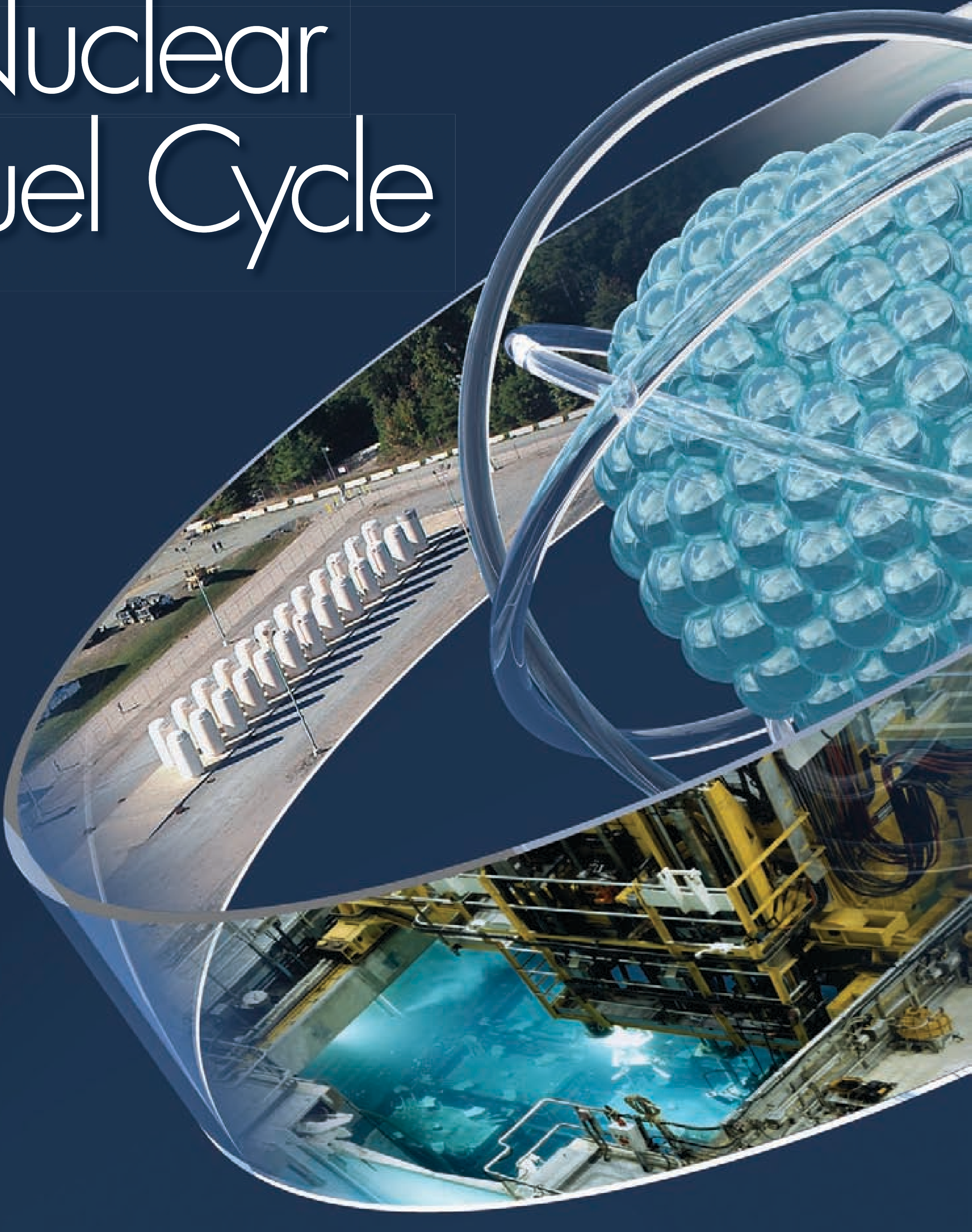
# Toward an Integrated Nuclear Fuel Cycle



# The Story in Brief

Nuclear power's long-term value as a clean and sustainable generation resource may depend on taking strategic action to close the fuel cycle. Momentum is building toward fully integrated fuel cycles based on fuel reprocessing and reuse, interim storage, secure transport, and geologic disposal. Closing the fuel cycle will not be easy, but with a global commitment to advanced technology development and demonstration, there is time to "get it right," leading to more-efficient resource utilization and waste disposal, along with competitive electricity generation costs.

Increased concern about greenhouse gas emissions, energy security, and volatile fossil fuel prices is driving the development of new nuclear power plants in a number of countries. EPRI's PRISM/MERGE analysis identifies a large role for nuclear energy in reducing electricity sector greenhouse gas emissions, with up to 64,000 MW of new capacity by 2030.

Nuclear power's long-term future is tied to the broader issue of sustainability, which encompasses continued safe, reliable, and economic operation; a secure fuel supply; effective waste management; and nonproliferation of nuclear materials.

"When we look at sustainability and how nuclear power can make substantial contributions to energy supply over the long term, we need to carefully reconsider the nuclear fuel cycle," says Albert Machiels, senior technical executive at EPRI. To ensure nuclear power's long-term viability, the fuel cycle must be integrated. That will mean holistically coordinating fuel production and use, spent fuel storage, transportation, and disposal. Integrating the fuel cycle would provide maximum energy recovery with lower quantities of waste for disposal.

Spent fuel reprocessing followed by recycling is central to advanced fuel cycles, providing the mechanism through which additional nuclear fuel is created and through which the quantities of high-level radioactive waste are minimized. Several countries, including France, Japan, Russia, and the United Kingdom, already reprocess nuclear fuel for reuse in existing power plants, storing the waste by-products until they can be permanently placed in a geologic repository. Other countries, including the United States, rely on a once-through, or "open," fuel cycle, in which spent fuel would be placed in a geologic repository without reprocessing.

Experience in fuel reprocessing will prove invaluable as the global nuclear industry moves to close the fuel cycle. While advanced fuel cycles are key to sustainability, there is no need to rush their deployment, says EPRI's Machiels. "There is time to get it right and make the best decisions, recognizing that technology must evolve over time. We need a picture of the advanced fuel cycle that we want 50 years from now, and that cycle has to be one we can successfully implement at a cost we can afford."

The U.S. nuclear industry is pursuing a three-part strategy for developing an integrated fuel cycle, according to Steven Kraft, senior director of used-fuel management at the Nuclear Energy Institute (NEI):

- Research, development, and commercial demonstration of advanced nuclear fuel reprocessing and recycling technologies to close the fuel cycle
- Interim storage until the fuel is recycled or disposal is available
- Disposal of by-products in a geologic repository

## Spent Fuel Reprocessing: What Is the State of the Art?

Reprocessing spent fuel separates materials that can be reused for power production—uranium, plutonium, and the minor actinides—from fission products, which are considered true radioactive waste. Differences in fuel cycles are largely a matter of whether, and how, these materials are separated and managed.

Countries committed to at least partially closing the fuel cycle, including France and Japan, use the PUREX reprocessing technology, which separates spent fuel constituents into three main streams:

- Reprocessed uranium (about 94%), which can be stored or reused in existing reactors
- Plutonium (about 1%), which can be used in mixed-oxide (MOX) fuel for recycling in existing or future reactors
- Fission products and minor actinides (about 5%), which are dealt with as high-level waste and require geologic disposal. Fission products include strontium, cesium, iodine, and technetium. Minor actinides include neptunium, americium, and curium.

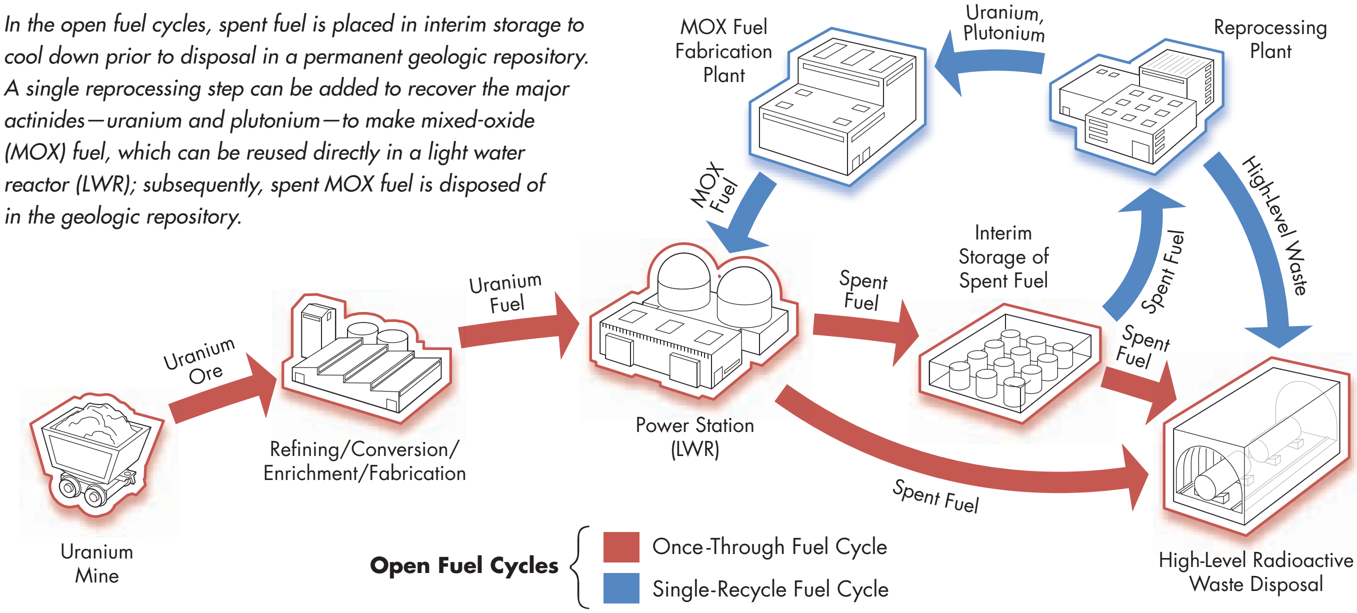
"France's strategy of reprocessing and recycling enables the country to preserve the option of nuclear power for the long term," says Jean-Michel Delbecq, program manager for future nuclear systems at the French utility EDF. French reprocessing has helped reduce the quantity of stored spent fuel and optimize interim storage of high-level waste. "The recycling of plutonium and uranium to fabricate MOX fuel significantly reduces the spent fuel inventory," says Delbecq. "We start with seven spent uranium oxide fuel assemblies, and at the end, we have one spent MOX fuel assembly. The process also substantially reduces the volume of high-level waste requiring disposal."

Recent French legislation mandated three studies that could move France toward a fully integrated closed cycle:

- Assess by 2015 interim storage capacity, including the potential for adapting existing facilities and the need for new ones
- Assess geologic disposal, and develop a licensing procedure by 2015, with implementation by 2025
- Assess by 2012 the transmutation of high-level waste in advanced reactors and the development of a prototype reactor by 2020

The 2012 decision on advanced "fast" reactors that can process plutonium and the minor actinides into fuel will be important for reducing the volume and radiotoxicity of reprocessed waste products, according to the French Atomic Energy Commission (see "The Status of Advanced Reactor Development," page 29). Deployment of the first such commercial reactor is expected by about 2040. EDF's goal is to evaluate the technological hurdles that must be overcome and the R&D programs that must be undertaken in order to develop fast reactors, with a focus on the sodium-cooled fast reactor. Studies indicate that the plutonium inventory in spent fuel from the current fleet of operating reactors—both spent uranium oxide fuel and spent MOX fuel—would be sufficient to enable operation of fast reactors by 2040, says Delbecq. For this reason, the plutonium resource in spent fuel must be managed with a view to the long term.

*In the open fuel cycles, spent fuel is placed in interim storage to cool down prior to disposal in a permanent geologic repository. A single reprocessing step can be added to recover the major actinides—uranium and plutonium—to make mixed-oxide (MOX) fuel, which can be reused directly in a light water reactor (LWR); subsequently, spent MOX fuel is disposed of in the geologic repository.*




**Open Fuel Cycles**
- Once-Through Fuel Cycle
- Single-Recycle Fuel Cycle

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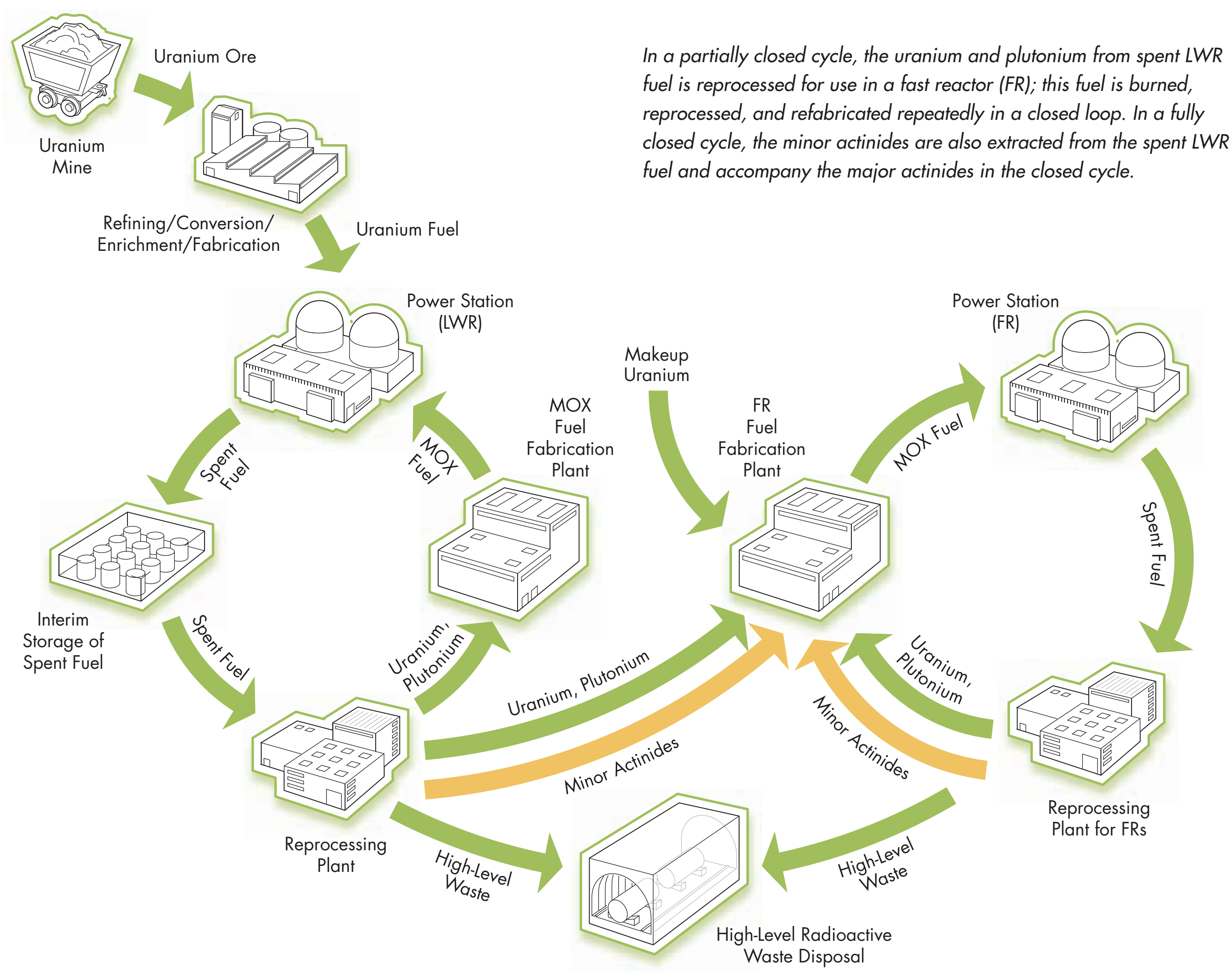
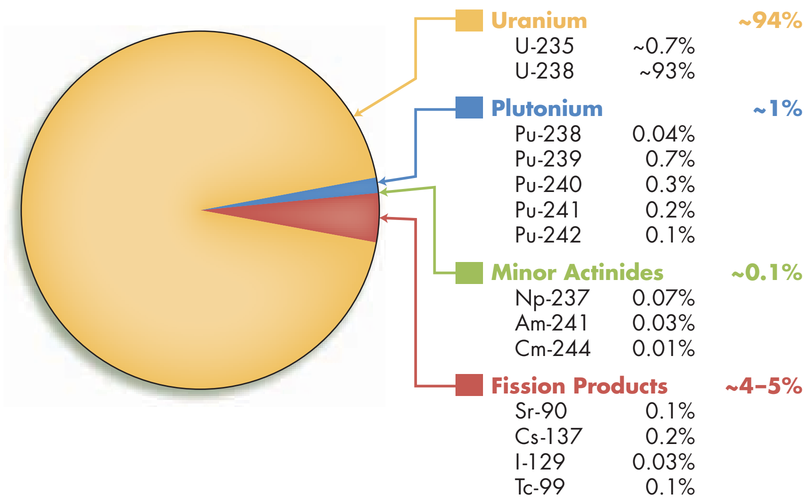
**Closed Fuel Cycles**
- Partially Closed Fuel Cycle
- Fully Closed Fuel Cycle

*In a partially closed cycle, the uranium and plutonium from spent LWR fuel is reprocessed for use in a fast reactor (FR); this fuel is burned, reprocessed, and refabricated repeatedly in a closed loop. In a fully closed cycle, the minor actinides are also extracted from the spent LWR fuel and accompany the major actinides in the closed cycle.*

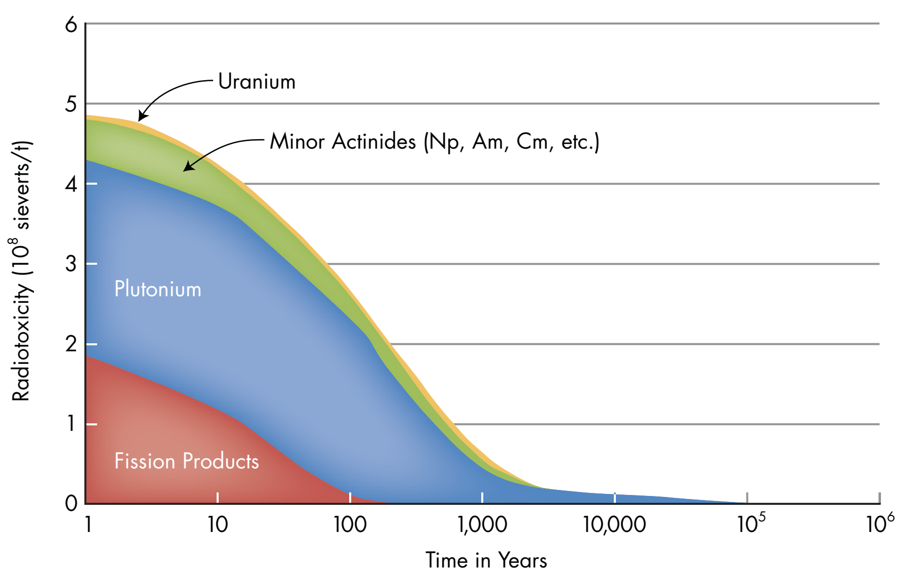


**LWR Spent Fuel Make-Up**




*Spent fuel from today's nuclear plants consists mostly of uranium unaffected by nuclear activity inside the reactor; this material can be recovered and processed for additional use. Plutonium and the minor actinides, which are formed from uranium in the reactor, are also potentially valuable as nuclear fuel. Fission products—more than two dozen elements that can be formed from split uranium atoms—are not suitable for power production and must be discarded as high-level waste.*

**Potential Radiotoxicity of Spent Fuel Components**




*Uranium, plutonium, and the minor actinides have significantly longer half-lives than most fission products. Removing these elements from spent fuel and burning them in a closed cycle will substantially reduce nuclear waste's radiotoxicity.*

Natural resource–constrained Japan, whose nuclear plants produce approximately 1000 metric tons of spent fuel annually, is pursuing reprocessing to address the dual concerns of waste reduction and resource enhancement. "Recycling spent fuel enables nuclear power to play a major role in energy supply over the long term and also minimizes the waste volume," says Sakae Muto, executive officer and deputy chief nuclear officer of Tokyo Electric Power Company. "Moreover, recycling spent fuel can yield uranium resource savings of 10–20%."

Muto expects reprocessing to remain central to Japan's nuclear program. In the near term, recycled uranium and plutonium will be used in light water reactors. Over the longer term, the development of fast reactors is a national technological priority.

The PUREX process presents some disadvantages related to disposal and proliferation. Because PUREX extracts the fission products and minor actinides in a single stream, the minor actinides contribute to waste volume, and their energy content is thrown away. PUREX also produces a plutonium stream, so its use raises proliferation concerns. Commingling plutonium with uranium or even small amounts of the minor actinides can increase its proliferation resistance.

In light of these issues, several technology variations have emerged or are being actively developed:

- Extraction of plutonium mixed with some uranium, and possibly with some neptunium
- Selective separation of minor actinides (by means of DIAMEX-SANEX in France, TALSPEAK in the United States, TOGDA in Japan) for interim storage, followed by recycling in fast reactors
- Group separation of actinides (by GANEX in France, UREX+ in the United States, NEXT in Japan) specifically intended for incorporation in recycled fuel for fast reactors

Large-scale implementation of these new processes depends on significant research, development, and demonstration and is not likely for several decades. *The Future of Nuclear Power,* a 2003 report issued by the Massachusetts Institute of Technology, notes that studies of the partitioning and transmutation of long-lived fission products have not yet shown that such products can be dealt with effectively. Moreover, it will be necessary to recycle MOX fuel several times to optimize economic efficiency, says Ernest Moniz, MIT professor of physics and engineering systems and one of the authors of the study. "We are not very far advanced in such multiple recycling."

The U.S. Department of Energy (DOE) has proposed the UREX+ reprocessing technology as part of its Global Nuclear Energy Partnership (GNEP) program. The UREX+ process would keep the transuranic elements—plutonium, neptunium, americium, and curium—together, minimizing waste and making the separation more proliferation-resistant than it is in the PUREX process. In general, recycling of the transuranics turns a potential waste liability into an energy asset, although it may involve significantly higher operational complexity and costs.

## Interim Storage: From Stopgap to Solution

Regardless of which advanced fuel cycles are eventually developed, interim storage will be key to the integrated system. Spent fuel from U.S. nuclear plants is currently stored on-site in spent fuel pools and in aboveground dry storage systems, awaiting the operation of a permanent geologic repository or centralized interim storage facilities. France currently provides interim storage for three products: spent uranium oxide and spent MOX fuel, stored at power plant and reprocessing-facility sites, and high-level waste from reprocessing, stored only at the reprocessing facility.

"The U.S. industry supports an integrated spent fuel management strategy that includes centralized interim storage until recycling or permanent disposal—or both—can be made available," says NEI's Steven Kraft. "Interim storage sites will enable the movement of used fuel from decommissioned and operating plants to volunteer locations before recycling facilities or a repository can begin operating. The short-term goal is to identify and develop volunteer sites for interim storage, while the medium-term goal is to move used fuel to these sites, ideally at locations where advanced fuel cycles are being developed."

Kraft points out that there is a need to explore the private sector's role in carrying out near-term reprocessing demonstrations as a way to spur reprocessing development in a real-world business setting. Communities that host interim storage are obvious candidates for hosting commercial reprocessing demonstrations.

The requirements for interim storage will depend largely on how storage will fit into efforts to close the fuel cycle. Interim storage allows heat and radioactivity levels to decrease and minimizes worker dose rates and industrial discharges from reprocessing facilities. "To obtain the best results for balancing risks and rewards in deploying advanced-fuel-cycle facilities, it may be best to leave spent fuel in interim storage for 60 to 100 years, at least initially" says John Kessler, EPRI's manager of high-level waste and spent fuel.

MIT's Moniz agrees: "It makes sense to store spent fuel for on the order of a century prior to doing whatever is planned. This conveniently provides several decades to find out if advanced fuel cycles will materialize. We favor the idea of a small number of consolidated storage sites on government property. Then, if the country moves toward a research, development, and demonstration program for an advanced fuel cycle, the pilot-, engineering-, and commercial-scale facilities should be fostered where there is consolidated spent fuel storage."

## Ultimate Disposal of Nuclear Waste Still Essential

In addition to interim storage, a common thread in all advanced fuel cycles is the need for a geologic repository. Although the volume and toxicity of the waste vary with the type of cycle, all cycles produce fission products and some unrecycled frac-

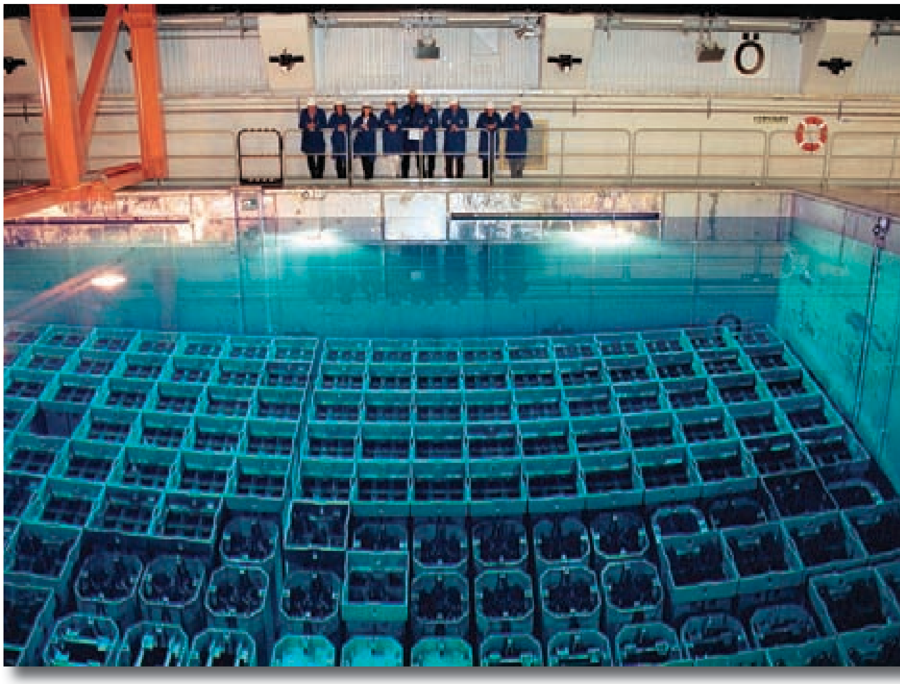
## The Status of Advanced Reactor Development

Fast reactors, known as Generation IV reactors, are critical to advanced fuel cycles. Several reactor types are being considered for design and development—gas-cooled, sodium-cooled, and lead-cooled fast reactors, for example.

A number of countries—including France, Japan, South Korea, the United Kingdom, and the United States—organized the Generation IV International Forum to coordinate international R&D on promising advanced reactor designs. Recently the U.S. DOE, the French Atomic Energy Commission, and the Japan Atomic Energy Agency agreed to coordinate the development of a prototype sodium-cooled fast reactor. These countries will establish design goals for prototypes and identify key technical innovations needed to reduce capital, operating, and maintenance costs.

EPRI analyses reveal that break-even uranium prices for recycling plutonium in fast reactors are generally lower than those for recycling in light water reactors. But an increase in capital cost for the fast reactor would possibly offset this difference. MOX recycling in light water reactors could dampen, but not stop, uranium price increases, whereas a switch to fast reactors could stop the rise, according to EPRI. Therefore, a mix of MOX-fueled light water reactors and fast reactors may prove appropriate, at least for a while. Commercial deployment of fast reactors is not likely for several decades.

Fast reactors are able to fission both of the major actinides (uranium and plutonium) and all of the minor actinides (e.g., neptunium, americium, curium). They can be operated in a breeder mode or in a burner mode, depending on whether the amount of plutonium is higher or lower than the initial amount of plutonium in the fuel. Breeder reactors are most efficient when concerns about the adequacy of natural uranium supplies dominate, while burner reactors are best suited to progressively destroying actinides, thus removing them from the waste stream.



*Interim storage is an important part of all fuel cycles, allowing the radioactivity and heat of spent fuel assemblies to decline before reprocessing or final waste disposal. The Clab facility in Oskarshamn, Sweden, stores about 4000 tons of uranium from Swedish nuclear plants. While Clab stores the spent fuel in deep water pools, dry storage systems are also an option.*

*AREVA NC's La Hague plant on the French Cotentin Peninsula reprocesses spent reactor fuel to recover uranium and plutonium, which can be recycled as MOX fuel. La Hague is the world's largest commercial spent fuel reprocessing site, serving the nuclear programs of half a dozen European nations.*

tion of the actinides, and these require disposal. "Isolation of radioactive by-products, used fuel, or both in a specially designed underground repository is consistent with the international scientific consensus that deep geologic disposal is the most effective means of protecting public health and the environment," says NEI's Kraft.

No country has yet developed, licensed, or operated a repository for spent fuel and high-level waste, although Finland and the United States have identified sites and begun development, France and Sweden have identified likely locations, and Canada and the United Kingdom are working on site-decision methodologies. The United States does have an operating nuclear waste disposal facility in southeastern New Mexico, but this facility does not accept spent fuel and high-level waste.

The U.S. Congress in 1987 designated Yucca Mountain, Nevada, as the potential site of a permanent repository for spent fuel and high-level radioactive waste. Yucca Mountain has been the subject of innumerable scientific and engineering analyses and assessments. DOE has coordinated a 20-year effort involving 2500 scientists to construct the world's largest underground laboratory. Scientists from the International Atomic Energy Agency (IAEA) and the Organisation for Economic Co-operation and Development's Nuclear Energy Agency have analyzed and endorsed DOE's repository performance assessments.

Still, the project's complexity and the continuing resistance from interveners and from some in the public have slowed progress, frustrating industry leaders. "It may take a national imperative to drive a decision on a repository," says Charles Pardee, chief nuclear officer of Exelon Generation. "If all 50 state governors took a united position on the issue, or if the governors and attorneys general of the states with spent fuel stored at nuclear plant sites started pressing this issue nationally, it would be more meaningful than the same actions by industry CEOs."

As the Nevada project moves slowly forward, questions are surfacing about whether it will be adequate for future needs. "Yucca Mountain has a statutory capacity limit of 70,000 metric tons, with 90% of that capacity designated for commercial spent nuclear fuel," says Kessler. "Projecting over 50 years, we will need a repository with twice as much capacity."

EPRI analyzed Yucca Mountain's capacity in its 2007 report *Room at the Mountain.* "We concluded that through design and waste loading modifications the repository could handle between four and nine times the statutory capacity," says Kessler. This expanded capacity at Yucca Mountain would allow time for the research and development to move toward a full-scale and economically competitive closed fuel cycle.

EPRI has also assembled technical experts in climate, hydrology, materials science, geochemistry, seismology, volcanology, and the biosphere to develop models for long-term processes at the site. These processes include climate change, the slow degradation of waste containers, the slow release of radionuclides, groundwater movement,

## Transporting Spent Fuel: New Cycles Bring New Challenges

Spent nuclear fuel has been safely transported for decades. According to the IAEA, there have been more than 20,000 shipments of spent fuel and high-level wastes over millions of kilometers since 1971. None has resulted in an accident in which a container was breached. Going forward, however, spent fuel will have to be moved in ever larger volumes.

Many U.S. nuclear utilities that store spent fuel at plant sites use canisters designed for both storage and transportation. The U.S. Nuclear Regulatory Commission (NRC) has licensed these canisters for use in dry storage, but it has restricted their use for transporting spent fuel that exceeds a certain fuel burnup level. Most spent fuel discharged from reactors today does exceed that level. EPRI is working with the NRC in collaboration with NEI to establish realistic standards for the transportation of spent fuel.

Many NRC concerns focus on the possibility that fissile material in the spent fuel could undergo an uncontrolled nuclear reaction. Water is a particular concern in this regard. As a moderator for neutrons, water slows them down, making it easier for them to be absorbed by fissile material in the fuel and thus increasing the probability of a chain reaction. NRC regulations require that spent fuel remain subcritical in the presence of water. EPRI is modeling the potential changes in criticality posed by the presence of water and the geometric rearrangement of the spent fuel that might occur during a transportation incident.


Regulatory concern has been heightened by the trend toward higher-burnup fuel, which may be subject to more damage during certain potential transportation events, such as accidents. EPRI has developed a probabilistic risk assessment of a criticality event occurring during transportation of spent fuel. "Criticality depends on the probability of an initiating event, the presence of a moderator, the fissile content of the spent fuel, and the presence of neutron 'poisons'—isotopes that capture neutrons, preventing them from sustaining a nuclear chain reaction," says Kessler. "Because of our work, the NRC is permitting licensees to take partial credit for certain actinides in the spent fuel that are neutron absorbers and that would shut down a chain reaction. We're doing similar research on fission products, which are also neutron absorbers."

EPRI research has helped to increase the amount of the so-called burnup credit for spent fuel—the degree to which neutron absorption by radionuclides in spent fuel reduces the risk of a nuclear reaction—that the NRC permits. Use of this burnup credit could increase the amount of spent fuel that could be transported in existing canister designs. "Without the credit, only about 20% of spent fuel could be shipped," says Kessler. "With the credit, that figure could increase to 90%."

"While encompassing all of the issues relevant to U.S. concerns," says Kessler, "our work on spent fuel transportation technical issues also applies to most spent fuel that international nuclear utilities will be moving."

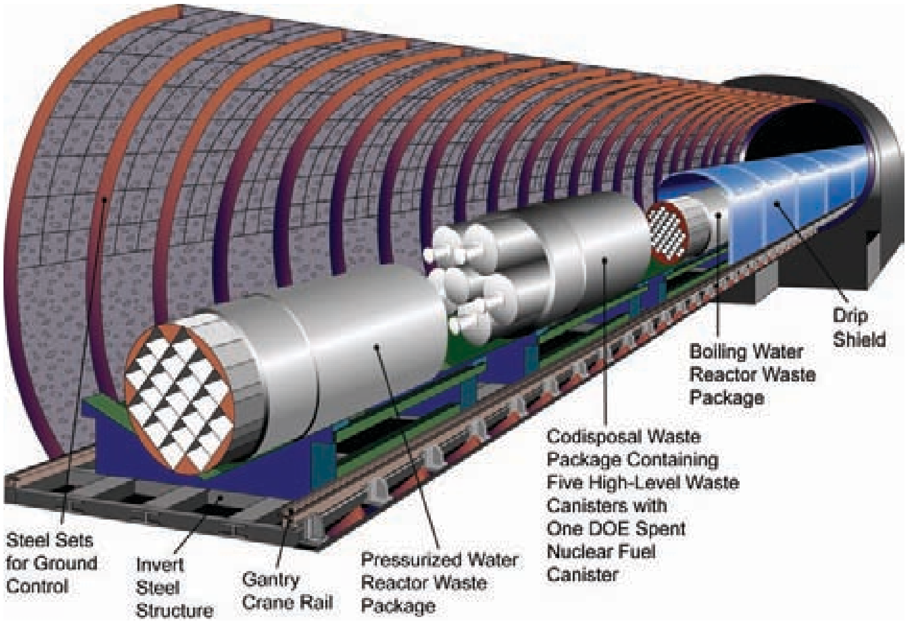
and the transport of radionuclides in the groundwater and their impact on public health. NEI will use the EPRI work in these areas when it represents the industry in the Yucca Mountain construction licensing process. DOE is expected to file an application for construction by June 2008.

### Technical Challenges for Advanced Cycles

Closing the nuclear fuel cycle will constitute a multidecade effort. EPRI research points to a number of technical challenges confronting advanced fuel cycles:

- Remote-control fabrication and testing of new fuel types containing minor actinides
- Construction and safe operation of fast reactors
- Chemical treatments that separate fission products from actinides
- Conditioning of waste streams
- Improved diversion resistance of separated fissile materials

Progress on these challenges will be informed by past and ongoing reprocessing and waste management practices, but some key issues have not yet been resolved. The MIT *Future of Nuclear Power* report argues that the best approach to pursuing advanced fuel cycles involves the development of basic tools and advanced codes: "We view the optimization of such fuel




*The Yucca Mountain repository in Nevada has been designed to accept a variety of high-level nuclear waste materials for permanent deep geological storage. The U.S. Department of Energy is expected to submit a license application to the U.S. Nuclear Regulatory Commission this year, although operation is unlikely for at least a decade.*

cycles as a systems issue, not separate issues about the fuel form or the reactor or the separation technology. They must be integrated all the way to the kind of waste form destined for geologic isolation."

EPRI has come to similar conclusions, calling for integrated process models that dynamically simulate nuclear power systems—from uranium mining to final disposal of the wastes—in order to select the most promising development paths. To further this approach, EPRI and NEI are supporting a five-year interdisciplinary research program at MIT carried out under the MIT Energy Initiative. The program will systematically study the options for managing the technical, economic, environmental, and institutional aspects of the nuclear fuel cycle and propose a technology development and deployment plan.

While this work will consider all aspects of both open and closed fuel cycle architectures, it is placing particular focus on the uncertainties in managing commercial spent fuel and the ultimate disposal of the waste. As part of the study, MIT is currently assessing the ability of four fuel cycle modeling codes to simulate a wide spectrum of fuel cycle scenarios, says EPRI's Machiels.

In addition to the work at MIT, EPRI is collaborating with EDF to develop optimal fuel cycle strategies. "EDF will analyze a scenario in which the current U.S. nuclear fleet of light water reactors moves to a future fleet of evolutionary light water reactors and fast reactors," says Claude Garzenne, a senior researcher in EDF's R&D division.

## Getting It Right

Planning out the future shape of nuclear power is a daunting task, complicated by lead times measured in decades and substantial uncertainties in future technical, institutional, and policy developments. But while the long time frames can be problematic, they also offer the opportunity to deal comprehensively with the challenge of closing the nuclear fuel cycle and to create durable, no-regrets solutions.

Success will depend to a great extent on developing a robust understanding of all the elements involved—advanced reactor designs, fuel options, separation technologies, waste forms, and geologic disposal alternatives—and integrating them into a holistic system. Given the many institutions and stakeholders involved, planning will need to include a great deal of flexibility, leading to effective, iterative decision making.

"The nuclear community has made a good start in choosing a systems approach to the nuclear fuel cycle issue," says Machiels. "Now we must get down to the hard work of developing the appropriate technologies and making it happen."

*This article was written by Alice Clamp. Background information was provided by Albert Machiels (amachiel@epri.com) and John Kessler (jkessler@epri.com).*

**Albert Machiels,** previously a senior program manager in the Nuclear Sector's Materials and Chemistry program, is currently senior technical executive. Before joining EPRI in 1982, he was an associate professor of nuclear engineering at the University of Illinois, Urbana-Champaign. Machiels received Ingénieur Civil Chimiste and Ingénieur en Génie Nucléaire degrees from the University of Liège in Belgium and a PhD in engineering from the University of California at Berkeley.

**John Kessler** is a program manager in the Nuclear Sector's High-Level Waste and Spent Fuel Management program. He came to EPRI in 1993, having earlier worked at Nutech Engineers and as a private consultant on dry spent fuel storage system design. Kessler earned BS and MS degrees in nuclear engineering from the University of Illinois, Urbana-Champaign, and a PhD in mineral engineering from the University of California at Berkeley.