The Future of the Nuclear Fuel Cycle

AN INTERDISCIPLINARY MIT STUDY

SUMMARY REPORT

The Future of the Nuclear Fuel Cycle

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While the members of the advisory committee provided invaluable perspective and advice to the study group, individual members may have different views on one or more matters addressed in the report. They were not asked to individually or collectively endorse the report findings and recommendations.

Daniel Poneman, Scowcroft Group, resigned from the committee upon his Presidential nomination for a government position.

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Foreword and Acknowledgments

In 2003 the MIT interdisciplinary study *The Future of Nuclear Power* was published. The thesis was that nuclear energy is an important option for the marketplace in a low-carbon world. At least for the next few decades, there are only four realistic options for reducing carbon dioxide emissions from electricity generation: increased efficiency in energy utilization, expanded use of renewables such as wind and solar, reducing carbon dioxide emissions at fossil-fueled power plants by switching from coal to natural gas or by transitioning to capture and permanent sequestration of the carbon dioxide, and nuclear power. The study perspective was that all options would be needed and it would be a mistake to exclude any of these four options from an overall carbon emissions management strategy. The report examined the barriers to nuclear power and made a series of recommendations to enable nuclear power as a market place option.

Since that report, there have been major changes in the US and the world, as described in our 2009 *Update of the 2003 Future of Nuclear Power* Report. Concerns about climate change have dramatically increased, many countries have adopted restrictions on greenhouse gas emissions, and the U.S. is also expected to adopt limits on carbon dioxide releases to the atmosphere sometime in the future. Because nuclear energy provides about 70% of the "zero"-carbon electricity in the U.S. today, it is a major candidate for reducing greenhouse gas emissions from the electric sector. Projections for nuclear power growth in the United States and worldwide have increased dramatically, even if recently tempered by the world-wide recession. In the United States this has resulted in various announcements of intent to build new reactors, 27 submittals of license applications, 8 applications for Federal loan guarantees, and some site preparation. However, no license for new construction has been issued in the U.S. as of mid 2010. Elsewhere in the world the construction of new plants has accelerated, particularly in China and India. In addition, South Korea joined the traditional global suppliers of nuclear plants by signing an agreement to build four reactors in the United Arab Emirates.

There have also been major developments in the nuclear fuel cycle. In the US, fuel cycle policies have been in a state of confusion. The Bush Administration initiated programs with the goal of commercially recycling fissile material from spent nuclear fuel (SNF) into new fuel assemblies, but failed to attract support in Congress. The U.S. Department of Energy spent many years in assessing, and submitted a license application for, a geological repository for SNF and high-level waste at Yucca Mountain (YM). However, the Obama Administration has now requested withdrawal of the license application. Overseas, Japan has started operation of a commercial nuclear fuel reprocessing plant. Finland and Sweden, after gaining public acceptance, have sited geological repositories for the disposal of SNF.

Because of the significant changes in the landscape, we have undertaken this study on the *Future of the Nuclear Fuel Cycle* to bring a sharper focus on the key technical choices available for an expanded nuclear power program in the U.S. and the near-term policy implications of those choices.

We acknowledge generous financial support from the Electric Power Research Institute (EPRI) and from Idaho National Laboratory, the Nuclear Energy Institute, Areva, GE-Hitachi, Westinghouse, Energy Solutions, and Nuclear Assurance Corporation.

Executive Summary

Study Context

In 2003 MIT published the interdisciplinary study *The Future of Nuclear Power*. The underlying motivation was that nuclear energy, which today provides about 70% of the "zero"-carbon electricity in the U.S., is an important option for the market place in a low-carbon world. Since that report, major changes in the US and the world have taken place as described in our 2009 *Update of the 2003 Future of Nuclear Power Report*. Concerns about climate change have risen: many countries have adopted restrictions on greenhouse gas emissions to the atmosphere, and the U.S. is expected to adopt similar limits. Projections for nuclear-power growth worldwide have increased dramatically and construction of new plants has accelerated, particularly in China and India. This study on *The Future of the Nuclear Fuel Cycle* has been carried out because of the continuing importance of nuclear power as a low-carbon option that could be deployed at a scale that is material for mitigating climate change risk, namely, global deployment at the Terawatt scale by mid-century.

To enable an expansion of nuclear power, it must overcome critical challenges in cost, waste disposal, and proliferation concerns while maintaining its currently excellent safety and reliability record. In the relatively near term, important decisions may be taken with far reaching long-term implications about the evolution of the nuclear fuel cycle—what type of fuel is used, what types of reactors, what happens to irradiated fuel, and what method of disposal for long term nuclear wastes. This study aims to inform those decisions.

For decades, the discussion about future nuclear fuel cycles has been dominated by the expectation that a closed fuel cycle based on plutonium startup of fast reactors would eventually be deployed. However, this expectation is rooted in an out-of-date understanding about uranium scarcity. Our reexamination of fuel cycles suggests that there are many more viable fuel cycle options and that the optimum choice among them faces great uncertainty—some economic, such as the cost of advanced reactors, some technical such as implications for waste management, and some societal, such as the scale of nuclear power deployment and the management of nuclear proliferation risks. Greater clarity should emerge over the next few decades, assuming that the needed research is carried out for technological alternatives and that the global response to climate change risk mitigation comes together. A key message from our work is that we can and should preserve our options for fuel cycle choices by continuing with the open fuel cycle, implementing a system for managed LWR spent fuel storage, developing a geological repository, and researching technology alternatives appropriate to a range of nuclear energy futures.

Study Findings and Recommendations

ECONOMICS

The viability of nuclear power as a significant energy option for the future depends critically on its economics. While the cost of operating nuclear plants is low, the capital cost of the plants themselves is high. *This is currently amplified by the higher cost of financing construction due to the perceived financial risk of building new nuclear plants. For new base load power in the US, nuclear power plants are likely to have higher levelized electricity costs than new coal plants (without carbon dioxide capture and sequestration) or new natural gas plants. Eliminating this financial risk premium makes nuclear power levelized electricity cost competitive with that of coal, and it becomes lower than that of coal when a modest price on carbon dioxide emissions is imposed. This is also true for comparisons with natural gas at fuel prices characteristic of most of the past decade*. Based on this analysis, we recommended in 2003 that financial incentives be provided for the first group of new nuclear plants that are built. The first mover incentives put in place in the US since 2005 have been implemented very slowly.

RECOMMENDATION

Implementation of the first mover program of incentives should be accelerated for the purposes of demonstrating the costs of building new nuclear power plants in the U.S. under current conditions and, with good performance, eliminating the financial risk premium. This incentive program should not be extended beyond the first movers (first 7–10 plants) since we believe that nuclear energy should be able to compete on the open market as should other energy options.

FUEL CYCLE

There is no shortage of uranium resources that might constrain future commitments to build new nuclear plants for much of this century at least.

The benefits to resource extension and to waste management of limited recycling in LWRs using mixed oxide fuel as is being done in some countries are minimal.

Scientifically sound methods exist to manage spent nuclear fuel.

RECOMMENDATION

For the next several decades, a once through fuel cycle using light water reactors (LWRs) is the preferred economic option for the U.S. and is likely to be the dominant feature of the nuclear energy system in the U.S. and elsewhere for much of this century. Improvements in light-water reactor designs to increase the efficiency of fuel resource utilization and reduce the cost of future reactor plants should be a principal research and development focus.

SPENT NUCLEAR FUEL MANAGEMENT

Long term managed storage preserves future options for spent fuel utilization at little relative cost. Maintaining options is important because the resolution of major uncertainties over time (trajectory of US nuclear power deployment, availability and cost of new reactor and fuel cycle technologies) will determine whether LWR spent nuclear fuel is to be considered a waste destined for direct geological disposal or a valuable fuel resource for a future closed fuel cycle.

Preservation of options for future fuel cycle choices has been undervalued in the debate about fuel cycle policy. Managed storage can be done safely at operating reactor sites, centralized storage facilities, or geological repositories designed for retrievability (an alternative form of centralized storage).

RECOMMENDATIONS

Planning for long term managed storage of spent nuclear fuel—for about a century—should be an integral part of nuclear fuel cycle design. While managed storage is believed to be safe for these periods, an R&D program should be devoted to confirm and extend the safe storage and transport period.

The possibility of storage for a century, which is longer than the anticipated operating lifetimes of nuclear reactors, suggests that the U.S. should move toward centralized SNF storage sites—starting with SNF from decommissioned reactor sites and in support of a long-term SNF management strategy.

This will have the additional benefits of resolving federal liability for its failure to start moving SNF from reactor sites starting in 1998.

WASTE MANAGEMENT

Permanent geological isolation will be required for at least some long-lived components of spent nuclear fuel, and so systematic development of a geological repository needs to be undertaken. The conclusion of the 2003 MIT report that the science underpinning long term geological isolation is sound remains valid.

The siting of a geological repository for spent nuclear fuel and high-level waste has been a major challenge for the United States. The failures and successes of U.S. and European programs suggest that *a nuclear waste management organization should have the following characteristics: (1) authority for site selection in partnership with state and local governments, (2) management authority for nuclear waste disposal funds, (3) authority to negotiate with facility owners about SNF and waste removal, (4) engagement with policy makers and regulators on fuel cycle choices that affect the nature of radioactive waste streams, and (5) long-term continuity in management.* These characteristics are not recognizable in the U.S. program to date. A key element of successful waste management programs is consistency of science-based decisions.

RECOMMENDATION

We recommend that a new quasi-government waste management organization be established to implement the nation's waste management program.

Closed fuel cycle design has focused on what goes back to the reactor but not on how wastes are managed.

RECOMMENDATION

We recommend (1) the integration of waste management with the design of the fuel cycle, and (2) a supporting R&D program in waste management to enable full coupling of fuel cycle and waste management decisions.

A key finding is that the U.S. classifies many radioactive wastes by source rather than by hazard. This has already created gaps in disposal pathways for wastes and this problem will be exacerbated with alternative fuel cycles.

RECOMMENDATION

We recommend that an integrated risk-informed waste management system be adopted that classifies all wastes according to their composition and defines disposal pathways according to risk.

FUTURE NUCLEAR FUEL CYCLES

The choices of nuclear fuel cycle (open, closed, or partially closed through limited SNF recycle) depend upon (1) the technologies we develop and (2) societal weighting of goals (safety, economics, waste management, and nonproliferation). Once choices are made, they will have major and very long term impacts on nuclear power development. Today we do not have sufficient knowledge to make informed choices for the best cycles and associated technologies.

Our analysis of alternative fuel cycles for nuclear power growth scenarios through 2100 yields several results of direct importance in fuel cycle choices:

- fuel cycle transitions take 50 to 100 years;
- there is little difference in the total transuranic inventories or uranium needs in this century
- for the standard plutonium-initiated closed fuel cycle, many LWRs are needed in this century for nuclear power growth scenarios.

A key finding is that reactors with very high conversion ratios (fissile material produced divided by fissile material in the initial core) are not required for sustainable closed fuel cycles that enable full utilization of uranium and thorium resources. A conversion ratio near unity is acceptable and opens up alternative fuel cycle pathways such as:

- *Very different reactor choices. such as hard-spectrum LWRs rather than traditional fast reactors for closed fuel cycles, with important policy implications and potentially lower costs.*
- *Startup of fast reactors with low-enriched uranium rather than high-enriched uranium or plutonium thereby eliminating the need for reprocessing LWR SNF for closed fuel cycle startup.*

There is adequate time before any choices for deployment need to be made to move away from the open fuel cycle. However, there are many viable technological choices that need to be examined, and the time needed to establish new commercial options in the nuclear power business is long. Consequently, the R&D needed should now be vigorously pursued to enable alternative fuel cycle options by mid-century.

RECOMMENDATION

Integrated system studies and experiments on innovative reactor and fuel cycle options should be undertaken with vigor in the next several years to determine the viable technical options, define the timelines of when decisions need to be made, and select a limited set of options as the basis for the path forward.

NONPROLIFERATION

Proliferation at its center is an institutional challenge. The civilian nuclear power fuel cycle is one of several routes to nuclear weapons materials. Establishment of enrichment and/or reprocessing capabilities are proliferation concerns and are not economic choices for small reactor programs. However, guaranteed supplies of fuel are important to countries that embark on electricity production from nuclear energy. Waste management will be a significant challenge for many countries.

RECOMMENDATION

The US and other nuclear supplier group countries should actively pursue fuel leasing options for countries with small nuclear programs, providing financial incentives for forgoing enrichment, technology cooperation for advanced reactors, spent fuel take back within the supplier's domestic framework for managing spent fuel, and the option for a fixed term renewable commitment to fuel leasing (perhaps ten years).

RESEARCH DEVELOPMENT AND DEMONSTRATION

Many decades are needed to research, develop, demonstrate, license, and deploy at scale any major new nuclear technology. A robust RD&D program, aligned with the possibility of substantial nuclear power growth, must be implemented if the U.S. is to have well-developed fuel cycle options in time to make wise strategic fuel cycle choices. The 2010 DOE roadmap is a significant improvement on previous agency plans

RECOMMENDATIONS OF RD&D PRIORITIES

- *Enhanced LWR performance and fuels.*
- A much broader set of spent fuel storage and nuclear waste disposal options than has been pursued for decades.
- Modeling and simulation capability for developing technology options and for understanding tradeoffs among options.

- Innovative nuclear energy applications and concepts, including provision of process heat to industrial applications and development of modular reactors.
- Rebuilding the supporting R&D infrastructure, such as materials test facilities and other key facilities to enable innovative fuel cycle and reactor R&D.

We estimate that about $1 B/year is appropriate for supporting the R&D and infrastructure programs. Additional funding will be needed for large-scale government-industry demonstration projects at the appropriate time.

Chapter 1 — The Future of the Nuclear Fuel Cycle — Overview, Conclusions, and Recommendations

In 2003 MIT issued the report *The Future of Nuclear Power*. The focus for that report was the role of nuclear power as an important option to avoid greenhouse gas emissions. A major conclusion of the report was that "In deregulated markets, nuclear power is not now cost competitive with coal and natural gas. However, plausible reductions by industry in capital cost, operation and maintenance costs, and construction time could reduce the gap. Carbon emission credits, if enacted by government, can give nuclear power a cost advantage." The primary recommendation was that the U.S. Government should provide assistance for the construction of the first few new nuclear plants. The recommendation was based on the need to operate within an untested regulatory regime, the failure of government to initiate spent nuclear fuel removal from reactor sites, and the public interest in understanding the economics of new nuclear power plants in the U.S. as part of a climate change risk mitigation strategy. There would be an opportunity to reduce or eliminate a substantial financing risk premium if the capability to build plants on schedule and within budget was demonstrated.

Since 2003 the urgency to address climate change has increased. The U.S. Congress has indeed adopted a set of incentives to aid the construction of the "first mover" nuclear plants and the Administration has proposed to expand the incentives. There has been a worldwide increase in projected growth of nuclear power and a large growth in the start of construction of new nuclear power plants in a few countries such as China. We undertook this study on the Future of the Nuclear Fuel Cycle to address two overarching questions in the context of the potential for significant growth in nuclear energy.

- What are the long-term desirable fuel cycle options?
- What are the implications for near-term policy choices?

Our analysis has led to three broad conclusions, the basis for which will be presented in this chapter and in the body of the report.

CONCLUSION

For the next several decades, light water reactors using the once-through fuel cycle are the preferred option for the U.S.

The "once through" or open fuel cycle with light water reactors and the need to manage spent nuclear fuel are likely to be the dominant feature of the nuclear energy system in the U.S. and elsewhere for a good part of this century. It is today the economically preferred option, there is no shortage of uranium resources that might constrain future commitments to build new nuclear plants for at least much of this century, and scientifically sound methods exist to manage spent nuclear fuel.

CONCLUSION

Planning for long term interim storage of spent nuclear fuel – for about a century – should be an integral part of fuel cycle design.

This will bring benefits for waste management and provide flexibility for future fuel cycle decisions. Those decisions will be influenced strongly by the scale and pace of future nuclear power development

CONCLUSION

For the longer term, there are multiple viable fuel cycle options with different economic, waste management, environmental, resource utilization, safety and security, and non- proliferation benefits and challenges. A significant research agenda is needed to explore, develop and demonstrate the advanced technologies to the point of allowing informed future market place and policy choices.

Historically it has been assumed that the pathway to a closed fuel cycle included recovery of plutonium from light water reactor spent nuclear fuel and use of that plutonium to start sodium-cooled fast reactors with high conversion ratios. The conversion ratio is the rate of production of fissile fuel from abundant fertile materials in a reactor divided by the rate of consumption of fissile fuel. Conversion ratios greater than one imply more fissile nuclear fuel is produced than consumed. This future was based on two assumptions: (1) uranium resources are extremely limited and (2) a high conversion ratio is required to meet future needs. *Our assessment is that both assumptions are false.*

- *Our analysis leads to the conclusion that a conversion ratio of one is a viable option for a long-term closed sustainable fuel cycle and has many advantages: (1) it enables use of all fissile and fertile resources, (2) it minimizes fissile fuel flows — including reprocessing plants throughput, (3) there are multiple reactor options rather than a single fast-reactor option, and (4) there is a wider choice of nuclear reactor core designs with desirable features such as omitting blankets for extra plutonium production*.

Some of these reactor options may have significantly better economic, nonproliferation, environmental, safety and security, and waste management characteristics. There is time for RD&D to evaluate options before major investment decisions are required. A corollary is that:

- *We must use the available time effectively if real options are to materialize in a few decades. This conclusion has important ramifications. For example, a future closed fuel cycle could be based on advanced hard-spectrum LWRs rather than the traditional fast-spectrum reactors, possibly with rather different costs and fuel forms, or it could consign current LWR SNF to a geological repository rather than recycling. Such fundamentally different technology pathways underpin the importance attached to preservation of options over the next several decades.*

ECONOMICS

FINDING

Nuclear power can be economically competitive for baseload power under appropriate market conditions.

RECOMMENDATION

First mover incentives put in place in the US since 2005 should be implemented rapidly.

Our updated economic analysis (MIT 2009) is summarized in Table 1.1. While the US nuclear industry has continued to demonstrate improved operating performance, *there remains significant uncertainty about the capital cost, and the cost of its financing,* which are the main components of the cost of electricity from new nuclear plants.

Table 1.1 Costs of Electric Generation Alternatives

			LEVELIZED COST OF ELECTRICITY		
	OVERNIGHT COST	FUEL COST	BASE CASE	W/ CARBON CHARGE \$25/TCO_2	W/ SAME COST OF CAPITAL
\$2007	\$/KW	\$/MBTU	¢/KWH	¢/KWH	¢/KWH
Nuclear	4,000	0.67	8.4		6.6
Coal	2,300	2.60	6.2	8.3	
Gas	850	4/7/10	4.2/6.5/8.7	5.1/7.4/9.6	

Nuclear electricity costs are driven by high up-front capital costs. In contrast, for natural gas the cost driver is the fuel cost. Natural gas prices are volatile relative to other fuels; thus, a range of gas prices are presented. Coal lies in-between. The track record for the construction costs of nuclear plants completed in the US during the 1980s and early 1990s was poor. Actual costs were far higher than had been projected. Construction schedules experienced long delays, which, together with increases in interest rates at the time, resulted in high financing charges. Whether the lessons learned from the past can be factored into the construction of future plants has yet to be seen. These factors have a significant impact on the risk facing investors financing a new build. For this reason, the 2003 report and our 2009 analysis applied a higher weighted cost of capital to the construction of a new nuclear plant (10%) than to the construction of a new coal or new natural gas plant (7.8%). Lowering or eliminating this risk-premium makes a significant contribution to the competitiveness of nuclear electricity. These construction cost and schedule difficulties have occurred in some countries but not others.

Nuclear power can be economically competitive under appropriate market conditions.

With the financial risk premium and without a carbon emission charge, electricity from nuclear is more expensive than either coal (without sequestration) or natural gas (at 7\$/MBTU). If this risk premium can be eliminated, the nuclear levelized cost decreases from 8.4¢ /kWh to 6.6 ¢/kWh and becomes competitive with coal and natural gas, even in the absence of carbon emission charges. With carbon emission charges, nuclear becomes either competitive or lower cost than either coal or natural gas. The first few U.S. plants will be a critical test for all parties involved. The risk premium will be eliminated only by demonstrated construction cost and schedule performance. Based on this analysis, we recommended in 2003 that financial first mover incentives be provided for the first group of new nuclear plants that are built. The first mover incentives put in place in the US since 2005 have been implemented slowly. This should be accelerated for the purposes of determining construction costs and schedules at multiple plants. *The incentives should not be extended beyond the first mover program (i.e. for 7–10 plants).*

URANIUM RESOURCES

FINDING

Uranium resources will not be a constraint for a long time.

Uranium resources will not be a constrainit for a long time.

The cost of uranium today is 2 to 4% of the cost of electricity. Our analysis of uranium mining costs versus cumulative production in a world with ten times as many LWRs and each LWR operating for 60 years indicates a probable 50% increase in uranium costs. Such a modest increase in uranium costs would not significantly impact nuclear power economics. However, given the importance of uranium resources for both existing reactors and decisions about future nuclear fuel cycles, we recommend:

RECOMMENDATION

An international program should be established to enhance understanding and provide higher confidence in estimates of uranium costs versus cumulative uranium production.

LIGHT WATER REACTORS

FINDING

LWRs will be the primary reactor choice for many decades and likely the dominant reactor for the remainder of this century.

For the next several decades, a once-through fuel cycle using LWRs is the preferred option for the United States.

The expanded deployment of LWRs should be an important option in any strategy to mitigate climate risk. LWRs are the commercially existing technology and the current lowest-cost nuclear electric production option. They can be operated safely and built in sufficient numbers to match any credible nuclear power growth scenario. The market entry of other reactor types will be slow in part because of time-consuming testing and licensing of new technologies.

Originally it was thought that the commercial lifetime of an LWR would be 40 years. Today more than half the LWRs have obtained, and most of the others are expected to obtain, license amendments to operate for 60 years. Many may operate for even longer time periods. Simultaneously, improvements in operations and technology have increased the output of these reactors. The U.S. has made and will likely make major additional investments in LWRs. Because of the extended lifetimes of these reactors, there is time for improvements in LWR economics, safety, nonproliferation characteristics, and fuel cycles—including possible closed fuel cycles with sustainable conversion ratios near unity. Many of the potential improvements involve advanced fuels and related technologies that would benefit both existing and future LWRs. To protect and enhance the investments already made in LWRs:

RECOMMENDATION

We recommend a long-term RD&D program to further improve LWR technology.

SPENT NUCLEAR FUEL MANAGEMENT

Historically the United States has not considered SNF storage as a major component of fuel cycle policy. However, repository programs worldwide have adopted a policy of storing SNF (or the HLW from reprocessing) for 40 to 60 years before disposal in a geological repository to reduce the radioactivity and decay heat. This reduces repository costs and performance uncertainties. Countries such as France with its partly closed fuel cycle and Sweden with its open fuel cycle built storage facilities several decades ago for this purpose. The failure to include long term storage as part of the spent fuel management has had major impacts on the design of the proposed Yucca Mountain Repository (YMR). Due to the heat load of SNF, the repository was required to be ventilated to remove decay heat while the SNF cooled. The YMR would have, after 30 years of filling, become functionally an underground storage facility with active ventilation for an additional 50 years prior to closure.

Fuel cycle transitions require a half century or more. It is likely to be several decades before the U.S. deploys alternative fuel cycles. Long term interim storage provides time to assure proper development of repositories and time to decide whether LWR SNF is a waste that ultimately requires disposal or whether it is a valuable resource. For multiple reasons, we recommend:

RECOMMENDATION

Planning for long term interim storage of spent nuclear fuel—on the scale of a century—should be an integral part of nuclear fuel cycle design.

In recommending century-scale storage, we are not precluding earlier reprocessing or geological disposal of SNF or much longer term managed storage if the technology permits. These options are preserved. The key point is that fuel cycle decisions should be taken over the next decade or two in the context of a century time scale for managed storage.

Planning for long-term managed storage of spent nuclear fuel — for about a century — should be an integral part of nuclear fuel cycle design and preserve options.

FINDING

Either distributed storage (at reactor), centralized long-term storage, or storage in a repository is technically sound.

The choice between these options will be decided by a variety of technical, economic, and political factors. The burden of SNF storage is small at an operating reactor site because SNF storage is required after discharge from the reactor and before shipment off site. However, this is not true for decommissioned sites where there are no longer the normal reactor operations associated with SNF handling, storage, and security; SNF storage limits reuse of these sites (which are often attractive for development because of access to water and transportation infrastructure) for other purposes; and the tax and employment benefits of the reactor no longer exist. *Spent nuclear fuel should be removed as soon as possible from decommissioned reactor sites* to centralized storage facilities or operating reactor facilities.

Today the total quantities at decommissioned sites are small—about equal to a year's production of SNF in the U.S. Centralized interim storage on a large scale would have the benefit of satisfying federal obligations to remove spent nuclear fuel from reactor sites. Building upon our recommendation for long-term interim SNF storage:

RECOMMENDATION

We recommend that the U.S. move toward centralized SNF storage sites—starting initially with SNF from decommissioned sites and in support of a long-term SNF management strategy. The Federal government should take ownership of the SNF under centralized storage.

Spent nuclear fuel should be removed from decomissioned sites.

The costs of SNF storage are small because the total quantities of SNF (~2000 tons/year in the United States requiring a total of 5 acres/year if placed in dry-cask storage) are small. Licenses for dry-cask SNF storage have been granted for 60 years at some plants.

Managed storage is believed to be safe for a century. Nevertheless, degradation of the spent fuel and storage casks occurs over time due to its heat load, radioactivity and external environmental conditions. Spent fuel in interim storage will need to be shipped either to a reprocessing plant or a repository. The ability of transporting spent fuel after a century of storage will require an understanding of the condition of the spent fuel and storage canisters. At present, limited research and testing on degradation mechanisms of high burnup fuel has been performed and there has been a trend towards higher burnup fuels. High confidence in the integrity of SNF after a century of storage, adequate for transportation and possibly reprocessing, and the possibility for even longer storage times are important considerations for informed fuel cycle decisions. A strong technical basis is essential.

RECOMMENDATION

An RD&D program should be devoted to confirm and extend the safe storage and transportation period.

WASTE MANAGEMENT

Geological disposal is needed for any fuel cycle option.

FINDING

All fuel cycle options create long-lived nuclear wastes that ultimately require geological isolation, and the MIT 2003 report found the science underpinning geologic isolation to be sound.

RECOMMENDATION

Efforts at developing suitable geological repositories for SNF from LWRs and HLW from advanced fuel cycles should proceed expeditiously and are an important part of fuel cycle design.

There have been many failures and some successes in the siting, development, licensing, and operation of geological repositories. There are today no operating repositories for disposal of SNF. However, the United States operates one geological repository—the Waste Isolation Pilot Plant (WIPP) for defense wastes with small concentrations of transuranic elements (plutonium, etc.). WIPP is in its tenth year of operation. Commercial and defense SNF and HLW were to be disposed of in the Yucca Mountain Repository, and thus are now left without a known destination. Sweden and Finland have sited geological repositories for SNF near existing reactor sites with public acceptance. Both countries are in the process of licensing these facilities. Multiple geological repositories for the disposal of long-lived chemical wastes (primarily heavy metals such as lead) have been operating in Europe for decades.

Defining characteristics of successful repository programs are not recognizable in the U.S. program.

Successful repository programs have several defining characteristics: the waste generators are engaged in the programs; there is long-term program and funding continuity; and the programs are characterized by transparency, major efforts at public outreach, and support by local communities. Furthermore, social science is used to understand what features consolidate public acceptance and the program builds this into the technical design basis for a repository. For example, French social assessments resulted in explicitly including long-term retrievability of wastes as a design requirement to provide public confidence. All successful programs had major voluntary siting components. In countries such as Sweden, this strategy resulted in several communities willing to host the repository. Last, the programs as a policy examined multiple sites and technologies to provide (1) alternative options if any one approach failed and (2) confidence to the program and the public that a reasonable set of options had been evaluated before major decisions were made. The Swedish program examined multiple sites and two technologies (geological disposal and boreholes). The French program includes three options (direct disposal, multi-century storage, and waste destruction by transmutation).

Ideally a nuclear waste management organization would have the following characteristics: (1) authority for site selection in partnership with governments and communities, (2) management authority for nuclear waste disposal funds, (3) authority to negotiate with facility owners about SNF and waste removal, (4) engagement with policy makers and regulators on fuel cycle choices that affect the nature of radioactive waste streams, and (5) long-term continuity in management. These characteristics are not recognizable in the U.S. program to date.

RECOMMENDATION

We recommend that a new quasi-government waste management organization be established to implement the nation's waste management program with such characteristics.

Successful repository programs do not close out options until there is high confidence in the selected option. Different options have different institutional characteristics that provide policy makers with choices and increase the likelihood of success. Some options, such as borehole disposal, may provide alternative methods of geological isolation that can be implemented economically on a small scale with desirable nonproliferation characteristics—suitable for countries with small nuclear power programs. The U.S. program had been frozen with one option for decades.

RECOMMENDATION

We recommend an R&D program to improve existing repository options and develop alternative options with different technical, economic, geological isolation, and institutional characteristics.

How wastes are classified (high-level waste, transuranic, etc.) determines disposal requirements. The U.S. classifies many radioactive wastes based on the *source* (Atomic Energy Act of 1954 based on the technologies of 1954)—not the *hazard* of the waste. The U.S. has developed policies for specific wastes rather than a comprehensive waste strategy and thus by default has created orphan wastes from the open fuel cycle with no disposal route. For example, the licensing application for the Yucca Mountain Repository was for the disposal of SNF and HLW; but, there are small quantities of other highly radioactive orphan wastes that will likely require geological disposal. If the U.S. adopted a closed fuel cycle, additional types of orphan wastes would be generated where the waste classification and disposal requirements would be unknown. The current system would become unworkable. Accordingly:

RECOMMENDATION

We recommend that an integrated risk-informed waste management system be adopted that classifies all wastes according to composition and defines disposal pathways according to risk.

This will eliminate regulatory uncertainties with some existing wastes and establish the foundation for waste management decisions associated with alternative fuel cycles. The Nuclear Regulatory Commission should take the lead in developing the appropriate framework. Such a framework can build upon the experiences of other nations and the efforts of the International Atomic Energy Agency. Many countries that developed nuclear programs at later dates used our waste management experiences (with both its positive and negative elements) to develop improved regulatory frameworks.

An integrated risk-informed waste management system should be adopted.

The U.S. has not historically integrated waste management considerations into the fuel cycle decisions adequately. The high cost of the defense waste cleanup programs was partly a consequence of the failure to integrate defense fuel cycles with waste management considerations. The policy failure to include SNF storage drove some costly design decisions for the proposed Yucca Mountain repository.

Closed fuel cycle design has focused on what goes back to the reactor but not on how wastes are managed. A closed fuel cycle entails processing of SNF to produce (1) reactor fuel elements and (2) waste forms designed to meet storage, transport, and disposal requirements. Fuel cycle studies to improve waste management (such as by actinide burning) have only considered a limited set of reactor-based options—not the full set of fuel cycle and waste management options (better SNF disposal packages, alternative nuclear fuel designs, actinide burning, special waste forms for specific long-lived radionuclides, borehole disposal, etc). Historically it was assumed the U.S. would first close the fuel cycle by recycling the fuel and then build geological repositories for separated wastes; later, the U.S. adopted an open fuel cycle policy and pursued siting a repository for SNF. Since a repository is needed irrespective of the fuel cycle, the U.S. should pursue a repository irrespective of when decisions are made on fuel cycles. Because repositories can be designed to allow retrievable waste packages, they can be used for SNF storage while maintaining the option for future closed fuel cycles—a strategy that disposes of what are considered wastes today while maintaining the intergenerational benefits of maintaining options. If repositories are sited before adoption of closed fuel cycles, this would allow co-location of reprocessing and repository facilities; that, in turn, could improve economics while reducing risks (reduced transportation, simplified reprocessing plant, etc.), could improve repository performance by choosing waste forms optimized for the specific repository, and may assist repository siting by coupling future industrial facilities with the repository.

RECOMMENDATION

We recommend (1) the integration of waste management with the design of fuel cycles, and (2) a supporting R&D program in waste management to enable full coupling of fuel cycle and waste management decisions.

FUTURE NUCLEAR FUEL CYCLES

The choice of nuclear fuel cycle (open, closed, or partially closed [limited SNF recycle]) depends upon (1) the features of proven technology options and (2) societal weighting of goals (economics, safety, waste management, and nonproliferation). That fuel cycle choice will lead to fundamentally different futures for nuclear power. We do not today have sufficient knowledge about future options and goals to make informed choices .

To understand the implications of alternative fuel cycles for the United States, we created a dynamic model of the nuclear energy system through the year 2100 . Dynamic modeling is a method to follow in time the consequences of deployment of alternative fuel cycles for different sets of assumptions. Such comprehensive mathematical models of fuel cycles have only been developed in the last few years. Several alternative futures were examined.

A reactor with a conversion ratio near unity may be the best option for a closed fuel cycle. It could be started with uranium rather than plutonium.

- *Nuclear growth scenarios*. Three nuclear growth scenarios were considered: 1% per year (low), 2.5% per year (medium), and 4% per year (high). Fuel cycle choices partly depend upon nuclear growth rates. At low growth rates continuation of today's open fuel cycle is the preferred choice. At high growth rates there are incentives for improved utilization of the energy potential of mined uranium and for reduction of the long-term burden of SNF, but technical constraints exist and incentives may change depending upon the available technology and economics.
- *Fuel cycles*. Three fuel cycles were modeled in detail: today's once-through fuel cycle with LWRs, a partly-closed LWR fuel cycle with recycle of plutonium from LWR SNF back into LWRs and direct disposal of the recycle SNF, and a closed fuel cycle with LWRs and fast reactors. In the closed fuel cycle, LWR SNF is reprocessed and the transuranic elements including plutonium are used to start up fast reactors. The SNF uranium and transuranics from discharged fuel of fast reactors are recycled back to the fast reactors.
- *Fast reactors*. Our analysis of closed fuel cycles included three classes of fast reactors with different goals. In the first scenario the goal was to destroy actinides; thus, the fast reactors had a conversion ratio of 0.75. In the second scenario the goal was a self-sustaining fuel cycle; thus, the fast reactors had a conversion ratio of 1.0. In the third scenario the goal was to rapidly expand the availability of fissile fuel for fast reactors; thus the fast reactors had a conversion ratio of 1.23 with the excess transuranics used to start added fast reactors.

Results from the models under the stated assumptions indicate that:

- The transition from a system dominated by one fuel cycle to another requires 50 to 100 years.
- For medium and high growth scenarios, there were relatively small differences in the total transuranic (plutonium, americium, etc.) inventories between different fuel cycles in this century.

NUCLEAR FUEL CYCLES

The United States uses the once-through open fuel cycle to fuel light water reactors (LWRs). This fuel cycle is the simplest and the most economic fuel cycle today. There are six major steps (Top line of Fig. 1).

- *Uranium mining and milling*. Uranium is the starting fuel for all fuel cycles. Uranium mining and milling is similar to the mining and milling of copper, zinc, and other metals. Uranium is often found with copper, phosphates, and other minerals and thus a co-product of other mining operations. About 200 tons of natural uranium is mined to fuel a 1000-MW(e) light-water reactor for one year.
- *Uranium conversion and enrichment*. The uranium is chemically purified. Uranium contains two major isotopes: uranium-235 and uranium-238. Uranium-235 is the initial fissile fuel for nuclear reactors. Natural uranium contains 0.7% uranium-235. In the uranium enrichment process, natural uranium is separated into an enriched uranium product containing 3 to 5% uranium-235 and ≥95% uranium-238 that becomes LWR fuel and depleted uranium that contains ~0.3% uranium-235 and ~99.7% uranium-238. There will be 10 to 20 times as much depleted uranium as product.
- *Fuel fabrication*. The enriched uranium is converted into uranium dioxide and fabricated into nuclear fuel. An LWR requires ~20 tons of fuel per year.
- *Light-water reactor.* All power reactors in the United States are LWRs. The initial fuel is uranium-235 that is fissioned to produce heat. The fuel also contains uranium-238, a fertile non-fuel material. In the nuclear reactor some of it is converted to plutonium-239—a fissile fuel that is also fissioned to produce heat. The heat is converted into electricity. With a fresh fuel assembly, all the energy is from fissioning of uranium-235. When the fuel is discharged from the reactor as SNF, about half the energy being generated is from the fissioning of plutonium-239 that was created in the reactor.
- *Storage of SNF.* A typical LWR fuel assembly remains in the reactor for three to four years. Upon discharge of the SNF, it contains ~0.8% uranium-235, ~1% plutonium, ~5% fission products, and uranium-238. The SNF is stored for several decades to reduce radioactivity and radioactive decay heat before disposal.
- *Waste disposal.* After interim storage, the SNF is disposed of as a waste in a repository.

Nuclear fuel cycles are different from fossil fuel cycles because nuclear reactors burn only a fraction of the fuel before the fuel is discharged as SNF. Full burnup of the fuel before discharge is not possible.

- The reactor produces heat by fissioning uranium-235 or plutonium-239. The resultant fission product "ash" in high concentrations will shut down the reactor
- The materials of fuel element construction have a limited endurance in the reactor and limit fuel burnup.

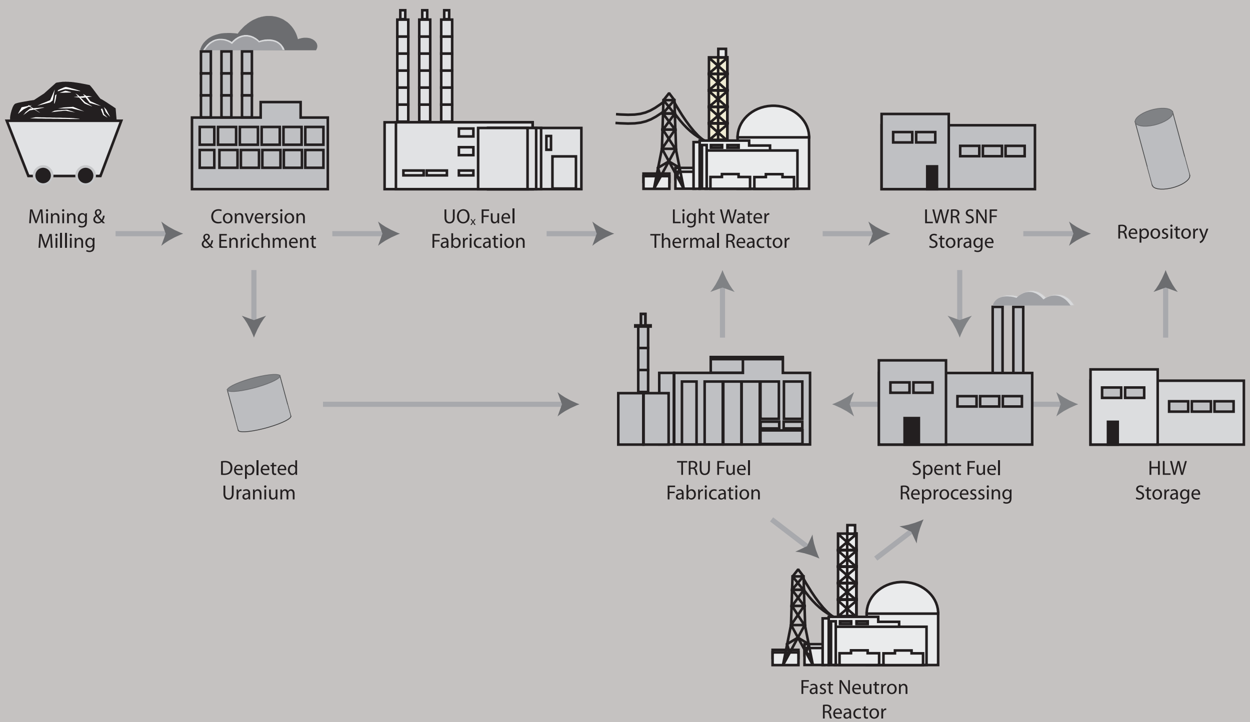
Because reactors can not fully utilize the fissile and fertile materials in a fuel assembly, there are many possible fuel cycles.

- *LWR partly closed fuel cycle (Top two lines of Fig. 1)*. The fissile material in LWR SNF can be recycled back into LWRs. The LWR SNF is reprocessed, the plutonium and uranium recovered, and the plutonium and some uranium are fabricated into fresh fuel, and the resultant transuranic fuel is sent to the LWR. Because of the low fissile content of the LWR SNF, recycle of the plutonium reduces uranium fuel demand by only 15% and recycle of the uranium reduces uranium fuel demand by only 10%. The high-level waste (HLW) from reprocessing is stored for several decades to reduce radioactivity and radioactive decay heat before disposal. LWR SNF recycle changes the plutonium isotopes such that the SNF can only be recycled one or two times. The recycle SNF must either wait to go to a repository or could fuel fast reactors. Several countries recycle LWR SNF.

continued next page

NUCLEAR FUEL CYCLES *(continued)*

Figure 1 Alternative Fuel Cycle



- *Fast reactor fuel cycle*. Fast neutron-spectrum reactors can convert fertile uranium-238 to fissile plutonium-239 faster than they consume that fuel and thus convert all uranium-238 into fissile fuel over time. This enables full utilization of the depleted uranium from LWR uranium enrichment facilities, the uranium in LWR SNF, and the plutonium in LWR SNF. Such reactors can recover 50 times as much energy per kilogram of mined uranium as an LWR; however, fast reactor startup requires a large fissile inventory. The traditional strategy is to reprocess LWR SNF and use the recovered plutonium to fabricate fast reactor fuel. The plutonium in LWR SNF from 30 years of operations is required to start one fast reactor with a high conversion ratio. After fast-reactor startup and operation, fast reactor SNF is reprocessed to recover plutonium and uranium. Plutonium and uranium from fast reactor SNF, and makeup depleted uranium are used to fabricate new fast reactor fuel assemblies. Each fast-reactor SNF assembly has sufficient plutonium for a new fast reactor fuel assembly. Fast reactors are under development in several countries but are today uneconomic and have not been deployed.

There are many other fuel cycles. A more complete description of fuel-cycle choices, criteria, and history is in Chapter 2.

– The primary differences were in the locations of those inventories. In a once-through fuel cycle the inventories were in repositories whereas in partly and fully closed fuel cycles the inventories were in reactors and SNF storage facilities.

– For scenarios where the goal was burning of long-lived transuranics (conversion ratio of 0.75), only a small fraction of the transuranics will be burnt in this century.

- There are relatively small differences between fuel cycles in the total uranium mined within this century for any given nuclear power growth rate. Mined uranium savings would be 25% at most.
- For medium and high growth scenarios, fast reactors started on plutonium fuel require construction of many LWRs and deployment of large capacity reprocessing and fuel fabrication facilities throughout the century in order to supply the initial cores.

FINDING

A key finding of this analysis is that reactors with conversion ratios much higher than one are not materially advantageous for a sustainable fuel cycle—a conversion ratio near unity is acceptable and has multiple advantages. It enables options that may have significantly better economic, nonproliferation, and waste management characteristics than traditional advanced fuel cycles.

Since the 1970s major decisions on development of sustainable closed fuel cycles have been based on the assumptions that uranium resources are limited and that consequently a reactor with as high a conversion ratio as feasible (which turns out to be 1.2 to 1.3) is required. These assumptions drove fuel cycle decisions. Our assessment is that both assumptions are incorrect—uranium resources are large and a conversion ratio of unity is preferred. This has multiple implications.

- *Efficient uranium utilization*. A conversion ratio of unity allows fast reactors to fully utilize all uranium and thorium[1] resources—including depleted uranium from uranium enrichment facilities and SNF.
- *Minimize the required throughput in the closed fuel cycle facilities*. A conversion ratio of unity implies that one fast reactor SNF assembly has sufficient fissile material when recycled to create one new fast reactor fuel assembly. This minimizes the quantities of fuel to be recycled and fabricated.
- *There are multiple reactor choices*. Sodium-cooled reactors have been the preferred choice for long-term sustainable reactors with closed fuel cycles because of their high conversion ratios, but this fuel cycle has not been commercially deployed. If the requirement is a conversion ratio of unity, other reactor options become feasible (Appendix B) including hard-spectrum (modified) light water reactors. With the wide industrial familiarity with water cooled reactors, economic advantages and acceptance by electricity producers are likely to be higher than alternatives.
- *Startup of fast reactors using low-enriched-uranium is viable*. A fast reactor with a high conversion ratio requires high concentrations of fissile fuel in the reactor core—plutonium or enriched uranium with uranium enrichment levels above 20% (weapons useable). A fast reactor with a conversion ratio near unity has lower total fissile fuel inventories and concentrations. It can be started on plutonium or low-enriched non-weapons-usable (enrichment levels below 20%) uranium. After start up, fast reactor SNF would be recycled to fast reactors to enable full utilization of uranium and thorium resources.

The startup of fast reactors with low-enriched uranium instead of plutonium has several advantages.

- *Economics*. Fast reactor enriched uranium reactor startup avoids the need to invest in LWR SNF reprocessing plants. Enriched uranium is likely to remain less expensive than plutonium from LWR SNF.
- *Uranium resource utilization*. With fast reactor startup on LWR plutonium, the rate of introduction is limited by plutonium availability. Low-enriched uranium startup avoids this limitation and enables earlier large-scale use of fast reactors with lower long-term uranium requirements.

It is unclear if LWR SNF will ultimately be a waste or a fuel resource.

- *It is unclear if LWR SNF will ultimately be a waste or a fuel resource.* The fissile content of the LWR SNF is low. Seven or eight LWR SNF assemblies must be recycled to create one new LWR fuel assembly. Fast reactors require greater fissile loadings, thus many more LWR SNF assemblies must be reprocessed to produce a fast reactor fuel assembly. In contrast one fast reactor fuel assembly can be made from one fast reactor SNF assembly. Given uranium resources, the option of starting fast reactors on enriched uranium, and recycle of fast reactor SNF, it may remain uneconomic to recycle LWR SNF.[2]

  In this framework, we emphasize that a *once-through fuel cycle could, in the future, involve processing (i.e. partitioning) of SNF.* Particular radionuclides that pose waste management or non proliferation challenges could be separated for alternative disposal (Appendix B) — such as small packages for deep borehole disposal. Science-based risk-benefit analysis of the system would be required.

- *There are a wide range of fuel cycle choices*. If fissile resources are not a major constraint (uranium is available and a conversion ratio of unity is preferred) there is no requirement for very high recoveries of fissile materials from LWR SNF and there is a broader set of closed fuel cycles that may have better economic and nonproliferation characteristics. The concentrations of fissile materials in fuel can be lower and other impurities can remain with the fuel that may provide barriers to illicit use of SNF.

Our analysis leads to two conclusions.

There is adequate time before any choices for deployment need to be made to move away from the current open fuel cycle. Uranium resources are relatively abundant with respect to the uranium requirements for credible growth rates of the nuclear power system. Evolution from the open cycle will in any case be gradual.

The preferred long-term path forward is not certain today. For the long term, the incentives for development of alternative fuel cycles are: extension of fissile resources; possible mitigation of waste management challenges; and possible minimization of proliferation concerns. However, in the last decade there have been major changes in our understanding of uranium resources, implications of different fuel cycle assumptions such as the conversion ratio for advanced reactors, and new technologies. Multiple factors will influence the ultimate choice of a nuclear fuel cycle, including (1) the pace and scale of nuclear power deployment and (2) evolving technical, economic, and safety performance of fuel reprocessing methods, reactor types (both LWR and fast spectrum reactors), and disposal pathways for waste streams, and (3) the relative importance society places on different goals. Accordingly, we recommend that

RECOMMENDATION

Integrated system studies and experiments on innovative reactor and fuel cycle options should be undertaken in the next several years to determine the viable technical options, define timelines of when decisions need to be made, and select a limited set of options as the basis for the path forward.

For several decades little work has been done on new reactor and fuel cycle options (hard-spectrum light water reactors, once-through fast reactor fuel cycles, integrated reprocessing-repository systems, etc.) that have potentially attractive characteristics. Too much has changed to assume that the traditional fuel cycle futures chosen in the 1970s based on what was known at that time are appropriate for today. There is a window of time, if used wisely with a focused effort, to develop better fuel cycle options before major decisions to deploy advanced fuel cycles are made.[3]

In the context of fuel cycle choices, some have invoked intergenerational equity—usually in considering long-term hazards from radioactive waste and the impact on future generations—as a basis for decisions. The intergenerational benefits of closing the fuel cycle are largely based on extending the availability of nuclear fuel for future generations, but these must be balanced against the risks to present generations of undertaking spent fuel reprocessing and its associated activities. Net risks and benefits are partly dependent upon the available technologies, pointing to an intergenerational benefit of preserving options.

NONPROLIFERATION

Nuclear weapons proliferation is a national security challenge and requires diplomatic and institutional solutions. As nations advance technologically, it becomes increasingly difficult to deny them the technology and materials to develop nuclear weapons if they are motivated by security interests to do so. Thus proliferation at its center is an institutional challenge. The civilian nuclear power fuel cycle is one of several routes to nuclear weapons materials; therefore, strong incentives exist to adopt fuel cycle strategies that minimize the potential coupling of nuclear weapons and commercial nuclear fuel cycles. Hence, avoiding the creation of separated plutonium in future cycles would be an example of minimizing the potential coupling.

Nuclear weapons proliferation requires diplomatic and institutional solutions.

In the context of civilian fuel cycles and nonproliferation, the reactor is not the principal concern. The primary concerns are associated with uranium enrichment and/or reprocessing facilities—the front and backend fuel cycle facilities that would enable a nation to acquire weapon usable materials in a breakout scenario. Establishment of enrichment and/or reprocessing capability are not economic choices for small reactor programs; however, guaranteed supplies of fuel are important to countries that embark on electricity production from nuclear energy. Waste management will be a significant challenge for some countries.

RECOMMENDATION

The US and other nuclear supplier group countries should actively pursue fuel leasing options for countries with small nuclear programs, providing financial incentives for forgoing enrichment, technology cooperation for advanced reactors, spent fuel take back within the supplier's domestic framework for managing spent fuel, and the option for a fixed term renewable commitment to fuel leasing (perhaps ten years).

As analyzed in the *2003 report*, 80% of all SNF will likely be generated by the major nuclear states, at least until mid century; thus, if these countries chose to ultimately manage the world's SNF, there would be a small addition to their existing programs. *The failure to develop a broadly-accepted domestic SNF storage and disposal strategy limits U.S. nonproliferation policy choices in the context of nuclear fuel cycles; thus, nonproliferation objectives are served by effective waste management strategies.*

There is the possibility that advanced technologies could significantly decrease the attractiveness of SNF and other waste forms in the context of nonproliferation.[4] We recommend that

RECOMMENDATIONS

Research on advanced technology options that decrease the attractiveness of nuclear materials for weapons should, as a supplement to institutional approaches, be included as part of reactor and waste isolation R&D programs.

There should be an RD&D program to strengthen the technical components of the safeguards regime.

New technologies can significantly improve safeguards—including timely warning of diversion. While nonproliferation is fundamentally an institutional challenge, improved technology can assist the safeguards regime and raise the bar for diversion of fissile materials.

RESEARCH DEVELOPMENT AND DEMONSTRATION RECOMMENDATIONS

FINDING

A robust RD&D program, aligned with the possibility of substantial nuclear power growth, must be implemented if the U.S. is to have well-developed fuel cycle options in time to make wise strategic fuel cycle choices.

RECOMMENDATION

We therefore recommend RD&D for enhanced LWR capability should be increased significantly. RD&D for a broader set of spent fuel storage and nuclear waste disposal options should be pursued. Modeling and simulation is a core capability for developing technology options and for understanding tradeoffs among options. Research and development on innovative nuclear energy applications and concepts should play a more central role in the overall program.

A robust RD&D program consists of three components: research and development, supporting research and testing infrastructure, and demonstration projects. There is a need to expand the scope of the R&D programs, to invest in enhancing the supporting infrastructure and to conduct tests on highly promising technology choices, often based on scientific simulations of possible alternatives.

About $1B/year is appropriate for nuclear R&D and research infrastructure programs.

The R&D program recommended here would consist of seven core elements and will require an investment of about $670 million per year. A rough breakout is suggested in Table 1.2.

Table 1.2 Summary of R&D Recommendations

ITEM	$ 10^6 PER YEAR	EXPLANATION
Uranium Resources	20	Understand cost versus cumulative world production
LWR Nuclear Power Reactor Enhanced Performance	150	Enhanced performance and life extension for existing LWRs New build LWR technology (New materials, fuel clad, etc.) Advanced fuel development through lead test assemblies
SNF/HLW Management	100	Dry cask storage life-extension Deep borehole and other disposal concepts Enhanced waste forms/engineered barriers
Fast reactors and closed fuel cycles	150	Advanced fast reactor concept analysis and experiments, simulation, basic science, engineering, and cost reduction New separations and analysis Safety and operations analysis
Modeling and Simulation	50	Advanced nuclear simulation innovation; Advanced materials for nuclear applications
Novel Applications and Innovative Concepts	150	High-temperature reactors; Modular reactors; Hybrid energy systems (nuclear-renewable-fossil options for liquid fuels, industrial heat). Peer-reviewed, competitive program for novel concepts.
Nuclear Security	50	Advanced safeguards Nuclear materials containment, surveillance, security, and tracking technologies

There is also the need to rebuild much of the supporting R&D infrastructure. To support R&D for new reactors and fuel cycles, facilities will ultimately be required with special test capabilities. Examples include fast neutron flux materials test facilities, fuel-cycle separations test facilities, and facilities for novel nuclear applications (hydrogen production, heat transport to industrial facilities, etc.). Some of these facilities are billion-dollar facilities—separate from the R&D expenditures listed above. A structural investment on the order of $300 million per year will be required for a decade or so to make a significant difference.

There are large incentives for cooperative international programs where different nations build different facilities with agreements for long-term sharing. Unlike in the past, most new nuclear reactors and most fuel cycle research will be done elsewhere (France, Japan, Russia, China, and India)—there are both financial and policy incentives for cooperative programs.

Lastly, to support commercial viability of new types of advanced reactors and associated fuel cycles, demonstration projects are ultimately required. Such demonstration projects should be joint government-industrial programs and may involve investments of several billion dollars. This is the most difficult step in the development and deployment of new technologies where the U.S. has traditionally had great difficulties. There will be relatively few demonstration projects. International collaboration should be considered for such projects to expand the set of options that can be investigated.

The highest priority choices will emerge in time given the R&D program outlined above. These choices should be made with a view toward supporting licenseability of economically viable new technologies.[5] The cost of licensing of our new technologies has become a serious barrier — particularly to adoption of small-scale reactor designs.

RECOMMENDATION

The federal government should explore ways to reduce the time and cost of licensing new technologies using a risk-based technologically-neutral licensing framework.

CITATIONS AND NOTES

1. Our analysis of thorium versus uranium fuel cycles (Appendix A) found advantages and disadvantages for both fuel cycles—but the differences were not sufficient to fundamentally alter conclusions.
2. In a fuel cycle driven by economics, reprocessing is like uranium mining—the higher the "ore assay" the better the economics. We only mine higher-assay uranium ores. Similarly, we may in the future only recycle higher-fissile-assay SNF.
3. We do not have a good understanding of future nuclear power growth; consequently, we do not know when major fuel cycle deployment decisions will be made. The historical vision of the fuel cycle, recycle LWR SNF and transition to a sodium-cooled fast reactor system with plutonium from LWR SNF, is being developed by multiple countries. It becomes the path forward by default if options are not examined. Because of the potential for fuel cycles with substantially better characteristics—the nation has large incentives to evaluate and develop options to make choices rather than default decisions.
4. Analysis of existing fuel types (Appendix C) shows significant differences in the proliferation resistance of different types of SNF. The question is whether reactors with such fuel types can be economic.
5. Safety regulations for nuclear power plants have been designed for LWRs. The regulations for LWR safety are not appropriate for other reactor technologies. The U.S. Nuclear Regulatory Commission is moving toward "technology-neutral" licensing where new technologies must meet the same safety goals but can use different approaches to meet those goals. However, cost and time to license any new technology is a major barrier to innovation and better systems—including nuclear systems with better safety, waste management, and nonproliferation characteristics. Federal funding in demonstration projects reduces the barriers for technologies with large social benefits but small economic benefits to the companies commercializing such technologies.

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