Policy Options for Nuclear Waste Management: Sustainable Solutions for Expanded Nuclear Energy

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This experience has been an amazing opportunity to blend my two passions, engineering and policy. The Washington Internships for Students in Engineering (WISE) Program provided a different type of application of science, into a political arena where decisions are made based on how a given technology can help the United States succeed and not just on technical merit. From this experience I have learned the invaluable importance, but also complexity, of scientific advising; helping politicians to understand and evaluate what those helpful technologies might be and how best to incentivize them.

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Executive Summary

In 2007, the United States consumed 4,157 billion kilowatt-hours (kWh) of electrical energy and produced 6 billion metric tons of carbon dioxide. With electricity demand expected to increase by 26 percent by 2030 (2) and associated carbon emissions becoming more expensive due to probable cap and trade legislation, the United States will need cheap, reliable, “carbon-free” energy generation technologies to play an increasing role. It will require a combination of energy efficiency, increased renewable generation, and expanded nuclear power to meet projected demand and achieve mandated carbon dioxide (CO$_2$) reduction goals. As the source of 70 percent of “carbon free” electricity generation in the U.S. today, nuclear energy could be poised to play an important role in America’s energy future. While still about 6 to 13 percent more expensive than conventional coal and gas electricity generation, nuclear power presents the lowest cost electricity generation resource available and will be an important resource for base load generation capacity, in contrast to more intermittent sources like wind and solar.

Yet, the future of nuclear power in the United States remains uncertain due to a number of issues including nuclear waste management. The Nuclear Waste Policy Act (NWPA) directs that spent nuclear fuel (SNF) resulting from a “once-through” fuel cycle in light water reactors (LWR) be stored in the Yucca Mountain deep geologic repository. However, political opposition has significantly impeded development of the site, culminating in the recent announcement by the Obama Administration of the unsuitability of the Yucca Mountain site. In light of this, The Department of Energy is now exploring other options for nuclear waste management, each of which will have different legal, economic, and policy-related implications. It is important that the U.S. find a sustainable solution to nuclear waste management that will provide the requisite flexibility to dispose of SNF in the most economical and efficient manner based on changing circumstances.

Without a sustainable nuclear waste disposal solution, it will be difficult for nuclear to continue its role as an important electricity generation resource. The article explores
the three primary scenarios for the future of nuclear power in the United States. These are no new nuclear investment and a declining generating capacity, growth of the nuclear power industry with continuance of a “once-through” fuel cycle, and growth of the nuclear industry with the institution of reprocessing and recycling of SNF. Each of these scenarios will have different implications with respect to future policy options for waste management in the context of the NWPA, as well as licensing, government funding, and technological readiness.

With no new investment in nuclear power, most nuclear reactors would be decommissioned by 2050, with current and future energy demand having to be met by another source. One likely source is natural gas, which has recently experienced disruptive price volatility. If a carbon cap and trade system is enacted, to achieve projected carbon emissions reductions the generation gap will have to be replaced by other “carbon free” generation technologies, such as wind and solar. To achieve this level of growth would be costly and difficult given current wind and solar technology.

A “once-through scenario” with the nuclear industry continuing to generate 20 percent of U.S electricity demand in the future will require consistent funding and licensing to provide a sustainable foundation for growth. Maintaining nuclear power’s 20 percent stake in U.S. electricity generation will require the construction of more than 150 new reactors in the next few decades, which is estimated to cost between $750 billion and $1 trillion dollars. The NRC is currently reviewing license applications for 26 new reactors under a new Combined Operating License that hopes to shorten and simplify the licensing process. The DOE has also, for the first time, issued $18.5 billion dollars in loan guarantees made available in the 2005 Energy Policy Act to four utilities to provide financial backing to the first plants that will be built. To provide loan guarantees for all the applications currently pending with the NRC would require more than $122 billion dollars. However, the nuclear industry has stated that governmental funding is not necessary for nuclear growth. If expansion of nuclear power occurs, a “once-through” scenario with direct disposal of SNF in a deep geologic repository will require 3 to 4 Yucca Mountain-sized repositories this century. Given the history of commissioning a repository site in the U.S., this option would require a selection program that avoids some
of the political inconsistency experienced in the Yucca Mountain project. Such a program, however, may be difficult to achieve.

The third option is closing the fuel cycle through the reprocessing and recycling\(^1\) of SNF. The option of a closed fuel cycle is beneficial because it has the ability to minimize the volume and radioactivity of high level waste (HLW) that will finally be stored in a repository and recover additional energy value from the original fuel. Reprocessing technology has the ability to decrease the volume of HLW by a factor of 4 while at the same time decreasing the required storage timeframe from hundreds of thousands of years to less than 1,000 years. The HLW produced from reprocessing is also vitrified in glass, to produce a stable, homogenous waste product. Reprocessing and recycling SNF could require only one Yucca Mountain-sized repository this century and decrease the amount of fresh uranium fuel required by 25 percent.

The technology is, however, still very controversial because of the increased cost and proliferation risk it can present. Reprocessing and recycling SNF is generally thought to present a 10 percent increase in total levelized cost of electricity over a direct disposal scenario, although there is a large amount of variability in these estimations because of the large uncertainty in interest rates, the price of uranium, construction timelines, and the cost and availability of new technology. As very capital intensive projects, costing from $4 to 7 billion dollars to build, nuclear power plants are very risky and difficult to finance. Reprocessing and recycling technology compounds this problem because of the increased risk of First-of-A-Kind technology.

Another issue that has halted the reprocessing program in the U.S. in the past is the risk of proliferation of nuclear weapons associated with the separation of SNF. Separation using the Plutonium Uranium Recovery by Extraction (PUREX) method, as currently used internationally, separates pure plutonium which has the potential to be diverted and used to produce nuclear weapons. New separation methods that do not separate plutonium independently have been developed to address this problem, however, even separated plutonium from SNF would be very difficult to use to create nuclear

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\(^{1}\) Although the terms reprocessing and recycling can be used ubiquitously, in this document reprocessing will represent the chemical separation and treatment of SNF and recycling will refer specifically to the burning of that reprocessed fuel package in a nuclear power reactor.
weapons. A possibly more significant proliferation risk is the spread of reprocessing technology and capability, which would give a state the technological capacity to manufacture a nuclear weapon independently. To address this, it is important the United States support strong international safety and proliferation standards and increase international cooperation in this area.

Nuclear energy presents an important resource for cheap, reliable, safe, “carbon free” electricity generation technology. However, realization of the benefits presented by nuclear power will require consistent and sustainable nuclear funding and policy with the flexibility to respond to changing circumstances and incorporate innovative technology.
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4S – Super-Safe, Small and Simple; New reactor design by Toshiba
10 CFR 50 - Title 10, Chapter I, Part 50 of the Code of Federal Regulations
10 CFR 52 - Title 10, Chapter I, Part 52 of the Code of Federal Regulations
AEA – Atomic Energy Act
AEC – Atomic Energy Commission
AFCI – Advanced Fuel Cycle Initiative
ARC – Advanced Reactor Corporation
CCS – Carbon Capture and Storage
CO₂ – Carbon Dioxide
COL – Combined Operating License
CWIP – Construction Work-In-Progress
DOE – Department of Energy
DOI – Department of Interior
EIA – Energy Information Administration
EPA – Environmental Protection Agency
ERDA – Energy Research and Development Administration
FOAK – First of A Kind
GNEP – Global Nuclear Energy Partnership
HLW – High Level Waste
IAEA – International Atomic Energy Agency
kWh – Kilowatt hour
LIS – Laser Isotope Separation
LLW – Low Level Waste
LWR – Light Water Reactor
MIT – Massachusetts Institute of Technology
MOX – Uranium/Plutonium Mixed Oxide Fuel
MWe – Megawatt electricity
MWh – Megawatt hour
NGNP – Next Generation Nuclear Plant
NRC – Nuclear Regulatory Commission
NWF – Nuclear Waste Fund
NWPA – Nuclear Waste Policy Act
PFS – Private Fuel Storage
PRISM – Power Reactor Innovative Small Module
PUREX – Plutonium Uranium Recovery by Extraction
RES – Renewable Electricity Standard
RSSSF - Retreivable Surface Storage Facility
RU – Reprocessed Uranium
SFR – Sodium-Cooled Fast Reactor
SNF – Spent Nuclear Fuel
TVA – Tennessee Valley Authority
UO₂ – Uranium Dioxide
WIPP – Waste Isolation Pilot Plant
1.0 The Role of Nuclear Energy in U.S. Electricity Production

1.1 Overall Energy Use and Expected Growth of Nuclear Energy

In 2007, the United States consumed 4,157 billion kWh of electrical energy, 19.4 percent of which was generated by 104 nuclear power plants located in 39 states across the country. While overall electrical energy consumption has increased steadily over the past two decades, the percentage contribution from nuclear energy has remained constant despite only one new reactor\(^2\) coming on-line in that period. This increase in energy generation has been achieved by increases in efficiency that have lead to a fleet average capacity factor of 90 percent, much higher than any other energy generation technology (1).

Electricity power generation demands are expected to grow 26 percent by 2030 (2) and could exceed this estimate if an electrical transportation infrastructure is realized. With reactors operating at capacity factors of 90 percent, further expansion of nuclear power will have to occur through capital investment in new nuclear infrastructure. To maintain a generating capacity of 20 percent of total U.S. electricity use will require the construction and start up of as many as 50 new 1000 megawatt (MWe\(^3\)) nuclear plants in the next few decades. This number does not include construction of new reactors that

\(^2\) In 1996 Watts Bar I nuclear reactor operated by TVA began commercial operation. This reactor first began construction in 1973, but construction was delayed cost overruns, political climate, protests by environmentalists, and lower estimates in demand.

\(^3\) MWe = megawatt electricity and represents the electric output of a power plant in megawatts. The electric output of a power plant is equal to the thermal overall power multiplied by the efficiency of the plant. The power plant efficiency of light water reactors amounts to 33 to 35%.
will be required to replace the current, aging reactor fleet. Most reactors currently operating have reached the end of the 40 year operating license they were initially issued by the Nuclear Regulatory Commission (NRC). Many of these are being relicensed for 20 additional years as the previous operating licenses expire. As of May 29, 2009, the NRC has issued 54 license extensions with 18 renewals undergoing review and 24 expected to apply in the near future (16). While the continued operation of the current reactor fleet ensures a continued contribution of nuclear power to the national electricity grid, most reactors are expected to be decommissioned following the 20 year renewal. This means that in addition to expanding nuclear capacity, more than 100 new reactor facilities will have to be licensed and constructed to maintain current generating capacity. While the current operating fleet was constructed in approximately 20 years, even with the most optimistic levels of investment, achieving this rate of growth will be difficult because of difficulties in licensing and availability of construction materials.

Figure 2. Status of Operating Licenses for the 104 Nuclear Power Reactors Currently Operating in the United States. Source: NRC
1.2. **Carbon Dioxide Emissions Reduction and Nuclear Energy**

Energy related emissions accounted for 98 percent of U.S. CO₂ emissions in 2008 with the greatest contribution coming from electrical energy generation, 41 percent (3). Electrical energy generation in 2008 produced about 2,400 million metric tons of CO₂, due to the use of fossil fuels (4). The science of global warming, with the established impact of greenhouse gases including carbon dioxide has lead to global concern which motivates efforts to limit greenhouse gas emissions and mitigate their effects. Nationally, these efforts include a proposed carbon cap and trade system that establishes a price for CO₂ emissions that exceeded a projected reduction timeline (5). To achieve these reductions, the United States will need “carbon-free” energy generation technologies that are available on a realistic timescale. The most promising possibilities for decreasing carbon emissions are increased energy efficiency, expanded use of renewable energy resources, carbon dioxide capture and storage, and nuclear power.

Nuclear energy is currently the source of 70 percent of “carbon-free” electricity production. Maintenance of nuclear power’s 20 percent electrical energy stake would represent an additional 27,000 MWe of annual generating capacity, which would displace from 100 to 400 million tons of carbon dioxide emissions compared to if that electricity had instead come from new natural gas or coal fired plants, respectively. This represents about 10 to 40 percent of President Obama’s mid-term, 2020, carbon reduction goal of 1 gigaton (7).

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4 “Carbon-free” in this context defines no carbon emissions due directly to energy generation and does not account for Life-Cycle related emissions in plant construction and materials.
1.3. The Economic Competitiveness of Nuclear Energy

Nuclear power currently offers the lowest cost option for new, low carbon electricity generation resources. The U.S. Department of Energy’s Energy Information Administration (EIA) found nuclear to be more expensive only than conventional coal and natural gas, as shown in the table below (2). This is based on the total levelized cost of electricity, which includes plant construction, operating and maintenance, fuel, and interest costs. If carbon capture and storage (CCS) is required on fossil fuel technologies, nuclear becomes the least expensive electrical energy source.

![Figure 4. Estimated Levelized Cost of New Generation Resources in 2016. Reported in 2007 dollars per megawatt-hour (MWh). Source: EIA, 2009 Annual Energy Outlook.](image)

A major contributor to the higher price of nuclear compared to conventional coal or natural gas is the large capital costs associated with unique reactor construction, which are compounded by delays in the licensing process. In a base case scenario, nuclear power is typically about 6 to 13 percent more expensive than generation using coal or natural gas, with nuclear costing about $107 per MWh. High costs are in large part due to the higher risk premium of nuclear plants because of their high and unpredictable capital costs. Nuclear plants typically carry a risk premium of 10 percent, compared to 7.8 percent for coal and natural gas plants. If the risk premium difference can be eliminated, nuclear power life-cycle costs could be decreased to make nuclear power
competitive with coal and natural gas even in the absence of a carbon emission charge (9).

The introduction of a charge associated with carbon emissions, such as the cap and trade program proposed in the House Climate Bill (5), would be highly beneficial to the cost competitiveness of nuclear power. The recently released Update to a study conducted by MIT on the economics of nuclear power found that a cost as low as $5 to $15 per ton CO$_2$ was enough to produce favorable economics for nuclear plants (9).

Nuclear energy could also help stabilize the cost of electricity by reducing the United States’ dependence on volatile natural gas prices. Although nuclear requires a larger initial investment, its long-term fuel costs are smaller and more predictable than other generating technologies. While other alternative energy sources do not require a fuel cost, nuclear offers a more well-developed technology than other renewables and thus its large-scale implementation costs may be more well-defined.

1.4. **Nuclear in Perspective: Comparison to Other Energy Generation Technologies**

Nuclear power is currently and will continue to be an important part of the United States’ energy mix. While there are some concerns about the impacts of nuclear electricity generation, there are environmental and economic issues presented by all forms of energy generation. Nuclear energy has the potential to have the lowest life cycle impact of any energy source provided a suitable long term waste storage solution can be found.

One major benefit of nuclear energy is the huge energy density and economy of scale it presents. For example, one metric ton of uranium fuel in a LWR, even with an open, once-through fuel cycle, is equivalent to 165,000 tons of coal. This means that nuclear plants can produce the most energy on the smallest amount of land and fuel. One 1000 MWe nuclear power plant can produce enough energy to provide electricity for 780,000 average family homes (10). Comparatively, it would take more than 1000 three megawatt wind turbines operating at a capacity factor of 30 percent to produce an equivalent amount of electricity. From a land-use perspective, placed off-shore, these wind turbines would require almost two full rows spanning the coast of South Carolina.

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5 30% is an average capacity factor for wind turbines. Wind farms operate with a capacity factor from 20 to 40% based on the duration and intensity of wind in the area. (NINA)
Likewise, it would require 30,000 acres of solar panels, which is equivalent to an area almost the size of Washington DC (11). Another important distinction is the type of power produced from these different sources of renewable energy. Solar and wind provide distributed generation sources that, currently, are intermittent and unreliable.

Nuclear, on the other hand, provides a scalable, base load power source.

Nuclear power also has the capacity to reduce emissions compared to other “carbon-free” sources, on a life cycle basis. A recent German study concluded that the environmental impact of nuclear power, including mining, transportation, enrichment, and use, presented one of the lowest carbon footprints of all electricity generation resources, equivalent to that of wind turbines. For each kilowatt of energy generated, nuclear produces CO$_2$ emissions four times lower than photovoltaic technology, three times lower than hydro-electric plants, five times lower than natural gas, and thirty times lower than coal (8).

One major issue with nuclear power plants is that the waste they create contains radioactive material. This raises a concern about the amount of radiation that the environment near the reactor site may be exposed to and the ecological and human health impacts of those exposures. While this is an important consideration and, as such, many safety measures are taken to limit radioactive emissions, it is important to place this concern in context. Fly ash, a by-product from burning coal for power, releases up to 100 times more radiation than a nuclear power plant producing the same amount of electricity (12).

More importantly, even the radiation from coal fly ash amounts to an increase of only 0.1 to a maximum of 5 percent in radiation exposure, depending on location relative to the smoke stack (12). The average person is exposed to 360 millirem of radiation...
annually from natural sources of radiation, such as cosmic rays. By comparison, the radiation exposure from the Three Mile Island event was about 8 millirem to people living within a 10 mile radius of the plant, equivalent to the dose one would receive from a chest X-ray. It is also important to mention that radiation is not necessarily a life-threatening phenomenon. Only gamma radiation, like that generated from plutonium, can cause radiation poisoning if an excessive dose is received. In the nuclear industry’s 50 year history in the United States, there have been no deaths and no excessive radiation exposures to residents or workers (23). In contrast, health problems linked to aging U.S. coal-fired power plants shorten nearly 24,000 lives a year, including 2,800 from lung cancer (24).

While long-term disposal of nuclear waste is still an important issue, coal plants also face much larger problems with respect to storage if ‘clean’ coal is ever to be realized. Coal plants today emit approximately 1.3 billion tons of carbon dioxide per year. This means if CCS is to be implemented, safe underground storage must be found for 1.3 billion tons of captured CO\(_2\). Considering the problems the United States has encountered attempting to find storage for the just over 2,000 tons of SNF generated annually by the nuclear industry, this will be no small feat. To put these volumes in context, if an American got all his or her electricity from coal over a lifespan of 77 years, that person's mountain of solid waste would weigh 68.5 tons and fill about six 12-ton rail cars. If they got their electricity from nuclear power, their share of the waste would weigh only 2 pounds and fit into one Coke can (48).

Ultimately, all forms of energy generation will be needed to meet the needs of our future energy system. Nuclear is not the only solution to climate change and climate change is not the only reason we should build nuclear reactors. What is important is what will be the most economical to build for a new generation of energy technologies that focuses on environmental impact and energy security. Nuclear does, however, compare favorably on the issues of economic viability, environmental health and safety, and energy security.
2.0 Historical Background and Current State of US Nuclear Power

2.1. History of Nuclear Power in the United States

The civilian nuclear power program in the United States began with the creation of the Atomic Energy Commission (AEC) in 1946, which authorized the construction of the Experimental Breeder Reactor I at the site now recognized as Idaho National Laboratory. This reactor generated the first electricity from nuclear power on December 20, 1951. The first commercial scale nuclear reactor was built in Shippingport, Pennsylvania and reached design power in 1957. Also in 1957, the Price-Anderson Act was introduced to provide financial protection to the public, AEC licensees, and contractors if a major public accident occurs. This year also marks the formalization of international nuclear energy cooperation in the International Atomic Energy Agency (IAEA). This period showed industry and utilities that nuclear power could be used safely and economically generate electricity and the industry grew rapidly in the 1960’s and 70’s, reaching a peak in 1973 with the commissioning of 41 nuclear power plants in one year.

At the inception of the commercial nuclear industry in the United States, reprocessing was viewed as the logical method for waste disposal to ensure the most efficient use of valuable natural resources. AEC planned to draw on the experience of the U.S.’s weapons program’s experience with reprocessing, which separated uranium and plutonium from the waste and vitrified all other components in glass. However, understanding that ultimate long-term geologic disposal of this vitrified waste was still required, the AEC pursued the Cary Salt Mine site in Lyons, Kansas as a location for the repository. This site was selected in 1970 and subsequently abandoned in 1972 due to technical and environmental concerns raised by the state of Kansas. The AEC then pursued a Retrievable Surface Storage Facility (RSSF), which was also terminated in 1975. Meanwhile, two private recycling facilities were built in West Valley, New York and Morris, Ill in 1966 and 1971. The West Valley facility successfully processed 1,000 used fuel assemblies before financial issues from additional AEC regulatory requirements made the plant uneconomical to operate.
To better deploy resources, in 1974 the Energy Reorganization Act divided the AEC into the Energy Research and Development Administration (ERDA), responsible for technology research and development, and the NRC, to oversee licensing and regulation. The ERDA was later transferred to the DOE in 1977 under the Energy Organization Act. The 1970’s also marked an increased attention to the risks associated with nuclear power. On March 5th, 1970, the United States signed, with the United Kingdom, the Soviet Union, and 45 other nations, the Treaty for Non-Proliferation of Nuclear Weapons. In light of proliferation concerns, President Jimmy Carter announced in 1977 that the U.S. will defer indefinitely plans for reprocessing spent nuclear fuel. Because of this mandate, the NRC was required to cease all licensing activities for recycling facilities and the U.S.’s first commercial reprocessing facility in Barnwall, South Carolina was subsequently abandoned (7, 35).

Then, in 1979, the worst accident in U.S. commercial reactor history occurred at Three Mile Island nuclear power station in Harrisburg, Pennsylvania. The accident was caused by a loss of coolant to the reactor core due to a combination of mechanical failure and human error. Although no one was injured and no overexposure resulted from the accident, the event marks a turning point in nuclear power generation in the United States, bringing the issues of environmental and public safety to the forefront of the nuclear debate. In response, the NRC enacts stricter safety regulation and more rigid inspection procedures to improve the safety of reactor programs.

Nuclear power continued to grow through the 1980’s, with 46 plants entering service in this decade, bringing the total to 109 operating reactors in 1989. In addition, President Reagan lifted the ban on reprocessing in 1981, encouraging development in advanced fuel cycle systems. In opposition to renewed governmental support, the environmental and health risks associated with nuclear power caused much of the United States to oppose nuclear power. One specific environmental concern is the ultimate disposal of HLW from these reactors. This lead to the 1982 Nuclear Waste Policy Act to establish a site for disposal of SNF from nuclear power plants, funded by a fee charged to owners and generators of nuclear waste. In addition, this act charges the US DOE with the responsibility of removing HLW from reactor sites and supplying adequate interim storage until such a permanent disposal site can be found (36). In 1983 DOE selected nine sites as potential repository locations, which was amended in 1987 to only consider
Yucca Mountain, Nevada as a final waste depository (37). Yucca was selected principally because it provided the best option for retrieval of the material at a later date, as required by the NWPA.

Work on advanced nuclear reactors continued into the early 1990’s through cooperation between the DOE and a consortium of the nuclear energy utilities, the Advanced Reactor Corporation (ARC). Investment in the expansion of nuclear energy was discontinued in 1993 when President Clinton introduced a policy statement against reprocessing and recycling because of concerns with safety, sustainability, economic feasibility, and proliferation. In light of this proclamation, between 1996 and 1998, only one nuclear reactor has been brought online, the Watts Bar I plant operated by the Tennessee Valley Authority (TVA). In the same time period, five nuclear power plants were retired, bringing the current total to 104 operating civilian nuclear power plants.

In 2000, the Yucca Mountain site was affirmed scientifically and technically sound by the National Academy of Sciences and again by the DOE in 2002. Following this, congress and President Bush designated Yucca Mountain as the site for the repository, overturning a state veto by the state of Nevada. President Bush also renewed the United States government’s investment in advanced nuclear technology in the Energy Policy Act of 2005. This legislation authorized DOE to share cost with selected applicants submitting licenses to the NRC to help test new licensing procedure and share first-mover costs through loan guarantees, insurance against delays not caused by the utility, and production tax credits for the first 6 GWe of new plants. In 2006, the U.S. introduced the Global Nuclear Energy Partnership (GNEP), an initiative focused on developing and making available proliferation resistant nuclear power.

Slowed by many legal battles and funding shortfalls, the Yucca Mountain license application was finally submitted to the NRC in 2008 and is currently under review. If Yucca Mountain is to proceed on the predicted schedule, DOE would begin removing SNF from utility sites in 2020. By the ramped schedule established for removal of the waste, this process would not be fully accomplished until 2066 (7).

However, the Administration and Secretary Chu have expressed that they do not believe Yucca Mountain is a suitable site for the geologic repository and will pursue a new nuclear waste policy that explores other options (31, 32). In FY2010, Obama has requested $196.8 million, which is only enough for DOE to explore alternatives for
nuclear waste disposal and to continue participation in the repository license proceeding before the NRC (33). On March 11, 2009, Secretary Chu proposed the formation of a blue ribbon commission to examine the options for nuclear waste management that would report back in two years, at which time the management strategy would be reassessed.

Figure 6. Historical Timeline of Nuclear Energy with depiction of Number of Operating Nuclear Power Reactors, Capacity Factor, and Percent of US Electricity Generation.
2.2. *The Nuclear Fuel Cycle*

When considering issues with nuclear power, as with any energy generation technology, it is important to consider the fuel cycle in its entirety, from resource extraction to waste deposition. The nuclear fuel cycle can be divided into three sections:

I. the front end where uranium ore is processed into fuel assemblies for use in nuclear reactors,

II. electricity production by fission in nuclear power plants, and

III. the back end of the fuel cycle which describes the processing, storage, and ultimate disposal of SNF.

The chart below and following discussion will describe each of the three sections, with references to both the current technology used in U.S. reactors, and possible future technologies. These future technologies are usually discussed as a management scheme for the back-end of the fuel cycle, however, their adoption would impact all sections of the fuel cycle.
Figure 7. Block Diagram of Complete Fuel Cycle with Once-Through and Reprocessing Routes Depicted
2.2.1. **Front End**

In the front end of the fuel cycle, uranium ore is extracted through conventional mining in open pit and underground methods similar to those used for mining other metals. Mined uranium ores are processed by chemically treating the ore to extract the uranium, yielding a dry powder-form material consisting of natural uranium, called yellowcake, which is sold on the uranium market as U$_3$O$_8$. Milled U$_3$O$_8$ must be converted to uranium hexafluoride, UF$_6$, and enriched from a natural concentration of the fissionable isotope U-235, 0.71 percent, to 4 percent U-235 for it to be used as nuclear fuel. Gaseous diffusion and gas centrifuge are the commonly used uranium enrichment technologies. In addition, separation using a laser isotope enrichment process is beginning to see commercial use with the possibility of achieving higher initial enrichment factors than the diffusion or centrifuge processes can achieve.

For use as nuclear fuel, enriched UF$_6$ is converted into uranium dioxide (UO$_2$) powder which is then processed into pellet form. The pellets are then fired in a high temperature furnace and ground to create hard, ceramic pellets of enriched uranium. The pellets are stacked into tubes of corrosion-resistant metal alloy, zircaloy, to form fuel rods. The finished fuel rods are grouped in special fuel assemblies that are then used to build up the nuclear fuel core of a power reactor.

Advancements in the front end include new enrichment techniques, such as laser isotope separation (LIS), as well as new fuel fabrication methods associated with reprocessing. In a reprocessing scenario, a mixed oxide (MOX) fuel would be fabricated in a similar method to the traditional uranium fuel, but reprocessed uranium or mixed plutonium/uranium oxide from the separation process would serve as the feed stock instead of mined uranium. If more advanced pyroprocessing methods are used, new remote handled fabrication methods for metal fuels would need to be developed.
2.2.2. **Current Reactor Technology**

All of the U.S.’s 104 currently operating commercial reactors are LWRs located in 39 states across the nation (13).

![Figure 9. Location of U.S. Operating Nuclear Power Reactors. Source: NRC](image)

Heat generated from the fission occurring in the reactor core heats water to make steam, which turns turbines to generate electricity. In LWR designs, ordinary water is used to control the reaction, as the coolant and the moderator. The fuel assemblies can fuel a nuclear reactor for 18 to 24 months before a build-up of unfissionable elements, called fission products, poison the fuel so it is no longer able to sustain a nuclear reaction.

Nuclear reactor technology is divided into a series of levels, or Generations, describing the evolution of advanced safety measures and efficiency increases. The fundamental LWR designs are Generation II technology. Through upgrades and implementation of passive safety mechanisms, the new reactor designs currently being licensed are Generation III+ technology.

2.2.3. **Back End**

The back end of the nuclear fuel cycle can be viewed in two fundamentally different ways. One possibility is a “once-through” scenario, which is the method currently employed in the United States. In a “once-through” fuel cycle, the SNF is run one time in a nuclear power reactor and then stored in interim storage vessels, typically pools or above ground dry casks. The SNF would then ultimately be destined for permanent storage in a deep geologic repository, such as Yucca Mountain.
The other possibility for disposal of SNF involves first reprocessing the SNF to extract the residual fissile materials from the “poisons” and other undesirable material. Only about 95 percent of the original energy in the fuel has been used up, while the remaining usable fuel can be separated and recycled as fuel in another nuclear reactor. The remaining cladding, hulls, and fission products are disposed of as HLW. The HLW is cast in glass in a process called vitrification, which simplifies the handling and disposal of the radioactive material. The packaged HLW is then disposed of in a similar geologic repository for permanent storage. This is currently practiced, as in France, through the aqueous separation of uranium and plutonium, by a method called Plutonium Uranium Extraction (PUREX). Some of the separated uranium is recycled with plutonium to form a mixed oxide fuel (MOX) that can be loaded into current LWRs for recycling. The balance of the uranium is called reprocessed uranium. It is typically about 0.9 percent enriched in fissionable uranium (U-235) and thus must be re-enriched to be manufactured into uranium fuel assemblies.

More advanced aqueous separation methods that involve more steps have been developed to remove additional elements from the SNF that are particularly heat generating and long-lived. There separations are beneficial from a waste management standpoint, but then must be burned down in a fast reactor or similarly stored in a repository.

Figure 10. Main Components of a Spent Nuclear Fuel Assembly from a conventional LWR and possible uses in a reprocessing fuel cycle.
2.3. Storage and Disposal of Spent Nuclear Fuel

Spent nuclear fuel is composed of many elements that are currently disposed of all as one package in the once-through fuel cycle. These elements have varying half-lives and levels of radioactivity. Some components are still fissile and can be recycled as MOX or reprocessed uranium (RU) fuel, some can be recycled only in fast reactors, while some are non-recyclable and must be disposed of as waste, as displayed in the table below:

Table 2. Radionuclides present in spent nuclear fuel, percentage of fuel, radioactivity and storage or reuse options.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>% SNF</th>
<th>Radioactivity</th>
<th>Reuse?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>95</td>
<td>Low, comparable to ore</td>
<td>Can be recycled as MOX or re-enriched</td>
</tr>
<tr>
<td>Plutonium and Neptunium</td>
<td>~1</td>
<td>Long half-life and significant heat source</td>
<td>Can be recycled as MOX</td>
</tr>
<tr>
<td>Americium and Curium</td>
<td>0.1</td>
<td>Long half-life and significant heat source</td>
<td>Can be recycled to fast reactors</td>
</tr>
<tr>
<td>Cesium and Strontium</td>
<td>0.3</td>
<td>~30 year half-life and significant heat source</td>
<td>Stored as HLW. Can be stored above ground initially to reduce heat load on repository.</td>
</tr>
<tr>
<td>Iodine and Technetium</td>
<td>0.1</td>
<td>Very long half-life. Mobile in ground water</td>
<td>Released as gaseous effluents. Capture and store as low level waste (LLW)</td>
</tr>
<tr>
<td>Other Fission Products</td>
<td>~3.5</td>
<td>Low heat and toxicity</td>
<td>Stabilize for long term storage as HLW</td>
</tr>
</tbody>
</table>

The current reactor fleet in the United States generates 2,100–2,400 tons SNF per year. Over the more than 50 year history of nuclear energy generation, the industry has generated and currently stores 58,000 tons of SNF (10). To put this amount in perspective, this volume of SNF, if stacked end to end, would cover an area the size of a football field to a depth of less than 10 yards (22).

In the absence of a permanent storage solution, the SNF is currently stored at reactor sites in pools or dry casks. In pool storage the SNF is kept in steel-lined, concrete pools filled with water or boric acid, which acts as a natural barrier for radiation from the used fuel. When the capacity of pool storage at reactor sites is exceeded, utilities have constructed above ground, dry cask storage that stores SNF in airtight canisters made of
steel, steel-reinforced concrete or steel-enclosed concrete. Through diligent monitoring and maintenance of safety systems, the NRC has ensured safe and secure storage of the spent fuel at these interim locations for the next century. However, these solutions were originally meant to only serve temporary storage requirements and are costly to electricity consumers, who must pay for both storage and disposal. Each year of delay in the federal program for removing used nuclear fuel from reactor sites will add an estimated $1 billion in temporary storage costs (22).

As part of the Nuclear Waste Policy Act, the DOE signed contracts with all operating utilities taking responsibility for removing SNF from utility sites for final disposal. The utilities fund this effort through the Nuclear Waste Fee, which charges utilities mill\(^6\) per kWh produced and increases its value $750 million per year. Under the contracts all nuclear operators have signed with the DOE as part of the NWPA, the DOE was supposed to begin removing waste from reactor sites in 1998. DOE’s failure to do so has put it in breach of contract for the past decade. As such, many utilities are exceeding their primary pool storage capacity and have had to add additional dry cask storage systems to accommodate the SNF. To pay for these additional storage systems, the utilities have brought more than 60 breach of contract law suits against the DOE. To date, about $750 million has been awarded in damages. Recent DOE estimates predict the federal government will be liable for another $13 billion in the future even if disposal were to begin in 2020, as is the current schedule for Yucca Mountain. If unable to provide a permanent waste management solution, DOE would enter full breach of contract and be responsible for returning the full amount of funds collected with interest, totaling more than $28 billion dollars (10).

\(^6\) a mill is equal to one tenth of a cent
3.0 Changes in the Nuclear Waste Policy Act

Obviously, the current waste management situation is unsustainable. The NWPA authorizes only one site, Yucca Mountain, which can be considered for a repository location. However, the site has now been taken off the table and all except minimal programmatic funding has been pulled from the project. Several options exist for future nuclear waste management, the most plausible of which are discussed in detail below as well as the implications each would have. Whichever the option is chosen, the NWPA would need to be amended to reflect either the specific new direction, or to allow the consideration of a diversity of options.

3.1. Withdraw Yucca License

As the Administration does not view Yucca Mountain as a suitable site for a nuclear waste repository, Secretary Chu has the authority to withdraw the Yucca Mountain license application currently being reviewed by the NRC. However, if this were to occur, DOE would likely enter full breech of contract and, as mentioned above, be liable for returning the full amount collected as part of the Nuclear Waste fee plus interest, totaling more than $28 billion dollars. Thus, this is probably not an option the DOE will pursue and the Yucca application will continue to be reviewed while DOE looks to explore alternatives to the site.

3.2. Stop Collecting Fees

Another option is for the DOE, until a feasible path is chosen, to stop collecting the nuclear waste fee. Monies already paid would remain in the fund to be used on the chosen solution, but additional fees would not be collected until such a solution is chosen. Many believe this is the most equitable solution because the utilities should not be forced to pay for a non-existent solution. Every year the DOE, under NWPA, is supposed to assess the adequacy of the fee. In absence of disposal plan and associated life-cycle cost, there is no current basis to judge the adequacy of the fee. Thus, several groups have recommended to DOE that they stop collecting fees beginning with in this year’s assessment until some solution is found (40).
3.3. ***Continued On-Site Storage***

This is the default, short term solution, as current storage in pools or dry casks has been deemed safe and secure for as long as 100 years. Even if a sustainable solution is found in the next two years of review by the blue ribbon panel, established by Secretary Chu and tasked with exploration of other waste management options, and waste removal is started on schedule in 2020, nuclear waste will continued to be stored on site until 2066 at the earliest. Given the history of delays in the government’s efforts to address long-term storage issues, it is likely that continued on-site storage will probably continue for much longer than the 2066 projections.

The lack of a long-term solution for SNF could also have implications for the 17 applications for new plants that are currently pending with the NRC, as it is the NRC’s policy “not to continue to license nuclear reactors if it did not have reasonable confidence that the wastes can and will in due course be disposed of safely.” In 1984 NRC found that there was reasonable assurance if the repository would be opened by 2007 to 2009 and that waste could be safely stored at reactor sites for at least 30 years after the reactors had shut down. As the removal date slips farther and farther into the future, the NRC is considering new legislation that would find reasonable assurance that a repository will be available within 50 to 60 years after the reactor’s licensed operating life and that spent fuel can safely be stored for at least 60 years after the reactor has ceased operation, totaling over a hundred years of safe on-site storage (35). The NRC is expected to vote on this update later this month.

However, the technological and scientific merit of surface storage beyond 100 years is uncertain because maintenance and security of the storage sites cannot be extrapolated beyond the 100 year time frame. The environmental impact statement for the interim storage sites found that substantial amounts of radioactivity would leech into the environment within 10,000 years, having potentially catastrophic impacts on human and environmental health (38). Given that the SNF, as it currently exists, would require storage for hundreds of thousands of years, permanent surface storage in not a viable option.

It is conceivable that the time required for SNF storage could be shortened through transmutation in a fast reactor. If SNF is transmuted in a fast reactor, the
required storage time for the material to reach levels equivalent to that of natural uranium are drastically reduced to less than 1,000 years (39). With a 1,000 year time frame, it is possible that surface storage could be pursued if all long-lived transuranic elements could be transmuted in a fast reactor. Given current technology, however, the National Academy of Sciences has stated that in all cases final deep geologic disposal will be required.

There has been some suggestion that DOE take responsibility for spent fuel at reactor sites to reduce the cost to utilities and the cost of federal liability. Most utilities and state regulators are opposed to this solution as they see it as an avenue for continued deference of a long-term disposal site. In addition, they oppose using the Nuclear Waste Fund to pay for activities that do not present a permanent solution (35).

3.4. **Central Interim Storage**

A government-funded central interim storage facility or a number of regional interim facilities would allow DOE to fulfill its contractual obligation to the utilities to remove SNF generated to date, preventing further litigation, and could begin receiving waste as soon as 2020. In addition, an interim storage site or sites would centralize the waste in convenient locations that could be then licensed as recycling facilities if reprocessing is to be explored. There are many communities that, given appropriate governmental assurances and compensation, have offered sites for an interim storage facility.

Some groups oppose centralized interim storage on the grounds that it is safer to leave waste at reactor sites to avoid additional and unnecessary transportation risks. The DOE maintains that the 1987 NWPA amendment prohibits it from pursuing another repository site, interim or otherwise, until Yucca Mountain is licensed. Congress has attempted several times in the last decade to pass legislation that would institute interim storage, but no bill has ever been enacted (35). Under current legislation an interim storage location would be limited to 15,000 metric tons of fuel and could not be located in Nevada.\(^7\) The NWPA would need to be amended to allow DOE to consider options other than Yucca Mountain before federally run, centralized interim storage locations

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\(^7\) NWPA sections 145 and 148
could be sited and licensed (7). In the end, such sites may prove as controversial to license as a long-term storage site.

Another possibility is a private interim storage location, such as a facility in Utah that has already received an NRC license. This facility, operated by a company called Private Fuel Storage (PFS), was commissioned specifically to accept waste from decommissioned nuclear reactor sites so that those sites could allow the owning utilities to cease operations completely at those sites, preventing costly additional expenditures when there is no other activity on the site. The PFS planned to run the facility on land leased from the Native American Band of Goshutes that own the land. The license is limited to 40,000 metric tons of spent fuel, which can be stored for no longer than 40 years. The site has never operated, as the opening of this site was blocked by two decisions issued by the Department of the Interior (DOI). The Native American Band and PFS brought suit in federal court to overturn the Department’s decisions in 2007. The federal government could move to revisit the DOI’s decisions that are blocking the project. However, the site would still face a challenge to the NRC license filed by the State of Utah. Even if a private facility such as that proposed by PFS was available to accept SNF, the DOE would remain responsible for removing the fuel at some point in time, as the site would not be licensed to serve as a permanent storage site (35).

3.5. **Different Repository**

While Yucca Mountain does represent a technically and scientifically sound site to store nuclear waste, it is by no means the only location. Yucca was selected in large part because its unique geology meets the requirement that the waste be retrievable. If the SNF were to be recycled, all useful elements would be removed and the fuel would not need to be retrievable. In addition, the vitrified waste product is very stable, more resistant to leaching, and suited for many geologic disposal mediums like clay, granite, or basalt (7). Storage for vitrified waste could be found in a number of suitable geologic forms, such as salt caverns, for example.

Salt formations present unique characteristics that could be beneficial for a storage site, such as their aridity and the flow of salt to encapsulate the vitrified waste canisters, making their retrieval virtually impossible. DOE has extensive experience operating salt repositories to serve as storage sites for nuclear waste, for example at the
Waste Isolation Pilot Plant (WIPP) in New Mexico. WIPP currently stores transuranic waste (TRU)\textsuperscript{8} from defense operations. WIPP has demonstrated the licensing process and technical fidelity of disposing of radioactive waste in salt formations, which could serve as a foundation for a similar site for civilian waste. Alternatively, WIPP could be re-licensed to accept civilian waste. Although locals support the site, the state of New Mexico continues to strongly oppose HLW disposal at WIPP.

In fact, many of the alternative long-term storage sites have already been identified as part of the original NWPA, which was designed to be a fair, technically sound, and extensive selection process. The original NWPA instructed DOE to establish five sites, from which three were to be chosen for more extensive characterizations. The five promising areas were the salt domes along the Gulf Coast, bedded salt in the Great Plains and Midwest, volcanic tuff\textsuperscript{9} in the West, and basalt in the Pacific Northwest. From these five areas, a basalt site at Hanford, WA; a bedded salt site in Deaf Smith County, TX; and the volcanic tuff at Yucca Mountain, Nevada were selected.

To address concerns about the equitability of a single state or region being responsible for the entire country’s waste, the first site was to be limited to 70,000 metric tons until a second repository could be licensed. The second repository was to be located in a different region and “to the extent practicable” in a different geologic media. Twelve promising rock formations in seven states were released by DOE in 1986. Intense political pressure from the states selected and unrealistic estimates by DOE as to the anticipated cost and schedule led to concerns about whether the program’s goals could be realized. In an effort to save money, time, and the program, the NWPA was amended in 1987 to consider only one site, Yucca Mountain, which was at the time the most highly rated site. Since then, the site has received persistent and unrelenting opposition on scientific and political grounds. The history of site selection in the United States suggests that a process that could overcome such political pressures would be very hard, if not impossible, to design.

\textsuperscript{8} Transuranic waste is waste that contains high levels of radioactive transuranic elements with half-lives greater than 20 years. Transuranic elements are elements higher than uranium on the periodic table, for example, americium-241 and several isotopes of plutonium, and are typically alpha emitting.

\textsuperscript{9} Tuff (from the Italian "tufo") is a type of rock consisting of consolidated volcanic ash ejected from vents during a volcanic eruption.
4.0 Projected Nuclear Energy Expansion Scenarios

There are several different options for the future of nuclear power in the United States. Each has implications for necessary government involvement, technical feasibility, risk, and approximate time line. In addition, each option requires different changes in licensing, waste management, and incentives for development and has different effects on future energy growth. The three primary scenarios are discussed more fully below. They are no new investment, continued expansion of a once through cycle, and nuclear growth with reprocessing and recycle of SNF.

4.1. No Further Nuclear Investment/Nuclear Phase-Out

A scenario with no future nuclear investment and a phase out of nuclear energy in this county will have broad implications for our energy security and future energy mix. In this scenario, the government would cease all government sponsored civilian nuclear investment and, in light of the difficult political and financial situation, the nuclear industry would discontinue investment in the United States.

While most of the 104 operating reactors will be re-licensed for an additional 40 year operating period, there is no opportunity for increased nuclear generation, as plants are already operating with a 90 percent capacity factor. Thus, nuclear energy’s contribution to national energy generation will decline as demand increases and begin to decline rapidly in 2040 or 2050 as these reactors reach the end of their operating life and are decommissioned.
The projected increase in energy demand, along with the 20 percent previously provided by nuclear power, will account for 2,557 billion kWh of additional generating capacity that must be met by another source.

Many project that the gap could be met by more natural gas plants. Natural gas plants are relatively inexpensive to build and operate and there is already an established transportation network, so expansion of natural gas electricity generation capacity would be possible. However, natural gas has recently been an economically volatile resource and more natural gas plants could further exacerbate price fluctuations. In addition, natural gas is a valuable resource for heating and much of it is wasted when used for electricity generation. In addition, natural gas plants contribute significantly to carbon dioxide emissions, releasing about 150 grams of CO$_2$ per kWh of electricity produced, five times more than the CO$_2$ emissions of nuclear power plants (8).

With the probable enactment of a carbon cap and trade scheme and renewable electricity standard (RES), renewable energy resources would be required to replace much of the additional generating capacity that would be needed without nuclear power. This expansion would most likely come in the form of wind and solar, which currently are more expensive than nuclear generation. If the increased capacity is met with half
wind and half solar, the increased expansion required would represent 3 million acres of new solar, an area roughly the size of Connecticut, and over 200,000 new wind turbines. Even the most optimistic estimates for growth of wind and solar generation find this level of expansion uneconomical, if not impossible. Thus, projected carbon limits cannot be met without expanded nuclear generation.

4.1.1. Waste Management

Even if there is no new investment in nuclear generation capacity, by law the government would still be responsible for the disposal of SNF that has been or will be generated by the current reactor fleet, as mandated by the Nuclear Waste Policy Act. In the “no new investment” scenario, direct, long-term disposal of the SNF would be the most economical option. As the Administration has announced the decision to remove Yucca Mountain as an option for the repository, “no new investment” would require the NWPA to be changed to allow the explorations of other disposal sites.

4.2. Nuclear Growth with Once-Through Cycle

The second scenario involves investment in new LWRs to expand nuclear generating capacity. In this scenario, SNF would continue to be stored on site until a centralized interim storage or long-term deep geologic storage solution is found.

Expanding nuclear power to maintain 20 percent of the United States’ electricity consumption will involve building approximately 150 new 1000 MWe nuclear power plants over the next 50 years, about 100 to replace the 104 existing plants that will be decommissioned in the next 50 years, and 50 new reactors. While the newest Generation III/III+ reactor designs have larger generating capacity, as much 1600 MWe, the number of new reactors still represents a massive investment in the atrophied nuclear power infrastructure in the United States. With such a hugely capital intensive and long lead time project, investors and utilities need to be able to reliably plan many years into the future to create an effective business model for the plant. Changes in licensing, waste management policy, and government funding will be needed to effectively implement new nuclear growth.
4.2.1. **Licensing**

A long, costly, and unpredictable licensing structure has prevented investment in new plants because plants could be held up, sometimes indefinitely, in the licensing process. This could add years to the time it takes to design and build a reactor, as well as millions or even billions of dollars to the price to build the reactor.

All of the reactors currently operating in the United States are licensed by the NRC under Title 10, Chapter I, Part 50 of the Code of Federal Regulations (10 CFR 50). The process required licensees to first apply to build a plant by submitting preliminary environmental, safety, and technical analysis reports to obtain a construction permit. During the construction phase, the utility applied for a separate operating license referencing final environmental, safety, and technical analysis reports, reflecting the as-built plant design. In the past this process has caused delays because of the number of opportunities for public comment and appeal, taking on average 10 to 14 years. The last plant to be built using the 10 CFR 50 licensing process will be TVA’s Watts Bar 2. TVA was issued a construction permit for Watts Bar 2 in 1973, but delayed construction indefinitely in 1985. TVA has now expressed renewed interest in completing the project. Watts Bar 2 was sanctioned in August 2007 and is on schedule and on budget for construction completion in 2012 (14). Watts Bar 2 has applied for an operating license and is currently receiving public comment on its application. Several environmental groups have voiced opposition but it is not believed they will be successful in delaying or stopping the license application (49).

Because of the delays and additional costs caused by the two-step process, the Energy Policy Act of 1992 adopted a new streamlined, one-step process for a combined operating license (COL) in Title 10, Chapter I, Part 52 of the Code of Federal Regulations (10 CFR 52). The combined operating license also references a design certification and early site permit. The design certification is a rule for standardized plant
designs that may be referenced anytime that type of plant is built; thus each specific plant design need only receive certification one time. Also, the early site permit allows utilities to perform environmental reviews on sites, obtain site permits, and bank those sites for future reactor applications. Then, when completing the final COL, the utility will reference the previous design certification and early site permit, hopefully shortening and simplifying the licensing process.

Although conceived in 1992, this process was not implemented until 2006. On July 13, 2007, UniStar Nuclear, LLC, filed the first COL application with the NRC for construction of a new reactor at the Calvert Cliffs Nuclear Station. While the first applications to go through this process may only decrease the licensing time slightly, as both the NRC and the licensees become more familiar with it and as more reactor designs are granted certifications, the new COL process is expected to be a substantial improvement on the previous system, decreasing overall licensing time considerably, although the process is still projected to take 6-8 years from licensing to operation (15).
Currently, NRC has issued three early site permits, with another permit request undergoing review. The NRC has also certified two standardized reactor designs, with three more undergoing review. In addition, the NRC is also currently reviewing 17 applications for 26 new reactors. The first of these plants is expected to be issued a COL by 2011 and begin producing power for the grid by 2015 or 2016 (15).

![Proposed Reactor Design](image)

Figure 14. Proposed New Reactor Sites and Type of Reactor of Combined Operating License Applications Currently Under Review by the NRC. Source: NRC.

4.2.2. Waste management

Expanding nuclear power will also require changes in U.S. nuclear waste policy. Uncertainties about a permanent solution for the back end of the waste cycle may deter the investment needed for the construction of new plants that will only contribute more waste to the storage problem. To facilitate investment in new nuclear reactors, the United States needs a sustainable, consistent, and long-term solution to waste storage that is not subject to the changing political leanings of policy makers.
The DOE has recently organized a blue ribbon commission to analyze options for the disposal of nuclear waste that will report to Congress in two years. If the U.S. hopes to expand the country’s nuclear generating capacity and build new reactors, it is important a permanent solution be found as soon as possible. If Yucca Mountain is no longer an option, the U.S. needs to explore other locations for deep geologic disposal. Perhaps licensing these sites could come with incentives so that states would bid for a repository as opposed to having it mandated. This could make the siting decision more attractive from a political standpoint. Additionally, the blue ribbon commission should consider more than one site, as nuclear expansion with a once-through fuel cycle will necessitate several Yucca Mountain-sized facilities this century. Alternatively, if Yucca Mountain is re-evaluated and approved for operation as scheduled, the commission could consider a recommendation to expand the capacity of the site. As mentioned previously, the capacity of 70,000 tons SNF was set due to political, not technical, reasoning.

4.2.3. Governmental Funding

Developing a nuclear power capacity of the scale required to maintain 20 percent electricity generation is feasible, as we have built 100 nuclear reactors in a decade before. It nonetheless represents a massive undertaking, especially considering the state of the U.S. nuclear manufacturing infrastructure today. Consensus opinion is that U.S. would need to invest between $750 billion and $1 trillion in new generating capacity (41).

Given the current political and regulatory environment, the first plants to be built in the new generation of nuclear power will have unreasonably high risk associated with them, making private investors unwilling to advance loans to such projects. The average stock market value of current utilities is around $25 billion dollars, while the average cost of a 1000 MWe reactor is about $4 billion, with new Gen III/III+ reactors closer to $6 to $7 billion (23). With plant construction costs from $4 to 7 billion, it is difficult for utilities to finance these projects alone. The DOE’s Energy Policy Act of 2005 was designed to help mitigate some of these issues by authorizing the DOE to share costs with selected applicants submitting licenses to the NRC. This assistance is available to all
low-carbon electricity generation technologies,\textsuperscript{10} while still ensuring the utilities and industry maintain some financial responsibility to motivate cost and schedule discipline. However, only recently have nuclear facilities received appropriated funding. In June 2009, DOE announced four applicants, UniStar Nuclear Energy, NRG Energy, Scana, and Southern Co., who will receive a total of $18.5 billion in loan guarantees. Many industry and utility representatives, such as Bryan Dolan of Duke Energy have recognized that “[a loan guarantees] lowers the cost of capital and therefore enables owners to deliver to ratepayers at a lower rate,” which make nuclear power more cost competitive. Although, he adds, “they are not critical for us to move forward.” (23)

In addition to loan guarantees, the 2005 Energy Policy Act provides a production tax credit\textsuperscript{11} of 1.8 cents per kilowatt-hour to qualified advanced nuclear power facilities certified by the NRC after December 31, 1993 for an 8-year period after the facility is placed in service after enactment of the Act and before January 1, 2021. The legislation limits the national megawatt capacity for production tax credits to 6,000 MWe (34). If this tax credit were to be realized and effective for new plants, the section would have to be amended to extend past the initial deadline of January 1, 2021. With the first new plant that would fulfill the criteria scheduled to begin operation in 2016, the tax credit would run out before the plant had realized the full benefit. Future plants would have even less time under the subsidy. The loan guarantees are allocated to the first four plant builds. Perhaps the tax credit could be extended to accommodate the expected construction time of these plants and allow them to realize the tax credit for the fully allotted time or production amount. Extension of the tax credit, however, is not necessary for construction of new plants.

As an alternative to the initial subsidy, state governments could allow utilities to include construction work-in-progress (CWIP) costs in the rate base, meaning utilities could raise rates before the new plant was actually generating electricity. Including

\textsuperscript{10} Title 17 of EPAct 2005 allows the Secretary of Energy to provide loan guarantees for up to 80 percent of eligible project costs after consultation with the Secretary of the Treasury. The guarantee is for projects that avoid, reduce, or sequester air pollutants or anthropogenic emissions of greenhouse gases; and employ new or significantly improved technologies as compared to commercial technologies in service in the United States today. Incentive covers a broad range of technologies that include advanced nuclear energy facilities.

\textsuperscript{11} The Advanced Nuclear Generation Tax Incentives occur as Title XIII Section 1306 of the EPAct 2005
CWIP costs in the current rate base allows the utility to better off-set some of the large up-front costs of new reactor construction. A bill to allow this type of utility pricing is currently being considered in Georgia’s general assembly (50).

Another policy that could affect the economics of nuclear power involves how the government responds to the issue of global warming. A carbon cap and trade system is expected to benefit nuclear power pricing and encourage new plant construction, as nuclear power presents the lowest cost option for carbon-free base-load electricity generation capability currently available.

4.3. **Nuclear Growth with Recycle and Reprocessing of Spent Nuclear Fuel**

The third scenario focuses on increased expansion of nuclear power generation, along with the development of an aqueous reprocessing facility and MOX fabrication plant to facilitate recycling of fissile materials from SNF. In this scenario, research would be on-going for the transition to an advanced recycling center with pyroprocessing and fast reactor facilities to be implemented as technically and economically feasible.

All of the aspects associated with new plant build, as discussed in the previous section, are relevant for this scenario, as reprocessing would not make sense without increased investment in a vital nuclear power sector. In addition, a deep geologic repository will still be required in all recycling scenarios, however, the timing of ultimate disposal is more flexible in a recycling scenario. Recycling facilitates the removal of material from utility sites to reprocessing facilities, fulfilling the DOE’s responsibility in the NWPA more quickly, and the HLW can then be stored in a more compact and secure package until a final geologic storage solution is found.

Reprocessing is also beneficial because it can greatly reduce the volume of HLW destined for final disposal by reducing the heat load on that repository. With recycle of reusable fuel in thermal reactors, the volume of HLW that must be stored in a repository can be decreased by a factor of 4 to about 11 cubic feet per ton of original fuel (42). Reprocessing also decreases the heat load on the repository by eliminating the most heat producing elements, specifically plutonium and the minor actinides (Americium and Curium). Yucca Mountain, as licensed, would have reached capacity by 2011, even with
no additional nuclear activity (10). Recycling eliminates the need for another Yucca size repository in this century.

In removing the heat generating actinides for delayed disposal in a vitrified waste form, the heat load on the repository is decreased, but also continues to decrease much faster than in traditional once-through storage. Thus, the timeframe of long-term storage can be significantly decreased from hundreds of thousands of years to thousands of years (39). The ultimate transmutation of those elements in fast reactors eliminates the problem of their disposal, thereby decreasing the time required for long-term storage of HLW to less than 1,000 years, see figure 12, below. It would take used fuel straight from the reactor 300,000 years to reach a comparable level of radiotoxicity.

Using conventional PUREX/MOX technologies initially, a reprocessing facility could be open by 2023, but would require significant scale up to process fuel on the scale equivalent to the Yucca Mountain schedule for spent fuel removal. Even in the most aggressive estimates, a steady-state recycling program could not be implemented until 2070 at the earliest (10).
4.3.1. Licensing

The Nuclear Regulatory Commission does not currently provide adequate regulations for the nuclear industry to begin recycling activities. The gaps in regulation have been identified by NRC staff working with representatives from industry, utilities, and others and a path has been developed for closing those gaps. NRC is currently working on drafting regulation and licensing procedures for a recycling facility. It is conceived to be a new part to the Code of Federal regulations, 10 CFR 7x. However, licensing, design certification and First-of-a-Kind (FOAK) engineering will be difficult problems for the first plants. NRC will struggle to review all of the license applications and design certifications according to its current schedule, but Commissioner Klein has expressed his determination at maintaining and even further abbreviating the current schedule to ensure on-time and on-schedule delivery of plant licenses (17, 18, 19).

To ensure regulation will not impede nuclear growth, more extensive modeling to effectively analyze environmental, economic, and social impacts of reprocessing facilities is necessary. DOE should work in partnership with universities, the Department of Transportation, and other countries pursuing advanced reprocessing techniques to achieve technical certification of MOX fuel and transportation schemes, as well as advanced recycling technologies. In this way the government, industry, and academia can work together, with academia leading licensing and qualification of fuels and more fundamental research, while industry focuses on commercialization and pilot scale testing facilities.

4.3.2. 10 CFR 7x

A commercial reprocessing plant in the United States would be licensed as a “production facility” under the Atomic Energy Act (AEA), which outlines most of NRC’s regulatory activity. Thus, in the preparation of regulation to license a recycling facility, the NRC considered 10 CFR Part 50, which pertains to “production and utilization facilities” and is the regulation under which all current nuclear reactors are licensed. However, as Part 50 pertains mostly to LWRs, it would have limited applicability to commercial reprocessing facilities.
10 CFR Part 70, which currently licenses many different types of fuel cycle facilities, is more flexible and was deemed by NRC staff as capable of licensing aqueous separation techniques, as well as any potential pyroprocessing techniques (44). However, a number of modifications would be required to incorporate reprocessing activities, including the possibility of a two-step or combined license process. Thus, the NRC has proposed creating a new Part 7x that could be designed specifically to license recycling activities. The Part 7x is envisaged as being modeled after the risk-informed and performance-based approach that Part 70 uses, while incorporating specific related aspects of Part 50, and the combined licensing procedure of Part 52. The new Part 7x would provide flexibility with the capability of licensing a separation facility under Part 7x as part of an existing plant site, or as licensing many aspects of the recycling fuel cycle under the same license. This also makes it possible to add facilities, such as a new LWR under Part 52, to an existing Part 7x recycling facility license.

![Figure 16. NRC Licensing Options for Recycling Facilities Under 10 CFR Part 7x, Part 52, and Part 70. Source: NRC.](image)

The NRC is currently working on the technical basis of the license and expects to be able to accept applications by 2012.

In order for a licensee to submit an application, a great deal of testing and demonstration must occur on the engineering scale to prove the safety and integrity of specific process operations. For example, while much initial work has been done, a demonstration facility of the specific combination of separation steps used in a facility
would be required to provide data to the NRC to convince them of the safety of the design.

4.3.3. Additional Licensing and Regulation

In addition, MOX fuel would need to be qualified for use in designated reactors and those reactors would need to receive license amendments for operation with MOX fuel. The safe and secure transportation of fuels to and from reprocessing facilities would need regulation and licensing to comply with AEA and IAEA guidelines. Safe and proliferation resistant transportation containers would be licensed by the NRC, while in transit shipments would require oversight from the Department of Transportation. The NRC has recognized these deficiencies in regulation and is addressing them in conjunction with their goal of licensing the first reprocessing facility by 2012.

Two fast reactor designs, both sodium-cooled fast reactors (SFR), have been submitted to the NRC for review prior to formal submittal of an application, GE-Hitachi’s Power Reactor Innovative Small Module (PRISM) and Toshiba’s Super-Safe, Small, and Simple (4S). However, extensive work will have to be done to license these reactors, as well as qualify the fuel, fuel fabrication facility, and separation methods.

4.3.4. Waste Management

It has been suggested that for sustainable management of the nuclear fuel cycle associated with reprocessing activity, management of nuclear waste should be transferred to an independent organization. Many believe this organization might be more efficient and less affected by politics. This organization could be private, governmental, or a public-private partnership. The most popular model today is that of a government corporation, similar to the TVA model (21). In this model, the entity would have a board of directors made up of utilities but would receive oversight from the DOE. This could be the most efficient because it would create an independent entity with requisite flexibility and dependability in funding to effectively achieve a solution to the nuclear waste management issue, while still allowing DOE to fulfill its contractual obligations.

To be effective the organization should have the ability to assess options and choose sustainable solutions without necessitating changes to the law or congressional
approval. The organization would also require reliable funding and the ability to raise debt. The organization’s board would be responsible for contracting with industry for construction and operation, waste disposal, spent fuel take-back, and transport of fuel. The Nuclear Waste Fund (NWF) could provide the requisite investment for these programs and could be given to the board to manage, ensuring the NWF funds are spent only on permanent spent fuel disposal, weather recycled first or not.

If a private or public-private entity were pursued, all the contracts DOE signed with licensees would need to be terminated or transferred and a new funding scheme would be required (35). Although an new organization would have more ability to act independent of the political process, it is not clear whether a new entity would in fact be able to avoid the political controversy that has stalled the current program.

As another alternative, ownership and responsibility for the back-end of the fuel cycle could simply be returned to the utilities. This would require new legislation to negate the NWPA and negotiations to rescind the contracts between the utilities and DOE. Premature ending of these contracts without the terms of the contract being realized would mean that the government would be responsible for returning all the money paid to the NWF and the utilities would be required to privately site, license, and finance waste management activities. Legally, it would be very difficult to get out of the contracts without extensive negotiations. Also, this would be difficult to enact because of the legacy of governmental waste management in the nuclear industry. Most utilities have formulated their business plans around this model and restructuring their nuclear operations would be costly and difficult.

However, it is possible that, once the transition had occurred, the private community would be more efficient at implementing a successful solution than the government has been. Many believe that for nuclear energy to be sustainable in the long term it needs to be able to fully commercialize. While utility control of the back-end of the fuel cycle could increase the economic competitiveness of nuclear power, it would be important that governmental organizations, such as the NRC and the EPA, remain closely involved to ensure the safe and environmentally sound operation of any private facilities. In this way, a fully privatized nuclear fuel cycle could give continuity in regulation and
management because it is not as affected by changing political opinions, but would not be completely free of public and governmental involvement.

4.3.5. Research in Advanced Technologies

Due to the cost of reprocessing, one competing development path that has been suggested is the direct implementation of fast reactor technology, as it becomes available. This would prevent needless expense on aqueous separation and MOX fuel fabrication facilities and would allow the U.S. to move directly to advanced pyroprocessing and SFR technologies, which may realize economic and waste benefits because of their more simple design. However, because these technologies are not yet demonstrated and still require a substantial amount of development, waiting to reprocess until such facilities exist is much more risky than first pursuing known and demonstrated technologies. In an industry as risk averse as the energy industry, all previous technological innovations have been realized by an evolutionary approach. While a revolution could ultimately result in a more economical solution, it would add much more risk to an industry that already suffers from the high risk associated with developed technologies.

Research efforts and demonstration facilities for advanced recycling technologies should be initiated immediately or continued in the National Labs, in conjunction with commercial construction of new GenIII+ reactors to make sure technology is ready for deployment around 2050. Programs such as Advanced Fuel Cycle Initiative (AFCI), Next Generation Nuclear Plant (NGNP), and the now defunct GNEP should be continued to work towards the eventual full closure of the full cycle in the most efficient and cost effective manner. However, timely execution of an integrated nuclear waste management plan is fundamental to continued reliance on nuclear energy in the United States. The longer reprocessing is delayed, the more expensive it becomes, as the graph below shows (51).
Figure 17. Cost and Revenue of Nth of A Kind (NOAK) Advanced Recycling Technology with Project Start Today and When Start of Project is Delayed 20 Years. Source: GE-Hitachi GNEP Project Plan.

An evolutionary scheme, first implementing developed and currently operating reprocessing methods before transitioning to more advanced, fully closed technologies, presents the least risk option for nuclear waste reprocessing that can be implemented right away. This option, as being the most demonstrated and technologically mature, is also the most commercially viable and presents the greatest access to possible commercial financing (46, 47). In fact, an initial 800 tons heavy metal\(^{12}\) (tHM) per year recycling center equipped with LWR upgraded to handle MOX fuel, separations and waste treatment facilities can be constructed with no necessary government investment for $12.6 billion and can be fully operational in 15 years (10).

\(^{12}\) Ton heavy metal (tHM) is the weight of spent nuclear fuel, excluding cladding and hulls, which will be separated. It is named as such because most of the constituents are heavy metals.
5.0 Sustainable Policy Solutions for Expanded Nuclear Energy

As shown above, almost all advanced nuclear technology is of a technological readiness that is implementable today or in the near future. The main challenges that must be addressed for future nuclear expansion are building public acceptance, determining a disposal path for all wastes, establishing optimal governmental and private funding schemes, and resolving licensing issues.

Public perception of nuclear power is already changing, as many view it as a safe, reliable, and low-carbon form of electricity generation. In a survey by Bisconti Research Inc. found feelings about nuclear power overwhelmingly positive in the 10-mile radius surrounding a nuclear power plant. Of those surveyed, 86 percent had a favorable impression of the nuclear power plant and gave the plant a high safety rating, with 91 percent acknowledging that nuclear power will be important in meeting future energy needs.

However, this positive public opinion is subject to change if a sustainable path cannot be found for SNF. As the blue ribbon commission considers the possibilities for nuclear waste management, it is important the resultant nuclear waste policy be flexible enough to allow for a variety of options to be pursued and the program to change if circumstances change to favor another solution. In any event, current technology requires the ultimate geologic disposal of at least some of the SNF. Thus, any nuclear policy should move to consider a new siting scheme, possibly placing sites in competition, to resolve the current political dispute surrounding repository siting.

In order for the nuclear waste management program to retain the requisite flexibility to be effective and sustainable, a new organization should be formed of industry and utility stakeholders, but answerable to DOE, to oversee management of the nuclear waste fund and provide funding for programs that would most efficiently dispose of current and future SNF. This corporation would be less affected by changing political positions and provide more consistent goals and funding for the program. Lastly, the NRC should move towards regulations that accommodate future and diverse technology solutions in a timely manner and that do not impede innovation.
To meet our future energy demands and at the same time address the growing concern surrounding carbon dioxide emissions in a cost effective manner, expanded generation of nuclear power will be required, along side increased energy efficiency, expanded renewable generation, and CCS. With effective organization and management, policy related to nuclear energy can transition from a hindrance to a catalyst for expansion of the sustainable, safe, clean and cost-effective electrical energy source presented by nuclear power.
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