Charting the Course for American Nuclear Technology: Evaluating the Department of Energy's Nuclear Energy Research and Development Roadmap

Testimony to

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Summary

The United States should conduct a science-based, advanced nuclear fuel cycle research, development, and demonstration program to evaluate recycling and transmutation technologies that minimize proliferation risks and environmental, public health, and safety impacts. This would provide a necessary option to reprocessing technologies deployed today, and supports evaluation of alternative national strategies for commercial used nuclear fuel disposition, effective utilization and deployment of advanced reactor concepts, and eventual development of a permanent geologic repository(s). This should be done as part of robust public-private partnerships involving the Department of Energy (DOE), its national laboratories, universities, and industry; and conducted with a sense of urgency and purpose consistent with the U.S. retaining its intellectual capital and leadership in the international nuclear energy community.

Introduction and Context

Sustainable Nuclear Energy

World energy demand is increasing at a rapid and largely unsustainable pace. In order to satisfy the demand, reduce greenhouse gas emissions, and protect the environment for succeeding generations, energy production must evolve from the current reliance on fossil fuels to a more balanced, sustainable approach based on abundant, clean, and economical energy sources. Therefore, there is a vital and urgent need to develop safe, clean, and secure global energy supplies. Nuclear energy is already a proven, reliable, abundant, and "carbon-free" source of electricity for the U.S. and the world. In addition to contributing to future electricity production, nuclear energy could also be a critical resource for "fueling" the transportation sector (i.e. electricity for plug-in hybrid and electric vehicles and process heat for hydrogen and synthetic fuels production) and for desalinating water. However, nuclear energy must experience significant growth to support the goals of reliable and affordable energy in a carbon-constrained world.

Key challenges associated with the global expansion of nuclear energy include: assurance of ample uranium resources for fuel; the need for increased numbers of trained engineers and technicians to design, build, and safely operate the plants; the need for increased industrial capacity for manufacturing and construction; the need to expand the regulatory infrastructure requisite for safe and secure operations; the need for integrated waste management; and the need to control proliferation risks associated with greater access to sensitive nuclear technologies.

Moreover, domestic expansion of nuclear energy will increase the need for effective nuclear waste management in the U.S. Any advanced nuclear fuel cycle aimed at meeting these challenges must simultaneously address issues of economics, uranium resource utilization, nuclear waste minimization, and a strengthened nonproliferation regime, all of which require systems analysis and investments in technology research and development, demonstration, and test and evaluation. In the end, a comprehensive and long-term vision for expanded, sustainable nuclear energy must include:

- Safe and secure fuel-cycle technologies,
- Cost-effective technologies for an overall fuel-cycle system, and
- Closed fuel cycle for waste and resource management.

Used Nuclear Fuel Management

It is the composition of used nuclear fuel that make its ultimate disposal challenging. Fresh nuclear fuel is composed of uranium dioxide (about 96% Uranium-238, and 4% Uranium-235). During irradiation, most of the Uranium-235 is fissioned, and a small fraction of the Uranium-238 is transmuted into heavier elements (known as transuranics). The used nuclear fuel contains about 93% uranium (mostly Uranium-238), about 1% plutonium, less than 1% minor actinides (neptunium, americium, and curium), and about 5% fission products. Uranium, if separated from the other elements, is relatively benign, and could be disposed of as low-level waste or stored for later re-use, but some of the other byproducts raise significant concerns:

- The fissile isotopes of plutonium, americium, and neptunium are potentially usable in weapons and, therefore, raise proliferation concerns. However, used nuclear fuel remains intensely radioactive for over one hundred years. Without the availability of remote handling facilities, these isotopes cannot be readily separated, essentially protecting them from diversion.
- Three isotopes, which are linked through a decay process (Plutonium-241, Americium-241, and Neptunium-237), are the major contributors to long-term radiotoxicity (100,000 to 1 million years), and hence, potential significant dose contributors in a repository, and also to the long-term heat generation that is a key design limit to the amount of waste that can be placed in a given repository space.
- Certain fission products (notably cesium and strontium) are major contributors to any storage or repository's short-term heat load, but their effects can be mitigated through engineering controls.
- Other fission products (Technetium-99 and Iodine-129) also contribute to long-term potential dose in a repository.

The time scales required to mitigate these concerns are daunting: several of the isotopes of concern will not decay to safe levels for hundreds of thousands of years. Thus, the solutions to long-term disposal of used nuclear fuel are limited to three options (not necessarily mutually exclusive): the location of a geologic environment that will remain stable for that period; the identification of waste forms that can contain these isotopes for that period; or the destruction of these isotopes. These three options underlie the major fuel cycle strategies that are currently being developed and deployed in the U.S. and abroad.

The nuclear fuel cycle is a cradle-to-grave framework that includes uranium mining, fuel fabrication, energy production, and nuclear waste management. There are two basic nuclear fuel-cycle approaches. An open (or once-through) fuel cycle, as currently planned by the U.S., involves treating used nuclear fuel as waste, with ultimate disposition of the material in a geologic repository (see Figure 1). In contrast, a closed

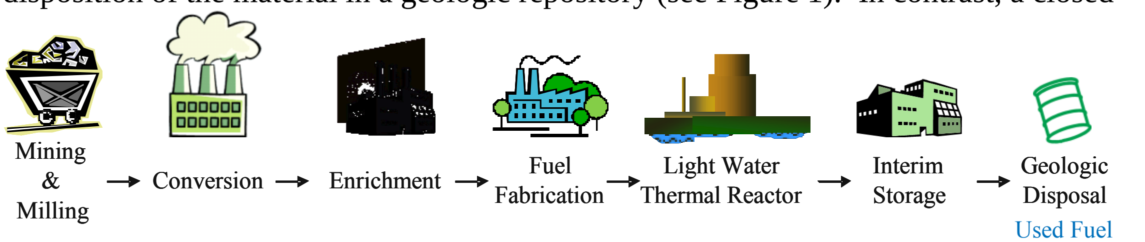

Figure 1. Open (or once-through) nuclear fuel cycle

(or recycle) fuel cycle, as currently planned by other countries (e.g., France, Russia, and Japan), involves treating used nuclear fuel as a resource whereby separations and actinide recycling in reactors work with geologic disposal (see Figure 2).

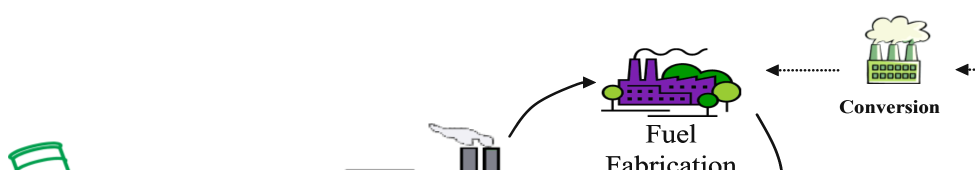

Figure 2. Closed nuclear fuel cycle (or reprocessing/recycling)

In the open nuclear fuel cycle, used nuclear fuel is sent to a geologic repository that must contain the constituents of the used nuclear fuel for hundreds of thousands of years. Several countries have programs to develop these repositories. This approach is considered safe, provided suitable repository locations and space can be found. It should be noted that other ultimate disposal options have been researched (e.g., deep sea disposal, boreholes, and disposal in the sun) and are not focused on currently. The challenges of long-term geologic disposal of used nuclear fuel are well recognized, and are related to the uncertainty about both the long-term behavior of used nuclear fuel and the geologic media in which it is placed.

For the closed nuclear fuel cycle, limited recycle options are commercially available in France, Japan, and the United Kingdom. They use the Plutonium and Uranium Recovery by Extraction (PUREX) process, which separates uranium and plutonium, and directs the remaining transuranics to vitrified waste, along with all the fission products. The uranium is stored for eventual reuse. The plutonium is used to fabricate mixed-oxide fuel that can be used in conventional reactors. Used mixed-oxide fuel is currently not reprocessed, though the feasibility of mixed-oxide fuel reprocessing has been demonstrated. It is typically stored for eventual disposal in a geologic repository. Note that a reactor partially loaded with mixed-oxide fuel can destroy as much plutonium as it creates, but this approach always results in increased production of americium, a key contributor to the heat generation in a repository. This limited recycle approach has two significant advantages:

- It can help manage the accumulation of plutonium.
- It can help significantly reduce the volume of used nuclear fuel and high-level waste destined for geologic disposal (the French experience indicates that volume reductions by a factor of 5 to 10 can be achieved).

Several disadvantages have been noted:

- It results in a small economic penalty by increasing the net cost of electricity a few percent.
- The separation of pure plutonium in the PUREX process is considered by some to be a proliferation risk.
- This process does not significantly improve the use of the repository space (the improvement is around 10%, as compared to many factors of 10 for closed fuel cycles).
- This process does not significantly improve the use of natural uranium (the improvement is around 15%, as compared to several factors of 10 for closed fuel cycles).

Full recycle approaches are being researched in France, Japan, and the U.S. These typically comprise three successive steps: an advanced separations technology that mitigates the perceived disadvantages of PUREX, partial recycle in conventional reactors, and closure of the fuel cycle in fast reactors. Note: the middle step can be eliminated and still attain the waste management benefits; inclusion of the middle step is a fuel cycle system-level consideration.

The first step, using advanced separations technologies, allows for the separations and subsequent management of highly pure product streams. These streams are:

- Uranium, which can be stored for future use or disposed of as low-level waste.
- A mixture of plutonium and neptunium, which is intended for partial recycle in conventional reactors, followed by recycle in fast reactors.
- Separated fission products intended for short-term storage, possibly for transmutation, and for long-term disposal in specialized waste forms.

- The minor actinides (americium and curium) for transmutation in fast reactors.

The advanced separations approach has several advantages:

- It produces minimal liquid waste forms, and eliminates the issue of the “waste tank farms.”
- Through advanced monitoring, simulation, and modeling, it provides significant opportunities to detect misuse and diversion of weapons-usable materials.
- It provides the opportunity for significant cost reduction.
- Finally, and most importantly, it provides the critical first step in managing all hazardous elements present in the used nuclear fuel.

The second step – partial recycle in conventional reactors – can expand the opportunities offered by the conventional mixed-oxide approach. In particular, it is expected that with significant R&D effort, new fuel forms can be developed that burn up to 50% of the plutonium and neptunium present in used nuclear fuel. (Note that some studies also suggest that it might be possible to recycle fuel in these reactors many times – i.e., reprocess and recycle the irradiated advanced fuel – and further destroy plutonium and neptunium; other studies also suggest possibilities for transmuting americium in these reactors. Nevertheless, the practicality of these schemes is not yet established and requires additional scientific and engineering research.) The advantage of the second step is that it reduces the overall cost of the closed fuel cycle by consuming plutonium in conventional reactors, thereby reducing the number of fast reactors needed to complete the transmutation mission of minimizing hazardous waste. As mentioned above, this step can be entirely bypassed, and all transmutation performed in advanced fast reactors, if recycle in conventional reactors is judged to be undesirable.

The third step, closure of the fuel cycle using fast reactors to transmute the fuel constituents into much less hazardous elements, and advanced reprocessing technologies to recycle the fast reactor fuel, constitutes the ultimate step in realizing sustainable nuclear energy. This process will effectively destroy the transuranic elements, resulting in waste forms that contain only a very small fraction of the transuranics (less than 1%) and all fission products. These technologies are being developed in the U.S. at Argonne National Laboratory and Idaho National Laboratory, with parallel development internationally (e.g., Japan, France, and Russia).

Several disadvantages have been noted for a closed fuel cycle, including:

- The economics of closing the fuel cycle. (Note, in practice, closed fuel cycle processes would actually have limited economic impact; the increase in the cost of electricity would be less than 10%.)
- Management of potentially weapons-usable materials may be viewed as a proliferation risk.

These disadvantages can be addressed through a robust research, development, and demonstration program focused on advanced reactors and recycling options. In the end, the full recycle approach has significant benefits:

- It can effectively increase use of repository space.

- It can effectively increase the use of natural uranium.
- It eliminates the uncontrolled buildup of isotopes that are a proliferation risk.
- The advanced reactors and the processing plant can be deployed in small co-located facilities that minimize the risk of material diversion during transportation.
- A fast reactor does not require the use of very pure, weapons-usable materials, thus decreasing proliferation risk.
- Finally, it can usher the way towards full sustainability to prepare for a time when uranium supplies will become increasingly difficult to ensure.

In summary, the overarching challenge associated with the choice of any fuel cycle option is used nuclear fuel management. For example, current U.S. policy calls for the development of a geologic repository for the direct disposal of used nuclear fuel. The decision to take this path was made decades ago, when the initial growth in nuclear energy had stopped, and the expectation was that the existing nuclear power plants would operate until reaching the end of their design lifetime, at which point all of the plants would be decommissioned and no new reactors would be built. While it may be argued that direct disposal is adequate for such a scenario, the recent domestic and international proposals for significant nuclear energy expansion call for a reevaluation of this option for future used fuel management (see Figure 3). While geologic repositories will be needed for any type of nuclear fuel cycle, the use of a repository would be quite different for closed fuel-cycle scenarios.

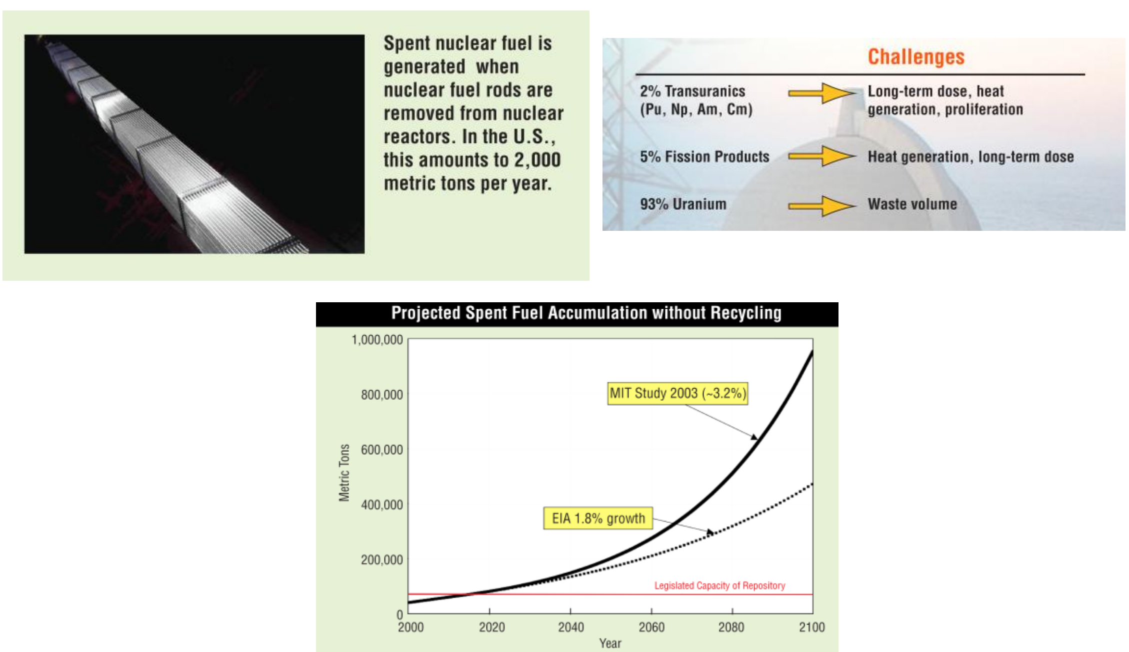

Figure 3. Used nuclear fuel generation and management

For reprocessing to be beneficial (as opposed to counterproductive), it must be followed by recycling, transmutation, and fission destruction of the long-lived radiotoxic constituents (i.e., plutonium, neptunium, americium). Reprocessing (with PUREX) followed by thermal-recycling (mixed-oxide [MOX] fuel in light water reactors [LWRs]) is well established, but is only a partial solution. It is not at all clear that the U.S. should embark on this path, especially since we have not made a massive investment in a PUREX/MOX infrastructure. (Although, the U.S. is proceeding with a plan to reduce excess-weapons plutonium inventory using MOX in LWRs.) In contrast, advancement of fast reactor technology for transuranic recycling and consumption would maximize the benefits of waste management and also allow essential progress toward the longer term goal of sustainable use of uranium (and subsequently thorium) with fast reactors.

There is no urgent need to deploy recycling today, but as nuclear energy expands, a once-through fuel cycle will not be sustainable. To maximize the benefits of nuclear energy in an expanding nuclear energy future, it will ultimately be necessary to close the fuel cycle. Fortuitously, it is conceivable that the decades-long hiatus in U.S. investment circumvents the need to rely on dated recycling technologies. Rather, we have the option to develop and build new technologies and develop business models using advanced systems.

Detailed Discussion

Argonne National Laboratory

Located 25 miles southwest of Chicago, Argonne National Laboratory was the country's first national laboratory – a direct descendant of the University of Chicago's Metallurgical Laboratory where Enrico Fermi and his colleagues created the world's first controlled nuclear chain reaction. Appropriately, Argonne's first mission 64 years ago was to develop nuclear reactors for peaceful purposes. Managed by the UChicago Argonne, LLC for the U.S. Department of Energy, Argonne has grown into a multidisciplinary laboratory with a unique mix of world-class scientists and engineers and leading-edge user facilities, working to create new technologies that address the most important scientific and societal needs of our nation.

Argonne's experience over many years of research in the advancement of nuclear energy positions it as a leader in the development of future generation reactors and fuel cycle technologies. A primary goal of the Laboratory's nuclear energy research program is to *advance the sustainable use of nuclear energy* through research and development of technologies that enable waste minimization, enhanced resource utilization, competitive economics, and increased assurance of reliability, safety, and security. Expertise in reactor physics, nuclear and chemical engineering, computational science and engineering, and fuel cycle analysis is applied in the assessment and conceptual development of advanced nuclear energy systems that meet these important goals.

In collaboration with other DOE laboratories and universities, Argonne is advancing a new science- and simulation-based approach for optimizing the design of advanced nuclear energy systems and assuring their safety and security. This approach seeks increased understanding of physical phenomena governing system behavior and incorporates this understanding in improved models for predicting system performance in operating and off-normal situations. Once validated, these models allow the simulation and optimization of system design and operation, to enhance safety assurance and cost competitiveness with alternative energy supply options. They also promise to accelerate the demonstration of commercially attractive systems in partnership with industry.

Argonne's waste management and reprocessing research and development activities are supported primarily by the DOE's Office of Nuclear Energy (DOE-NE) through its Fuel Cycle Research and Development program. The objective of Argonne's research in this area is to develop and evaluate separations and treatment processes for used nuclear fuel that will enable the transition from the current open fuel cycle practiced in the U.S. to a sustainable, environmentally acceptable, and economic closed fuel cycle. Our research focuses on the science and technology of chemical separations for the treatment of used fuel from both commercial and advanced nuclear reactors, used fuel characterization techniques, and waste form engineering and qualification. Ongoing projects related to reprocessing and waste management include:

- Using advanced modeling and simulation coupled with experiments to optimize the design and operation of separations equipment.
- Exploring an innovative one-step extraction process for americium and curium, radionuclides that are major contributors to nuclear waste toxicity, to reduce the cost of used-fuel treatment.
- Further developing pyrochemical processes for used fuel treatment. These processes enable the use of compact equipment and facilities, treatment of used fuel shortly after discharge from a reactor, and reduction of secondary waste generation.
- Developing highly durable and leach-resistant waste forms of metal, glass, and ceramic composition for safe, long-term disposal.

In addition, Argonne's nuclear science and engineering expertise utilizes theory, experiment, and modeling and simulation in the assessment and conceptual development of innovative, advanced reactors operating with a variety of coolants, fuel types, and fuel cycle schemes. Argonne also leads U.S. development of innovative technologies that promise to reduce the cost of fast-neutron reactors and increase their reliability. These technologies include high-performance fuels and materials; compact, low-cost components for the heat transport systems; advanced power conversion and refueling systems; and improved capabilities for in-service inspection and repair.

Argonne's research into the behavior of irradiated fuels and materials supports the U.S. Nuclear Regulatory Commission (NRC) in the regulation of industry initiatives to extend the operational lifetime and optimize the operation of existing and evolutionary nuclear reactors. Leading-edge systems analysis and modeling capabilities are used to assess the relative merits of different advanced nuclear energy systems and fuel cycles for various domestic and global scenarios of energy demand and supply consistent with environmental constraints and sustainability considerations. Argonne also has expertise in the components of nuclear technology that are critical for national security and nonproliferation, including the conversion of research reactors to low-enrichment fuels, technology export control, risk and vulnerability assessments, and national-security information systems.

Current Nuclear Waste Reprocessing Technologies

As discussed above, current commercial used nuclear fuel reprocessing technologies are based on the PUREX process, which is a solvent extraction process that separates uranium and plutonium and directs the remaining minor actinides (neptunium, americium, and curium) along with all of the fission products to vitrified waste. The PUREX process has over fifty years of operational experience. For example, the La Hague reprocessing facility in France treats used fuel from their domestic and foreign power reactors. Plutonium recovered is recycled as a mixed-oxide fuel to generate additional electricity. Other countries using this technology for commercial applications include the United Kingdom and Japan.

PUREX does not recover the minor actinides (neptunium, americium, curium, and heavier actinide elements), which compose a significant fraction of the long-term radiotoxicity of used fuel. Advanced reactors can transmute and consume minor actinides if separated from the fission product elements, but incorporation of minor actinide separations into existing PUREX facilities adds complexity and is outside commercial operating experience. Moreover, existing international facilities do not capture fission gases and tritium, but rather these are discharged to the environment within regulatory limits. Although plutonium is recycled as mixed oxide fuel, this practice actually increases the net discharge of minor actinides. Finally, the production of pure plutonium through PUREX raises concerns about materials security and proliferation of nuclear weapons-usable materials.

Pyroprocessing is presently being used at the Idaho National Laboratory to treat/stabilize used fuel from the decommissioned EBR-II reactor. The key separation step, electrorefining, recovers uranium (the bulk of the used fuel) in a single compact process operation. Ceramic and metallic waste forms, for active metal and noble metal fission products, respectively, are being produced and have been qualified for disposal in a geologic repository. However, the demonstration equipment used for this treatment campaign has limited scalability. Argonne has developed conceptual designs of scalable, high-throughput equipment as well as an integrated facility, but to date only a prototype advanced scalable electrorefiner has been fabricated and successfully tested.

Advanced Reprocessing Technologies

Research on advanced reprocessing technologies focuses on processes that meet U.S. non-proliferation objectives and enable the economic recycle of long-lived actinides in used fuel, while reducing the amount and radiotoxicity of high-level wastes that must be disposed. Main areas of research include:

- Aqueous-based Process Design - Current studies target the simplification of aqueous processes that can recover the long-lived actinides as a group in one or two steps.

- Pyrochemical-based Process Design - Present work is focused on development of scalable, high-throughput equipment and refining our understanding of the fundamental electrochemical process. We are targeting greater control of the composition of the recovered uranium/transuranic alloy, which will facilitate safeguards consistent with U.S. non-proliferation goals.
- Off-gas Treatment – Environmental regulations limiting the release of gaseous fission products require the development of materials that will efficiently capture and retain volatile fission products. Because these volatile fission products are generally difficult to retain, development of novel materials with strong affinities for particular fission products is essential.
- Product/Waste Fabrication – This development effort includes concentrating the product streams and recovery/recycle of process fluids, solidification of products for both waste form and fuel fabrication/recycle. The products must meet stringent requirements as nuclear fuel feedstocks or must be suitable for waste form fabrication.
- Process Monitoring and Control - Advanced computational techniques are being developed to assess and reduce uncertainties in processing operations within a plant. Such uncertainties in design, in processing, and in measurements significantly increase costs through increased needs for large design margins, material control and accounting, and product rework.
- Sampling Technologies - The tracking of materials is critical to the safeguarding and operational control of recycle processes. Improving the accuracy of real-time measurements is a major goal for material accountancy and control. Reducing the turnaround time for analysis by applying state-of-the-art sampling and analytical techniques will enable "on-line" material accountancy in real time. Advanced spectroscopic techniques are under study to reduce gaps in our ability to identify key species at key locations within a plant.

Impact on Future Nuclear Waste Management Policy

The Blue Ribbon Commission is evaluating options for the management of used nuclear fuel, which will result in recommendations for changes in U.S. nuclear waste policy. In parallel with these efforts, advances in used fuel processing and waste storage and disposal technologies will support the development of an integrated policy for nuclear waste management in the U.S., consistent with our energy security, nonproliferation, and environmental protection goals. In particular, advances in nuclear fuel processing and storage and disposal technologies would enable actinide recycle as fuel for advanced reactors, allowing for additional electricity generation while drastically reducing the amount of nuclear waste and the burden on future generations of ensuring its safe isolation.

Development and implementation of advanced reprocessing, recycle, and waste storage and disposal technologies should be done as part of an integrated waste management policy. Reprocessing and disposal options and long-term waste management policies should go hand in hand. Alternative technologies will have different economies of scale based on the type and number of wastes. In addition, waste packages may be retrievable or not and the waste form should be tailored to the site geology. This does not preclude the possibility of multiple disposal sites for selected wastes.

High-level waste disposal facilities are required for all fuel cycles, but the volumes and characteristics of the wastes will be different. Consequently, a waste classification system is needed to define the facilities needed to support waste disposal. The U.S. does not have a cohesive waste classification system, but rather an ad hoc system that addresses management of specific wastes. The current point of origin system requires a complex dual waste categorization system, one for defense wastes and another for civilian wastes. This approach has resulted in high disposition costs, wastes with no disposition pathways, limited disposition sites, and a system that will be difficult to align with any alternative fuel cycle that is adopted.

The International Atomic Energy Agency (IAEA) recommends a risk-based classification system that accounts for the intensity of the radiation and the time needed for decay to an acceptable level. The intensity of radiation is given by a range of radioactivity per unit of weight. Decay time is split into short lived (< 30 years) and long lived (>30 years). There is no distinction in either categorization or disposition options based on the sources of nuclear waste. The result is a simple, consistent, standard system. Lacking a consistent waste classification system, it is not possible to compare waste management costs and risks for different fuel cycles without making arbitrary assumptions regarding theoretical disposition pathways.

DOE's Nuclear Energy Research and Development Roadmap

Observations

The DOE-NE "Nuclear Energy Research and Development Roadmap" (April 2010) provides a comprehensive vision for advancing nuclear energy as an essential energy source. Argonne strongly supports the R&D objectives described in the Roadmap, namely:

1. Sustaining and extending the operation of the current reactor fleet;
2. Improving the affordability of new reactors, for example, through development of small modular reactors;
3. Enhancing the sustainability of the nuclear fuel cycle through increased efficiency of uranium utilization and reduced discharge of actinides as waste; and
4. Quantifying, with the objective of minimizing nuclear proliferation and security risks.

Argonne also agrees with the R&D approach described in the Roadmap, in particular the synergistic use of experiment, theory, and modeling and simulation to achieve the foregoing objectives.

While all four objectives are clearly important, Argonne believes that the public sector has a proportionately larger role to play in the efforts supporting objectives 2, 3, and 4. Objective 1 will be met largely through industry-financed initiatives and will build on decades of developments achieved by industry. Objective 4 requires an integrated systems approach to safeguards and security in developing an advanced nuclear fuel cycle(s), and complementary assessment work by the National Nuclear Security Administration (NNSA); its achievement will depend substantially on implementation and enforcement of international nonproliferation agreements and security arrangements.

Concerning Objective 2, Argonne believes that deployment of small modular reactors (SMRs) is a potential game-changer to enable nuclear energy to be a significant contributor in addressing the world's climate and energy security challenges. SMRs may be financially competitive for countries and regions that cannot support commercial-sized units in the 800-1400 MWe range. Additionally, they offer flexibility, more broadly, by enabling smaller increments of capacity addition and may provide a route to competitive economics by shifting much of the plant assembly and construction work into factories from the plant site. For SMRs based on existing (light water) reactor technology, the domestic and international industry is best positioned to complete the development that is needed, so the Government's principal role may be to eliminate technical barriers to NRC licensing. Argonne, in collaboration with economists at the University of Chicago, is analyzing the economic competitiveness of SMRs. Two of the SMR attributes that the study is focusing on are: the increased flexibility for utilities to add appropriately-sized units as demand changes; and deployment of SMRs as on-site replacements of aging fossil-fueled power plants.

Concerning Objective 3, Argonne supports a greater emphasis on coupling the science-based approach for system development with an active design and technology demonstration effort that would guide and appropriately focus R&D, and enable assessment of programmatic benefits in a holistic manner. This would be accomplished by close cooperation of DOE, national laboratories, universities, and industry. The overall approach would seek to:

- Increase understanding of the diverse physical phenomena underlying reactor and fuel cycle system behavior;
- Improve ability to predict system behavior through validated modeling and simulation for design, licensing; and operation; and
- Develop advanced materials, processes, and designs for reactor and fuel cycle systems through application of scientific discoveries and advanced modeling and simulation capabilities, as well as the insights and lessons learned from past nuclear energy development programs.

These efforts would allow for fuel cycle demonstration in a timeframe that could influence the course of fuel cycle technology commercialization on a global basis. Moreover, the individual elements of the planned R&D (e.g., separations, waste forms, transmutation fuels) are each potentially vast in scope and can absorb substantial resources, without commensurate benefit, if the different areas are not sufficiently integrated for the results to fit together in a viable system.

An Effective Nuclear Energy R&D Strategy Going Forward

The objectives of the DOE-NE "Nuclear Energy Research and Development Roadmap" can be met in a reasonable time frame if the appropriate priorities are identified and sufficient funding is provided to allow acceleration of high priority areas. In particular, Argonne believes that advanced fast-neutron reactors (of small or large capacity), recycle processes, and waste management technologies should be developed and demonstrated at engineering scale during the next 20 years. Concurrently, support should be provided for facilitating the NRC review and certification of advanced reactors designed by commercial organizations, including small modular reactors.

To enable an effective nuclear energy research and development strategy, the development of advanced fuel treatment technologies and waste forms must be closely coordinated with R&D on:

- Advanced fuels and interim storage strategies for current light water reactors (LWRs), as these affect the requirements on reprocessing and waste technologies. Research on advanced fuels for light water reactors is one of the proposed thrusts of the DOE-NE Light Water Reactor Sustainability program (Objective 1 in the Roadmap).
- Advanced reactors such as liquid metal and gas cooled "Generation IV" reactors, which employ different fuel types and thus discharge used fuel that is very different from that of LWRs. In the administration's budget request for 2011, this research would be funded as part of the "Advanced Reactor Concepts" program. Advanced *fast spectrum* reactors can efficiently consume the residual actinides in used nuclear fuel, effectively converting these actinides to electricity instead of discharging them as waste.

Overall, an effective research and development strategy for advanced fuel cycles must include:

- A fuel cycle system development activity to guide and appropriately focus the research.
- Improved systems analysis of nuclear energy deployment strategies.
- Science and discovery contributions to technology and design.
- Increased role of modeling and simulation in nuclear energy research, development, and system design.
- Advances in separations and fuel technologies to close the fuel cycle:
  - Develop and demonstrate aqueous-based technologies;
  - Develop and demonstrate pyroprocessing technologies; and
  - Develop and demonstrate transmutation fuels.
- Advances in nuclear reactor technology and design to generate electricity and close the fuel cycle:
  - Develop advanced reactor concepts; and
  - Develop advanced reactor component testing facilities.
- Advancement of safe and secure use of nuclear energy on an international basis:
  - Enhance safety assurance capabilities in countries newly adopting nuclear energy; and

    - Improve and deploy safeguard and security technologies and practices.
- Education and training of future nuclear energy professionals.
- University programs and partnering with institutions that have nuclear energy programs.
- Support for modernization of aging research facilities for conducting experimental work; such facilities should be regionally located in close proximity to universities in order to develop the human capital needed to sustain research advances in the future.
- Coordination and integration of R&D in separations and waste sponsored by different government agencies and offices (DOE-NE, DOE-EM, DOE-OCRWM, and DOE-SC).
- Close cooperation with industry in research and development, demonstration, and commercialization efforts as part of robust public-private partnerships.

Summary and Recommendations

The United States should conduct a science-based, advanced nuclear fuel cycle research, development, and demonstration program to evaluate recycling and transmutation technologies that minimize proliferation risks and environmental, public health, and safety impacts. This would provide a necessary option to reprocessing technologies deployed today, and supports evaluation of alternative national strategies for commercial used nuclear fuel disposition, effective utilization and deployment of advanced reactor concepts, and eventual development of a permanent geologic repository(s). This should be done as part of robust public-private partnerships involving the Department of Energy, its national laboratories, universities, and industry; and conducted with a sense of urgency and purpose consistent with the U.S. retaining its intellectual capital and leadership in the international nuclear energy community.

Over the next several years, the research, development, and demonstration program should:

- Complete the development and testing of a completely integrated process flow sheet for all steps involved in an advanced nuclear fuel recycling process.
- Characterize the byproducts and waste streams resulting from all steps in the advanced nuclear fuel recycling process.
- Conduct research and development on advanced reactor concepts and transmutation technologies that consume recycled byproducts resulting in improved resource utilization and reduced radiotoxicity of waste streams.
- Develop waste treatment processes, advanced waste forms, and designs for disposal facilities for the resultant byproducts and waste streams characterized.
- Develop and design integrated safeguards and security measures for advanced nuclear fuel recycling processes that enable the quantification and minimization of proliferation risks associated with deploying such processes and facilities.
- Evaluate and define the required test and experimental facilities needed to execute the program.
- On completion of sufficient technical progress in the program:

    - Develop a generic environmental impact statement for technologies to be further developed and demonstrated; and
    - Conduct design and engineering work sufficient to develop firm cost estimates with respect to development and deployment of advanced nuclear fuel recycling processes.
- Cooperate with the NRC in making DOE facilities available for carrying out independent, confirmatory research as part of the licensing process.