The case for nuclear fuel recycling

A transition to used nuclear fuel reprocessing and recycling in the United States would best be started in the near future to allow for two to three decades for implementation and to facilitate the consideration of various options, including further nuclear power plant license extensions.

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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. Today, however, a primary driver for recycling UNF is to minimize the volume of radioactive waste requiring emplacement in a geologic repository and to package the high-level waste in an encapsulated form designed for optimum long-term storage and permanent disposal. This would help address public concerns about nuclear waste disposal. Other drivers for recycling are to ensure energy security and to avoid fuel market disruptions.

The Blue Ribbon Commission on America's Nuclear Future [1] concluded that it is premature to seek consensus on recycling UNF and instead recommended that it be stored pending the development of a geologic repository. The American Nuclear Society recognizes that interim storage of UNF for a limited time is necessary but is not a permanent solution to the problem of nuclear waste treatment and disposal. Moreover, ANS takes the position that there should be a national energy policy and a legal framework in place to support a comprehensive and sustainable program for the U.S. nuclear fuel cycle.

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 tHM reprocessed in the United States. [2,3]

Nuclear fuel cycle basics

A nuclear fuel cycle that includes reprocessing and recycling is referred to as a *closed nuclear fuel cycle* (which usually also includes ultimate waste disposal, but in this discussion does not). 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 fuel cycle access less than 1 percent of the total energy content in natural uranium (considering fissile and fertile isotopes).

A closed fuel cycle, which involves reprocessing the fissile uranium and plutonium 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.

In the last quarter of the 20th century, several factors pushed the United States away from plans to employ a closed fuel cycle to the current practice of an open fuel cycle. The growth rate of electricity demand, which had been between 5 and 10 percent per year since the end of World War II, decreased to only about 1 percent per year. A forecasted depletion of economic uranium resources failed to materialize, and new uranium ore reserves were discovered. On April 7, 1977, President Jimmy Carter issued an executive order announcing a new federal policy to defer indefinitely the reprocessing of spent commercial nuclear fuel in the United States, based on proliferation concerns.[a] Also, the number of nuclear power plants did not increase to the level projected because many orders for new U.S. nuclear power plants were canceled.

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a. This action was intended both to preclude other countries from having easy access to Pu for weapons production and to encourage other countries to foreswear reprocessing. In 1982, President Ronald Reagan rescinded Carter's policy, but the industrial momentum for reprocessing in the United States was gone, and companies were not willing to risk capital in light of potential future changes in policy.

	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/Karlsruhe) Russia (Khoplin, Bochvar) United Kingdom (Sellafield) United States (national laboratories)	Russia France Japan United Kingdom United States (Argonne National Laboratory and Oak Ridge National Laboratory)
Commercial Reprocessing Facility	France (Marcoule and La Hague facilities) United Kingdom (THORP and Magnox reprocessing facilities at Sellafield) Russia (RT-I facility) United States (West Valley) India (Trombay, Tarapur, Kalpakkam)	France

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. [4] Although the act did not preclude reprocessing or recycling, it was clearly focused on a once-through fuel cycle.

The current back end of the nuclear fuel cycle in the United States involves continued storage of UNF for an indefinite period of time. UNF is stored in spent fuel pools and in air-cooled, dry-storage casks at nuclear power plant sites awaiting a decision regarding its ultimate disposition. Within the last 10 years, however, approximately half of the UNF discharged annually around the world was slated for reprocessing. [5]

Thermal reactor recycle

Recycling of U and Pu as mixed uranium-plutonium oxide (MOX) fuel in thermal reactors is a commercially mature and proven technology. Essentially all recycled U-Pu is recovered using aqueous-based technologies based on the PUREX (Plutonium Uranium Redox EXtraction) process developed in the United States. Newer evolutions 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, if necessary. [6] Recycling of U and Pu in thermal reactors requires blending due to the depletion of fissile isotopes.

Fast reactor recycle

Prior to President Carter's executive order prohibiting reprocessing, plans were that U and Pu would eventually be recycled in advanced fast reactors ("fast" here refers to the average energy of the neutrons that produce fission in these reactors and is close to the energy at which new neutrons are emitted during the fission process). 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. [7] 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 percent from its value of about 1 percent in current thermal reactors without UNF recycle.

Reprocessing technology status

UNF reprocessing yields two types of products or materials: fissile isotopes that have further value for reuse in nuclear fuel, and fission product isotopes and structural materials that are stored and disposed of as waste. UNF also contains isotopes that have value for industrial or medical purposes, and although it is possible to separate these isotopes for recycling, most current commercial reprocessing does not do so. Aqueous-based reprocessing and non-aqueous–based pyroprocessing stand out as the most important and relevant in terms of their technical and/or commercial maturity. [8]

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. [9]

Three commercial facilities using aqueous reprocessing technology have been built in the United States: the Nuclear Fuel Services (NFS) facility located near West Valley, N.Y.; the General Electric Midwest Fuel Recovery Plant at Morris, Ill.; and the Allied General Nuclear Services plant at Barnwell, S.C. [10] The NFS facility was the first and only private plant in the United States to reprocess UNF, operating commercially from 1966 to 1972 using the PUREX process. [3] The two other commercial reprocessing facilities were built but never operated. Since 1972, 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 from both thermal reactors and fast reactors in research/pilot/demonstration and commercial facilities is summarized in Table I. [11]

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. The United Kingdom has reprocessed UNF from Japan, Germany, Switzerland, Belgium, Italy, the Netherlands, Sweden, and Canada, and Russia has reprocessed UNF from Ukraine.

France has made a firm commitment to continue reprocessing UNF from commercial thermal reactors. China, Japan, and India have announced plans to establish reprocessing of UNF from com-

mercial thermal reactors. South Korea and Taiwan have expressed their desire to reprocess UNF from commercial reactors in the future, but both are currently prohibited from doing so by their nuclear trade agreements with the United States. Belgium and Switzerland are currently considering the option of resuming reprocessing by a foreign supplier. The International Atomic Energy Agency publishes periodic reports on the world's current and planned reprocessing capacity. [8,10]

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

Only one pyroprocessing technique has been used in the United States on a pilot scale: the integral fast reactor electrolytic process developed by Argonne National Laboratory. It was used for processing UNF from the EBR-II experimental fast reactor, which operated from 1963 to 1994. [11] Because plans for commercial fast reactors were canceled in the early 1980s,[b] 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 on producing fuel for fast reactors. [11]

Recycling of plutonium

Plutonium can be recycled for use in fresh thermal reactor fuel in the form of ceramic MOX fuel pellets. MOX fuel is predominantly composed of uranium dioxide blended with plutonium dioxide. The PuO_2 component of MOX fuel provides most of the fissile material. Typically, 5 to 10 percent of the heavy metal in thermal reactor MOX fuel is plutonium, and the remainder is uranium. Thus, MOX fuel is mechanically and chemically similar to conventional UO_2 fuel because the MOX fuel is predominantly UO_2. The structure of MOX fuel assemblies is essentially identical to that of UO_2 fuel assemblies.

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b. No commercial fast breeder reactors were built, beyond the Fermi-1 demonstration unit, primarily because President Carter vetoed funding for the Clinch River Breeder Reactor in November 1977. Congress persisted in funding the project, and President Reagan revived it in 1981, but the Senate denied any further funding on October 26, 1983, discouraging industry from further efforts to develop commercial FBRs.

MOX performance characteristics

The performance of Pu as a fuel in a light-water reactor is demonstrated by all commercial nuclear power reactors because LWRs using uranium fuel produce substantial quantities of plutonium, several isotopes of which—such as U-233 and U-235—are fissile, and hence can fission in the LWR. As fuel burnup increases, more and more of the fissions occur in plutonium rather than uranium. In a typical commercial thermal reactor, about one-third of the total energy is produced by the fissioning of Pu.

MOX fuel has compiled a good performance record in LWRs, commensurate with that of conventional UO_2 fuel, but there are some differences: The thermal conductivity of MOX fuel is slightly lower than that of UO_2 fuel, and fission gas release tends to be higher for MOX fuel, producing a higher fuel rod internal pressure. The differences between conventional UO_2 and MOX fuel pellets are relatively minor, however, and are accommodated by the normal fuel and core design processes.

The biggest difference between the two fuel types is their neutronic behavior. The primary fissile isotope in MOX fuel, Pu-239, has a significantly higher fission cross section than the U-235 in UO_2 fuel, leading to a lower thermal neutron population in MOX fuel assemblies, thereby making thermal neutron absorbers (control rods, soluble boron) slightly less effective (that is, they have a lower "worth"). The lower thermal absorber worth with MOX fuel has the beneficial effect of making the reactors more stable neutronically and less susceptible to xenon-induced transients following changes in power level. Extra control rods have been added to some reactors using MOX fuel to provide additional shutdown margin, and beginning-of-cycle boron concentrations are higher for reactors containing MOX fuel. Thus, these neutronic differences are accommodated in the normal fuel and reactor design process.

The lower thermal neutron flux in MOX fuel also produces steeper thermal neutron flux gradients at the boundary between MOX fuel and UO_2 fuel assemblies. High power peaking associated with those gradients is managed in the fuel assembly design by lowering the plutonium concentrations in MOX fuel rods on the exterior of the MOX fuel assemblies.

Although the thermal neutron population is markedly lower in reactors with MOX fuel, the fast neutron flux is 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 will not limit the usable lifetime of reactor vessels.

International MOX fuel experience [12–15]

The first use of MOX fuel in a thermal reactor took place in the Belgian BR-3 pressurized water reactor in 1963. As is standard practice today, BR-3 had a partial MOX fuel core (some of the fuel assemblies were MOX, while most were conventional UO_2 fuel). During the 1960s and 1970s, MOX fuel demonstration programs were conducted in thermal reactors in several countries. Germany began larger-scale use of MOX fuel in 1981, and Switzerland, France, and Belgium followed suit. Japanese reactors began to recycle significant quantities of MOX fuel (reprocessed in France) shortly before the 2011 accident at Fukushima Daiichi. France is the largest user of MOX fuel in the world today, with 21 of its PWRs having reactor cores containing both MOX and UO_2 fuel assemblies.

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 (t) of separated reactor-grade plutonium, with MOX fuel for thermal reactors being the preferred option.

MOX fuel has also been used in fast reactors in several countries, particularly France, Japan, the United Kingdom, and the United States. 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 with MOX. Operation of the world's largest fast reactor, the 750-MWe BN-800 at Beloyarsk in Russia reached criticality in June 2014. Several other projects are being developed in France and China, and India plans to construct six 500-MWe fast reactors initially fueled with MOX or carbide fuel.

Excess weapons Pu disposition

In 2000, Russia and the United States signed an agreement stating that each country would dispose of 34 t of its surplus weapons-grade plutonium. The current understanding is that the United States will convert the bulk of its surplus Pu into MOX fuel and use that fuel in domestic commercial nuclear power reactors, while Russia will convert its surplus Pu into fuel for fast reactors and will use the fuel in its BN-600 and BN-800 reactors. [16]

A MOX fuel lead test assembly program using diluted weapons-grade Pu was conducted successfully from 2005 to 2008 at Unit 1 of the Catawba nuclear station in the United States, as demonstrated by poolside and hot cell post-irradiation examinations after the second cycle. [17] 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.

TABLE II: WORLDWIDE MOX FUEL FABRICATION CAPACITIES (tHM/yr) IN 2009 AND 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	60
United Kingdom: Sellafield	40	0
Total for thermal reactors	**250**	**400**

Therefore, the Department of Energy began construction of the Mixed Oxide Fuel Fabrication Facility (MFFF) at the Savannah River Site in South Carolina in 2007, and fuel fabrication operations were originally expected to begin around 2018. Due to the radiotoxicity of Pu, MOX fuel cannot be manufactured at a conventional U fuel fabrication plant, and pellet fabrication must be carried out in gloveboxes. Although construction of the MFFF presently continues, with another $340 million authorized on November 25, 2015, the fate of the facility and of the program remains to be determined due to government concerns over cost.

Russia plans to dispose of its surplus weapons plutonium by converting it to fuel (with the use of both MOX and VIPAC, or vibratory-compacted, fuel being considered) for use in fast reactors. Russia has operated the 560-MWe BN-600 at Beloyarsk since 1980. The reactor currently uses high-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 HEU fuel. An industrial-scale plutonium fuel fabrication facility is planned. [18]

MOX fuel fabrication

MOX fuel fabrication for thermal reactors has taken place in Belgium, Germany, the United Kingdom, and France. While the German, Belgian, and U.K. facilities have now ceased production, several new units are currently under construction. MOX fabrication capacity in 2009 and in 2015 is summarized in Table II. [19]

Inherent differences between PuO_2 and UO_2 that must be addressed by MOX facility design include PuO_2's significantly higher radiotoxicity if inhaled or ingested and its higher gamma radiation source, as well as its potential for use as the fissile material for a nuclear weapon without the additional enrichment required for UO_2.

Specific plant design features and operation accommodate these additional constraints.

The manufacturing process for MOX fuel is derived from the standard UO_2 fuel fabrication process with the following three main additions:
■ U and Pu oxide powders are micronized and blended to produce a homogeneous mix with the required Pu content, typically between 5 and 10 percent, before being pressed into pellets.
■ All steps in the process up to rod welding take place in shielded gloveboxes in order to protect staff from contamination and radiation.
■ A MOX fuel fabrication line is shielded because the external radiation levels from plutonium are higher than those from uranium.

Nonproliferation, safeguards

Alternatives to the PUREX process intended to be made less attractive to a proliferator by involving methods to separate fissile materials that are more technically difficult are UREX, COEX, THOREX, and PYROX. Bathke, et al., [20,21] examined the "attractiveness" of materials mixtures containing a wide range of nuclear materials associated with reprocessing. Bathke's conclusion 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 subnational groups." This is because the materials mixtures still contain separable plutonium.

Bari, et al., [22] used the results of Bathke, et al., to evaluate the relative proliferation resistance of particular processes that do not produce separated plutonium: COEX, the UREX suite of separation technologies, and pyroprocessing. Bari considered five measures: proliferation technical difficulty, proliferation cost, proliferation time, detection probability, and detection resource efficiency. There were only modest improvements over existing technologies, and these improvements apply primarily to nonstate actors. Furthermore, several of the processes introduce challenges in measurement

capabilities needed for safeguarding any large-throughput bulk-processing facility.

Collins and Ehinger [23] concluded that sufficient engineered safeguards and physical protection could be obtained using "safeguards by design." In this approach, all operations for UNF treatment would be colocated and integrated within the same "recycle plant." Thus, the inventory of plutonium "in process" could be minimized, and no large inventory of partially separated plutonium would be accumulated within or transported outside the plant. This approach would ensure that a 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 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." [24] Bjornard, et al., provides a good summary of the safeguards-by-design concept for international safeguards, as well as security by design to protect against subnational threats. [25]

Economic considerations

Numerous studies have compared the cost of fuel cycle options. The Electric Power Research Institute (EPRI) conducted parametric economic analyses of four different U.S. fuel cycles using an OECD Nuclear Energy Agency equilibrium model. [26] 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. [27,28,29] The analyses considered fuel cycle costs only, and did not consider the reactors' capital costs (see Fig. 1). [30]

The cost of uranium concentrate reported in October 2014 by the World Nuclear Association [31] is about half of the lower end value represented in the EPRI study shown in Fig. 1. Simple extrapolation of the results shown in Fig. 1 to this cost indicates that the cost for Fuel Cycle 1 is less than that for Fuel Cycle 2 for the range of reprocessing costs considered. The same
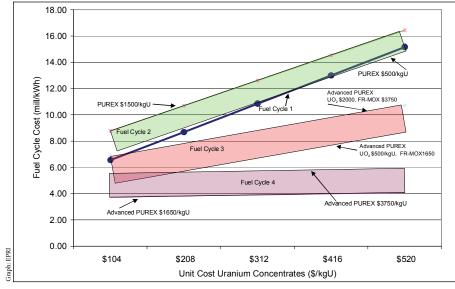
Fig. 1. Comparison of fuel cycle cost as a function of uranium ore concentrates and PUREX and advanced PUREX reprocessing.

extrapolation indicates that the cost for Fuel Cycle 1 is in the midrange of cost for Fuel Cycle 3 and at the upper end of the range of cost for Fuel Cycle 4. These extrapolations are tenuous given the significant uncertainties in the cost associated with advanced reactor fuel cycles noted in the EPRI reports.

Oak Ridge National Laboratory (ORNL) conducted a study of four different fuel cycles with differing degrees of product recycle, from none to nearly full reuse of all actinides. [32] 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[c] 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.

Numerous other studies of fuel cycle cost comparisons have been made by the Massachusetts Institute of Technology Nuclear Power Study, [34] the Organization for Economic Cooperation and Development, [35] nongovernmental organization reports and papers, [36] a multilab study completed for the former Advanced

Fuel Cycle Initiative program, [37] and another EPRI report. [38] 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 percent 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, [33] 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 percent higher than that for LWRs, and operating and maintenance costs were assumed to be less than 2 percent higher in both the study represented by Table III and in the symbiosis study.

The ORNL studies [32] 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 that the facilities are optimized relative to one another in terms of capacity and throughput for sustained nuclear energy. Investment decisions, however, must consider the current state of commercial nuclear power. In the United States, for example, there are 99 operating thermal nuclear power reactors as of the end of 2015, 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 the construction of new power reactors (either to replace existing ones or in addition to them), consideration of U.S. fuel cycle economics alone leads some to decide 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.

Transitioning to recycling

The overarching reason to begin the transition toward reprocessing and recycling now is that industrial-scale reprocessing and recycling will require two to three decades for implementation after a decision has been made. 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. [39] Beginning the transition toward reprocessing and recycling now will facilitate options to be considered, such as further license extensions (to 60 to 80 years, with a relatively modest capital investment), replacements with thermal reactors designed for MOX recycling, or replacements with fast reactors.

Furthermore, the most recent projections by the DOE's Energy Information Administration [40] forecast that electricity demand in the United States will increase 24 percent by 2040; minor extrapolation indicates a demand increase of about 33 percent by mid-century. Even just maintaining the current fraction of approximately 20 percent of electricity generated by nuclear energy [40] would require not only the replacements noted in the previous paragraph but also an additional 40 percent 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 and will provide the following benefits:

1. A national energy policy and legal framework that support a comprehensive and sustainable program for the U.S. nuclear fuel cycle would stimulate private investment. [41]

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

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	UO₂ Thermal Reactor, Direct Disposal[a]	UO₂/MOX Thermal Reactor, Current Recycle[b] (Pu only)	Thermal Reactor, Advanced Recycle (U, TRU,[c] Zr, and Some Fission	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/UO₂ fabrication/ UO₂ 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 UO₂ assemblies displaced by MOX or recycle-derived UO₂ taken in this row. Costs to prepare the MOX or recycle-derived UO₂ assemblies are in the "recycling" row (U₃O₈ to UF₆ 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% U-235 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.[33] 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.

2. Knowledge and operational experience from pilot reprocessing and recycling programs, mostly conducted by the national laboratories, would avoid becoming completely dependent on foreign experience.

3. Transition to reprocessing and recycling would provide "a place at the table" for discussions of U.S. nonproliferation goals and would significantly improve U.S. relations with other countries in the context of nuclear trade agreements.

4. Limitations on the storage of UNF at commercial reactor sites would be relieved by the transporting of UNF to a recycle plant, described earlier (under the subhead "MOX fuel fabrication").

5. The volume of nuclear waste that must ultimately be disposed of in a geologic repository would be significantly reduced. This would reduce the required size of a repository and could obviate the need for additional repositories.

6. An ongoing recycle program would reinvigorate important educational programs in radiochemistry and radiochemical separations.

7. Thousands of new U.S. jobs would be created.

References

1. Blue Ribbon Commission on America's Nuclear Future, *Report to the Secretary of Energy* (Jan. 26, 2012).

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

3. *Plutonium and 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 (Feb. 26, 2001).

4. Nuclear Waste Policy Act of 1982, U.S. Public Law 97-425 (Jan. 7, 1983).

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

6. P. Murray, et al., *Opportunities for the Multi-Recycling of Used MOX Fuel in the U.S.*, Annual Waste Management Symposium 2012: Improving the Future in Waste Management, Phoenix, Ariz., February 26–March 1, 2012, pp. 911–921, Curran Associates, Red Hook, N.Y. (2012).

7. *Advanced Nuclear Fuel Cycles—Main Challenges and Strategic Choices*, Electric Power Research Institute, Palo Alto, Calif. (2010).

8. *Spent Fuel Reprocessing Options*, TECDOC-1587, IAEA, Vienna (2008).

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

10. *Status and Trends in Spent Fuel Reprocessing*, TECDOC-1467, IAEA, Vienna (2005).

11. *Processing of Used Nuclear Fuel*, World Nuclear Association (updated Aug. 2014); <www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Processing-of-Used-Nuclear-Fuel>.

12. *MOX Fuel Design Report*, BAW-10238(NP), Rev. 1, Framatome ANP, Lynchburg, Va. (May 2003).

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

14. 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, S.C. (Oct. 2003).

15. S. P. Nesbit, et al., "Non-LOCA Safety Analysis for Operation with Weapons Grade MOX Fuel Lead Assemblies," paper presented at the 2003 American Nuclear Society Winter Meeting, New Orleans, La. (Nov. 2003).

16. *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* (Sept. 2000).

17. *Summary Report on Postirradiation Examinations of MOX Fuel*, ANP-10320NP, Rev. 0, Areva NP, Charlotte, N.C. (Feb. 2012).

18. S. P. Nesbit, "Nonproliferation Initiatives and Plutonium Disposition in Russia and the United States," *Nuclear News,* Vol. 53, No. 12, p. 70 (Nov. 2010).

19. *Mixed Oxide (MOX) Fuel*, World Nuclear Association (updated Dec. 2014); <www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Mixed-Oxide-Fuel-MOX/>.

20. C. Bathke, et al., "An Assessment of the Attractiveness of Material Associated with a MOX

Fuel Cycle from a Safeguards Perspective," Proc. 50th Annual Meeting of the Institute of Nuclear Materials Management, Tucson, Ariz., July 12–16, 2009.

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

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

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

24. *International Safeguards in Nuclear Facility Design and Construction*, IAEA Nuclear Energy Series No. NP-T-2.8, International Atomic Energy Agency, Vienna (2013); <www-pub.iaea.org/MTCD/Publications/PDF/Pub1600_web.pdf>.

25. T. Bjornard, et al., "Safeguarding and Protecting the Nuclear Fuel Cycle," *Nuclear News,* Vol. 53, No. 12, p. 76 (Nov. 2010).

26. *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, NEA No. 5990, OECD-NEA Publishing, Paris (2006).

27. 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, Calif. (Feb. 2009).

28. 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, Calif. (Mar. 2010).

29. 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, Calif. (Nov. 2010).

30. 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, N.M., Apr. 10–14, 2011.

31. *Uranium Markets*, World Nuclear Association (updated February 2015); <www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Uranium-Markets>.

32. 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, Tenn. (Apr. 2010).

33. 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, Idaho (Jan. 2009).

34. *The Future of Nuclear Power (2003),* and *Update of the MIT 2003 Future of Nuclear Power*, Massachusetts Institute of Technology, Cambridge, Mass. (2009).

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

36. 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, Mass. (Sept. 2009).

37. 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)," Proc. Global 2009, Paris, France (Sept. 2009).

38. 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, Calif. (Sept. 2010).

39. "Reactor License Renewal," U.S. Nuclear Regulatory Commission, Washington, D.C.; <www.nrc.gov/reactors/operating/licensing/renewal.html>.

40. *Annual Energy Outlook 2015 with Projections to 2040*, DOE/EIA-0383(2015), Energy Information Administration, U.S. Department of Energy, Washington, D.C. (Apr. 2015).

41. Loan Programs Office, U.S. Department of Energy, Washington, D.C.; <http://energy.gov/lpo/loan-programs-office>. **NN**