Current Comparison of Advanced Nuclear Fuel Cycles

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ABSTRACT

This paper compares potential nuclear fuel cycle strategies – once-through, recycling in thermal reactors, sustained recycle with a mix of thermal and fast reactors, and sustained recycle with fast reactors. Initiation of recycle starts the draw-down of weapons-usable material and starts accruing improvements for geologic repositories and energy sustainability. It reduces the motivation to search for potential second geologic repository sites. Recycle in thermal-spectrum nuclear reactors achieves several recycling objectives; fast nuclear reactors achieve all of them.

INTRODUCTION

A nuclear fuel cycle addresses cradle (uranium ore) to grave (disposal of residual wastes) and all components of fresh and used fuel. The uranium and transuranic (TRU) elements in used nuclear fuel still have considerable energy content, but must be removed from the reactor because of the accumulation of fission products that spoil the nuclear reaction. The two basic approaches for used fuel are once-through or recycle. The once-through approach disposes of 100% of the used fuel as waste. There are several variations on the recycle approach, which are compared in this paper. Each recycle option separates and recycles some or all of the energy-containing materials - uranium (94% of used fuel mass) and transuranic elements (1%). The fission products (5%) are waste and can be further separated so that the management of each waste stream is tailored to its characteristics. A complete fuel cycle must address uranium, all the transuranic elements (not just plutonium), and key groups of fission products.

OBJECTIVES

Nuclear energy's contribution to improving sustainability and energy security can be enhanced by reducing the long-term environmental burden of nuclear waste, improving proliferation resistance, and enhancing the use of nuclear fuel resources. We summarize the objectives of the Advanced Fuel Cycle Initiative (AFCI) as provided by the Department of Energy to Congress.[1]

Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient use and disposal of waste materials. Under all strategies and scenarios for the future of nuclear power, the United States will need to establish a permanent geologic repository to deal with high-level radioactive wastes resulting from nuclear power. *The AFCI aims to defer the need for a second repository at least until the next century.* 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. Without recycling, scenarios that postulate a growing energy market share for nuclear power could produce over 3.5 million tonnes of used nuclear fuel by 2100 at nuclear energy growth rates up to 4.5% as envisioned by six national laboratory directors,[2] hence requiring up to 50 repositories, each repository with an assumed capacity of 70,000 tonnes.

Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for used fuel management. Any program or project aimed at future nuclear energy technologies must properly address the issue of "proliferation resistance" of the overall system in which the advanced technologies would be deployed. Both institutional (not considered here) and technological measures must be considered. Technological measures to reduce proliferation risk include those that will reduce the attractiveness of materials and processes for weapons purposes. Also, the technical proliferation risk measures include a variety of steps to increase the efficacy of international safeguards such as improved monitoring equipment. *The AFCI aims to develop a progressive fuel cycle approach that will set a high standard of proliferation resistance that the rest of the world may be willing to adopt.* To provide a higher standard of proliferation resistance, AFCI technologies must reduce nuclear proliferation risk relative to current nuclear fuel cycle technologies such as plutonium separation technology (PUREX). Proliferation resistance measures include proliferation technical difficulty (the inherent technical difficulty, arising from the need for technical sophistication and materials handling capabilities, to overcome barriers to proliferation), fissile material type, time and cost to overcome proliferation barriers, and detection probability.[3]

Objective 3. Enhance energy security by extracting energy from used fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power. Nuclear power requires raw fuel material, either uranium or thorium. Essentially all nuclear power plants today use uranium for fuel. Uranium resources are currently adequate and the uranium purchase price 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 incentive in recent decades to explore for new uranium resources. As nuclear energy continues to expand globally and current stockpiles are used, new technological options may be required to ensure domestic energy security against resource depletion. *The AFCI aims to develop ways to increase the energy extracted from uranium and transuranics, both extending the resource and increasing the fraction of uranium ore sources that can be economically used.*

Objective 4 (part 1). Continue Competitive Economics:[1] The economics of the nuclear fuel cycle is an essential component in any consideration of the future of nuclear power as a primary energy source. The average cost of electricity from current U.S. nuclear power plants is less than $0.018/kilowatt-hour or 18 mills/kilowatt-hour (18 mills/kW-hr) because their capital costs have mostly been retired.[4] Projections for the average cost of electricity from new nuclear power plants in the next decade range from 47 to 71 mills/kW-hr including capital recovery.[4] Fuel cycle costs for the current once-through fuel cycle are about 6 mills/kW-hr.[4] Of this, 1 mill/kW-hr is the fee paid by U.S. utilities to the Federal government for future geologic disposal, covering projected disposal costs.

Objective 4 (part 2). Continue Excellent Safety Performance: Safety and reliability are critical to all nuclear facilities. The Nuclear Regulatory Commission licenses U.S. commercial nuclear facilities and requires such facilities to meet rigorous safety requirements.

ALTERNATIVES

The first question in generating alternatives is once through or recycle. The second question is what types of nuclear power plants are involved in the fuel cycle. There are two basic types of nuclear power plants – thermal and fast – differentiated by their average neutron energy. Worldwide, essentially all commercial nuclear power plants today are thermal reactors, including the light water reactors (LWR) used in the U.S. The French, Japanese, and Russians have operating fast reactors, all sodium cooled. There are therefore four basic strategies – once through, thermal reactors only, mix of thermal and fast reactors, or fast reactors only. A complete fuel cycle

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[1] The wording of this objective does not claim that alternative alternatives are necessarily competitive, but rather to denote the objective that alternative fuel cycles allow nuclear power (with the alternative fuel cycle) to be as competitive with other energy sources as today's nuclear power. Fortunately, the fuel cycle is a small portion of total nuclear power cost, so the competitiveness of nuclear power economics is relatively insensitive to fuel cycle

specification must address uranium, transuranic elements, short-lived fission products such as cesium and strontium, and long-lived fission products such as iodine and technetium.

The current U.S. strategy is **once-through**. After one pass through a reactor, the components of used fuel are kept together and sent to a geologic repository. One variation is to assume that the burnup (the amount of energy extracted per mass of input fuel) stays about constant at 50 MW-thermal-day/kg-fuel. The other variation analyzed is to assume burnup doubles to 100 MW-thermal-day/kg-fuel.

The second strategy is to **recycle in thermal reactors only**. Uranium in used fuel would be recycled for reuse in reactors, stored for future use, or disposed as low-level waste. Depleted uranium would be disposed as low-level waste.[2] Transuranic elements would be recycled several times, deferring the need for a second geologic repository. Long-lived fission products would also go to geologic disposal. Targeted short-lived fission products would be first stored while they decay and become less radioactive and ultimately might be disposed of as low-level waste. This strategy uses existing types of nuclear power plants, which are thermal reactors. One variation would be to recycle only once; this accomplishes few objectives. The other variation would be to recycle repeatedly.

The third strategy is **sustained recycle with a symbiotic mix of thermal and fast reactors**, recycling transuranic elements from used fuel repeatedly until destroyed. The introduction of fast reactors makes this strategy sustainable from the repository standpoint; the accumulation of transuranic elements during repeated recycle passes is controlled and limited by fast reactors serving as transuranic element burners. A very limited amount of transuranic elements would go

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cost.

[2] The uranium could be stored rather than disposed; this would be appropriate if an eventual shift to the fourth

to geologic disposal, namely those in processing losses. Recovered uranium, depleted uranium, and fission products would be disposed of as with thermal recycling, except a small fraction of the recovered uranium would be converted to energy. This strategy requires a significant fraction of future nuclear power plants to be fast reactors. One variation is that mined uranium would fuel the thermal reactors (as in once-through) while recycled transuranic material is used in only fast reactors. In this approach, the fast reactors are designed to generate less transuranic material than they consume. Such fast reactors are described as "burners." The ratio of transuranic production to destruction is less than one (transuranic conversion ratio is less than one). Another variation is that recycled transuranic material would be recycled in both thermal and fast reactors.[3] The fleet of thermal reactors then uses a mixture of fresh uranium fuel and recycled transuranic material. This approach is envisioned by some countries that currently do limited recycle in thermal reactors. This approach could also be used to lower the fraction of required fast burner reactors.

The fourth strategy is **sustained recycle in fast reactors only**, recycling both uranium and transuranic elements repeatedly until all energy is extracted. If thermal reactors are phased out in favor of fast reactors, then all types of uranium ultimately serve as fuel. Thus, this strategy is sustainable both in terms of repository constraints and in terms of uranium ore resources. In this strategy, the fast reactors would be designed to generate more transuranic material than they consumed. Such fast reactors are described as "breeders." The ratio of transuranic production to destruction is greater than one (transuranic conversion ratio is greater than one). Essentially no recovered uranium, depleted uranium, or transuranic elements would be wasted, except for

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strategy were anticipated and considered within the planning horizon.

[3] One reviewer referred to this case as a "confused novelty", only appropriate for a transitional period. Our analyses do show unique advantages (and disadvantages) for this case such as an undisputed ability to recycle indefinitely

processing losses. As with other recycle strategies, long-lived fission products go to permanent disposal; targeted short-lived fission products would be stored and ultimately could be disposed of as low-level waste after sufficient decay.

COMPARISON OF ALTERNATIVES VERSUS OBJECTIVES

Table 1 summarizes the comparison of fuel cycle strategies; the numerical targets are from DOE.[1] The once-through fuel cycle is considered the *status quo*.

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while minimizing the fraction of fast reactors in the system; the economics of fast reactors remain unproven.

Table 1. Comparison of Fuel Cycle Strategies

Strategy and Variations	Once through		Recycle strategies				
			Recycle in thermal reactors only		Sustained recycle with symbiotic mix of thermal and fast reactors		Sustained recycle in fast reactors only
	Current burnup	Doubled burnup	Once	Repeated	Recycle in thermal & fast	Recycle in fast only	
Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.							
Number of 70,000-tonne geologic repositories by 2100, per heat-load limits [1]	10 at 1.8%/yr nuclear growth Range of 4-50 for 0-4.5%/yr growth		3-10 at 1.8%/year. Range of 1-50 for 0-4.5%/yr growth	1-5 at 1.8%/yr Range of 0.4-25 for 0-4.5%/yr growth	1		
Reduce long-term hypothetical repository dose by 10x per GWe	Status quo	1.13x	1.3x to 2.1x	2x to 10x	~100x		
Reduce long-term radiotoxicity by ~100x per GWe	Status quo	1.38x	1.1x to 2.5x	2x to 10x	~100x		
Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for used fuel management.							
Enable the U.S. to be a reliable service provider	Status quo		Development and deployment would enable the U.S. to be a reliable provider of used fuel services.				
Enhance use of proliferation barriers	Status quo		Grouped TRU products can complicate weapon design, especially by sub-national groups. Use separation technologies that do not separate plutonium. Protect against theft/diversion by embedding safeguards into designs.				
Consume weapons-usable material	Status quo		Little reduction	Weapons-usable inventory minimized by matching conversion ratio and nuclear power growth			
Objective 3. Enhance energy security by extracting energy recoverable from used fuel and depleted uranium, ensuring that uranium resources do not become a limiting factor for nuclear power.							
50x more energy from uranium ore	Status quo	1.03x worse	1.07x to 1.15x better	1.15x to 1.20x better	~1.4x for conversion ratio 0.25 ~2.1x for conversion ratio 0.75		50x to 150x
Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.							
Fuel cycle cost ranges	5.3 to 8.1 mills/kW-hr		9.2 to 18.0 mills/kW-hr for MOX case		8.6 to 11.6 mills/kW-hr for 2-tier case	6.1 to 10.2 mills/kW-hr for metal fuel case	6.3 to 11.3 mills/kW-hr
Avoidance of new reactor types	None needed	No new reactor types are needed, but existing ones would have to be licensed for new fuels.			Needs new reactor types; associated cost of such reactors not included.		
Minimize transport of used and recycle fuels	No change	50% lower	Little change	Off-site recycling – little change On-site recycling could reduce transport to about 10% of once-through			
Color code	Pink Option does not meet objective			Yellow Option partially meets objective	Green Option meets objective		
1. The current 70,000 tonne statutory limit applies only to the first geologic repository and then only until a second repository is operational.							

Improve waste management (Objective 1). Assuming nuclear power continues throughout this century, the once-through strategy would lead to the need for many geologic repositories. Successful recycle can achieve large reductions in the longer-lived transuranic isotopes remaining in radioactive wastes sent to geologic disposal. The once-through strategy leads to waste that remains more radiotoxic than the original natural uranium ore for hundreds of thousands of years, although safe geologic disposal protects the public from these wastes. Complete consumption of uranium and transuranic elements via recycling has the potential to reduce the time horizon from hundreds of thousands of years to thousands of years or less. This can also change transuranics from waste management liabilities into energy assets.

Reduce proliferation risk (Objective 2). The proliferation risk management objective includes components such as improving international arrangements and incorporating better risk reduction into the design of all new facilities ("safeguards by design"). Many of these considerations do not discriminate among fuel cycle options and therefore are not addressed in this report. Among fuel cycle options, the comparison examines metrics that address the five threat strategies: material theft, information theft, clandestine diversion of declared material or misuse of declared facilities, clandestine production in undeclared facilities, and overt misuse following abrogation of responsibilities under the Non-Proliferation Treaty by a nation leaving the treaty.[4]

Improve energy security (Objective 3). The next part of Table 1 addresses energy recovery. The energy content in uranium ore can be used more effectively as the energy content in used fuel is recovered. With the once-through strategy, only about 1% of the energy content in the original uranium ore is used; 99% is unused. Eventually, uranium ore resources could become an issue. All components of used fuel remain liabilities

If burner reactors (both thermal and fast) are phased out in favor of breeder reactors, there is substantial improvement; up to 99% of the energy content in the original uranium ore could be used. Only about 1% of the energy content in uranium ore would be wasted because of

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[4] This paper takes the middle ground between two extremes - (1) proliferation risk is independent of what technology is deployed in the U.S., therefore this comparison is meaningless, versus (2) proliferation risk depends critically on fuel cycle technologies therefore recycling should not be contemplated unless a totally proliferation resistant set of technologies is identified. Rather, the comparison here is based on the position that fuel cycle technology choices in one major nuclear country (the U.S.) do matter elsewhere, that all options involve risk, and

cumulative losses through repeated recycle passes. Depleted uranium in existing low-level waste would be converted from waste liabilities to energy assets. And, lower grades of uranium ore become economical, including the vast quantities of uranium from very unconventional sources such as seawater and phosphates. Uranium ore resources would not become a constraint.

Objective 4 (part 1) Continue Competitive Economics: Table 1 includes fuel cycle cost ranges representing the 95% cost uncertainty bounds for equilibrium fuel cycles for each strategy. The cost ranges indicate significant cost uncertainties across all strategies and a significant overlap of the cost distributions across the fuel cycle strategies.[5]

The cost ranges reflect uncertainty in key input parameters for a specific case; they do not reflect uncertainty in reactor capital cost nor different ways to implement each strategy. In particular, the uncertainties of fast reactor costs are not included in the cost ranges for the third and fourth strategies. The cost range reflects the unknowns including reprocessing technology performance and cost, fast reactor performance, geologic repository costs, and waste form/disposal unknowns. The costs for the once-through fuel cycle will be driven by uncertainties in market pricing of uranium and fuel services, and policies that will define the costs for partially used fuel disposition. Technology uncertainties associated with separation, refabrication, and (except for the strategy of recycle in thermal reactors only) fast reactors are important to the recycle strategies. These fuel cycle costs do not reflect the potential higher cost for new reactor types,

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that technological choices can impact the total risk.

[5] The cost estimates assume learning from past cost overruns so that the same mistakes are not repeated. The U.S. fuel cycle program is also actively seeking industry involvement (and risk sharing) in the next recycling facility with the potential for cost incentives to keep the costs contained. This is not to say that these facilities will not be expensive. They will be large, complex, expensive, industrial complexes. But, they will still only contribute a small portion of the nuclear power production costs. For example, if one looks at an Integrated Gasification Combined Cycle (IGCC) facility with geologic carbon sequestration, these are also be large, complex, expensive, large industrial complexes. One of the authors recently visited an IGCC facility and described the gasification portion as a football-field sized cube of massive plumbing.

which would be relevant for strategies using a symbiotic mix of thermal and fast reactors or those using fast reactors alone.

Continue Excellent Safety Performance (Objective 4, part 2). This objective must apply to the entire fuel cycle, including power plants. One potential discriminator among fuel cycle strategies is whether chemical separation and fuel fabrication are co-located with associated nuclear power plants ("on-site" in Table 1) or are large centralized facilities servicing dozens of nuclear power plants ("off-site"). On-site separation and fabrication would involve less transportation of radioactive fuel as only "makeup" new fuel must be sent to the site and waste must be shipped away; the recycled material would stay on site. However, this also makes each nuclear power plant site a more complex facility with a reactor, separation, and fabrication.

CONCLUSIONS

To minimize the long-term environmental impacts from nuclear energy, transuranic elements must be recycled. Initiation of recycling would reduce the need for stored used fuel inventories and defer the need to develop a second geologic repository. Recycling transuranics and effective management of short and long-lived isotopes would allow the U.S. to defer the need for a second geologic repository until the 22nd century. Fast-spectrum reactors are more efficient than thermal-spectrum reactors in using neutrons to fission isotopes or destroy unwanted isotopes.

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