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ABSTRACT

This paper summarizes the current comprehensive comparison of four major fuel cycle strategies: once-through, thermal recycle, thermal+fast recycle, fast recycle. It then proceeds to summarize comparison of the major technology options for the key elements of the fuel cycle that can implement each of the four strategies - separation processing, transmutation reactors, and fuels.

I. INTRODUCTION

The AFCI program addresses critical national needs associated with past and future use of nuclear energy. First, the AFCI provides alternatives to building multiple geologic repositories for disposal of past and future commercial spent nuclear fuel, while supporting an expanding role for nuclear energy. Second, the AFCI provides fuel cycles that recover most of the energy content in spent nuclear fuel, in conjunction with the complementary Generation IV Nuclear Energy Systems Initiative (Generation IV). Third, the AFCI provides nuclear fuel cycles that improve proliferation resistance via advanced separations and fuels technologies, by reducing the inventory of weapons-usable material, and by eventually reducing the need for uranium enrichment. While accomplishing these goals, the AFCI program also will ensure competitive economics and excellent safety for the entire nuclear fuel cycle.

This document begins with a brief program background, followed by an explanation of the major AFCI objectives. These sections provide the context for the key comparison of the four major fuel cycle strategies being pursued. The comparison contains substantial information in response to the Congressional request, while also assuring that a full range of objectives and options be considered.

AFCI Program Background

The AFCI program evolved from the Office of Nuclear Energy, Science and Technology's Accelerator Transmutation of Waste (ATW) program, initiated in 1999. As a result of the research results produced by the ATW program and its successor, the Advanced Accelerator Applications (AAA) program, the direction of the AFCI program is focused on developing and demonstrating technologies that will enable the United States and other advanced countries to implement an improved, long-term nuclear fuel cycle that provides substantial environmental, nonproliferation, and economic advantages over the current once-through fuel cycle. These new technologies are intended to support the operation of current nuclear power plants, Generation III+ light water reactors, and Generation IV high temperature reactors in order to achieve a significant reduction in the amount of high-level radioactive waste requiring geologic disposal; to reduce significantly accumulated plutonium in civilian spent fuel; and to extract more useful energy from nuclear fuel.

Improve Waste Management and Geologic Disposal

Under all strategies and scenarios, the United States will need to establish 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 reactors. 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 2001 Yucca Mountain Science and Engineering Report 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 follow-on repositories to address the additional wastes from new nuclear plants or begin advanced treatment of spent fuel to reduce the weight, volume, long-term heat output, and radiotoxicity of nuclear waste. In May 2004, a subcommittee to the Nuclear Energy Research Advisory Committee (NERAC) reported that any substantial growth projected in the use of nuclear energy in the United States (such as is called for in the *National Energy Policy*) will require the construction of additional geologic repositories to address the nuclear waste generated over time. Even under conservative scenarios that assume merely the replacement of existing nuclear plants by new nuclear plants, at least one and as many as three additional repositories could be required by 2100. Scenarios that postulate a growing energy market share for nuclear power could require up to 22 repositories, each with a capacity of 70,000 metric tonnes, by 2100.

The AFCI provides an alternative to building multiple geologic repositories while still supporting an expanding role for nuclear energy. AFCI's primary near-term goal is to develop advanced, proliferation-resistant fuel cycle technologies to provide the technical basis to inform a recommendation by the Secretary of Energy regarding the potential need for additional geologic repositories. Current legislation requires the Secretary to make a recommendation to Congress regarding the need for a second repository as early as January 1, 2007, but before January 1, 2010.

Enable Energy Recovery from Spent Fuel and More Effective Uranium Use

Working together, the Generation IV program and the AFCI program will make nuclear energy more sustainable, recover most of the energy content in commercial spent nuclear fuel, and make more effective use of uranium resources. The Generation IV Initiative is exploring a range of reactor technology options for future nuclear energy for production of clean electricity, hydrogen for transportation, clean water, and other important products. The AFCI is assessing fuel cycle options for either a continuation or expansion of nuclear energy in the United States. This report compares fuel cycle strategies and technology options for managing the associated spent fuel.

Enhance Proliferation Resistance

Advanced fuel cycles will improve proliferation resistance by making material diversion/theft or technology diversion more difficult than the existing system (once-through in the U.S., plutonium separation in several other countries). All parts of any fuel cycle have to be protected against terrorist threats and diversion of materials; fuel cycle facilities in non-weapon states have to be protected against diversion of technology to weapon activities.

AFCI can increase security against material diversion or theft in several ways, especially by eliminating the lasting inventories of spent fuel that could lead to long-term proliferation risks. The once-through fuel cycle offers good proliferation resistance for a short period of time, but the decay of fission products makes unprocessed spent fuel a potential diversion risk after a hundred years. Advanced fuel cycles can enhance long-term proliferation resistance by reducing plutonium production and inventory, increasing intrinsic protection properties of weapons-usable material, and decreasing the amount of uranium enrichment technology required. Most importantly, AFCI technologies will provide advanced countries with a fuel cycle technical option that avoids the proliferation concerns caused by current reprocessing technology while still providing for a very efficient, very long-term nuclear fuel cycle.

In the intermediate term, AFCI transmutation technologies 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. In the long term, Generation IV and AFCI technologies can provide nuclear power without uranium enrichment needs and with transuranic recycle and significant benefits for repository storage.

Provide Competitive Economics

The economics of the nuclear fuel cycle is an essential component in any consideration of the future of nuclear power. In current U.S. nuclear power plants, fuel cycle costs are approximately $0.006/kW-hour. Of this, $0.001/kW-hour 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. Similarly, advanced technologies hold the promise of significantly reducing costs for alternative fuel cycles. As the AFCI program advances, the costs for alternative fuel cycles will become clearer. No fuel cycle technology that does not provide an overall reduction in the long-term costs of the nuclear fuel cycle can or should be adopted by industry.

Provide Excellent Safety

Safety is the one major goal that is not explicitly addressed in any of the comparison tables, though the tables present information that bears on safety. Safety and reliability are critical to current and future separation plants. All future plants deployed in the United States will be licensed by the Nuclear Regulatory Commission and will meet rigorous safety objectives and 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.

Current Comparison

The R&D conducted during the last year permits us to compare more fully some of the major strategy and technology options that best support the major objectives of geologic waste repository capacity, energy security and sustainability, proliferation resistance, and fuel cycle economics. This is a required step before narrowing the range of options in the future. We are gaining increased confidence that there are practical ways to accomplish the major AFCI objectives. Future work will further increase confidence in potential solutions, optimize solutions for the array of objectives, and develop attractive development and deployment paths for selected options. This will allow the Nation to address nearer-term issues such as avoiding the need for additional geologic repositories while making nuclear energy a more sustainable energy option for the long-term.

Our current comparison comprises four tables:

Table 1. Comparison of Advanced Fuel Cycle Strategies
Table 2. Comparison of Separation Technologies
Table 3. Comparison of Reactor Technologies
Table 4. Comparison of Transmutation Fuel Technologies

Table 1 illustrates how separation, transmutation reactors, and fuel technologies combine to create strategies and options that can systematically address national objectives for waste repository capacity, sustainability, proliferation resistance and economics. Tables 2, 3, and 4 provide more information on separation, reactor, and transmutation fuel options, respectively.

While the tables show a number of options, only the most promising are the focus of current AFCI research. The additional entries demonstrate the breadth of options initially considered and include alternatives that may be investigated in more depth in the future if research uncovers performance issues in the currently preferred technologies. Systems analysis studies will combine research results with industry trends to narrow the options to be considered for scale-up development. A summary of AFCI R&D results and future plans is provided in the last section of this report.

II. COMPARISON OF ADVANCED FUEL CYCLE STRATEGIES

Table 1 shows four major potential strategies for the disposal of civilian spent fuel.

- The current U.S. strategy is **once through:** water-cooled nuclear power plants, standard fuel burnup, direct geologic disposal of spent fuel. The table shows variants to the once-through strategy – higher burnup fuels in water-cooled power plants, once-through gas-cooled power plants, and separation (without recycling) of spent fuel to reduce the number and cost of geologic waste packages.
- The second strategy is **thermal recycle**, recycling some spent fuel components in thermal reactors. (See the discussion regarding Table 3 for an explanation of “thermal” and “fast” reactors.) The table shows several variations.
- The third strategy is **thermal+fast recycle**. The difference from the second strategy is that more components of used fuel can be recycled, but at the cost of developing and deploying a fast reactor or accelerator driven system. A mix of thermal and fast reactors would implement this strategy.
- The fourth strategy is pure **fast recycle**; fuel would not be recycled in thermal reactors, which would be phased out in favor of deploying fast power reactors.

Adaptability

This section of Table 1 shows how technology options for reactors, fuels, and separation processes can be combined to implement a given strategy and provide complete energy systems. Note that many technology options are helpful in multiple potential strategies. AFCI is focusing on a set of the most promising technologies addressing the range of potential strategies. The range of potential strategies will be further explored and narrowed over the next several years as it becomes clearer which energy futures are more likely and desirable.

Technology Readiness Levels

The technology readiness levels that are the target of current research for the key technologies for each option are as follows:

- Concept Development – The concept is still at a basic level. Suitable options for various applications are defined based on first principles and fundamental knowledge, with the critical technical issues or “showstoppers” identified, a work-around for showstoppers defined, and a verification plan developed.
- Proof of Principle – The concept has been shown to be technically feasible, but performance characteristics for operational plant performance are uncertain. Development is performed using laboratory scale experiments and analytic extrapolations to full-scale behavior.
- Proof of Performance – The concept is known to be technically feasible and there is considerable performance data, but scale-up to commercial scale is uncertain. Large-scale demonstrations on portions of the processes are performed, yielding final performance specifications, including statistical assessments and initial indications of economic performance.

- Commercial Experience – The technology has analogous commercial experience somewhere in the world and there is good understanding of economic performance.

All of the recycle strategies represent lower technology readiness and hence more need for R&D compared to the once-through fuel cycle strategy. This is most true for the recycle strategies that include fast reactors and associated fuels and separation technologies.

Waste Management Indicators

By working together, separation, transmutation, and fuel technologies provide complete energy systems that can improve waste management compared to the current "once-through/no separation" approach. To understand waste management implications, consider four major components of spent fuel: uranium (U), transuranic (TRU) elements, short-lived fission products, and long-lived fission products. All components of spent fuel must be addressed in each strategy.

- As illustrated in Table 1, most options separate uranium to reduce the weight and volume of waste and the number and cost of waste packages that require geologic disposal. Separated uranium can also be used as reactor fuel.
- Most options provide means to recycle TRU elements - plutonium (Pu), neptunium (Np), americium (Am), curium (Cm). The United States. is not pursuing any option that would separate plutonium by itself.[1] Recycling offers the potential to increase geologic disposal capacity, decrease the long-term waste burden, and extract more energy from a given quantity of uranium resource. There is small potential for improved waste management in the once-through strategy, perhaps a factor of 1.2 (20 percent) for high-burnup light water reactor fuels. There is more potential for improved repository capacity in some thermal recycle options, up to a factor of 2. Adding fast reactor recycle options appear to offer the potential for 40 to 60 times improvement of repository capacity utilization. In these cases, a single geologic repository would be adequate to handle the commercial high-level waste this century, even in high nuclear energy growth cases.
- Most options separate short-lived fission products cesium and strontium to allow them to decay in separate storage facilities tailored to that need, rather than complicate long-term geologic disposal. This can also reduce the number and cost of waste packages requiring geologic disposal. These savings are balanced by costs for separation and recycle systems.
- All options in Table 1 show that several long-lived fission products, such as technicium-99 and iodine-129 go to geologic disposal in improved waste forms, recognizing that transmutation of these isotopes would be a slow process; however, the program has not precluded their transmutation as a future alternative. All options require some amount of geologic disposal, but some options would avoid the need for a follow-on repository for at least a century and perhaps indefinitely.

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[1]The May 2001 *National Energy Policy* specifically states on pages 5-17 and 5-22 that "the United States will continue to discourage the accumulation of separated plutonium, worldwide."

Thus, AFCI's development of a system involving a) the combination of spent-fuel partitioning, b) recycling of transuranic and other long-lived radioactive components in thermal-spectrum reactors, followed finally by c) a treatment in a fast-spectrum facility and separation of cesium and strontium could result in a *de facto* forty to sixty fold increase in the capacity of a geologic repository, based on reducing the long-term heat generation. This *de facto* increase would come from the destruction of transuranic elements that generate the heat that limits repository capacity. The capacity increase would be adequate to handle all the spent fuels generated in this century from any conceivable nuclear energy deployment scenario.

Additional Sustainability Indicators

The next part of Table 1 addresses sustainability and energy recovery. The energy content in uranium ore can be more effectively used as the energy content in spent fuel is recovered. The pattern is similar to that of waste management because the same principle is at work - recycle and use TRU elements. Small improvements in energy recovery are possible with once-through, modest improvements with thermal recycle, and large improvements with fast and thermal recycle working together.

Proliferation Resistance Indicators

Four key components of proliferation resistance are addressed, as explained above: plutonium production and inventory, intrinsic barriers to weapons use, protection of weapons usable material, and the amount of uranium enrichment technology required. The program is aware of the importance and complexity of proliferation resistance. It aims at reducing the inventory of weapons-usable material while increasing the protection of what material remains by both improved safeguard technologies and retention of intrinsic protection from heat rate, radiation field, and spontaneous neutron emission. Work continues to clarify overall proliferation resistance, rather than focusing on only one part of the situation.

Economics Indicators

The final part of Table 1 summarizes indicators of fuel cycle economics: economic energy extraction from fuel, economic separation of spent fuel components, fuels technology, and waste management. These are not simply additive because they do not contribute equally to total fuel cycle cost impact.

Table 1. Comparison of Advanced Fuel Cycle Strategies

Strategy	Once Through				Thermal Recycle				Thermal+Fast Recycle		Fast Recycle	Commments
Illustrative Transmutation Reactor Option	Standard Burnup LWR	High Burnup LWR	High Burnup VHTR	Standard Burnup LWR	LWR with recycle			VHTR with recycle	Keep LWR, add fast reactors	Keep LWR, add accelerator driven system	Phase out thermal, shift to fast reactors	LWR = Light Water Reactor VHTR = Very High Temperature Reactor
Illustrative Transmutation Fuel Option	Uranium oxide	High burnup uranium oxide	High burnup uranium oxycarbide	Uranium oxide	Mixed (U, Pu) oxide 1 pass	TRU mixed (U, Pu, Am, Np) oxide multi pass	Pu, Am, Np in IMF 1 pass	Mixed (Pu, Am, Np) oxide or carbide	U/TRU oxide & U/TRU metal	U/TRU oxide & U/TRU metal	U/TRU metal	IMF = inert matrix fuel TRU = transuranic elements (Pu, Np, Am, Cm)
Illustrative Separation Option	---			UREX	PUREX [1]	UREX+	UREX+	Hybrid Aqueous/ pyroprocess	UREX+, pyroprocess	UREX+, pyroprocess	Pryoprocess	PUREX = Plutonium-Uranium extraction UREX = Uranium extraction UREX+ = Uranium + Pu/MA extraction
Adaptability												
Adaptability to different energy futures	Appropriate for existing reactor fleet. Can support modest nuclear energy growth with technology development.		Supports modest growth. Requires VHTR development.	Supports modest growth futures. Requires UREX development.	Needed if a significant number of new power plants are built. Supports moderate growth futures. Requires fuel and separations technology development.				Needed for high growth futures, esp. growing nuclear market share. Requires significant technology development for advanced reactor and fuel cycle systems.			
Technology Readiness Level												
Reactor Technology	Commercial		Proof of Performance	Commercial	Commercial, but licenses and acceptability for recycle have to be addressed			Proof of Performance	Proof of Performance	Proof of Concept	Proof of Performance	See definitions in text. More advanced options have lower technology readiness. Concepts with lower technology readiness (e.g. concept development) have higher uncertainties.
Fuel Technology	Commercial	Proof of Performance	Proof of Principle	Commercial	Commercial	Concept Development	Concept Development	Concept Development	Concept Development	Concept Development	Concept Development	
Separation Technology	---			Proof of Performance	Commercial	Proof of Performance		Proof of Principle	Proof of Principle			
Waste Management Indicators												
Materials to be recycled	---	---	---	---	Pu	Pu, Np, Am	Pu, Np, Am	Pu, Np, Am	Uranium, TRU	Uranium, TRU	Uranium, TRU	Recycle increases repository capacity, decreases hazardous inventories.
To be sent to geological repository	Spent nuclear fuel	Spent nuclear fuel	Spent nuclear fuel	TRU, LLFP	U, TRU, fission products, oxide fuel after 1 pass[2]	LLFP, spent TRU mixed oxide fuel after multiple passes	LLFP, spent IMF after 1 pass	LLFP, spent fuel after final recycling	LLFP	LLFP	LLFP	LLFP = long lived fission products, e.g., Technium-99 and Iodine-129.
Held in decay storage, later return to fuel cycle	---	---	---	---	---	Curium	Curium	Curium	---	---	---	Curium held in storage for Cm-244 decay (18 year halflife), then return to fuel cycle.[3]
Held in decay storage, later sent to near-surface disposal	---	---	---	Cesium, strontium	---	Cesium, strontium	Cesium, strontium	Cesium, strontium	Cesium, strontium	Cesium, strontium	---	Separation of these short-lived fission products may increase geological repository capacity.
To be sent to near-surface disposal	---	---	---	Uranium	---	Uranium	Uranium	Uranium	Uranium	Uranium	---	Uranium disposed near-surface or retrieved for later use.
Repository benefits	Baseline	Slight capacity improvement due to higher burn-up		Fewer packages due to reduced volume and short term heat load; possibly better waste form	Reduces volume (U), perhaps short-term heat load (Cs-Sr), long-term heat load and toxicity (if Am241 burned); residual waste form can be improved versus baseline				Reduces volume (U), perhaps short-term heat load (Cs-Sr), perhaps long-term heat load and toxicity (TRU, Tc, I); residual waste form can be improved versus baseline			Possible repository benefits include fewer repositories and fewer expansive packages.
Relative repository waste loading per energy produced	Baseline	10-20% improvement due to higher burn-up		Same as baseline unless separated material is recycled	0-10% improvement versus baseline	1.3x to 2.0x improvement due to limited recycle of minor actinides and Pu. Improvement would approach that of thermal+fast recycle if it becomes practical to continuously recycle. 1-pass IMF can achieve 1.3x to 2.0x improvement faster than multi-pass TRU mixed oxide, but has less potential for further improvement.			40x to 60x improvement due to recycle of minor actinides and Pu; even a small fraction of fast reactors allows more complete and continued recycling of several key isotopes than does recycle in purely "thermal" reactors.			Relative number or size of geological repositories assuming long-term heat dominate definition of capacity.
Additional Sustainability Indicators												
Energy security	Baseline: Discard spent nuclear fuel	Slight improvement due to higher burn-up		Same as baseline	Extracts up to 2x more energy from uranium ore than once-through				Extracts up to 50-100x more energy from uranium ore than once through			Uranium recycle is not envisioned in the thermal recycle strategy,[4] limiting the potential energy extraction from the original uranium ore.
Proliferation Resistance Indicators												
Pu production and inventory	Baseline (25 tonnes/year for all US nuclear power plants, inventory does not stabilize)	Production rate down to perhaps half for plants that shift to high burnup, inventory does not stabilize	Production rate down to perhaps half for high burnup VHTRs, inventory does not stabilize	Same as baseline	Reduces Pu inventory ~25% for plants that operate on this material. Inventory does not stabilize for 1-pass.	Production rate slows and inventory stabilizes depending on how many plants burn this fuel	Reduces Pu inventory ~2x for plants that operate on this material. Inventory does not stabilize for 1-pass.	Production rate slows and inventory stabilizes depending on how many plants burn this fuel	No net Pu production, Pu inventory stabilizes. Stabilization level depends on mix of power plant type and burner mode.			Less inventory, less to protect.
Intrinsic barriers to weapons use	Fissile species are not separated. Material has high radiation field for >century, but stored indefinitely.			Material with Cs/Sr removed has high radiation field for < 50 years	Denatured Plutonium [5]	Inclusion of higher actinides gives separation product significant heat fields			Inclusion of higher actinides gives separation product significant heat and spontaneous fission fields			Higher radiation field, heat rate, spontaneous fission increases the difficulty of stealing material and making into weapons
Potential for diversion of weapons-usable material	Baseline	Same as baseline			Recycle materials significantly degraded compared to weapons grade, may not be weapons usable				Recycle materials significantly degraded compared to weapons grade, may not be weapons usable			Uranium always < 20% enrichment, Pu is substantially denatured and remains mixed with assorted minor actinides and possibly other constiuents
Degree and amount of U enrichment technology	Baseline	Slightly reduced due to increased burnup, but fuel would have to be enriched beyond current limit of 5%.		Same as baseline	Slightly reduced due to partial recycle				Slightly reduced due to recycle		U enrichment technology not needed	Higher U enrichment percent, more enrichment technology decreases proliferation resistance
Economics Indicators												
Energy production (economic energy extraction from fuel)	(0) Neutral: Baseline	(+) somewhat higher energy produced	(++) somewhat higher energy produced + hydrogen	(0) Neutral:	(++) increased energy produced	(++) increased energy produced	(++) increased energy produced	(+++): higher burnup and recycling + hydrogen	(++): higher burnup and recycling	(+): energy loss to drive accelerator system	(+++) variable (as breeder)	Economic Benefit Legend: (0) neutral or baseline, (+) positive or more economic, (-) negative or less economic These four rows are not additive because they do not contribute equally t total cost impact and because there would be double-counting of some key considerations. HLW = high level waste LLW = low level waste SWU = separative work unit (measures how much enrichment is needed)
Separations required (economic separation of streams)	(0) Neutral: Baseline	(0) Same as Baseline	(0) Same as Baseline	(-) single aqueous separation	(-) proven, but expensive	(--) incremental cost each recycle	(--) single recycle, multistep separation	(---) complex, 2 part separation technology	(---) UREX+ and pyro process	(---) UREX+ and pyro process	(-) single pyro process	
Fuels technology (economic production of fuel)	(0) Neutral: Baseline	(-) higher enrichment, more SWUs	(-) higher enrichment, more SWUs	(0) Neutral:	(-) developed fuel, recycled	(--) developed fuel, recycled	(--) new IMF fuel form, recycled	(---) higher enrichment, recycled	(--) new TRU fuel form, recycled	(--) new TRU fuel form, recycled	(--) new TRU fuel form, recycled	
Waste management (economic disposition of waste streams)	(0) Neutral: Baseline	(0) less final waste for disposition	(+) reduced HLW, more LLW at lower disposition cost (graphite core)	(+) reduced HLW, more LLW at lower disposition cost	(0) neutral repository loading benefit	(++) U separation as LLW, Actinide reduction for higher repository loading	(++) U separation as LLW, Actinide reduction for higher repository loading	(++) benefits similar to other thermal recycle	(+++) burning all actinides reduces repository loading	(+++) burning all actinides reduces repository loading	(+++) burning all actinides, plus driver fuel for fast reactor systems	

[1] PUREX values are provided for comparison purposes only; this option is not being considered in the AFCI program.

[2] The current standard PUREX approach does not purify uranium sufficiently to meet U.S. LLW criteria so that in PUREX, uranium goes to geological disposal.

[3] This avoids accumulation of isotopes like Californium-252 from neutron capture reactions that are strong gamma emitters. In contrast, fast reactors tend to fission more isotopes with less accumulation of such troublesome isotopes.

[4] Used uranium could be recycled in thermal reactors, but the presence of U-234 and U-236 in the recycled uranium is an issue. Fast reactors are more robust to fuel composition changes.

[5] Plutonium isotopics are inferior to weapons plutonium, but Pu is separated with relatively low radiation field

III. COMPARISON OF ADVANCED FUEL CYCLE TECHNOLOGIES

This section provides more detail on the technology options corresponding to the strategies described in Table 1. The technology options are organized into three primary areas, with corresponding comparison tables:

Table 2: Comparison of Separation Technologies
Table 3: Comparison of Reactor Technologies
Table 4: Comparison of Transmutation Fuel Technologies

The top rows of each technology table indicate the fuel cycle strategies supported by each technology. These strategies correspond to the main column headings in Table 1. Next, each table provides a technical compatibility crosswalk that ties it to the other two technology tables. These rows indicate the combinations of separation, reactor, and transmutation fuel technologies that could work together as part of a full fuel cycle option.

The middle section of each technology comparison table provides information on the development status of the technology.

The AFCI program has five main goals - waste repository capacity and cost, resource use and sustainability, proliferation resistance, economics, and safety. The lower sections of the technology comparison tables provide major indicators for these goals as appropriate.

Comparison of Separation Technologies

Commercial reprocessing is in use today in Europe and is planned to begin in Japan in the near future to separate the materials in SNF to support fissile material recycle and improved waste management. The technology used by these commercial operations is Pu-U Extraction (PUREX). PUREX technology, which separates plutonium from SNF, was originally developed by the United States at Oak Ridge National Laboratory in the late 1940s. The May 2001 National Energy Policy recommends development of alternative reprocessing and fuel treatment technologies that reduce waste streams and enhance proliferation resistance and sharing these technologies with international partners with highly developed fuel cycles. In doing so, the United States will improve advanced fuel cycle economics and waste management while continuing to discourage the accumulation of separated plutonium.

Table 2 provides a picture of the alternative technologies for spent fuel management. Five technologies – PUREX, Uranium Extraction Plus (UREX+), the hybrid UREX/pyrochemical pyroprocess, the entirely pyrochemical pyroprocess, and molten fuel salt treatment – are compared against the direct disposal of spent fuel (the baseline case). Table 2 only includes PUREX technology as a point of comparison. The UREX+ technology supports near-term and intermediate-term Advanced Fuel Cycle Initiative (AFCI) objectives. These objectives are, among other things, aimed at separating uranium and transuranic elements as well as certain fission products from spent nuclear fuel. Such separations could benefit the geologic repository at Yucca Mountain and also recover some of the energy remaining in the spent fuel by allowing it to be recycled in existing light water reactors (LWRs). In the case of the gas-cooled Very High Temperature Reactor (VHTR), such recycle is less likely because of the high burnup of its fuel and the technical challenges facing the reprocessing of the fuel type. All of the advanced separations processes being considered support longer-term AFCI objectives, which aim at extracting material from spent nuclear fuel for recycle in a future generation of Generation IV reactors that may be commercially deployed around 2040. For the purposes of comparison, this analysis assumes that all spent fuel initially treated is generated by LWRs.

Comparison of Reactor Technologies

Table 3 compares transmutation reactor technologies regarding their impact on advanced fuel cycle objectives, including technology readiness, destruction rate of TRU isotopes, potential for repeated recycle, and maximum conversion ratio. Current reactors, advanced reactors (Generation IV), and accelerator driven systems are compared.

"Generation I" experimental reactors were developed in the 1950s and 1960s. "Generation II" large, central-station nuclear power reactors were built in the 1970s and 1980s. This category includes most of the commercial nuclear power plants in the world today, including the 104 in the United States. The vast majority of these are light water reactors (LWRs) that use boiling water or pressurized water as their coolants. They extract energy in ways that are similar to power plants that burn coal, natural gas, or petroleum. The difference is that nuclear fission is the source of heat rather than combustion of fossil fuels.

Generation III advanced water reactors were built in the 1990s primarily in East Asia to meet that region's expanding electricity needs. Generation III+ advanced reactors include both water- and gas-cooled reactors with advanced economics and safety, such as the AP1000 and Pebble Bed Modular reactors, which are being proposed as commercial or development projects in various countries; some are presently offered for construction in the United States.

Looking ahead, Generation IV advanced nuclear energy systems are the focus of future R&D. The *Technology Roadmap for Generation IV Nuclear Energy Systems* issued in 2003 documents the comprehensive evaluation and describes the most promising candidates for next-generation nuclear energy systems. More than 100 experts from twelve countries and international organizations collaborated on the Roadmap. The Roadmap was issued jointly by DOE's Nuclear Energy Research Advisory Committee (NERAC) and the Generation IV International Forum (GIF). The GIF is comprised of member nations that share the goals for future nuclear energy systems expressed in the Roadmap. The GIF coordinates member nation research and development programs to magnify the resources available for technology development.

There are six Generation IV reactor concepts that are recommended in the roadmap as having the most promise for meeting the Generation IV goals. Advanced Generation IV nuclear concepts would use gas (the Very High Temperature Reactor, or VHTR, and the gas fast reactor, or GFR), supercritical water (the Super Critical Water Reactor, or SCWR), liquid sodium metal (the sodium fast reactor, or SFR), liquid lead metal (the lead fast reactor, or LFR), or molten salt (the molten salt reactor, or MSR) as coolants. These Generation IV concepts offer the potential to improve sustainability, proliferation resistance, safety and reliability, and economics. They also offer the potential to expand the use of nuclear energy beyond electricity generation to include other uses of process heat. Generation IV options vary significantly in their technological readiness. There have been test power reactors with earlier versions of the gas, sodium, and molten salt options. Russian submarines have used lead/bismuth-cooled reactors. The supercritical water concept is very new.

One of the key characteristics of nuclear plants is the energy of neutrons, thermal or fast. Thermal reactors use lower energy ("thermal") neutrons to sustain the fission process. Isotopes that help sustain the fission process in thermal reactors are called "fissile," *e.g.* uranium-235. Water is commonly used in such reactors for a coolant since the hydrogen contained in water effectively slows down the highly energetic neutrons generated during fission. Virtually all nuclear power plants today are "thermal." As listed in Table 3, three of the six Generation IV concepts are also thermal reactors and therefore could support the thermal recycle fuel cycle strategy. Often, the reactor design and fuel specifics would have to be tailored according to which fuel cycle strategy was adopted.

Three of the six Generation IV concepts are fast reactors; two others may partially be adapted to "fast" conditions. These fast concepts could support the fast recycle strategy (typically with conversion ratios near 1) or the thermal+fast recycle strategy.

Selection among Generation IV concepts depends also on factors beyond direct fuel cycle considerations. For example, concepts with potentially very high coolant outlet temperatures may allow more economic uses of process heat, *e.g*., for hydrogen production. Also, safety and reliability are critical to current and future nuclear power plants and all plants will continue to meet rigorous safety objectives and requirements. Generation IV plants aim for yet further improved safety characteristics. As the expected design of advanced reactor types is better known, safety indicators can be added to reactor comparisons in future years.

One of the transmutation options involves the use of an Accelerator Driven System (ADS), which provides a sub-critical fast spectrum burn option. The ADS could be used in combination with the thermal recycle of plutonium and other TRU such as neptunium and americium. The remaining degraded plutonium and minor TRU would be sent to the ADS for further transmutation. ADS development is continuing, primarily in Europe and Japan. Low power experiments have been completed, and several higher power demonstrations are in the design phase.

Taken together, Tables 1 and 3 provide insights into how the AFCI and Generation IV programs work together. The VHTR thermal Generation IV option is a relatively nearer-term option that is the focus of the Next Generation Nuclear Plant (NGNP) effort. It appears to provide the highest potential outlet temperature (hence potential for higher thermal efficiency and hydrogen production). Fast spectrum Generation IV options provide transmutation of more isotopes, thereby offering greater potential benefits to geological repositories and energy extraction from uranium ore. Future work is needed to explore the potential for attractive mixes of reactor types, *e.g*., make maximum use of the existing LWR infrastructure, add VHTR for high-temperature benefits, and eventually add dedicated fast reactors to transmute isotopes that would not be easily transmuted in an LWR and VHTR fleet.

Comparison of Transmutation Fuel Technologies

Table 4 compares several transmutation fuel technologies with regard to status, waste management indicators, and proliferation resistance indicators. Fuels literally link the various parts of the fuel cycle – nuclear power plant, separation facility, fuel fabrication plant, and ultimate waste disposal. Therefore, the options for fuels and these fuel cycle facilities must work together.

Fuel behavior, performance, and management strategies have strong influences on waste management. There are four general fuel management strategies – once through/direct disposal, recycle once, limited number of recycles, recycle repeatedly. From a fuel technology standpoint, “limited number of recycles” is the same as “recycle repeatedly” and is therefore not reflected in Table 4. The AFCI and Generation IV are pursuing advanced fuels for all fuel management strategies.

Used, irradiated “spent” fuels can be disposed directly; this is the baseline U.S. for the current fuel cycle using uranium oxide fuel. In this case, there is no separation facility. There is only one kind of fuel fabrication plant – the plant to make the initial fuel.

Used fuel can be processed and separated and some components made into new fuels, which can then be used once or repeatedly. In these cases, there must be a separation facility to process the initial used fuel and multiple fuel fabrication facilities to make both the initial fuel and the recycle fuel. (If the initial fuel and recycle fuel are similar, they may use the same fabrication plant.) If the management strategy is repeated recycle, there must also be a separation facility to process the recycled fuel. This would probably be the same separation facility used for the first recycle.

There are not specific safety and economic indicators for individual fuel options because safety and economic performance is primarily associated with the operation of the fuel cycle facilities - reactors and separation plants.

Table 2. Comparison of Separation Technologies

Separation Approach	None (Current US Approach)	PUREX [1]	UREX+	Aqueous/ Pyroprocess Hybrid	Pyroprocess	Molten Coolant Salt Processing	Comments
Strategies Supported							
Once Through	Yes	---	---	---	---	Yes	Dashes denote the fuel option does not support the strategy.
Thermal Recycle	---	Yes	Yes	Yes	Yes	Yes	
Thermal+Fast Recycle	---	Yes	Yes	Yes	Yes	Yes	
Fast Recycle	---	Yes	Yes	Yes	Yes	Yes	
Compatible Transmutation Reactor Options							
Light Water Reactor (LWR)	Yes	Yes	Yes	Yes	---	---	
Very High Temperature Reactor (VHTR)	Yes	---	---	Yes	Yes	---	
Supercritical Water Reactor (SCWR)	Yes	Yes	Yes	Yes	---	---	
Molten Salt Reactor (SFR)	---	---	---	---	---	Yes	
Sodium Fast Reactor (SFR)	---	---	---	Yes	Yes	---	
Lead Fast Reactor (LFR)	---	---	---	Yes	Yes	---	
Gas Fast Reactor (GFR)	---	---	---	Yes	Yes	---	
Compatible Transmutation Fuel Options							
Oxide	Yes	Yes	Yes	Yes	---	---	
Carbide/oxycarbide	---	---	Yes [2]	Yes	Yes	---	
Metal	---	---	---	Yes	Yes	---	
Nitride	---	---	Yes	Yes	Yes	---	
Molten salt	---	---	---	---	---	Yes	
Status							
New technology needed	None	Adapt foreign technology to US situation	Processing plant, Waste forms	Processing plant, Waste forms	Processing plant, Waste forms	Processing plant, Waste forms	Waste forms are required for each separation stream that is not recycled.
Technology Readiness Level	In Commercial Operation	In Commercial Operation	Proof of Performance; In Final Phase of Laboratory Scale Demonstration	Proof of Principle; UREX Demonstrated at Lab Scale; pyroprocess in conceptual development	Proof of Principle; Lab scale research in progress; partial engineering demonstration of metal fuel treatment	Proof of Principle; Partial engineering scale demonstration; lab scale development needed	All options require a geological repository, which is approaching licensing in the U.S.
Waste Management Indicators [3]							
Able to separate isotopes that dominate short-term heat load	No	No	Yes	Yes	No	Not developed [4]	Cesium and strontium isotopes and their daughters
Able to separate isotopes that dominate long-term heat load	No	No	Yes	Yes	Yes	Yes	Plutonium and americium isotopes
Able to separate isotopes that dominate long-term toxicity	No	No	Yes	Yes	Yes	Yes	Technium and iodine isotopes, TRU isotopes
Avoids liquid waste generation	Yes	No	Yes	Yes	Yes	Yes	Important to waste management and safety
Recycle to LWRs/year	-0-	17 tonne Pu	18 tonne Pu-Np	21 tonne TRU	21 tonne TRU	None; fuel is recycled internally	Some options would allow recycle to LWRs and/or future advanced reactors.
Recycle to future reactors per year (if not to LWRs)	-0-	-0-	3.2 tonne Am-Cm	21 tonne TRU	21 tonne TRU; 170 tonne U	Fuel recycled to MSRs	
High-level waste/year	2,000 tonne heavy metal in spent nuclear fuel; 660 tonne cladding	490 tonne glass; 1,900 tonne U	230 tonne glass [5]	280 tonne ceramic waste form	490 tonne ceramic waste form	490 tonne fission product waste form (similar to pyroprocess)	U is HLW in PUREX because of Tc-99. Other separation processes (UREX, pyro, etc.) are instead tailored to meet U.S. LLW criteria.
Low-level waste/year	-0-	350 tonne raffinates and process materials; 660 tonne cladding	1,900 tonne U; 660 tonne cladding	1,900 tonne U; 660 tonne cladding	1,700 tonne U; 660 tonne cladding	1,700 tonne U in oxide form; no cladding	Waste from processing, not reactor operation.
Secondary waste/year	42 tonne contaminated resins from shipping cask cleaning	2.1 tonne used equipment	3.5 tonne used equipment	4.2 tonne used equipment	2.1 tonne equipment	Similar to pyroprocess; integral to reactor operation.	Waste from processing, not reactor operation.
Net Chemical Consumption per year	-0-	4.2 tonne reagents; 420 tonne glass frit	7 tonne reagents; 124 tonne glass frit	5.6 tonne reagents; 280 tonne zeolite + glass; 42 tonne salt	420 tonne zeolite + glass; 80 tonne salt	420 tonne waste; 80 tonne salt	Reagents are substances that take part in other reactions, e.g., nitric acid in which the separation occurs.
Proliferation Resistance Indicators							
Avoid separation of pure Pu?	Yes	No	Yes	Yes	Yes	Yes	U.S. policy is to avoid separation of pure Pu.

[1] The PUREX estimates in this table are provided for comparison purposes only; this process is not being considered in AFCI planning.

[2] UREX+ can be applied to TRISO fuels if a grind-leach progress can be applied. If not, either once-through or hyrbrid processing may be required.

[3] Assumes addition of nuclear generating capacity, to keep constant output of 2000 tonne/year and fuel burnup of 50,000 MW-days/tonne.

[4] From volatility considerations, cesium separation should be tractable; strontium is unknown.

[5] This waste form may not be borosilicate glass; less expensive waste forms are being developed to take advantage of the very low heat load presented by the wastes from this process. For purposes of comparison, a 30% waste loading in glass was assumed here.

Table 3. Comparison of Reactor Technologies

Reactor Approach	Light Water Reactor (LWR)	Very High Temperature Reactor (VHTR)	Super Critical Water Reactor (SCWR)	Molten Salt Reactor (MSR)	Sodium Fast Reactor (SFR)	Lead Fast Reactor (LFR)	Gas Fast Reactor (GFR)	Accelerator Driven System (ADS)	Comment
Strategies Supported									
Once Through	Yes	Yes	Yes	Yes	---	---	---	---	Dashes denote the fuel option does not support the strategy.
Thermal Recycle	Yes	If configured for recycle	Yes	Yes	---	---	---	---	
Thermal+Fast Recycle	Yes	If configured for recycle	Yes	Yes	Yes	Yes	Yes	Yes	
Fast Recycle	---	---	If fast spectrum option	If fast spectrum option	Yes	Yes	Yes	---[1]	
Compatible Separation Options									
UREX+	Yes	---	Yes	---	---	---	---	---	
Pyroprocess	---	Yes	---	---	Yes	Yes	Yes	Yes	
Aqueous/pyroprocess hybrid	Yes	Yes	Yes	---	Yes	Yes	Yes	Yes	
Molten salt processing	---	---	---	Built in	---	---	---	---	
Compatible Transmutation Fuel Options									
Uranium oxide	Yes	Yes	Yes	---	---	---	---	---	
U/TRU mixed oxide	Yes	Yes	Yes	---	Yes	---	---	---	
TRU inert matrix	Yes	Yes	Yes	---	Yes	---	---	---	
Americium targets	Yes	Yes	Yes	---	---	---	---	---	
Coated oxycarbide	---	Yes	---	---	---	---	Yes	---	
U/TRU metal	---	---	---	---	Yes	Yes	---	Yes	
U/TRU nitride	---	---	---	---	Yes	Yes	---	Yes	
Dispersion	---	---	---	---	---		Yes	---	
Molten fluoride salt	---	---	---	Yes	---	---	---	---	
Status									
Nuclear Power Plant Generation	II, III, III+	III+, IV	IV	IV	III+, IV	IV	IV	Not applicable	See definitions in text.
Technology Readiness Level	Commercial experience	Proof of performance scale experience with VHTR predecessors	Concept development	Proof of Principle	Proof of performance experience with SFR predecessors	Limited proof of principle	Concept development	Proof of principle	See definitions in text. Generation IV roadmap has more information.
Robustness of reactor operation to fuel composition changes before irradiation or during irradiation.	Low: fertile isotopes are neutron consumers, but fissile isotopes are neutron suppliers.			High: controllable, homogenous liquid	High: both fertile and fissile isotopes are net neutron suppliers.			ADS operates subcritical, therefore not as important	Fuel composition (Pu, MA) may change before irradiation (due to isotope decay) or during irradiation. Composition changes can impact reactor performance.
	Pu241 to Am241 D-factor[2] change = 1.3	Similar to LWR	Similar to LWR	Pu241 to Am241 D-factor change intermediate values depending on spectrum	Pu241 to Am241 D-factor[2] change = 0.5	Pu241 to Am241 D-factor[2] change = 0.6	Pu241 to Am241 D-factor[2] change = 0.7		
Waste Management Indicators									
TRU Destruction Rate in Burner Mode (Low Conversion Ratio), kg/year per MWt of capacity	0.31 for IMF 0.12 for oxide fuel	Similar to LWR	Similar to LWR	Intermediate values depending on spectrum and design	0.24 (corresponds to conversion ratio of 0.25)	Similar to SFR	Similar to SFR	0.28	TRU destruction reduces long-term heat load and doses.
Potential for Repeated Recycle	Yes with curium removal and enriched uranium support			Yes, default operation mode	Yes				Repeated recycle minimizes geological waste. Practical limitations on repeated recycle need further assessment.
Sustainability Indictors									
Maximum Conversion Ratio	0.8	0.8	0.8	0.8 (once through) - 1.1 (on-line processing)[3]	1.3	1.3	1.3	Only burner mode is being considered	Increased conversion ratio improves energy utilitization of original ore; reduced conversion in recycle more effectively burns TRU. Minimum conversation ratio is near zero.
Proliferation Resistance Indicators									
On-line Versus Batch Refueling	Batch	On-line (pebble bed variant) or batch (prismatic)	Both	On-line [3]	Batch	Batch (but infrequent in the "cassette" design)	Batch		Batch processing may be a proliferation resistance advantage.
Fuel Processing Location	Central plant			On-site	Can be on-site				On-site processing may be an advantage because of reduced transportation needed.
Other Economic Indicators									
Maximum Outlet Temperature (°C)	320	850-1000 [4]	550 [4]	700-850 [4]	550 [4]	550-800 [4]	850 [4]	Not defined nor relevant	Temperatures >850°C permit hydrogen production, higher temperatures improve thermal efficiency

[1] There is little need for an ADS in a pure fast reactor system as there would be sufficient fast spectrum power reactors to transmute.

[2] D-factors measure neutron balance, negative=neutron surplus, positive=neutron consumer.
Larger changes because of composition change (e.g. Pu-241 decay to Am-241) means reactor operation is more sensitive to the change.

[3] On-line/on-site processing required for high conversion ratio to allow Pa-233 decay to U-233 out of reactor. Burner mode (lower conversion ratio) could be operated batch/off-site processing.

[4] "A Technology Roadmap for Generation IV Nuclear Energy Systems", GIF-002-00, December 2002

Table 4. Comparison of Transmutation Fuel Technologies

Transmutation Fuel Option [1]	Mixed Oxide Fuel without Minor Actinides [2]	TRU Mixed Oxide Fuel (with Minor Actinides)	Inert Matrix Fuel (IMF) with Minor Actinides	Americium targets	TRISO with TRU (carbide, oxycarbide)	Metal	Nitride	CERCER (ceramic/ceramic), CERMET (ceramic/metal)	General Dispersion	Comment
Strategies Supported										
Once Through	---	---	---	---	---	---	---	---	---	Dashes denote fuel option does not support the strategy.
Thermal Recycle	Yes	Yes	Yes	Yes	Yes	---	---	---	---	
Thermal+Fast Recycle	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Fast Recycle [2]	---	---	---[3]	---[3]	---	Yes	Yes	Yes	Yes	
Compatible Separation Options										
Uranium Extraction Plus (UREX+)	Yes	Yes	Yes	Yes	---	---	Yes	Yes	Yes	
Pyroprocess	---	---	---	---	Yes	Yes	Yes	---	---	
Aqueous/pyroprocess hybrid	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Plutonium-Uranium Extraction (PUREX) [2]	Yes	---	---	---	---	---	---	---	---	
Compatible Transmutation Reactor Options										
Light Water Reactor (LWR)	Yes	Yes	Yes	Yes	---	---	---	---	---	
Very High Temperature Reactor (VHTR)	Yes	Yes	Yes	Yes	Yes	---	---	---	---	
Supercritical Water Reactor (SCWR)	Yes	Yes	Yes	Yes	---	---	---	---	---	
Sodium Fast Reactor (SFR)	---	Yes	Yes	---	---	Yes	Yes	Yes	---	
Lead Fast Reactor (LFR)	---	---	---	---	---	Yes	Yes	Yes	---	
Gas Fast Reactor (GFR)	---	---	---	---	---	---	---	Yes	Yes	
Accelerator Driven System (ADS)	---	---	---	---	---	Yes	Yes	---	---	
Status										
Technology Readiness Level	Commercial in Europe	Concept Development	Concept Development	Ready to Start Proof of Principle	Ready to Start Proof of Principle	Early Proof of Principle			Concept Development	Key issue is often the inclusion of Np, Am, and Cm. Thus, confidence increases as Np-Am-Cm fraction (left over from LWR recycling) decreases.
Experience	Extensive experience/ database	Some experience (small scale)	Some experience with U & Pu. No meaningful experience with Np, Am, Cm	Some experience	Extensive experience with U. Some experience with Pu	Extensive experience for U-Pu metal fuels	Extensive experience for U fuels	Some experience for U-Pu oxide fuels	Some experience for U-Pu oxide fuels	
Overseas interest	Already being used in Europe and Japan	Some	Some	Some	Some	Some	European back-up option (considerable research). Considerable lab property data in Japan.	European baseline (considerable research)	Considerable research in France	Fuel development could benefit from continued international cooperation.
Waste Management Indicators										
Potentially reduces MA inventory?	No	Yes, but inefficient because TRU are produced from fertile material	Yes, efficient without generating more TRU in those pins	Yes, reduces Americium using LWR technology.	Very efficient	Yes, very efficient as all such isotopes can be consumed in a fast spectrum reactor.				TRU isotopes typically dominate repository long-term heat and estimated dose.
Suitable waste form if not recycled?	Same as baseline	Same as baseline	Yes, probably better waste form than baseline			To be assessed. Fast reactor fuels are being designed for repeated recycling.				Baseline is spent uranium oxide
Suitable form for repeated recycling?	Yes	Yes	Depends on matrix material	Yes	Yes if recycling is needed, materials and technology must be developed and tested	Yes	Yes	Yes	Potentially yes, but an effective matrix material has not been decided yet.	Each fuel is generally developed for recycling. However, some IMF and carbides are difficult to recycle.
Possible matrix materials	Uranium and Oxygen (possibly Thorium)	Uranium and Oxygen (possibly Thorium)	MgAl2O4 (recycling), ZrO2 (difficult to recycle), SiC (difficult to recycle)	Americium metal	Carbon, SiC, Oxygen	Uranium and Zirconium	Zirconium nitride	Ceramic: SiC, TiC, TiN, ZrC, ZrN Cermet: Nb or Mo, UO2	Not yet developed	Matrix determines ease of separation or quality of waste form; they must be recycled or become waste.
Maximum expected burn-up (GW-day per tonne of initial heavy metal)	50-100	50-100	550	Not defined	Stable fuel for very high burnup	250	500	Stable fuel for very high burnup	Stable fuel for very high burnup	Higher burnup decreases waste generated per GW.
Proliferation Resistance Indicators										
Reduces Pu inventory	Yes, but inefficient, requires multiple recycles to obtain significant Pu-239 inventory reduction.		Yes, efficient without generating more Pu in those pins	Not applicable	Yes, efficient because of high burnup potential.	Yes, efficient because all Pu isotopes are consumed in fast reactor spectrum.				Less inventory, less to protect

[1] Table only includes fuels that can transmute one or more TRU (Pu, Np, Am, Cm); therefore current uranium oxide fuel and TRISO without TRU are not shown.

[2] Included for comparison with foreign programs; U.S. program not considering pure separating plutonium, other TRU would always be included.

[3] There is little value in using separate Am targets in fast reactors as all TRU will transmute adequately in a single fuel type; similarly, the likely separation technique (pyro and variations thereof) would not separate Am from other elements. There is little reason to use IMF in fast reactors as IMF is aimed at quickly eliminating Pu-Np-Am inventory via dedicated targets instead of an integrated fast burner configuration.

IV. STATUS OF ADVANCED FUEL CYCLE INITIATIVE RESEARCH

This section presents the significant accomplishments of AFCI supporting the U.S. transition to a sustainable nuclear energy future. The highlighted program achievements make measured progress towards closing the nuclear fuel cycle and assuring a secure, reliable, and environmentally advantageous source of energy for the nation. The AFCI research efforts are organized in four technical areas: Separations, Fuels, Transmutation and Systems Analysis. Notable accomplishments in university collaboration are presented, along with a brief discussion of planned future milestones.

Separations

AFCI separations research focuses on partitioning and waste management supporting both the near-term fuel cycle and future Generation IV systems. Chemical separations are the key to reducing high-level waste volume, heat load imposed on the geologic repository, and the time needed for waste to decay to background levels. Separations research includes both advanced aqueous processing and non-aqueous technology. Advanced aqueous processing focuses on the UREX process, while non-aqueous processing has been concentrated on the electrometallurgical technique. Highlighted accomplishments include:

- Laboratory-Scale UREX+ Demonstration –UREX+ is an advanced aqueous solvent extraction process under development for the treatment of commercial Light Water Reactor (LWR) spent fuel. Laboratory scale separation of very pure uranium (99.998%) from irradiated fuel was demonstrated using all required steps including U, Cs/Sr, Pu/Np, and Am/Cm separation.

- UREX+ Solvent Extraction Hot Test – Laboratory-scale demonstration of the U/Pu/Np co-extraction process, an advanced version of UREX+, has been completed using radioactive materials.

- Cs/Sr Extraction Process Development – Laboratory testing of a chlorinated cobalt dicarbollide/polyethylene glycol-based solvent extraction process for separation of Cs and Sr from dissolved LWR fuel has been completed.

- Actinide Crystallization Process – This process is a possible front-end for separation of uranium prior to UREX+ extraction, greatly reducing quantity of liquid to be processed. Bench-scale tests have been completed and a crystallizer of sufficient size is being built to obtain data applicable to a full-scale unit.

- PYROX Process Development – The pyrochemical reduction (PYROX) process is being developed for treatment of Generation IV oxide fuels. High-capacity reduction experiments and improvements in cell design have been completed.

- Advanced U/TRU Recovery – Operation of fully integrated electrolysis equipment has been successfully demonstrated, with future efforts considering definition of operating parameters and a design concept for a commercial-scale electrolysis cell.

- EBR-II Fuel Electrometallurgical Treatment (EMT) – The Experimental Breeder Reactor-II (EBR-II) driver fuel contains elemental sodium, which is not acceptable for direct repository disposal. The EMT activity is recovering pure uranium from the fuel, leaving the transuranic elements in an electrolyte salt for disposal along with fission products such as Cs and Sr.

- Ceramic Waste Form (CWF) Qualification Testing – Laboratory tests support qualification of the CWF by characterizing degradation behavior, developing models to calculate long-term degradation behavior under repository conditions, and confirming the applicability of models.

Fuels

AFCI fuels development includes fast spectrum Generation IV fuels, proliferation-resistant LWR and Advanced LWR fuels, and prototypic transmutation fuels for Generation IV reactors. Highlighted accomplishments include:

- Metal Fuels – Efforts have been focused on providing small samples of metal fuels with well-characterized microstructures for irradiation testing, with experience gained in fabricating small samples providing a basis for developing large-scale fuel manufacturing processes in subsequent years.

- Nitride Fuels – Development is continuing on nitride fuels capable of high-burnup, compatible with low-loss separations processing, easily fabricated in a remote environment, and exhibiting benign behavior during core steady-state and off-normal events.

- Mixed Oxide Fuels – Mixed oxide (U+Pu+Np) fuels are being developed for LWRs to demonstrate thermal spectrum burning of actinides.

- Advanced Test Reactor Irradiation Tests – Irradiation performance data from ongoing tests of fuel capsules will be combined with physical, thermal, and chemical property data to develop models of the complex behavior of fuels. Although the current TRISO fuel focus is on NGNP reactor design, the irradiation performance data can be used for future gas reactor concepts.

- FUTURIX Collaboration – FUTURIX is a collaborative experiment in which Pu, Np, and Am bearing nitride and metallic fuels will be fabricated in the U.S., encapsulated in Germany, irradiated in France, and finally shipped back to the U.S. for post-irradiation examination (PIE) and separations testing.

Transmutation

Transmutation is the process of transforming one nuclide into another via neutron-induced fission or capture, to reduce isotopes in spent nuclear fuel that dominate the issues of nuclear material management and waste disposition. Isotopes of interest dominating the long-term heat load and radiotoxicity are Am-241, Pu-241, and Np-237, and isotopes affecting global nuclear materials management are U-235 and Pu-239. Transmutation may lower decay timescales to hundreds of years reducing toxicity and heat-load challenges to a geologic repository. Highlighted accomplishments include:

- DELTA Loop Corrosion Tests – Technology development is centered on a lead-bismuth test loop, in which 1000-hr corrosion tests on a large matrix of materials were recently completed. Test specimen analysis showed the efficacy of oxygen control in mitigating corrosion, and indications of Si and Cr alloying enhancing corrosion resistance by forming stable and protective oxides.

- Irradiated Materials Testing – Three-point bend tests have been completed at room temperature, 250°C, 350°C and 500°C on steels irradiated in rod form, providing important data on the effects of high energy protons and neutrons on the mechanical properties of prototypic structural materials.

- AFCI Materials Handbook – The Materials Handbook section on properties and characteristics of fast spectrum reactor materials has been revised to include data on the effects of irradiation on the mechanical properties of prototypic structural materials.

System Analysis

Systems analysis bridges the program technical areas and provides the models, tools, and analyses required to assess the feasibility of design and deployment options and inform key decision maker. The systems analysis activity is conducted jointly with the Generation IV Program. Highlighted accomplishments include:

- Evaluating the capability of various reactor systems to handle transmutation, including extended burn-up of Pu in LWR and gas-cooled reactors, potential for destroying minor actinides in LWR, and consumption of transuranics in fast reactors and accelerator driven systems.

- Assessing the benefits of advanced fuel cycles to reduce the need for additional geological waste repositories and more efficiently use the first repository.

- Performing dynamic simulations of fuel cycles to quantify infrastructure requirements and identify key trade-offs between alternatives.

- Evaluating repository performance for characteristics such as volume, mass, and heat load; comparing various fuel cycles, reactor facility requirements, life cycle costs, and repository savings.

University Collaborations

The AFCI supports university research and funds fellowships for students in nuclear engineering. AFCI supports directed research at a number of universities, and has dedicated University Programs with (1) the University of Nevada at Las Vegas in advanced radiochemistry, materials and transmutation technologies, (2) the Idaho Accelerator Center for facilities used in research and education in charged particle accelerator applications in nuclear and radiation science, and (3) the University Research Alliance, managing the Fellowship Program supporting students in disciplines related to transmutation research and technology development.

Future Objectives

The AFCI is focused on research and development supporting the advanced fuels and fuel cycles for Generation IV, and informing the Secretarial recommendation in the 2007-2010 timeframe on the technical need for a second repository. High priority AFCI program objectives over the next ten years include:

- 2008 – Provide engineering data and analysis to support the Secretarial Recommendation to Congress on the technical need for a second repository.
- 2010 – Quantitatively define feasible nuclear fuel cycle options and technologies for implementation, and develop fuel cycle technologies that enable transition to an advanced fuel cycle.
- 2015 – Provide engineering data and analysis for a recommendation of the best option for an advanced nuclear fuel cycle incorporating Generation IV technology.