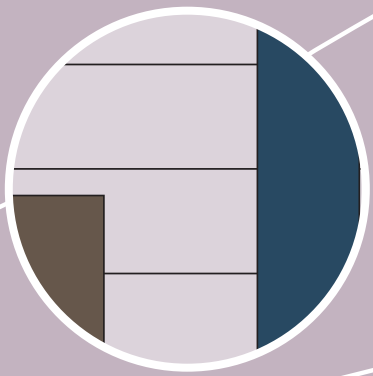
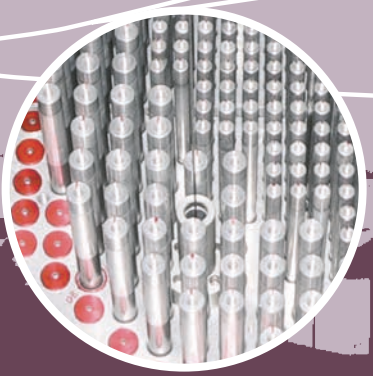
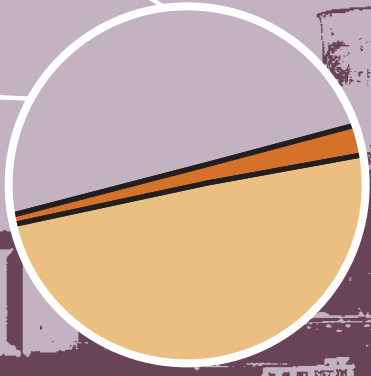
Nuclear Energy

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE







A TECHNOLOGY REPORT FROM THE SECOND PHASE OF THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM

GTSP

Global Energy Technology Strategy Program

Nuclear Energy

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE

PHASE 2 FINDINGS FROM AN INTERNATIONAL PUBLIC-PRIVATE SPONSORED RESEARCH PROGRAM

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May 2007

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TO THE READER

This report reflects research conducted as part of the Global Energy Technology Strategy Program (GTSP) at the Joint Global Change Research Institute and in collaboration with partner research institutions around the world. The first phase of the GTSP began at a time when the importance of a technology strategy in addressing climate change was unappreciated. GTSP Phase 1 made the case that a technology strategy was an important part of a larger strategy to address climate change and needed to be included along with the other major components: climate science research, adaptation to climate change, and emissions mitigation.

The second phase of the GTSP recognized that to craft a global energy technology strategy it was important to develop a deeper understanding of potentially important technologies and technology systems, and to embed that knowledge in the context of the larger global energy and economic systems. In Phase 2 we identified six energy technologies and technology systems with the potential to play a major role in a climate-constrained world: CO_2 capture and storage, biotechnology, hydrogen systems, nuclear energy, other renewable energy, and end-use technologies that might be deployed in buildings, industry and transportation. Knowledge gained in each area has been integrated into a larger global energy-economy-climate frame. That combination of depth of study and integrated assessment produced a unique strategic perspective and a bounty of fresh insights. In this document, we have distilled and summarized some of the most salient.

The past nine years have flown by and, looking back from the present, it is amazing to see how far we have come. The GTSP has accomplished much, but much work remains. As we enter Phase 3, we will build on the knowledge gained thus far. We will continue to deepen our understanding of technology and we will continue to integrate that understanding into a larger energy and economic context. And, we will add a new dimension to our work to provide a deeper understanding of the *regional* and *institutional* contexts in which technology is developed and deployed.

Our research has been supported by numerous firms, nongovernmental organizations, and government agencies. Their support has enabled us to continue to explore the implications of designing and implementing a technology strategy. Moreover, we have received the help of many peer reviewers, who throughout the process of developing this document provided their expertise and advice. And for that support we are grateful. Of course, the views and opinions of the authors expressed herein do not necessarily state or reflect those of the sponsoring, participating institutions, or reviewers and any errors that remain are our own.

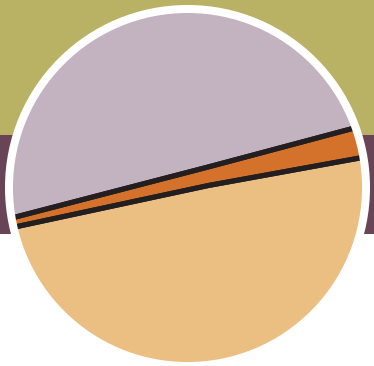
Jae Edmonds
May 2007

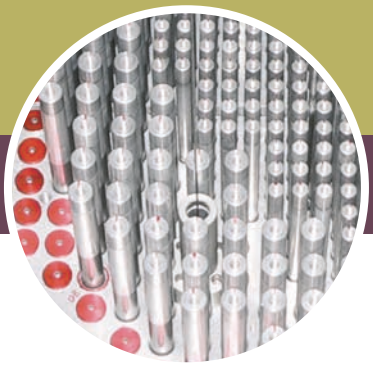
Nuclear Energy

The attractions of nuclear energy in addressing climate change are clear.

Nuclear power production has no direct CO_2 emissions and is already a significant component of the global energy system. In 2006, 435 operational nuclear power stations around the world generated approximately 16 percent of global electricity production. Improved economic competitiveness and safety of nuclear power along with concern for energy security and climate change are leading to a steady increase in worldwide nuclear power capacity. Waste disposal and proliferation concerns associated with expanding nuclear energy use remain important and unresolved issues. Key GTSP insights include the following:

- Nuclear power is cost-competitive with other means of generating baseload electricity in many parts of the world. Nuclear power is steadily expanding; 24 new nuclear power plants were under construction around the world in 2006.
- The world's reliance on nuclear power is expected to grow whether or not there are constraints on greenhouse gas emissions. In a carbon-constrained world, nuclear power would expand even further. The majority of this future deployment will occur outside of the present day Organization for Economic Cooperation and Development (OECD) nations.
- The cost savings from using nuclear technology in a carbon-constrained world are denominated in trillions of U.S. dollars.
- The supply of uranium, which is the principal feedstock for nuclear power, is not likely to be a limiting factor on the future deployment of nuclear power. The potentially significant expansion of nuclear power will require the





use of lower quality and more expensive grades of uranium in the long term, but this will have only a modest impact on the cost of electricity from nuclear power.

- Sufficient uranium is likely to be available to support an expansion of nuclear energy without reprocessing well into the second half of the century. If uranium should prove to be in short supply, then reactors capable of breeding nuclear fuels, along with recycling of used fuels, could continue to support the global expansion of nuclear energy; otherwise, nuclear energy use would decline in the second half of the century.

- If nuclear power expands rapidly in the United States and around the world, permanent waste repositories many times the capacity of the U.S. Yucca Mountain repository will be required. This concern has motivated reactor designs that recycle nuclear materials and minimize high-level wastes. Limited availability of permanent waste disposal capacities around the world could induce an earlier transition to advanced reactors that can recycle used fuels.

- The global expansion of nuclear energy implies greater movement of nuclear materials and proliferation risks. However, new concepts for nuclear fuels, fuel cycles, and reactor designs, along with innovative international agreements, may reduce these proliferation concerns.

THE EVOLUTION OF NUCLEAR POWER PLANT TECHNOLOGIES

Commercial electricity generating nuclear power reactors are fission reactors in which a sustained chain reaction causes atoms (e.g., uranium) to split, causing other atoms to split and so on, releasing energy at each split. To control the rate of splitting, a moderating substance is needed. The most common medium for controlling the reaction is normal or "light" water.

The Currently Installed Fleet of Nuclear Power Plants

All of the 435 present-day nuclear reactors currently licensed to operate in the world are nuclear fission reactors and can be broadly categorized as second generation reactors (Gen II); Figure 1 shows an operating reactor and a reactor core. The first generation included early prototype reactors of the 1950s and 1960s. The majority of the currently installed reactors are light-water reactors, either boiling water reactors (BWRs) or pressurized water reactors (PWRs).

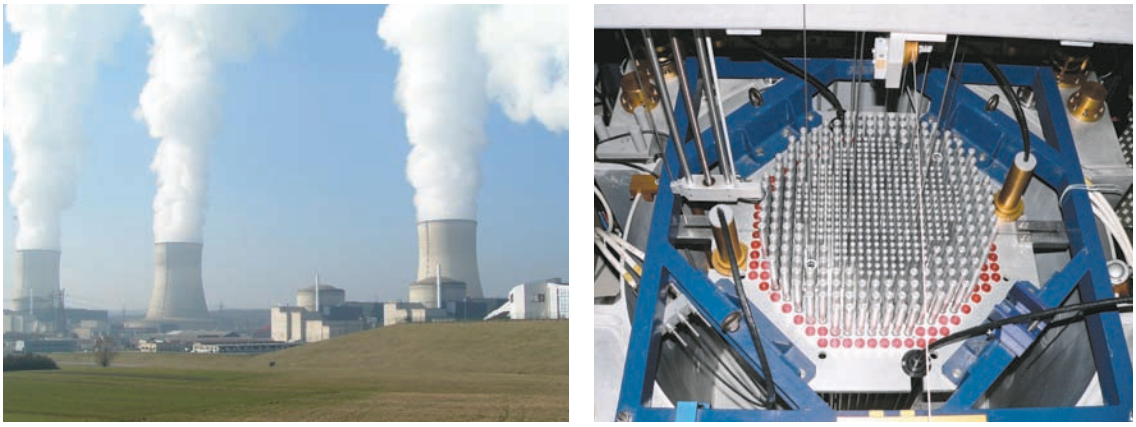
In 2006, existing commercial nuclear power stations accounted for approximately 16 percent of global electric power generation, 20 percent of United States electric power generation, 45 percent in South Korea, and more than 75 percent of power generation in France.

No new Gen II reactors are being built today. By the middle of the century, all of these legacy reactors will reach the end of their physical lifetimes and probably be retired. These reactors are being replaced by the next generation of reactors, so-called Gen III reactors.

Advanced Nuclear Power Plants

Decades of experience with existing reactors have resulted in the next generation of advanced reactors with cost and reliability improvements and passive safety features. These reactors, including advanced light-water reactors currently available for deployment, are referred to as third generation reactors (Gen III). These advanced reactors, including BWR and PWR designs, are being built around the world and are technically superior in many ways.

Other third generation reactors not based on light-water reactor designs are also available for deployment, such as the pebble bed reactor, a high-temperature gas-cooled reactor. The pebble bed reactor replaces water with an inert gas as the coolant and has the advantages of greater thermal efficiency and modularity. Moreover, the pebble bed reactor is designed to withstand high core temperatures and shut down without an active system in the event of a loss of coolant. Pebble bed reactors are smaller in size and require lower capital investments and less time for construction than larger units. Pebble bed reactors are sometimes referred to as Gen III+ reactors.



▲ **Figure 1.** Nuclear power today. Nuclear plants are an important component of the world's energy system.

The Next Generation of Advanced Nuclear Power Plants

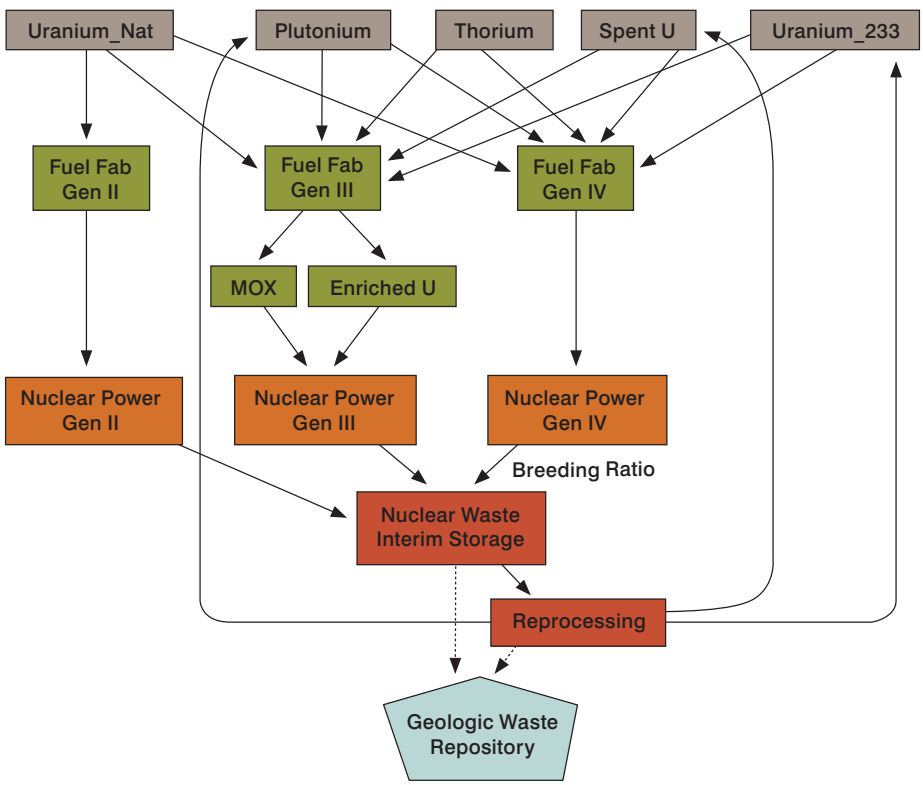
Future reactor technologies and fuel systems for the fourth generation of reactors are currently being explored with the explicit goal of improving the nuclear energy system in the areas of fuel utilization, economics, safety, waste minimization, and proliferation resistance. These reactor designs are referred to as Gen IV and may have the potential for creating or breeding nuclear fuels and for minimizing long-lived high-level wastes. Successful realization of next-generation nuclear systems can support the long-term future of nuclear energy in the global energy system.

Several candidate reactor concepts have been identified for development: gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), sodium-cooled fast reactor (SFR), supercritical-water-cooled reactor (SCWR), very high temperature reactor (VHTR), and molten salt reactor (MSR).

These candidate reactors vary markedly in design: nuclear fuel composition, coolant, moderator, and containment structure. Their similarities, however, are in their ability to utilize converted or recycled fuels, effectively achieving the goals of extending the life of natural uranium resources and minimizing the high-level waste requiring permanent disposal. Other similarities in these candidate reactors are their smaller size, modularity, passive safety features, higher thermal efficiencies, and continuous refueling or long refueling intervals that contribute to their improved economics, safety, and proliferation resistance.

The Nuclear Fuel Cycle

The present (Gen II) fuel cycle begins with natural uranium (see Figure 2). Natural uranium is enriched with higher concentrations of fissile uranium-235, processed into fuel pellets and fabricated into fuel assemblies that are inserted into the core of a nuclear reactor.



▲ **Figure 2.** The nuclear fuel cycle. This diagram shows a schematic of the nuclear fuel cycle with potential alternative pathways for energy production from nuclear power.

Uranium is the principal natural resource used in the production of nuclear energy, and therefore the availability of uranium resources is an important consideration in shaping the role that nuclear energy can play in meeting future energy needs and in addressing climate change.

As nuclear chain reactions occur in the nuclear reactor, the fissile uranium and some fertile uranium are consumed, producing heat energy, and are transformed into a spectrum of nuclear waste, which includes products that retain high levels of radioactivity for up to thousands of years.

Currently, the spent fuel assemblies, which retain significant amounts of fertile and fissile material as well as fission fragments and minor actinides, are stored in intermediate storage facilities near the power plant. The present Gen II fuel cycle is a once-through system, i.e., it does not recycle the fertile and fissile material in the spent fuel. Long-term storage would be at a permanent, geologic waste repository. In the United States, that permanent repository is planned to be at Yucca Mountain in Nevada.

New Gen III reactors, as well as existing reactors, use enriched uranium or can be modified to utilize alternative nuclear fuel options. These options include uranium and plutonium mixed oxide (MOX) fuels, and the use of thorium along with uranium. As with traditional nuclear fuels in any light-water reactor, the use of these alternative fuels creates a spectrum of radioactive waste products, which need to be stored.

Solutions for disposing of intermediate to high-level radioactive nuclear waste in a safe manner for extremely long periods of time need to be realized. If nuclear power expands rapidly in the United States and around the world, permanent waste repositories many times the capacity of Yucca Mountain will be required. This concern, in part, has motivated reactor designs that recycle nuclear materials and minimize high-level wastes.

Gen IV technologies can potentially utilize reprocessed fuels, in which case the spent fuel would be shipped to a reprocessing plant where fertile and fissile material in the spent fuel is separated or isolated and used to produce new fuel. Reprocessing spent fuel in a manner that minimizes long-lived high-level wastes can reduce the fraction of original spent waste requiring permanent geologic disposal.

Reactors designed for breeding nuclear fuels can produce more fuel than is consumed, actually extending the amount of potential nuclear energy available from existing uranium resources. The proliferation concern with breeder reactors and reprocessing is that the fissile material, which is also used in nuclear weapons, is created in greater quantities and is potentially more accessible. Thus, while breeder and "near breeder" reactors reduce the problem of uranium resource limitation, they inherently create a potentially larger nuclear proliferation problem.

URANIUM: THE KEY FUEL RESOURCE FOR NUCLEAR POWER

Uranium is the principal natural resource used in the production of nuclear energy, and therefore the availability of uranium resources is an important consideration in shaping the role that nuclear energy can play in meeting future energy needs and in addressing climate change.

Other than the limited quantities of known conventional uranium resources, there is no consensus on the ultimate size of the global uranium resource base or on the cost of mining and processing speculative conventional and unconventional sources of uranium.

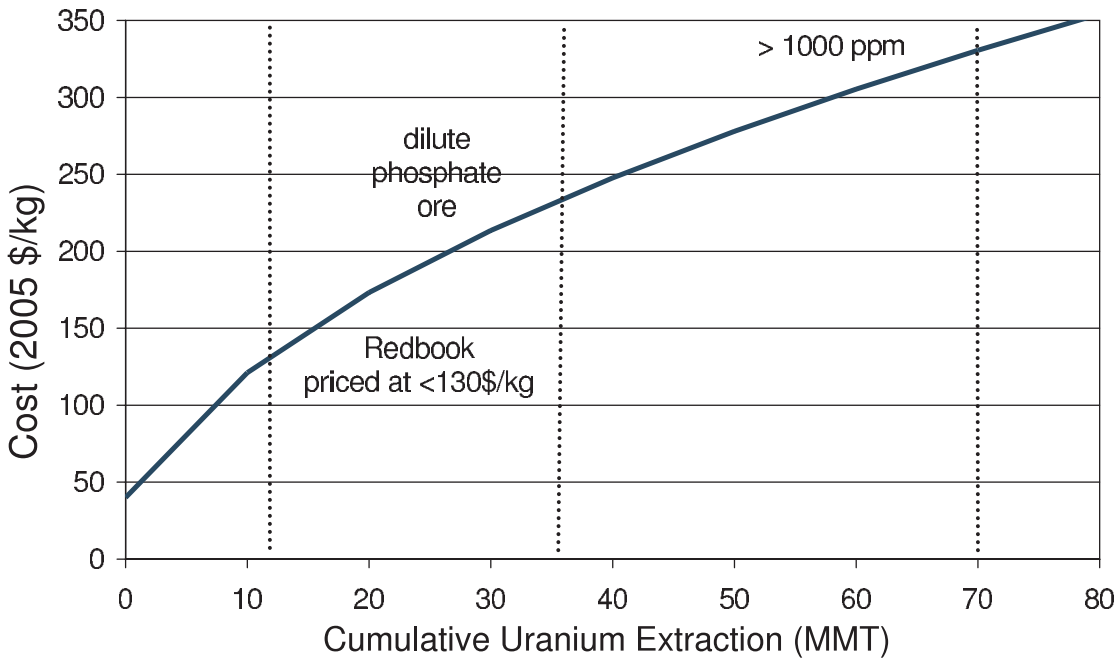
Various estimates exist of conventional uranium resources. A joint report by the OECD's Nuclear Energy Agency and the International Atomic Energy Agency (IAEA) contains the most authoritative estimates of known and undiscovered conventional uranium resources, otherwise known as the *Redbook*. According to the *Redbook*, the amount of uranium available at a price less than $130/kg is approximately 11 million tonnes of uranium (MTU). An additional 3 MTU is reported available without a cost range assigned.

Beyond these conventional resources, the existence of unconventional resources in which uranium exists at very low grades is not well established. Unconventional resources are, however, likely to be available, although at increasingly lower uranium concentrations and higher costs.

While the *Redbook* estimates are a good start to understanding the uranium resource base, the GTSP study looks out over a hundred years or more and must consider technological progress not only in new reactor designs but also in new resource extraction technologies. Technologies for recovering natural resources have improved significantly in the past and will likely continue to improve in the future. Also, the market price and our willingness to pay for natural resources will change with time.

A natural uranium supply curve that extends beyond the amounts reported in the *Redbook* was developed for modeling purposes. Using a geological estimate of the relationship between uranium abundance and ore concentration, a relationship between uranium cost and abundance was fitted to the *Redbook* cost estimates to continuously extend the supply curve beyond the *Redbook* totals (see Figure 3). A wide range of uranium supply curves are found in the literature, both more and less optimistic than the uranium supply curve as represented in Figure 3.

While significantly more uranium is likely to exist around the world in lower concentrations than the *Redbook* amount, the assumption of uranium availability limited to the *Redbook's* estimate of conventional resources implies that either nuclear energy production will decline in the second half of the 21st century or nuclear technologies that breed fissionable fuels will be needed.



▲ **Figure 3.** Natural uranium supply curve. In the future, demand for uranium will likely require the use of what is currently seen as unconventional grades, although the use of these unconventional grades will have only a modest impact on the cost competitiveness of nuclear power.

SCENARIOS OF NUCLEAR ENERGY DEPLOYMENT

GTSP has examined the market penetration of nuclear technology on the basis of cost and performance in a world in which other technologies compete for market share and in which all technologies improve over time. This analysis presumes that the issues of safety, waste disposal, and weapons proliferation are adequately addressed.

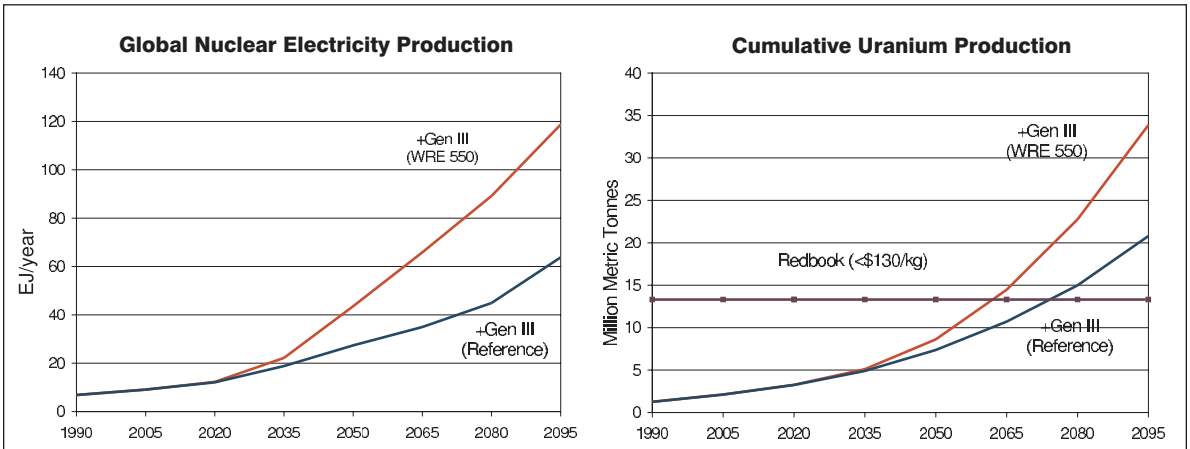
The paired figures in Figure 4 show the deployment of Gen III nuclear power for electricity generation in a reference case without climate policy and in a scenario where global CO_2 emissions are constrained so that stabilization of CO_2 concentration at 550 ppmv is achieved. As can be seen in the reference case, the deployment of nuclear power multiplies seven-fold while in the 550 case nuclear power deployment grows thirteen-fold by the end of the century.

While most of the world's current reactors are presently located in highly industrialized regions and nations such as Europe, North America, Japan, South Korea, and nations of the former Soviet Union, rapidly growing demands for electric power in developing countries such as China, India, and South Africa imply growing potential for deployment of nuclear technology. Figure 5 shows that in the reference case depicted above, by the middle of the century the majority of deployment in nuclear power occurs in the developing nations (so-called non-Annex 1).

The cost of stabilizing the concentration of CO_2 at 550 ppm without a nuclear option was about $4 trillion (present discounted costs at five percent per year over the period 2005 to 2095). That cost is idealized and assumes that all nations participate in limiting CO_2 emissions in the most cost-effective way possible. Adding an option to deploy Gen III nuclear reactors to the portfolio for electric power reduces the cost of CO_2 concentration stabilization by half or nearly $2 trillion. Figure 6 shows the cost reduction resulting from adding a nuclear technology option for alternative CO_2 stabilization concentrations. The reduction in cost associated with adding the nuclear power option to the portfolio of technologies for stabilization varies with the target concentration of CO_2. The lower the target concentration level, the more valuable it is to add nuclear power as an option. The higher the stabilization concentration, the lower the overall cost and therefore the smaller the incremental value of adding a technology to the portfolio.

In order for this deployment to take place, the world must be able to access and utilize significantly more uranium ore than the 11 MTU that is estimated in the Redbook as being available for less that $130/kg.

The cost of uranium ore, however, plays a relatively minor role in the overall cost of generating power. The power production cost is dominated by capital, operating, fuel enrichment, and fabrication costs. The original uranium resource accounts for only a few percent of the final cost of electricity from a new power plant today. In the scenarios above, the cost of uranium ore exceeds $200/kg, which corresponds to an increase in the



▲ **Figure 4.** The future of nuclear. Nuclear power production expands in the future, but the expansion is considerably more extensive in a greenhouse-gas-constrained world (top curves). Consequently, the expansion of nuclear power in response to climate change implies demands for uranium resources well beyond the *Redbook* estimates(right graph).

cost of nuclear power of approximately 0.4 cents/kWh. For this reason, GTSP analysis suggests that nuclear power could be competitive in the future at higher uranium prices, and unconventional resources drawn from more dilute and expensive deposits could be utilized.

Estimates of capital and operating costs (non-fuel costs) are given in Table 1, which is representative of the range of estimates for Gen III and Gen IV technologies. There is a wide range of construction costs, from $1,100 per kW to $2,300 per kW, for nuclear reactors that are classified as Gen III. Firmer estimates of cost will become available as reactors currently under construction are completed. The Gen III non-fuel costs used in the GTSP analysis are representative of the cost of advanced light-water reactors. The typical capital cost difference between a light-water reactor and a fast reactor is in the range of $0–$400/kWe or 0 to 27% based on light water reactor cost of $1,500 per kW. Gen IV reactor designs can be anticipated to have additional capital and operating costs, but potentially reduced waste disposal costs in the long term.

Nuclear fuel costs include the cost of uranium ore; and the conversion, enrichment, and fabrication of the ore into fuel assemblies. In the scenarios above, uranium ore costs were determined by the model from the interplay of the supply curve and the demand for uranium over time. Fixed charges for interim storage and permanent disposal of spent fuel waste were also included in the nuclear power costs. Gen IV reactors capable of breeding and using recycled nuclear fuels are expected to have lower interim storage and permanent waste disposal costs, but have higher fuel fabrication costs and include the additional cost of reprocessing.

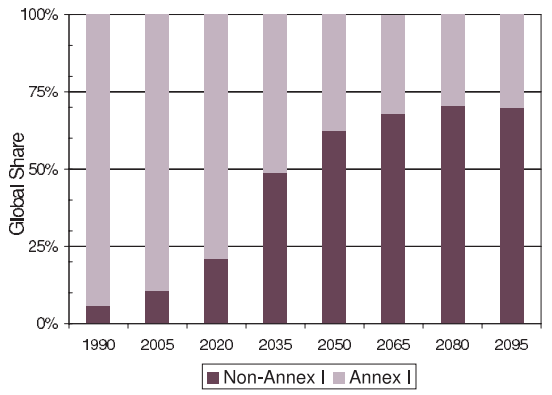


Figure 5. Nuclear electricity generation reference scenario. Over the 21st century, the majority of nuclear power generation shifts to developing nations.

Table 1. Nuclear power generation technology non-fuel costs for new plants (2003 USD/MWhr)

Year	Gen II	Gen III	Gen IV
2005	60	50	n/a
2035	n/a	48	57
2050	n/a	47	56
2095	n/a	45	54

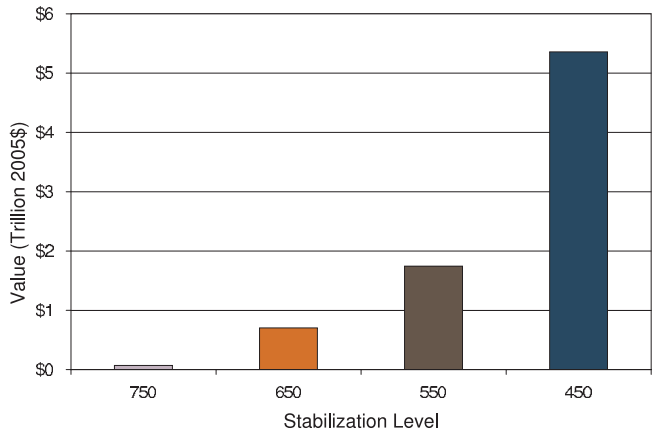


Figure 6. Value of nuclear in the GTSP portfolio. The cost of stabilizing greenhouse gases in the atmosphere is significantly reduced when nuclear power technologies are a part of society's broad portfolio of responses to climate change.

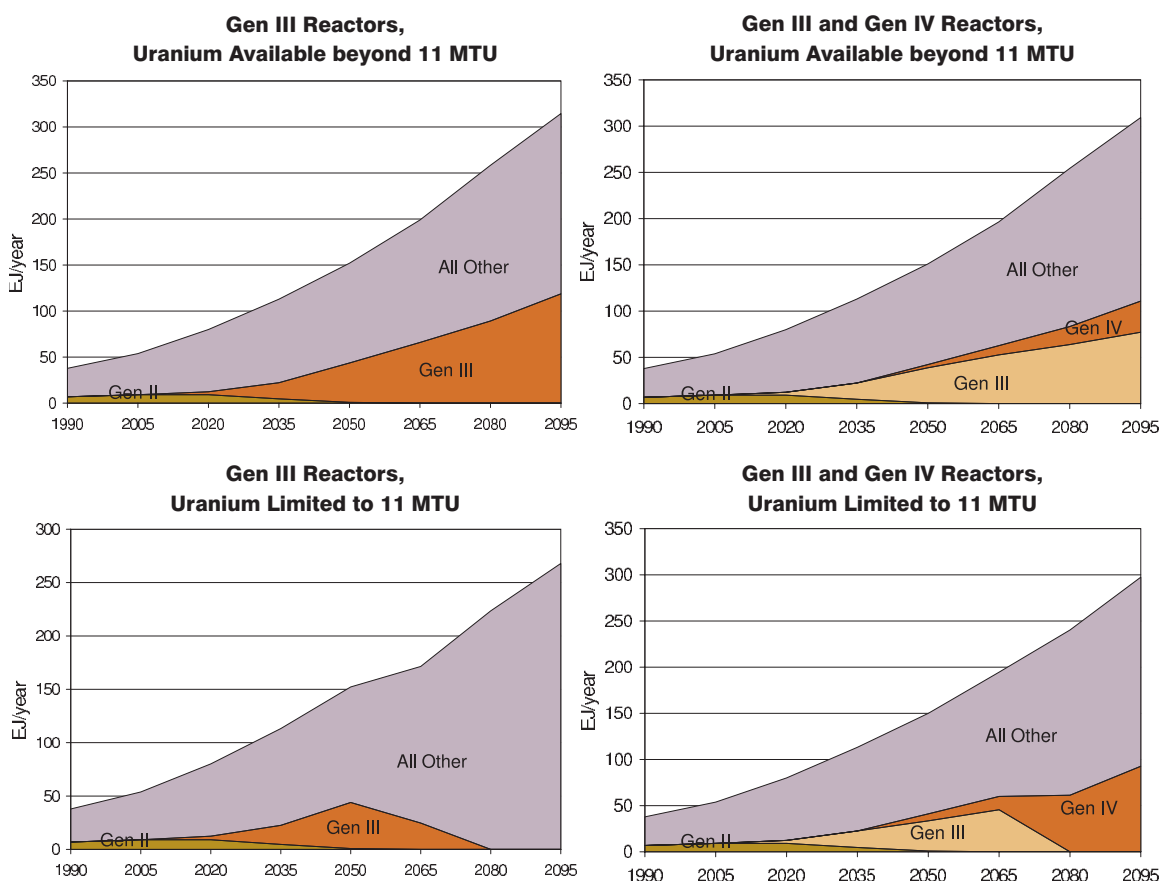
The four graphs in Figure 7 examine two critical elements that are often discussed in analyses of nuclear energy: (1) the global supply of uranium and (2) the need for breeder reactors. All four of these graphs assume that global emissions of CO_2 are constrained to reach stabilization in concentration of 550 ppm and that a broad array of other technologies is available and capable of generating competitively priced electricity.

The top set of graphs assumes that the availability of uranium is not limited and that more uranium is available at higher costs and lower concentrations than the *Redbook* estimates. In this case, as shown earlier, Gen III reactors based on a once-through fuel cycle continue to expand throughout the century. The addition of advanced Gen IV reactors does not expand the nuclear share of the power market; rather, Gen IV technologies compete with Gen III technologies.

The bottom set of graphs assumes that the availability of uranium is limited to 11 MTU. Under these circumstances, it is clear that reactors with fuel breeding capability are needed in the second half of the century in order for nuclear power to maintain its role as an important contributor to the world's source of electricity and response to climate change. If uranium resources are limited and Gen IV reactors are not available, nuclear power's ability to contribute to electricity generation will peak around mid-century and then decline.

OTHER CONSIDERATIONS

While cost and performance are critical to any commercial future of nuclear power, nuclear energy technology must address other issues as well: nuclear



▲ **Figure 7.** Global nuclear power production relative to other sources of electricity under a 550 ppm CO_2 stabilization case. The size of the uranium resource base and whether breeder reactors are deployed both strongly influence the scale of future nuclear power generation and which types of reactor technologies are employed. The top graphs show stabilization cases in which uranium fuel is available, the bottom graphs with limited uranium. Left-hand graphs do not include breeder (Gen IV) reactors, while right-hand graphs do.

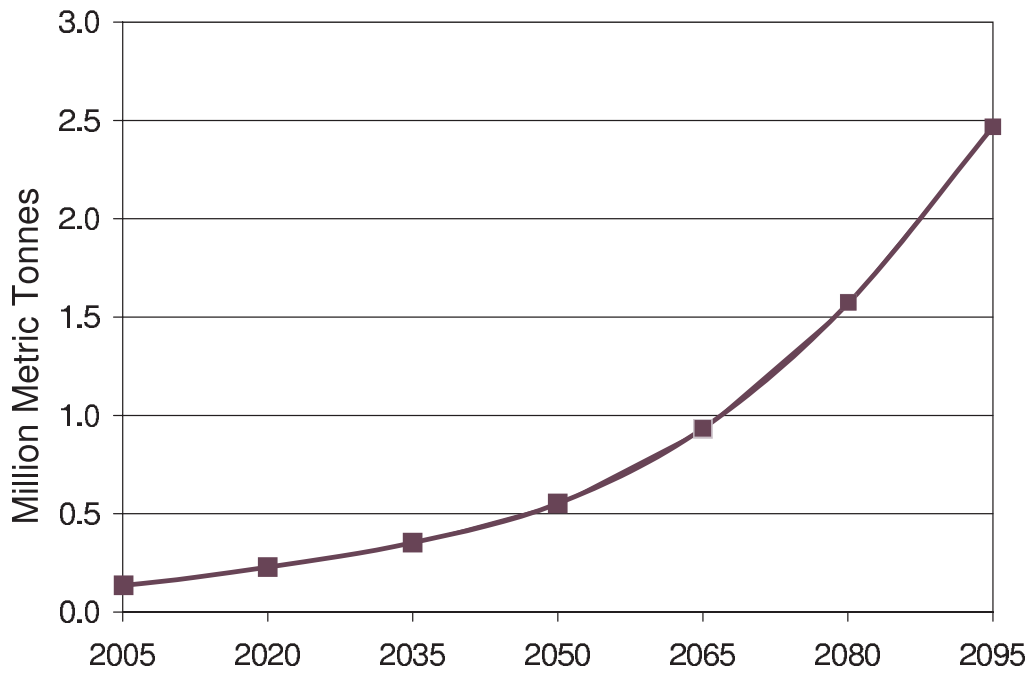
waste disposal, safety, and proliferation. Each issue is complex, and all three are ultimately interconnected with cost and performance.

The availability of uranium resources and geologic waste repositories, and the choice of nuclear reactors and fuel systems affect all three of these issues. The potential improvements to nuclear technology for increased safety, waste minimization, and increased proliferation resistance have not been exhausted, and new nuclear technologies and systems that can alleviate these issues are under investigation.

Waste Disposal

In the scenarios above, we have assumed that interim storage of spent fuel and permanent waste disposal costs are fixed and that the disposal of nuclear waste does not present an obstacle to nuclear energy use. Expansion of global nuclear energy use and reliance on the once-through fuel cycle, however, results in significant spent fuel waste accumulation. Up to 2.5 million metric tons of spent fuel could be generated by the end of the century (see Figure 8). The accumulated global waste of

The potential improvements to nuclear technology for increased safety, waste minimization, and increased proliferation resistance have not been exhausted, and new nuclear technologies and systems that can alleviate these issues are under investigation.



▲ **Figure 8.** Waste generation in a stabilization case. Significant quantities of spent fuel are created and need to be disposed of during this century with large-scale global deployment of advanced (but not breeder) reactors.

this scenario would require storage capacity equivalent to 36 times the legislated capacity of the United States' Yucca Mountain repository site.

It is unknown at this time whether multiple geologic waste repositories or other disposal options located throughout the world will be acceptable, available, and economical. The inevitable byproduct of nuclear energy use is the generation of nuclear waste. In this regard, nuclear technologies that minimize waste production and consequently, reduce the demands for geologic waste repositories are likely to be increasingly valued but only to the degree that they do not jeopardize the economic competitiveness of nuclear power.

Safety

The issue of safety has always been a concern with nuclear energy. However, two accidents, at Three Mile Island in 1979 and at Chernobyl in 1986, dramatically increased safety and health concerns. These incidents, along with decades of accumulated experience with nuclear reactor operation, have resulted in new reactor designs with reduced potential for catastrophic events. These designs are evident in the additional passive safety features of advanced light-water and other reactor designs such as the pebble bed reactor. Safety of nuclear reactors, fuel systems, and waste handling remains an important issue for nuclear energy, however.

Weapons Proliferation

Nuclear weapons remain a feature of the modern world, and the same nuclear materials that provide energy for peaceful use are also used in nuclear weapons. Expansion of nuclear energy use globally implies greater movement of nuclear materials, both fuel and waste, and potential for their easier access. New concepts for nuclear fuels, fuel cycles, reactor designs, and trade in nuclear technology are being pursued that may reduce these proliferation concerns. However, we must recognize that proliferation issues are not purely technical in nature, and that international agreements, institutions, and monitoring must remain central in addressing proliferation concerns.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

Nuclear power is already a significant part of the global energy system. However, the extent to which it can maintain its current market share or significantly expand it in a greenhouse-gas-constrained world depends in part upon continued R&D. Also, with the bulk of new nuclear power plant deployment occurring outside the present-day OECD nations, new improved reactor designs and features may be developed outside of the traditional Western nuclear powers. Selected R&D, demonstration, and commercial deployment challenges and opportunities for nuclear power include:

- Establish the economic viability of next-generation nuclear energy systems.
- Demonstrate the capability of safe high-level waste disposal.
- Develop recycling and fuel processing technologies for breeder reactors to enable a transition from a once-through to a closed nuclear fuel cycle. The commercial deployment of these advanced reactor and fuel system technologies could reduce the quantities and toxicity of spent nuclear fuels and reduce the need for geologic waste disposal.

Expansion of nuclear energy use globally implies greater movement of nuclear materials, both fuel and waste, and potential for their easier access.

- Develop the nuclear capacity to generate hydrogen for use in transportation and other end-use sectors. Advances in thermo-chemical and high-temperature electrolysis based on nuclear technology will determine the economic viability of nuclear-based hydrogen production.
- Create innovative international policies for trade in nuclear technology and fuel that allow for global expansion of nuclear energy for electric power generation while addressing proliferation concerns.

APPENDIX Notes and References

Most of the CO_2 emissions in this study are stated in units of million or billions of tons of carbon (MtC or GtC, respectively). This differs from the conventions of the CCS technical community, which expresses values in millions or billions of tons of CO_2 ($MtCO_2$ or $GtCO_2$, respectively). Cost data can be converted to dollars per ton of ($/$tCO_2$) by dividing by 3.667, and mass data can be converted to CO_2-based units of the climate change technical community by multiplying the mass expressed in carbon-based units by 3.667.

This report makes frequent use of a very large measure of mass known as a "gigaton." A gigaton of CO_2 ($GtCO_2$) is a standard measure for scientists and policy makers familiar with carbon management, yet for most other audiences the magnitude of this unit is sometimes hard to comprehend. A gigaton is approximately equal to 77 Empire State Buildings if they were made completely of lead, 10,718 aircraft carriers the size of the USS Enterprise, or all of the iron ore annually mined in the world. For more examples of how massive a gigaton is please consult C.L. Davidson and J.J. Dooley, "A Gigaton Is…" PNWD-3299, Joint Global Change Research Institute, Battelle Pacific Northwest Division (July 2003).

Unless otherwise indicated, all scenarios and analyses result from the GTSP research, using several well-established modeling tools.

References of interest for further exploration of this topic include the following:

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THE **GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM**

The Global Energy Technology Strategy Program (GTSP) began in 1998 with the goal of better understanding the role that energy technologies might play in addressing the problem of global climate change. The GTSP is unique, a global, public and private sector sponsored research program, whose sponsors and research collaborators are drawn from around the world.

The completion of the first phase of the GTSP in 2001 was marked by the release of a seminal report during a special session of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change. This report, *A Global Energy Technology Strategy Project Addressing Climate Change: Initial Findings from an International Public-Private Collaboration,* demonstrated the importance of technology development and deployment as key cornerstones of a broader set of activities designed to address climate change. A central conclusion was that a robust technology strategy required the development of a *technology portfolio*. It found no evidence for a single technology whose development promised to "solve" the climate problem. That is, *a priori*, there is no technological "silver bullet." Rather, the GTSP concluded that various technologies and technology systems show promise for making a substantially expanded contribution to the global energy system in a climate-constrained world. These included biotechnology, hydrogen energy and other advanced transportation technology systems, nuclear power, renewable energy technologies, end-use energy technologies, and carbon dioxide capture and storage. The first phase of the GTSP produced groundbreaking research, including many results that have made their way into the frequently cited literature. This phase of the GTSP successfully added to the dialogue about responses to climate change a new, previously missing, element—technology. But building productive, long-term, real-world technology strategies to address climate change requires a deeper understanding of technologies and their potential. Thus, the GTSP launched its second phase in 2002. GTSP Phase 2 pushed the frontiers of our knowledge to gain a much deeper understanding of how these key carbon management and advanced energy technologies will deploy in practice, and the means for launching and sustaining a meaningful global energy technology strategy.

GTSP Phase 3 will delve into the regional diversity and institutional dimensions of developing and deploying technologies to address climate change.

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