The Future of the Nuclear Fuel Cycle

AN INTERDISCIPLINARY MIT STUDY

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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 U.S. 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 However, this expectation is rooted in an out-of-date understanding about uranium scarcity.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 U.S., 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 U.S. 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 U.S. 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 U.S. 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.

Postscript

The tragic 9.0-magnitude earthquake and resulting tsunami that struck Japan on March 11, 2011 occurred as this report was in the final stages of production. Consequently, the severe consequences at the Fukushima Dai-ichi nuclear complex have not been factored into the study. The analysis of fuel cycle options presented in the report stands, but national discussions about the future of nuclear power in the U.S. and in other countries will be re-opened to varying extents. The importance of preserving options, a major theme in our discussion of spent nuclear fuel management and fuel cycle choices, is highlighted by the uncertain path that lies ahead.

It will take some time to investigate and fully understand the progression of events at the Fukushima reactors and spent fuel pools and, for the Nuclear Regulatory Commission, to reexamine safety systems, operating procedures, regulatory oversight, emergency response plans, design basis threats, and spent fuel management protocols for operating U.S. reactors. Some of these issues were addressed in the aftermath of the TMI-2 accident and the September 11 World Trade Center attacks, resulting both in hardening of U.S. nuclear plants against a number of accident scenarios and in improved emergency response preparations. The outcomes of the various inquiries are unknown as this report goes to press. Nevertheless, some consequences seem probable in the U.S.:

- Costs are likely to go up for currently operating and future nuclear power plants. For example, requirements for on-site spent fuel management may increase and design basis threats may be elevated. While events beyond the design basis accidents are routinely considered in the U.S. licensing procedures, their importance may increase. As discussed in the report, new plant economics are already challenging. Furthermore, some erosion of the recent gains in public acceptance of expanded nuclear power can be anticipated.
- The relicensing of forty year old nuclear plants for another twenty years of operation will face additional scrutiny, with outcomes depending on the degree to which plants can meet new requirements. Indeed, some of the license extensions already granted for more than 60 of the 104 operating U.S. reactors could be revisited. This may not affect the anticipated sixty-year lifetime for new plants (which rely much more on passive safety systems). Our fuel cycle analyses incorporated such sixty-year operating lifetimes for current and future nuclear power plants.
- The entire spent fuel management system – on-site storage, consolidated long-term storage, geological disposal – is likely to be reevaluated in a new light because of the Fukushima storage pool experience. Our view that SNF storage has been something of an afterthought in U.S. fuel cycle policy has been brought into sharper relief, and there could be a renewed impetus to move SNF away from reactor sites to consolidated storage and disposal.

- In line with many of our R&D recommendations, significant shifts in R&D plans could occur, with increased emphasis on: enhanced performance and life extension for existing LWRs; new materials for improved safety margins; dry cask storage life-extension; advanced technology for prevention or mitigation of severe accidents; and improved simulation of plant behavior under multiple unusual events.

How these and other post-Fukushima issues are resolved will have major implications for the future of nuclear power and for the optimum fuel cycle choices needed to support that future. We hope that this report will provide constructive input to the public and private decision-making processes over the next several years.

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