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Objectives, Strategies, and Challenges for the Advanced Fuel Cycle Initiative

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ABSTRACT

This paper will summarize the program objectives, fuel cycle strategies, and key chemical separation challenges for the Advanced Fuel Cycle Initiative (AFCI). The major objectives are as follows:

- Waste management - defer the need for a second geologic repository for a century or more,
- Proliferation resistance - be more resistant than the existing PUREX separation technology or uranium enrichment,
- Energy sustainability - turn waste management liabilities into energy source assets to ensure uranium ore resources do not become a constraint on nuclear power, and
- Systematic, safe, and economic management of the entire fuel cycle.

There are four major strategies for the disposal of civilian spent fuel:

- Once-through - direct disposal of all discharged nuclear fuel,
- Limited recycle - recycle transuranic elements once and then direct disposal,
- Continuous recycle - recycle transuranic elements repeatedly, and
- Sustained recycle - same as continuous except depleted uranium that has been previously discarded is also recycled.

The key chemical separation challenges stem from the fact that the components of spent nuclear fuel vary greatly in their influence on achieving program objectives.

- Separate uranium with sufficient purity that it qualifies for near-surface burial, rather than geologic disposal. There is no set target for separation recovery of uranium from other components.
- Separate the transuranic elements - plutonium (Pu), neptunium (Np), americium (Am), curium (Cm). Over 99.5% of plutonium, neptunium, and americium must be recovered from waste destined for geologic disposal and recycled in reactors. At the present time, curium recycle provides relatively little benefit; curium can be recycled in thermal reactors (with accumulated increases in radiation levels in separation and fuel fabrication plants), held for recycle in fast reactors, held until curium decays into plutonium, or sent to geologic disposal.
- Separate cesium and strontium with sufficient purity that they will quality for near-surface burial after interim storage. It appears that over 99% of the cesium and strontium should be recovered from waste destined for geologic disposal.
- It may become important to separate long-lived fission products, such as technetium-99 and iodine-129, from waste destined for geologic disposal to enable their transmutation in reactors.

INTRODUCTION

The AFCI program addresses critical national needs associated with past, present, and future use of nuclear energy. First, the AFCI is developing technologies that have the potential to allow more efficient disposal of spent fuel and high-level waste, thus delaying into the next century the need for additional geologic repositories for the waste from future nuclear power plants. Second, the AFCI fuel cycle would incorporate more proliferation-resistant technologies and designs than employed in current international practice, would reduce the inventory of weapons-usable material, and would eventually reduce the need for uranium enrichment. Third, the AFCI investigates fuel cycles that recover most of the energy content in spent nuclear fuel, in conjunction with the complementary Generation IV Nuclear Energy Systems Initiative. While accomplishing these objectives, the AFCI program also seeks to ensure competitive economics and excellent safety for the entire nuclear fuel cycle.

The AFCI's fundamental objective is to provide technology options that would enable long-term growth of nuclear power while improving sustainability and energy security. As a prime example, the AFCI provides an alternative to building multiple geologic repositories while still supporting an expanding role for nuclear energy. In short, that alternative is reduce, reuse, and recycle.

The next section defines the four major fuel cycle strategies being analyzed. Next, each of the objectives is discussed. For each objective, three questions are answered: (1) what does the objective mean, (2) how well do each of the strategies defined below meet the objectives, and (3) what are the key separation challenges? The overall assessment is summarized at the end.

POTENTIAL FUEL CYCLE STRATEGIES

A strategy is a general approach to fuel management that encompasses a range of options with similar basic characteristics. A strategy identifies which materials are recycled (if any), the type of nuclear power plant, the type of spent fuel processing technology, and which materials go to geologic disposal. There are four primary strategies:

1. The current U.S. strategy is **once through** - all the components of spent fuel are kept together and eventually sent to a geologic repository. Depleted uranium, produced during enrichment of uranium to make fuel, is disposed in land burial sites. Currently, light-water-cooled power plants are used in the U.S.

2. The second strategy is **limited recycle**, recycling at least some transuranic elements once. Remaining transuranic elements and the long-lived fission products would go to geologic disposal. Uranium in spent fuel, depleted uranium, and short-lived fission products would be disposed in land burial sites in a form commonly called low-level waste. This strategy emphasizes use of current thermal light-water-cooled reactors and technology. However, thermal reactors with other coolants could also be used. The selection among thermal reactors is generally outside the scope of the AFCI program. For present purposes, there are two major fuel variants of the limited recycle strategy. The first is mixed-oxide fuel (MOX), in which transuranics are recycled by mixing them with uranium. The resulting fuel is similar from most separation and fabrication perspectives to existing uranium oxide fuel,

but the inclusion of uranium means that more transuranics are created as it is used. (There is still a next consumption of transuranics.) The second approach is inert matrix fuel (IMF), by which transuranics are recycled without uranium in the IMF. IMF uses other materials matrix, such as ZrO_2 or $MgO\text{-}ZrO_2$. IMF is therefore a bigger change from current separation and fabrication technologies, but offers the potential for more rapid consumption of transuranics.

3. The third strategy is **continuous recycle**, recycling transuranic elements from spent fuel repeatedly. Continuous recycle is more difficult than limited recycle and therefore more research, development, and deployments would be required. Uranium in spent fuel can be recycled or disposed. Essentially no transuranic elements would go to geologic disposal. Long-lived fission products would either go to geologic disposal or some could be transmuted in power plants. Key shorter-lived fission products would be separated, allowed to decay, and then disposed as low-level waste. This strategy would primarily use thermal reactors; however, a small fraction of fast reactors may be required. (Thermal reactors must sustain the fission process using fissile isotopes, primarily uranium-235, plutonium-239, and plutonium-241. Fast reactors can sustain the fission process using (to varying degrees) all uranium and transuranic isotopes.)

4. The fourth strategy is **sustained recycle**, which differs from continuous recycle primarily by enabling the recycle of depleted uranium to significantly extent fuel resources. This strategy would primarily use fast reactors, which allow the fission process to be sustained completely by recycled materials.

OBJECTIVE 1. Reduce the long-term environment burden of nuclear energy through more efficient disposal of waste materials.

What does the objective mean?

Under all strategies and scenarios, the United States will need a permanent geologic repository to deal with the relatively small quantity of radioactive wastes resulting from the operation of nuclear power plants. The geologic repository site at Yucca Mountain, Nevada, has the technical capability to accommodate all the U.S. commercial spent nuclear fuel that has been or will be generated by the current fleet of U.S. nuclear power plants. If all of these plants' lifetimes are extended 20 years, the projected cumulative spent fuel will be approximately 120,000 metric tonnes. While the statutory limit for Yucca Mountain is 70,000 metric tones, the Yucca Mountain Science and Engineering Report[1] explores options that would accommodate this higher amount.

Should a significant number of new nuclear plants be built in the future, the United States would need to construct additional repositories to address the additional wastes or begin treat spent fuel to reduce the weight, volume, long-term heat output, and radiotoxicity of nuclear waste. From the specific perspective of long-term heat output, figure 1 shows the required increase in repository capacity as a function of growth rate throughout this century. These increases must be met by either physical expansion of the first repository, by recycling, or by both. For example, if nuclear power continues throughout this century at no growth, level market share, or modest market gain (growth rates of 0.0%, 1.8%, or 3.2% per year respectively), then fuel discharged by 2100 would necessitate increases in geologic repository capacity of factors of 4, 9, or 22 to avoid the need for a second geologic repository. Some experts have suggested yet higher growth rates than these considered by AFCI, e.g., a group of the national laboratory directors[2] have suggested a nuclear market share by 2050 that translates into a growth rate of about 4.5% per year. If this is continued to 2100, a repository capacity improvement factor of 54 would be required to avoid a second repository.

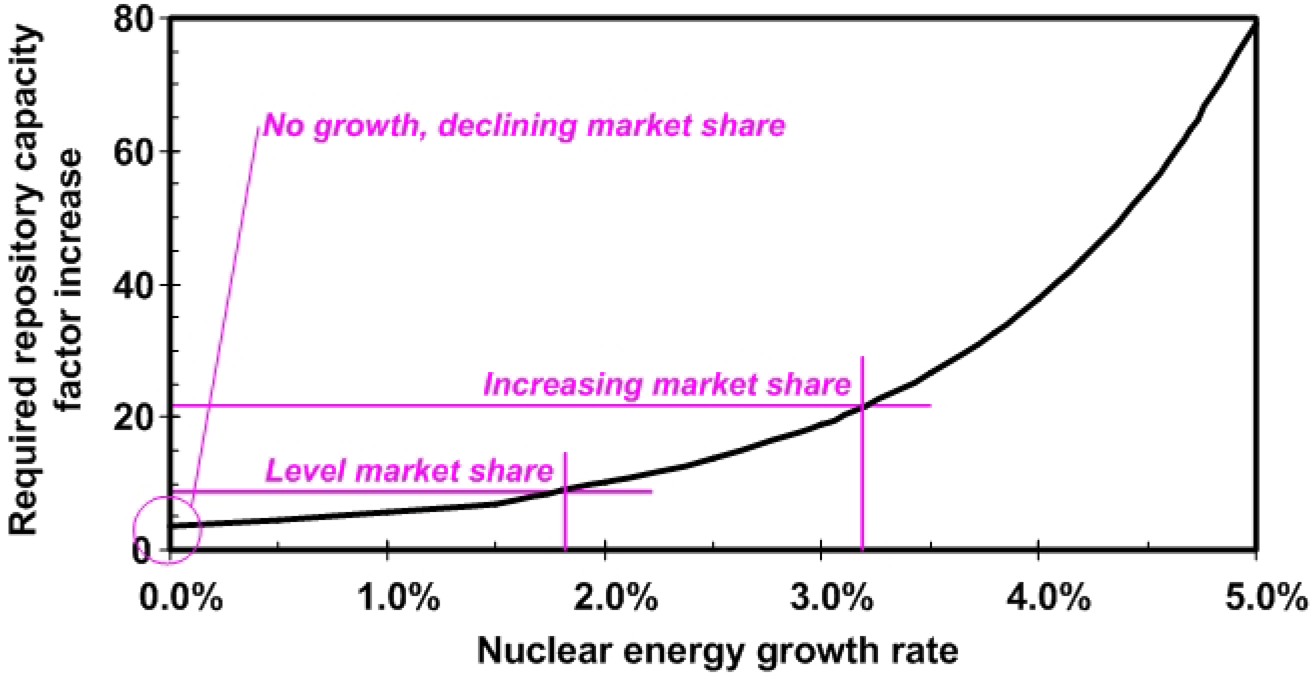

Figure 1. Required geologic repository capacity improvements as a function of domestic energy growth rates through 2100. Capacity improvements can be achieved by a combination of physical expansion of the first repository, additional repositories, or recycling.

Because of their political, litigious, economic, and technical challenges, geologic repositories are a limiting resource for use of nuclear energy. Packaged volume and mass are dominated by the uranium in spent nuclear fuel. The technical limits on geologic repository capacity include long-term heat load, long-term peak doses from hypothetical releases, and long-term radiotoxicity of the waste. These characteristics are dominated by the transuranic elements – neptunium, plutonium, americium, and curium. Options exist to separate uranium and transuranic elements from spent fuel. The uranium can either be recycled into new fuel or (because of its low radiotoxicity) disposed in non-geologic ways, as waste uranium is disposed today. Transuranic elements can be recycled, which extracts energy and converts them into fission products that pose shorter-term disposal problems. Fission products and waste generated during recycling would be disposed in appropriate ways, a mix of geologic repository and near-surface burial.

Which strategies work?

The legislated initial capacity of the first geologic repository per the Nuclear Waste Policy Act[3] is 70,000 metric tonnes; an increase in capacity of a factor of 2 by a mix of recycling or repository expansion would ensure sufficient repository capacity if all current nuclear power plants' lifetimes are extended from 40 to 60 years, while reserving some repository capacity for the future. Without recycling, at growth rates of 0.0%, 1.8%, or 3.2%/year, the status quo would lead to the need for 4, 9, or 22 geologic repositories respectively by 2100, each assumed to have capacity for 70,000 metric tonnes. As there is little possibility for physical expansion of the first repository by such factors, to stay within one geologic repository, spent fuel must be recycled.

Figure 2 graphs the repository capacity improvement relative to the status quo and to the improvement required to avoid the need for a second geologic repository this century. The once-through fuel cycle with higher burnup fuel offers little improvement. Neither the MOX nor IMF variant to limited recycle are adequate. However, continuous or sustained recycle can limit the national need to a single geologic repository until well into the 22nd century.

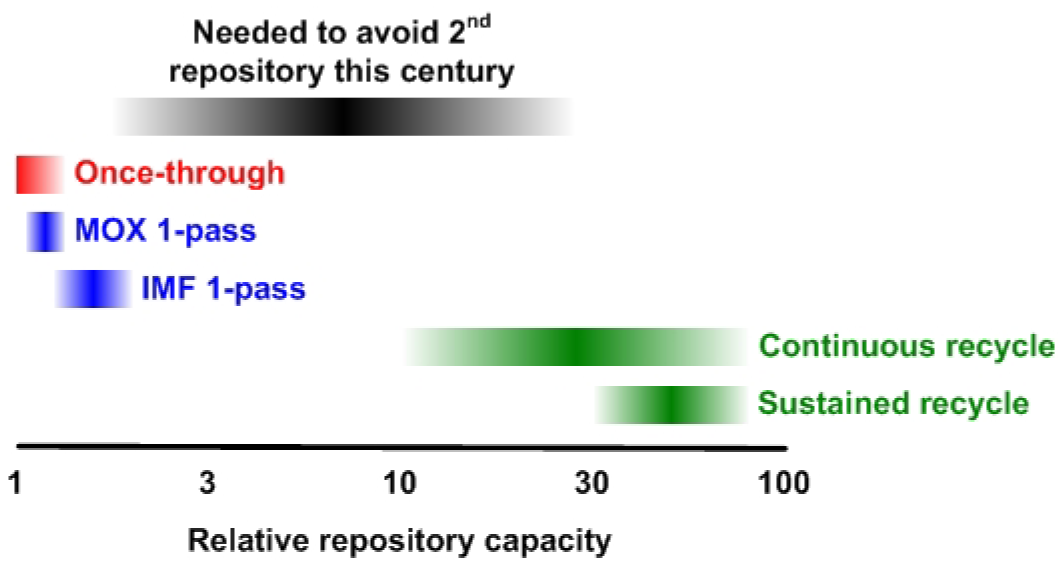

Figure 2. Relative repository capacity improvement, the status quo is defined as 1.0.

Another issue is the long time period of stewardship for spent fuel. This is driven by the time necessary for radioactive decay of waste constituents, which varies by isotope from a few years to over a million years. Successful application of AFCI technologies and new reactors can achieve large reductions in the longer-lived transuranic isotopes remaining in radioactive wastes sent to geologic disposal. If only fission products are disposed, the time frame for human responsibility is several centuries, rather than many tens or hundreds of millennia.

Figure 3 shows the reduction of long-term radiation dose (via groundwater) and radiotoxicity sources relative to the status quo. The status quo leads to waste that remains more radiotoxic than the original natural uranium ore for hundreds of thousands of years. Limited recycle offers little improvement. However, either continuous or sustained recycle offer substantial improvement. That improvement is sufficient to alter the geologic disposal time horizon from hundreds of thousands of years to only several centuries, by recycling the transuranic isotopes. (See Figure 4.) This changes transuranic isotopes from waste management liabilities into energy resource assets.

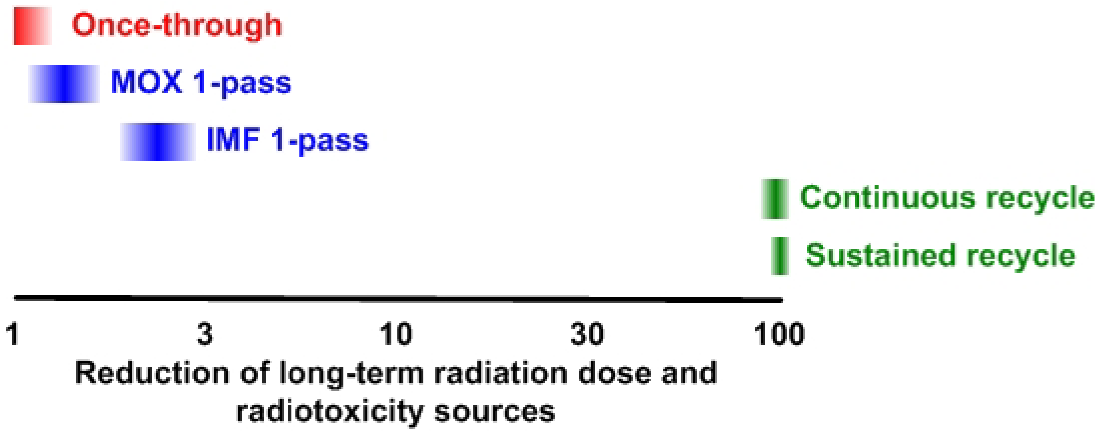

Figure 3. Relative reduction in long-term hazard from nuclear fuel waste

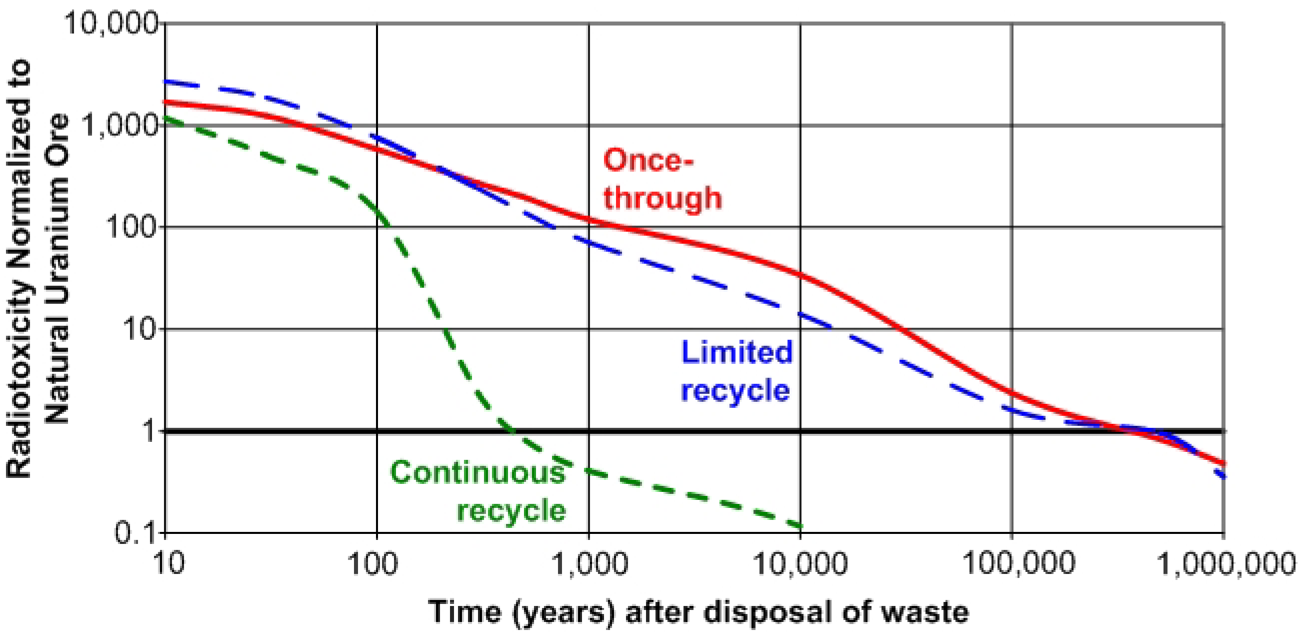

Figure 4. Radiotoxicity of geologic waste relative to natural uranium ore; reduction of radiotoxicity of ~100 by continuous or sustained recycle (vertical comparison in the diagram) alters the time horizon from 100,000's of years to 100's of years (horizontal comparison in the diagram).

What are the key separation challenges?

All AFCI recycle options separate uranium to reduce the mass and volume of material that must be subsequently processed and ultimately of waste generated. This may decrease the number and cost of waste packages that require geologic disposal. Separated uranium can also be used as reactor fuel. There is no fixed requirement for the fraction of uranium that must be separated from other spent fuel components. However, the separated uranium must be sufficiently pure so as to qualify for near-surface burial.[4]

All AFCI recycle options separate the transuranics, but the disposition of the separated materials varies by strategy. Note that the United States is not pursuing any option that would separate plutonium by itself.[5] Thus, at least one other transuranic element must be recovered and recycled with plutonium; the easiest element appears to be neptunium.

Continuous recycling of plutonium and americium with a separation factor over 99% can achieve repository capacity factor increases of 5-6 for five recycling passes.[6] The repository factor improvement increases with the number of recycling passes, the shortness of fuel aging after discharge, and use of IMF versus MOX. The key isotopes are Am-241, Pu-238, Pu-240, and Pu-239. (Without americium recycle, the repository factor increases are much lower, less than 2.) Thus, there are three major challenges for transuranics:

- In the near-term, develop fuel cycle technologies and facilities that remove more than 99.5% of transuranics from waste destined for geologic disposal and initiate their recycle in existing reactors.
- In the longer-term, enable continuous/sustained recycling to reduce disposed transuranics by a factor of more than 100, delaying the need for additional geologic repositories for a century or more even with growing energy production. (This factor of ~100 then becomes the upper bound for the repository capacity improvement; in practice the net repository capacity improvement will be lower as fission products are included.)
- In the longer-term, reduce the longer-lived radiation dose sources by a factor of 10 and radiotoxicity by a factor of 100, simplifying the design of a waste isolation system.

These challenges apply to plutonium, neptunium, and americium. Further work is required to determine to what extent they apply to curium.

All AFCI recycle options separate short-lived fission products cesium and strontium to allow them to decay in separate management tailored to that need, rather than complicate long-term geologic disposal. When combined with transuranic recovery, recovery efficiencies of 99.9% for cesium and strontium can increase the repository capacity factor to 40-60.[6,7] This may also reduce the number and cost of waste packages requiring geologic disposal. These savings may be balanced by costs for separation and recycle systems. Therefore, another key challenge is as follows:

- In the near term, improve management of the primary heat producing fission products in spent fuel (cesium and strontium) to reduce geologic repository impacts. The separated cesium and strontium should be sufficiently pure that they would quality for near-surface burial after interim storage. (Other disposal options may exist, but separation for near-surface burial provides the most flexibility.)

All current AFCI recycle options lead to long-lived fission products, such as technetium-99 and iodine-129, going to geologic disposal in improved waste forms. However, the program has not precluded their transmutation as a future alternative. As more analyses are performed with long-term heat load and radiotoxicity/dose, it is possible that technetium and iodine destruction via transmutation may become important, i.e., they may be part of the the radiotoxicity and dose challenge noted above.

OBJECTIVE 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.

What does the objective mean?

The objective is to improve proliferation resistance by making material theft, material diversion, and technology diversion more difficult than existing systems, which are once-through in the U.S. and plutonium separation and recycle in several other countries. This cannot be accomplished by the status quo, only by implementing a combination of new technologies (such as from AFCI) and new international strategies.

All nuclear fuel cycle strategies – once-through or recycle – exhibit some level of proliferation risk. To minimize proliferation risks, all nuclear systems use a combination of intrinsic protection (radiation, physical barriers) and extrinsic protection (safeguards, institutional controls). Although nuclear proliferation issues minimally impact domestic implementation of fuel cycle strategies, choices of technologies and systems by the U. S. can have significant international implications. U.S. global leadership in proliferation resistance requires an underpinning of technical credibility and innovation, particularly in advanced fuel cycles that could see widespread implementation.

The premise behind the 1977 U.S. decision to forego spent fuel processing was that other countries would follow. Today, the U.S. continues this course of the once-through approach, in which spent fuel is discarded. Many other countries use the Plutonium-URanium EXtraction (PUREX) process, in which weapons-usable plutonium is separated from spent fuel for eventual recycle in nuclear power plants. Most countries with nuclear power also pursue uranium enrichment to obtain uranium for fresh fuel. The current international nonproliferation regime could be improved by reducing the motivation for countries with smaller nuclear programs to develop either uranium enrichment or fuel reprocessing capabilities. This could be achieved by the U.S. and other countries with large nuclear programs becoming reliable, economical international suppliers of fuel services.

Proliferation resistance approaches are evolving.[8,9,10] This evolution represents broad recognition that both enrichment and reprocessing technologies provide proliferation risks, which can be best reduced by limiting the dispersion of enrichment and reprocessing capabilities to states that do not already have substantial, well-established fuel cycle activities. In countries that already have comprehensive fuel cycle capabilities, including enrichment, AFCI technologies are unlikely to increase proliferation risk. AFCI technologies could reduce proliferation risks. If AFCI technologies enable more rapid development of markets for comprehensive fuel cycle services, such as fuel leasing, they would help stop broader dispersion of fuel-cycle technologies and infrastructure. Under such a policy, technology exports from all countries would be limited to states with existing commercial fuel cycle capabilities.

A complete approach to proliferation and safeguards requires addressing the range of threat strategies and proliferation targets. AFCI development focuses on advanced fuel cycle technology that achieves high levels of proliferation resistance through optimization of intrinsic barriers to materials misuse, coupled with superior systems for monitoring and materials accountability. Consistent with the Generation IV program, proliferation measures include quantity and quality of material, time needed to divert material versus time to detect irregularities, and inherent barriers against proliferation. The potential benefits of AFCI technology relative to both present once-through and PUREX fuel cycles could lead to a new international consensus and a fuel cycle inherently more resistant to material diversion.

Which strategies work?

Three key indicators of proliferation resistance are addressed: using inherent proliferation barriers, reducing weapons usable material from waste destined for geologic disposal, and stabilizing the inventory of weapons usable material in storage. These are relevant to differing degrees to the four threat strategies: theft of weapons usable material, clandestine diversion of material from facilities declared under the Non-Proliferation Treaty, clandestine production in undeclared facilities, and abrogation of responsibilities under the Non-Proliferation Treaty by a nation state leaving the treaty. A mix of technology and policy-control measures must protect against the four proliferation targets of weapons-usable materials, equipment, facilities, and technology information.

Material theft: The AFCI will increase security against theft by reducing plutonium production and stabilizing inventories, increasing intrinsic protection properties of weapons-usable material, and by incorporating anti-theft features into designs. In the intermediate term, AFCI transmutation will be able to destroy most residual transuranic elements, reducing the need for long-term waste storage, and making spent fuel less attractive to potential proliferators. The once-through fuel cycle offers good proliferation resistance for only a short period of time, because the decay of fission products makes unprocessed spent fuel a potential diversion risk after a hundred years. Figure 5 shows that recycling reduces this potential legacy problem by eliminating the lasting inventories of unprocessed spent fuel that could become long-term proliferation risks. Equipment and facility design will also be critical.

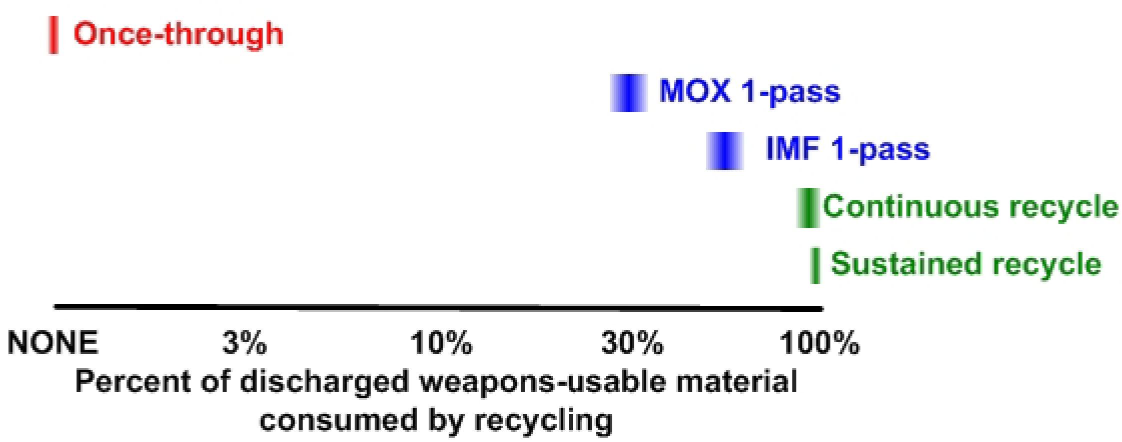

Figure 5. Percent of weapons-usable material in discharged spent nuclear fuel that can be consumed by subsequent recycling passes. To enable continuous and sustained recycle, a source of appropriate nuclear fuel is required. Thus, in practice, the following parameters must be optimized to stabilize but not eliminate weapons usable material inventories – use of fresh uranium, production of transuranics, consumption of transuranics.

Clandestine diversion from declared facilities: AFCI will increase security against clandestine diversion by research and development leading to improved monitoring technologies and "safeguard by design," i.e., design of facilities such that any attempt to divert material is more difficult to accomplish ("tamper proof") or more easily detected. Improving inherent barriers and reducing material in storage are significant contributors to increasing security against clandestine diversion. Equipment and facility design will also be critical.

Clandestine production in undeclared facilities: No research and development program can eliminate knowledge of PUREX or uranium enrichment as potential strategies toward proliferation. Potential proliferators can use such existing technologies in clandestine, undeclared facilities. However, AFCI will increase security against clandestine production by decreasing the international motivation to use PUREX or uranium enrichment technologies – by developing fuel cycle technologies that are more attractive for recycling but less attractive for weapons-usable production than PUREX. As AFCI technologies show their worth commercial purposes, detection of manufacture, purchase, or use of technological equipment associated with PUREX would be a clearer signal of proliferation intent. Inherent barriers provide some assistance in increasing security against clandestine production, but equipment and technology design are likely paramount.

Abrogation: No research and development program can prevent a nation from abrogation of its responsibilities under the Non-Proliferation Treaty. However, AFCI may be able to increase security against the impact of abrogation by providing attractive technologies for international spent nuclear fuel recycling centers (reducing the motivation for national programs) or by use of technologies that require periodic attention, i.e. use recycle equipment that would cease to be effective if not periodically checked by inspectors. Reductions in weapons-usable inventories can contribute to increasing security against the effects of abrogation, but equipment and facility design are probably more important.

In summary, the status quo continues the abrogation of U.S. technological leadership, continued international use of the PUREX technology, and ever increasing inventories of weapons usable material in spent fuel. The range of AFCI recycle strategies offer the potential for more proliferation resistant technologies and stabilization of weapons usable material inventories.

What are the key separation challenges?

The overall technological challenge is to develop fuel cycle technologies and facilities that enhance the use of inherent proliferation barriers and incorporate superior monitoring and materials accountability. Also, it would be beneficial if fuel cycle technologies and facilities were "tamper proof", i.e., designed to make theft or clandestine diversion difficult.

The step in the nuclear fuel cycle with the "cleanest" weapons-usable material (lowest inherent barriers) is between separation and fuel fabrication because the output of separation must be in a form for fuel fabrication. Proliferation resistance is therefore likely increased to the extent that separation and fabrication are co-located or indeed a continuous process.

Plutonium must be recycled to obtain repository, proliferation, and energy recovery benefits. U.S. non-proliferation policy forbids separation of plutonium by itself; therefore, one or more of the other transuranic elements must be kept with the plutonium; neptunium is considered the easiest transuranic element to keep with plutonium. Recycling neptunium also provides repository benefits. Americium recycling is also required to obtain repository benefits. At the present time, curium recycle provides relatively little benefit; indeed, recycling curium in thermal reactors would significantly increase the hazard (hence cost) of the resulting fuel. Thus, the challenge for AFCI system analysis is to identify which of the following situations is best, considering separation and other aspects:

- Pu+Np together, Am+Cm together – Simplest in aqueous processing, but few repository benefits unless Am is eventually recycled.
- Pu+Np together, Am separate, Cm separate – Multiple separation steps required, but this provides the most flexibility. Am can be recycled either with Pu+Np, or as separate americium targets. Cm can be stored.
- Pu+Np+Am together, Cm separate – A variation of the above case.
- Pu+Np+Am+Cm – This involves the least number of separations, but may lead to prohibitively expensive fuel fabrication and handling.

Said another way, there are two challenges specific to transuranic separation and consumption:

- In the near-term, demonstrate the capacity to eliminate more than 99.5% of transuranic weapons-usable materials from waste streams destined for direct disposal by destroying these materials through recycling.
- In the longer-term, stabilize the inventory of weapons-usable material in storage by consumption for sustained energy production.

As in the case of geologic waste management, these challenges apply to plutonium, neptunium, and americium. They may not apply to curium; because discharged curium produces sufficiently high heat loads that (by itself), it would not be considered weapons usable.[11] However, because Cm-244 has only an 18.1-year halflife, curium will become weapons usable in ~50 years from the standpoint of self heat-generation; it would still be poor weapons material as the decay product, Pu-240, is unattractive.

OBJECTIVE 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.

What does the objective mean?

Uranium resources are currently plentiful and uranium purchase represents only a few percent of the cost of nuclear-generated electricity. However, the size of the uranium ore resource base is uncertain because there has been little financial incentive in recent decades for exploration. As nuclear energy continues to expand globally and current stockpiles are used, technological options may be required to ensure domestic energy security against resource depletion. Today's fuel cycle uses less than 1% of the theoretical energy content in uranium ore. Direct disposal of spent fuel discards the energy content remaining in such fuel. Current nuclear power plants cannot use the ~90% of uranium that is "depleted" of fissile uranium-235 and discarded after enrichment of natural uranium ore.

The 500 tonnes of recoverable fissile material (mostly plutonium) contained in existing U.S. spent fuel has an energy equivalence to 6.6 billion barrels of oil, which is half of the estimated resources in Prudhoe Bay, Alaska. In the longer-term, the energy content in the 50,000 tonnes of spent fuel already accumulated in the U.S. is equivalent to more than twice the energy content of Saudi Arabian oil reserves. The energy content of the 470,000 tonnes of existing depleted uranium could avert over 1000 years of emissions from fossil fuel combustion (at current energy use rates) if new power plants are deployed that use depleted uranium. Thus, AFC technology could be utilized to ensure that known domestic uranium resources are adequate well beyond this century to both sustain nuclear energy and reduce dependence on other energy sources.

Which strategies work?

Figure 6 shows the relative energy recovery from uranium ore. The energy content in uranium ore can be more effectively used as the energy content in spent fuel is recovered. Sustained recycling is needed to substantially improve energy recovery.

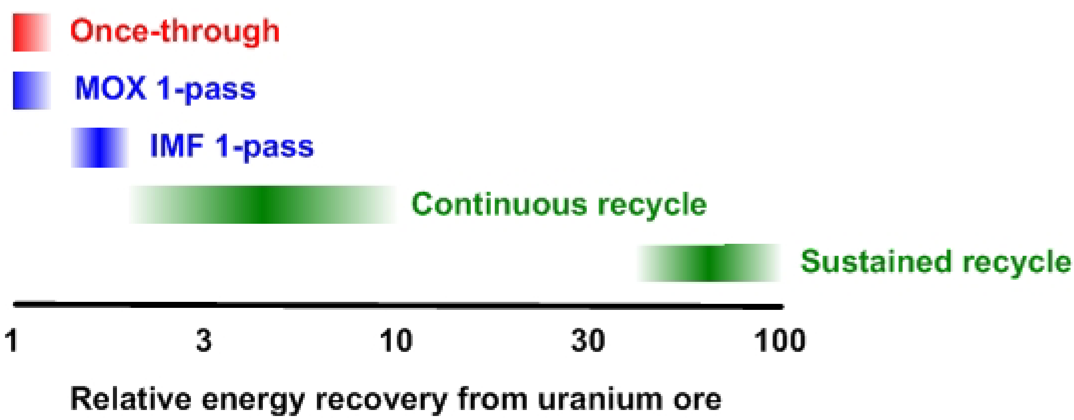

Figure 6. Relative energy recovery from uranium ore

With limited recycle, some of the transuranic elements are converted from a liability to an energy asset; everything else (including all waste uranium) remains a liability. Even this slight improvement in energy recovery is comparable to half the estimated oil resources in Prudhoe Bay, Alaska.

Continuous recycle converts transuranic elements from waste liabilities to energy assets. This modest improvement in energy recovery is comparable to the estimated oil resources in Saudi Arabia.

With sustained recycle, depleted uranium in existing low-level waste is converted from waste liabilities to energy assets. The energy potential in the large quantities of existing waste uranium is sufficient to replace all sources of domestic electricity production (at current usage rates) for over 1000 years. And, if needed, lower grades of uranium ore become economic, including uranium from very unconventional sources such as sea water. Uranium ore resources would not become a limit.

What are the key separation challenges?

The separation challenges are not appreciably different than for waste management – separate uranium for potential future use, and separate transuranics. From an AFCI perspective, the challenges are stated:

- In the near-term, develop the technologies needed to extend nuclear fuel supplies by up to 15 percent by recycling the fissile material in spent nuclear fuel – this means to do limited recycle (or better).
- In the long-term, extend nuclear fuel resources at least 50-fold by recycling uranium in spent fuel and previously discarded depleted uranium, converting current wastes into energy assets – this means enable sustained recycle.

OBJECTIVE 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

This objective has three parts – competitive economics, excellent safety performance, and overall system management.

Objective 4a. Continue Competitive Economics

What does the objective mean?

The economics of the nuclear fuel cycle is an essential component in any consideration of the future of nuclear power.

The average cost of electricity from current U.S. nuclear power plants is under $0.018/kilowatt-hour or 18 mills/kW-hr because the capital costs of existing plants have been mostly depreciated. Projections for new plants in the next decade range from 47 to 71 mills/kW-hr.[12] Fuel cycle costs are about 6 mills/kW-hour. Of this, 1 mill/kW-hr is the fee paid by utilities to the Federal government for future geologic disposal. This fee covers projected disposal costs. As experience is gained with the Yucca Mountain project, the actual costs for geologic disposal will become better known. However, the potential cost of future geologic repositories (if needed) should be considered uncertain.

For perspective, consider that wind energy is currently given a tax credit equivalent to 18 mills/kW-hr.[13] This is equivalent to the entire current cost of generating electricity from nuclear power! Natural gas price fluctuations during 2004 have been more than $2 per million BTU, equivalent to over 12 mills/kW-hr.[12] A hypothetical carbon tax of $50/tonne-carbon is equivalent to 5 mills/kW-hr (natural gas) or 12 mills/kW-hr (coal).[12] Thus, a potential increase in nuclear costs of 1-2 mills/kW-hr to accommodate the potential difference between the cost of recycling versus direct geologic disposal would be a modest price to significantly improve energy sustainability and security, while reducing the environment impacts from energy production.

Which strategies work?

It is premature to provide comparative economic calculations because there are so many factors involved, many of which have high uncertainties. There is also the complication of having two potential nuclear power markets – electricity and hydrogen production.

There is a large economic uncertainty associated with the cost of additional geologic repositories. Indeed, the viability of the once-through fuel cycle requires establishing the feasibility and cost of siting and constructing many additional geologic repositories; however, no government program has the authority to explore the potential for many new repositories.

The importance of cost uncertainties for alternative thermal reactors varies from the importance for fast reactors. From an AFCI perspective, the selection among types of thermal reactors is of low importance because (to first order) they perform the same function in the fuel cycle as current light-water reactors.

In contrast, the cost uncertainty of fast reactors is very relevant to AFCI. Figure 7 shows the percent of the reactor fleet that must be new fast reactors for each strategy to work. At least one type of fast reactor must be made economical for the sustained recycle strategy to be viable. The importance of fast reactor cost uncertainty to the continuous recycle strategy depends on the percent of fast reactors required to make the strategy work, which requires more analysis.

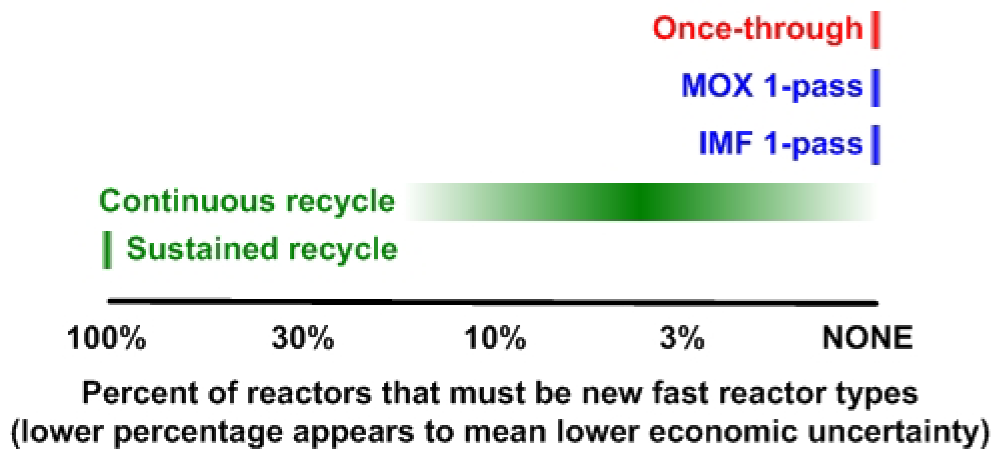

Figure 7. Percent of power reactors that must be new fast reactors.

Separation costs are uncertain. All recycle strategies depend on separation. The amount of separation required does not vary greatly among the recycle options.

The costs of new fuels that can use recycled TRU are uncertain; all recycle strategies require new fuels. However, figure 8 shows that the fraction of all fuel used that must be new varies considerably with respect to the recycle options, ranging from 5-10% for limited recycle with IMF (best case) to 100% for sustained recycle.

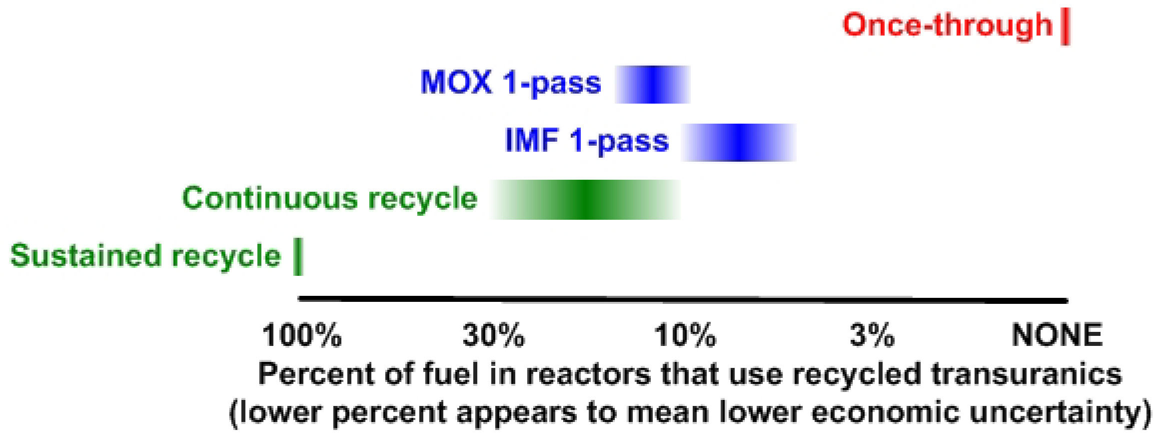

Figure 8. Percent of fuel in the reactor fleet that must use recycled transuranics. Such fuels are new (hence higher economic uncertainty) and necessarily higher radioactivity than current uranium oxide fuels (hence potential for higher cost).

With sustained recycle, there is no economic uncertainty associated with the need for new geologic repositories, but fast reactors are required.

What are the key separation challenges?

At all times, ensure advanced fuel cycle technologies cause no significant increase in the total cost of nuclear electricity. The simplest way to meet this objective is for separation costs (not required in the once-through fuel cycle) to be balanced by savings in geologic repositories, energy recovered, so forth.

With limited recycle, there is relatively little repository benefit (objective 1) and relatively little energy recovery (objective 3). Therefore, the challenge for separations is to keep the cost increment to perhaps 1-2 mills/kW-hr. This is comparable to the 1-mill/kW-hr waste management fee collected today, which would still be required for fuel after its one recycle pass. Indeed, the 1-mill/kW-hr fee may have to increase if costs for additional repositories are higher than the first. 1-2 mills/kW-hr is also much smaller than the economic penalty associated with other energy options, e.g., the 18 mill/kW-hour credit given to wind energy.

With continuous recycle, there is more repository benefit and more energy recovery. The 1-mill/kW-hr fee would virtually disappear. But, the potential impacts of new reactors is difficult to assess. If only thermal reactors are used, the practicality (hence cost) of continuous recycle is relatively uncertain. If fast reactors are added, the practicality of sustained recycle is not in doubt; however, the cost penalty (if any) of fast reactors is uncertain. Fast reactor development is the responsibility of the Generation IV program.

Objective 4b. Continue Excellent Safety Performance

What does the objective mean?

Safety and reliability are critical to all nuclear facilities. All nuclear facilities deployed in the United States will be licensed by the Nuclear Regulatory Commission and will meet rigorous safety requirements. By learning from past experience and improving technologies, any future fuel cycle facilities resulting from AFCI research will be at least as safe as current technology, possibly superior.

Well designed reactors achieve exceptional levels of safety. Advances in reactor design, whether in terms of evolutionary improvement (Advanced Light Water Reactors) or systems such as those developed under the Generation IV initiative, aim towards consistent improvement in safety. Advanced fuel cycle technologies and systems are also being developed to achieve the highest levels of safety and to minimize exposures to workers and the general public.

Which strategies work?

This objective applies to the entire fuel cycle, including power plants. The safety of the entire system is likely dominated by the safety of the reactors, because they are more numerous than geologic repositories or recycling plants.

- With the once-through strategy, there will be at least 1 repository per 100 nuclear power plants, each assumed to be about 1 GWe capacity.
- With limited recycle, there will be less than 1 repository and about 1 recycle plant per 100 nuclear power plants.
- With continuous or sustained recycle, there will be 1 repository irrespective of the number of nuclear power plants. There will be either about 1 large centralized recycle plant per 100 nuclear power plants or distributed recycling at each nuclear power plant.

This means that a complete assessment of fuel cycle safety must include the impact of new recycle fuel types on reactor operation. Indeed, reactor safety parameters are routinely included in exploring the appropriate composition of recycle fuels.

Another issue is the amount of transportation of highly radioactive fuel, which does not include fresh uranium fuel. (Here, we refer to all discharged fuels, fuels with recycling transuranics, residual high-level waste after separations.) Figure 9 shows a preliminary estimate of the relative amount of shipping (distance x trips) required, relative to the once-through fuel cycle. There are two major pathways toward substantially reducing the amount of shipping. The first is extended refueling intervals, so-called “battery” reactor designs (also called cassettes) whereby refueling intervals are ~30 years instead of 1.5 years. The potential shipping reduction advantages must be weighed against such disadvantages as the need for increased uranium enrichment of the fuel. The second is separation and fuel fabrication co-located with power plants. The potential shipping reduction advantages must be weighted against potentially higher cost (lower economies of scale of separation and fuel fabrication) and the potential proliferation concerns with having more separation plants.

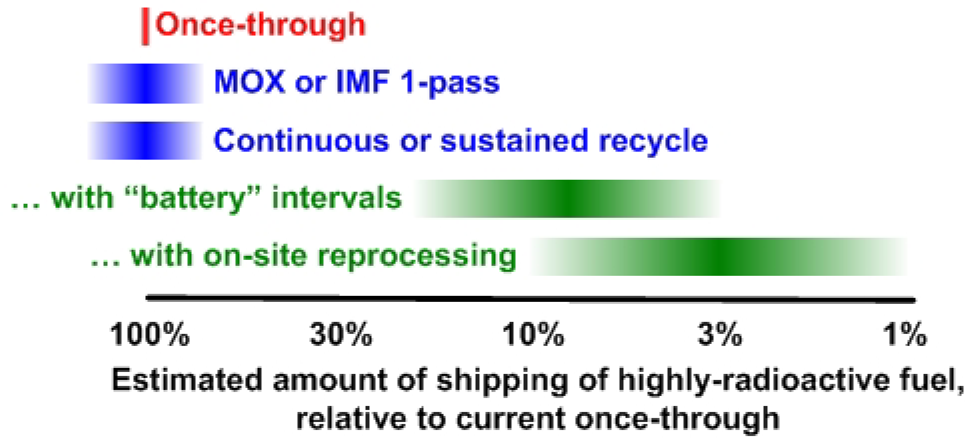

Figure 9. Relative amount of shipping of highly-radioactive fuel - all discharged fuel, fuel using recycled transuranics, residual high-level waste after separations

What are the key separation challenges?

At all times, researchers and industry must maintain excellent safety performance of nuclear fuel cycle facilities and operations. There may be advantages to co-locating power plants, separation, and fuel fabrication; this requires more analysis.

Objective 4c. Improve fuel management to reduce storage at nuclear power plants

What does the objective mean?

A specific issue is the accumulation of spent fuel at nuclear power plants; an improved fuel cycle management system will ensure timely removal of spent fuel. This will meet the government's legal obligation to take ownership of spent commercial spent fuel while reducing proliferation, safety, and environmental risks at power plant sites. Ideally, the inventory of discharged spent fuel stored at power plants should be the minimum required for cooling to the point that the material can be shipped (or processed on site). For light-water reactor fuel, that is thought to be 5 years.

Which strategies work?

With once-through, there is already ~50,000 MT of accumulated spent fuel in storage at commercial nuclear plants. By the time the first geologic repository opens, there will be sufficient waste accumulated to exhaust its legislated capacity. It is possible that this pattern would continue – build geologic repositories after waste has accumulated – in which case significant interim storage inventories will persist. Alternatively, the rate of geologic repository construction would need to substantially accelerate.

With limited recycle, there is substantial delay in the need for interim storage because spent fuel would be recycled once or twice. This allows time for either building interim storage or building additional geologic repositories. With continuous or sustained recycle, there is a reduction in the need for interim storage as recycling plants are brought into operation. Spent fuel components would be routinely recycled, rather than stored.

What are the key separation challenges?

All of the recycle strategies work. The challenge is obtaining the resources to do the R&D to validate one or more recycle concepts, so that an informed decision can be made to build recycling facilities.

SUMMARY

Selection and optimization among fuel cycle strategies and technologies is complex. This summary is divided into three subsections – what is needed to meet the first three AFCI objectives (waste management, proliferation resistance, energy sustainability), what is needed to meet the fourth AFCI objective (economics, safety, system management), and what is required to progress from the status quo to various recycle strategies.

Waste management, proliferation resistance, and energy sustainability

The once-through fuel cycle cannot be advanced much further in terms of the first three AFCI objectives. At best, high burnup fuels can provide 20% improvements to geologic repository needs and energy sustainability. At growth rates of 0.0 to 3.2% per year, four to twenty two geologic repositories would be required this century, assuming each was 70,000 metric tonnes. U.S. technological advances in the once-through fuel cycle would lead to little or no improvement in proliferation resistance because a quarter-century of history indicate that it does not discourage international recycling of plutonium and because uranium enrichment needs will remain. (At higher burnup, less material must be enriched, but it must be enriched to a higher level; the effects generally balance.)

As one transitions through the recycle strategies – limited recycle, continuous recycle, sustained recycle – the AFCI objectives for waste management, proliferation resistance, and energy sustainability are increasingly met. There are four major “breakpoints”:

- Limited recycle starts the draw-down of weapons-usable material and begins accruing improvements for geologic repositories and energy sustainability that are at least as significant as the high burnup variation of the once-through fuel cycle.
- Continuous recycle achieves the key AFCI objective to avoid the need for a second geologic repository until the next century, ensuring repository space resources do not become a limiting factor for nuclear energy.
- Continuous recycle also converts TRU from waste management liabilities into energy resource assets.
- Sustained recycle converts waste from both enrichment (depleted uranium) and spent fuel from liabilities into energy resource assets, thereby using ~99% of the energy content in original uranium ore and ensures uranium resources do not become a limiting factor for nuclear energy.

Economics, safety, and system management

There are three major economic uncertainties. 1) The cost of future geologic repositories is unknown and not being studied; this is therefore a major uncertainty for both the once-through and limited recycle strategies. 2) The cost of fast reactors is also unknown, but is being studied. Fast reactors are critical to sustained recycle. Fast reactors may be required for continuous recycle, but, even so, their impact on overall economics would be muted because they can be limited to 10-20% of the reactor fleet. The approach of continuous recycle with thermal reactors alone (no fast reactors) has relatively low economic uncertainty, but there are significant technical issues with such an approach. 3) The cost of new recycle fuels and associated separation plants is uncertain, but is being studied.

There are three major safety uncertainties. 1) The safety of new reactor types must be demonstrated. 2) The impact of new fuels on reactor safety performance must be ensured. 3) The relative amount of transport of radioactive material depends on multiple factors, but it can be noted that “battery type” reactor fueling or recycling at reactor sites offer the potential for an order of magnitude reduction in radioactive transport relative to once-through.

All recycle strategies may accelerate removal of spent fuel from power plants.

Getting from here to there

All options except the status quo require research and development. Benefits from research and development are cumulative. With few exceptions, each new technology that is demonstrated and implemented continues to provide benefit later, if additional technologies become available.

- Recyclable transuranic mixed oxide and recyclable transuranic IMF start providing benefits with limited recycle (even if recycling does not proceed further) and also provide benefits in continuous recycle. They may cease to be used if sustained recycle is adopted.
- UREX+ is viable for limited recycle, continuous recycle, and possibly sustained recycle (depending on fuels used for sustained recycle).
- Advanced thermal reactors and their associated fuels, e.g., the Very High Temperature Reactor potentially used to produce both electricity and hydrogen, do not adversely impact the fuel cycle – provided the fuels are recyclable.
- Implementation of fast reactors and associated fuels would make continuous recycle easier and enable sustained recycle.
- The only technology potentially used for limited recycle that would not be applicable for continuous or sustained recycle would be new non-recyclable fuels, such as non-recyclable forms of IMF.

While greater benefits are obtained by progressing through fuel cycle strategies: limited recycle → continuous recycle → sustained recycle, the relevant technologies are generally less mature. Many of the necessary technologies are only in the concept development or proof of principle stages. At these stages, most research is bench scale, and therefore relatively inexpensive. Maturation through proof of performance research will typically require scale-up research and engineering before the technologies can be fielded and the advanced fuel cycles achieved.

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