Nuclear Fuel Recycling

Background Information, Position Statement 45

I. Introduction and Summary

A. World energy needs and available resources

Nuclear power is a proven technology that will continue to be part of the mix of energy sources used by future generations due to its enormous energy potential with near-zero emissions of greenhouse gases and other harmful pollutants. Currently, coal and natural gas are relied on heavily for global energy needs, but these valuable resources are limited in the long term and are significant contributors to the buildup of greenhouse gases in the atmosphere. The energy from nuclear fission is essentially inexhaustible when fully exploited by using nuclear fuel recycling along with advanced fuel cycles, just as is the energy from sources traditionally considered "renewable."

Renewable energy technologies with low greenhouse gas emissions, such as wind, solar, and hydro, should be used where appropriate. However, they have a limited capability and, with the exception of hydro, produce energy intermittently, requiring backup power generators or storage facilities. Their land-use requirements are high, and they have nonnegligible external costs, such as degradation of the environment, displacement of populations, and destruction of natural habitats.[1] All of these factors must be considered in the total cost associated with these energy sources when comparisons are made with nuclear power and the option of nuclear fuel recycling.

The initial technical driver for recycling the usable components of used nuclear fuel (UNF) was to recover the residual energy sources of unfissioned uranium and plutonium. However, recently updated projections for natural uranium resources indicate ample supplies through the end of the 21st century and beyond under a wide range of nuclear energy demand scenarios. The 2014 edition of the joint OECD/NEA–IAEA "Red Book"[2] indicates continued growth in identified uranium resources, albeit with increases in production costs. All trends point to adequate supplies for 100 years or more, even under the highest assumed growth rate for nuclear power (e.g., from 375 GWe net in 2010 to 746 GWe net in 2035). Therefore, natural resource utilization does not appear to provide a market-based driver for recycling UNF in the near future. However, greater uranium utilization remains a compelling technical driver for recycling in the long term.

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Today a primary driver for recycling UNF is waste volume reduction by extraction of high-level waste to be placed in encapsulated form designed for optimum long-term storage and permanent disposal in a geologic repository. This would help address public concerns about nuclear waste disposal. Other drivers for recycling are to ensure energy security, to avoid market disruptions, and to respond to price increases.

The Blue Ribbon Commission on America's Nuclear Future[3] concluded that it is premature to seek consensus on recycling UNF and instead recommended storage of UNF pending the development of a geologic repository. The American Nuclear Society (ANS) recognizes that interim storage of UNF for a limited time is a necessary but not permanent solution to the problem of nuclear waste treatment and disposal. Moreover, ANS takes the position that continued research and development of nuclear fuel recycling without a policy and plan for industrial-scale deployment will not make the technology a practical reality. Transitioning to a policy that allows and encourages UNF to be recycled will significantly enhance resource utilization and radioactive waste management, and will ensure that the United States can restore its influence in international fuel cycle policies in the current era of expanded, global nuclear power deployment.

The two concerns most frequently raised relative to making a decision to recycle UNF have long been (1) costs and (2) nonproliferation uncertainties. However, recent studies as summarized in this background report have shown that the capital and financing costs for new reactors dominate the life-cycle costs of nuclear energy and that UNF recycle costs do not contribute significantly to overall life-cycle costs. Moreover, recent nonproliferation studies have indicated that safeguards-by-design can be applied effectively to a nuclear fuel recycling facility and can meet International Atomic Energy Agency (IAEA) guidelines in a cost-effective manner.[4] Furthermore, effective extrinsic (institutional) measures to counter proliferation and security threats are necessary regardless of the nuclear fuel cycle technology chosen.[4] In addition, improved methods for recycling UNF are now available.[5] These technology enhancements enable more components to be recycled and the amounts of waste generated, especially that material requiring placement in geologic repositories, to be significantly reduced.

This paper describes the historical incentive and the significant advantage of recycling to improve resource utilization. It summarizes the extensive experience gained by many other countries during the past four decades with recycling and the future plans of these countries and others to expand or to initiate commercial recycling. The options available to recycle unused and newly produced fissile materials from UNF are presented. Advances in nonproliferation technology, particularly using safeguards-by-design in reprocessing and recycling facilities, are described. Current economic studies that put the cost of reprocessing and recycling into proper perspective are summarized.

A near-term decision to begin transitioning to an industrial-scale UNF recycle capability in the United States would produce many benefits over the current situation in which UNF is being stored indefinitely with only the long-term intention of geologic disposal having been identified. The many benefits of beginning this transition now are presented in the last section of this paper.

B. Inventory of UNF for disposal or recycle

Each year an average of approximately 11,500 metric tons heavy metal (tHM) of UNF are discharged from operating commercial reactors around the world, including approximately 2,000 tHM discharged annually in the United States. Approximately 340,000 tHM had been discharged worldwide by the end of 2010 including 72,000 tHM in the United States. Thus, by 2020 approximately 440,000 tHM of UNF will have been discharged worldwide, including approximately 84,000 tHM in the United States. Through the end of 2010, approximately 90,000 tHM had been reprocessed worldwide with only 242.1 tHM reprocessed in the United States.[2,6]

Section I References

[1] "Nuclear Power: The Leading Strategy for Reducing Carbon Emissions," ANS Position Statement 44, American Nuclear Society, La Grange Park, IL (June 2006); htpp://www.ans.org/pi/ps.

[2] "Uranium 2014: Resources, Production and Demand," NEA No. 7209, OECD-NEA Publishing, Paris (2014).

[3] Blue Ribbon Commission on America's Nuclear Future, "Report to the Secretary of Energy" (January 26, 2012).

[4] "International Safeguards in Nuclear Facility Design and Construction," IAEA Nuclear Energy Series No. NP-T-2.8, IAEA, Vienna (April 2013).

[5] E. D. Collins et al., "A Practical Solution to Used Nuclear Fuel Treatment to Enable Sustained Nuclear Energy and Recovery of Vital Materials," ORNL/TM-2010/81, Oak Ridge National Laboratory, Oak Ridge, TN (April 2010).

[6] "Plutonium & Uranium Recovery from Spent Fuel Reprocessing by Nuclear Fuel Services at West Valley, New York from 1966 to 1972," U.S. Department of Energy report (revised Nov. 1999); accessible from EDMS as DW:2001:0156 (February 26, 2001).

II. Nuclear Fuel Cycle Basics

The term *nuclear fuel cycle* refers to the facilities, processes, and infrastructure involved in the extraction and preparation for use of a fuel resource (referred to as the "front end" of the fuel cycle), use of that fuel for energy generation, and disposition and management of energy-generation products (referred to as the "back end"). This paper focuses on the back end of the nuclear fuel cycle.

The process of converting fossil fuel to energy is chemical in nature and involves oxidation, i.e., burning. The energy conversion is effectively complete and produces wastes, for example, ash and carbon dioxide (CO_2), that have little or no further value for energy production. The process to convert nuclear fuel to energy involves fission, which splits the nucleus of the *fissile* fuel atoms and produces both products with further energy value and wastes.

The fuel-to-energy conversion in a nuclear reactor begins with the only naturally occurring *fissile* isotope, ^{235}U (0.72% of uranium found in nature), but also involves production of new fissile isotopes, and therefore new fuel resources, by transmutation of so-called *fertile* materials by neutron absorption. Two abundant forms of fertile material are found in nature: ^{238}U and ^{232}Th, which comprise 99.27% and 100% of the naturally occurring elements, respectively. Incorporation of ^{238}U alongside a fissile isotope, ^{235}U, in nuclear fuel leads to the production of fissile ^{239}Pu and ^{241}Pu, whereas incorporation of ^{232}Th as a fertile material in fuel produces fissile ^{233}U.[a]

Thermal reactors[b] fueled with uranium enriched[c] to 3% to 5% ^{235}U in the form of uranium dioxide (UO_2) comprise the dominant nuclear technology in use today in the United States and globally. Fission produces the buildup of neutron-absorbing isotopes (fission products), which dilute the neutron population below the level needed to sustain energy production and, thus, limit the length of time that the nuclear fuel can be used in the reactor for electricity generation. When that dilution point has been reached, the concentration of fissile isotopes, ^{235}U and $^{239-241}Pu$, has been depleted to less than 2% and the nuclear fuel must be replaced. The fuel removed from the reactor is referred to as *spent* or *used*, i.e., UNF. Nuclear fuel is typically kept in commercial thermal reactor for 3 to 6 years depending on

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[a] For brevity, the remainder of this paper will deal only with production and utilization of fissile Pu and not transmutation of Th.

[b] The term *thermal* refers to the average energy of the neutrons, which produce fission in these reactors. Thermal reactors include boiling water reactors (BWRs) and pressurized water reactors (PWRs), which are generally referred to collectively as light water reactors (LWRs), pressurized heavy water reactors (PHWRs), light-water-cooled graphite-moderated reactors (RBMKs), and gas-cooled graphite-moderated reactors (Magnox and AGRs).

[c] *Enrichment* is the process of increasing the fraction of ^{235}U in uranium above the fraction that occurs in nature.

the initial enrichment and period between refuelings (typically 18 to 24 months in the United States).

However, the fissile fuel isotopes are not fully consumed during this process. Most of the initial ^{235}U is fissioned, and if the remainder is separated from the neutron-absorbing fission products (reprocessed) and enriched, it can be recycled to produce nuclear energy. In addition, a substantial quantity of fertile ^{238}U is transmuted to fissile ^{239}Pu and ^{241}Pu, which can then fission to produce energy. Because of this continuous transmutation process, approximately one-third of the energy produced by nuclear fuel in commercial thermal reactors is derived from the fissioning of plutonium produced over the period of time that fuel spends in the reactor. Similar to the ^{235}U, only a fraction of the fissile Pu fissions prior to the fuel being removed from the reactor. If the remainder of fissile Pu is separated from the neutron-absorbing fission products (reprocessed), it too can be recycled to produce energy.

A nuclear fuel cycle that includes reprocessing and recycling is referred to as a *closed nuclear fuel cycle*.[d] A nuclear fuel cycle that excludes reprocessing and recycling is referred to as a *once-through* (or *open*) *nuclear fuel cycle*. Thermal reactors operated with a once-through nuclear fuel cycle access less than 1% of the total energy content in natural uranium (considering fissile and fertile isotopes). A closed nuclear fuel cycle, which involves reprocessing the fissile U and Pu from UNF and recycling (reusing) it as new fuel, has the potential to increase the utilization of the natural uranium resource for energy generation by two orders of magnitude. Recycling Pu from UNF in thermal reactors, as is currently done in France, represents an intermediate step between the once-through fuel cycle and closed fuel cycles being pursued by many countries.

A major historic driver for establishment of commercial nuclear power was that of natural resource utilization, which translated into security of nuclear fuel supplies and electricity production in the face of what was projected to be otherwise unsustainable growth in electricity demand in the third quarter of the 20th century. Growth of nuclear power was predicated on early adoption of nuclear fuel recycling and relatively rapid development and commercial deployment of advanced reactors capable of maximizing energy generated from the known supply of naturally occurring uranium.

However, several factors underlying establishment of nuclear fuel recycling in the United States changed in the last quarter of the 20th century. The growth rate of electricity demand, which had been between 5% and 10% per year since the end of World War II, decreased to

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[d] Rigorously, a closed fuel cycle includes not only reprocessing and recycling, but also ultimate waste disposal. This latter step is ignored in the discussion of this paragraph.

only about 1% per year. The depletion of economic uranium resources failed to materialize. To the contrary, new uranium ore reserves were discovered. Thus, the focus on resource utilization in the United States waned. President Jimmy Carter issued an executive order announcing a new federal policy to defer indefinitely the reprocessing of spent commercial nuclear fuel based on his concern about potential proliferation.[e] The number of nuclear power plants did not increase to the level projected because many orders of new U.S. nuclear power plants were cancelled due to a number of factors including the reduced rate of increase in electricity demand, construction and licensing delays (following regulatory changes in response to the 1979 Three Mile Island accident), escalating capital costs, and high interest rates.

A. Once-through fuel cycle

In 1983 the U.S. government passed the Nuclear Waste Policy Act, which required the government to take ownership of UNF and dispose of it in a deep geologic repository.[1] Although the act did not preclude reprocessing or recycling, it was clearly focused on a once-through fuel cycle in which UNF is disposed of as a waste without further processing. The once-through approach ignores and discards the tremendous energy value that remains in UNF.

As a result of uncertainty and continued delays by the federal government in taking ownership of UNF and implementing disposal, the current back end of the nuclear fuel cycle in the United States effectively involves continued storage of UNF for an indefinite period of time. Most UNF is stored in spent fuel pools at nuclear power plant sites under utility ownership. However, UNF inventories began to exceed spent fuel pool storage capacity in the 1980s, so there is a universal need for on-site (at nuclear power plant sites) storage of UNF in air-cooled, dry-storage casks. Nearly all utilities have implemented this option.

Thus, the current U.S. implementation of the once-through fuel cycle represents not so much the result of a deliberate national strategy or policy but rather the lack thereof. The *New York Times* has referred to this situation as "a state of perpetual indecision."[2] This has caused the commercial nuclear power industry to adapt to (1) incremental and sometimes dramatic shifts in government policy, (2) changing regulatory environment, (3) market

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[e] On April 7, 1977, President Carter issued an executive order announcing that his new policy would be to defer indefinitely the reprocessing of spent commercial nuclear fuel in the United States and close out work on the breeder reactor. President Carter was concerned that the production of separated plutonium during reprocessing would contribute to the proliferation of nuclear weapons by making it too easy for other nations to obtain plutonium for weapons. The action was intended to encourage other nations to foreswear reprocessing as well. Although President Reagan rescinded the Carter policy, the industrial momentum for reprocessing in the United States was gone. Companies were not willing to risk capital on this technology in light of possible changes in government policy.

conditions, and (4) public opinion. The UNF stored at nuclear power plant sites awaits a decision regarding its ultimate disposition.

From a technical perspective, any UNF in the once-through fuel cycle sent for permanent disposal represents the loss of a potential energy resource, primarily in the form of the remaining uranium and plutonium that can be recovered and recycled for electricity production. Moreover, sending UNF for direct disposal leaves the fuel in a containment configuration package that was designed for optimum reactor performance, not in a containment package designed for optimum waste disposal. These factors are addressed in national policies in France and Japan, which explicitly consider most of the components of UNF as a resource and recognize the advantages of packaging the high-level waste components in a form designed for storage and disposal. In fact, as recently as less than 10 years ago, approximately one-half of the UNF discharged annually around the world was slated for reprocessing.[3]

B. Thermal reactor recycle

Recycling of the U and Pu remaining in UNF has the potential to decrease partially the demand for natural U resources. Savings in demand for natural U up to 25% are possible using existing thermal reactor technology if U and Pu are recycled to the maximum extent; however, 10% to 20% is probably a more realistic range based on experience to date.[4]

Recycling of U and Pu as mixed uranium-plutonium oxide (MOX) fuel in thermal reactors is a commercially mature and proven technology. To date, this U-Pu recycling in thermal reactors continues to rely on the aqueous-based PUREX (Plutonium Uranium Redox EXtraction) chemical separation process developed and used in the United States for defense applications, although substantial improvements have been made over the intervening years to improve efficiency and reduce waste streams and environmental impacts. Moreover, newer evolutions of PUREX have been developed to address proliferation concerns.

Only one irradiation of MOX fuel is practiced currently, but studies have shown that continuous recycle could be done in thermal reactors for multiple centuries of time if necessary.[4–7] Recycling of U and Pu in thermal reactors without blending would not be practical due to the depletion of fissile isotopes.

C. Fast reactor recycle

Prior to 1977 when President Carter issued his executive order prohibiting reprocessing, plans were that U and Pu would eventually be recycled in advanced fast reactors.[f] Recycling in fast reactors has the potential to decrease the demand for natural uranium resources by up to two orders of magnitude. The degree to which fast reactors maximize nuclear fuel resource utilization depends on the conversion ratio of the reactor technology.[8,9] A conversion ratio of less than one indicates more fissile material is consumed than is produced; accordingly, such fast reactors are referred to as *burner reactors*. A conversion ratio of greater than one implies more fissile material is produced than is consumed; accordingly, these fast reactors are referred to as *breeder reactors*. Fast breeder reactor systems with high conversion ratios maximize resource amplification. A fast reactor optimized for breeding fissile fuel could increase natural U resource utilization to about 95%.

> With the current growth of nuclear energy use worldwide, and the uncertainty of how long the availability of low-cost natural uranium will continue, it is reasonable to continue improvement of advanced fast reactor design and to expect eventual widespread deployment. Furthermore, the transition period from the current situation of using exclusively thermal reactors for electricity production to a situation of using a mix of thermal and advanced fast reactors in the United States will take many decades of time after a decision is made to begin. Anticipating the need for this transition to occur as soon as the end of the 21st century, deployment of the required reprocessing and recycling technologies at an industrial scale should begin as soon as possible.

Section II References

[1] Nuclear Waste Policy Act of 1982, U.S. Public Law 97-425 (January 7, 1983).

[2] "Is the Solution to the U.S. Nuclear Waste Problem in France?" *The New York Times* (May 18, 2009).

[3] Harold F. McFarlane, "Reprocessing Nuclear Fuel," NRGY 00298 in *Encyclopedia of Energy*, Vol. 4, Elsevier, New York (2004).

[4] "Management of Recyclable Fissile and Fertile Materials," NEA No. 6107, OECD-NEA Publishing, Paris (2007).

[5] "Spent Fuel Reprocessing Options," TECDOC-1587, IAEA, Vienna (2008).

[ff] Here the word *fast* refers to the average energy of the neutrons that produce fission in these reactors. Fast is close to the energy at which new neutrons are emitted during the fission process.

[6] E. D. Collins et al., "Preliminary Multicycle Transuranic Actinide Partitioning—Transmutation Studies," ORNL/TM-2007/24, Oak Ridge National Laboratory, Oak Ridge, TN (2007).

[7] P. Murray et al., "Opportunities for the Multi-Recycling of Used MOX Fuel in the U.S.," in *Annual Waste Management Symposium 2012: Improving the Future in Waste Management*, Phoenix, AZ, February 26–March 1, 2012, pp. 911–921, Curran Associates, Red Hood, NY (2012).

[8] "Advanced Nuclear Fuel Cycles—Main Challenges and Strategic Choices," Electric Power Research Institute, Palo Alto, CA (2010).

[9] A. Waltar, D. Todd, and P. Tsvetkov, *Fast Spectrum Reactors*, Springer, New York (2012).

III. Status of Reprocessing Technology

The principal purposes of reprocessing UNF are to enable fuel recycle, waste reduction, and encapsulation in a form designed for long-term storage and disposal by separating reusable material from other components that either do not have further value or wastes that are determined to be undesirable for reuse for various reasons; for example, because they are highly radioactive fission products including those with high neutron-capture cross sections. In simplified terms reprocessing of UNF generally yields two types of products or materials: (1) fissile isotopes that have further value for reuse in nuclear fuel and (2) fission product isotopes and structural materials that are stored and disposed of as waste.[g]

There are numerous conceivable reprocessing approaches and variations on each, and many have been proposed and even demonstrated at some scale over the years. However, aqueous-based reprocessing and non–aqueous-based pyroprocessing[1,2] stand out as the most important and relevant in terms of their technical and/or commercial maturity. Accordingly this discussion focuses on these two technologies.

A. Aqueous-based reprocessing

Aqueous-based reprocessing is technically mature and is in commercial use in several countries. Aqueous reprocessing technologies are distinguished from other methods by their use of mechanical, chemical, and pyrochemical calcinations as a means to separate, recover, purify, and convert desirable constituents of UNF from an aqueous (water-based) acid solution produced by the dissolving UNF components. The aqueous separations

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[g] UNF also contains isotopes that have value for industrial or medical purposes. Most current commercial reprocessing does not separate these isotopes to be recycled, although it is technically possible to do so.

technologies in use today are direct descendants of the PUREX process initially developed in the United States for defense applications and are mainly used for UNF from thermal reactors.[1] The current fleet of commercial thermal reactors worldwide is generally fueled with oxide-based ceramic fuels, e.g., as uranium oxide (UOX) or MOX, contained in a zirconium-based alloy cladding. Commercial experience to date with reprocessing oxide fuel is exclusively with aqueous/PUREX-based processes.

Three commercial facilities using aqueous reprocessing technology have been built in the United States: the Nuclear Fuel Services (NFS) facility located near West Valley, New York; the General Electric (GE) Midwest Fuel Recovery Plant at Morris, Illinois; and the Allied General Nuclear Services (AGNS) plant at Barnwell, South Carolina.[3] The NFS facility was the first and only private plant in the United States to reprocess UNF. The facility used the PUREX process and had a design capacity of 300 metric tons heavy metal per year (tHM/yr). It operated commercially from 1966 to 1972 and reprocessed a total of 242.1 tHM commercial UNF.[4] The two other commercial reprocessing facilities were built but never operated. The GE facility (also 300 tHM/yr) was declared inoperable during preoperational testing in 1974. AGNS began construction of a 1,500 tHM/yr facility in 1970, and it was scheduled to begin operation in 1974. However, following delays in construction and licensing, construction still had not been completed nor had the facility been licensed in 1977 when President Carter issued his executive order to defer indefinitely all U.S. reprocessing of commercial UNF (see footnote f in Section II). AGNS terminated its reprocessing facility in 1981 due to concern that it would not be commercially practical with existing government restrictions. Since then no commercial reprocessing has been done in the United States, while other countries have gained extensive experience with industrial-scale reprocessing operations.

Worldwide experience with reprocessing UNF in both research/pilot/demonstration and commercial facilities from both thermal reactors and fast reactors is summarized in Table I.[5]

TABLE I

Worldwide Experience with UNF Reprocessing

	Thermal Reactor UNF	Fast Reactor UNF
Research/Pilot/Demonstration Reprocessing Facility	Japan (Tokai facility) China (at Lanzhou) France (Atalante) India (BARC, IGARC) Italy (at Rotondella) Belgium (Eurochemic facility) Germany (WAK) Russia (Khoplin, Bochvar) U.K. (Sellafield) U.S. (national laboratories)	Russia France Japan U.K. U.S. (Argonne National Laboratory and Oak Ridge National Laboratory)
Commercial Reprocessing Facility	France (Marcoule and La Hague facilities) U.K. (THORP and Magnox reprocessing facilities at Sellafield) Russia (RT-1 facility) U.S. (West Valley) India (Trombay, Tarappur, Kalpakkam)	France

It is notable that France, the United Kingdom, and Russia have reprocessed not only domestic UNF but also UNF from other countries. France has reprocessed UNF from Japan, Germany, Switzerland, Belgium, Italy, Spain, and the Netherlands; it is currently reprocessing UNF from Italy and the Netherlands.[5] The United Kingdom has reprocessed UNF from Japan, Germany, Switzerland, Belgium, Italy, the Netherlands, Sweden, and Canada.[5] Russia has reprocessed UNF from Ukraine.[5]

France has made a firm commitment to continue reprocessing UNF from commercial thermal reactors.[5] China, Japan, and India have announced plans to establish reprocessing of UNF from commercial thermal reactors.[6] South Korea and Taiwan have expressed their desire to reprocess UNF from commercial reactors in the future; however, both countries are currently prohibited from doing so by their nuclear trade agreements with the United States.[7] Belgium and Switzerland are currently considering the option of resuming reprocessing by a foreign supplier.[5]

The most recent tabulation of the world's reprocessing capacity published by the IAEA in 2008 reports a current worldwide capacity of 5,950 tHM/yr for UNF from thermal reactors.[6] Country capacities are reported as follows: France, 2,000 tHM/yr; India, 260 tHM/yr; Japan, 890 tHM/yr; Russia, 400 tHM/yr; and the United Kingdom, 2,400 tHM/yr. The United States is, of course, listed as having no capacity. More important is the tabulation in the same report of planned future reprocessing capacity. Country capacities (which include continued operation or shutdown of specific current capacities) are reported as follows: China, 825 tHM/yr; France, 2,000 tHM/yr; India, 560 tHM/yr; Japan, 90 tHM/yr[h]; Russia, 2,050 tHM/yr; and the United Kingdom, 1,000 tHM/yr. The total worldwide planned future reprocessing capacity is reported to be 6,525 tHM/yr. The United States is again listed as having no planned future reprocessing capacity.

B. Pyroprocessing

Pyroprocessing of UNF is based on a mature electrochemical technology used extensively in the metal refining industry. It has been demonstrated in several countries including the United States at a pilot scale. It is generally considered well suited for accommodating metal fuel from fast reactors. Advanced fast reactor fuels may be metal alloys, oxides, carbides, or nitrides. However, pyroprocessing has not yet been deployed on a commercial scale anywhere in the world for reprocessing of UNF from either thermal or fast reactors.

Only one pyroprocessing technique has been used in the United States on a pilot scale. This is the IFR (integral fast reactor) electrolytic process developed by Argonne National Laboratory. It was used for processing UNF from the EBR-II experimental fast reactor that ran from 1963 to 1994.[1] Because plans for commercial fast reactors were cancelled in the early 1980s,[i] no commercial reprocessing of fast reactor UNF has been initiated in the United States.

Research on pyroprocessing is being conducted in Russia, Japan, and South Korea with the major emphasis being on producing fuel for fast reactors.[1] The immediate goal of Russian research is to reprocess UNF in order to recycle Pu, neptunium, americium, and curium, as well as U to produce fuel for the BN-800 fast reactor. One goal of Japanese research is to recycle the same elements to produce fuel for future PRISM (Power Reactor Innovative Small Module) fast reactors. South Korea's research is being conducted with assistance and

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[h] The IAEA tabulation has an unexplained omission of the 800 tHM/yr capacity at Rokkasho.

[i] The primary reason no commercial fast breeder reactors were built (beyond the Fermi I demo unit) was that President Carter vetoed funding for the Clinch River Breeder Reactor in November 1977. Although Congress persisted in funding the project, and President Reagan revived it in 1981, the Senate denied any future funding on October 26, 1983. Industry was sufficiently discouraged that no further effort was mounted to develop commercial fast breeder reactors.

cooperation from the United States; however, as noted previously, South Korea's nuclear trade agreement with the United States currently prohibits commercial reprocessing.

Section III References

[1] "Processing of Used Nuclear Fuel," World Nuclear Association (updated August 2014); http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Processing-of-Used-Nuclear-Fuel.

[2] R. Herbst, P. Baron, and M. Nilsson, "Standard and Advanced Separation: PUREX Processes for Nuclear Fuel Reprocessing," in *Advanced Separation Techniques for Nuclear Fuel Reprocessing and Radioactive Waste Treatment*, K. Nash and G. Lumetta, Eds., pp. 141–175, Woodhead Publishing, Oxford (2011).

[3] "Status and Trends in Spent Fuel Reprocessing," TECDOC-1467, IAEA, Vienna (2005).

[4] Section I, Ref. 6.

[5] Unpublished communication from AREVA, e-mail from P. Murray to M. Buckner and W. Burchill (October 13, 2014).

[6] Section II, Ref. 5.

[7] "Nuclear Power in South Korea," World Nuclear Association (updated September 2014); http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/South-Korea; and "Nuclear Power in Taiwan," World Nuclear Association (updated July 2014); http://www.world-nuclear.org/info/Country-Profiles/Others/Nuclear-Power-in-Taiwan.

IV. Recycling of Plutonium

As has been previously stated, concern over the potential for proliferation of weapons due to availability of separated Pu has stopped plans in the United States for reprocessing of UNF and hence recycling of Pu in either thermal or fast reactors (see footnote f in Section II). However, as has also been previously stated, commercial nuclear power reactors using uranium fuel continue to produce substantial quantities of plutonium, several isotopes of which are, like ^{233}U and ^{235}U, fissile (usable as thermal or fast reactor fuel). In fact, as shown in Fig. 1, the fraction of fissions, i.e., the fraction of power produced, from U in a typical thermal reactor decreases continuously with fuel burnup, and the fraction of fissions from Pu increases and becomes dominant. At a burnup of about 30 GWd/tU (about three-fourths of average burnup) the power produced by Pu fissions is about equal to that produced by U fissions. Beyond this burnup, the majority of power is produced by Pu fissions. In a typical commercial thermal reactor, about one-third of the total energy, i.e., the electricity, is produced by fission of Pu.
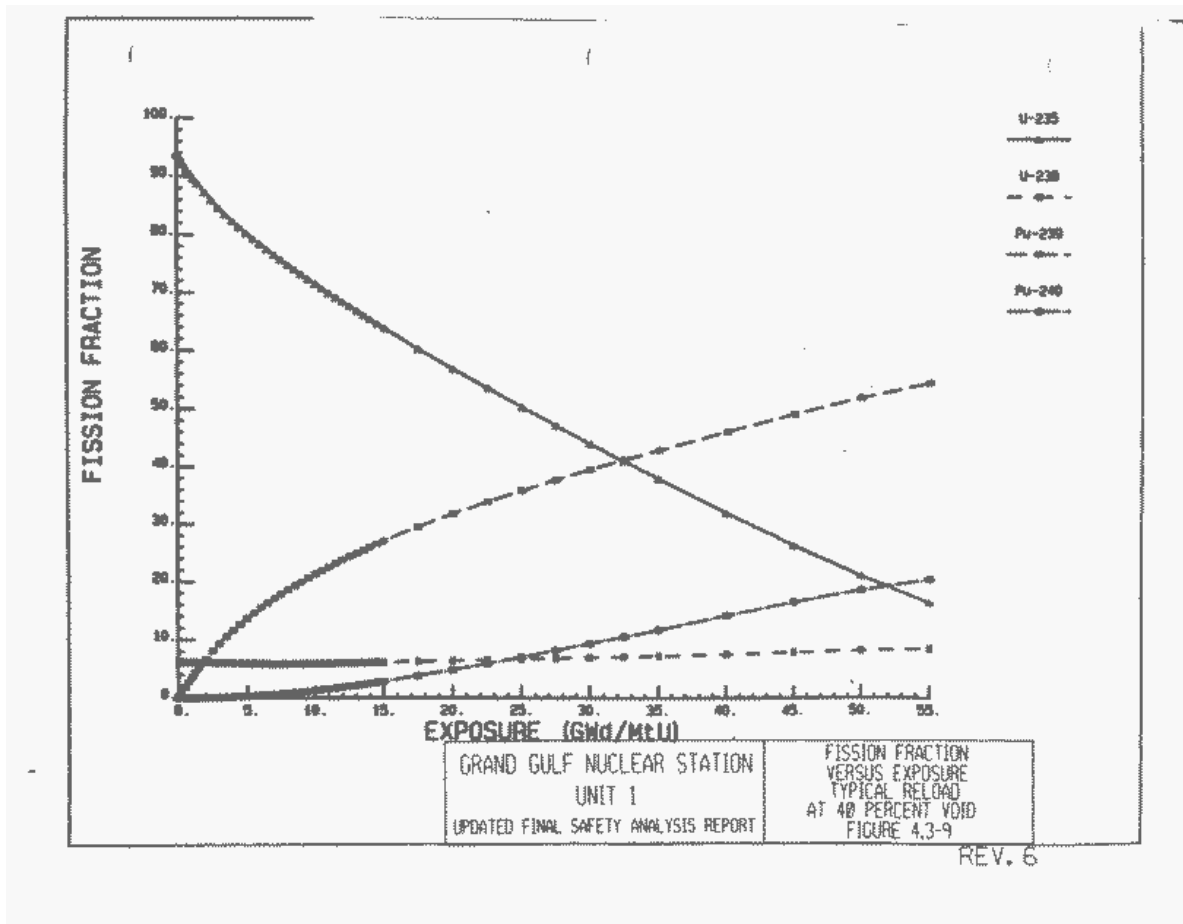
Fig. 1. Power production in a typical thermal reactor.

As nuclear technology developed and began to be commercialized in the 1950s and 1960s, it was generally expected that the unfissioned plutonium would be recovered from UNF and stored until it could be used as fast breeder reactor fuel. As the time for fast breeder reactor deployment became more distant, attention turned to recycling the unfissioned plutonium as fuel for thermal reactors. This plutonium recycling would require reprocessing of UNF and would also avoid the buildup of substantial plutonium inventories. Most of the world's experience using plutonium for thermal reactor fuel has been accumulated in Europe, where reprocessing used to be widespread and where it is still practiced in France for many of its 58 operating commercial power reactors.

Plutonium derived from reprocessing UNF is referred to as "reactor grade" because the long residence times of the fuel in a reactor led to the development of substantial amounts of ^{240}Pu (undesirable for nuclear weapons[j]) in addition to the fissile ^{239}Pu and ^{241}Pu isotopes.

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[j] Plutonium-240 has a relatively high spontaneous fission rate. Emission of a neutron at the wrong time during the nuclear detonation process leads to a premature explosion of much lower than desired magnitude (sometimes

Plutonium produced intentionally for use in nuclear weapons has much less [240]Pu and is referred to as "weapons grade"; however, it is also quite suitable for reactor fuel.[1]

In conventional fresh uranium fuel pellets, the uranium is slightly enriched to 3% to 5% in the fissile [235]U isotope[k] in order to attain and to maintain a self-sustaining chain reaction in the reactor core. Plutonium can be recycled for use in fresh thermal reactor fuel in the form of ceramic MOX fuel pellets. MOX fuel is predominantly comprised of UO_2 blended with plutonium dioxide (PuO_2). The UO_2 in current MOX fuel contains primarily [238]U and very little [235]U. The PuO_2 component of MOX fuel provides most of the fissile material. Typically, 5% to 10% of the heavy metal in thermal reactor MOX fuel is plutonium, with the remainder being uranium. Thus, MOX fuel is mechanically and chemically similar to conventional UO_2 fuel because the MOX fuel is predominantly UO_2.

A. Summary of European MOX fuel experience[2–5]

The first use of MOX fuel in a thermal reactor took place in the Belgian BR-3 pressurized water reactor (PWR) in 1963. As is standard practice today, BR-3 had a partial MOX fuel core (some of the fuel assemblies were MOX, while most assemblies were conventional UO_2 fuel). During the 1960s and 1970s MOX fuel demonstration programs were conducted in thermal reactors in several countries, including Germany and the United States. The United States never moved beyond MOX fuel lead test assembly programs, because of the U.S. government's decision to forego reprocessing due to proliferation concerns (see footnote f in Section II).[e]

Unlike the United States, several European countries did reprocess large amounts of UNF and, therefore, produced substantial amounts of separated plutonium. Accordingly, Germany began larger scale use of MOX fuel in 1981, and Switzerland, France, and Belgium followed suit. The Netherlands is about to commence MOX fuel use in the Borssele reactor. The United Kingdom is currently evaluating several options for using its 120 metric tons of separated reactor-grade plutonium, with MOX fuel for thermal reactors being the preferred option. France is the largest user of MOX fuel in the world today; 21 of its pressurized water reactors have reactor cores comprised of both MOX and UO_2 fuel assemblies.

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referred to as a "fizzle"). Only plutonium with less than 7% [240]Pu is considered weapons grade. Plutonium from recycled reactor fuel is typically 20% or greater [240]Pu.
[k] Heavy water reactors are thermal reactors that can use natural (unenriched) uranium in their fuel. This is due to the lack of parasitic neutron absorption in the heavy water coolant and moderator. Light-water-cooled and -moderated reactors (the vast majority of thermal reactors) must have enriched uranium fuel to produce a nuclear chain reaction.

American Nuclear Society

For decades Japan had plans to reprocess UNF and recover plutonium for use as MOX fuel in its current generation of thermal reactors. After years of delays obtaining the necessary state and local government approvals, Japanese reactors began to recycle significant quantities of MOX fuel (reprocessed in France) shortly before the 2011 Fukushima Daiichi reactor accidents. In January 2013, high-level waste vitrification was demonstrated successfully concluding preliminary operations at the Rokkasho 800 tHM/yr reprocessing plant.

Other than Europe and Japan, the only near-term prospects for use of MOX fuel in thermal reactors is in the United States as part of the surplus weapons plutonium disposition program. Russia has plans to dispose of its surplus weapons plutonium by using it as fuel for the BN-600 and BN-800 fast reactors in Beloyarsk. Both plutonium disposition programs are discussed further in the next subsection.

MOX fuel has compiled a good performance record in light water reactors, commensurate with that of conventional UO_2 fuel. As noted earlier, a MOX fuel pellet is similar mechanically and chemically to a UO_2 fuel pellet because both are comprised primarily of UO_2 in ceramic form. There are some differences, however, in the microstructure of the pellets that are traceable to the manufacturing process for MOX fuel. Plutonium dioxide does not conduct heat as well as uranium dioxide, so the thermal conductivity of MOX fuel is slightly lower than that of UO_2 fuel. For a given burnup, fission gas release tends to be higher for MOX fuel, producing a higher fuel rod internal pressure. These fuel pellet differences are relatively minor and are accommodated by the normal fuel and core design processes. Other than the fuel pellet material, MOX fuel assemblies are essentially identical to UO_2 fuel assemblies.

The biggest difference between the two fuel types is in their neutronic behavior, i.e., how the nuclear fuel material interacts with the neutrons that produce and sustain the chain reaction in the reactor. The primary fissile isotope in MOX fuel is ^{239}Pu, which has a significantly higher fission cross section (probability of absorbing a neutron) than the ^{235}U in UO_2 fuel. This leads to a lower thermal neutron population in MOX fuel assemblies, making thermal neutron absorbers (control rods, soluble boron) slightly less effective (i.e., they have a lower "worth"). As with differences in mechanical and chemical characteristics, the lower worth of neutron absorbers can be accommodated in the normal fuel and reactor design process. However, extra control rods have been added to some of the reactors using MOX fuel to provide additional shutdown margin, and some PWRs have transitioned to

operation with enriched soluble boron[l] to counteract the higher beginning-of-cycle boron concentrations otherwise required for reactors containing MOX fuel.

The lower thermal neutron flux in MOX fuel also produces steep thermal neutron flux gradients at the boundary between MOX fuel and UO_2 fuel assemblies. High power peaking associated with those gradients is addressed by lowering the plutonium concentrations in MOX fuel rods on the exterior of the MOX fuel assemblies. The lower thermal absorber worth in reactors with MOX fuel has the beneficial effect of making the reactors more stable neutronically and, therefore, less susceptible to xenon-induced transients following changes in power level. Although the thermal neutron population is markedly lower in reactors with MOX fuel, the fast neutron flux is only marginally higher with MOX fuel. This has the potential to increase the fast fluence (exposure to neutron bombardment) experienced by the metal reactor vessel. This effect has been evaluated and shown to be minor with respect to reactor vessel embrittlement, and it should not limit the usable lifetime of reactor vessels.

B. MOX fuel for excess weapons plutonium disposition (U.S.–Russian agreement)

The end of the Cold War brought with it the potential for large reductions in the nuclear weapons stockpiles of the United States and Russia. Considering the political and economic instability in Russia following the end of the Soviet Union, many nations expressed significant concern that Russian weapons-usable material (highly enriched uranium or plutonium) would fall into the wrong hands and lead to the proliferation of nuclear weapons. That concern led to a number of cooperative national security and nonproliferation initiatives, including a surplus weapons plutonium disposition program. In 2000 Russia and the United States signed an agreement stating that each country would dispose of 34 metric tons of its surplus weapons-grade plutonium. The current understanding is that the United States will convert the bulk of its surplus plutonium into MOX fuel and use that fuel in domestic commercial nuclear power reactors,[6] while Russia will convert its surplus plutonium into fuel for fast reactors and use the fuel in its BN-600 and BN-800 reactors.[7]

In the United States the construction of a dedicated facility for fabrication of MOX fuel from weapons-grade plutonium is well under way.[m] Construction of the facility on the

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[l] Soluble boron is dissolved into the coolant of PWRs to provide negative reactivity at the beginning of an operating cycle. The soluble boron is gradually removed during cycle operation to balance the reactivity loss from depletion of fissile material in the nuclear fuel. Typically reactors use natural boron of which around 20% is the ^{10}B isotope with strong neutron absorption capability. With enriched boron, the amount of ^{10}B is increased (e.g., to 30%) to provide the same negative reactivity worth with a lower dissolved boron concentration.

[m] Due to the radiotoxicity of plutonium, MOX fuel cannot be manufactured at a conventional uranium fuel fabrication plant. The plutonium oxide powder and MOX fuel pellet fabrication processes must be carried out in glove boxes.

Department of Energy's (DOE's) Savannah River Site in South Carolina began in 2007, and fuel fabrication operations were originally expected to begin around 2018. However, in early 2014 DOE announced it would put the MOX Fuel Fabrication Facility construction into "cold standby" as a result of concerns with program costs and would look for alternative means of accomplishing the plutonium disposition mission. The announcement prompted bipartisan concern in Congress and a lawsuit by the state of South Carolina. DOE then announced it would continue MOX Fuel Fabrication Facility construction through the end of fiscal year 2014, and South Carolina dropped its lawsuit. However, the long-term fate of the facility and the program remains unresolved.

As noted earlier, there is a substantial experience base in Europe with MOX fuel using plutonium recycled from thermal reactors. To supplement that experience base, a MOX fuel lead test assembly (LTA) program using diluted weapons-grade Pu was conducted at Catawba Nuclear Station Unit 1 in the United States between 2005 and 2008. The four MOX fuel LTAs were examined in the spent fuel pool after each cycle of use, and after the second cycle of MOX fuel LTA operation, five fuel rods from one of the assemblies were transported to the Oak Ridge National Laboratory (ORNL) for destructive examination in a hot cell. Based on the examination results, researchers concluded that MOX fuel fabricated using diluted weapons-grade plutonium performs acceptably in a U.S. thermal reactor environment.[n] The U.S. government intends to enter into an arrangement with one or more nuclear power plant operators to dispose of at least 34 metric tons of weapons-grade plutonium by converting it to MOX fuel and using the fuel in domestic commercial power reactors.[8]

Russia plans to dispose of its surplus weapons plutonium by converting it to fuel[o] for use in fast reactors. Russia has operated the 560-MWe BN-600 at Beloyarsk since 1980. The reactor currently uses highly enriched uranium fuel, but it will be converted to operate with a partial loading of MOX fuel as part of the plutonium disposition program. The BN-800 is a 750-MWe modernized and updated version of the BN-600, and it was designed to operate with a full MOX fuel core. The BN-800 started up in 2014, and the initial core contained some MOX fuel in addition to highly enriched uranium fuel. An industrial-scale plutonium fuel fabrication facility is planned.[9]

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[n] The original plan was for some of the MOX fuel assemblies to be used in a third cycle, but technical concerns not related to MOX fuel led to the decision to terminate irradiation after two cycles.
[o] Russia is considering the use of both MOX fuel and VIPAC (vibratory-compacted) fuel for its fast reactor plutonium fuel.

American Nuclear Society

Section IV References

[1] "Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options," National Academy of Sciences, Washington, DC (1995).

[2] "MOX Fuel Design Report," BAW-10238(NP), Rev. 1, Framatome ANP, Lynchburg, VA (May 2003).

[3] S. L. Anderson et al., "Mixed Oxide Fuel Effects on the Integrity of the McGuire and Catawba Reactor Vessels," paper presented at Fifth Topical Meeting on Spent Nuclear Fuel and Fissile Materials Management, Charleston, SC (September 18, 2002).

[4] S. P. Nesbit and J. L. Eller, "Basis for the Design of Reactor Cores Containing Weapons Grade MOX Fuel," paper presented at Advances in Nuclear Fuel Management III, Hilton Head, SC (October 2003).

[5] S. P. Nesbit et al., "Non-LOCA Safety Analysis for Operation with Weapons Grade MOX Fuel Lead Assemblies," paper presented at American Nuclear Society Winter Meeting 2003, New Orleans, LA (November 2003).

[6] "Utilization of Surplus Weapons Plutonium as Mixed Oxide Fuel," ANS Position Statement 47, American Nuclear Society, La Grange Park, IL (November 2009); htpp://www.ans.org/pi/ps.

[7] "Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation" (September 2000).

[8] "Summary Report on Postirradiation Examinations of MOX Fuel," ANP-10320NP, Rev. 0, Areva NP, Charlotte, NC (February 2012).

[9] S. P. Nesbit, "Nonproliferation Initiatives and Plutonium Disposition in Russia and the United States," *Nuclear News* (November 2, 2010).

V. MOX Fuel Fabrication

This section summarizes worldwide MOX fuel fabrication capacity and describes briefly the differences between a UO_2 fuel assembly fabrication plant and a MOX fuel assembly fabrication plant. There are several important inherent differences between plutonium oxide and UO_2 that must be addressed by facility design. First, plutonium oxide has significantly higher radiotoxicity than UO_2 if inhaled or ingested. Second, plutonium oxide has a significantly higher gamma radiation source than UO_2. Third, if stolen or diverted plutonium oxide can be used as the fissile material for a nuclear weapon without the additional enrichment that is required for UO_2. Specific features in plant design and operation accommodate these additional constraints.

A. Worldwide MOX fuel fabrication capacity

MOX fuel fabrication for thermal reactors has taken place in several countries, with plants in Belgium, Germany, the United Kingdom, and France exceeding 200 tHM/yr total capacity. While the German, Belgian, and U.K. facilities have now ceased production, several new units are currently under construction.

In 2006 the 40 tHM/yr Belgian plant closed, and in April 2007 the French MELOX plant was licensed for an increase in production from 145 to 195 tHM/yr. After the Sellafield MOX plant in the United Kingdom was downrated from 128 to 40 tHM/yr, the U.K. Nuclear Decommissioning Authority announced in August 2011 that it had reassessed the plant's prospects and would close it. Japan is planning to start up a 130 tHM/yr MOX plant at Rokkasho in 2015. A 70 tHM/yr MOX fabrication facility is being constructed at the Savannah River Site in the United States. It is scheduled for a 2016 start-up. MOX fabrication capacity projected in 2015 is summarized in Table II.

TABLE II

Forecast of Worldwide MOX Fuel Fabrication Capacities (tHM/yr) in 2015

	2009	2015
France, MELOX	195	195
Japan, Tokai	10	10
Japan, Rokkasho	0	130
Russia, Mayak, Ozersk (pilot)	5	5
Russia, Zheleznogorsk (fast reactor fuel)	0	10
United Kingdom, Sellafield	40	0
Total for thermal reactors	**250**	**340**

MOX fuel has also been used in fast reactors in several countries, particularly France, Japan, the United Kingdom, and the United States. It was first developed for this purpose, with experimental work being done in the United States, Russia, the United Kingdom, France, Germany, Belgium, and Japan. Today, Russia has two fast reactors in operation (BOR-60 and BN-600), mainly fueled with enriched uranium, and has long-term plans to build a new generation of fast reactors fueled by MOX. Operation of the world's largest fast reactor, the 800-MWe BN-800 at Beloyarsk in Russia reached criticality in June 2014. Several other projects are being developed in France and China. India plans to construct six 500-MWe fast reactors initially fueled with MOX or carbide fuel.

B. Fabrication description

The manufacturing process for MOX fuel is derived from the standard UO_2 fuel fabrication process with three main additions:

- Before oxide powder is pressed into pellets, U and Pu oxide powders are micronized and blended in order to produce a homogeneous mix with the required Pu content, typically between 5% and 10% (mean values).
- All steps in the process up to rod welding take place in shielded glove boxes in order to protect staff from contamination and radiation. The process is fully automated and remote controlled from a control room separate from the process rooms with manual intervention being required only for maintenance. This design ensures that individual radiation doses do not exceed occupational limits.
- The MOX fuel fabrication line is shielded, because the external radiation levels from plutonium are higher than those from uranium. Modern facilities incorporate automation to minimize the need for human access to the line and the resulting worker radiation exposure.

As in any nuclear plant with fissile material, MOX fuel fabrication plants are under a continuous system of safeguards. As an example, the MELOX plant in France is monitored by Euratom and IAEA through video cameras, independent automatic input/output measurements, sample analysis, annual inventory control, and the presence of permanent inspectors. The fact that plutonium can be used as the fissile material in nuclear weapons without additional enrichment requires more rigorous safeguards and security measures than uranium fuel fabrication facilities.

Environmental protection is also an integral part of the design and operations. Static material confinement using three physical barriers, combined with dynamic confinement

through a continuous ventilation system, provides protection for both staff and the environment. These additional measures are required due to the high radiotoxicity of plutonium.

MOX fuel fabrication facility operating experience demonstrates that such facilities can be operated in compliance with safety, safeguards, and security requirements. However, capital and operating costs for MOX fuel fabrication facilities are much higher than those of uranium fuel fabrication facilities due to the additional radiological and nonproliferation measures.

VI. Nonproliferation and Safeguards

The potential for proliferation from the nuclear fuel cycle has had a long history dating back to the original proposal by Acheson and Lilienthal in 1946 on international control of atomic energy. Particular attention has been given to the back end of the fuel cycle and reprocessing UNF in which plutonium is separated and may become potentially attractive for use in nuclear weapons. Proliferation resistance to diversion of materials or misuse of facilities may be achieved by *intrinsic* characteristics (e.g., material attractiveness or technical difficulty of achieving a proliferation objective) and by *extrinsic* features (e.g., international safeguards or other institutional measures). Proliferation risk is a broader topic than proliferation resistance in that it addresses the intent, capabilities, and strategies of the adversary in overcoming a given level of proliferation resistance. Further, proliferation resistance focuses on the host-state of a nuclear energy capability as the adversary, whereas physical protection addresses the security of the host-state peaceful nuclear energy capability against a subnational adversary.

During the past several years, much attention has been given to potential alternatives to the conventional PUREX process for separating plutonium in reprocessing. These alternatives (e.g., UREX, COEX, THOREX, and PYROX) sought either to identify materials mixtures that are less attractive to a potential proliferator or to develop alternative methods to separate fissile materials that are more technically difficult. Bathke et al.[1,2] examined the "attractiveness" of materials mixtures containing a wide range of nuclear materials associated with reprocessing processes for separation of the components of UNF. The primary conclusion of the work by Bathke et al.[1,2] was that "all fissile material needs to be rigorously safeguarded to detect diversion by a state, and provided with the highest levels of physical protection to prevent theft by sub-national groups." This is because the materials mixtures still contain separable plutonium.

Bari et al.[3] used the results of Bathke et al.[1,2] to evaluate the relative proliferation resistance of particular reprocessing separation technologies of interest: COEX, the UREX suite of

separation technologies, and pyroprocessing. While Bathke et al.[1, 2] considered material attractiveness as one measure of proliferation resistance, Bari et al.[3] assessed proliferation resistance against five additional measures: proliferation technical difficulty, proliferation cost, proliferation time, detection probability, and detection resource efficiency. Because the processes considered do not produce separated plutonium, the focus was on determining if any of these methods of separating UNF components could provide nonproliferation advantages compared with the PUREX technology. The finding was that only modest improvements could be obtained in increasing proliferation resistance over existing technologies and that these modest improvements apply primarily to subnational threats. Furthermore, several of the projected processes introduce challenges in measurement capabilities needed for safeguarding any large-throughput bulk-processing facility.

Because the nonproliferation differences are small between the alternative coprocessing technologies analyzed in Refs. 1, 2, and 3, any future selection of spent fuel reprocessing technologies should consider the benefits of a particular technology in enabling process efficiency, maturity, and cost effectiveness and the long-term management of nuclear waste.

Recently Collins and Ehinger[4] concluded that while plutonium has no *intrinsic* safeguards because it can be chemically separated, effective *extrinsic* engineered safeguards and physical protection can be obtained by using "safeguards-by-design" for new facilities. In this particular approach, it is proposed that all operations for UNF treatment be co-located and integrated within the same "recycle plant." By having all facilities co-located and integrated within the recycle plant, the inventory of plutonium "in process" can be minimized, and no large inventory of partially separated plutonium will be accumulated within or transported outside the recycle plant, except in the form of recycle fuel assemblies. This approach could enable cost-effective international safeguards to ensure that the host-state is not proliferating and could minimize the possibility of a subnational threat by having a small footprint for the recycle plant.

The IAEA defines[5] safeguards-by-design as "an approach whereby international safeguards requirements and objectives are fully integrated into the design process of a nuclear facility, from initial planning through design, construction, operation, and decommissioning." The United States and many other countries actively support and complement the IAEA approach to make international safeguards implementation more cost effective and to minimize its impact on nuclear operations without compromising the IAEA safeguards objectives. Reference 6 provides a good summary of both the safeguards-by-design concept for international safeguards as well as "security-by-design" to protect against subnational threats.

American Nuclear Society

In summary, a particular material mixture or a particular separation method that has intrinsic properties that substantially increase proliferation resistance cannot be identified because plutonium will always be present and, if diverted, can be chemically separated. However, by adhering to rigorous safeguards and physical protection objectives and requirements to protect against host-state and subnational threats, extrinsic methods can be applied to provide continuing assurance of acceptability of reprocessing and recycling of used nuclear fuel. Without fuel recycle, production of plutonium and the plutonium inventory will continue to grow and the resulting long-term proliferation risk will have to be addressed.

Section VI References

[1] C. Bathke et al., "An Assessment of the Attractiveness of Material Associated with a MOX Fuel Cycle from a Safeguards Perspective," in *Proc. 50th Annual Meeting of the Institute of Nuclear Materials Management,* Tucson, AZ, July 12–16, 2009.

[2] C. G. Bathke et al., "The Attractiveness of Materials in Advanced Nuclear Fuel Cycles for Various Proliferation and Theft Scenarios," in *Proc. Global 2009*, Paris, France (September 2009).

[3] R. Bari et al., "Proliferation Risk Reduction of Alternative Spent Fuel Processing Technologies," in *Proc. 50th Annual Meeting of the Institute of Nuclear Materials Management,* Tucson, AZ, July 12–16, 2009.

[4] E. Collins and M. Ehinger, "Nonproliferation Uncertainties: A Major Barrier to Used Nuclear Fuel Recycle in the United States," in *Proc. 52nd Annual Meeting of the Institute of Nuclear Materials Management*, Palm Desert, CA, July 17–21, 2011.

[5] "International Safeguards in Nuclear Facility Design and Construction," IAEA Nuclear Energy Series No. NP-T-2.8, International Atomic Energy Agency, Vienna (2013); http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1600_web.pdf.

[6] T. Bjornard et al., "Safeguarding and Protecting the Nuclear Fuel Cycle," *Nuclear News,* **55**, *12*, 76 (November 2010).

VII. Economic Considerations

Numerous studies have compared the cost of the current plan in the United States for direct disposal of UNF to the cost of fuel cycles that involve various degrees of current and future reprocessing and recycling. The Electric Power Research Institute (EPRI) conducted parametric economic analyses of four different U.S. fuel cycles using an OECD-NEA equilibrium model.[1] The analyses considered the following four fuel cycles:

- *Fuel Cycle 1:* once-through fuel cycle with direct disposal of UNF in a geologic repository
- *Fuel Cycle 2:* single recycle of Pu in thermal reactors with direct disposal of MOX UNF in a geologic repository
- *Fuel Cycle 3:* multiple recycle of Pu in fast reactors with no direct disposal of UNF in a geologic repository
- *Fuel Cycle 4:* multiple recycle of Pu and minor actinides in fast reactors with no direct disposal of UNF in a geologic repository.

EPRI's analyses determined fuel cycle cost as a function of the cost of uranium with parametric variation of the reprocessing cost. Other costs represented included:

- Front-end costs of uranium conversion, enrichment, and fuel fabrication
- UNF storage (for up to 50 years) and transport
- Reprocessing method (PUREX and advanced PUREX)
- Packaging and long-term storage for materials such as depleted uranium and reprocessed uranium
- Disposal of all wastes, including short-lived and long-lived waste, low- and intermediate-level waste, high-level waste, and UNF
- Operation of both thermal and fast reactors.

The analyses considered fuel cycle costs only, and did not consider the reactors' capital costs.

Detailed descriptions of these analyses and results comparing Fuel Cycle 1 to Fuel Cycles 2, 3, and 4 are presented in Refs. 2, 3, and 4, respectively. All of the results are summarized in Fig. 2 (Ref. 5). The results shown in this figure are summarized in Ref. 5 as follows:

> Fuel cycle costs for Fuel Cycle 2 are only lower than those for Fuel Cycle 1 when uranium prices are at the upper bounding values and PUREX reprocessing costs are at the lower end of values evaluated. Fuel cycle cost for Fuel Cycle 3 and Fuel Cycle 4 are lower than those for the Fuel Cycle 1 and Fuel Cycle 2 except when uranium prices are at lower bounding value and reprocessing prices are at the upper values for Fuel Cycle 3. While there appears to be a potential cost savings associated with an advanced fuel cycle, such as Fuel Cycle 3 or 4, compared to the once-through fuel cycle and single Pu Recycle in thermal reactors, much of the technology associated with fast reactors, MOX fabrication for fast reactors, and Advanced PUREX reprocessing has yet to be demonstrated on a commercial-scale basis. The technical and economic conditions for breakthrough of these advanced technologies are challenging and their performance will have to be consistent. Their competitiveness may be anticipated on paper, but it will have to be proven by experience. Thus, the costs associated with these advanced fuel cycle schemes should be regarded as highly speculative at this time.
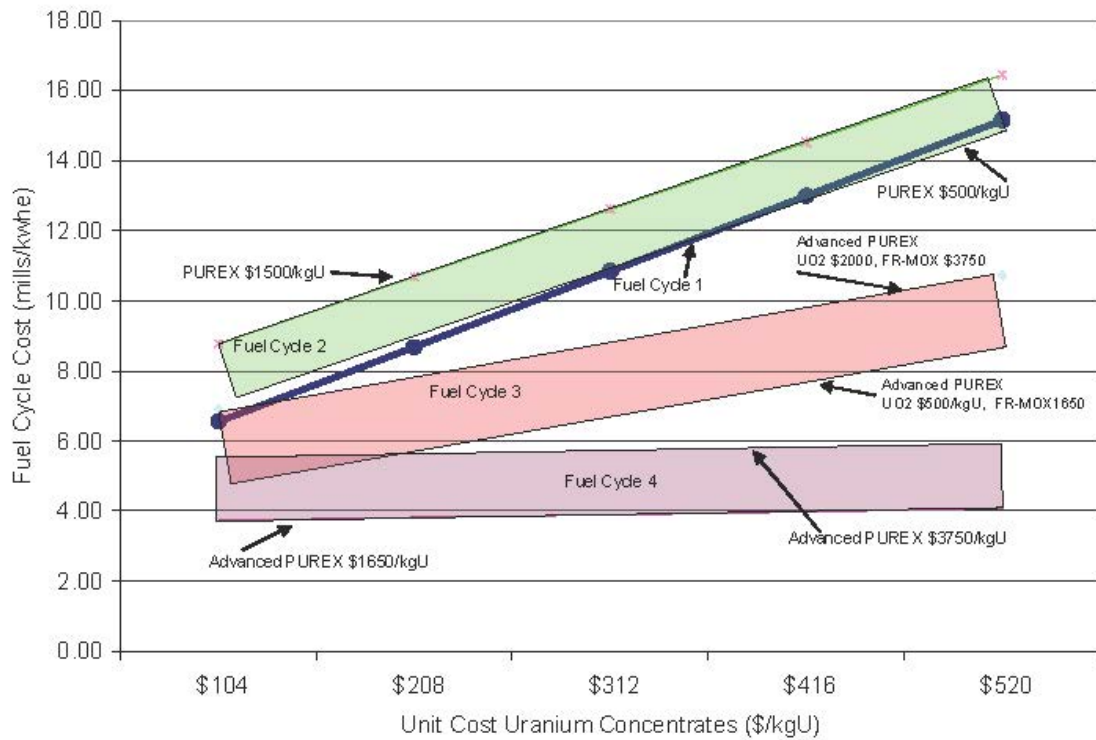
Fig. 2. Comparison of fuel cycle cost as a function of uranium ore concentrates and PUREX and advanced PUREX reprocessing.

The current (October 2014) cost of uranium concentrate reported by the World Nuclear Association[6] is about half of the lower end value represented in the EPRI study shown in Fig. 2. Simple extrapolation of the results shown in this figure to the current cost of uranium indicates that the cost for Fuel Cycle 1 (direct disposal of UNF) is less than that for Fuel Cycle 2 (single recycle of Pu in thermal reactors) for the range of reprocessing costs considered. The same extrapolation indicates that the cost for Fuel Cycle 1 is in the midrange of cost for Fuel Cycle 3 (multiple recycle of Pu in fast reactors) and at the upper end of the range of cost for Fuel Cycle 4 (multiple recycle of Pu and minor actinides in fast reactors). These extrapolations are tenuous given the significant uncertainties in the cost associated with advanced reactor fuel cycles as noted in the EPRI reports.

ORNL made a study of four different fuel cycles with differing degrees of product recycle from none to nearly full reuse of all actinides.[7] This study determined the levelized unit electricity cost (LUEC) broken down by major fuel cycle steps, including the cost of future reactors, for the four different fuel cycles. Fuel cycle costs were converted to LUEC units of

mills per kilowatt-hour[p] from estimates of costs in dollars per kilogram of heavy metal that were applied to the heavy metal equilibrium mass balance for a typical current Generation III+ thermal reactor (51,000 MWth-day/tHM fuel burnup). The results, summarized in Table III, show that the high capital and financing costs of the reactors dominate all other cost effects. This is true even though the capital and financing costs of fuel cycle facilities are higher than those for a single reactor, because the fuel cycle facility life-cycle costs are spread over a large fleet of reactors (typically 20 to 50 reactors). The entire fuel cycle costs are <15% of the overall costs for any option shown in the table, and the difference between the fraction of the LUEC of direct disposal and advanced recycle is relatively insignificant.

TABLE III

Fuel Cycle Cost Contributions to the Levelized Unit Electricity Cost Including Total Contribution Attributable to Reactor Financing, Construction, and Operations

Fuel Cycle Type	UO$_2$ Thermal Reactor, Direct Disposal[a]	UO$_2$/MOX Thermal Reactor, Current Recycle[b] (Pu only)	Thermal Reactor, Advanced Recycle (U, TRU,[c] Zr, and Some Fission Products)	Advanced Reactors, Breeder Recycle (U, Pu) Drivers Depleted U Blankets
Percentage of used fuel assembly mass in waste	100%	99%	5%	5–10%
Comparable levelized costs, mill/kWh[d,e]				
U ore/U enrichment/UO$_2$ fabrication/UO$_2$ credits[f]	4.3	3.9	3.5	0.1
Reactors[g]	49.5	49.5	49.5	59.0
Used fuel dry storage	0.3	0.0	0.0	0.0
Recycling[h]	0.0	3.4	3.9	5.0
Waste disposal	1.6	1.0	0.3	1.5
Total	**55.7**	**57.8**	**57.2**	**65.6**
Fuel cycle component of above costs	**6.2(11.1%)**	**8.3(14.4%)**	**7.7(13.5%)**	**6.6(10.1%)**

[a] This is similar to the present U.S. fuel cycle, although in the United States there is currently no active pursuit of disposal.

[b] This is analogous to the current fuel cycle in France and the planned approach in Japan.

[c] TRU is transuranic elements.

[d] Units of mill/kWh are equivalent to $/MWh.

[e] Fuel transportation and safeguards costs are similar for all fuel cycles.

[f] Credit for UO$_2$ assemblies displaced by MOX or recycle-derived UO$_2$ taken in this row. Costs to prepare the MOX or recycle-derived UO$_2$ assemblies are in the "recycling" row (U$_3$O$_8$ to UF$_6$ conversion also included).

[g] Assumes that capital costs for an nth-of-a-kind sodium-cooled fast reactor are 20% higher than those of a thermal reactor.

[h] Recycle cost includes (U, Pu) refabrication cost.
Material balance for thermal reactor based on 51,000 MWth-day/tHM reactor utilizing ~4.3% [235]U low-enriched uranium (equilibrium reloads). Material balance for sodium fast reactor "breeder" based on Japanese data. Unit fuel cycle costs from INL/EXT-09-15254.[8] Used fuel assembly mass in the first row includes heavy metal (fuel) plus cladding and hardware. Sodium fast reactor fuel is assumed to be stainless steel clad.

[p] One mill per kilowatt-hour is one-tenth of a cent per kilowatt-hour. The average production cost of generating nuclear electricity in the United States (no capital cost included) ranges was 2.55 cents per kilowatt-hour. The average retail price for electricity in the United States during the first 6 months of 2014 was 12.3 cents per kilowatt-hour. Note that transmission distribution and cost of capital are significant components of the retail electricity price, but are not included in the LUEC.

Numerous other studies of fuel cycle cost comparisons have been made by the Massachusetts Institute of Technology Nuclear Power Study,[9] the Organization for Economic Co-operation and Development,[1] nongovernmental organization reports and papers,[10, 11] a multilab study completed for the former Advanced Fuel Cycle Initiative program,[12] and another EPRI report.[13] In nearly all of these studies, the difference between recycle and direct disposal costs never exceeded 3 mill/kWh. For comparison, the fuel cycle costs for current thermal reactors have ranged from 4 to 10 mill/kWh. As shown in Table III, this is less than 20% of the overall LUEC range projected for new Generation III+ thermal reactors.

Differences in reactor technology have been shown to have greater effects on the LUEC than technology differences in the fuel cycle options. For example, in the LWR/fast burner reactor "symbiosis" study,[8] the projected higher life-cycle costs associated with fast reactors in comparison with those for LWRs (thermal reactors) had a greater effect on the LUEC than the difference in costs for "closed" versus "direct disposal" fuel cycles. The capital cost for a fast reactor was assumed to be 20% higher than that for LWRs, and operating and maintenance costs were assumed to be <2% higher in both the study represented by Table III (Ref. 7) and in the symbiosis study.[8]

Compared to the uncertainties of the capital costs of advanced reactors, geologic repositories, and fuel recycle facilities, the cost differences in the different fuel cycle choices appear to be relatively insignificant. Attributes of recycling such as reduction of nuclear waste sent to repositories; nonproliferation improvements through reduction and even elimination of plutonium; resource utilization improvement provided by breeder reactors/closed fuel cycles; and the time required to design, to construct, and to license industrial-scale fuel recycle facilities are more important considerations than the relatively small differences in non–reactor-related cost among fuel cycles.

The ORNL studies[7] consider mature (nth-of-a-kind), steady-state fuel cycles and address all capital and operating costs, including those of reactors and recycling facilities, assuming the facilities are optimized relative to one another in terms of capacity and throughput for sustained nuclear energy. However, investment decisions must consider not only this ideal end state but also the current state of commercial nuclear power. In the United States, for example, there are 100 operating thermal nuclear power reactors as of 2014, but no reprocessing facilities, no plutonium fuel fabrication facilities, no fast reactors, and no geologic repositories for commercial UNF. The reactors are in the middle of their operating lifetimes; most have only 20 to 30 years of operation remaining unless license renewals are allowed beyond 60 years; and many have been completely amortized.

Without construction of power reactors (either to replace existing ones or in addition to them), consideration of U.S. fuel cycle economics alone leads some to a conclusion not to make fuel cycle facility investments and instead to continue UNF storage for an indefinitely long time while awaiting an ultimate decision on UNF disposal. In contrast, the situation in France, where investments were made in reactors and reprocessing and MOX fuel fabrication facilities in the 1970s and are largely amortized, makes recycle a much more economically attractive option today. However, although economics are a very important consideration in fuel cycle choices, other considerations addressed in the next section indicate that it would be prudent to make fuel cycle facility investments now in order to realize benefits associated with recycle and to enable and to preserve options for the future.

Section VII References

[1] "Advanced Nuclear Fuel Cycles and Radioactive Waste Management," NEA No. 5990, OECD-NEA Publishing, Paris (2006).

[2] E. M. Supko and A. Machiels, "Nuclear Fuel Cycle Cost Comparison Between Once-Through and Plutonium Single-Recycling in Pressurized Water Reactors," EPRI 1018575, Electric Power Research Institute, Palo Alto, CA (February 2009).

[3] E. M. Supko, A. Machiels, and A. Sowder, "Nuclear Fuel Cycle Cost Comparison Between Once-Through and Plutonium Multi-Recycling in Fast Reactors," EPRI 1020660, Electric Power Research Institute, Palo Alto, CA (March 2010).

[4] E. M. Supko, A. Machiels, and A. Sowder, "Nuclear Fuel Cycle Cost Comparison Between Once-Through and Fully Closed Cycles," EPRI 1021054, Electric Power Research Institute, Palo Alto, CA (November 2010).

[5] E. M. Supko, A. Machiels, and A. Sowder, "Comparison of Fuel Cycle Costs for Alternative Fuel Cycles," paper presented at 2011 ANS International High-Level Radioactive Waste Management Conference, Albuquerque, NM , April 10–14, 2011.

[6] "Uranium Markets," World Nuclear Association (updated April 2014); http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Uranium-Markets.

[7] Section I, Ref. 5.

[8] D. E. Shropshire et al., "Advanced Fuel Cycle Economic Analysis of Symbiotic Light-Water Reactor and Fast Burner Reactor Systems," INL/EXT-09-15254, Idaho National Laboratory, Idaho Falls, ID (January 2009).

[9] "The Future of Nuclear Power, 2003; Update of the MIT 2003 Future of Nuclear Power," Massachusetts Institute of Technology, Cambridge, MA (2009).

[10] M. Bunn et al., "The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel," *Nuclear Technology*, **150**, 209–230 (June 2005).

[11] J. E. Parsons and G. DeRoo, "Nuclear Fuel Recycling: The Value of the Separated Transuranics and the Levelized Cost of Electricity," MIT Center for Energy and Environmental Policy Research, Cambridge, MA (September 2009).

[12] K. Williams and D. Shropshire, "Economic Analysis of 'Symbiotic' Light Water Reactor/Fast Burner Reactor Fuel Cycles Proposed as Part of the U.S. Advanced Fuel Cycle Initiative (AFCI)," in *Proc. Global 2009*, Paris, France (September 2009).

[13] E. M. Supko, A. Machiels, and A. Sowder, "Advanced Nuclear Fuel Cycles—Main Challenges and Strategic Choices," EPRI 1020307, Electric Power Research Institute, Palo Alto, CA (September 2010).

VIII. Advantages of Transitioning Now Toward Reprocessing/Recycling in the United States

The overarching reason to begin the transition toward reprocessing and recycling now is that implementation of industrial-scale reprocessing and recycling will require two to three decades after a decision has been made to implement it. Thus, beginning the transition now will produce commercial capability after the mid-21st century. The operating licenses of all commercial nuclear power reactors currently operating in the United States, including approved extended operating licenses, will expire in this time frame.[1] Beginning the transition toward reprocessing and recycling now will facilitate options to be considered, e.g., further license extensions,[q] replacements with thermal reactors designed for MOX recycling, or replacements with fast reactors. Conversely, deferring the development of industrial-scale facilities in favor of interminable research and development effectively forecloses the option of nuclear fuel recycling in the United States for decades to come.

Furthermore, the most recent projections by the DOE Energy Information Administration[2] forecast that electricity demand in the United States will increase 29% by 2040; minor extrapolation indicates a demand increase of about 40% by midcentury. Even just maintaining the current fraction of approximately 20% of electricity generated by nuclear energy[2] would require not only the replacements noted in the previous paragraph but also an additional 40% of capacity. Reducing greenhouse gas emissions significantly from current levels will require an even higher additional capacity of nuclear-generated electricity. Beginning the transition toward reprocessing and recycling now will facilitate the options listed in the previous paragraph to be considered for this growth.

A decision to allow and to begin transitioning to industrial-scale UNF reprocessing and recycling in the United States now would produce the following benefits:

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[q] Serious consideration is being given to extending the operating licenses of some currently operating reactors from 60 to 80 years in order to realize the benefits of reliable, emissions-free electricity generation with a relatively modest investment of capital.

1. Investment by private industry would be facilitated by a national energy policy and legal framework that supports a comprehensive and sustainable program for the U.S. nuclear fuel cycle, including reprocessing UNF for recycling and geologic disposal of long-term nuclear waste. This investment could be stimulated by partnerships among the private, government, and academic sectors. It could also be stimulated by a system of government loan guarantees similar to those currently being granted for new low-emission electricity generation capacity.[3]

2. The United States would benefit from application of its knowledge and operational experience from numerous pilot reprocessing and recycling programs, mostly conducted by the national laboratories, to the challenges that are presented by scaling up to industrial-scale, commercial operations rather than having this knowledge and experience further eroded by time. Both the U.S. government and industry could establish partnerships with counterparts in other countries that have accumulated nearly 40 years of valuable experience with commercial reprocessing to avoid mistakes others have made in order to reduce the time required to reach commercial operation.

3. The United States would be better enabled to ensure safe and secure implementation of reprocessing and recycling in those countries that choose to do so. The U.S. transition to reprocessing and recycling would provide "a place at the table" for discussions of issues of concern to the United States, particularly those involving assurance that U.S. nonproliferation goals are met. The transition could significantly improve U.S. relationships with other countries in the context of nuclear trade agreements.

4. Limitations on storage of UNF at commercial reactor sites would be relieved by transportation of UNF to a recycle plant, described in Section VI, which would typically have storage capacity for 10 times its annual processing inventory. Relocation of the UNF would also eliminate the economic uncertainty of indefinite on-site UNF storage. In addition, it could eventually remove the bases for many judicial proceedings between utilities and the U.S. government over the ultimate disposition of nuclear waste.

5. The volume of nuclear waste that must ultimately be disposed of in a geologic repository would be significantly reduced by reprocessing and recycling. This would reduce the required size of a repository and may obviate the need for additional repositories. Co-location of recycling facilities with thousands of good jobs would be an attractive economic incentive for siting a repository (which has proven to be quite a challenge). Furthermore, reprocessing allows separation of short-lived and long-lived nuclear waste isotopes, which increases the eventual waste disposal options beyond only deep geologic repositories.

6. An ongoing recycle program would reinvigorate important educational programs in radiochemistry and radiochemical separations, thereby enhancing the country's technological infrastructure.

7. Thousands of new U.S. jobs would be created in the transition to commercial reprocessing and recycling and later when building and operating these commercial facilities. In addition, as has been demonstrated at every commercial nuclear power plant location, these facilities provide huge economic benefits to their local communities, generally being one of the largest or the largest source of tax revenue in the community.

Section VIII References

[1] "Reactor License Renewal," U.S. Nuclear Regulatory Commission, Washington, DC; http://www.nrc.gov/reactors/operating/licensing/renewal.html.

[2] "Annual Energy Outlook 2014 with projections to 2040," DOE/EIA-0383, Energy Information Administration, U.S. Department of Energy, Washington, DC (2014).

[3] "Loan Programs Office," U.S. Department of Energy, Washington, DC; http://energy.gov/lpo/loan-programs-office.

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