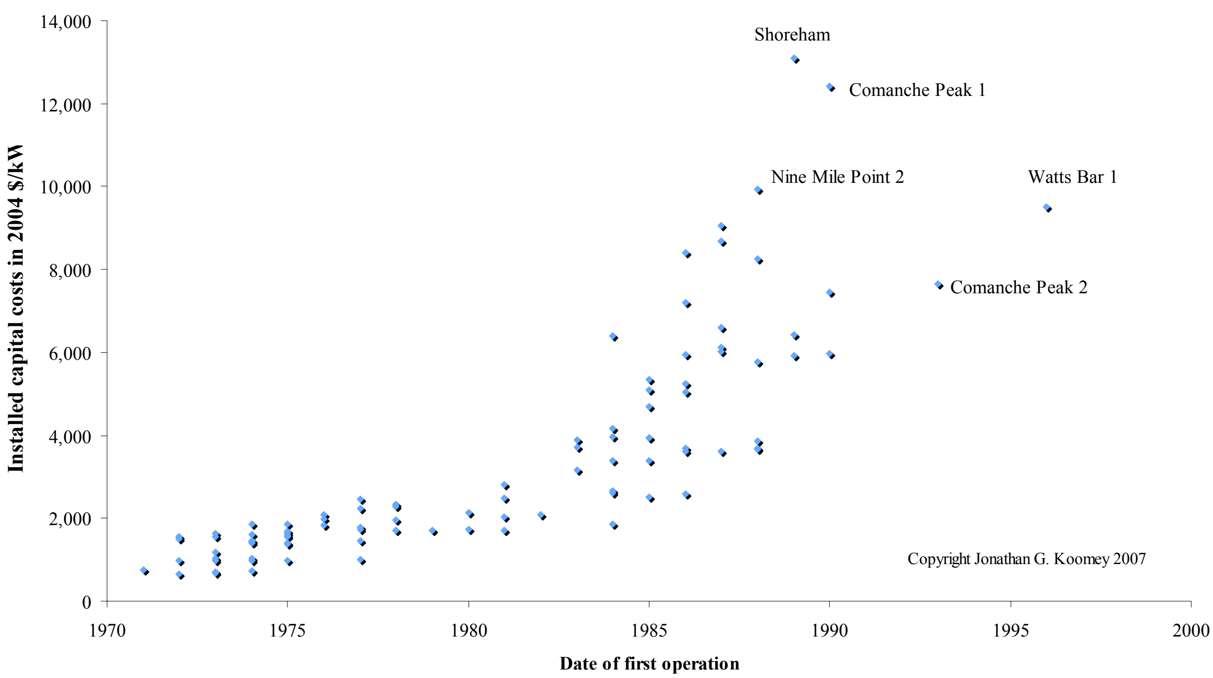
It is difficult to generalize about the cost of future nuclear power plants that will be built around the world. But the cost of building and the ultimate price of electricity from nuclear power are questions that individual utility CEOs, investors, and regulators are already grappling with in order to determine whether new nuclear capacity should be added to the existing generation portfolio to meet growing regional energy demands in a carbon-constrained world. The NJFF used a simplified model to look at the range of costs for constructing and operating new nuclear plants in the U.S. and the implications of a range of assumptions for the cost of nuclear power going forward.

Construction Cost

The most important factor influencing the lifetime cost of a nuclear reactor is capital or construction cost. To project future costs, it would be best to rely on recent U.S. nuclear construction experience, but it has been over a decade since a nuclear plant has been completed in the U.S. The chart below, Figure 7, describes U.S. experience in the period when we last built many nuclear reactors. In the early years, before either a streamlined licensing process or standardized design, many plants entered service at low cost.

As the industry scaled up its building rate and the size of plants, costs increased.[25] At the same time, the U.S. also experienced a decline in the electricity growth rate, high interest and inflation rates, and growing opposition to new nuclear capacity. These factors, coupled with poor project management and regulatory changes to address lessons learned from experience (e.g., new fire protection standards that emerged from the Browns Ferry fire and a variety of changes that resulted from the TMI accident), caused costs for many plants to increase dramatically.

Figure 7: Installed capital costs of U.S. reactors built between 1970 and 2000



Note: Costs include real interest during construction.
Source: Data for graph taken from analysis documented in Koomey, Jonathan, and Nate Hultman. 2007. "A Reactor-Level Analysis of Busbar Costs for U.S nuclear plants, 1970-2005." *Energy Policy* (accepted, conditional on revisions).

[25]Komanoff, *Power Plant Cost Escalation*, Van Nostrand Reinhold, 1982; James Hewlett (EIA), *Energy Journal*, 1986; Martin Zimmerman, *Bell Journal of Economics*, 1982. Hultman, Koomey, Kammen paper, forthcoming in *Environmental Science and Technology*, 2006.

There is no easy way to separate these factors. Stated differently, we cannot provide an analytic answer to the question of whether new, more standardized designs built in an environment of low inflation and a streamlined NRC approval process will look a lot more like Zion ($1,108 per kilowatt [kW]) than Nine Mile Point 2 ($10,769/kW). Capital costs for the U.S. fleet, in thousands of 2004 dollars per kW, including real interest during construction, are shown in Figure 7, by date of initial commercial operation.[26]

The NJFF participants looked at a number of studies with forecasts for the cost of nuclear construction.[27] These studies generally rely on vendor estimates and computer models and assume that the improvements in productivity and construction time achieved in Asia can also be achieved in the U.S. Many vendor estimates are generic and do not reflect site-specific owner's costs, such as land, contingencies, interest during construction, possible construction delays, or transmission integration. Studies and vendor estimates also may not reflect recent run-ups in commodity costs or potential "pinch points" all along the supply chain.

Therefore, we looked at recent construction experience in Asia and Finland.[28] We believe that we have reasonably accurate information on seven units recently completed in South Korea and Japan. Some of that information comes from the 2003 MIT study, "The Future of Nuclear Power." We also considered more recent information from Paul Joskow (a co-author of that report) and from trade publication reports on the Olkiluoto-3 project underway in Finland. All are advanced pressurized- or boiling-water reactors licensable in the U.S. Ultimately, we chose not to rely on the Finnish project cost information, because delays in construction and changing cost estimates made it difficult to determine what the final cost is likely to be.

This is a not a large database, and it is also not altogether comparable given varying accounting practices and the degree of government involvement, among other things. Electricity markets in both countries are less competitive than those in the U.S. and Europe, and utilities generally have experienced streamlined approval processes and few financial uncertainties. Nevertheless, we found this to be the best publicly available data from which to draw inferences about future U.S. construction costs. There have been some innovations that have clearly improved productivity and reduced lead time (e.g., more advanced and standardized design, leaving the containment open during construction, and the use of large cranes and batch concrete plants). The U.S. industry may be able to learn from this ongoing experience. At the same time, we are also following the less successful experience at Olkiluoto-3 in Finland, which now appears from press reports to have suffered from several mistakes early in construction that, to date, have led to an 18-month delay and possible 30- to 60-percent cost increase.[29]

Table 3. Recent Construction Cost Experience
(2002 U.S. Dollars)

Name of Reactor	Construction Cost	Completion Date
Genkai 3	$2,818/kW (overnight)	March 1994
Genkai 4	$2,288/kW (overnight)	July 1997
Onagawa	$2,409/kW (overnight)	January 2002
KK6	$2,020/kW (overnight)	1996
KK7	$1,790/kW (overnight)	1997
Yonggwang 5 & 6	$1,800/kW (overnight)	2004-2005

Note: "Overnight costs" is a convention for expressing the cost of construction as if the plant could be built overnight and therefore does not include escalation or interest costs during construction. **Source:** Joskow, Paul, "Prospects for Nuclear: A US Perspective," Presentation at University of Paris, Dauphine, May 2006.

[26] Koomey and Hultman, submitted to Energy Policy. Data is in real 2004 dollars.
[27] See the references for the most recent studies reviewed.
[28] We did not look at the refurbishments underway at Browns Ferry or completed at Fort Calhoun and Turkey Point because they are not comparable to building an advanced reactor from the ground up.
[29] Areva, "First Half 2006 Financial Results," Press Release on Sept. 27, 2006 and *Nucleonics Week*, "Host of Problems Caused Delays at Olkiluoto-3, Regulators Say," Sept. 13, 2006, pp 3-8. The original contract cost was $2,350/kW, and current overrun estimates yield a final cost as high as $3,750/kW. Neither number includes owner's costs.

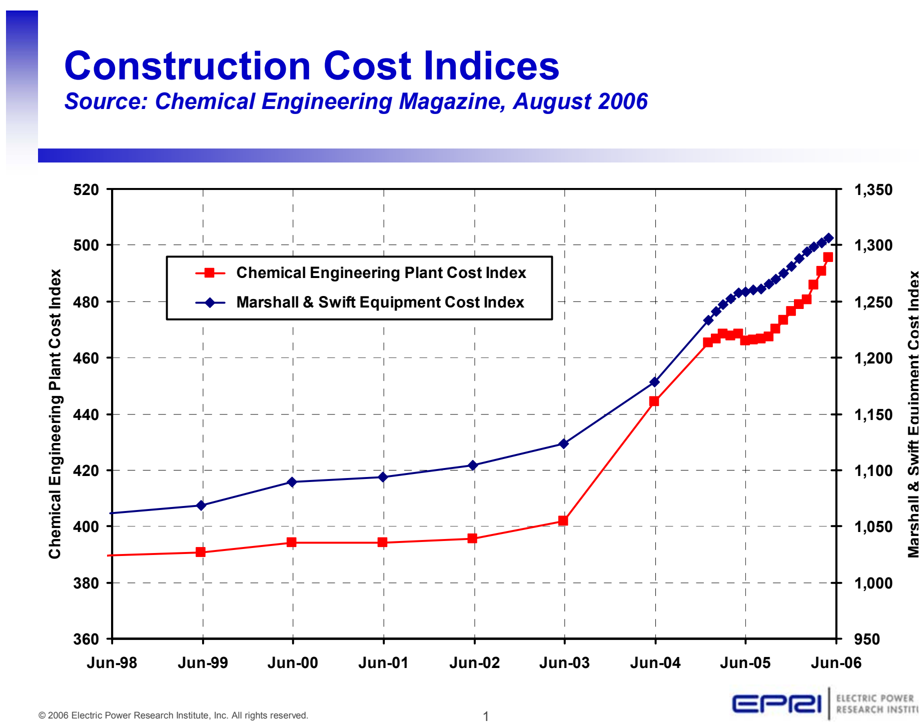
There is obviously a large range in these numbers, and there is no easy way to sort out the underlying causes for differences. The earliest plant was completed in 1994, and the last unit was completed in 2005. Changes in materials and commodities costs, exchange rates, and differences in labor costs are all important factors in cost variation. Some projects may have first-of-a-kind design costs, or instead be loss leaders; some may benefit from government incentives and subsidies.

There are also many market and regulatory differences between the U.S., Finland, South Korea, and Japan, and it is important to analyze in detail how those differences would affect U.S. costs. Siting and permitting requirements, construction lead times, public involvement and acceptability, and other factors vary from country to country. However, quantifying these differences is extremely difficult, because the available data from the different countries are not always transparent on these points, and some assumptions (e.g., public acceptability) do not lend themselves to easy quantification.

The arithmetic average for the first seven units above is approximately $2,150/kW in 2002 dollars, which we used as a starting point for developing a range of construction cost estimates for future plants.

The first step was to escalate 2002 dollars to 2007 dollars.[30] Escalation is not always straightforward, especially when overall inflation and construction industry costs diverge. The Electric Power Research Institute provided us with several different construction industry cost indices. Two of those are shown in Figure 8 below. After several years of trivial cost escalation (0.3% real), the period 2002-2006 was remarkably different (2.2-4.4% real escalation). The most probable explanation involves rising prices for key materials (e.g., steel, concrete, and copper), international competition for these materials (driven heavily by growth in China and India), and tight capacity up and down the supply chain.[31]

Figure 8. Construction Cost Indices



Source: *Chemical Engineering Magazine*, 2006.

[30]This is very close to the estimate of $2,000/kW (2002 dollars) developed in the MIT study.
[31]"Supply Chain Could Slow the Path to Construction, Officials Say," *Nucleonics Week*, February 15, 2007. (Comments by Ray Ganthner, Senior Vice President, Areva; Phillippe Tollini, Commercial Vice President, Sfarsteel; and John Atwell, Principal Vice President, Bechtel.)

To escalate the average cost of the eight units ($2,130/kW) from 2002 to 2007 dollars, we escalated costs at 3.3% real.[32] This yields a construction cost estimate of $2,950/kW in 2007 dollars,[33] not including interest during construction or future real escalation. Our assumptions are based on a 5- to 6-year construction schedule from ground-breaking to commercial operation. While some studies and Japanese experience support the possibility of 4-year construction schedules,[34] the NJFF participants, including industry representatives currently evaluating nuclear construction proposals, agreed that 5 to 6 years is a more realistic construction time over the next 10 years.

To develop a range of final construction costs, we assumed no further real escalation in our low case and continued escalation at the same rate in our high case. We also relied on the basic financial parameters (e.g., debt and equity costs and ratios) of the MIT study. Construction costs (rounded to the nearest hundred, in real 2007 dollars, including interest during construction) based on these assumptions fall in the range of:

- **$3,600/kW (0% real escalation, 5-year construction period) to**
- **$4,000/kW (3.3% real escalation, 6-year construction period)**.

The optimistic assumption of no further real cost escalation is not based on any information we evaluated, and while some vendors and utilities believe it may be achievable, others do not. Neither value includes a cost for transmission expansion, which can be quite significant but will also vary widely from site to site. If we examined the cost of construction for a coal or wind plant, we would expect to find similar cost increases, although the effects on final cost of production vary substantially, based on capacity factor, lead time, financing, and other factors.

First Unit Costs and Scale-Up Issues

Some analyses distinguish between the cost of a "first-of-a-kind" unit and the "Nth" unit, on the theory that vendors need to charge more for a first unit, and costs are reduced through learning and experience. We have chosen not to draw a sharp distinction. First units may include first-of-a-kind design and engineering costs, but they can also be subsidized, either by vendors willing to sell a few loss leaders or by governments willing to provide below-market financing to "prime the pump." For instance, in the U.S. the EPACT 2005 legislation specifies limited incentives for the first plants to help overcome these first-of-a-kind costs. The incentives are limited, however, and when they end, Nth units will have to be competitive on actual costs. Likewise, while vendors may be willing to take risks and losses on one or two early plants, they must recoup their costs and losses through the sale of follow-on units.

It is also possible that costs could actually rise over time rather than decline. As shown in Figure 7, U.S. nuclear plants had higher costs in the late 1970s and early 1980s—nearly an order of magnitude higher than the costs for plants started in the late 1960s.[35] Many factors were responsible for the cost increases: utilities often started construction before they had completed plant design; operating experience and the Three Mile Island accident led to regulatory changes during construction; and designs were not standardized.

[32]This is consistent with the Chemical Engineering Plant Cost Index for 2002-2006, as shown in the Figure 8.
[33]Our estimate is reasonably consistent with the $2,500/kW value used by Paul Joskow in recent presentations.
[34]We also considered the possibility of a 4-year construction period in the low case and a 7-year construction period in the high case. With the assumption of no real escalation during construction, using 4 years has very little effect on capital cost or lifetime levelized cost. A 7-year construction period increases the higher cost case to $4,200/kW.
[35]Joskow, Paul, Conference Call with Keystone NJFF Economics Workgroup, Oct. 2006.

On these three points, the environment may have improved. Advanced light-water reactors may benefit from standard designs, completion and regulatory certification of design before construction, incorporation of safety features that would have required retrofits in the past, and a shorter combined construction and operating license process. Other future outcomes are also possible, driven by more experienced contractors and crews, more competition among suppliers, standard contracts, and greater levels of public and financial acceptance and regulatory support.

But building more units does not necessarily lower the cost. Initially, it can lead to labor and material shortages, the need to find "greenfield" sites, heightened public attention and controversy, litigation, and regulatory uncertainty. Supply-chain pinch points (e.g., labor issues and materials shortages) can also account for significant cost increases.

At a recent nuclear industry conference, some key pinch points were described. Two decades ago, the U.S. had about 400 suppliers and 900 nuclear or N-stamp certificate holders (sub-suppliers) licensed by the American Society of Mechanical Engineers. Today those numbers are 80 and 200.[36]

There is also limited world-wide forging supply for key components, including pressure vessels, steam generators, and pressurizers. There are only two qualified companies in the world that can supply heavy forgings (Japan Steel Works and France's Creusot Forge), and the nuclear industry will be competing with simultaneous forging demands for new refinery equipment. Only Japan Steel Works currently has the capability to manufacture ultra-heavy forgings, above 500 tons; the company's prices have reportedly increased by about 12% in 6 months, with a 30% down payment requirement.[37] About 6 years is needed to procure and manufacture other long lead-time components, including reactor cooling pumps, diesel generators, and control and instrumentation equipment. NRC Chairman Dale Klein noted that heavy reliance on foreign suppliers could require more time for quality control inspections, to make sure substandard materials are not incorporated in U.S. plants.[38] Expansion of domestic production capacity in all these areas is possible but will take time.

Availability of skilled labor is also a question. A recent study prepared for TVA[39] identified a lack of craft labor availability within a 400-mile radius, which forced the adoption of a longer construction schedule. Other sources have pointed to the potential for skilled labor shortages if nuclear construction expands.[40] One can argue that these are good problems to have, as they stimulate investment, new business development, and jobs for the next generation of construction workers. The fact that industry meetings are already focused on addressing this work force and supply chain limitation indicates that, in time, these pinch points can clear; but they can also be daunting for an industry that hopes to grow quickly.

Finally, construction costs are sensitive to actual and perceived risks, as discussed earlier, and how they are allocated among taxpayers, ratepayers, utilities, investors, and vendors. The greater the uncertainty of construction costs, rate recovery, and performance, the higher the cost of capital and overall construction costs will be. The cost of

[36] "Supply Chain Could Slow the Path to Construction, Officials Say," *Nucleonics Week*, February 15, 2007. Comments of Ray Ganthner, Areva.
[37] *Ibid*.
[38] *Ibid*.
[39] "GE, Toshiba, USEC, Bechtel, Global Nuclear Fuel America, ABWR Cost, Schedule, COL at TVA's Bellefonte Site," Aug. 2005, pp. 4.1-2 and 4.1-23.
[40] NPR Marketplace, "A Missing Generation of Nuclear Energy Workers," April 26, 2007. "Vendors Relative Risk Rising in New Nuclear Power Markets," *Nucleonics Week*, January 18, 2007. http://marketplace.publicradio.org/shows/2007/04/26/PM200704265.html.

capital will be lower if the risk of cost recovery shifts more to electricity consumers and/or taxpayers. However, such shifting of costs and risks—unlike reductions in construction time or materials used—does not represent true reductions in costs to society. They are essentially transfers among investors, customers, and taxpayers.

It is also important to point out that there are substantial "cultural" differences throughout the U.S. that affect cost and regulatory issues. Some states and state regulatory commissions may welcome new nuclear construction, for example, by allowing utilities to recover some or all construction work in the rate base.[41] In other states, charging costs to customers before the plant comes into service would not be acceptable or consistent with current law.

Federal loan guarantees and other provisions of EPACT 2005 (NRC licensing delay insurance and production tax credits) can affect overall price. Federal loan guarantees and other financial incentives/subsidies (e.g., NRC licensing delay insurance and production tax credits) included in provisions of EPACT 2005 may serve to reduce some of the risks associated with construction and operation of the first few nuclear units built before the 2020 deadline.[42] Some in the industry view these incentives as significant drivers in the decision-making process. Others have elected to exclude them from their analyses due to the uncertainties surrounding timing, persistence, ultimate allocation amounts, and regulatory treatment.

Loan guarantees are considered highly important by some (typically, merchant generators) but less so by larger regulated utilities.[43] DOE's rules are not final. If loan guarantees ultimately result in a full faith and credit pledge for all the debt issued for a new nuclear power plant (80 percent of total project cost), over its full commercial life, the life-cycle price of power from such a plant could be reduced from 8-11 cents/kWh in our low and high cases to 6-7.5 cents/kWh.[44]

While capital costs are extremely important, they are not the whole story. To convert capital construction costs to life-cycle costs, we need to consider assumptions for:

- capital cost recovery (debt and equity, depreciation, etc.)
- net capital additions during operation (e.g., steam generator replacement)
- capacity factor
- operations and maintenance costs
- decommissioning costs
- long-term waste management
- fuel costs
- operating life.

[41]The Florida Public Service Commission, for example, recently adopted a rule that permits recovery of annual construction costs in current rates following an annual prudence review. Similar proposals are under consideration in North and South Carolina.
[42]Caren Byrd, "Myth or Reality: Is New Nuclear Power a Cost-Effective Option for Meeting Anticipated Future Load? A View from the Investment Community," NARUC Winter Meeting, Feb. 2007. www.naruc.org.
[43]"House Panel Grills Bodman on Nuclear Loan Guarantees," *Nucleonics Week*, March 8, 2007. DOE is asking for $9 billion in loan authority in its fiscal 2008 budget request.
[44]We distinguish here between price and cost to emphasize that government subsidies do not change costs; the difference is allocated to taxpayers.

Capital Cost Recovery

The MIT study assumed a merchant developer (i.e., non-utility operator) building new plants in a fairly competitive market structure. At the time, it was assumed that such a builder could use 50% debt financed at 8% interest and 50% equity at a premium 15% return. In the past few years, Wall Street has become significantly less comfortable with the merchant plant model, and even very strong non-utility generators building plants in competitive wholesale markets now need 65% to 70% equity to access the bond market.

Our high case retains the MIT study assumptions (50% debt at 8%, 50% equity at 15%) as a reasonable average for utilities building in both restructured and unrestructured wholesale markets. Our low case includes no equity risk premium (12% nominal return) for a nuclear investment. Reactors financed in highly competitive wholesale markets are likely to cost builders 10% to 15% more than traditional utility finance, because some risks are shifted—at least in the short run—from utility customers to investors. Federal loan guarantees can make a significant difference, but utilities that are taking this sort of decision to boards of directors do the arithmetic both with and without federal subsidies.

Capacity Factor: Low End, 75%; High End, 90%

Average annual U.S. nuclear capacity factors have increased from below 60% during most of the 1980s to nearly 90% in the post-2000 period.[45] This increase in capacity factor has a significant effect on the kWh costs of a nuclear plant. For the most part, we have assumed a range of estimates that reflects best experience with current plants at the high end and possible start-up problems, but far better than the 1980s experience at the low end. Depending on other assumptions, this range of capacity factors has a 5% to 10% effect on the cost of nuclear power at the point of generation.

Total Construction Costs for Capital Additions: Low End, 25%; High End, 50%

The current U.S. fleet average for capital additions over the life of the unit is about 50% of original construction costs.[46] There are a number of issues that are tough to disentangle. Some early plants built at low capital costs had higher than average capital additions to improve safety after the Browns Ferry fire, TMI-2 accident, and other experiences.

It may be fair to assume that new advanced designs with fewer components and greater inherent safety will have fewer lifetime capital additions than the current U.S. fleet. If we use the current fleet average in the high case and one-half the fleet average in the low case, the effect on cost of generation ranges from 2% to 5%. We have treated these costs as being "expensed" as operating costs, rather than being capitalized for the remaining life of the plant.

Decommissioning

Decommissioning costs are based on the cost of a sinking fund to recover about $500 million in 2007 dollars and are treated as an O&M expense. As with the treatment of capital additions, this simplifies but does not seriously change our results.

Operations and Maintenance

Vendors have suggested that advanced-design reactors will have lower operations and maintenance (O&M) costs than historically, because there are fewer moving parts and smaller plant staffing levels. One report suggests that O&M cost savings may be about 15%, which is reflected in the low end of the range of O&M costs in the NJFF model.[47] The high end of the O&M cost range is based on historical cost trends. Increased security costs might also be considered if information about expected security standards and implementation costs can be found.

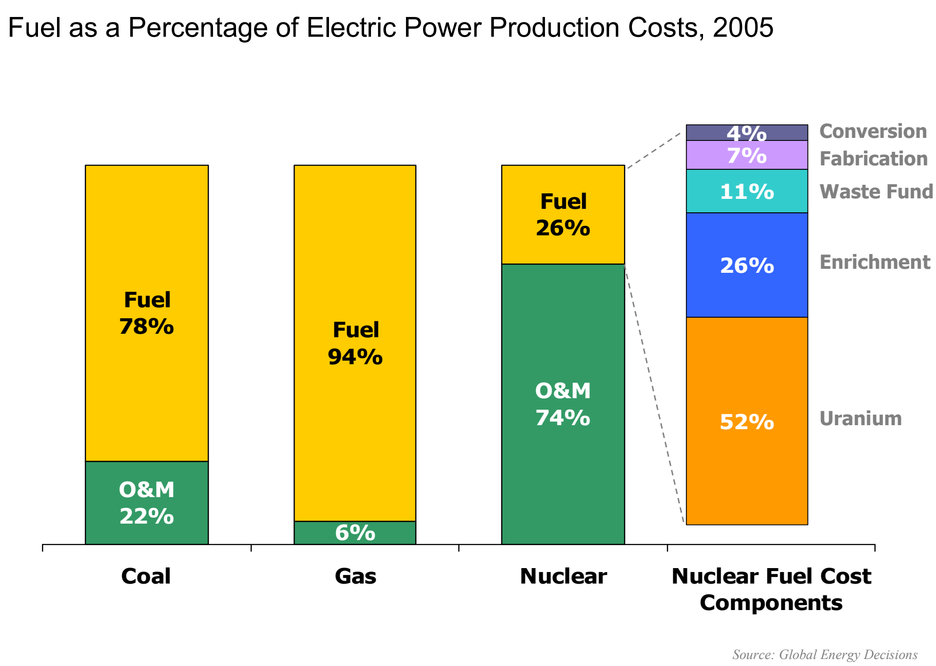
[45] MIT, "The Future of Nuclear Power," 2003; and Joskow, "Future Prospects for Nuclear-A US Perspective," Presentation at University of Paris, Dauphine, May 2006.
[46] Joskow, Paul, Conference Call with Keystone NJFF Economics Workgroup, Oct. 2006.
[47] U.S. DOE, "Study of Construction Technologies and Schedules, O&M Staffing and Cost, Decommissioning Costs and Funding Requirements for Advanced Reactor Designs," May 2004.

Fuel Costs

Nuclear fuel costs have many components—uranium mining and milling, conversion to UF6, enrichment, reconversion, fuel fabrication, shipping costs, interest costs on fuel in inventory, and spent fuel management and disposition. Historically, all these costs add up to less than 10% of the total cost of producing electricity from a nuclear reactor or approximately 25% of the variable costs. (See Figure 9, below.) The two most important components of delivered fuel price are uranium and enrichment prices. In our analysis, nuclear fuel cycle costs in the low case are based on $160/kg uranium (about $72/lb), which is significantly below current spot prices, and enrichment prices of $200/kg SWU. In the high case, nuclear fuel cycle costs are based on $265/kg uranium (about $120/lb), which is the May 2007 spot market price. Enrichment prices are estimated to be $250/kg SWU. Other assumptions (e.g., for conversion, fuel fabrication, and waste storage and disposal) are equivalent in both cases. Neither escalates beyond those levels over time; however, as discussed below, there is considerable uncertainty about future uranium fuel costs.

Uranium prices have been volatile over the past 30 years. Although real uranium spot prices declined by 74% between 1970 and 2000, this included a sharp spike in prices in the early 70s. In the past 7 years, prices have increased by a factor of 9 in real terms (see Figure 10). Further price increases appear probable in the near term, even without substantial expansion of the world-wide nuclear fleet. Enrichment prices have increased by about 40% in the past 2 years, and some believe that substantial further increases are probable.

Figure 9. Fuel as a Percentage of Electric Power Production Costs, 2005



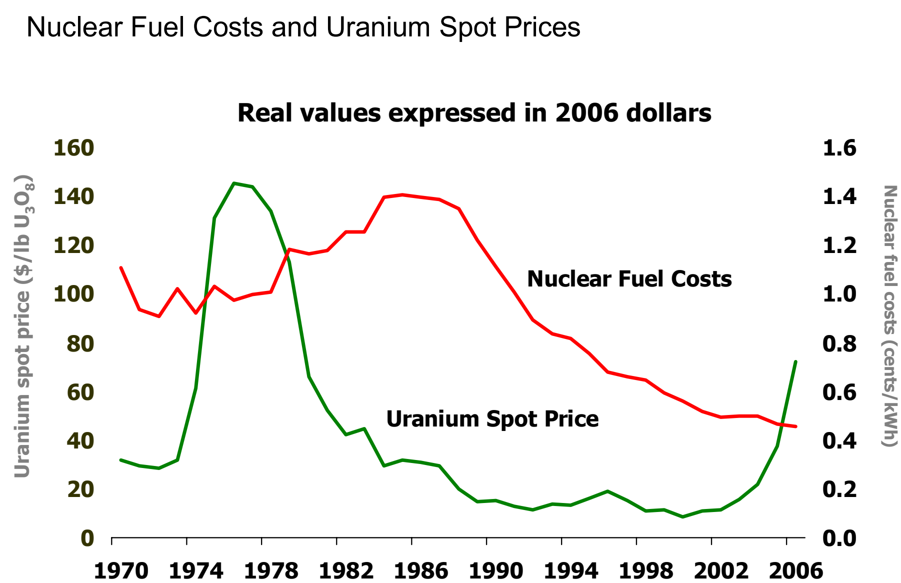
Source: Global Energy Decisions

There is plenty of uranium in the ground; the problem is mining and enrichment capacity. Uranium fuel is for the most part a thinly traded market, but the price rise has also been steady and rapid (Figure 10)—to $120/lb on the spot market in May 2007. The reasons for rising spot-market prices are complex, but recent analyses by Neff (MIT) and Combs (UX) suggest that low production, dampened investment related to long-term contracts, and lagging expansion of enrichment capacity are likely to lead to continued higher prices into the future.

For at least the past 20 years, natural uranium production from mines has been supplemented by "secondary supplies"—first, by surplus inventories from cancelled or shut-down units (1980s-1990s), then by purchase of cheap surplus Russian uranium and privatization of U.S. enrichment capacity and associated uranium stockpiles (mid-1990s), and finally by the use of highly enriched uranium from surplus Russian nuclear weapons (1998-2013). As a consequence, non-Russian uranium production is now about 60 % of current uranium demand.[48]

Nuclear plant owners have been buffered from these recent rising prices, but this may ultimately dampen investment in new production. Utilities typically acquire uranium under long-term contracts, and they did so when prices were low and price ceilings could be negotiated. The same practice applies to enrichment services. As a result, reported nuclear fuel costs do not track spot market prices. There is also a substantial lag (3 to 5 years) between the time utilities pay for uranium and enrichment services and the time they recover the costs in current rates. Long-term contracts can moderate short-term price fluctuations. Most current long-term contracts expire by 2012, and secondary supplies decline rapidly during that period. The price ceilings in long-term contracts also mean that those parties that might pursue new mines or enrichment plants have not benefited substantially from price signals in the spot market.

Figure 10. Nuclear Fuel Costs and Uranium Spot Prices



Note: In 2006, most U.S. utility had long-term contracts in place and therefore did not pay spot market prices for uranium. Consequently, fuel prices in 2006 reflect uranium prices in 2002 ($15/lb).
Sources: TradeTech, Utility Data Institute, FERC/Electricity Utility Cost Group, and Global Energy Decisions.

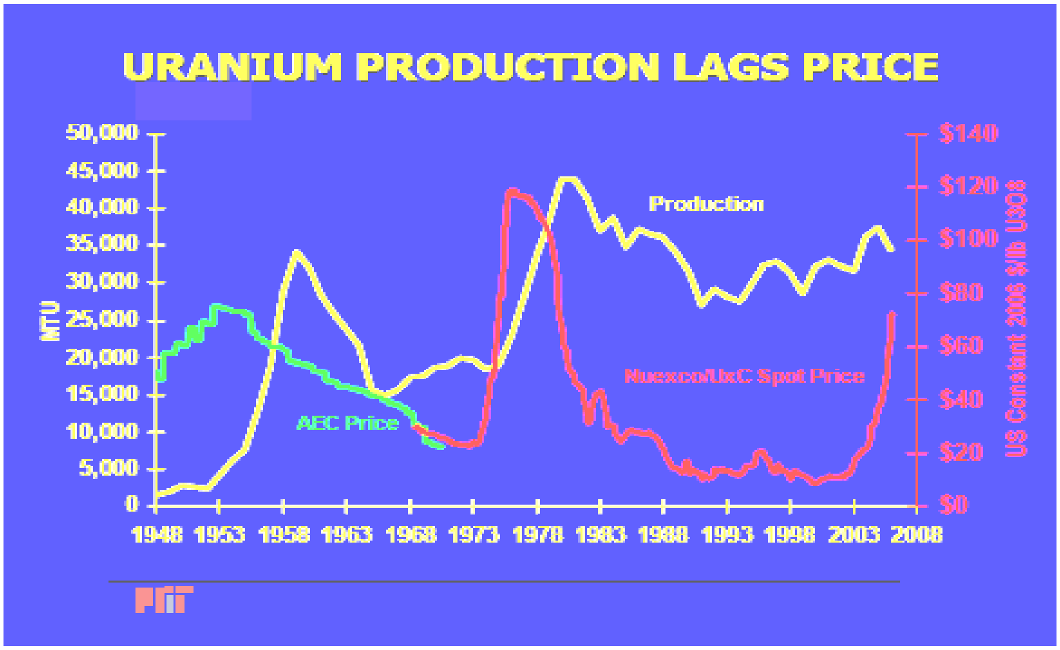
[48] Dr Thomas Neff, Center for International Studies, MIT, "Dynamic Relationships Between Uranium and SWU Prices: A New Equilibrium, Building the Nuclear Future: Challenges and Opportunities."

Nonetheless, new mining and enrichment capacity is being added. The question is whether new capacity can keep up with declining secondary supplies or growing demand. As indicated in Figure 11 below, there has been a time lag historically between when development is completed and when production occurs. Ultimately, higher prices stimulate further primary uranium production, which reduces costs; however, it is very difficult to guess when new capacity will catch up with existing or future demand, and uranium fuel prices will stabilize.

Finally, with higher future uranium prices, pressure on enrichment capacity also increases. At higher prices, there is pressure to use uranium more efficiently, meaning that utilities may prefer enrichment plants to operate at a lower "tails assay." That can be done, but it decreases the production of enriched uranium—perhaps by 25%.

At current uranium prices, nuclear fuel costs for both new reactors and the existing fleet would increase by a factor of roughly 2.5 from current levels. With substantial growth in nuclear capacity, these problems may get worse before they get better.

Figure 11. Uranium Production



Source: Thomas L. Neff, Center for International Studies, MIT, "Uranium and Enrichment Supply: Supply, Demand and Price Outlook;" Presentation Winter 2006.

Spent Nuclear Fuel Disposal Costs

The U.S. government currently collects a spent fuel disposal fee of 1 mill per kWh of nuclear power sold. Although we did not analyze whether the current level of revenue collection will be sufficient to cover a second repository, higher estimates of waste disposal costs would affect nuclear power production costs by less than 1%. (See discussion of spent fuel management and disposal in Chapter III.)

Externalities

Although external costs and benefits can be calculated for all fuels and generating technologies, we have not included external costs in this analysis. Key external costs include uranium mine remediation and accident risk.

Costs of Once-Through and Closed Fuel Cycles

In the past, price increases for nuclear fuel have triggered discussions about the wisdom of reprocessing to take advantage of the U-235 and Pu-239 remaining in spent fuel. Mixed oxide (MOX) fuel is a blend of plutonium and depleted uranium that can be used to supplement low-enriched uranium (LEU) fuel in light-water reactors.[49]

The 2003 MIT study compared these options, with much lower uranium prices than we see today ($30/kg or $13.60/lb). Their estimates were $0.005/kWh for an open cycle and $0.022/kWh for a closed cycle—a factor of more than 4. We have used the same simple methodology found in that report but with updated fuel-cycle prices.

At today's prices, reprocessing still appears to be more expensive than using natural uranium in a once-through fuel cycle, although the margin has shrunk since the MIT report was released in 2003. A utility buying uranium and enrichment services at today's spot market prices would pay about 1.4 cents/kWh for fuel, including disposal.[50] Table 4 compares the cost of a once-through fuel cycle at spot market prices of about $250/kg (or $113/lb) with a closed cycle. The reprocessing cost estimate is probably conservative, based on estimated completion costs (more than $20 billion) for the Rokkasho (Japan) facility with a capacity of 800 metric tons per year.

It is also important to emphasize that reprocessing is itself highly capital intensive, and it would therefore not be easy to finance or justify construction on the basis of what appears to be a supply-demand imbalance rather than a true physical shortage.[51]

Table 4. Comparison of Costs With Once-Through and Closed Fuel Cycles

Process Step	Kg SWU*	$/kg SWU	Tons/yr	Direct $	Indirect $
Ore	9.79	250	4.25	2,448	1,040
UF6	9.79	11	4.25	108	46
Enrichment	6.47	140	3.25	906	294
Fabrication	1.00	300	2.75	300	83
Storage	1.00	400	-2.25	400	-90
				4161	1,373
Total	**$0.014/ kWh**				**5,534**
Reprocess	5.26	1,500	4.25	7,890	3,353
Storage	5.26	400	3.25	2,104	684
MOX fabrication	1.00	1,500	3.25	1,500	488
MOX storage	1.00	400	-2.25	400	-90
SF credit	5.26	-400	4.25	-2,104	-894
				9,790	3,540
Total	**$0.034/ kWh**				**13,330**

Source: NJFF calculations based on the same approach used in MIT study.
*A separative work unit (SWU) is a unit of measurement of the effort needed to separate the U-235 and U-238 atoms in natural uranium in order to create a final product that is richer in U-235 atoms.

[49]Most U.S. reactors were not designed to handle more than 25% MOX; Combustion Engineering System 80+ pressurized-water reactors were designed to handle full cores.
[50]This value is between our low and high *future* cost cases.
[51]Dr Thomas Neff, Center for International Studies, MIT, "Dynamic Relationships Between Uranium and SWU Prices: A New Equilibrium, Building the Nuclear Future: Challenges and Opportunities."

Summary of Construction Cost Estimates

There is a 30% difference in capital cost between our low and high estimates. When we add the factors considered above, the difference in levelized cost per kWh at the point of generation grows from roughly 8 cents per kWh to 11 cents per kWh in real dollars (Table 5).[52]

Table 5. Summary of Cost Assumptions

Main Assumptions (2007$)	Low Case	High Case
Overnight Cost	$2,950/kW	$2,950/kW
Plant Life	40 years	30 years
Capital Cost, Including Interest	$3,600/kW	$4,000/kW
Capacity Factor	90%	75 %
Financial	8% debt, 12% equity, 50/50 ratio	8% debt, 15% equity, 50/50 ratio
Depreciation	15-year accelerated	15-year accelerated
Fixed O&M	$100/kW/year	$120/kW/year
Variable O&M	5 mills/kWh	5 mill/kWh
Fuel	1.2 cents/kWh	1.7 cent/kWh
Grid Integration	$20/kW/year	$20/kW/year

Table 6. Summary of Levelized Cost
(Cents/kWh)

Cost Category	Low Case	High Case
Capital Costs	4.6	6.2
Fuel	1.3	1.7
Fixed O&M	1.9	2.7
Variable O&M	0.5	0.5
Total (Levelized Cents/kWh)	8.3	11.1

In both cases, we have used accelerated depreciation for calculating federal income taxes, which is proper from the perspective of utility finance. For ratemaking purposes, however, most commissions use straight-line depreciation for determining rates.

A rapidly growing nuclear industry can be expected to encounter more cost challenges in skilled labor and materials, uranium and enrichment services, and possibly public and regulatory support. A more slowly growing industry should face fewer challenges in these areas.

[52]For calculational ease, administrative and general (A&G) costs, decommissioning, and net capital additions are treated as O&M expenditures. Fuel costs include all fuel cycle steps, including payments for spent fuel disposal and interest on uranium in inventory.

Other Factors Affecting Risk

Factors other than cost can have an acute impact on the potential risk of a nuclear investment, but they cannot be easily quantified. In addition to capital cost uncertainties, an analyst from Morgan Stanley[53] stated that the major issues of concern and possible risk to investors were:

- untested NRC licensing process and regulatory requirements
- public perception
- spent fuel storage and disposal
- assurance that costs will be passed on to customers when incurred.

Others might add the risk of a serious accident or sabotage of a nuclear facility anywhere in the world, or diversion of materials for weapons production.

In addition to the regulatory risks discussed earlier, the threat of unmitigated regulatory risk from the NRC licensing process is also a concern to utilities and investors. The new licensing process is untested and hence unpredictable, and therefore there is some doubt about developers' ability to meet timelines and cost estimates. This concern is based on past experience, when plants were often delayed after approval had been given and even after construction had begun. Significant unanticipated delays and challenges caused costs to escalate and projects to be abandoned. Wall Street agrees that an uncertain regulatory environment will hamper private investment in new plant development. While delay insurance[54] can mitigate the risk of clearly NRC-driven delays, the coverage provided in EPACT 2005 is limited to six reactors, and potential delays may not be easily attributable to either the NRC or the utility.

Public perception of nuclear power varies substantially across the U.S. and could make construction of a new reactor, particularly at a "greenfield" site in the Northeast or West, both challenging and unpredictable. The same cultural issues would come into play with regard to spent fuel storage, given the current status of the Yucca Mountain project and its statutory volume limit.

Market Structure and Regulatory Oversight

The NJFF group concludes that while some companies have announced their intentions to build "merchant" nuclear power plants, it will be easier to finance nuclear power in states where the costs are included in the rate base with a regulated return on equity.

The type of market structure and regulatory oversight will have an effect on cost recovery, the allocation of risks, and the price and economic outlook for new nuclear power plants. Electricity markets and regulatory oversight have evolved substantially over several decades and continue to do so. All regions of the country have more competitive markets than they did during the late 1970s, when the construction of most existing reactors was started; however, the nature and degree of competition vary. In some regions, utilities have sold much of their generation to entities not subject to state rate regulation; and in some states, retail sales are also open to competition. However, many regions (including the Southeast and most of the West) have retained a more traditional cost-of-service integrated utility model.

In the 2003 MIT study, the authors assumed that most new nuclear generation would be built as "merchant" plants in fully competitive electricity markets.[55] This has two implications for the cost and risks of building new nuclear power plants.

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[53] Caren Byrd, "Myth or Reality: Is New Nuclear Power a Cost-Effective Option for Meeting Anticipated Future Load? A View from the Investment Community," NARUC Winter Meeting, Feb. 2007. www.naruc.org.

[54] The risk insurance authorized in 2006 covers costs associated with federal regulatory or litigation related delays—that are no fault of the company—that stall the startup of these plants. Up to $500 million in coverage is available for the initial two plants for which construction is started, and up to $250 million is available for the next four plants.

[55] MIT, *The Future of Nuclear Power*, 2003, p. 37.

First, higher investor risk will translate into higher overall cost of capital. As noted by the MIT authors, a competitive generation market places the risk of construction costs, length of construction, permitting, and performance uncertainties of new plants squarely on the investors. As a result, the capital cost structure and cost of debt and equity will reflect this higher risk profile.

Second, financial institutions typically require some assurance that there will be a market for the power through a long-term contract or an obligation to meet jurisdictional load. In current competitive market structures, independent generators are rarely, if ever, able to negotiate contracts much longer than 3 to 5 years, and even utilities in more traditional regulated environments are making shorter commitments for the sale and purchase of power. Finally, the level and timing of cost recovery in competitive markets is more uncertain, particularly where some or all power is sold in the wholesale spot market. Federal government loan guarantees could alleviate some of the increased investor risks. On balance, however, financing a nuclear power plant without traditional ratebase recovery could be difficult.

During the Joint Fact Finding, we heard from Constellation Energy President, Michael Wallace, that the company is seriously considering building "merchant" nuclear plants and has announced its intention to begin site planning for one in the state of Maryland.[56] In addition, Amarillo Power, Exelon, NRG, and TXU have also announced plans to develop and submit combined operating applications for nuclear plants in Texas as merchant units. Nevertheless, most companies that have sought early site approval or Combined Construction and Operating Licenses are planning to build in the Southeast, where more traditional cost-of service regulatory oversight prevails.[57] For a number of reasons, we concluded that it may be more difficult to finance new nuclear power plants outside a traditional cost-of-service regulatory framework. We also recognize, however, that developers may face regulatory challenges in cost-of-service states.

The power plant cost overruns of the 1970s and 80s have led to a number of changes in the traditional cost-of-service framework that make it a more rigorous environment for new capital-intensive generation.

In the 1970s, procurement decisions typically began when the utility sought a "certificate of public convenience and necessity" from state regulators. Once such a certificate was issued, the utility had some expectation of cost recovery, provided that subsequent investments were prudently incurred. Now, many states require utilities to complete integrated resource plans, run periodic bidding processes, or both, to determine the cost of new supply and demand resources, whether built by the utility or by an independent party.[58]

Such a procurement process can also form the basis for recovering costs in rates, thereby protecting customers from cost overruns on any particular project. In addition to all-source procurements, other types of competitive procurement have been developed, such as bidding systems targeted to particular resources, particularly renewable energy (encouraged by state renewable portfolio standards) and investments in energy efficiency.[59]

Achieving the lowest long-term cost for power is typically the most important factor that regulators consider; however, they have increasingly placed value on achieving other goals, such as fuel diversity, maintaining reliability, minimizing the impact of the resource on rates or customers' bills, and the ability of the project owner to finance and complete the project. Another important factor is how the risks will be borne by ratepayers and shareholders.

[56] Energy Daily, "Unistar Nuclear Identifies Constellation's Calvert Cliffs as the Site for First Potential New NPP," May 02, 2007.
[57] NEI "New Nuclear Plant Status," http://www.nei.org/index.asp?catnum=2&catid=344.
[58] GA PSC to Hold Hearings on Georgia Power & Light's Integrated Resource Plan, May 10, 2007. http://www.psc.state.ga.us/newsinfo/releases/2007/20070510.pdf.
[59] These approaches are common throughout the United States, in both restructured and unrestructured markets.

In California, legislation prohibits construction of new nuclear plants until there is a solution to the problem of long-term storage of nuclear waste. Eleven other states have adopted similar conditions on nuclear construction.[60] Environmental considerations, such as the impact of a reactor's thermal discharges, may be considered by state or federal environmental regulators but typically are not factors in the economic regulators' review.

Although we cannot predict how regulators will treat requests for cost recovery of new utility-owned nuclear generation, it is likely that they will be looking for ways to balance the risks of utility shareholders and electricity ratepayers better than was done in the past. A number of circumstances have undermined initial regulatory approvals in the past and could do so again, including changes in design and safety requirements, mistakes in management of the construction or operation of the plant, longer-than-expected outages, or changes in demand for electricity. All these factors have led to actual costs that have exceeded initial estimates and, in some cases, higher costs and prices for ratepayers.

To internalize the lessons of the past, state regulators may take a number of steps, such as imposing cost caps as a condition of approval, performance-based rate recovery, or more rigorous analysis of the portfolio of alternatives before approval.[61] Utilities operating under such caps may try to impose them on vendors through contract clauses. The caps are unlikely to apply to all categories of cost or risk (e.g., they may have labor and material escalators or exclusions for events that are beyond vendor or utility control, such as strikes or weather). Efforts to impose cost caps on vendors often lead to protracted litigation (and additional costs) over whether the owner or the vendor was responsible for delays or cost escalation. In short, regulators can attempt to manage and control risk at the beginning of a project, but the risks may fall quite differently in the end.

States can take further action to facilitate new nuclear investment. For example, they can allow utilities to recover construction work in progress in current rates, rather than waiting for plant completion and prudence review. The advantages to utilities and investors are considerable, easing cash flow, accelerating capital recovery, and reducing the risk that the owner cannot complete the plant. The challenge is that this approach generally increases rates in the short term and could increase rates in the long term (e.g., in the case of a project cancelled during construction).

Nuclear power developers receive funding from both equity and credit markets. The lower the risks for investors and creditors, the lower the cost of (and return to) capital. In order to look favorably on financing new nuclear construction, investors and creditors must perceive that the return expected is commensurate with the risk.

In addition to market structure and regulatory environment, a number of other factors influence the real and perceived risks for nuclear plant investors, including:

- the level and structure of required capital investment
- the record of experience of the industry generally, and an applicant developer's specific history on the cost and performance of nuclear power
- the cost and performance of alternative energy resources
- the expectations about energy demand and the availability of long-term contracts for the power
- government policies and regulatory decisions, such as government decisions that place high fixed costs at risk through policy changes (such as electricity restructuring)
- government supports that help mitigate risk.

According to a recent briefing by a Fitch analyst, the storage of spent nuclear fuel is not considered to be a major financial risk factor: "Although a permanent solution for the storage of spent nuclear

[60]Memo to: Wisconsin Legislative Council, Members of the Special Committee on Nuclear Power, Nov. 29, 2006.

[61]In New York, the Nine Mile Point 2 reactor was subject to a cost cap by regulators. Limerick Unit 2 also faced a cost cap imposed by Pennsylvania regulators.

fuel remains unresolved, onsite storage has provided an interim solution at a manageable cost."[62] On the other hand, the absence of long-term waste storage has been noted by companies such as Exelon as a factor in any decision to build a new nuclear unit.[63]

Performance risk is also very important. "The potential for an extended unplanned outage is a primary credit risk of nuclear ownership," according to Fitch.[64] The NRC has the authority to shut down a reactor, although it has rarely done so. Still, the potential for an extended outage worries investors. While Fitch believes that the probability of an extended shutdown is low today, it argues that the financial consequences could be quite severe, requiring nuclear plant owners to have greater liquidity and use more conservative financial criteria than companies without nuclear power.

Investors will look more favorably on nuclear power to the extent that ***government policies*** protect them from particular risks. Current incentives in EPACT 2005 include federal loan guarantees (loan guarantees are for all emission-free resources, including renewable generation and coal facilities with carbon sequestration); a production tax credit for up to 6,000 MW (for 8 years); insurance against NRC licensing delays; and sharing of application costs. Continuation of key past financial assistance includes Price-Anderson limited liability insurance and accelerated depreciation. These policies could encourage those already seriously considering the option of constructing new reactors to move forward more expeditiously to take advantage of the incentives.

Most utilities and investors are considering the relative economics of building new nuclear plants with and without federal financial supports, in part because of uncertainty about how the policies will be implemented. Some potential builders have described these measures as essential for moving forward, while others have not.[65] In our examination of the economics of expanding nuclear power, we did not take into account the current subsidies since their intent is to kick-start the industry, not maintain it over the long term. However, as noted earlier, incentives/subsidies such as the proposed loan guarantees in EPACT 2005 could reduce ratepayer costs of the first few U.S. nuclear reactors substantially.

Environmental policies also can mitigate or increase the risks for investors. As discussed earlier, climate change policy could enhance the competitiveness of nuclear power relative to fossil fuel generation.

The ***risk of a major accident*** at a nuclear facility is not seen as a significant risk by investors today, in large part because of the Price-Anderson Nuclear Industries Indemnity Act, which was first passed in 1957 and has since been renewed several times. Price-Anderson establishes a no-fault insurance type of system, in which the first $10 billion of damage would be covered by the industry, and the remaining costs would be covered by the federal government. It covers all non-military nuclear facilities constructed in the U.S. before 2026 against off-site liability claims arising from nuclear incidents, while still ensuring compensation coverage for the general public. At the time of the Act's passage (and subsequently) it was evidently considered necessary for production of nuclear power, because utilities are unwilling to accept, or insurance companies are unwilling to offer, insurance without limitations on liability.

Finally, investors are concerned that the ***price of alternative fuels*** could fall, potentially making the investment in nuclear power less economically advantageous.

We agreed that these issues are mostly about risk allocation among investors, consumers, and taxpayers, but they may affect the cost of capital and the price of nuclear generation to the consumer.

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[62]Fitch, "U.S. Nuclear Power: Credit Implications," Nov. 2006.
[63]The Yucca Mountain Project is the "linchpin" to solving the waste problem and building new plants, John Rowe, Exelon CEO told *U.S. News and World Report* for an Oct. 22, 2006, article, "Mired in Yucca Muck."
[64]Fitch, 2006.
[65]Michael Wallace, Constellation President, Presentation at NJFF, November 2007. Statements of Southern Company and Florida Power & Light, JFF participants, 2007.

III. Safety and Security of Nuclear Power

This chapter addresses the safety and security of existing and proposed commercial nuclear power reactors and related fuel cycle facilities, with emphasis on the U.S. nuclear power situation. It does not address safety or security issues associated with other elements of the nuclear fuel cycle, including uranium mining and milling, transportation, and nuclear fuel fabrication or reprocessing.

For both safety and security, the central questions relate to the probability and potential consequences associated with release of substantial quantities of radioactivity from a nuclear power reactor or from spent nuclear fuel at the reactor site. Reactor design features, including required safety equipment and emergency-response measures, as well as numerous other regulatory requirements, are intended to prevent radiological releases from occurring accidentally during power-plant operations, and to mitigate the consequences from a possible—but very low probability—event. Security measures are intended to prevent on-site attacks and sabotage that could result in substantial radiological releases. Whether these design features and regulatory requirements are sufficient in both theory and practice have been the subject of debate and controversy for decades.

The Probability of a Severe Nuclear Power Plant Accident

In more than 10,000 cumulative reactor-years of operations worldwide,[66] there have been two major accidents involving nuclear-power reactors—at Three Mile Island (TMI-2) in the U.S. (1979) and at Chernobyl in the U.S.S.R. (1986)—as well as several smaller events.[67] In the U.S. there have been no immediate radiological injuries or deaths among the public attributable to accidents involving commercial nuclear power reactors, and the number of public injuries or deaths from latent cancers resulting from such accidents is at most a few.

Since the TMI-2 accident in 1979, numerous improvements[68] have been made to plant safety equipment, procedures, and training in U.S. reactor operations. Still, a severe accident at a nuclear power plant is both physically and statistically possible for existing plants, for plant designs under consideration for construction in the near term, and for advanced designs—the Generation IV reactors.

[66]IAEA PRIS Data Base, www.iaea.org/programmes/a2/index.html.
[67]As a recent example, Davis-Besse was a major near miss (USA, 2002), revealing problems with both industry and NRC inspections and oversight (see Davis-Besse side-bar). Other nuclear power plants that suffered serious accidents include Fermi I in Michigan and Browns Ferry in Alabama.
[68]See NUREG 0660 and NUREG 0737 for examples.

How Safe Are Today's Reactors?

According to the U.S. Nuclear Regulatory Commission (NRC) assessment, U.S. nuclear power plants meet the NRC's safety goal. Some NJFF participants agree with this assessment. Others believe that the methodology used cannot adequately demonstrate that the NRC's safety goal is being met.

The NRC is the primary federal regulatory agency for the U.S. commercial nuclear power industry. The NRC's safety goal stipulates that the operation of commercial nuclear power plants should not increase the likelihood that a member of the public (living within 10 miles of a nuclear power plant) will die from cancer related to nuclear plant operations, including accidents, by more than one-tenth of one percent (0.1%) of the likelihood that an individual will die from all forms of cancer.[69] Using data from the U.S. Bureau of Labor Statistics,[70] this goal translates into an annual level of about 2.2 cancer deaths per reactor per million people living within the 10-mile radius. The U.S. health safety goal is similar to those of several other countries with nuclear power programs; however, unlike some other countries, the NRC does not consider the impact of land contamination.

The method that the NRC currently uses to assess the safety of a nuclear power plant is a quantitative risk assessment technique called Probabilistic Risk Assessment (PRA). The PRA is a statistical model that estimates the likelihood of events that damage the nuclear core of a nuclear power plant; the likelihood of reactor containment-building failure, given a core-damage event; and, finally, the likelihood of prompt and latent fatalities, given a reactor containment failure. While the PRAs' quantitative estimates suggest that the commercial U.S. nuclear power plants meet and exceed the NRC's safety goal, the PRAs have inherent limitations.

High-probability events, such as automobile accidents or cancer occurrences, can be analyzed by using actuarial data. In the case of very low-probability events, such as major nuclear-plant accidents, actuarial data are either too limited to be meaningful or nonexistent. PRA incorporates probabilistic tools to make statistical calculations based on "event trees" and "fault trees." PRA also analyzes data for equipment performance and for human reliability, and is considered by many, both within and outside the NRC, as an effective modeling tool for providing information that is useful when assessing the nuclear power industry's low-probability events. The PRA process has been, and continues to be, applied to nuclear power plants to simulate performance for the key operating and safety systems during normal, abnormal, and accident conditions. PRA modeling permits a more rigorous and quantitative assessment of (1) *what* can go wrong, (2) the *likelihood* that it can go wrong, and (3) the *consequence* if it does go wrong.

Every U.S. nuclear power plant has its own PRA model. These models have brought some major insights and improvements to light. For example, using PRA modeling, the NRC conducted an assessment of the likelihood of severe (core-damaging) accidents at five operating nuclear power plants in 1990.[71] Based on this study, the NRC estimated that annual mortality rates resulting from severe accidents were substantially—between factors of 100 and 10,000—below the NRC Safety Goal.

PRAs are only as good as the data, models, and assumptions on which they are based. The scenarios are arguably uncertain due to the difficulty of quantifying human responses. There are variations

[69]Meserve, R.A., "The Evolution of Safety Goals and Their Connection to Safety Culture." U.S. NRC Meeting on Safety Goals And Safety Culture, June 18, 2001. http://www.nrc.gov/reading-rm/doc-collections/commission/speeches/2001/s01-013.html.
[70]John Gaertner et al., "Safety Benefits of Risk Assessment at U.S. Nuclear Power Plants."
[71]"Severe Accident Risks: An Assessment of Five U.S. Nuclear Power Plants," NUREG 1150, 1990.

in PRA quality from one reactor to the next. For these and other reasons, some members of the group believe the assessments are too optimistic. These participants believe that quantitative risk calculations cannot reliably measure the absolute risk of low-probability catastrophic accidents but can be used in a relative measure to compare relative safety. That is, while the ratio of two risks may be meaningful, neither is a reliable measure of absolute risk.

For these reasons, the NJFF group did not agree as a whole that the overall safety of nuclear plants can be adequately demonstrated.

Are U.S. Nuclear Plants Becoming Safer?

On balance, commercial nuclear power plants in the U.S. are safer today than they were before the 1979 accident at Three Mile Island.

A number of factors lend support to the view that commercial nuclear power reactors in the U.S. are safer today than they were in the 1970s. These factors include organizational and risk insights and improvements in plant equipment and human performance. Some of these factors are also relevant to commercial power reactors abroad.

Risk Assessment Insights

As noted above, the NJFF participants agreed that a number of safety insights have been developed in the conduct of the nuclear plant PRA analyses.[72]

As a result of these insights and actions, the Electric Power Research Institute (EPRI) has estimated that the average frequency for power reactors to suffer damage to their radioactive, heat-producing cores has declined by a factor of 3 from 1992 to 2000.[73] There are individual power plants for which the estimated risk reductions have increased more dramatically. EPRI estimated the core-damage frequency at one plant to have been reduced by a factor of 5 over 23 years through a series of focused plant upgrades.[74]

Equipment-Related Factors

Aging. Today, many existing U.S. plants are approaching the end of their original 40-year licenses. As previously indicated, about one-half of the existing U.S. nuclear power plants have been granted 20-year license extensions, and about one-half of the remaining plants have announced plans to file renewal applications.

Because elements of many U.S. plants are unique in design and construction, effective materials management programs are required at each facility. Failure to maintain these programs for key systems, structures, and components of a nuclear power plant throughout its entire life could result in serious safety and reliability issues due to corrosion, erosion, material embrittlement, wear, and fatigue.

New Technologies. Many new technologies that provide safety benefits, both for safer operations and for accident prevention and mitigation, have been developed and deployed at nuclear power reactors over the past 30 years. For example, all plants now have reactor simulators specific to their own design and operations to enhance training capabilities. Digital technologies have allowed for improved instrumentation and control systems. Improvements have also been made for inspection and surveillance technologies to help assess the condition of materials and equipment. Improved replacement materials have been developed for steam generators, piping, and other components in order to make them more durable and reliable.

[72] Electric Power Research Institute (EPRI) study "Safety Benefits of Risk Assessment at U.S. Nuclear Power Plants."
[73] Taken from the EPRI study, "Safety Benefits of Risk Assessment at U.S. Nuclear Power Plants." Based upon NRC docketed information, the mean (average) core damage frequency was 9.1E-5/year in 1992. The median in 1992 was 4.7E-5/year, showing an asymmetric distribution. In 2000, the mean core damage frequency had dropped to 3.2E-5/year.
[74] *Ibid.* This type of improvement is typical for those plants that had substantial vulnerabilities early in life.

Upgrades. As nuclear power plants age, an effective life-cycle equipment management system becomes necessary to identify and correct weakness and damage. The challenge facing the industry is to identify issues associated with aging and to take corrective actions in a timely way. In July 1996, the NRC updated its maintenance rule (10 CFR 50.65) to make this industry action a requirement. It made explicit the importance of proper maintenance in the safe operation of nuclear power plants, and it has led to greater focus by licensees and by the NRC on maintenance efforts.

Life-cycle equipment management programs have been developed and demonstrated for commercial nuclear plants by incorporating insights gained from PRA studies that highlight issues and problems most important to maintaining the safety and reliability of the plants. Improved inspection and surveillance techniques are being used to assess the condition and reliability of the key safety systems, structures, and components. The systems must be in place when plants submit license renewal applications to allow plants to operate up to 60 years. To date, the NRC has approved license renewals for 48 of America's 103 nuclear power plants. In addition, 8 applications are under review, and 25 more plants have announced plans to file renewal applications. The NRC and the nuclear industry expect that virtually all of these plants will ultimately extend their licensed operation.

In spite of the industry's efforts to manage nuclear plant equipment aging, some NJFF participants agree with the criticism that material aging is not managed well enough to maintain safety. The Davis-Besse incident (see sidebar discussion) is an example of how the lack of proper inspection and maintenance can degrade one of the main safety barriers.

Human-Related Factors

Staffing. Many nuclear power plants have experienced significant staff reductions.[75] Some of these reductions have been the result of efforts to reduce operations and management costs through consolidation, achieved by enabling corporate staff to support multiple plants and by standardizing fleet operations and maintenance protocols. The industry has also suffered from a loss of expertise as older, experienced operator and maintenance personnel have retired. Recognizing that attracting talented and skilled employees will be necessary to replace an aging workforce, the industry has launched several initiatives in an attempt to address this looming workforce issue.[76]

Utility Consolidation. Currently, there are 26 utilities and energy-generating companies operating nuclear power plants in the U.S., a reduction of 25 since the 1970s.[77] Almost 70% of today's nuclear power plants are operated by the largest 12 companies. Today's companies have many years of experience in operation, and they have dedicated resources to improve operation and maintenance.

Thus, there is general agreement both among the NJFF participants and within the broader debate that increased centralization among utilities and plant operators has improved the "safety culture" at nuclear power plants.

Training. There have been significant advances in training to enhance plant operations, maintenance, radiation protection, chemistry, and engineering. These improvements have been accredited by an independent safety board.[78] The plant-specific simulators are being used extensively to train

[75] http://econ-www.mit.edu/faculty/download_pdf.php?id=1358.
[76] The industry is working with the Department of Defense's "helmets to hardhats" program to employ our military men and women when they are discharged from active service. One innovative program leverages Department of Labor grants to universities to develop specialized curriculum for use by community colleges in partnership with local nuclear utilities. In some cases technology can be utilized to enable fewer skilled workers to accomplish tasks that once required significant manual labor.
[77] http://www.nei.org/index.asp?catnum=2&catid=345.
[78] National Academy for Nuclear Training, Suite 100, 700 Galleria Parkway, SE, Atlanta, GA 30339.

reactor operators. There have been many improvements in human-performance standards and principles of professionalism that are being reinforced through course work and seminars. Required seminars for supervisors and managers have also become standard.

Evaluation and Inspection. Since TMI, the NRC has made some improvements in implementing its many regulatory responsibilities. There is broad agreement that public trust in the regulators and the regulatory process is a necessary element of public acceptance. The Reactor Oversight Process (ROP) and the Enforcement Program are two examples of enhancement in NRC oversight. The ROP applies to reactor operations performance indicators developed by the Nuclear Energy Institute and adopted by the NRC. Appendix C provides further information on these programs.

The nuclear power industry itself has developed new safety performance indicators, approved by the NRC, along with both annual and 5-year goal-setting procedures. Inspections, involving peers from other power plants, are conducted at each site at least every 2 years. These inspections use simulators to evaluate operator performance.

Information-Sharing and Oversight. Within the nuclear power industry, new institutions have been created to administer oversight and information-sharing. The most significant example in terms of the U.S. reactor experience is the Institute of Nuclear Power Operations (INPO), established after the TMI-2 accident to address several shortcomings identified in the Kemeny Commission report.[79] INPO functions to promote safety in a number of ways, including peer evaluations, self-policing, and advising on insurance premiums. INPO also facilitates internal information-sharing programs, including the Significant Event Evaluation and Information Network (SEE-IN), Significant Operating Experience Reports (SOERs), and Significant Event Reports (SERs). The details of these programs are not available to the general public; however, nuclear industry participants assure us that the programs enable valuable sharing of "best practices" and "lessons learned."

INPO's global counterpart, the World Association of Nuclear Operators (WANO), was established after the Chernobyl accident to provide assessments and shared-experience "feedback" to the international nuclear power community. WANO's mission is to increase the safety and reliability of nuclear power plant operations by information exchange and friendly rivalry among member utilities world-wide. The WANO experience-feedback program aims at improving operational capabilities among member utilities by accumulating and sharing operating-experience reports, peer reviews, and professional and technical development data, and by exchanging technical support.[80]

The International Atomic Energy Agency (IAEA) is an organization engaged globally in nuclear verification; security, safety, and technology transfer and promotion of nuclear energy.[81] In 1982, the IAEA initiated Operational Safety Review Team (OSART) missions. OSART visits are intended to improve operational safety at nuclear power plants by using a team of international experts to assess safety performance objectively, to provide useful information on opportunities for improvement, to make recommendations, and to encourage and enable information exchange. OSART teams do not attempt to rank performance among nuclear power plants; rather, they seek to provide an independent international assessment of operational safety performance as a "snapshot in time" that might identify areas for improvement. By 2003, 117

[79] *Report of The President's Commission on the Accident at Three Mile Island.* October 30, 1979. See http://www.pddoc.com/tmi2/kemeny/index.html.
[80] http://www.nsc.go.jp/english/scsympo.pdf.
[81] http://www.iaea.org/About/history.html.

OSART missions had been carried out in 31 countries.[82] An OSART mission is not a regulatory inspection, however, and lacks the power of national or international law. Despite the OSART efforts, a wide range still exists in the safety culture among reactors in countries of the former Soviet Union and states operating reactors supplied by the Soviet Union.

In addition to these independent agency efforts, power plant licensees also conduct self-oversight initiatives. These include independent nuclear safety review boards; corrective-action programs such as personnel screening, Corrective Action Review Boards (CARBs), root-cause identification for problems, and shared "lessons learned"; and enhanced quality control.

Safety Culture. While there is agreement both among NJFF participants and in the broader debate that a strong "safety culture" is necessary to ensure protection of the health and safety of the public, not all believe that it is strong enough at all the U.S. nuclear plants. There is some concern that there are "outlier" plants that lack a strong safety culture. Again, Davis-Besse is cited as the example, due primarily to organizational and leadership issues. Much of NRC's focus is on the identification of plants with poorer scores in the ROP. The response of the NRC is to increase the amount of inspection and evaluation at those plants above the base level of 2,000 inspection hours each year.

In terms of oversight, there is a high degree of disagreement among the NJFF participants as to how appropriately and effectively the NRC has responded to safety issues. While there is broad agreement within this group as to the capability and dedication of the NRC working-level staff, there is no such agreement with regard to the Commission and the senior management staff. As to the concerns, some NJFF members believe that most Commissioners, responding in part to Congressional oversight, have emphasized industry economic and promotional interests inappropriately in relation to public protection.[83] This concern undermines the extent to which these members are willing to rely on NRC assurances on matters of safety.

Other members of the NJFF believe that the Commission has made significant strides in appropriately balancing the public interest in nuclear safety with the operational interests of the industry. These members believe that the views of any given Commissioner are tempered by the views of other Commissioners in deciding matters of policy, thus ensuring a reasonably balanced stewardship of the nuclear industry. They point to recent examples of NRC regulatory stringency.[84] Further, for these NJFF members, the fact that no serious accidents have been experienced since the operational failure at TMI-2 attests to the prudence of nuclear industry oversight.

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[82]Lipar, Miroslav. "Operational Safety Review Team History and Evolution." Presented at the 15th Annual Regulatory Information Conference, Session T13, International Experience. April 17, 2003, Washington, DC.

[83]Examples interpreted by some NJFF members as indicating a tendency by the NRC to inappropriately emphasize industry economic and promotional interests over public health and safety include:

- When the NRC assessed its own safety culture in 2002, more than half of its employees did not think it was "safe to speak up" at the NRC, an improvement from a similar survey done 4 years earlier.
- In his book, nuclear-enthusiast Senator Pete Domenici claimed that, by threatening to cut its budget by one-third during a 1998 meeting with the chair, he successfully persuaded the NRC to make changes to its regulatory approach that some NJFF members view as a weakening of oversight. Senator Pete V. Domenici, *A Brighter Tomorrow; Fulfilling the Promise of Nuclear Energy (Rowman and Littlefield, 1998, pp. 74-75).*
- The NRC adopted a new owner/operator rating system under which Davis-Besse received the top rating in all 18 categories just before it was discovered to have a hole in the pressure vessel head.
- Dale Klein appeared in paid industry ads attesting to the safety of Yucca Mountain before his 2006 appointment as Chairman of the NRC.
- "The top U.S. nuclear regulator vouched for the safety of a new Westinghouse nuclear reactor—yet to be built anywhere in the world—in a sales pitch to supply China's growing power industry." Associated Press, October 19, 2004.

[84]Beattie, Jeff. "NRC To Call Nuke CEOs on Carpet," *Energy Daily*, May 14, 2007.

Other entities also play a role in supporting and improving safety culture. For example, INPO's plant-evaluation programs help to identify outliers and incorporate "lesson learned" and "best practices" from other plants. The issue cited by some about INPO is that their processes and results are strictly confidential. This lack of transparency challenges the credibility of the results to some of the outsiders.

From a global perspective, not all government regulators have a consistent vision of the role of safety culture in nuclear plant operation. There is agreement that the ultimate responsibility for safe nuclear plant operation rests with the plants' owners and operators. The IAEA administers an array of services for its member states, directed specifically at monitoring and improving safety culture. For example, it recently began offering a safety review service called SCART (Safety Culture Assessment Review Team), which provides an evaluation of the main characteristics of safety culture in nuclear facilities and assists in the enhancement of safety culture.[85] Factors affecting nuclear facility management and the performance of personnel, such as organizational structure, management goals, and personnel qualification, are reviewed. In addition, WANO provides peer assistance in nuclear operations to members. However, neither WANO nor SCART has direct supervisory authority over the nuclear plants; their role is purely advisory.

The Current State of Nuclear Reactor Security in the U.S.

There is agreement that, while plants have become safer since the Three Mile Island accident, public concern over plant security is greater today than it was before September 11, 2001. There is not agreement among participants about whether it has been demonstrated that the security systems and procedures to protect existing reactors are sufficiently robust. In the current classification environment, it is difficult for outside entities lacking security clearances to adequately assess security measures, as well as their implementation and oversight.

Safety and security are interconnected, because the systems, processes, and procedures that protect a plant and the public from accidents during normal operations are the same systems that are used to prevent a release of radiation in the event of a terrorist attack or sabotage. It is possible that terrorists who might be successful in overtaking plant security could disable safety systems and trigger a fuel meltdown and the release of radioactive materials that would have a major impact on public health and safety and on the environment.

Security at nuclear power plants is a serious concern in the context of the terrorist attacks against targets in New York City and Washington, DC, on September 11, 2001. Soon thereafter, it was reported in the press that the Indian Point Nuclear Station, 35 miles north of New York City, had been mentioned in documents confiscated from terrorism suspects. And in 2003, Energy Secretary Spencer Abraham said there was evidence that terrorists may have specifically targeted the Palo Verde nuclear power station in Arizona, the largest nuclear plant in the country.[86]

[85] http://www-ns.iaea.org/downloads/ni/publications/s_culture_leaflet.pdf.
[86] *Homeland Security and the Private Sector*. U.S. Congressional Budget Office. (December 2004). See especially Chapter 2, "Civilian Nuclear Power."

The Design Basis Threat

In the U.S., nuclear plant security, like safety, is regulated and monitored by the NRC. The NRC and its licensees use a Design Basis Threat (DBT) that profiles the type, composition, and capabilities of an adversary as a basis for designing safeguards and security systems to protect against acts of radiological sabotage, and to prevent the theft of special nuclear material.[87] The DBT serves to clearly identify for each licensee the level and types of threat its facility is expected to be capable of defending against. Beyond this capability, local, state, and federal law enforcement and U.S. military resources are responsible for assisting the facility to defend against "enemies of the state."

The DBT in force before the 9/11 attacks on the World Trade Center and the Pentagon in 2001 had been explicit in NRC's regulations since the 1970s[88] and was described publicly in a 1998 historical review of nuclear plant security by the NRC historian, J. Samuel Walker.[89] The DBT considers a postulated threat group significantly smaller than the 19 adversaries who attacked four targets on 9/11. Subsequently, the DBT has been increased, at least marginally. The details of the post-9/11 DBT are no longer available to the public and, therefore, can be thoroughly assessed only by those with a security clearance. Some general information about the current DBT is available. The current DBT defines radiological sabotage as a determined violent external assault, attack by stealth, or deceptive actions, by several persons with the following attributes, assistance, and equipment:

- well-trained (including military training and skills) and dedicated individuals
- inside assistance, which may include a knowledgeable individual who attempts to participate in a passive role (e.g., provide information), an active role (e.g., facilitate entrance and exit, disable alarms and communications, join in violent attack), or both
- suitable weapons, up to and including hand-held semi-automatic weapons equipped with silencers and having effective long-range accuracy
- hand-carried equipment, including incapacitating agents and explosives for use as tools of entry or for otherwise destroying reactor, facility, transporter, or container integrity or features of the safeguards system
- a four-wheel drive land vehicle used to transport personnel and their hand-carried equipment to the proximity of vital areas
- a four-wheel drive land vehicle with a bomb.

There remains debate, even among some NRC commissioners and staff, about how prescriptive a DBT should be.[90] Defenders of the DBT concept say that it is a *minimum* standard that prudent plant operators will augment as necessary. In contrast to U.S. practices, some Organization for Economic Cooperation and Development (OECD) countries with large nuclear power programs do not rely on the individual plant operators to defend against such postulated terrorist attacks. Rather, the national police or military provide this defense.

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[87]The DBT is described in detail in Title 10, Section 73.1(a), of the Code of Federal Regulations [10 CFR 73.1(a)], http://www.nrc.gov/reading-rm/doc-collections/cfr/part073/part073-0001.html. Special Nuclear Material is uranium enriched above 20% U235, the element's most common explosive isotope.
[88]*Ibid.*
[89]J. Samuel Walker. "Regulating Against Nuclear Terrorism: The Domestic Safeguards Issue, 1970-1979." *Technology and Culture*, January 2001, Vol. 42; pp. 107-132, especially p. 128. For more information on how the NRC set the DBT, see the NRC Secretary paper SECY-76-242A (26 April 1976), "NRC Stiffens Security Rules," *Nuclear Industry,* March 1977, p. 30; "New Physical Protection Requirements Adopted," *Nuclear News,* April 1977, pp. 39-40; and U.S. House Committee on Interior and Insular Affairs, Subcommittee on Energy and the Environment, *Safeguards in the Domestic Nuclear Industry*, pp. 144-146 and 253-258.
[90]See *Nuclear Power Plants: Efforts Made To Upgrade Security, But the Nuclear Regulatory Commission's Design Basis Threat Process Should Be Improved.* GAO-06-388. March 2006. http://www.gao.gov/new.items/d06388.pdf.

NJFF participants, some of whom on both sides of the debate have security clearances and have analyzed the DBT and assessed current measures, disagree about whether the DBT and its oversight are adequate.

Spent Fuel Pools

Spent fuel pools are located within the plant grounds and are protected by the same security force and electronic surveillance equipment as the rest of the plant. Since 9/11, the National Academy of Science (NAS), EPRI, the NRC, the Government Accountability Office (GAO), and others have conducted safety assessments of spent fuel pools.

There are hypothetical scenarios by which a spent fuel pool could lose its cooling water, resulting in a catastrophic release of radioactive material. Some members of the NJFF do not believe these catastrophic scenarios are credible; others do.

Assessments of these findings are complicated, because many of the details are classified and unavailable for general public review. However, summaries of these studies have been published.

At boiling-water reactors (BWRs) using Mark 1 and Mark 2 containments, which account for about 30 percent of all U.S. plants, the spent fuel pools containing highly radioactive spent nuclear fuel are elevated about five floors above the ground. These structures are designed to withstand earthquakes, hurricanes, and tornado-generated debris, but they are not specifically hardened against attack.

The potential vulnerability of BWR reactor buildings and their elevated spent fuel pools was recognized in the early 2000s from preliminary assessments carried out by the NRC and the nuclear industry. For example, the industry conducted a simulation study in 2003 using a direct side impact from a large commercial airliner (a fully loaded 757-400 traveling at 350 mph).[91] This study showed that the reinforced concrete structure of the spent fuel pool absorbed the energy of the crash, and the ductile stainless steel liner prevented coolant loss.

A classified study conducted by a committee of the National Research Council of the NAS in 2004 was released, in part, to the public in 2005.[92] It underscored the pools' vulnerability to terrorist attacks that engage commercial aircraft or explosive charges to cause structural failure. Spent fuel pools are most vulnerable shortly after the reactor has been refueled. During refueling of a large U.S. nuclear power plant, typically, on the order of 20 tons of fuel are removed from the reactor and replaced. Because the recently removed spent fuel contains a higher concentration of short-lived radioactive isotopes, relative to fuel kept in the pool for several years, it is still generating considerable heat. Indeed, this heat is sufficient to cause the fuel to melt quickly, absent the cooling provided by the water in the pool or from emergency supplies.

The NAS study[93] concluded that terrorists could successfully attack the pools, but the likelihood of widespread harm from a terrorist attack or a severe accident involving commercial spent nuclear fuel is low. It further determined that, in the long run, dry casks are inherently more secure than pools.

The NRC agreed with many of the points raised by the NAS report, including some indications that spent fuel storage systems are safe and secure and that the NRC is taking further actions to improve their safety and security. However, in testimony

[91] *Resistance of Nuclear Power Plant Structures Housing Nuclear Fuel to Aircraft Crash Impact*, Final Report. Electric Power Research Institute, Palo Alto, CA, prepared by ANATECH Corp, ABS Consulting, ERIN Engineering, February 2003.
[92] National Research Council, *Spent Fuel Stored in Pools at Some U.S. Nuclear Power Plants Potentially at Risk From Terrorist Attacks; Prompt Measures Needed To Reduce Vulnerabilities*. 2005.
[93] Ibid.

before the Senate Subcommittee on Energy and Water,[94] then NRC Chairman Nils Diaz also noted several areas of disagreement with the NAS Council's conclusions, indicating that the NRC found some scenarios identified by the report to be unreasonable and questioned its technical basis.

After the NAS report, the nuclear industry in 2004-2005 conducted more detailed vulnerability assessments of three different BWR building spent fuel pools.[95] Assuming the same reference commercial aircraft impact at building floor levels beneath the pools, and not at their sides, the crashes caused significant damage to the underlying support structure. In none of the cases analyzed did collapse of the spent fuel pool occur, and no loss of pool water inventory was postulated, owing to a combination of redundant structural support and robust connections to the Mark I and Mark II drywell structure. These studies indicated that the spent fuel pool's vulnerability depends on where the aircraft hits, among other parameters.

The current DBT does not consider attacks by aircraft. NRC Commissioners did not include airplane attacks in the revised DBT, because they believed that nuclear plants are inherently robust structures that other studies have shown would provide adequate protection against an airplane crash. Plant operators are required to be able to manage the consequences of large fires or explosions no matter what the cause; and the NRC is actively involved with other federal agencies—including the military and the Federal Aviation Administration—to protect nuclear plants from aircraft attacks.[96] Some NJFF participants agree with the NRC Commissioner's exclusion. Others agree with the GAO's assessment that the process NRC used to obtain feedback from stakeholders, including the nuclear industry, created the opportunity for, and appearance of, industry influence on the threat assessment regarding the characteristics of an attack.[97] In either case, all agree that increased use of dry cask storage will decrease the risk by reducing the inventory in spent fuel pools.

NRC Oversight of Security Measures

The NJFF participants also considered concerns raised about NRC oversight of security measures. In particular, the GAO has also posed broader questions about the NRC's oversight of security measures at commercial nuclear power plants.[98] In particular, GAO found that NRC inspectors often used a process involving "non-cited violations" that may have minimized licensee attention to security problems.[99] Also, the NRC has no routine, centralized process for collecting, analyzing, and disseminating security-inspection findings that may be common to other plants.

According to a March 2006 GAO report, the NRC has improved its force-on-force inspections—for example, by conducting inspections more frequently at each site. Nevertheless, in observing three inspections and discussing the program with NRC, GAO noted potential issues in the inspections that warrant NRC's continued attention. For example, a lapse in the protection of information about the planned scenario for a mock attack GAO observed may have given the plant's security officers knowledge that allowed them to perform better than they otherwise would have.[100]

[94]Diaz, Nils. Testimony before Senate Subcommittee on Energy and Water Development. March 14, 2005. http://www.nrc.gov/reading-rm/doc-collections/congress-docs/correspondence/2005/domenici-03142005.pdf.
[95]*Aircraft Impact at Nuclear Power Plants- Analyses for Impact into BWR Spent Fuel Pool Support Structures*. Prepared for the Electric Power Research Institute by ANATECH Corporation. July 2005.
[96]NRC press release No. 07-013, "Statement from Chairman Dale Klein on Commission's Affirmation of the Final DBT Rule." Jan. 29, 2007. http://www.nrc.gov/reading-rm/doc-collections/news/2007/07-013.html.
[97]GAO-06-388, pages 12 and 21.
[98]http://pogo.org/p/homeland/ht-060401-nrc.html.
[99]See *Nuclear Regulatory Commission: Oversight of Nuclear Power Plant Safety Has Improved, But Refinements Are Needed.* September 2006. GAO-06-1029.
[100]http://www.gao.gov/new.items/d06388.pdf

Classification of Security Measures

The public ought to be able to trust both the nuclear industry and the federal agency conducting its security oversight. Transparency is a key cornerstone for public trust-building. However, when it comes to the security of nuclear power plants, full disclosure may be counter-productive.

There is universal agreement that the details of security measures (e.g., the number and location of guards, barriers, and alarms) should be kept classified to ensure their effectiveness. Debate continues about how much information should be made public on the security measures the nuclear industry takes and the oversight its federal regulator provides.

Before the 9/11 terrorist attacks, the DBT was published without including specific countermeasures. Under current classification, there is no way for anyone without a security clearance to assess whether protective systems now in place are meeting the standards the NRC set for baseline protection against attack or sabotage.

Some NJFF participants find merit in charges that the NRC's unwillingness to publish the DBT stems more from a reluctance to reveal the relative leniency of the requirements than from a need to keep security secrets from potential terrorists.[101] Other participants believe that the motivation behind the classification is purely security-related. All participants agree, however, that it is difficult for outside entities to assess the adequacy of today's security measures within the current classification environment.

Consideration of the Terrorist Threat in Environmental Impact Statements

Still unsettled is the issue of whether the NRC should consider the possibility of a terrorist attack on a nuclear plant when reviewing the Environmental Impact Statement (EIS) required for plant licensing and relicensing.[102] Some NJFF participants concur with the June 2006 ruling by the U.S. Ninth Circuit Court of Appeals in San Francisco, which concluded that the environmental impacts of potential terrorist attacks must be assessed as part of the EIS and should be applied nation-wide. In January 2007, the U.S. Supreme Court declined to consider the Ninth Circuit's decision, a refusal that seems to support the ruling.[103] Other participants agree with the NRC and the utility involved in the case, which together appealed the Ninth Circuit's ruling, contending that the potential environmental effect of a terrorist attack is both too speculative to quantify and "too far removed from the natural or expected consequences of agency action to require a study under NEPA."

Safety and Security Implications of a Global Expansion of Nuclear Power Plant Capacity

The safety and security implications of a global nuclear expansion will likely depend, at least in part, on where the expansion occurs. As of today, some projected nuclear plant construction during the next decade is expected to occur in developing countries.[104] This section explores safety and security issues associated with further construction of the U.S. nuclear fleet and elsewhere in the world. What happens to safety and security in non-U.S. reactors anywhere in the world could have significant impacts on the extent, timing, and cost of any U.S. nuclear expansion, and vice versa.

[101] Testimony of Danielle Brian, House Committee on Government Reform, 2005. See http://www.pogo.org/p/homeland/ht-040601-nuclear.html.
[102] http://www.epa.gov/fedrgstr/EPA-IMPACT/2001/February/Day-15/i3823.htm.
[103] http://www.msnbc.msn.com/id/16666978/.
[104] According to IAEA data, as of 2002, new reactors were under construction in Argentina (1), China (4), Korea (1), India (7), Iran (2), Japan (3), Romania (1), Russia (3), Slovakia (2), and Ukraine (4). The greatest expansion is projected in China and India.

Chernobyl's impact in slowing nuclear construction world-wide illustrates how reactor accidents anywhere can affect nuclear fleets everywhere.

Expansion Within the U.S.

While new reactor designs have improved safety and security features, over the next two or three decades, the safety and security of the U.S. nuclear plant fleet will largely be determined by the safety and security of existing reactors. Principal concerns for the U.S. fleet will continue to be those related to aging equipment and materials, and potential terrorist threats.

At least over the next two to three decades, the fleet of U.S. reactors will be dominated by existing reactors, not by new reactors with improved designs, because most existing reactors are expected to receive operating-license extensions. Thus, the issues of central safety and security concern are likely to persist.

While existing reactors will dominate the fleet, some will be retired and replaced by plants with newer designs. These are likely to be light-water reactors, incorporating features that improve both safety and security. The newer designs have evolved to increase safety levels, as estimated hypothetically by probable core-damage frequency, and have incorporated certain core-melt-mitigation features as part of their designs. Some of the new design features include lower core-power densities, stronger containment structures, lower operating temperatures, simpler systems designed to increase reliability, and larger quantities of cooling water within the reactor containment building. Additionally, the designs have incorporated "lessons learned" about materials, fuels, design, construction, and operation since the 1960s by using the Utilities Requirements process.[105] These new safety features will also enhance security, since they make a core-melt less likely.

While it will be difficult to make major modifications to the existing reactor fleet, the new U.S. designs will likely incorporate specific target-hardening features in response to the attacks on September 11, 2001. These features might include, at a minimum, separating back-up diesel generators on-site, hardening firewalls to be able to withstand blasts, and locating spent fuel storage areas away from frontal-access points, such as rivers.

Two factors may serve to counteract the potential benefits of the improved design features. The first is related to public engagement in the licensing process. Some would argue that robust public intervenor participation in U.S. nuclear licensing has resulted in increased safety of reactors ultimately built. For this reason, some NJFF participants raised concerns that the new NRC combined construction and operating license (COL) process will reduce safety and security of any new generation of reactors by reducing public intervention. This issue is discussed in further detail in the Public Involvement in Plant Licensing section.

Secondly, there is the sheer law of numbers. The more plants that are operating, and the longer they run, the greater the statistical chance of a significant core-damage event, either accidental or malicious in origin. Some NJFF participants maintain, however, that even if the number of U.S. plants were doubled, the risk of a core-damage event per year would not change appreciably, because the new designs are believed to be significantly safer than existing ones.

Expansion Outside the U.S.

On balance, this group has concerns about nuclear plant expansion in certain other countries that currently have significant weaknesses in legal structure (rule of law); construction practice; operating, safety, and security cultures; and regulatory oversight.

[105] The Utility Requirement Document, The Electric Power Research Institute.
See http://www.osti.gov/bridge/servlets/purl/10185524-7WNCbE/webviewable/10185524.PDF.

Safety and security issues associated with overseas nuclear expansion can be divided into three parts: reactor design, plant construction, and plant operation and oversight safety. In broad terms, there is more concern about construction, operation, and regulatory oversight, which vary widely among countries, than about basic reactor design.

Reactor Design

As in the U.S., the current fleet of commercial power reactors outside the U.S. is dominated by light-water reactors (see Table 7). While expansion in the U.S. and much of the world will continue to be dominated by advanced light-water reactors, one nuclear power plant with a fundamentally different design—the Pebble Bed Modular Reactor (PBMR)—is under development in South Africa and China. The PBMR is similar to the high-temperature gas-cooled reactor, but it uses a different fuel design (graphite-coated enriched uranium spheres), and the modular reactor units are each 165 MWe, much smaller than today's water-cooled reactors. The PBMR's smaller unit size and its fuel and cooling characteristics have safety advantages over other designs. Also, the smaller modules may be practically suited for countries with less-developed transmission systems or where it is difficult to assimilate more than 1,000 MWe into the electric distribution system. On the other hand, the economics and reliability of the PBMR design have yet to be demonstrated, and so it is premature to conclude that experience will match aspirations.

Plant Construction

Some NJFF participants express substantial near-term concern about the *construction* of reactors in some countries. At the core of the problem is a laxer "safety culture," which infuses construction practices as well as plant operations in many countries. No matter how well a plant is operated, basic construction flaws will forever limit its ultimate safety and the protection its new design affords against sabotage.

In this regard, some members of the NJFF heard expert concern[106] about nuclear plant construction practices in China—including lax workplace conduct and critical piping installation that deviates from plans.[107] A similar concern was voiced about

Table 7. Status of Various Reactor Types

Reactor Type	Operational	Under Construction***	Number of Countries Operating this Reactor Type
Light Water Reactors	358	19	26****
Heavy Water Moderated Reactors	43	10	7
Light Water-Cooled Graphite- Moderated	16	2	2
Gas- Cooled Reactors	19*		2*
Liquid Metal Fast-Neutron Reactors	3**	2	2**

*Includes Beijing Tsinghua HTR-10, a 10-MWe high-temperature gas-cooled demonstration reactor in China.
**Includes two research/demonstration liquid metal fast breeder reactors: Phenix in France and BOR-60 in Russia.
***Excludes 14 plants whose construction has been stalled or suspended, of which perhaps as many as 5 may eventually be completed.
****Total of 27 if Taiwan and China were counted separately.

[106]Unfortunately, as noted below, there is very little public information available about the state of security and safety in non-OECD countries, due to the ground rules of IAEA and other involvement. Accordingly, the working group on this section spoke with several U.S.- and European-based experts who are currently involved in advising non-OECD countries on reactor safety and security. However, these experts did not wish to have their remarks attributed. Accordingly, in the remainder of this section, some expert opinions are noted without attribution.
[107]China does have an independent nuclear regulatory authority overseeing civilian nuclear material, known as the National Nuclear Safety Administration (NNSA). Established in 1984, it leads the organizational system for nuclear safety in China, and is responsible for standards/regulations, construction permits/operating licenses, monitoring plant operations, and conducting joint research on nuclear safety with other countries. It is also responsible for regulating and licensing nuclear power plants and nuclear facilities for civilian use. To the extent that explicit safety culture initiatives take place in China, they would most likely be administered through NNSA and through self-monitoring by licensees or their overseas contractors.

reactors built by Russia both in Russia and abroad, despite generally good designs. Some concerns were also expressed about practices in India; lacking external capital, India has done substantial in-country engineering and construction, and its advanced reactor development program has been carried out in close coordination with its nuclear military program. This collaboration has resulted in greater isolation from world-wide standards and practices than would have otherwise been the case. As a result, India may not be able to benefit from global design improvements and construction experience.

Plant Operation and Oversight: Safety

An equal concern in any expansion scenario is the wide array of "safety culture" in place among the countries where new nuclear power plants will be built and operated. As noted elsewhere, the 2002 Davis-Besse incident in the U.S. demonstrates that poor safety culture and regulatory oversight are concerns even in advanced OECD countries. Sweden's Forsmark reactor was also criticized by an internal technician's report earlier this year, citing degradation of the company's security culture over a long period of time.[108] Similarly, in Japan, there have been several documented incidents of "near misses" and data falsification in connection with mishandling of nuclear fuel rods and other safety events.[109]

A solid safety culture is critical to any safe nuclear regime. However, analysis of safety culture can be challenging given the lack of international agreement on performance indicators. It is easier to define the characteristics of a bad safety culture: the downgrading of field experience, technical capabilities, and knowledge levels; low levels of information-sharing among operators; low levels of collaboration between operators and contractors; seasonal workload imbalance; and the competing requirements of high quality assurance versus cost reduction.[110]

The current status of safety culture varies greatly among countries as a function of their economic, legal, and financial structures as well as the national cultures themselves. For example, experts we interviewed indicated that safety culture varies greatly among countries, with some exhibiting very weak attitudes and practices. Moreover, as previously described, government regulators world-wide lack a clear role for assuring safety culture, since, ultimately, responsibility for safe plant operation rests with the owners and operators.

Plant Operation and Oversight: Security

Because plant security and safety are so closely related, it is not surprising that similar issues have been raised about security implications for different nations' nuclear security cultures. Beyond the security implications of design and operation for reactors there is, of course, a larger security situation on the ground. One expert underscored that countries like China, with tight social controls, may pose fewer reasons for worry than countries with substantial civic unrest and terrorism. The same expert noted, however, that any country-level situation can change rapidly.

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[108]According to one news report: "An electricity failure at the plant on July 25, 2006, led to the immediate shutdown of the Forsmark 1 reactor after two of four backup generators, which supply power to the reactor's cooling system, malfunctioned for about 20 minutes. Some experts have suggested that a potentially catastrophic reactor meltdown was narrowly avoided at the plant, located on Sweden's east coast. But Swedish authorities have classed it a level-two incident on a scale from zero to seven." The internal report said that lax security has led to "potentially fatal accidents." It cited among other things a nitrogen gas leak, employees handling live electrical wires, falls in the workplace, and employees sent home for failing sobriety tests. The Swedish Nuclear Power Inspectorate said it has asked prosecutors to investigate whether the Forsmark operator, FKA, broke the law in its response to the malfunction. See http://www.abcmoney.co.uk/news/30200714337.htm.

[109]"Tokyo Electric said on March 22, 2007 an accident that likely occurred at its Fukushima Daiichi plant in 1978 could have caused a nuclear chain reaction. Hokuriku Electric Power Co. was ordered to halt operations at its Shika No. 1 reactor on March 15, 2007 after the company said it covered up an accident eight years ago. Tohoku Electric Power Co., the No. 4 power utility, said on March 12 it failed to report an emergency shutdown of a reactor that occurred nine years ago." http://www.bloomberg.com/apps/news?pid=20601101&sid=agdcx26jItOo.

[110] http://www.nsc.go.jp/english/scsympo.pdf.

According to one expert, at least five elements support an effective security regime to protect against sabotage—in addition to initial reactor design and construction. These are:

- a design basis threat (DBT) reflecting today's terrorist potentials
- effective regulation requiring all facilities with potential special nuclear material or posing a significant sabotage risk to have security capable of defeating the DBT
- inspections and enforcement conducted efficiently
- a strong security culture, to ensure that all relevant staff understand threats and their implications for security, and police and intelligence capabilities and efforts focused on ensuring that nuclear conspiracies will be detected
- regular reviews and adaptations to ensure that security systems adapt to changing threats and opportunities.[111]

Some analysts have questioned whether these elements are even met within the OECD, whose countries share decades of experience in managing nuclear power. For example, one recent survey observed that:

> For cultural reasons Japan employs very different security measures than those used in the United States or Europe. In particular, its guard forces tend to be unarmed. Concerns have also been raised that Japan has not adopted a design-basis threat that reflects today's terrorist threat.[112]

Arguably, the task will become more challenging in developing nations, and progress may be difficult to gauge due to a lack of transparency. For example, the same 2004 survey cited above noted:

> China publishes little information about the security of its nuclear facilities…Informal discussions by the authors with Chinese diplomats and nuclear experts indicate a growing Chinese appreciation of the dangers posed by nuclear terrorism It is not yet evident, however, that practical steps will be taken by China to address these threats.[113]

Systematic assessments of non-U.S. security preparedness proved nearly impossible for the NJFF, as there are no binding international standards that require countries with commercial nuclear power to meet minimum security standards. Furthermore, no publicly available information exists indicating how well those standards might be followed. For example, a recent IAEA statement notes that "the responsibility for the establishment, implementation and maintenance of a physical protection regime within a State rests entirely with that State."[114]

As with safety, the IAEA and other associations provide substantial assistance to countries to support nuclear reactor security. For example:

- The NEA provides advice on reactor design to ensure best security design features, through a program called the Multinational Design Evaluation Process.
- Upon request of member states, the IAEA observes and comments on plant construction.
- The IAEA has issued extensive written guidance on engineering practices to enhance plant security.[115]
- The IAEA Office of Nuclear Security (NSNS) provides frequent and thorough on-site reviews of plant security in operation in member states and makes recommendations upon a state's request.

[111] Matthew Bunn. "A Vision for Nuclear Security in 2015: How Do We Get There?" Presentation to IAEA Seminar on Strengthening Nuclear Security in Asian Countries, Tokyo, Japan, 7-10 November 2006.

[112] C. Ferguson and W. Potter. "Four Faces of Nuclear Terrorism." Monterey Institute (2004). p. 246.

[113] *Ibid.*, p. 246.

[114] IAEA, GC(45)/INF/14 September 2001. International Atomic Energy Agency General Conference, "Measures to Improve the Security of Nuclear Materials and Other Radioactive Materials."

[115] IEA. "Engineering Safety Aspects of the Protection of Nuclear Power Plants against Sabotage." STI/PUB/1271. IAEA Nuclear Security Series No. 4. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1271_web.pdf.

As with safety, however, any security advice rendered by the IAEA is non-binding. Moreover, inspection reports are confidential unless a member state assents to their disclosure, which rarely happens, even on a confidential basis with other member states. While the security reasons for this confidentiality are understandable, issues of national sovereignty and consequent lack of transparency make informed assessment of prevailing nuclear security and safety practice by outside efforts like the Keystone NJFF Project extremely difficult.[116]

The group questioned experts in this area about whether a strengthened protocol for reactor security, similar to the current IAEA inspection regime for fuel enrichment and materials diversion, with such tools as unannounced inspections, would reduce security risks created by a nuclear expansion outside the U.S. They agreed that it would, but they also indicated that such a protocol is not currently being considered seriously due to disagreements on the desirability of such a regime among IAEA members.

Public Involvement in Plant Licensing

Substantial changes have been made to the nuclear power plant licensing process in the last 15 years. These include moving consideration of public input toward the front of the process before significant capital expenditures are made. They also include new procedural modifications in such areas as raising contentions, cross-examination and discovery. Some members of the NJFF believe that the procedural modifications limit effective public involvement and could have a deleterious effect on safety and security.

The NRC is responsible for licensing and regulating the operation of commercial nuclear power plants in the U.S. Before 1989, nuclear power plants were licensed to operate under a two-step process described in Title 10 of the Code of Federal Regulations (10 CFR Part 50). This process required a Construction Permit (CP) before safety-related construction could take place, e.g., pouring the concrete foundation for the plant, and subsequently an Operating License (OL) before the plant could be started up. In addition, the applicant could seek a Limited Work Authorization (LWA) permitting limited non-safety-related site work prior to obtaining a CP.

In 1989, the NRC established an alternative licensing process (10 CFR Part 52), called the Combined Operating License (COL), which proposed a combined construction and operating license with conditions for plant operation. Congress affirmed this new licensing process in 1992 as part of the Energy Policy Act of 1992. The NRC proposed the alternative licensing process, in its own words, "in an effort to improve regulatory efficiency and add greater predictability to the process."[117] In addition, the applicant, if it chooses to do so, can seek an Early Site Permit (ESP) well before the COL process. The ESP is designed to resolve environmental and alternative siting issues related to the plant site. In addition, in separate proceedings, reactor suppliers can seek design certifications for generic designs. In the design certification process the NRC attempts to address many of the reactor safety issues that previously would have been addressed in CP and OL proceedings.

Both the COL licensing regulations and the previous two-step CP/OL licensing process permit public involvement in the licensing of a nuclear power plant. However, the degree of public involvement has changed considerably. Under the old protocol, the NRC conducted all reactor licensing hearings according to procedures that

[116] It should noted that this lack of transparency regarding security preparedness also characterizes other global industries, such as chemicals manufacture.
[117] U.S. NRC. "Backgrounder on Nuclear Power Plant Licensing Process." http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/licensing-process-bg.html.

resembled those associated with judicial proceedings. They included opportunity for traditional discovery (e.g., requests for document production, interrogatories, and depositions); motions practice; and an evidentiary hearing at which testimony was presented through direct and cross-examination of witnesses by the parties.

Under the new COL and generic design certification processes, public and intervener participation is restricted to the submission of written and in some cases public comments. The opportunity for the public and intervener groups to engage in formal discovery and cross-examination of witnesses has been eliminated. The NRC staff is required to create and make available a hearing file in lieu of traditional discovery. The hearing file must be made available to the public for its inspection and copying. While cross-examination is not available as a right, as it was in past practice, a party may request permission to conduct cross-examination that it deems "necessary to ensure the development of an adequate record for decision."

Appendix E provides an overview of the licensing process with the points for public intervention under the two-step process of 10 CFR Part 50, or the points for public comment under the COL process of 10 CFR Part 52.

Stakeholder Concerns

Public involvement has two basic functions: it permits the raising of issues that will improve the safety of nuclear power plants, and it enhances the transparency and the level of confidence and trust that the public can have in nuclear regulation and decision-making. When public participation is overly constrained, both of these functions are undermined. Due to federal preemption, the only forum available to those who want to oppose nuclear plant construction and operation is the one authorized to consider radiological health and safety issues, namely, the NRC.

In the view of various stakeholder and watchdog groups, the change in the form of public involvement in the licensing process has been detrimental to public safety. The Union of Concerned Scientists, which has closely monitored commercial power reactor safety issues since the early 1970s, stated in 2004 that "public intervention in licensing proceedings led to numerous safety improvements, but recent changes to the licensing process limit the public's role to essentially that of a casual observer."[118]

Stakeholder and watchdog groups have also been critical of the fact that safety, environmental, and alternative siting issues can also be "resolved" years before a commitment is made to construct a nuclear plant, thus making it less likely that issues of concern will be addressed. An ESP, for example, is good for 20 years and can be renewed for another 20 years, making it difficult, if not impossible, to raise substantive environmental and alternative issues years later when a commitment to construct a new plant is made. Similarly, safety issues are addressed in generic design certification reviews that can occur years prior to a commitment to construct a plant.

In many NRC proceedings, intervenor contentions were either accepted by the agency or sustained by reviewing courts. These proceedings included review of the emergency core cooling system; the generic environmental impact statement on mixed oxide fuels; and license hearings for Allen's Creek, Seabrook, and Calvert Cliffs, to name but a few.

[118]David Lochbaum. *U.S. Nuclear Plants in the 21st Century: The Risk of a Lifetime*. Union of Concerned Scientists, May 2004, p 1.

One NRC Appeals Board decision described the safety significance of public participation as follows:

> Public participation in licensing proceedings not only can provide valuable assistance to the adjudicatory process, but on frequent occasions demonstrably has done so. It does no disservice to the diligence of either applicants generally or the regulatory staff to note that many of the substantial safety and environmental issues which have received the scrutiny of licensing boards and appeal boards were raised in the first instance by an intervenor.[119]

One former chairman of the NRC's Atomic Safety and Licensing Board has described the benefits of the NRC public hearing process as follows:

> (1) Staff and applicant reports subject to public examination are performed with greater care; (2) preparation for public examination of issues frequently creates a new perspective and causes the parties to reexamine or rethink some or all of the questions presented; (3) the quality of staff judgment is improved by a hearing process which requires experts to state their views in writing and then permits oral examination in detail...; and (4) staff work from two decades of hearings and Board decisions on the almost limitless number of technical judgments that must be made in any given licensing application.[120]

When faced with the argument that the new rules eliminated all access to information from opposing parties, the U.S. Court of Appeals for the First Circuit ruled that the new rules "provide meaningful access to information from adverse parties in the form of a system of mandatory disclosure." The court found that, even if less information is available to citizen-intervenors under the new rules, "the difference is one of degree" (and the Court found the degree acceptable). Some NJFF participants agree with this assessment; others do not.

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[119]Gulf States Utility Company, quoted in Union of Concerned Scientists, *Safety Second: The NRC and America's Nuclear Power Plants* (Indiana University Press, 1987).

[120]Memorandum of B. Paul Cotter, May 8, 1981, quoted in *Safety Second*, p. 58. This conclusion was echoed in the independent analysis of the Three Mile Island nuclear accident commissioned by the NRC, which stated, "Intervenors have made an important impact on safety in some instances—sometimes as a catalyst in the prehearing stage of proceedings, sometimes by forcing more thorough review of an issue or improved review procedures on a reluctant agency." Another Licensing Board member suggested that public involvement improves agency conduct even when the improvement cannot be documented: "You can't decide how many robberies a policeman on the beat has prevented by checking how many arrests he's made. Just his presence on the beat discourages a lot of robberies." *Safety Second*, p. 59.

The Davis-Besse Event

In 2002, during a refueling shutdown at the Davis-Besse Nuclear Plant near Toledo, Ohio, workers discovered a football-sized cavity in the head of the reactor pressure vessel that had nearly penetrated the entire pressure boundary. The cavity resulted from erosion-corrosion of the carbon steel head from leaks in the housing that surrounded the control-rod drive mechanisms used to regulate the rate of nuclear fission when the reactor is operating and to assure its safe shutdown. Fortunately, the 3/16th-inch stainless steel liner surrounding the reactor pressure vessel contained/held the pressure—a function it was not designed to serve.

The Davis-Besse event represents a significant breakdown in safety standards at several levels. The safe operation of commercial nuclear power plants is primarily the responsibility of the owner/operator, which is licensed by the NRC. In this case, First Energy Nuclear Operating Company (FENOC) failed to maintain the appropriate level of safety required, by missing or minimizing telltale warning signs during years of routine inspections. As a result of the pressure-vessel damage, FENOC has made substantial and significant changes to its management structure, hired well-regarded executives to reform the operation, and instituted major changes in the way the company operates all of its nuclear units, not just Davis-Besse. The Davis-Besse event stimulated a proactive research and development program to study the aging of critical materials used in nuclear power plants—by both reactor manufacturers and some nuclear utilities.

Despite the many regulatory changes that have been made since the TMI accident, the Davis-Besse incident also exposed a failure by the NRC to assure that plants are operated in a way that protects public health and safety. Just prior to the discovery of the damaged reactor-vessel head, the Davis-Besse plant received the highest ratings possible in the NRC's Reactor Oversight Process, with "green" ratings in all 17 performance indicators. After reviewing the Davis-Besse incident, the NRC Inspector General found that:

> The fact that (the licensee) sought and the [NRC] staff allowed Davis-Besse to operate past December 31, 2001, without performing these inspections was driven in large part by the desire to lessen the financial impact on (the licensee) that would result in an early shutdown.[121]

In the wake of these discoveries, the NRC conducted a "lessons learned" review of the event. The published report has several recommendations, as well as action plans to put the recommendations into practice. These actions range from technical corrections for dealing with corrosion to programmatic changes in the regulatory process itself. Substantive changes were made in the NRC's Reactor Oversight Process and the agency's internal procedures. However, some members of the group maintain that these "lessons learned" have not addressed a fundamental weakness in the regulatory process itself—the disposition of some Commissioners and NRC staff to favor the financial interests of the nuclear power industry, sometimes at the expense of public health and safety.

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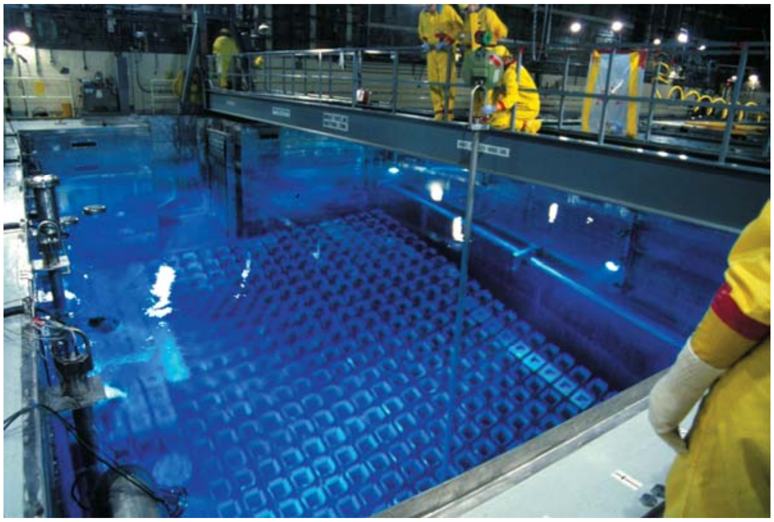
[121] NRC Inspector General. "NRC's Regulation of Davis Besse Regarding Damage to the Reactor Vessel Head." Dec. 30, 2002. p. 23.

IV. Waste & Reprocessing

Nuclear power plants produce spent fuel that is radioactive and thermally hot. The radiation from these wastes could potentially endanger people if not properly managed, and so the waste must be sequestered in shielded environments. Radiotoxicity of the spent fuel's constituents varies by isotope and time, and by the body's reaction to individual elements.

Spent Nuclear Fuel: The Basics

Through the nuclear fission process, fuel assemblies become intensely radioactive and must be safely stored in environments that sequester and contain the radioactivity. Essentially all used nuclear fuel from nuclear power plants is in ceramic form. A typical 1,000-megawatt nuclear power plant produces about 20 metric tons of spent uranium fuel per year. The country's 103 commercial nuclear reactors together produce about 2,000 metric tons of used fuel annually.



Spent fuel radioactivity is generated by:

- fission products (e.g., isotopes of cesium and strontium)
- transuranic elements, also known as actinides (e.g., plutonium, americium, and neptunium)
- fission product gases, such as krypton and xenon, trapped within used fuel rods and pellets
- spent fuel assembly metals, such as cobalt, nickel, and niobium, which became radioactive in the neutron flux of an operating reactor.

The radiotoxicity of an isotope is a measure of its potential to cause damage to living tissue. Radiotoxicity depends on the residence time in the body and on the type of radiation emitted by the isotope.[122] Radioactive decay of the waste is dominated for a few hundred years by highly radioactive fission products and after that by heavy elements in the actinide series, which are less radioactive (i.e., take a long time to decay).

The decay of fission products also produces heat. Spent fuel that has just been removed from a reactor generates about 2,000 watts per kilogram.[123] The heat rate drops after a year to about 10 watts; after 5 years to about 3 watts; and after 100 years to about 0.5 watts. After 1,000 years, the thermal output of the spent fuel is negligible.

[122] Alpha, beta, gamma or neutron.
[123] For comparison, a powerful hair dryer can put out nearly 2,000 watts of heat.

Long-Term Disposal of Nuclear Waste Is Necessary

There is consensus among the NJFF group that spent nuclear fuel must be ultimately placed in long-term disposal facilities, and that the best disposal option is a deep underground geologic repository. A consensus also exists regarding the suitable environments for geologic repositories. However, thus far, nations have yet to actually site and complete these repositories.

There is international consensus and among the NJFF group that a deep underground geologic repository is the best option for long-term disposal of nuclear waste. The International Atomic Energy Agency (IAEA) states that "while the debate is not yet closed on the issue...the scientific and technical aspects of geological disposal over recent decades gives assurance to the waste management community that this is a sound technical solution which is supported by good scientific understanding."[124] No spent fuel repository has been built for high-level waste, to date, anywhere in the world. Finland has selected a site and appears to be on track to build the first geologic repository.[125,126,127] The U.S. has permitted, and is operating, a deep geological repository for long-lived transuranic radioactive waste in a salt formation at the Waste Isolation Pilot Project in New Mexico.[128]

Suitable Environments for Geologic Repositories

There are several main features of the repository environment to be considered for long-term geologic disposal. The NJFF group agrees with the technical group convened by the IAEA, which found that, typically, a suitable environment for deep disposal would display properties such as:

- long-term (millions of years) geological stability, in terms of major earth movements and deformation, faulting, seismicity, and heat flow[129]
- low groundwater content and flow at repository depths, which can be shown to have been stable for periods of at least tens of thousands of years
- stable geochemical or hydrochemical conditions at depth, mainly described by a reducing environment and a composition controlled by equilibrium between water and rock-forming minerals
- good engineering properties, which readily allow construction of a repository as well as operation for periods that may be measured in decades.

[124] "Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes." Technical Reports Series No. 413. International Atomic Energy Agency, Vienna, 2003, p. v.
[125] The Finnish program has only four operating reactors, two under construction and one under consideration.
[126] The "decision in principle" to build the repository at the Olkiluoto site was ratified by the Finnish parliament in May 2001. Repository construction is dependent on outcomes of the stage of ongoing laboratory research. See "Principles and Operational Strategies for Staged Repository Systems Progress Report," Board on Radioactive Waste Management, National Academies Press, 2002. http://books.nap.edu/openbook.php?record_id=10329&page=18.
[127] Further, the Federal Institute for Geosciences and Natural Resources in Germany released a report indicating that a large chunk of northern Germany, and a bit of the south as well, is geologically suitable for the indefinite storage of highly radioactive nuclear waste. It did not draw any conclusions about the appropriateness of different sites, however. Hawley, Charles, "Europe's Nuclear Waste Conundrum," *Der Spiegel*. Apr. 19, 2007 http://www.spiegel.de/international/germany/0,1518,478309,00.html.
[128] The waste in the WIPP site is not heat-producing. See http://www.wipp.energy.gov/.
[129] The exact nature of the host rock is not a controlling factor in the choice of a site. Countries around the world are considering various host-rock types, including granite, gneiss, consolidated clays, plastic clays, salt domes, bedded salt, and other formations.

The report states that "a well chosen geological environment will act as a cocoon for the repository EBS [Engineered Barrier System], protecting it from gross fluctuations in physical stress, water flow and hydrochemistry."[130] The group also agrees with the IAEA report's observation that "suitable geological environments for disposal of long lived radioactive wastes exist widely throughout the world. They can vary considerably in their nature and thus, provide the desirable features mentioned above in different combinations and to different extents."[131]

Some have explored finding alternate approaches to deep geological disposal. For example, disposal in deep boreholes (over 2 km depth) drilled from the surface has received some study, but on the whole would require substantial research and development and may be impracticable.[132] Options other than geologic storage have been considered, including launching waste into space and disposal in deep sea beds. These have been judged too risky or infeasible, or they violate international treaties.[133]

U.S. Policy

In the U.S., the Nuclear Waste Policy Act of 1982 (NWPA) set the national policy framework for ultimate disposition of commercial spent nuclear fuel and high-level radioactive waste (HLW) from defense nuclear activities and other government programs. The NWPA establishes that the Department of Energy (DOE) is responsible for developing the repository under license to be obtained from the Nuclear Regulatory Commission (NRC). The NRC regulations for licensing are required by law to be consistent with the radiation protection standards to be developed by the Environmental Protection Agency (EPA) for the Yucca Mountain site.

The Repository Site Selection Process Was Altered by Congressional Action

The process for selecting a site based on the NWPA was initially well conceived; however, subsequent legislative amendments by Congress and related regulatory processes by DOE altered the site evaluation process and changed the selection guidelines. DOE developed repository guidelines and conducted a site selection process through the mid-1980s. In 1983, DOE selected nine locations in six states for consideration as potential repository sites, and in 1984 it established the geologic site selection guidelines required by the NWPA. In 1986, President Reagan approved three sites for further scientific site characterization—Hanford, Washington; Deaf Smith County, Texas; and Yucca Mountain, Nevada. Subsequently, DOE's "multi-attribute utility analysis" determined Yucca Mountain to be the most favorable site.[134] Congress then limited site characterization to one candidate site—Yucca Mountain. In the 1987 Amendments Act to the NWPA, DOE was directed to discontinue work at other sites until the Yucca Mountain licensing process was completed or until Yucca was found to be unsuitable by DOE.

Some of the NJFF group agree that the decision by Congress to dismiss alternative sites from consideration was ill-advised. They feel that it led to concerns that the federal government would find Yucca Mountain suitable even if it failed to meet acceptable criteria.

[130] "Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes." TRS No. 413. IAEA, Vienna, 2003, p. 6.
[131] *Ibid.*
[132] The evaluation of these options was documented in Department of Energy Environmental Impact Statement for Management of Commercially Generated Radioactive Waste (DOE/EIS-0046F, October 1980).
[133] "Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes." IAEA, 2003.
[134] "A Multi-Attribute Utility Analysis of Sites Nominated for Characterization for the 1st Radioactive-Waste Repository—A Decision-Aiding Methodology (DOE/RW-0074, May 1986), pp. 5-16.

In 2001, DOE adopted new regulations on how it would evaluate the site suitability of Yucca Mountain.[135] The new rule stated that "if the [total system performance assessment] results indicate a repository at Yucca Mountain is likely to meet the applicable radiation protection standard, then DOE may determine, on the basis of site characterization activities, that the site is suitable for the post-closure period."[136] The original 1984 geologic guidelines no longer applied to the site suitability determination for Yucca Mountain. They were replaced by a "performance-based guidelines" test to evaluate the repository's projected ability to meet EPA's radiation standard.

In 2002, the DOE Secretary concluded, based on DOE scientific studies and international peer review, that Yucca Mountain would be capable of meeting the EPA radiation standard. This was the basis for the suitability determination and for the Secretary's recommendation to the President and Congress to go forward with the Yucca Mountain site.[137]

NWPA Section 161 directs the Secretary of Energy to report to the President and Congress on or after January 1, 2007, but no later than January 1, 2010, on the need for a second repository. The Secretary may also consider the option of expanding the Yucca Mountain repository as part of this process, even in advance of its initial licensing.[138] The Secretary of Energy is precluded by law from examining other specific potential disposal sites unless authorized by Congress.

The NJFF group observes that the Yucca Mountain project has repeatedly failed to meet its own schedule. There is little confidence that currently established DOE schedules will be met. Projected delays in the commissioning of a repository mean added liability for the federal government, open-ended obligations on the part of nuclear plant owners to manage spent fuel, and additional physical and financial requirements for interim storage. Given this experience, the search for a second or an alternative site would benefit from a different approach.

The original schedule for building the Yucca Mountain repository has slipped by about 20 years. The latest schedule, which was presented to Congress in July 2006 by DOE, is as follows:

Licensing Support Network Certification	December 2007
Submit license application to NRC	June 2008
NRC issues construction authorization	
(3-year review)	September 2011
Initial receipt and emplacement of waste	March 2017.

DOE has cautioned that this is the "best achievable" schedule and has conceded that the initial underground waste emplacement might more likely be in 2020 or 2021.[139] After the repository has been completed, waste transportation and reception to its current statutory capacity of 70,000 metric tons of heavy metal (MTHM) will continue for another 24 years, at the rate of 3,000 MTHM per year. Thus, even on an optimistic schedule, the final shipment of spent fuel to Yucca will not take place until 2041.

[135]DOE promulgated 10 CFR 963 to replace the earlier 10 CFR 960.
[136]U.S. Department of Energy, 10 CFR Parts 960 and 963. http://www.ocrwm.doe.gov/info_library/newsroom/documents/10cfr960_frn.pdf.
[137]When President Bush made a 2002 recommendation to build the repository at Yucca Mountain, the Governor of Nevada exercised his authority under NWPA to reject the siting with a notification to Congress on April 8, 2002. Congress overrode the veto by House Joint Resolution 87, which President Bush signed on July 23, 2002. The House of Representatives voted 306-117, and the Senate approved by voice vote, the decision to approve Yucca Mountain as the site for a national used nuclear fuel repository.
[138]On March 6, 2007, DOE proposed legislation that would remove the statutory limit and have the capacity be determined in the licensing process. A similar proposal (S. 2589) was introduced in the 109th Congress but not enacted.
[139]DOE repository program director Ward Sproat, testimony to the House Energy and Water Appropriations Subcommittee (March 28, 2007).

Political and Legal Issues

Nevada objected to the designation of Yucca Mountain as the sole site for a repository, on the grounds that the site was chosen for political reasons rather than scientific merit. In the state's view the characteristics of the site make it unacceptable as a waste repository. The State of Nevada and other stakeholders have successfully sued the EPA over the radiation protection standards applicable to Yucca Mountain.

EPA established the radiological standards for acceptable exposure as 4 millirem (mrem) in drinking water[140] and 15 mrem of whole-body radiation per year to a "reasonably maximally exposed individual" living 18 kilometers south of Yucca Mountain, for up to 10,000 years after the repository closes.[141] It should be noted that these standards are measured against results of computer simulations, and are used for licensing purposes only.

In 1995, however, the U.S. Court of Appeals for the District of Columbia found that the 10,000-year compliance limit violated Section 801 of the Energy Policy Act of 1992 (EPACT 1992). Congress had directed the EPA to promulgate standards for Yucca Mountain that were to be "based on and consistent with" recommendations of the National Academy of Sciences (NAS). The NAS recommended that the standard be based at the point of peak dose, which occurs after waste packages fail,[142] indicating at the time that the peak dose might occur several hundred thousand to a million years in the future. In the context of the U.S. licensing system, the peak dose is thus the measure of the site's ability to protect the biosphere from radioactive leakage—i.e., the lower the peak dose, the better the site, given identical modeling assumptions and regulatory rigor.

In accordance with the court's decision, EPA has published a new proposed standard that extends the radiological exposure period from 10,000 years to 1 million years, thus covering any likely projected peak dose. In addition to the 10,000-year EPA dose limit, this proposed standard adds a limit of 350 mrem per year for the period from 10,000 to 1 million years. The final rule is expected to be released in 2007. The NRC must await the final EPA rule before revising its licensing regulation (10 CFR Part 63).

In addition, there is an important change in the way the standard would be applied. Whereas DOE was to compare the standard to the *mean* dose obtained in its computer simulations over the 10,000-year period, EPA has proposed that DOE compare the standard to the *median* dose obtained in its computer runs for the post-10,000-year period. Some members of the NJFF believe that, in terms of the *mean*, the equivalent standards could be 3 or more times higher. If this proposal is included in the final rule, it may raise questions by some about the validity of the proposed final rule, because the NAS recommended that EPA use the mean. If promulgated, the change is likely to foster further legal challenges to the EPA proposed rule**.**

Technical Issues

Yucca Mountain has an oxidizing environment, meaning that there is free oxygen available to combine with container metals and waste forms. In an oxidizing environment, spent fuel, which is essentially uranium dioxide, is not stable in the presence of water. Therefore, it becomes essential

[140]EPA has established drinking water standards for several types of radioactive contaminants -- combined radium 226/228 (5 pico-Curies per liter - pCi/L); beta emitters (4 mrems); gross alpha standard (15 pCi/L); and uranium (30 micrograms per liter - µg/L). Picocurie (pCi) is a term that scientists use to describe how much radiation is in the water. A pCi is a unit that can be directly measured by laboratory tests. From NRC, "Fact Sheet on Tritium, Radiation Protection Limits, and Drinking Water Standards" at http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/tritium-radiation-fs.html and EPA, "Radionuclides in Drinking Water," at http://www.epa.gov/safewater/radionuclides/index.html.
[141]EPA's Proposed Public Health and Environmental Radiation Protection Standards for Yucca Mountain, www.epa.gov/radiation/docs/**yucca**/402-f-05-026.pdf. This standard includes no more than 4 mrem per year from drinking water.
[142]*Technical Basis for Yucca Mountain Standards*, National Academy Press, Washington, DC, 1995.

to understand how much water might infiltrate over the lifetime of the repository. The amount of water that gets to the repository is dependent first on future changes in climate, which could affect the infiltration rate into the mountain.[143] A second direct implication of the oxidizing environment has to do with the potential for corrosion of the waste package material, including the canister. Another set of implications has to do with how fast water travels from the surface to the repository level, some 200 to 300 meters below. Evidence from 1996 suggests that some fractures and faults are associated with fast water pathways, and questions consequently remain as to which fractures in the repository can carry water, what volume of water is carried, and how events like thousand-year storms will affect the system.[144]

The burden will be on DOE to show how water that reaches the waste deposited in the repository may then transport radionuclides through the engineered and geologic barriers to the water table below the repository, mix with what volume of groundwater, and how it eventually is drawn to the surface to be ingested by an individual on the surface. According to NRC regulations and DOE guidelines, DOE must then calculate whether the dose received exceeds the level set for that pre- or post-10,000-year period.

In order to obtain an NRC license for the repository, DOE must show that water reaching the waste will not transport enough radioactivity down through the mountain to the water table and on to Nevada's Amargosa Valley to exceed the permissible dose level at the biosphere. NRC must then make a licensing decision based on the technical adequacy of DOE's analysis.

The area around Yucca Mountain is also seismically and volcanically active. The last major earthquake was a magnitude 5.6 event in 1992 on an unexposed fault about 20 km southeast of Yucca Mountain. Seismic activity could create new fast water pathways and affect indirectly the geochemistry of the repository level. More problematic is the potential for future volcanism at the site, which could result in rapid release of radionuclides into the accessible environment. The potential consequences of volcanic and seismic events for the repository will also be evaluated in the NRC licensing process.

Capacity Constraints

Yucca Mountain has a statutory capacity limit that is less than the amount of spent fuel expected to be produced from currently operating reactors over their licensed lifetimes. Any net expansion of U.S. nuclear power generation would require significantly greater repository capacity than currently established by law for the Yucca Mountain site.

- The *statutory capacity* limit at Yucca Mountain established by the NWPA is 70,000 MTHM, of which 63,000 MTHM is civilian waste and 7,000 MTHM is military waste.[145]
- The *capacity analyzed* in the DOE Yucca Mountain Environmental Impact Statement (EIS) is 119,000 metric tons of commercial and government high-level waste. Some estimates indicate that the total geologic capacity could be above 200,000 metric tons, but there is no analytical consensus for the higher estimates.[146]

[143] Mugrove, M.L. and Schrag, D. "Climate Change at Yucca Mountain: Lessons from Earth History," in A. Macfarlane and R.C. Ewing, Eds., *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*. Cambridge, MA: MIT Press (2006).
[144] Fabryka-Martin, J., Flint, A., Meijer, A., and Bussod, G. "Water and Radionuclide Transport in the Unsaturated Zone," in A. Macfarlane and R.C. Ewing, Eds., *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*. Cambridge, MA: MIT Press (2006).
[145] While 70,000 MTHM is often referred to as a statutory limit, Sec. 114 (d) of NWPA sets it as a limit *for the first repository*, "until such time as a second repository is in operation."
[146] Apted, Mick, et al. "Preliminary Analysis of the Maximum Disposal Capacity for CSNF in a Yucca Mountain Repository," Electric Power Research Institute (2006).

- *Thermal limitations* include the thermal output of the waste and the design temperature of the repository. The current design limits the temperature of the drift (tunnel) walls to 200 degrees Celsius and the temperature of the rock between drifts to below the boiling point of water.

- *Geologic limits* on capacity include the locations of faults and fractures, which should be avoided as much as possible; the extent of the repository rock in all directions; the location of the crystal-filled "holes" in the rock; and the location of the water table, especially to the north and west, where it appears to be higher in elevation.

- *Dose limitations* may ultimately determine the capacity. DOE has yet to demonstrate compliance with radiation dose standards at the design capacity, to be defined in the license application.

Other National Repository Programs

Finland and Sweden provide alternative examples to the U.S. experience with Yucca Mountain. They have smaller nuclear industries than the U.S., and companies set up by their nuclear utilities manage the nuclear waste repository projects. Finland has selected a final site. Sweden is characterizing two sites and plans to choose one and begin construction by 2011. Shipments from reactor sites to the waste sites will be mostly by ship, because reactors and potential repository sites are located along the coast.

The two countries have similar geology (mostly crystalline rock), and both plan to dispose of fuel in a reducing environment below the water table. Both will use copper canisters that, based on natural analogs at numerous ancient (>100 million years old) elemental copper deposits in reducing environments, will ensure that spent fuel will remain encased for millennia. Overall, the repository environment and canister design will reduce uncertainties in repository behavior.

Sweden and Finland have had relatively positive experiences with their publics over nuclear waste disposal. Finland allowed citizens of the affected municipality absolute veto power over the repository site. Sweden, in contrast, allows their affected municipality's veto to be overridden.[147]

Both countries have similar safety rules for repositories. Finland has a two-part radiation dose limit—a quantitative standard of 10 mrem for several thousand years and a less stringent standard of about 40 mrem per year thereafter, which is benchmarked against *terrestrial* radioactivity.[148]

Most importantly, the Finns require *redundant* barriers, with performance targets for each barrier—and that the overall performance target shall be achievable even if any single barrier fails.

It is also instructive to examine the previously cited 2003 IAEA document, "Scientific and Technical Basis for Geological Disposal of Radioactive Waste." It lists radiological criteria for national programs, including "providing similar levels of radiological protection to future generations as are provided at present." The Finnish program closely conforms to that criterion.

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[147] Juhani Vira, "Winning Citizen Trust: The Siting of a Nuclear Waste Facility in Eurajoki, Finland," *Innovations*, Fall 2006, pp. 67-82.
[148] The Finnish standard is defined in STUK Guide YVL 8.4 (23 May 2001).

Cost of Long-term Repository

The cost of building and operating Yucca Mountain as a long-term repository is uncertain. When Yucca Mountain was approved in 2002, the total system life cycle cost (TSLCC) estimate for the Yucca Mountain repository program (in constant 2000 dollars) was $57.5 billion.[149] However, changes in the schedule for completing and licensing the repository, including changes in design and requirements for spent fuel transportation, make this estimate outdated. A revised estimate that would extend cost projections beyond 2023 was promised to Congress by DOE for later in 2007. A total of $6.7 billion has been spent on the repository to date.

The NWPA established the Nuclear Waste Fund (NWF) to finance the portion of repository costs related to disposal of commercial spent nuclear fuel (73%), with the balance from the Defense budget to provide for disposal of high-level radioactive waste from weapons programs and other DOE activities. Annual payments by spent fuel owners to the NWF, which total around $750 million per year, are collected from utilities through an approved fee of 1 mill per kWh for all nuclear generation. DOE reports that the NWF since 1983 has received $15.1 billion in fees along with $10.9 billion in investment

State Restrictions on Nuclear Power Expansion

Existing state restrictions include:

- Hawaii: Hawaii's outright nuclear ban is found in its Constitution, Article XI, Section 8. No nuclear fission power plant shall be constructed or radioactive material disposed of in the state without prior approval by a two-thirds vote in each house of the legislature. Hawaii does not have any nuclear power plants.

- Minnesota (Minnesota Statutes): The Public Utilities Commission may not issue a "certificate of need" for the construction of a new nuclear-powered electric generating plant. Any certificate of need for additional storage of spent nuclear fuel for a facility seeking a license extension shall address the impacts of continued operations over the period for which approval is sought.

- Vermont (Vermont Statutes, Department of Public Service): Construction of a nuclear fission plant is dependent on approval of the general assembly and its determination that construction of the proposed facility will promote the general welfare.

In addition, eight states—California,[150] Connecticut, Illinois, Kentucky, Maine, Oregon, West Virginia, and Wisconsin—have statutes that are virtually identical in language and intent, preventing construction of new nuclear plants within the state absent establishment of (at least) a federal repository. Each of these states empowers a single state entity to make a finding that the U.S., through its authorized agency, has identified and approved a repository, and that there exists a demonstrable technology or means for disposal of high-level nuclear waste.

Two states, Minnesota and Vermont, also limit dry storage:

- The Minnesota legislature limited companies to 17 storage containers until a new law was passed in 2003. The new law gave the authority to grant storage requests beyond this limit to the Minnesota Public Utilities Commission. In September 2006, the Commission granted Xcel permission to store up to 30 storage containers for its Monticello plant, beginning in 2008.

- In Vermont, the legislature has authorized dry storage at the Vermont Yankee nuclear power plant through 2012. Legislative action is required for additional storage capacity beyond that.[151]

[149] *Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program*, DOE/RW-0533 (U.S. Department of Energy, May 2001).
[150] California actually has three separate statutes that deal with the need for a repository before plants can be built.
[151] According to Brian Cosgrove, Entergy's State Government representative.

returns.[152] As of the end of 2006, that leaves a net balance after disbursements to date of $19.3 billion.

Although the NWF was intended to serve as a dedicated trust fund, it is available for investment in Yucca Mountain development only when Congress appropriates it. To date, congressionally appropriated funding for the repository has been consistently and substantially below budget requests.[153]

Failure to Site a Permanent Waste Repository May Affect Nuclear Expansion in Some States

Some states legally restrict the expansion of existing or new nuclear capacity until a long-term solution for waste management is in place. The NJFF group concludes that these statutes make the expansion of nuclear power difficult or impossible in those states that have adopted them. By law, however, spent nuclear fuel disposal is a federal rather than a state responsibility. New nuclear plant construction is fundamentally an investment decision, and widely varying views exist among states and utilities as to how the political and technical challenges facing Yucca Mountain affect prospects for new plant design, construction, and licensing.

Alternative Approaches

The NJFF did not analyze alternative decision-making processes to those used by DOE in the consideration of Yucca Mountain. Other organizations have assessed such alternatives, including the National Research Council of the NAS in a report titled *One Step at a Time.* The Council recommends a so-called "adaptive staging approach" aimed at ensuring that early decisions do not commit the project to a path that later proves inappropriate or unsafe. Adaptive staging seeks to focus attention on utilization of best available knowledge without foreclosing options for future generations who may decide to manage nuclear waste by other means. Similarly, the Nuclear Energy Agency in 2004 published a report titled *Stepwise Approach to Decision Making*, which included a number of recommendations on procedures likely to increase confidence in government decision-making on nuclear waste management and disposal.

Until a Permanent Facility Is Licensed and Built, Interim Storage Is Necessary

With regard to older spent fuel that must be stored on an interim basis until an operating repository is available, the NJFF participants believe that this spent fuel can be stored safely and securely in either spent fuel pools or dry casks, on-site.[154] The NJFF group also agrees that centralized interim storage is a reasonable alternative for managing waste from decommissioned plant sites and could become cost-effective for operating reactors in the future.

Storing spent fuel at reactor sites as an interim measure is today the only waste storage mode for commercial reactors. There are currently about 56,000 metric tons of spent fuel in on-site storage;[155] this would increase to more than 80,000 metric tons by the end of the existing licenses and would expand even further (>120,000 metric tons) given 100% license renewals.[156]

[152] The NWPA authorizes the Secretary of the Treasury to invest the balance of the Fund in securities and to credit interest earned as "investment returns" to the Fund. If funds are insufficient, the Fund can also borrow.

[153] As an example, in FY 2007, Congress appropriated $99 million from the NWF for the repository program. The balance is used for other, unrelated government activities, while crediting the amount borrowed to the NWF balance.

[154] With respect to the safety and security of spent fuel at operating reactors, see Chapter III, "Safety and Security Issues Related to Commercial Nuclear Power Reactors."

[155] Nuclear Energy Institute, "Quantifying Nuclear Energy's Environmental Benefits," http://www.nei.org/doc.asp?catnum=2&catid=43.

[156] See Macfarlane, Allison, "The Problem of Used Nuclear Fuel: Lessons for Interim Solutions from a Comparative Cost Analysis," *Energy Policy*, Vol. 29 (2001), pp. 1379-1389.

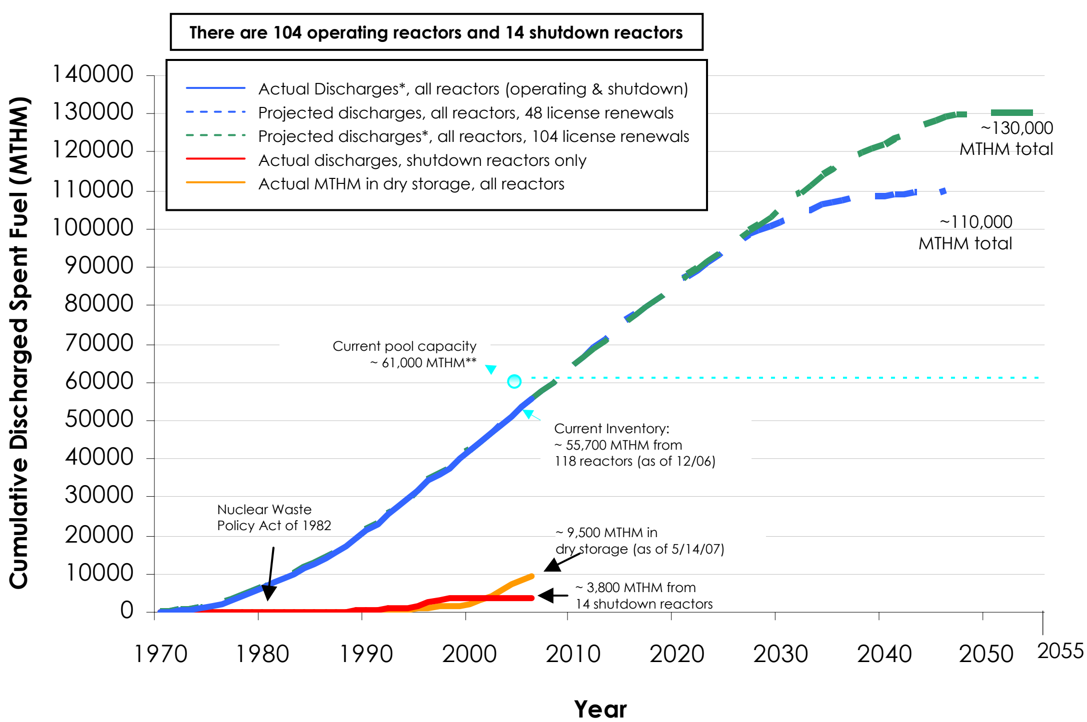
Figure 12, below, shows the current and projected amounts of spent fuel from existing reactors in the U.S. If the Yucca Mountain project cannot be licensed, the NWPA calls for the Secretary of Energy to report to Congress and "make recommendations as to future action, to assure safe, permanent disposal of spent nuclear fuel...including the need for new legislative authority."[157] Three options then exist for used fuel storage: on-site fuel pools, on-site dry cask storage systems or centralized storage in pools or dry casks.

Storage Pools[158]

When removed from a reactor, spent fuel is radioactively and thermally hot. It is stored in storage pools where active circulation cools the radioactive contents. As long as a nuclear reactor is operational, it requires a cooling pool for the hottest spent fuel.

About one-fourth to one-third of the total fuel load is removed to storage pools from the reactor every 18 to 24 months and replaced with fresh fuel. The spent fuel rods are immersed under at least 20 feet of water, which provides adequate shielding from the radiation for anyone near the pool. Spent fuel

Figure 12: Historical and Projected Commercial Spent Nuclear Fuel Discharges as of May 14, 2007



Sources: * Based on actual discharge data as reported on RW-859's through 12/31/02, and projected discharges, in this case, based on 104 license renewals.
** Represents the aggregate industry pool capacity based on pool capacities provided in 2002 RW-859 (less FCR) and supplemented by utility storage plans. However, the industry is not one big pool and storage situations at individual sites differ based on pool capacities versus discharges into specific pools.

[157] NWPA, Sec. 113(c)(3)(F).

[158] See http://www.nrc.gov/waste/spent-fuel-storage/pools.html.

pools have been managed safely in the U.S. and abroad for the past 56 years. They can hold spent fuel for the life of the plant (40-60 years) unless capacity is limited.[159] A discussion of the security risk of spent fuel pools is provided in Section III, "Safety and Security."

When a power plant's pool storage capacity is limited, NRC may approve replacement of existing fuel storage racks with higher density racks constructed with neutron-absorbing materials. Almost all nuclear power plants employ high-density racks now, but only limited additional storage capacity is available through continued re-racking. To allow for more newly discharged spent fuel to be added to pools, older and cooler fuel can be moved to dry cask storage.

Dry Casks

The NRC has authorized 14 models of dry casks.[160] There are currently 9,600 metric tons (MT) of spent fuel in dry cask storage at 41 sites. The Nuclear Energy Institute (NEI) projects that by 2017 there will be 22,300 MT stored in dry casks at 66 sites.[161] Spent fuel may be kept in casks for up to 60 years under current licenses (e.g., the Surry plant in Virginia had its original dry cask systems recertified for an extra/added 40 years beyond the original 20-year certification).

Although fuel pool storage is constrained, the dry storage option generally is not limited by capacity. As noted in the Safety and Security chapter of this report, dry casks provide *passive* cooling compared to the *active* cooling of storage pools and are therefore considered safer than spent fuel pools. However there are additional costs associated with dry cask storage, which are absorbed by either taxpayers or customers.

Current Government Liability for Spent Fuel Management

Owners of nuclear reactors are responsible under the NWPA for on-site spent fuel storage until DOE takes title to the spent fuel or removes it for disposal. Initial waste acceptance was to have begun by January 31, 1998. Utilities that operate nuclear power plants have sued DOE to recover the cost of storage beyond the statutory date of 1998, and federal courts have found DOE liable for damages. The U.S. Federal Court of Claims is processing the various individual damage cases. DOE has reached settlements in a few cases for costs incurred at the time of the settlements and has estimated the total storage liability to be $7 billion if the Yucca Mountain repository can begin waste acceptance by 2017 and approximately $500 million for each year of further delay past that date.[162]

The American Physical Society estimates that the cost of moving fuel to dry cask storage at all 103 active reactors and 14 shut-down reactors will be in the range of $400 million per year. This is comparable to DOE estimates of $500 million per year and within the "range of uncertainties."[163] DOE has made no recommendations for alternatives to on-site storage, other than to continue with repository development. Because the costs are for extended on-site storage are borne by either utility customers or taxpayers, they cannot be considered net costs but rather are considered as transfer payments.

[159] For power reactor licensees that select the SAFSTOR (safe storage) decommissioning option, up to an additional 50-55 years of wet storage could be utilized and still meet the 60-year decommissioning timeframe required by NRC regulation 10 CFR 50.82(a)(3). See NRC RG 1.184, "Decommissioning of Nuclear Power Reactors."

[160] NRC (10 CFR Part 72.214) as of 11/3/06. Available at http://www.nrc.gov/reading-rm/doc-collections/cfr/part072/part072-0214.html. Also see http://www.nrc.gov/waste/spent-fuel-storage/designs.html.

[161] Steven Kraft, Nuclear Energy Institute, Presentation at NRC Regulatory Information Conference, March 14, 2007.

[162] Edward F. Sproat III, Department of Energy testimony to the Senate Energy and Water Development Appropriations Subcommittee, March 7, 2007.

[163] American Physical Society, Panel on Public Affairs, "Consolidated Interim Storage of Commercial Spent Nuclear Fuel: A Technical and Programmatic Assessment" (February 2007). http://www.aps.org/policy/reports/popa-reports/upload/Energy-2007-Report-InterimStorage.pdf.

Centralized Storage

Current dry cask systems exist almost entirely at the sites of operating and decommissioned reactors. A centralized interim storage facility may provide benefits beyond status quo storage, but its development would face challenges, including cost and siting.

Centralized interim storage makes particular sense for waste currently stored at decommissioned reactors. It would allow more efficient oversight of the spent fuel at a consolidated central facility and would also allow the land at decommissioned reactor sites to be reclaimed and developed. In addition, if a permanent geologic repository is not constructed for another 40 or 50 years, centralized surface storage facilities may make economic sense for spent fuel currently stored at operating reactors and allay concerns that it may be left at the central storage sites indefinitely.

Centralized Storage Facilities for Spent Fuel

Notable centralized facilities are CLAB in Sweden and Gorleben in Germany. There are two NRC-licensed centralized interim storage sites in the U.S., at the Idaho National Laboratory. One is for storage of Three Mile Island fuel debris, and the other holds spent fuel from the decommissioned Peach Bottom and Shippingport reactors and various research reactors. Private Fuel Storage LLC, a utility consortium, received a license from the NRC in 2006, but it has not been built. No other away-from-reactor central storage facilities have been built since the NWPA was enacted in 1982.

Cost of Centralized Storage

A recent study of centralized interim storage found no compelling cost savings to the federal government. The American Physical Society noted that there would be no savings "so long as Yucca Mountain is not delayed well beyond its currently planned opening" in 2017.[164] The study further noted that the panel "is aware of no rigorous cost estimates showing whether or when consolidated interim storage might become an economically attractive option in the face of significant delays in opening the repository."

Private Fuel Storage LLC (PFS) has received a license to store up to 40,000 tons of spent fuel at a centralized site belonging to the Skull Valley Band of the Goshute Indians in Utah. Storage was premised on its being cheaper for members and other utilities to send their material to the site and pay a storage fee, instead of building additional storage at individual sites.[165] In a proposal submitted to the U.S. Senate's Energy and Natural Resources Committee in December 2005 and later to DOE, PFS offered to store up to 40,000 tons for $60 million per year. Although this projected cost was less expensive than what the courts have approved as payments to utilities, the proposal faced siting opposition, and the utilities have yet to build the facility.

Siting Centralized Storage

Centralized storage may be politically difficult to site, given concerns that such sites could become "permanent" if Yucca Mountain does not become a reality. Efforts to site the PFS project met with strong opposition from the state of Utah. Similar opposition was raised by the state government in Tennessee in the 1980s to a proposed "Monitored Retrievable Storage" facility near Oak Ridge. Given the strength of opposition to previous siting efforts and recent adverse land-use decisions by the Department of the

[164] *Ibid.*

[165] If a reactor produces approximately 25 tons of waste per year, the 40,000 tons of storage is approximately equal to the waste produced by 40 reactors over a 40-year lifetime. $60 million per year for 40 reactors is only $1.5 million per reactor, which is far less than what the courts have approved, although the court awarded damages for past added storage costs stemming from the government's failure to remove the spent fuel.

Interior, it is unlikely that the PFS facility will be built, even though the NRC has granted a license for it.

The PFS experience might be indicative of how the prospect of interim storage would be received at other potential sites. A number of governors reacted strongly to a proposal that was included in the U.S. Senate Appropriations Committee markup of the FY 2007 Energy and Water budget (Sec. 313 of H.R.5427), which would have authorized DOE to establish "Consolidation and Preparation" facilities in each state that has a commercial nuclear reactor and storage of spent fuel from reactors in the state for up to 25 years. After that, the waste would be moved either to the repository or to a reprocessing facility. In objecting to the proposal, one governor wrote, "Such a strategy is riddled with economic, political and security challenges, which are likely to be insurmountable and most certainly will result in years, if not decades, of delay in solving this critical national problem."[166] No further legislative action has been taken on the proposal.

A suggested different approach for centralized storage would be to create a small facility.[167] As indicated in Figure 12, 3,800 MT of spent fuel is currently in storage at shut-down reactors. A small facility would reduce the concern that it might become a *de facto* repository. To minimize transportation costs, such a facility might be sited in the East or Midwest, near the highest concentration of reactors. However, this concept is also untested.

Centralized Storage for Waste from Decommissioned Reactors

Spent fuel currently is stored at 14 shut-down plant sites. By choice, the spent fuel is either in wet storage, dry storage, or both. In most cases, all other reactor components and support structures were removed from the sites during the decommissioning process, leaving the spent fuel storage facility as the sole remnant of previous operations at the locations. The facilities are no longer generating revenue, and a small staff is maintained at the sites solely for oversight of the spent fuel.

A centralized facility that took all the spent fuel from decommissioned reactors would reduce the number of spent fuel installations, provide for consolidated and more efficient oversight of the waste, and allow the decommissioned sites to be reclaimed for other purposes. Furthermore, centralizing the management of the waste would relieve plant owners of the ongoing liability for facilities that no longer generate revenue and would provide a framework for DOE's assumption of direct responsibility for management of spent fuel.

Establishing small-scale regional storage facilities could address the concerns about "orphan" waste at decommissioned plant sites. Indeed, the American Physical Society study found that consolidated interim storage could facilitate the decommissioning of sites with reactors that have been shut down.[168] For example, if waste must be repackaged before it can be emplaced in Yucca Mountain, a centralized facility could provide consolidated fuel handling, eliminating the need at each shut-down reactor. Further, if the final Yucca Mountain design requires a buffer storage area so that a mix of wastes can be used to meet heat load requirements, this could also be done at a centralized facility.

[166] Letter from Pennsylvania Governor Edward G. Rendell, October 16, 2006.
[167] See Macfarlane, Allison, "The Problem of Used Nuclear Fuel: Lessons for Interim Solutions from a Comparative Cost Analysis," *Energy Policy*, Vol. 29 (2001), pp. 1379-1389.
[168] American Physical Society, Panel on Public Affairs, "Consolidated Interim Storage of Commercial Spent Nuclear Fuel: A Technical and Programmatic Assessment" (February 2007). http://www.aps.org/policy/reports/popa-reports/upload/Energy-2007-Report-InterimStorage.pdf.

NWPA Had Provisions for Some Interim Storage Along with Monitored Retrievable Storage

The NWPA envisioned a need for some centralized interim storage for commercial spent fuel, but none has been established. NWPA Subtitle B provided for an interim storage program to be developed on a limited scale and operated by DOE, storing no more than 1,900 MT of commercial spent nuclear fuel. Operation was to have begun by 1990. No action resulted, and DOE now considers that its authority has lapsed. In 1987, NWPA was amended to allow DOE to establish one or more monitored retrievable storage facilities to provide long-term centralized storage of high-level radioactive waste or spent nuclear fuel. Section 145 of NWPA states that no monitored retrievable storage facility may be constructed in the state of Nevada.

DOE has so far rejected responsibility for direct management of interim storage, although Department officials say they are keeping an open mind on interim storage. There have been various legislative proposals to amend the NWPA to authorize DOE to establish an interim storage facility at Yucca Mountain before the repository is licensed; all but one died in Congress. The most recent congressional initiative took place in 2000, when President Clinton vetoed a bill (S. 1287) that would have provided interim storage at Yucca Mountain.

Transportation

There is wide agreement among the NJFF group participants that transport of spent fuel and other high-level radioactive waste is highly regulated, and that it has been safely shipped in the past. Security requirements during transport have been enhanced in response to 9/11; however, transport security will require continued vigilance. Transport of spent fuel to any repository will take many years to complete, and will require ongoing regulatory oversight.

Since 1965, there have been more than 2,700 relatively small shipments of spent nuclear fuel in the U.S., covering more than 1.6 million miles. In that time, there have been four rail accidents and four highway accidents. There were no injuries, no breach of the containers, and no release of radioactivity. Since the 1970s, the Navy has shipped spent fuel by rail from ship and submarine reactors to a DOE facility in Idaho. More than 70,000 MT of spent fuel has been shipped in Europe, over shorter distances but through more densely populated areas. For many years, Japan shipped its spent fuel to the United Kingdom and France for reprocessing, using various routes including passage through the Panama Canal.

In the U.S., all shipments of spent fuel and HLW are regulated by the federal government and the individual states. Under the NWPA disposal program, DOE and commercial carriers will plan and conduct spent fuel shipments under extensive federal regulations for rail, highway, and water modes.[169] DOE has been working with regional organizations of state agencies with radioactive materials transportation responsibilities. DOE is expected to follow existing state-federal agreements and NWPA mandates, such as

[169]The DOE regulations are 49 USC 5101-5127. The NRC radioactive materials transportation regulation is 10 CFR Part 71. There are also DOT regulations by the various modal agencies (and the Coast Guard, which is now part of Homeland Security).

notifying the governors' offices when shipments are scheduled to move through each state. Interstate transportation protocols have been in place for the several decades that nuclear material has been shipped across the U.S. The management of this ultimate shipping campaign will be complicated by the multiple interests of the associated government agencies and stakeholders.

All spent fuel and HLW shipments will be transported in containers the NRC has certified to withstand severe accident conditions.[170] The containers provide necessary shielding for the radiation under both routine and accident conditions. To gain NRC certification for their containers, vendors must demonstrate that the casks meet specified tests, including a 30-foot drop onto an unyielding surface, a puncture test, exposure to a fully engulfing fire for 30 minutes at 1,475° F, and submersion in water for 8 hours—in that sequence.[171] Spent fuel transport casks are heavily shielded, with walls that are between 5 and 15 inches thick, depending on materials. Truck casks contain 1 to 2 tons of spent fuel and weigh about 25 tons. Rail casks contain 15 to 20 tons of spent fuel and weigh about 100 tons. Truck casks have a capacity of about 2 MTHM per cask, and rail casks may have a capacity of 6 to 12 MTHM each.[172]

Repository Shipment Planning

If the Yucca Mountain repository becomes licensed, spent fuel will have to be transported from various commercial and DOE sites to the repository. The cost of transporting the fuel is covered by the NWF in the Congressional appropriations process.

For Yucca Mountain repository shipments, up to the 70,000 metric ton level, DOE has indicated that it intends to use a "mostly rail" shipment method. DOE is planning to build a new rail line from Caliente, NV, to Yucca Mountain, taking a rather long route to avoid Nellis Air Force Range and a large portion of the Nevada Test Site. Preliminary cost estimates for the construction of a rail connection to the repository site over different routes have ranged from $880 million to more than $2 billion. DOE is preparing an EIS for the Nevada rail line that will address the Caliente route and another route that may be less expensive. It is scheduled for completion in 2008.

Under DOE's "mostly rail" approach, rail will be used to move materials from all 77 sites that have direct rail access or, perhaps, short heavy-haul highway or barge distances to a railhead. Otherwise, shipments will be made by legal-limit trucks. Further, DOE has stated that it will ship spent fuel in dedicated trains rather than mixed freight shipments. All shipments will be tracked electronically and will have armed escorts. Special cars for spent fuel shipments will meet Association of American Railroads standards, including improved brake performance.

Detailed shipment plans for each originating point have not been set yet, nor have routes been selected. DOE will develop those plans in consultation with utilities, states, and carriers. Shipment rates will begin with 900 MT the first year, building to a steady rate of 3,000 MT/year after 5 years. Total shipments for 70,000 MT are expected to take 24 years, starting in 2017 or later, depending on repository licensing and construction schedules. In the mostly rail scenario, DOE estimates that there will be 4,300 shipments arriving at the repository over 24 years or an average of 175 shipments each year.[173] (If trucks are used predominantly, the number of vehicles and shipments involved will, of

[170] See also Sec. 180(c) of NWPA, which provides that DOE will provide technical assistance and funds (from the Nuclear Waste Fund) to States, Indian tribes, and local governments for training in emergency response preparedness along transportation routes to the repository.

[171] The NRC conducted a simulation of a fire in the Howard Street tunnel in Baltimore, Maryland. NRC staff concluded that there would be no release of radioactive materials from this postulated event, and that existing programs provide reasonable assurance of adequate protection to the public. http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2003/secy2003-0002/2003-0002scy.html#conclusion.

[172] Per Yucca Mountain Draft EIS, Table J-2.

[173] This implies that the average cask would carry about 16 metric tons of spent fuel. Thus, the shipment number assumes very little transport by truck.

course, be substantially larger.) This compares to over 300 million hazardous material shipments per year in the U.S., of which 3 million are shipments of various types of radioactive materials—mostly, low-level radioactive materials that do not require accident-resistant packaging.

In 1977, the NRC completed a Final Environmental Impact Statement on transport of radioactive materials of all types and all modes (NUREG-0710), concluding that existing regulations for such shipments (10 CFR Part 71) are "adequate to protect the public." Other studies were done pertaining to various transportation scenarios, concluding with "Reexamination of Spent Fuel Risk Assessments" (NUREG/CR-6672) in 2000. That study found that the 1977 risk assessments were conservative. After September 11, 2001, the NRC issued orders to licensees[174] to increase security in the transportation of specific types of radioactive materials, including spent fuel shipments.[175]

One Waste Management Option with the Potential to Impact Waste Storage and Disposal Decisions Is Reprocessing

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No commercial reprocessing of nuclear fuel is currently undertaken in the U.S. The NJFF group agrees that while reprocessing of commercial spent fuel has been pursued for several decades in Europe, overall fuel cycle economics have not supported a change in the U.S. from a "once through" fuel cycle. Furthermore, the long-term availability of uranium at reasonable cost suggests reprocessing of spent fuel will not be cost-effective in the foreseeable future. A closed fuel cycle with any type of separations program will still require a geologic repository for long-term management of waste streams.

Current spent fuel reprocessing techniques separate uranium and plutonium from fission products and actinides. Existing reprocessing technology was originally developed to obtain plutonium for weapons. Commercial reprocessing in this country was indefinitely deferred by Presidents Gerald Ford and Jimmy Carter due to concerns over costs and nuclear weapons proliferation.[176]

The only existing commercial method to reprocess spent nuclear fuel is known as PUREX. In this process, plutonium is extracted separately from uranium, both of which can be reused in nuclear fuel.[177] The wastes from PUREX include fission products, actinides (elements on the periodic table from thorium and higher), and cladding hulls and contaminated equipment. In the U.S., a commercial plant used the PUREX separation process at West Valley, NY, from 1966 to 1972. Operations at West Valley were capable of processing 1 ton/day, or about 300 tons/year, of spent fuel.[178] The French currently use this technology at their La Hague facility, which operates at 800 tons/year (capacity is 1,700 tons/year). Also,

[174] http://www.nrc.gov/reading-rm/doc-collections/enforcement/security/2002/fr10102002.pdf.

[175] http://www.nrc.gov/security/faq-911.html#2.

[176] The immediate issue before President Ford was whether to subsidize the Barnwell plant, which faced delays and likely cost overruns.

[177] While this is true in principle, uranium is not reused.

[178] The West Valley plant was shut down due to difficulties in retrofitting the plant to meet new regulatory requirements and difficult negotiations with state and federal regulators that could not be resolved. The plant transferred management and storage to the New York State Energy Research and Development Authority (NYSERDA). See Federation of American Scientists, "Recovery from Spent Fuel Reprocessing by Nuclear Fuel Services at West Valley, New York." http://www.fas.org/main/content.jsp?formAction=297&contentId=532.

the THORP facility in the UK and operations in Japan, China, India, and Russia all use or used the PUREX process.

A reprocessing-based fuel cycle system is many times more expensive than a once-through fuel cycle system, as documented in other studies.[179] This is unlikely to change as long as the supply of uranium and the costs of mining and processing uranium remain within current projections. However, fuel cycle market conditions in the future may drive a reassessment of these economics.

According to the Organization for Economic Cooperation and Development-Nuclear Energy Agency (OECD-NEA), there are approximately 4 million metric tons of uranium (MMTU) that can be mined from conventional sources at prices less than $80/kg, and a total of approximately 5 MMTU at prices less than $130/kg.[180] This is enough to meet current world requirements for 80 to 90 years, and both prices are substantially lower than current spot market prices. Uranium prices in the future will depend heavily on how quickly uranium mining and enrichment capacity can be expanded and how quickly the nuclear industry expands. Currently identified resources are sufficient to support growth in nuclear capacity of 20% to 40% over next two decades.

The NEA estimates that an additional 22 MMTU could be recovered from phosphate deposits. The equivalent of about another 0.6 MMTU is stored in depleted uranium inventories but would require considerable enrichment capacity to "mine." At high and somewhat uncertain cost, an almost unlimited supply of uranium could theoretically be extracted from sea water and very low grade ores (e.g., granite).

Reprocessing and Waste Management

Reprocessing of spent nuclear fuel does not eliminate the need for a geologic repository, because there is residual high-level waste from the reprocessing stream that needs to be sequestered in a geologic repository. Reprocessing as currently practiced does not significantly reduce capacity requirements at Yucca Mountain, because the repository capacity is ultimately dependent on heat loading rather than volume. While reprocessing decreases the volume of high-level waste, the volume of low-, and intermediate-level wastes substantially increases. These additional radioactive waste streams need to be disposed of in facilities that require siting and must be managed.

Research

There is disagreement among the members of the NJFF as to the desirability of research on reprocessing technologies but general agreement that reprocessing technology research as proposed in the GNEP program is unlikely to secure congressional support and public and industry acceptance. There is agreement that research should continue on waste management technologies related to geologic disposal, on waste stream reduction technologies, on other methods of dry storage, and on optimization of the once-through fuel cycle, including the once-through thorium fuel cycle.

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[179] Deutch, Moniz. "Future of Nuclear Power," MIT.

[180] OECD Nuclear Energy Agency, "Uranium 2005—Resources, Production, and Demand" (June 2006). http://www.nea.fr/html/general/press/2006/redbook/.

Global Nuclear Energy Partnership

In 2006, the Bush Administration proposed a Global Nuclear Energy Partnership (GNEP)[181] to help expand nuclear power in the U.S. and abroad by attempting to reduce proliferation risks and reduce the number of geologic repositories or capacity requirements for geologic disposal of nuclear waste. From a waste management perspective, there are many potential problems with the GNEP concept:

- The proposed development of a more advanced reprocessing technology (UREX+) remains vague on both technological viability and cost-effectiveness. Furthermore, a rationale for the type of reprocessing proposed by GNEP is that extracting plutonium plus neptunium from the fuel cycle will make it more difficult (though by no means impossible) to make a nuclear weapon. The rationale is questionable, given that the critical mass for neptunium is not significantly greater than that for uranium-235 and, unfortunately, it is therefore entirely usable in a nuclear weapon.

- The proposal to extract short-lived fission products is designed to reduce the heat impact on the repository by storing the cesium and strontium in surface or subsurface facilities. Although storing those fission products may provide flexibility in repository operations, it will also add new waste management challenges overall, and fission products may be left above ground for hundreds of years.

- The proposal to build a fast reactor that can consume or destroy both plutonium and higher actinides represents a revival of a technology option that has been repeatedly rejected by U.S. policymakers. Developing fuel for such a reactor is but one of the technologically problematic aspects of GNEP. The other is the incompatibility between the commitment of civilian nuclear plant operators to move ahead with standardized reactor design of proven technology and the federal government's intent to commit to fast reactor designs that are unlikely ever to be adopted by industry. Fast reactors are substantially more expensive than light-water reactors, would require open-ended Federal investment, and would complicate the economic considerations for investment in new reactors.

- DOE's Advanced Fuel Cycle Initiative includes an effort to develop new reprocessing technologies for fast reactors,[182] but the kind of fuel has not yet been decided upon.

- The proposal that nations rely on U.S. and other supplier states for manufactured fuel, in exchange for their agreement not to develop their own reprocessing or enrichment facilities, is untested. It would appear unlikely that rogue states determined to develop nuclear weapons capability would be persuaded to give up their ambitions in exchange for a U.S.-provided fuel supply. Further, some feel that fuel assurance is not necessary in the first place.

Chapter V of this report, "Proliferation Risks," includes more discussion of GNEP.

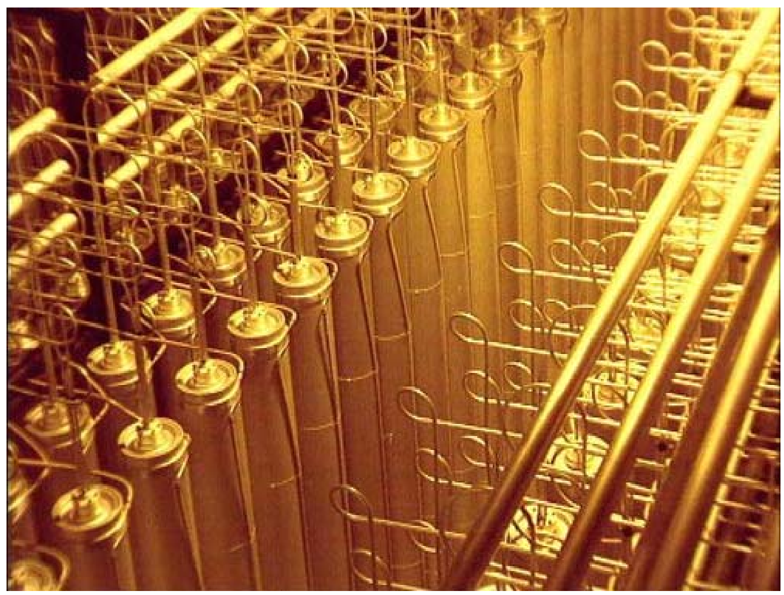
[181] For more from the Department of Energy on GNEP, see http://www.gnep.energy.gov.
[182] http://www.id.doe.gov/GNEP/06-GA50506-04.pdf.

V. Proliferation Risks

Expansion of nuclear power in ways that substantially increase the likelihood of the spread of nuclear weapons is not acceptable.

Concerns about nuclear weapons proliferation[183] from the commercial nuclear fuel cycle arise from fact that the principal explosive fissionable materials,[184] plutonium and highly enriched uranium (HEU), can be used either as a nuclear fuel or to produce nuclear weapons, and the principal facilities for their production can be used for either civil or weapons purposes, or both (see Appendix F: Fuel Cycle Overview). The proliferation issue is much broader than the risks associated with nuclear power; however, if growth in commercial nuclear power plants also results in the construction of fuel cycle facilities in countries that do not now possess nuclear weapons, the risk of proliferation will increase.

The State and Non-State Threat and Existing Safeguards



Proliferation can be facilitated by either national governments (state actors) or through sub-national, terrorist organizations (non-state actors). Weapon-usable materials can be obtained from other states or from non-state actors, or they can be developed by the non-nuclear weapons states using dedicated facilities or safeguarded civilian nuclear fuel cycle facilities.

Today there is a collection of treaties, agreements, and commitments that are applied to peaceful uses of nuclear energy and are designed to reduce the likelihood that special fissionable and other materials, services, equipment, facilities, and information will be used to further any military purpose. This collection of agreements, often referred to as the "international safeguards regime," includes: the Treaty on the Non-Proliferation of Nuclear Weapons, also known as the Nuclear Non-Proliferation Treaty (NPT); the numerous International Atomic Energy Agency (IAEA) safeguards agreements; the Treaty on the Prohibition of Nuclear Weapons in Latin America (Tlatelolco Treaty); the Trigger List; and the Zanger Committee. The objective of the international safeguards regime is to limit the potential spread of nuclear weapons to non-weapon states.

[183]For the purposes of this report, the NJFF group considers both state and non-state threats as proliferation concerns.
[184]Explosive Fissionable Material (EFM) is any fissionable material that can be, or potentially can be, assembled into a bare or reflected fast neutron supercritical state resulting in an explosive disassembly.

The IAEA is the international institution responsible for safeguarding civil nuclear activities in non-weapon states. As set forth in Article III.1 of the NPT, a primary purpose of IAEA's safeguards system is "to prevent diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices by the threat of timely detection." (In this context, timely detection means "in time to do something about it.") The IAEA "safeguards" system relies primarily on a system of inventory accounting requirements and inspection of declared facilities.

More recently, in states that have signed the Additional Protocol to their respective IAEA agreements, safeguards have been expanded to include inspection of suspect or undeclared facilities to assess compliance with the state's requirement to declare all its nuclear activities to the IAEA. The IAEA is not responsible for physical security or the adequacy of physical security programs at nuclear facilities. Physical security is ultimately the responsibility of the nation states. The degree of physical security at fuel cycle facilities varies among states.

Over the past 65 years, at least 22 countries have pursued nuclear weapon programs,[185] many on a clandestine basis and some in violation of both the NPT and their respective safeguards agreements with the IAEA. Five of these were original weapons-state parties to the NPT, and five more have developed nuclear arsenals (i.e., multiple warheads and possible delivery systems), although some in the latter category have given up that capacity. Both the trade press and the popular press have also reported growing interest in nuclear power on the part of such nations as Saudi Arabia, the United Arab Emirates, Turkey, Egypt, Yemen, Syria, Vietnam, Indonesia, Nigeria, Bangladesh, and many other small nations.[186]

The NJFF participants agree that there are critical shortcomings in the current IAEA safeguards and that the international community has not demonstrated that the enforcement mechanisms are effective.

First, the IAEA "safeguards" are currently unable to provide timely detection when weapon quantities of HEU and plutonium are diverted. This is in part because "conversion times" (defined as the time required to convert different forms of nuclear material to the metallic components of a nuclear explosive device) are short compared to the IAEA timeliness detection goals used to define the frequency of inspections (see Table 8). With regard to the IAEA's timeliness detection goals, it should be noted that the Agency's resource limitations and the resistance of member countries keep the actual inspection frequencies lower than the goals.[187]
(continued on page 88)

[185]The Unites States, the Soviet Union/Russia, the United Kingdom, France, and China are the original nuclear weapon-state parties to the NPT. Israel, India, Pakistan, South Africa, and North Korea have developed nuclear weapons. Japan and Germany had nuclear weapon development programs during World War II, and Sweden, Switzerland, Taiwan, South Korea, and Argentina after World War II. Brazil, Iraq, Iran, Libya, and Yugoslavia have had secret nuclear weapon development programs but have not developed such weapons.
[186]World Nuclear Association, "Emerging Nuclear Energy Countries," February 2007; and William Broad and David Sanger, "With Eye on Iran, Rivals Also Want Nuclear Power," *New York Times*, April 15, 2007.
[187]This point with regard to light-water reactor inspections is made by Victor Gilinsky, Marvin Miller, and Harmon Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors* (Washington, DC: The Nonproliferation Policy Education Center, September 2004), p. 22.

Table 8: Estimated Material Conversion Times and Inspection Goals

Beginning Material Form	Conversion Time	Inspection Goals
Plutonium (Pu), highly enriched uranium (HEU), or uranium-233 (^{233}U) metal	7 to 10 days	1 month
PuO_2, $Pu(NO_3)_4$ or other pure Pu compounds HEU, ^{233}U oxide, or other pure uranium compounds Mixed-oxide fuel (MOX) or other non-irradiated pure mixtures containing Pu and uranium (^{233}U + ^{235}U ≥20%) Pu, HEU, and/or ^{233}U in scrap or other miscellaneous impure compounds	1 to 3 weeks[a]	
Pu, HEU, or ^{233}U in irradiated fuel	1 to 3 months	3 months
Uranium containing <20% ^{235}U and ^{233}U Thorium	3 to 12 months	1 year

[a]This range is not determined by any single factor; however, the pure Pu and uranium compounds will tend to be at the lower end of the range and the mixtures and scrap at the higher end.
Source: International Atomic Energy Agency, *IAEA Safeguards Glossary*, 2001 Edition, International Nuclear Verification Series No. 3 (Austria, 2003), Table I, p. 22.

IAEA Safeguards Terminology

Conversion time is the time required to convert different forms of nuclear material to the metallic components of a nuclear explosive device. Conversion time does not include the time required to transport diverted material to the conversion facility or to assemble the device, or any subsequent period. The diversion activity is assumed to be part of a planned sequence of actions chosen to give a high probability of success in manufacturing one or more nuclear explosive devices with minimal risk of discovery until at least one such device is manufactured.[188] The conversion time estimates applicable at present are shown in Table 8.

The **IAEA timeliness detection goals**[189] are the target detection times applicable to specific nuclear material categories.[190] These goals are used for establishing the **frequency of inspections**[191] and safeguard activities at a facility or a location outside facilities during a calendar year, in order to verify that no abrupt diversion[192] has occurred. Where there is no additional protocol in force, or where the IAEA has not drawn and maintained a conclusion of the absence of undeclared nuclear material and activities in a state,[193] the detection goals are as follows:

- 1 month for unirradiated direct use material
- 3 months for irradiated direct use material
- 1 year for indirect use material**.**

Longer timeliness detection goals may be applied in a state for which the IAEA has drawn and maintained a conclusion of the absence of undeclared nuclear material and activities.[194]

[188]*IAEA Safeguards Glossary*, 2001 Edition, p. 22, No. 3.13.
[189]*IAEA Safeguards Glossary*, 2001 Edition, p. 24, No. 3.20.
[190]*IAEA Safeguards Glossary*, 2001 Edition, p. 33, No. 4.24.
[191]*IAEA Safeguards Glossary*, 2001 Edition, p. 88, No. 11.16.
[192]*IAEA Safeguards Glossary*, 2001 Edition, p. 21, No. 3.10.
[193]*IAEA Safeguards Glossary*, 2001 Edition, p. 99, No. 12.25.
[194]*IAEA Safeguards Glossary*, 2001 Edition, p. 24, No. 3.20.

(continued from page 86)
Second, the significant quantities (SQ) limits are significantly larger than the amount of material needed to make a nuclear weapon.[195] SQ is defined as the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded.[196] Bulk handling facilities constitute a special problem in detecting diverted materials, because there is commonly uncertainty in the inventories (called "inventory differences," or "material unaccounted for") of some materials in liquid or powder form. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with the minimum amount of material necessary for a nuclear explosive.

While there have been efforts in the past to preclude non-weapons states from acquiring reprocessing or enrichment technologies themselves (e.g., by amending the NPT and IAEA safeguards agreements), those efforts have not always been successful. Iran, for example, asserts that its clandestine centrifuge enrichment facility is consistent with NPT treaty obligations, despite the fact that its development was in violation of Iran's IAEA safeguards agreement and the NPT.

The NJFF participants agree that a principal proliferation concern is the diversion or theft of material from bulk fuel handling facilities (e.g., reprocessing, enrichment, mixed oxide fuel fabrication, and plutonium storage facilities) to develop weapons capability.

Non-weapons states obligated by treaty not to develop a nuclear weapon could acquire weapons-grade material through a number of means, including:

- construct and operate either an ostensibly commercial or dedicated enrichment plant for production of enriched uranium, usable for production of HEU
- use an exclusively commercial enrichment plant to train operators and as a cover to import equipment for a clandestine enrichment facility
- reconfigure a commercial enrichment plant for the production of HEU for weapons in violation of the NPT and IAEA safeguards
- build and operate either a declared or clandestine reprocessing facility for separating weapons-usable plutonium from spent commercial fuel
- divert separated plutonium for weapons purposes from a mixed-oxide fuel (MOX) fabrication plant.

Currently, there are 11 countries with operating enrichment facilities, some with more than one plant.[197] An additional several plants are under construction or planned. Four non-weapon states—Brazil, Japan, Germany, and the Netherlands—have operating gas centrifuge enrichment plants, and Iran is constructing a plant. It is a relatively simple matter to use enrichment technology to produce either light-water reactor fuel or HEU. Small gas centrifuge facilities, if clandestinely operated, are considered to be very difficult to detect because of their small footprint and low electric power requirements.

The amount of fissile material necessary to make a nuclear weapon depends heavily on weapons design. It can be as much as 5 to 10 kilograms of highly enriched uranium or as little as 1 to 3 kilograms of plutonium.[198]

[195] Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons," Natural Resources Defense Council, Revised 13 April 1995.
[196] The SQ for plutonium is 8 kg; the SQ for HEU is 25 kg.
[197] Brazil, China, France, Germany, India, Japan, Netherlands, Pakistan, Russia, United Kingdom and the United States.
[198] Thomas B. Cochran and Christopher E. Paine, *The Amount of Plutonium and Highly Enriched Uranium Needed for Pure Fission Nuclear Weapons* (Washington, DC: Natural Resources Defense Council, revised April 13, 1995), http://www.nrdc.org/nuclear/fissionw/fissionweapons.pdf.

The enrichment requirements to obtain a nuclear weapon can be substantially reduced if the feed for the enrichment plant is low-enriched uranium.[199]

Growing stocks of civilian separated plutonium (250 tonnes and growing at a rate of 10 tonnes/yr) pose a significant proliferation risk and require extraordinary protection and international attention. Diversion or theft of these stocks represents a risk of weapons development by sub-national terrorist organizations. Levels of physical protection and risk vary widely from country to country.

Five countries currently operate commercial nuclear fuel reprocessing plants.[200] Japan is constructing a new large reprocessing plant, and there are small reprocessing operations in other countries. A larger number of countries have sent spent fuel to be reprocessed in some of these plants. The result of this reprocessing is large stockpiles of separated plutonium awaiting use or disposal (see Table 9).

While a number of countries have reprocessed spent fuel, few have used the separated plutonium as fuel in light-water reactors, mainly because such "mixed oxide" fuel is currently more expensive than using enriched natural uranium, and in some cases its use has met with public resistance. Plutonium stockpiles have, therefore, grown to approximately 250 tonnes declared to the IAEA, or about the level of separated plutonium in the military sectors of declared weapons states.[201]

There are three options for dealing with the risk posed by civilian separated plutonium. First, it can be stored indefinitely. Doing so requires a very high level of physical protection to prevent diversion or theft. IAEA safeguards, which do not provide physical security, are of little value. Some of the material is in non-weapons states, most of which are unlikely to use it for a weapons program; however, several have considered this option.

Table 9: Estimated Quantities of Civilian Separated Plutonium by Country

Country	**Civilian Pu Stock at End of 2005 (Tonnes)**
Belgium	3.3 (plus 0.4 in France)
France	81.0 (30 foreign-owned)
Germany	12.5 (plus 15 in France and UK)
India	5.4
Japan	5.9 (plus 38 in France and UK)
Russia	41.0
Switzerland	<2.0 (in France and UK)
UK	105.0 (27 foreign owned plus 0.9 abroad)
Total	**250.0**

Source: F. von Hippel, *Managing spent fuel in the United States: The Illogic of Reprocessing, International Panel on Fissile Materials* (January 2007).

[199]Enrichment is not a linear process. Depending on operation of enrichment plant, as much as 80% of the work required to enrich natural uranium (0.711 percent) to weapons grade done in going to fuel grade (4 percent). Thus, if fuel grade material is used as a feedstock for enrichment, the time and effort to enrich to weapons grade is lower than one might otherwise imagine

[200]France, Russia, India, Japan.and the United Kingdom.

[201]Macfarlane, Allison, "The Problem of Used Nuclear Fuel: Lessons for Interim Solutions from a Comparative Cost Analysis," *Energy Policy*, Vol. 29 (2001), pp. 1379-1389.

Second, the plutonium can be fabricated into MOX fuel, burned in reactors, and converted to spent fuel.[202] This option poses additional proliferation risks associated with potential diversion from MOX fuel fabrication plants or during transportation. Finally, the plutonium can be "diluted" by adding it to materials that would allow for permanent underground storage with low risk of criticality.[203] Immobilizing separated plutonium in a rock-like form and disposing of it in a permanent underground storage facility is the least expensive of the three options.

Large stocks of HEU present similar security risks, but they are primarily associated with research, naval fuel, and nuclear weapon programs, as opposed to commercial nuclear power facilities.

Programs and Initiatives Intended to Limit Proliferation

There are a variety of initiatives in addition to IAEA safeguards, both internationally and domestically, that attempt to address nonproliferation objectives. There is a lack of agreement as to how effective these programs are in addressing proliferation concerns. In the case of the U.S. government's "Global Nuclear Energy Partnership" (GNEP), some participants in the NJFF process believe that the program as currently envisioned could actually further proliferation risks. The U.S. government also has a variety of programs and initiatives designed to limit proliferation risk, many of which go beyond issues associated with commercial nuclear power. The Megatons to Megawatts program, for example, involves the use of commercial U.S. reactors to burn surplus HEU from Russian weapons by adding the material to natural uranium in the enrichment process.[204] In 2004, a White House initiative was launched to combat the proliferation of nuclear weapons through greater cooperation among U.S. and foreign intelligence agencies. It also called for strengthening domestic laws and more stringent controls on enrichment and reprocessing facilities throughout the world.

While the NJFF agrees with several premises of the GNEP, the program is not a credible strategy for resolving either the radioactive waste or proliferation problem. The NJFF group agrees with the following proliferation concerns that GNEP attempts to address:

- ***All grades of plutonium, regardless of the source, could be used to make nuclear explosives and must be controlled.***
- ***Reprocessing poses a problem in non-weapons states. Widespread use of mixed-oxide fuel by both weapon states and non-weapon states is similarly troublesome.***
- ***Even in the weapons states, plutonium must be protected, and one should not increase stocks of plutonium in separated or easily separated forms such as mixed-oxide fuel.***

[202] Some of the separated plutonium is old, however, and much of the plutonium-241 has decayed into americium-241, which would require chemical removal before fuel fabrication. The energy value of the separated plutonium is not especially large: it would meet less than 1 year of global nuclear fuel demand. But 250 tonnes of separated plutonium is a huge amount of potential material for nuclear weapons (more than 30,000 nuclear weapons).

[203] National Academies of Science, "Management and Disposition of Excess Weapons Plutonium," 1994.

[204] There are also collaborative efforts to burn 34 tonnes of excess weapons plutonium in the U.S. and Russia.

Despite these positive intentions, the proposed program has serious deficiencies. GNEP proposes the following:[205]

- Develop a more advanced reprocessing technology (UREX+) that separates plutonium plus neptunium instead of pure plutonium.
- Extract short-lived fission products of spent fuel—cesium and strontium—and store them above the surface for several hundred years, that is, until they meet low-level waste disposal standards.
- Build an Advanced Burner Reactor, a fast reactor fueled with both plutonium and higher actinides.
- Build a Consolidated Fuel Treatment Center (advanced reprocessing plant), capable of separating the usable components contained in light-water reactor spent fuel from the waste products.
- Design an Advanced Fuel Cycle Facility to reprocess fuels from the fast reactors. Many reprocessing plants, fast reactors, and MOX fabrication plants would be needed to achieve the long-term goals.
- Provide fuel for non-weapons nations that agree to refrain from developing their own enrichment, reprocessing, and MOX fabrication facilities. Develop smaller unit size reactors better suited to the electric grids of smaller nations.

The GNEP plan acknowledges that these programs and facilities—even if rapidly and successfully developed—would not prevent the risk of nuclear proliferation.

Many questions remain about whether the GNEP program will be fully funded by Congress, whether it will succeed in building economically viable facilities if funded, whether the reprocessing path is consistent with industry needs, and whether the proposed contingent fuel assurances would reduce or increase proliferation risk. Questions also remain about whether the proposed technology meets the goals of plutonium protection.

The NJFF participants believe that critical elements of GNEP are unlikely to succeed because:

- ***GNEP requires the deployment of commercial scale reprocessing plants, and a large fraction of the U.S. and global commercial reactor fleets would have to be fast reactors.***
- ***Deployment of commercial reprocessing plants has been proven to date to be uneconomical.***
- ***Fast reactors have proven to date to be uneconomical and much less reliable than conventional light-water reactors.***

The GNEP program could encourage the development of hot cells and reprocessing R&D centers in non-weapon states, as well as the training of cadres of experts in plutonium chemistry and metallurgy, all of which pose a grave proliferation risk.

[205] GNEP Overview Factsheet. http://www.gnep.energy.gov/pdfs/06-GA50506-01.pdf.

Appendix A: Existing Nuclear Facilities

Table A.1. Existing Nuclear Facilities

Existing Nuclear Fuel Cycle Facilities
Operational

Geologic Nuclear Waste Repositories
None operational

Nuclear Fuel Reprocessing Plants

France	LaHague - UP2
	LaHague - UP3
India	Kalpakkam Fuel Reprocessing Plant (KFRP) (PREFRE-2)
	Power Reactor Fuel Reprocessing Facility (PREFRE-1)
Japan	Tokai Reprocessing Plant
	Rokkasho Fuel Reprocessing Plant (Undergoing Hot Testing)
United Kingdom	Thermal Oxide Reprocessing Plant (THORP) (Shutdown following an accidental spill)
	B205 Magnox Fuel Reprocessing Plant
Russia	RT-1

Uranium Enrichment Plants

Brazil	Resende Enrichment Plant
China	Hanzhong Uranium Enrichment Facilities (Shaanxi)
	Heping Gaseous Diffusion Uranium Enrichment Plant
	Lanzhou Gaseous Diffusion Uranium Enrichment Plant
France	Eorodif - Georges Besse Uranium Enrichment Plant (Tricastin Enrichment Plant)
Germany	URENCO Deutschland GmbH Gas Centrifuge Enrichment Plant

Table A.1. Existing Nuclear Facilities *(continued)*

India	Trombay Uranium Enrichment Plant
Iran	Natanz, Fuel Enrichment Plant
Japan	Rokkasho Uranium Enrichment Plant
Netherlands	URENCO - Almelo Uranium Enrichment Plant
Pakistan	Abdul Qader Khan Research Laboratories, Gas Centrifuge Facility
Russia	Novouralsk (Sverdlovsk-44) Urals Electrochemical Combine
	Zelenogorsk (Krasnoyarsk-45, Electrochemical Plant) Gas Centrifuge
	Seversk (Tomsk-7) Uranium Enrichment Plant
	Electrolyzing Chemical Combine (AEKhK) (at Angarsk)
United Kingdom	URENCO (Capenhurst) Ltd. Gas Centrifuge Enrichment Plant
United States	Paducah Gaseous Diffusion Plant
NatU and LEU Nuclear Fuel Fabrication Plants	
Argentina	Ezeiza Nuclear Fuel Fabrication Plant
Belgium	Dessel Nuclear Fuel Fabrication Plant, LWR Fuel Fabrication
Brazil	Resende Nuclear Fuel Fabrication Plant
Canada	GE Canada Toronto Nuclear Fuel Facility
	Peterborough Nuclear Fuel Facility
	Port Hope Nuclear Fuel Facility
China	Yibin Nuclear Fuel Fabrication Plant
	Baotou Nuclear Fuel Component Plant
France	Romans Nuclear Fuel Fabrication Plant
Germany	Lingen Nuclear Fuel Fabrication Plant
India	Nuclear Fuels Complex (NFC), Enriched Fuel Fabrication Plant
	Nuclear Fuels Complex (NFC), PHWR Fuel Fabrication Plant
Japan	Japan Nuclear Cycle Development Institute Tokai Works
South Korea	Yuseong Nuclear Fuel Fabrication Plant
Romania	Nuclear Fuel Fabrication Plant
Russia	Novosibirsk Nuclear Fuel Fabrication Plant
	Elektrostal Machine Building Factory/Plant
Spain	Juzbado Nuclear Fuel Reprocessing Plant
Sweden	Vasteras Nuclear Fuel Fabrication Plant
United Kingdom	Westinghouse/BNFL Springfields Plant
United States	AREVA Richland Nuclear Fuel Plant
	Columbia Fuel Fabricating Facility
	Global Nuclear Fuel-Americas Fuel Fabrication Plant
	AREVA Lynchburg Nuclear Fuel Plant
MOX Nuclear Fuel Fabrication Plants	
Belgium	Dessel Nuclear Fuel Fabrication Plant, MOX Fuel Fabrication (Shutdown)
France	Cadarache MOX Fuel Fabrication Plant
	MELOX Fuel Fabrication Plant
India	MOX Breeder Fuel Fabrication Plant
	Tarapur Nuclear Complex, Advanced Fuel Fabrication Facility
United Kingdom	Sellafield SMP MOX Fuel Fabrication Plant

Source: NRDC.

Appendix B: Description of Life-Cycle Cost Analysis Model

Electric utility professionals (e.g., utilities themselves, ratings agencies, regulators, consultants, and academics) use a variety of tools to estimate and compare the costs of alternative demand-side and supply-side resource alternatives. The simplest approaches can be handed in a small spreadsheet, with simplifying assumptions for many key variables. More sophisticated spreadsheets are usually necessary for comparing resources with varying lifetimes, different construction start dates, tax benefits, depreciation periods, or unique characteristics. As the economics chapter (Chapter II) points out, these approaches are generic screening tools that are useful for doing national average calculations. Specific plant calculations might consider regional differences in the cost of land, labor, and transmission interconnection that might affect the results.

We have used several reasonably sophisticated spreadsheets for our calculations. For the capital cost of the plant, we escalate overnight capital costs at differing rates, adding interest during construction as costs are incurred. Interest is calculated as if annual expenditures were made in one lump sum each year. When the plant is complete, direct and indirect (interest) costs are summed. This is the total completion cost in nominal dollars, at which point generation begins. We have assumed that construction begins in 2007, and that utilities starting construction have already incurred 2 years of relatively modest “pre-construction” expenses. This assumption is not particularly credible, and a more realistic construction start date (e.g., 2009) would widen the spread between our low and high cases.

Capital costs are recovered over the life of the debt and equity investments. In addition, federal income taxes, state taxes, property taxes, insurance, and depreciation must be collected. The model is able to handle these factors, as well as accelerated depreciation and its effects on tax liability. While we developed a range of possible costs for a plant with all debt guaranteed over the life of the plant by the U.S. Treasury, these values are highly speculative until DOE rules are final and other players—investors and state regulators—react.

Other operating costs are also incurred with operation, including fuel, operations and maintenance, net capital additions, and A&G (administration and general costs, which generally means pensions and insurance for plant employees). We have assumed no real escalation (over inflation) beyond the values described. With these inputs, the model produces a stream of annual “revenue requirements” that an owner must recover in rates (or wholesale sales) to meet financial needs. Annual revenue requirements for all these factors are calculated for the life of plant and then are discounted to 2007 dollars. By dividing by production (capacity factor times plant capacity), one gets cost per kilowatthour by year in both real and nominal dollars.

Discounting is primarily used to compare costs of technologies with very different expenditure patterns; for example, a facility with high upfront capital costs but relatively low and stable operating costs with a resource that has the opposite profile. It is not particular useful for calculating cost in comparison to existing rates or plants or rate impacts in early years of operation. The nominal dollar annual revenue requirements are appropriate for calculating those effects. The discount rate used in this analysis is the utility’s weighted after-tax cost of capital from debt (where bond interest is deductible) and equity (where returns to stockholders are not).

Two additional spreadsheets were used for economic analyses in this report. A small spreadsheet was used to escalate Asian unit capital costs to real 2007 dollars. Another relatively small spreadsheet was used for nuclear fuel cost calculations. The approach taken for nuclear fuel cycle cost analysis is the same as was used in the MIT 2003 nuclear study. A number of parameters were changed (including, most importantly, uranium price, enrichment cost, and probable future enrichment tails assay) to reflect current conditions. JNFF member Jim Harding generously contributed his time and expertise in doing these calculations and responding to requests made by other members for sensitivity analyses.

Appendix C: Three Mile Island

In its Fact Sheet on the Accident at Three Mile Island, the NRC concluded that TMI "... was the most serious in U.S. commercial nuclear power plant operating history..., even though it led to no deaths or injuries to plant workers or members of the nearby community." On the health effects, the NRC found:

> *Detailed studies of the radiological consequences of the accident have been conducted by the NRC, the Environmental Protection Agency, the Department of Health, Education and Welfare (now Health and Human Services), the Department of Energy, and the State of Pennsylvania. Several independent studies have also been conducted. Estimates are that the average dose to about 2 million people in the area was only about 1 millirem. To put this into context, exposure from a full set of chest x-rays is about 6 millirem. Compared to the natural radioactive background dose of about 100-125 millirem per year for the area, the collective dose to the community from the accident was very small. The maximum dose to a person at the site boundary would have been less than 100 millirem.*
>
> *In the months following the accident, although questions were raised about possible adverse effects from radiation on human, animal, and plant life in the TMI area, none could be directly correlated to the accident. Thousands of environmental samples of air, water, milk, vegetation, soil, and foodstuffs were collected by various groups monitoring the area. Very low levels of radionuclides could be attributed to releases from the accident. However, comprehensive investigations and assessments by several well-respected organizations have concluded that in spite of serious damage to the reactor, most of the radiation was contained and that the actual release had negligible effects on the physical health of individuals or the environment.*[1]

Writing independently, the NRC historian noted that:

> At least for the periods covered in extensive epidemiological studies, the accident did not increase rates of cancer or other diseases among the neighboring population. Except for the plant itself, it did not destroy or damage property in the region.[2]
>
> Three Mile Island exposed a multitude of weaknesses that had to be addressed, as several comprehensive postaccident reports made clear. The blame for the oversights, lapses, and failures that led to the crisis fell on both the U.S. nuclear industry and the NRC. The accident drove them out of a prevailing and dangerously complacent consensus that they had resolved the most critical reactor safety issues. Although they had never claimed that a major accident that released dangerous quantities of radiation was impossible, they regarded it as virtually inconceivable. Three Mile Island made the possibility disturbingly credible. As a result, both the industry and the NRC adopted wide-ranging reforms intended to focus ample attention on human factors in reactor safety, improve equipment and instrumentation, strengthen communications, upgrade emergency planning, and monitor the effectiveness of plant management. In that way they sought to avoid another three Mile Island. Engineers often learn more from technological failure than they do from success, and the accident provided a succession of failures from which to draw lessons.[3]

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[1] http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html.

[2] J. Samuel Walker. *Three Mile Island: A Nuclear Crisis in Historical Perspective*. Berkeley: University of California Press, 2004. p. 243.

[3] Ibid., pp. 241-242.

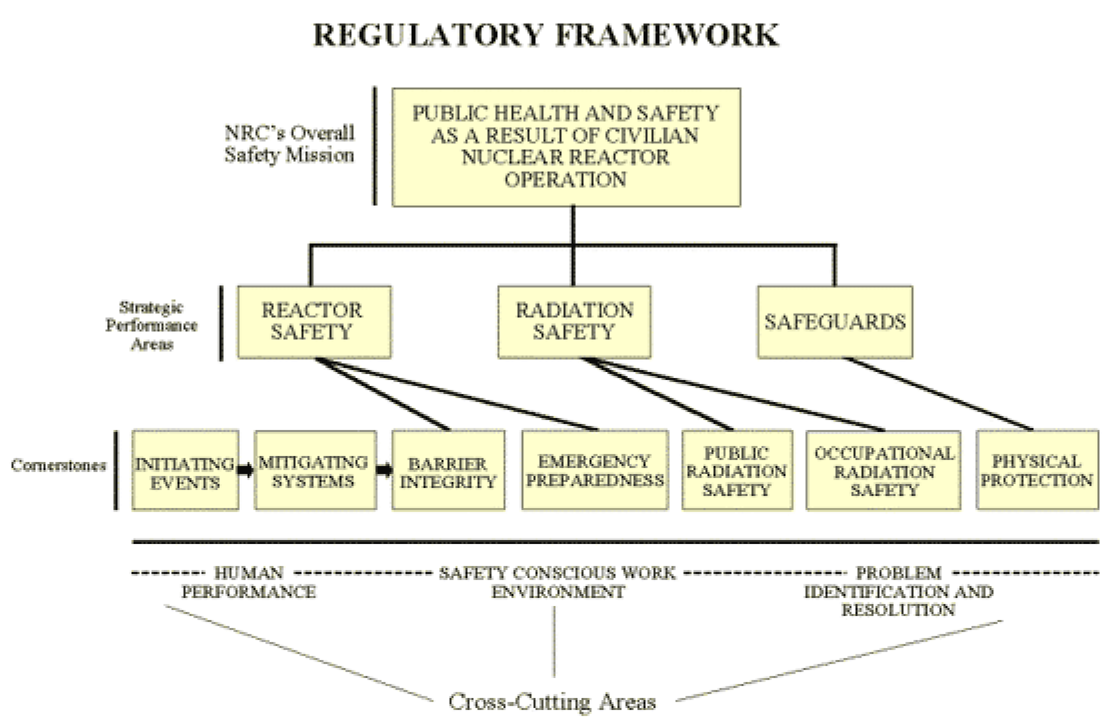
Appendix D: Reactor Oversight Process and Enforcement Program

Reactor Oversight Process

The NRC's Reactor Oversight Process (ROP), implemented in April 2000, integrates inspection, enforcement, and assessment of nuclear power plants in a risk-informed, performance-based system in an effort to ensure the appropriate level of NRC oversight of licensees. The process is designed to focus on those plant systems, structures, components, and activities that are most risk significant. The ROP provides a "closed loop" oversight process: the level of oversight increases as licensee performance declines, and it decreases to a minimum baseline of oversight as performance improves. NRC conducts a minimum baseline inspection of about 2,000 hours per reactor per year. Licensee safety performance determines the level of NRC oversight, which is increased above a minimum baseline of inspection as plant performance declines and decreases back to the baseline as performance improves.

The NRC's regulatory framework for reactor oversight (shown in Figure D.1) is a risk-informed, tiered approach to ensuring plant safety. It includes three key strategic performance areas: reactor safety, radiation safety, and safeguards. Within each strategic performance area are cornerstones that reflect the essential safety aspects of facility operation. The cornerstones are: (1) initiating events, (2) mitigating systems, (3) integrity of barriers to release of radioactivity, (4) emergency preparedness, (5) occupational radiation safety, (6) public radiation safety, and (7) physical protection. Satisfactory licensee performance in the cornerstones provides reasonable assurance that the facility is operating safely and that the NRC's safety mission is being accomplished.

Figure D.1. NRC Regulatory Framework for Reactor Oversight



In addition to the cornerstones, the ROP features three cross-cutting areas that can affect each of the cornerstones. The cross-cutting areas include:

- human performance
- safety-conscious work environment (SCWE)
- problem identification and resolution (e.g., the licensee's corrective action program).

The NRC's review and assessment of these cross-cutting elements play an important role in the ROP program. A recent change in how cross-cutting issues are assessed and integrated in the program began on July 1, 2006, and may be subject to additional changes as more experience is gained.

Nuclear plant safety performance outcomes are measured by a combination of objective performance indicators (PIs) and by the NRC inspection program. PIs use objective data to monitor performance within each of the cornerstones. Licensees generate the data that make up the PIs and submit them to the NRC quarterly. Each PI is measured against established thresholds of performance that are related to their effect on safety. The PIs are evaluated and integrated with the findings of the inspection program.

The ROP includes baseline inspections common to all nuclear plants. These inspections are conducted by resident inspectors (there are at least two resident inspectors at each nuclear power plant site) and by regional and headquarters staff. The baseline inspection program, based on the cornerstone areas, focuses on areas and systems that are risk significant. The baseline inspection program has three parts:

- inspection in areas not covered by PIs or where a PI does not fully cover the inspection area
- inspections to verify the accuracy of the licensee's reports on performance indicators
- a thorough review of the licensee's effectiveness in finding and resolving problems on its own.

Inspections beyond the baseline are performed at plants with performance below established thresholds. Additional inspections may also be performed in response to a specific event or problem at a plant. Special inspections, including those conducted by the Augmented Inspection Teams (AIT), are used to review the circumstances surrounding more significant events.

The NRC staff evaluates inspection findings identified during the inspection for safety significance using a significance determination process (SDP). Where possible, the SDP uses quantitative analysis (probabilistic risk analysis) to determine the risk significance. PI data are compared against prescribed risk-informed thresholds. These two distinct items—inspection findings and PIs—comprise the plant assessment. Both aspects of safety performance are evaluated and given a color designation based on their safety significance. Green inspection findings or PIs indicate very low risk significance. White, yellow, or red inspection findings or PIs represent an increasing degree of safety significance.

The NRC determines the appropriate level of agency response based on the plant assessment information, which may include supplemental inspection and pertinent regulatory actions ranging from management meetings up to and including orders for plant shutdown. Each plant assessment will fall in to one of the five columns of the NRC action matrix, ranging from performance that requires only baseline inspection and oversight (Licensee Response Column) to unacceptable performance, which may result in an order to modify, suspend, or revoke licensed activities:

- Licensee Response Column
- Regulatory Response Column
- Degraded Cornerstone Column
- Multiple/Repetitive Degraded Cornerstone Column
- Unacceptable Performance Column.

Enforcement action is taken on safety-significant inspection findings, as appropriate. The NRC communicates the results of its performance assessment and its inspection plans and other planned actions in publicly available correspondence, on its web site, and through public meetings with each licensee.

In conducting inspections, NRC inspectors follow guidance in the NRC Inspection Manual, which contains objectives and procedures for use in each type of inspection. The Inspection Manual does not contain regulatory requirements and cannot be used to establish any new regulatory requirements or new regulatory guidance.

The NRC issues Inspection Reports to document inspection findings. Inspection Reports may cover a specific time period for the baseline inspection or a particular event or problem examined in a reactive inspection. Inspection Reports are intended to be factual, not to reflect inspector opinion.

The results of the ROP, including inspection and assessment reports, performance indicators, and inspection findings, are posted on the NRC's public web site, with the exception of security-related issues, which are withheld from public access.

Enforcement Program

The purpose of the NRC enforcement program is to support the NRC's overall safety mission in protecting the public and the environment. Consistent with that purpose, enforcement actions are used as a deterrent to emphasize the importance of compliance with requirements and to encourage comprehensive correction of violations. The NRC's Enforcement Policy is contained in NUREG-1600, "NRC Enforcement Policy," and is outlined below as it applies to the reactor oversight process.

The NRC Enforcement Policy separates violations associated with inspection findings into two groups, depending on whether the SDP can be used to assess their significance. When possible, the SDP is used to evaluate the safety significance of inspection findings. The NRC response to assess the extent of the condition and the adequacy of the corrective actions taken is in accordance with the action matrix. Violations associated with findings evaluated as having very low safety significance (i.e., green) and that are addressed in the licensee's corrective action program are not normally cited. Violations associated with findings evaluated as having a greater significance (i.e., greater than green) are normally cited in a Notice of Violation (NOV). These violations are not normally subject to civil penalties.

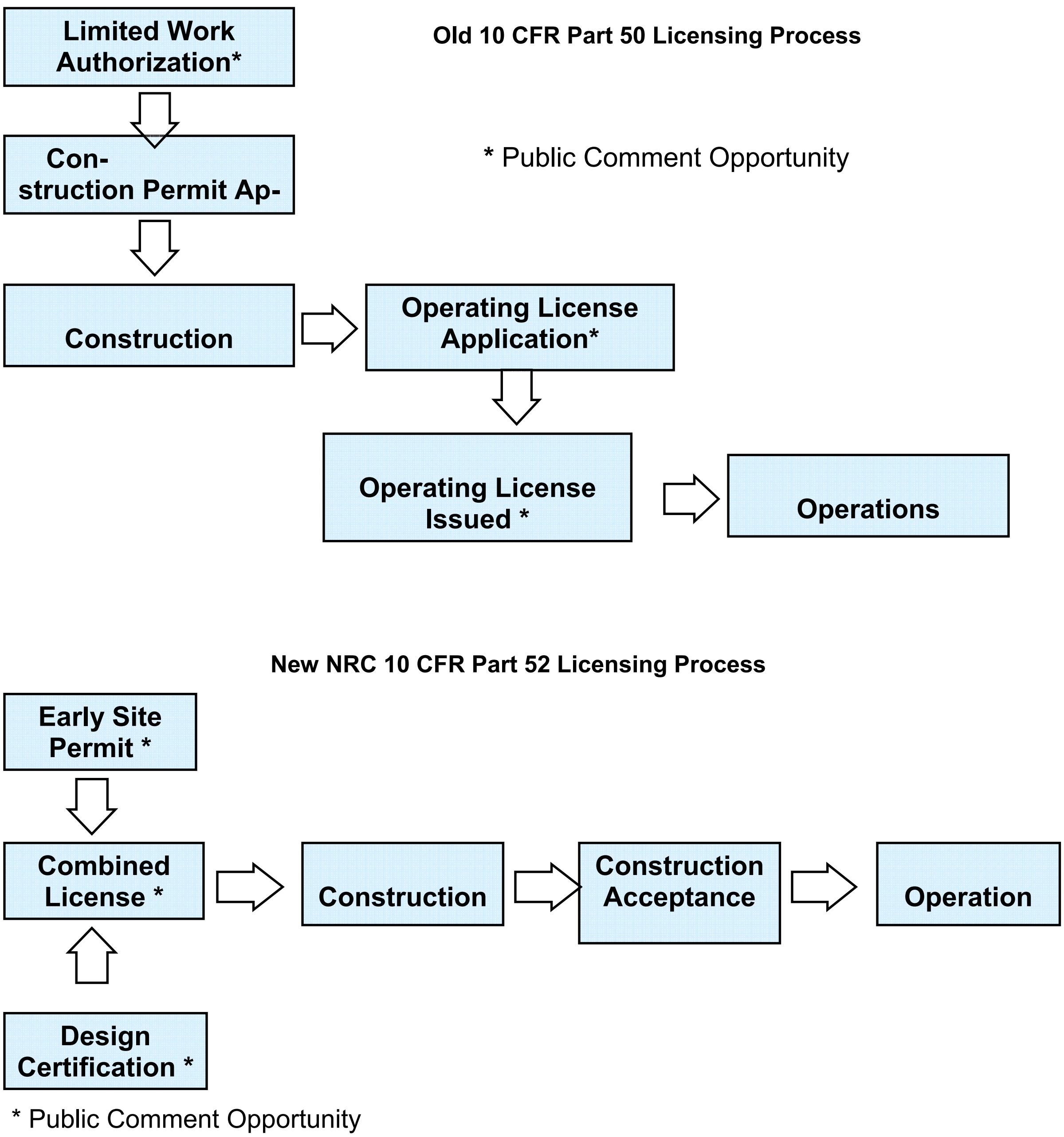
Violations that result in actual consequences, impede the regulatory process, or involve willful acts are processed under the traditional enforcement program, since the regulatory importance of these issues is not limited to the underlying technical significance of the findings. These violations are assigned a severity level, and licensees are subject to civil penalties in accordance with the criteria described in the NRC Enforcement Policy. Violations processed under the traditional enforcement program may not receive direct consideration under the action matrix.

Both the traditional enforcement program and the assessment program are exercised for cases in which a violation satisfies the criteria for traditional enforcement and is associated with a finding that has an underlying significance that can be processed under the SDP. Specifically, the violation would be given a severity level and would be considered for a civil penalty. In addition, the significance of the finding would be processed under the SDP, and the result would be entered into the action matrix, as appropriate.

Appendix E: New Licensing Process

In 1989 the NRC established the Combined Operating License (COL) (under 10 CFR Part 52), which authorizes construction and operation of nuclear power plants. The COL combines the construction permit with the plant operating license; previously, a nuclear plant operator had to obtain a construction permit before applying for a plant operating license (under 10 CFR Part 50). A comparison between the new 10 CFR Part 52 Process and the old 10 CFR Part 50 Process is shown in Figure E.1.

Figure E.1. Comparison of Licensing Processes



Appendix F: Fuel Cycle Overview

The nuclear fuel cycle can be divided into three stages: front end, reactor, and back end.

The **front end** of the fuel cycle refers to the preparation of uranium for use in a reactor. Uranium is mined from typically low-grade deposits, requiring the extraction of natural uranium by mining and a milling process or by *in situ* chemical leaching of underground ore deposits or above-ground tailing piles with acids. Further chemical refining of crushed uranium ores produces a product called "yellowcake" (U_3O_8).

Some reactors, including more than 60 power reactors in operation today, are fueled with natural uranium, which contains 0.711% uranium-235 (U-235), 99.3% uranium-238 (U-238), and trace quantities of uranium-234. Most power reactors, including all power reactors operating in the U.S. today, are fueled with enriched uranium, in which the concentration of the U-235 isotope has been increased over that in natural uranium. When the concentration of U-235 is less than 20%, it is called low-enriched uranium (LEU).

To fuel reactors operating on natural uranium, the yellowcake is sent to a chemical conversion plant, where it is converted to uranium hexafluoride gas (UF_6) that can be used in either a traditional gas diffusion or centrifuge plant that increases the U-235 concentration from the natural level of 0.711% to levels useful in a light-water reactor (3 to 5 percent U-235). It is then converted back to uranium dioxide (UO_2) and sintered (baked) into reactor fuel, typically in the form of solid pellets, and inserted into tubes to form fuel rods. The rods are combined into fuel assemblies or bundles and shipped to the reactor site. Often the chemical conversion facilities are co-located with the enrichment or fuel fabrication facilities.

There are some types of research and commercial reactors that use other fuel types, e.g., HEI or, as discussed below, a mixture of plutonium and uranium. For some reactor designs, the fuel is in metallic form, and the fuel itself may be coated with other materials, e.g, graphite.

There is a wide variety of nuclear **reactor** types in the world, differing in design, purpose, and power level. The primary types of reactors used in the U.S. can be classified by the type of neutron moderator and coolant used, as follows:

Graphite Reactors (graphite moderator, ordinary water serving as coolant)
- B, D, F, H, DR, C, KW, KE and N-reactors at the Hanford Reservation
- RMBK (Russian-made Chernobyl-type)

Light-Water Reactors (ordinary water serving as moderator and coolant)
- Pressurized-water reactor (PWR)
- Boiling-water reactor (BWR)
- VVER (Russian-made PWR)

Heavy-Water Reactors (heavy water [D_2O] serving as moderator and coolant)
- R, P, L, K, and C production reactors at the Savannah River Site

Candu Reactors (Canadian design, graphite moderator, heavy water serving as coolant)

MAGNOX Reactors (graphite moderator, air-cooled)

Liquid Metal Reactors (no moderator, sodium-cooled)
  Liquid metal fast breeder reactor
  Russian-made lead-bismuth-cooled fast reactor

High-Temperature Gas-Cooled Reactors (graphite moderator, helium-cooled)

For a reactor that is operated primarily for the production of plutonium for weapons, the residence time of the fuel in the reactor can be a little as a few months; for power reactors the residence time is typically a few years; and for naval reactors and some research reactors that use HEU fuel, the residence time can be more than a decade. A portion of the U-235 atoms in the fuel undergo fission, releasing heat that can be used in a variety of ways. In power reactors the heat is transferred via a coolant (typically, pressurized water) to a "steam generator" that drives turbines, which in turn generate electricity.

After the fuel is removed from the reactor it is referred to as "spent fuel." The spent fuel contains leftover (unfissioned) uranium, a variety of fission products, and plutonium and other elements created by the absorption of neutrons by isotopes that do not fission. This mixture of uranium, plutonium, and other elements is highly radioactive. In today's light-water reactors, the resulting spent fuel contains about 1% plutonium.

There are two approaches that various countries have taken to managing the **back end** of the nuclear fuel cycle. One of these, the open or once-through cycle, involves storing spent fuel on-site in wet storage or dry casks and ultimately disposing of the nuclear waste. To date, the U.S. and a number of other countries have taken this approach to handling spent fuel from civilian reactors. The second approach, the closed cycle, requires that the spent fuel be reprocessed to separate plutonium, unused uranium, and highly radioactive fission products into three streams. The plutonium and unused uranium can be reused as fuel in nuclear reactors after reprocessing and mixed oxide fuel fabrication. The radioactive fission products are then disposed of as nuclear waste after solidifaction in a glass or ceramic matrix. France, Japan, Russia, and until recently the United Kingdom have engaged in the reprocessing of commercial spent fuel for themselves and, in some cases, for other nations. None them has solidified significant quantities of liquid high-level waste.

A more in-depth explanation of the nuclear fuel cycle can be found in MIT's "The Future of Nuclear Power" Chapter 1 Appendix.

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