Current Comparison of Advanced Fuel Cycle Options

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ABSTRACT

The nuclear fuel cycle includes mining, enrichment, nuclear power plants, recycling (if done), and residual waste disposition. The U.S. Advanced Fuel Cycle Initiative (AFCI) has four program objectives to guide research on how best to glue these pieces together, as follows: waste management, proliferation resistance, energy recovery, and systematic management/economics/safety. We have developed a comprehensive set of metrics to evaluate fuel cycle options against the four program objectives. The current list of metrics is long-term heat, long-term dose, radiotoxicity and weapons usable material. This paper describes the current metrics and initial results from comparisons made using these metrics. The data presented were developed using a combination of “static” calculations and a system dynamic model, DYMOND. In many cases, we examine the same issue both dynamically and statically to determine the robustness of the observations. All analyses are for the U.S. reactor fleet.

This work aims to clarify many of the issues being discussed within the AFCI program, including Inert Matrix Fuel (IMF) versus Mixed Oxide (MOX) fuel, single-pass versus multi-pass recycling, thermal versus fast reactors, and the value of separating cesium and strontium. The results from a series of dynamic simulations evaluating these options are included in this report. The model interface includes a few “control knobs” for flying or piloting the fuel cycle system into the future. The results from the simulations show that the future is dark (uncertain) and that the system is sluggish with slow time response times to changes (i.e., what types of reactors are built, what types of fuels are used, and the capacity of separation and fabrication plants). Piloting responsibilities are distributed among utilities, government, and regulators, compounding the challenge of making the entire system work and respond to changing circumstances. We identify four approaches that would increase our chances of a sustainable fuel cycle system: (1) have a recycle strategy that could be implemented before the 2030-2050 approximate period when current reactors retire so that replacement reactors fit into the strategy, (2) establish an option such as multi-pass blended-core IMF as a downward Pu control knob and accumulate waste management benefits early, (3) establish fast reactors with flexible conversion ratio as a future control knob that slowly becomes available if/when fast reactors are added to the fleet, and (4) expand exploration of heterogeneous assemblies and cores, which appear to have advantages such as increased agility.

Initial results suggest multi-pass full-core MOX appears to be a less effective way than multi-pass blended core IMF to manage the fuel cycle system because it requires higher TRU throughput while accruing waste management benefits at a slower rate. Single-pass recycle approaches for LWRs do not meet AFCI program objectives and could be considered a “dead end.” We did not study the Very High Temperature Reactor (VHTR). Fast reactors appear to be effective options but a significant number of fast reactors must be deployed before the benefit of such strategies can be observed.

INTRODUCTION

Fundamentally, the Advanced Fuel Cycle Initiative (AFCI) is the nuclear energy answer to the societal imperative: “Reduce, Reuse, Recycle.” The AFCI strives to…

> Reduce the number of repositories that cause so much controversy.
> Reuse transuranics to maximize energy derived from uranium.
> Recycle to minimize waste generation and manage weapon-usable inventories.

This paper summarizes a detailed technical report [1] that provided insight into many of the issues being discussed within the Advanced Fuel Cycle Initiative (AFCI) program. It represents the first attempt to calculate a full range of metrics, covering all four AFCI program objectives [2 , 3] - waste management, proliferation resistance, energy recovery, and systematic management/economics/safety - using a combination of “static” calculations and a system dynamic model, DYMOND [4, 5, 6, 7, 8]. All analyses are for the U.S. reactor fleet.

LIMITATIONS

There are four major limitations of this study. First, thermal reactors (TR) are always represented by Light Water Reactors (LWR) and both converter fast reactors (CFR) and breeder fast reactors (BFR) are always represented by Sodium Fast Reactors (SFR). Processing of thermal reactor fuel is performed at centralized plants using UREX+ technology. Processing of fast reactor fuel is performed on location at the power plants using pyroprocessing technology. To first order, we do not believe that the conclusions in this paper would differ substantially for other thermal or fast reactor options, based on the AFCI evaluation of Generation IV transmutation impacts [9]. We have not considered ultra-high burnup with the Very High Temperature Reactor (VHTR) concept.

Second, there is no attempt to include economics *per se*. Instead, economic indicators are used such as separation and fuel fabrication throughputs and the relative amount of fuels that require remote handling (those including americium (Am) or curium (Cm)), glovebox operation (those including plutonium (Pu)), or current hands-on fabrication (uranium (U)-only). Economics will be included in future work.

Third, we assume that all options studied are technically feasible and available at the time indicated in various deployment scenarios, which implies the necessary underlying R&D&D has been completed.

Fourth, detailed fuel cycle data are only available for a finite subset of specific recycle approaches. Great care has been taken to assure that the fuel cycle performance for each case has been analyzed in a consistent manner. However, not all promising options have been considered. In future work, the scenario evaluations will be utilized to define additional cases for detailed analyses; and new fuel cycle transmutation data on specific options will be incorporated into the dynamic model, as available.

OBJECTIVES AND METRICS

The AFCI program objectives are now documented in a recent report to Congress [2], and are presented in Table I. In Table I, “short-term” refers to the period through 2025, when the AFCI program recommends the need for a commercially-deployed spent fuel treatment facility. “Intermediate-term” refers to the period from 2025 until the commercial availability of Generation IV fast spectrum reactors, projected to be about 2040. “Long-term” refers to the time after several of these fast reactors have been built.

Table I. AFCI Objectives from Report to Congress [2].

Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.
• In the short-term, develop and demonstrate fuel cycle technologies and facilities that remove more than 99.5 percent of transuranics from waste destined for geologic disposal and initiate their recycle in existing reactors.
• In the short-term, improve management of the primary heat-producing fission products in spent fuel (cesium and strontium) to reduce geologic repository impacts.
• In the intermediate- and long-terms, enable repeated 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.
• In the intermediate- and long-terms, reduce the long-lived radiation dose sources by a factor of 10 and radiotoxicity by a factor of 100, simplifying the design of a waste isolation system.
Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.
• In the short-term, develop fuel cycle technologies that enhance the use of intrinsic proliferation barriers.
• In the short-term, demonstrate the capability to eliminate more than 99.5 percent of transuranic weapons-usable materials from waste streams destined for direct disposal by destroying these materials through recycling.
• In the long-term, stabilize the inventory of weapons-usable material in storage by consuming it for sustained energy production.
Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and recycled material, ensuring that uranium resources do not become a limiting resource for nuclear power.
• In the short-term, develop the technologies needed to extend nuclear fuel supplies by up to 15 percent by recycling the fissile material in spent nuclear fuel.
• In the long-term, extend nuclear fuel resources more than 50-fold by recycling uranium in spent fuel and depleted uranium, thereby converting current wastes into energy assets.
Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.
• At all times, ensure that advanced fuel cycle technologies cause no significant decrease in the economic competitiveness of nuclear electricity.
• At all times, maintain excellent safety performance of nuclear fuel cycle facilities and operations.
• For the long-term, improve spent fuel management to reduce on-site storage at nuclear power plants.

As a part of the waste management objective, the AFCI program wishes to avoid the technical need for a second geological repository this century. At a nominal growth rate of 1.8%, we would need 10 Yucca

Mountain Project (YMP)-sized repositories, or improve the utilization of the first repository by a factor of 10. At a growth rate of 3.2%, the highest rate considered in this year’s report to Congress [2], we would need an improvement of a factor of 22. The 3.2% growth rate results in 370 GWe of installed capacity in 2050, similar to the MIT high-growth scenario of 477 GWe [10, 11]. The DOE laboratory directors published a report [12] with targets that imply a growth rate of 4.5%/yr at least until 2050. Dixon and Piet estimated the growth rate by noting the objective of “50 percent of U.S. electricity and 25% of U.S. transportation fuels produced by nuclear energy by 2050,” this results in 700 GWe installed capacity by 2050 [10]. If continued to 2100, this would require an improvement of a factor of 50 to stay within one repository. Therefore, we believe that avoidance of a second repository this century means we need to improve the utilization of the first repository by a factor of 10 to 50.

Three metrics have been developed for examining repository capacity: long-term heat (LTH), long-term dose (LTD), and long-term radiotoxicity (LTR).

One of the key repository capacity factors is long-term heat (LTH). As analyzed and explained by Wigeland [13, 14, 15, 16], a major factor determining the amount of waste that can be emplaced in an YMP-like repository is the heat generated from the waste form from the time when ventilation of the repository stops out to ~1500 years. The ventilation stops when the repository is closed (sealed). Current policy and regulations constrain the closure time from a minimum of 50 years to a maximum of 300 years. The end-period of the heating interval (~1500 years) is approximate; indeed, a single value is an approximation of a time-dependent heat transfer calculation. For present purposes, we use an LTH metric defined as the energy (watts-year) released per gram of isotopes emplaced in the repository. This requires us to account for the heat released from the isotopes and their decay products during the time interval from when ventilation-stops to 1500 years.

The LTH is a merely a simplifying metric for a more complex set of thermal design constraints resulting from analyses by Wigeland [13, 14, 15, 16], as follows:

- Temperature below 96 °C between drifts, so that water can drain between drifts
- Drift wall temperature below 200 °C, at time that waste is emplaced
- Drift wall temperature below 200 °C, at time that waste is no longer ventilated, i.e., repository closure

Fig. 1 shows the actual heat-limited repository capacity improvement (calculated by Wigeland) as a function of the LTH metric calculated by us. The figure contains several types of data, as follows:

- Black line = improvement if dictated solely by LTH improvement.
- Yellow squares = limited by 96 °C mid-drift temperatures
- Red triangles = limited by 200 °C drift wall temperature at closure
- Blue circles = limited by 200 °C drift wall temperature at emplacement

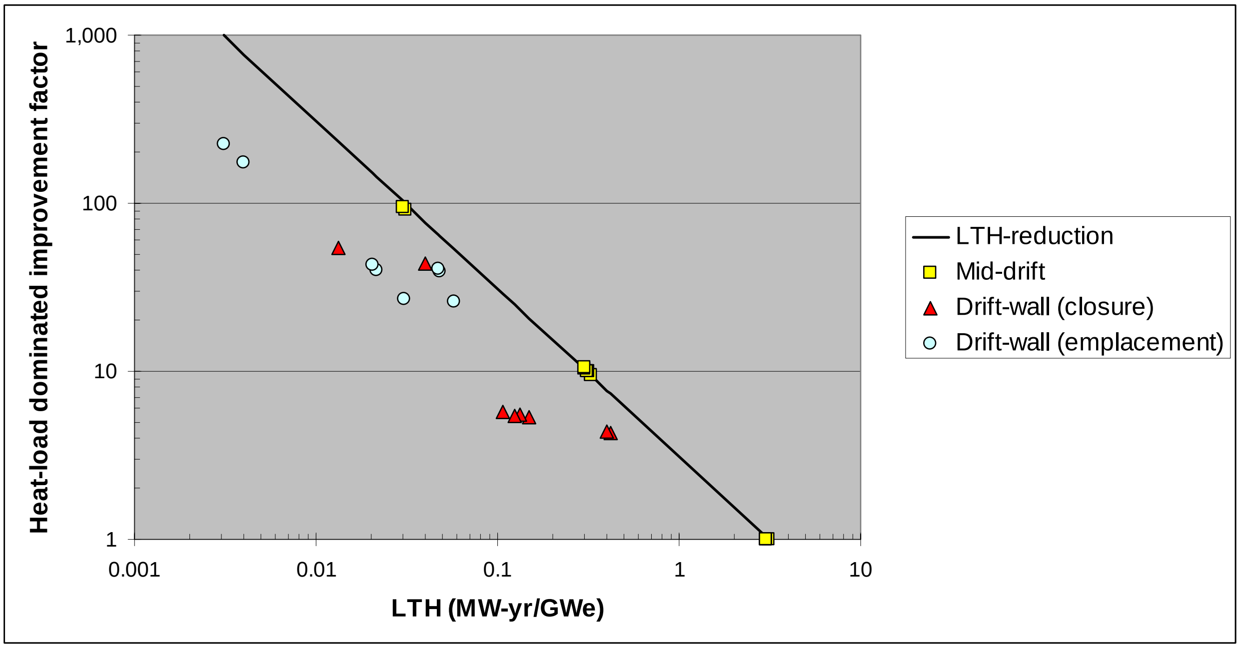


Fig. 1. Repository capacity improvement factors versus calculated LTH metric.

We see that the LTH metric is an excellent predictor for cases dominated by mid-drift temperatures. It overpredicts for cases dominated by drift wall temperatures. Therefore, judging from Fig. 1, if our goal is to reduce heat constraints on the repository by a factor of 10-50, we should reduce LTH by a factor of 10-200.

The second metric is long-term dose, which like LTH, is a potential limitation on the amount and nature of waste emplaced in the geologic repository. As of this writing, EPA has proposed two dose standards for the reasonasbly maximally exposed individual (RMEI) of the public living near the repository:

1. 15 mrem/year at time periods less than 10,000 years; the peak dose in this time period is typically at 10,000 years
2. 350 mrem/year at time periods between 10,000 and 1,000,000 years; the peak dose in this time period is typically ~500,000 years.

There are four possible targets:

1. Reduce all long-term dose sources (i.e. all long-term isotopes) by a factor of 10.
2. Reduce the long-term dose sources so that the peak long-term dose is reduced by a factor of 10.
3. Reduce the long-term dose sources so that the peak long-term dose is reduced by as much as the heat constraints are lowered (by a factor of 10-50), i.e., so that as more reactor-years’ worth of waste is emplaced, the net dose remains constant.
4. Reduce the long-term dose sources so that emplaced waste meets the proposed 15 and 350 mrem/year standards.

A literal reading of the current AFCI objectives would lead to target 1, but we reject this as outside the spirit of the AFCI objectives. It would automatically mean that all long-term isotopes would have to be reduced by a factor of 10, regardless of the totals, and regardless of how peak doses were impacted. Target 2 is a minimum objective to show compliance with AFCI objectives. Target 3 is more stringent than target 2 because the peak dose would have to be reduced by as much as a factor of 50 depending on the heat-reduction factor. Currrent estimates of repository dose provided by W. Halsey [17], as shown in Fig. 2, indicate that for once-through fuel the peak dose, occurring at 500,000 years, is about 31 mrem/year, a factor of 11 below EPA’s proposed peak dose standard of 350 mrem/year. If we reduced the peak dose by a factor of 10 (target 2) and emplaced a factor of 50 more waste (achieve heat reduction of a factor of 50), we would obtain 155 mrem/year. Thus, hypothetical target 4 is not controlling. In summary, we need to reduce the peak doses by at least a factor of 10 (target 2) and possibly as much as a factor of 50 (target 3). Of course, these targets need to be reexamined if the calculated hypothetical doses change significantly.

The third metric, long-term radiotoxicity (LTR), differs from LTD because it ignores how much of isotopes emplaced in the repository can actually transport to human receptors. The advantages of LTR as a metric are that it is independent of repository location and design, independent of repository calculational uncertainties, and one can compare LTR directly to U ore. The first two advantages are why international assessments of waste management advantages tend to use LTR rather than either LTD or LTH as metrics. The last advantage warrants discussion here. Used UOX-51 (U oxide fuel with a burn-up of 51 GW thermal-day/ton heavy metal) tends to have LTR higher than U ore for ~400,000 years, coincidentally about the time period of peak LTD.

We note that a reduction of LTR by a factor of ~100 would mean that recycle waste would have lower radiotoxicity than U ore within 1,000 years after emplacement. This brings the time scale for repository design hypothetically within engineering experience, whereas proving performance at 400,000 is problematical. This is the logic underlying the program objective of a factor of 100 reduction. So, the AFCI has a goal to reduce LTR by a factor of 100, especially at 1000 years. To meet the underlying “no worse than uranium ore” objective, the LTR reduction can be less for times greater than 1000 years, e.g. a reduction of a factor of 30 at 10,000 years, a factor of 10 at 50,000 years, and a factor of 3 at 100,000 years would appear sufficient.

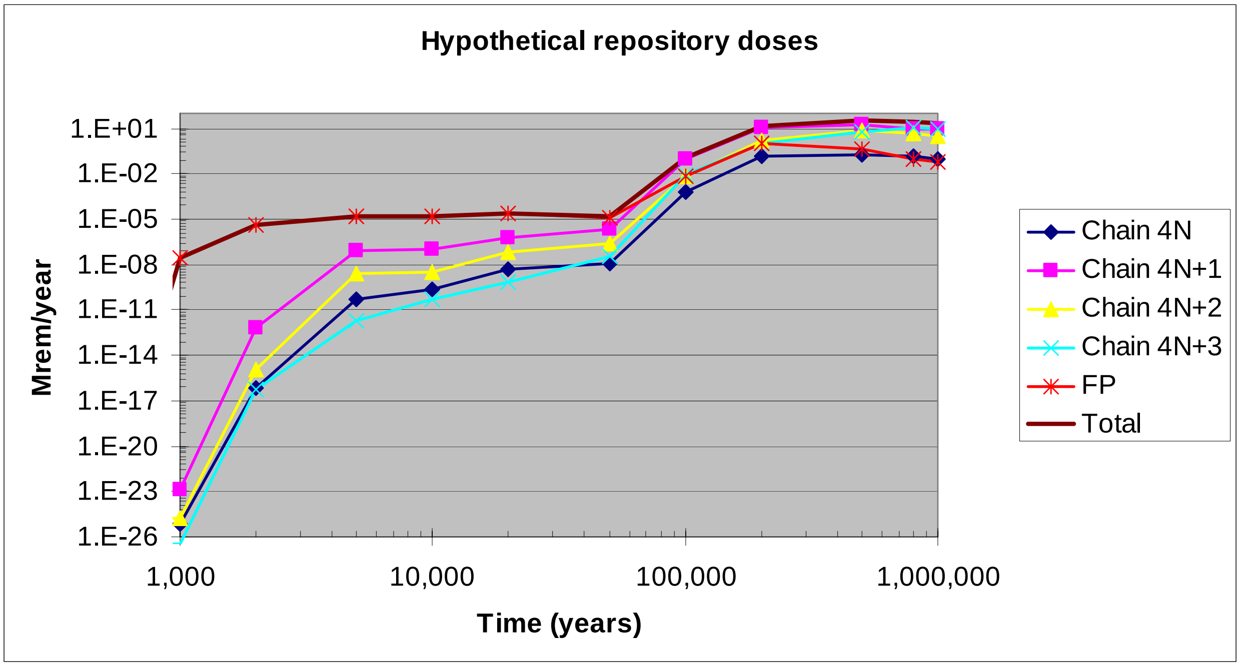


Fig. 2. Hypothetical repository dose [17] from isotopes grouped by decay chain.

ALTERNATIVES AND DEVELOPMENT TREES

Advanced fuel cycle planning focuses on four possible strategies. In this context, 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. The four strategies are:

- The current (first) U.S. strategy is **once-through -** all the components of spent fuel are kept together and eventually sent to a geologic repository.
- The second strategy is **limited recycle**, recycling transuranic elements once. Remaining transuranic elements and long-lived fission products would go to geologic disposal. Uranium in spent fuel, depleted U, and short-lived fission products would be disposed as low-level waste. This strategy uses existing types of nuclear power plants, which are all thermal reactors.
- The third strategy is **transitional recycle**, recycling transuranic elements from spent fuel repeatedly until destroyed. Transitional recycle is more technically challenging 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. Short-lived fission products would be disposed as low-level waste. This strategy would primarily use thermal reactors; however, a small fraction of fast reactors may be required.
- The fourth strategy is **sustained recycle**, which differs from transitional recycle primarily by enabling the recycle of depleted U to significantly extend fuel resources. This strategy would primarily use Generation IV fast reactors.

Table II presents the development trees that look at implementing the various strategies at different times. Basically, the development trees outline the overall strategies of when to progress to the next stage of recycle. Starting with once-through (the current strategy) and progressing up through a sustained recycle strategy.

Table II. Summary of Development Trees

Development Tree	Motivation for Analysis	Notes	Deployment constraints
1. Continue once-through until 2040, i.e., delay recycling	Explores continuation of once-through for an additional 15 years.	Branch 1.2 continues "once-through" until the end of the century.	N/A
2. Start IMF-NpPuAm in 2025 (using blended IMF/UOX cores)	Attempts fastest possible reduction in LTH, LTD, and LTR using thermal reactors and UREX+ separation technology, but an unproven fuel.	Assumes n-pass IMF fuels and their separation are practical. This IMF approach uses blended fuel assemblies, with ¾ UOX and ¼ IMF, with the TRU in used fuel UOX and IMF in one generation making the IMF in the next generation. Other n-pass IMF approaches require analysis, including increasing the IMF/UOX ratio to further accelerate benefits or require fewer reactors to use the blend.	3 kt/yr separation plant starts in 2025. All fuel that can be made from that separation plant is assumed to be used in the growing TR fleet.
3. Start MOX-NpPu in 2025	Closest to current international practice and current technology, while avoiding separation of Pu	Restricted to 1 recycling pass in current analyses.	
4. Start MOX-NpPuAm in 2025	Attempts modest repository benefits using thermal reactors, UREX+ technology, and fuels relatively similar to current UOX and MOX-Pu.	Assumes burned U is the U component in MOX; the Pu/U ratio increases each cycle to keep the cores critical. Other n-pass MOX approaches require analysis, including keeping the core critical by increasing the U enrichment instead of the Pu/U ratio.	
5. Start converter FR in 2025	Moves into FR, skipping recycling in TR. The early FR experience would set the stage for BFR when U resources warrant.	Balancing all the components of this type of system is not straightforward.	FR deployment is limited by the amount of Pu available for FR fuel, existing FR's have 1st priority on fuel over new FR's, if insufficient fuel is available for FR's to start, the missing capacity is met by starting thermal reactors
6. Start breeder FR in 2025	Moves into FR, skipping recycling in TR. Aims to accommodate a hypothetical combination of limited U resources and high nuclear growth.	Unique among the options in that BFR uses depleted U.	

In order to simulate the various strategies it is necessary to have the initial fuel recipes (what the fuel looks like when it is initially placed in the reactor) and the burnup fuel recipes (what the fuel looks like after it has been burned in the reactor). For multi-pass fuels, each pass is tracked in the model. When fast reactors are being requested for the reactor fleet, fuel is prioritized by youngest, fewest pass fuel first and then older more passes fuel next. Breeder fast reactors utilize transuranics (especially Pu) to increase the energy recovery from U, and work to some degree in opposition to thermal recycle and converter fast reactors.

The support ratio (number of reactors in pass n required to provide fuel for reactors in pass n+1) varies among fuel types and reactor types. For the multi-pass IMF (blended core) fuel used in this model, the support ratio is approximately one, which means the IMF available for successive cycles of IMF remains fairly constant. This allows IMF fuel to move into a large proportion of the reactor system quickly. The multi-pass MOX (full core) and one-pass MOX (full core) fuels used in this model have a support ratio of 7-11, depending on the cycle of the fuel. Which means that successive cycles of MOX move very slowly into the reactor system.

MAJOR CONCLUSIONS ON STRATEGIES

Fig. 3 summarizes our suggested strategy decision tree from a technical perspective. The branches of the first several decisions are relatively clear; the bottom half merit discussion. For example, if both (a) fast reactors are considered cheaper than thermal reactors and (b) we can wait for a sizeable fast reactor fleet to be built, then the fourth question suggests starting CFRs. If either of these questions is answered negatively, then one proceeds to the fifth question.

One strategy that does not appear in the tree is single-pass recycle. We define a single-pass option as one that precludes further recycling. Single-pass recycle options were found to not meet the AFCI program goals [1, 2]; for example, waste management benefits are limited to at most a factor of 2 and therefore are not discussed in detail in this paper.

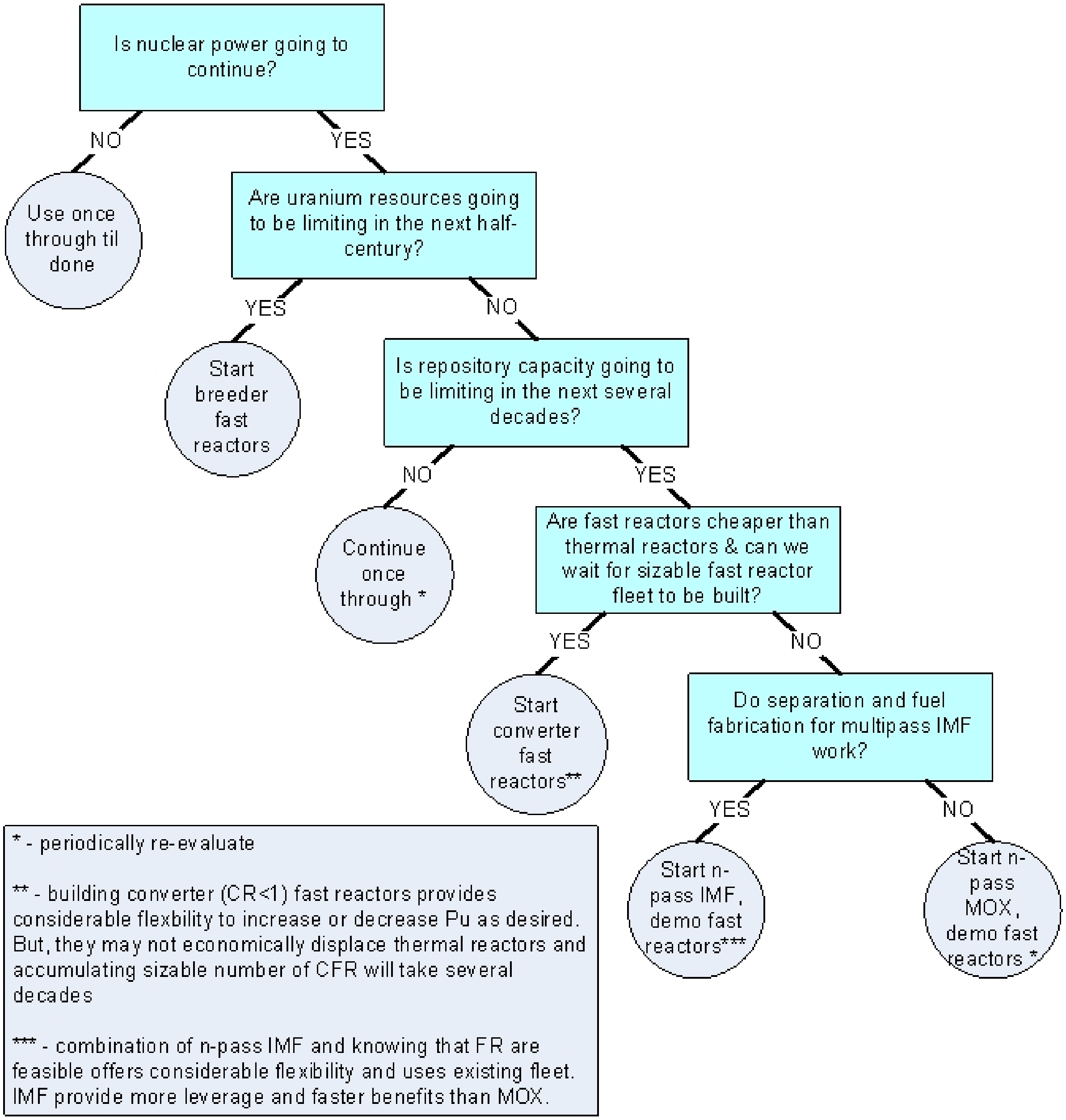
There are three multi-pass strategies explored in this paper:

- recycling in thermal reactors only,
- recycling in a symbiotic mix of thermal reactors and CFR, and
- recycling in BFR.

Recycling in thermal reactors only

This strategy can be continued until U resources become a constraint; however, the benefits are limited because unburned transuranics (TRU) accumulate in the recycling fuel. Eventually, the unburned TRU would be discarded; however, we believe that this could be deferred until the next century as 5 cycles of either multi-pass IMF or multi-pass MOX appear feasible (on paper).

The multi-pass MOX-NpPuAm approach, used for this paper [1], varied the Pu/U ratio each cycle; in FY2006, we will study a different approach varying U-235 enrichment, MOX-UE. It may give better performance. The multi-pass IMF-NpPuAm approach in this paper uses blended cores – about 3/4 UOX pins and 1/4 IMF pins in each assembly, which results in ~98% of the heavy metal being in the UOX pins. (A variation puts the Am in 4 targets among 264 pins in each assembly.) In FY2006 we will validate these results and further examine the multi-pass IMF option space. The UOX pins in the IMF blended core would be fabricated hands on. The MOX contains neptunium (Np), Pu, and Am; there is little doubt such MOX would require remote fabrication. IMF with NpPuAm and Am targets would also require remote fabrication. IMF-NpPu pins would probably qualify for glovebox fabrication.



* - periodically re-evaluate

** - building converter (CR<1) fast reactors provides considerable flexbility to increase or decrease Pu as desired. But, they may not economically displace thermal reactors and accumulating sizable number of CFR will take several decades

*** - combination of n-pass IMF and knowing that FR are feasible offers considerable flexibility and uses existing fleet. IMF provide more leverage and faster benefits than MOX.

Fig. 3. Suggested decision tree for selecting among recycle strategies.

Both approaches meet the waste management objectives until unburned TRU is discarded; it appears that multi-pass IMF (which uses the blended core) accumulates waste management benefits almost twice as fast as multi-pass MOX. The IMF-pin components of fresh IMF assemblies are a relatively attractive proliferation target; however, like other IMF concepts, it succeeds in burning Pu and degrading the Pu vector faster than MOX. Both meet the short-term U utilization objective (15% improvement) but only toward the end of the century when there has been time and sufficient separation/fabrication capacity to reach cycle 2 for multi-pass IMF and cycle 4 for multi-pass MOX. Safety and economics could prove to be dominated by the difference in TRU throughput (throughput of U and fission products varies little) – multi-pass IMF has typically 1/2 to 1/3 of the TRU throughput of multi-pass MOX. Building the infrastructure for thermal-only recycling (either MOX or IMF) provides much of the infrastructure for later CFR or BFR double-tier systems. However, if fast reactors are not readied for potential deployment, the pure-thermal strategy would require that much additional time to convert to one of the other strategies.

Recycling in a symbiotic mix of thermal reactors and CFR

On paper, this strategy can be continued until U resources become a constraint. Unburned TRU never has to be discarded. These options meet the waste management objectives provided the loss per recycle is acceptable and provided that one does not stop recycling. As the CFR fuels would contain Np, Pu, Am, and Cm, there is little doubt that they would require remote fabrication.

We studied three cases: (1) using the TRU in discharged UOX in CFR, (2) using TRU from discharged MOX in CFR; and (3) using TRU from discharged IMF in CFR. The three equilibria differ because of continuing makeup feed from the thermal reactors, which in turn differ.

The IMF-CFR combination generally provides the best performance, although on some metrics UOX-CFR is superior. The MOX-CFR system has the highest recirculating TRU throughput and the composition of the recirculating fuel has high fractions of undesirable isotopes. This could be good from the proliferation resistance perspective, but undesirable from economic and safety perspectives. Separation and fabrication loss goals derived from the first pass of used UOX are sometimes not adequate for CFR systems. If recycling in thermal reactors is not used, 27% of the UOX-CFR fleet would be CFRs. If thermal recycling is used, the fraction of CFR drops to 19% (IMF-CFR) or 20% (MOX-CFR). Thus, recycling in thermal reactors provides a hedge against potentially high CFR cost. Building the infrastructure for thermal/CFR symbiosis provides the experience and much of the infrastructure for later BFR systems. However, the thermal reactor component of this system would have to be phased out during transition to BFR; otherwise, the U utilization benefits are little better than pure thermal systems. Pure thermal systems can reach ~20% savings; CFR (conversion ratio ~25%) systems can reach ~40% U savings. Symbiotic systems have the most agility; if CFR performance is poor, they can be de-emphasized. If U begins to appear as a constraint, the breeding ratio of the fast reactors can be enhanced and eventually the thermal reactors phased out. If symbiotic systems have to be terminated, both the CFR and IMF can burn down remaining TRU leaving a relatively clean exit.

Recycling in BFR

This strategy can be sustained indefinitely. Unburned TRU never has to be discarded. These options meet the waste management objectives provided loss per recycle is acceptable and recycling is not halted. As the fuels contain Np, Pu, Am, and Cm, there is little doubt that they would require remote fabrication.

We studied two cases: (1) using the TRU in discharged UOX to start BFR and (2) using the TRU in discharged IMF to start BFR. The equilibrium BFR is the same; thermal reactors would be phased out.

The recirculating TRU mass is relatively high and the Pu “quality” in that mass is also high, hence the known proliferation criticisms of this approach. (However, note that the actual total system Pu inventory is lower than once-through with the modest breeding ratio [1.12] in this study. The BFR has a net Pu production of 0.10 tonnes-Pu/yr per GWe; UOX-51 creates Pu at 0.22 tonnes-Pu/yr per GWe.) The same characteristics mean that the recirculating mass appears easier to handle and slightly higher separation loss rates could be tolerated relative to CFR, once the isotopic mix evolved toward the BFR equilibrium values. If BFR systems have to be terminated, one would first want to convert the BFR into CFR to burn down as much TRU as possible.

If the processing capacity is unlimited, Fig. 4 shows the TRU mass flux to a separation plant for the multi-pass cases, compared to UOX-51. The fission product (FP) mass per GWe is unchanged, and therefore not included in the figure. Similarly, the U throughputs change only modestly. The program needs a cost algorithm as a function of the throughput of individual elements. For fixed waste management goals, as throughput increases, tolerable separation and fabrication loss rates decrease. Also, safety and proliferation risk would appear to scale with the recirculating inventory. The BFR case has the highest TRU recirculating inventory; it is mostly Pu, which makes handling and waste management goals easier than the other cases, but with higher proliferation issues. The MOX and MOX/CFR cases have the highest Am recirculating throughputs; work in FY2006 will seek better performance for MOX.

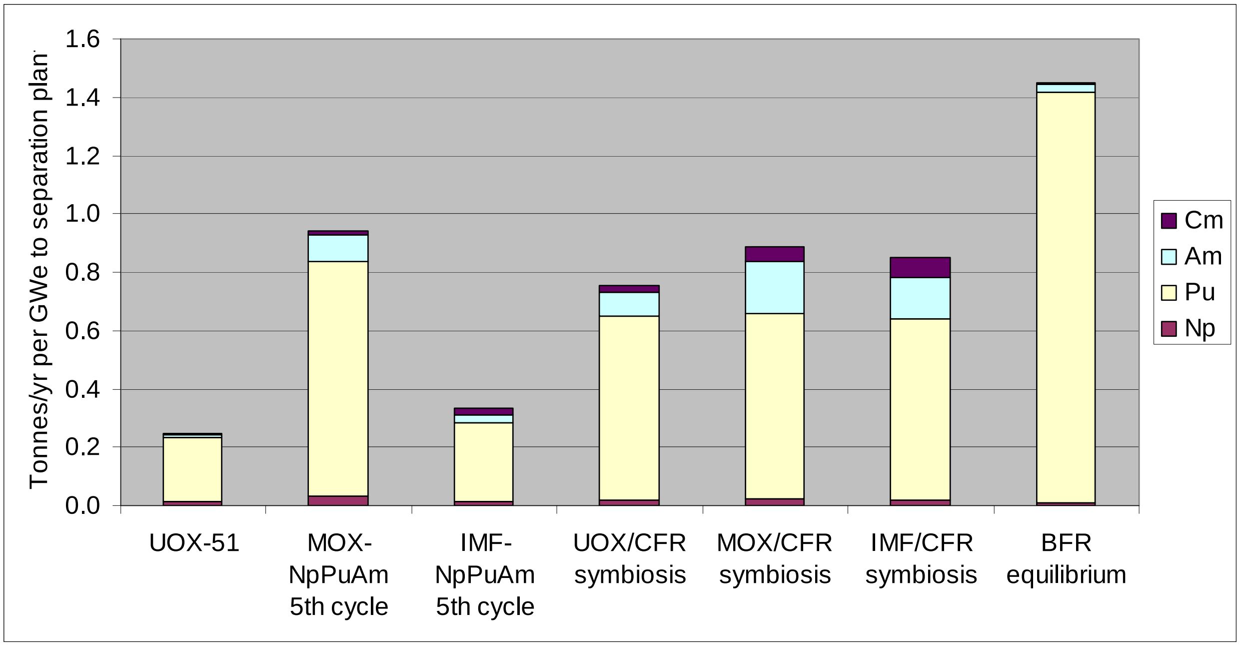


Fig. 4. TRU throughput for selected cases, unlimited processing capacity.

Table III summarizes results for multi-pass options when separation and fuel fabrication capacities are not limited. There are two numbers in most cells of the table. The first is the improvement factor this century (~5 recycles) if recycling then stops. The second is the improvement if recycling never stops, i.e., the system reaches a true equilibrium. It should be noted that this program includes "opposing" objectives. One objective is to make the fuel cycle more proliferation resistant and another is to maximize recovery of energy from spent fuel. The first is achieved generally by minimizing the amount of Pu-239 available in the fuel cycle and the second by maximizing the amount produced during irradiation. This dichotomy is reflected in Table III by the "Uranium ore use improvement" and "Pu-239-equivalent tonnes/yr per GWe for fresh fuel" factors.

MANAGING THE FUEL CYCLE SYSTEM IN SPITE OF UNCERTAINTIES

Managing the fuel cycle system in a real-time fashion will not be easy. There is the real potential to "out drive" our headlights. Consider that managing the fuel cycle is metaphorically like driving a car or flying a plane. There are few "**control knobs**" available: what types of reactors are built, what types of fuels are used, and the capacity of separation and fabrication plants. All of the controls are very sluggish – with response times measured in decades. To compound the problem, there is no single pilot; control is shared by utilities, other industry, government, and regulators. Worse, it is dark (uncertain) and our headlights only illuminate a short distance into the future.

Therefore, two criteria in selecting among options should be robustness and agility. Robustness measures how much preferences stay constant if postulated assumptions and future circumstances change. Agility measures the ease of adapting an option later if new circumstances warrant.

Table III. Key Results for Multi-Pass Cases (First number in each cell is the improvement factor this century (~5 recycles) if recycling stops. The second number is the improvement if recycling never stops.)

	Targets (see Chapter 3)	Thermal recycling with MOX	Thermal recycling with IMF	Converter fast reactor (CFR) with IMF	Breeder fast reactor (BFR)
Long-term heat (LTH) improvement	10x to 200x (to achieve actual repository improvements of 10-50x)	1.5x Improvement plateaus near this value	2.9x Improvement plateaus near this value	~4x ~50x at 99.5% removal of TRU+Cs+Sr	~4x ~70x at 99.5% removal of TRU+Cs+Sr
Long-term dose (LTD) improvement	10-50x reduction in peak dose	2x Improvement plateaus Eventually	3x Improvement plateaus eventually	~4x ~60x at 99.5% removal of TRU+U+Tc+I	~7x ~190x at 99.5% removal of TRU+U+Tc+I
U ore use improvement	1.15 short term 50x long term	1.17x Near 1.17x	1.17x 1.17x	1.23x 1.42x	2.0x 100-160x
Pu239-equivalent tonnes/yr per GWe for fresh fuel	Minimize weapons-usable throughput	0.50 Slowly increases	0.26 Slowly increases	Not estimated 0.36	Not estimated. 1.07
Avoid fully remote fuel fabrication (a)	For as much fuel as possible	True for the 80% of the fuel that is UOX, untrue for MOX-NpPuAm	True for the ¾ UOX pins, true for IMF-NpPu (with separate Am targets)	No	No
Minimize throughput of TRU (tonnes/yr per GWe)	As low as possible to minimize safety and economic issues	0.94 Slowly increase	0.34 Slowly increases	Not estimated 0.85	Not estimated 1.45
Is option sustainable per repository limits		NO, because unburned TRU must eventually be discarded, but probably after this century		Yes, unburned TRU does not ever have to be discarded, performance depends on loss rates	
Is option sustainable per U limits		NO			Yes

We consider the most important future unknowns, i.e., factors influencing major fuel cycle decisions, to be as follows:

- Growth of nuclear energy?
- Cost and acceptance of additional repositories?
- Which thermal reactors succeed in the market place?
- How much U is available?
- What proliferation policies exist?
- How much penalty is "hot" fuel separation and fabrication?

As an example, we find that the multi-pass blended-core IMF approach in this study would be more robust than the multi-pass full-core MOX approach in several ways. One is that the chemical composition of recycled material changes significantly cycle-by-cycle for MOX, but not for IMF. Separation and fabrication plants with fixed capabilities would therefore be able to handle a wider range of IMF situations than MOX.

Thus, one type of analysis we performed was to postulate and analyze six development trees (Table IV) against the range of AFCI metrics. One mild surprise was the importance of Pu-238. R. Wigeland has previously noted that heat from Pu-238 accumulation impacts long-term heat. Its daughter, U-234, becomes important in long-term dose and long-term radiotoxicity. When measuring weapons-usable inventory by Pu-239-equivalents (normalized by bare sphere critical mass), Pu-238 is equivalent to Pu-239. Thus, options with relatively high recirculating inventories of Pu-238 such as MOX and MOX-CFR are negatively impacted.

Table IV. Summary of Development Trees

Development Tree	Motivation
Continue once-through until 2040, i.e., delay recycling	Explores continuation of once-through for an additional 15 years.
Start multi-pass IMF-NpPuAm in 2025	Attempts fastest possible reduction in LTH, LTD, and LTR using thermal reactors and UREX+ separation technology, but an unproven fuel.
Start single-pass MOX-NpPu in 2025	Closest to current international practice and current technology, while avoiding separation of Pu
Start multi-pass MOX-NpPuAm in 2025	Attempts modest repository benefits using thermal reactors, UREX+ technology, and fuels relatively similar to current UOX and MOX-Pu.
Start CFR in 2025	Moves into fast reactors, skipping recycling in thermal reactors. The early fast reactor experience would set the stage for BFR when U resources warrant.
Start BFR in 2025	Moves into fast reactor, skipping recycling in thermal reactor. Aims to accommodate a hypothetical combination of limited U resources and high nuclear growth.

One final way we attempt to summarize the wide range of static and dynamic analyses is to identify four approaches that would increase our ability to drive or pilot the fuel cycle system.

1. Have a recycle strategy that could be implemented before the current reactor fleet retires in the 2030-2050 approximate time period so that replacement reactors fit into the strategy. The reactors built in that time period will determine much of the fuel cycle for the rest of this century.
2. Establish multi-pass blended core IMF as a downward Pu control knob. It can, for example, stabilize the Pu inventory even at 1.8% growth. And, for equivalent SNF throughputs, it can be implemented faster than MOX (if the technology is available) because of the low TRU throughputs. IMF options can be tuned from breeding/conversion ratios near zero to at least 0.6. The capital investment of reactors would appear to far exceed that of separation and fabrication facilities. If the IMF infrastructure is built and later not needed, thermal reactors can still be operated profitably. IMF appears a more effective and flexible control knob than MOX.
3. Establish fast reactors with flexible conversion ratio as a future control knob. This "control knob" takes longer to become available because fast reactors must first be several percent of the fleet.. The breeding ratio and conversion ratio (conceptually similar but not numerically the same) should be variable from ~0.25 to at least 1.3. Unlike the IMF control knob, this one can substantially reduce U ore needs if breeding/conversion is over one. However, deployment of FR should proceed cautiously because once built there is high incentive to continue their operation. IMF and MOX used in

conjunction with CFR reduces the number of CFR needed and therefore is a logical way to move into fast reactors.

4. Expand exploration of heterogeneous assemblies and cores, which appear to have advantages and agility. The need for heterogeneous cores in fast reactors is well known. Analyses suggest advantages for blended (heterogeneous) assemblies in thermal reactors. In particular, the blended core multi-pass IMF approach in this study offers significant advantages as well as agility. Even better, perhaps, could be separating IMF-NpPu versus Am targets, so that little of the fuel would require remote fabrication. Preliminary analysis [18] indicates similar transmutation performance, but segregating the Am into targets minimizes the amount of fuel requiring remote handling. And, one could imagine turning down Pu consumption by reducing the fraction of IMP-NpPu pins while keeping the waste management benefits of Am targets.

CONCLUSIONS FOR KEY FUEL CYCLE DECISIONS

Table V summarizes our conclusions for five suggested key fuel cycle decisions. The title and order of the suggested decisions is important, being structured with the most robust decisions first.

Table V. Status and Issues for Suggested Key Fuel Cycle Decisions in Decreasing Order of Readiness and Robustness

Key Decisions	Status and issues
Open 1st geological repository	Established US policy, implementation delayed. The basis for AFCI waste management calculations is YMP. We see no reason why YMP would not work well with a recycling strategy, but more work is warranted to confirm.
Determine credibility of recycling	There are only two sustainable high-level waste (HLW) approaches: multi-recycling and multi-repositories; neither is known to be credible today.
Determine need for recycling and build 1st separation plant for UOX	If "should recycle" is established, the question is what separation plant should be built. All recycle scenarios include a UOX separation plant(s) for existing UOX, for the >80% UOX in IMF and MOX scenarios, and for the >70% UOX in CFR scenarios. Capacity could be 3,000 to 5,000 tonnes/year to reduce at-reactor inventories without over-building capacity. We suggest the UREX+ plant should be configured to provide NpPu/Am/Cm. (Alternative: NpPu/AmCm) Purity of separated Cs-Sr and U should meet 10CFR61 standards. Tc and I should be set aside for specialized waste forms, specialized repositories, or transmutation targets.
Build 1st recycle-fuel fabrication plant	The main categories of options are IMF, MOX, fuels for converter fast reactors, and fuels for breeder fast reactors. The selection among these options depends on too many factors to down-select today. We can say that non-recyclable fuels should be given low priority; multiple recycles are required to meet AFCI program objectives.
Build future separation and fuel fabrication plants	The dynamics of managing the fuel cycle are difficult. Assuming a 1-decade delay between decision and implementation, spacing major decisions by 2-decades (as we have in this study) means there is 1-decade of implementation and 1-decade observation between decisions.

NEEDED FUTURE WORK

In support of future down-selection among options and the 2007-2010 Secretarial Recommendation on the need for a second geologic repository, additional work is needed along the following lines. Within system analysis, we must convert the Stella-based DYMOND model to another platform to resolve software-limitations faced this summer. In doing so, the system dynamic model will be combined with the economic database. The combined model is tentatively called VISION, for Verifiable Fuel Cycle Simulation.

AFCI in general

- Closer cooperation and cross-reviews among program elements.
- Work to clarify the six decision factors (uncertainties) and "control knobs" noted above.
- Improve the metrics for long-term dose, long-term heat, and long-term radiotoxicity.
- Better integrate this work with proliferation resistance methodology and analyses.

Reactor and transmutation analyses

- Examine MOX-UE for potentially higher performance than MOX-Pu/U in this study.
- Examine and validate multi-pass IMF.
- Examine VHTR options analogous to the LWR options in this study.
- Fill in missing cases in option matrix.
- Perform scoping analysis for symbiotic thermal-BFR cases to explore how BFR could be slowly brought on line and how the symbiosis could maximize both waste management and U performance.
- Examine reactor safety limits for multi-pass MOX and IMF.

Separation and system analyses

- Separation experts and system analysis colleagues should update separation and recovery targets.
- Cost algorithm as function of throughputs of individual elements

Fuel fabrication and system analyses

- Fuel experts and system analysis colleagues should identify and start addressing issues associated with heterogeneous assemblies.
- Cost algorithm as function of hands-on/glovebox/remote fabrication for pellets/pins and for assemblies.
- Calculate representative dose rates for prototypical fuel pins and assembly options.

Wine Cellar (how separation and fuel fabrication interact, where separated products are stored and blended into fuel fabrication)

- Identify algorithms for modifying both input/output fuel compositions with different strategies such as Pu/U, U-235 enrichment, Am/Pu.

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