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Advances in Nuclear Fuel Management IV (ANFM 2009)

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LESSONS LEARNED FROM DYNAMIC SIMULATIONS OF ADVANCED FUEL CYCLES

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ABSTRACT

Years of performing dynamic simulations of advanced nuclear fuel cycle options provide insights into how they could work and how one might transition from the current once-through fuel cycle. This paper summarizes those insights from the context of the 2005 objectives and goals of the Advanced Fuel Cycle Initiative (AFCI). Our intent is not to compare options, assess options versus those objectives and goals, nor recommend changes to those objectives and goals. Rather, we organize what we have learned from dynamic simulations in the context of the AFCI objectives for waste management, proliferation resistance, uranium utilization, and economics. Thus, we do not merely describe "lessons learned" from dynamic simulations but attempt to answer the "so what" question by using this context. The analyses have been performed using the Verifiable Fuel Cycle Simulation of Nuclear Fuel Cycle Dynamics (VISION). We observe that the 2005 objectives and goals do not address many of the inherently dynamic discriminators among advanced fuel cycle options and transitions thereof.

1. INTRODUCTION

Goals and objectives are typically static.[1,2,3] However, nuclear fuel cycles are inherently dynamic, yet many (if not most) comparisons of nuclear fuel cycle options compare them via static time-independent analyses. Assessments can benefit from considering dynamics in at least three senses - transitions from one fuel cycle strategy to another, how fuel cycles perform with nuclear power growth superimposed with time delays throughout the system, and variability of fuel cycle performance due to perturbations. This paper will explain some of what we have learned from dynamic fuel cycle simulations using the VISION[4,5] model in the context of AFCI objectives and goals.

In 2005, the Department of Energy provided Congress with a report detailing strategic and programmatic objectives of the AFCI.[1] Each of the four programmatic objectives had 2-4 goals such as separation efficiency or reduction of radiotoxicity of residual waste. These objectives and goals were used in 2005 and 2006 comparisons of fuel cycle options.[2,3] These objectives and goals provide the context for organizing what we have learned from dynamic fuel cycle system-level simulations.

Our intent is not to compare options, assess options versus objectives and goals, nor recommend changes to those objectives and goals. Rather, we organize what we have learned in the context of the AFCI objectives. Thus, we do not merely describe "lessons learned" from dynamic simulations but attempt to answer the "so what" question.

Analyses have been performed using the Verifiable Fuel Cycle Simulation of Nuclear Fuel Cycle Dynamics (VISION).[4,5] Most of the examples in this paper are based on 0, 1, or 2 tier recycling options as follows:

- 0-tier, once through, Light Water Reactor (LWR) with uranium oxide (UOX) fuel at 51 GWth-day/tonne-iHM burnup.[6]

- 1-tier, transuranic material from LWR-UOX-51 is recycled in fast reactors[7,8] with various transuranic (TRU) conversion ratios (CR). The TRU CR is defined as the production of transuranic material divided by all destruction pathways of transuranic material.

- 2-tier, plutonium and uranium from LWR-UOX is first recycled once in LWR as mixed oxide (MOX) fuel. The remaining material and the minor actinides from separation of used LWR-UOX are then recycled in fast reactors.[7]

All calculations start in 2000 and end in 2100. They use U.S. parameters, e.g., start with 104 LWRs providing 86 GWe-full-power-year of electricity per year. Most simulations use a nuclear power growth rate of 1.75%/yr, starting in 2015. However, we stress that the precise numbers are unimportant; the broad trends and system behavior provide the lessons learned.

Fuel cycle system analyses can be either static or dynamic; they each have value. Static equilibria are easier to calculate, to understand, and to use to compare options. Dynamic simulations are more realistic.[9] The 2005 AFCI objectives[1] and recent U.S. comparisons[2,3] are primarily static in nature.

Consider three examples of the differences between static and dynamic. First, assume in fast reactors that zirconium (fast reactor metal fuel alloy) and steel (fast reactor metal fuel cladding) are recycled. At static equilibrium, the only required makeup zirconium and steel would be the small amount required to balance processing losses. However, in a dynamic analysis with increasing numbers of fast reactors, zirconium and steel would be required to supply the new fast reactors. The amount of makeup material required would increase as either the growth rate or recycle timelag from fuel fabrication back around to new fuel fabrication increase.

The second example is system evolution. A static equilibrium analysis tells us little about how to manage the system; or, how the system can evolve from one strategy to another. A dynamic analysis provides some insights into the sequencing of events. Understanding the true system evolution requires a fully time dependent calculation, as provided by system analysis models such as VISION.[4,5]

The third example is economics. A static equilibrium is appropriate when discount rates, the time value of money, and cash flows are not addressed. If the time value of money is accounted for, then cash flows that lead others are given greater weight; cash flows that lag others are given less weight.

2. STRATEGIC OBJECTIVES

The strategic objectives of the AFCI program are stated as follows:

1. "Develop and make available for industry the separations technology needed to deploy by 2025 a commercial-scale spent fuel treatment facility capable of separating transuranics in a proliferation-resistant manner for their recycle and destruction through transmutation."[1]

2. "Develop and make available the fuel cycle technology needed for commercial deployment by 2040 of fast spectrum reactors operating either exclusively as transuranics transmuters or as combined fuel breeders and transmuters. Actual decisions to deploy fast reactors will, of course, be made by industry in response to market needs."[1]

These objectives relate to availability of technologies for deployment - UOX separation (objective 1) and fast reactors, fuel fabrication, and separation (objective 2). The objectives specify when deployment is enabled. For dynamic simulations, one must also specify the size and rate of deployment.

All advanced fuel cycles require separation of used UOX fuel. All simulation results depend not only on when the first UOX separation plant starts (2025 in objective 1), but also its capacity. In the simulations presented here, the first separation plant starts in 2020 at 800 tonnes-iHM/yr. It also matters how soon a second UOX separation plant might be deployable. In these simulations, the second plant starts in 2030 at 1600 tonnes-iHM/yr. Consider that the U.S. is currently accumulating used UOX at ~2000 tonnes-iHM/yr and there are few proposals that the first UOX plant be that large. So, just to build capacity equal to the UOX discharge rate in 2020-2030, multiple separation plants will be required and simulation results depend on how soon that is possible.

All advanced fuel cycles require new fuels that recycle some or all of the transuranic material. Many require new types of reactors. In most simulations, commercial fast reactor deployment starts in 2032 (1-tier) or 2047 (2-tier), near the 2040 date in objective 2. Simulation results also depend on how fast the new technologies can be deployed, not just when deployment starts. For example, many of the calculations we use in this report constrain fast reactor deployment to 1 GWe of capacity/yr for 5 years, followed by 2 GWe/yr for 5 years. MOX or fast reactor deployment is also constrained by availability of recycled material, which is in turn constrained by deployment of UOX separation capacity. Reactor deployment can also be constrained in low nuclear growth scenarios because new reactors are not built until existing reactors retire. This growth constraint does not occur at the 1.75%/yr growth assumed in most of the calculations. Deployment is not constrained by fuel fabrication capacity.

3. PROGRAMMATIC OBJECTIVE 1 - WASTE MANAGEMENT

Programmatic Objective 1 is "Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials."[1] Quantitative environmental goals that support this objective include:

1. "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."[1]

2. "In the short-term, improve management of the primary heat producing fission products in spent fuel (cesium and strontium) to reduce geologic repository impacts."[1]

3. "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."[1]

4. "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."[1]

Our first observation is that one way to reduce waste burden is not to make the waste. Note that reactors fueled with enriched uranium are net producers of TRU (TRU CR>1),[*] while reactors fueled with recycled TRU may be net producers (CR<1) or consumers (CR>1). Fig. 1 shows the reduction of TRU inventory this century as a function of fast reactor TRU CR for 1-tier dynamic simulations. TRU reduction occurs for two reasons; one is consumption of TRU in fast reactors. (In other simulations, TRU is consumed in thermal reactors.) The other is avoidance of TRU production by displacing reactors with net TRU production (such as LWR-UOX) with other reactors and fuels. As an example, a CR=1 fast reactor is not a net consumer of TRU; but the more electricity generated by such reactors, the less that must be generated by LWR-UOX and therefore significant TRU production is avoided. In this sense, the fourth goal is stated in the most flexible way because it only specifies reduction in waste burden, allowing "credit" for any fuel cycle characteristic that helps, including "avoidance."

The second observation is that while interpreting these goals numerically, it is important to determine whether they apply "per recycle pass" or "integrated across multiple recycles." The first objective can reasonably be interpreted as the former; the fourth objective is written to account for the cumulative effect of multiple recycles.

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[*] The TRU CR is TRU production/destruction so that CR=1 means the output TRU content equals the input TRU content. Systems with uranium fuel thus "breed" TRU. For systems operating with TRU fuel, the TRU CR is often numerical similar to the fissile breeding ratio as U238 (non-TRU, fertile) is converted to TRU, which is mostly fissile. Indeed, as the TRU CR increases, it approaches the fissile breeding ratio as a higher fraction of the produced TRU is Pu239, which is fissile.

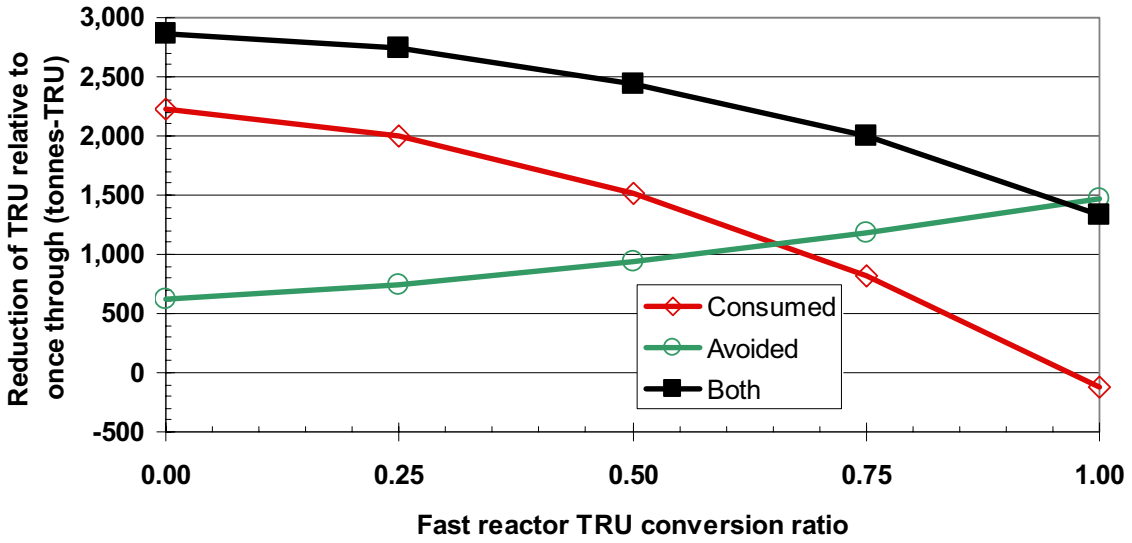

Fig. 1 Consumption and avoidance of TRU, both reduce TRU inventories.

Fig. 2 shows the reduction in long-term radiotoxicity (LTR) in disposed high-level waste this century (relative to once-through) for 1-tier cases with TRU CR=0.50. In this instance, radiotoxicity is evaluated 1000 years after reactor discharge. A factor of 100 reduction in LTR-1000 relative to once-through means that the radiotoxicity falls below that of natural uranium ore in less than 1000 years. When recycling starts (in 2020 in these calculations), the reduction is simply the inverse of the assumed loss factor per recycle, e.g., 100x from 1% loss/recycle. Thereafter, the improvement declines as material is repeatedly recycled. As an example, to achieve a reduction of 100 (per the fourth goal above) requires a loss rate ~0.3%/recycle; 1% loss/recycle is not adequate to achieve 100x cumulative reduction. The impact of transitioning to a closed fuel cycle on waste management is large and depends on processing loss rate (fig. 4).

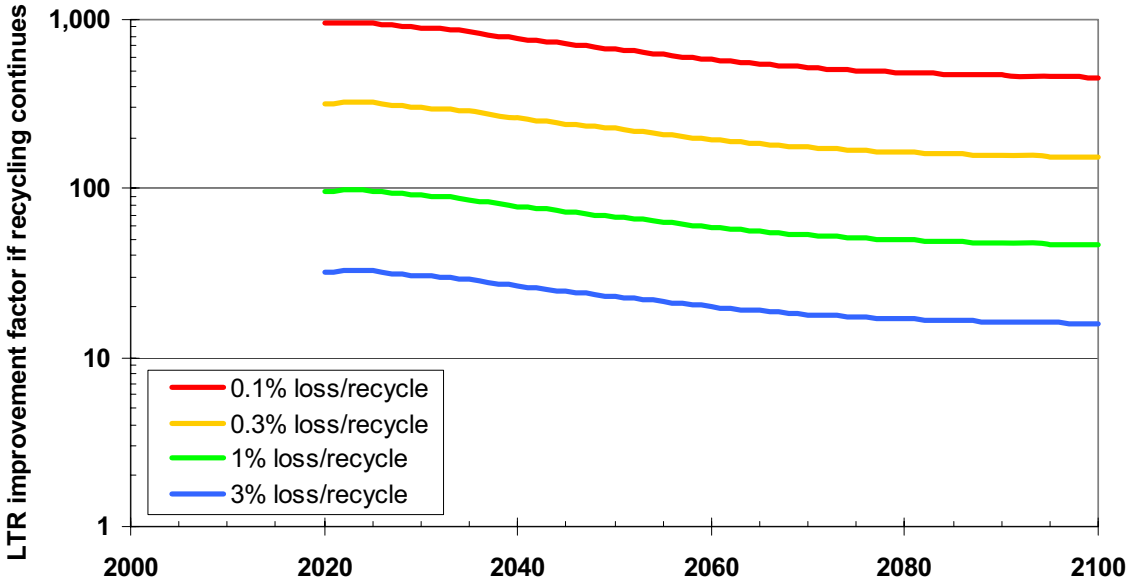

Fig. 2 Improvement of long-term radiotoxicity as function of assumed processing rate for a 1-tier CR=0.50 recycle approach.

The third waste management observation is that the radiotoxicity results depend strongly on which transuranics are recycled, processing loss rates, and the time at which radiotoxicity is to be evaluated. Individual isotopes vary as to their contribution (per mass) to radiotoxicity. Consider the example in fig. 3. It shows that if UOX-51 is not recycled or if only uranium from UOX-51 is recycled; the radiotoxicity stays above natural uranium ore until ~400,000 years; there is no reduction in the radiotoxicity source term (waste goal 4). If 99% to 100% of the uranium and plutonium are recycled, the radiotoxicity remains above natural uranium ore until ~20,000 years; a reduction of LTR-1000 by factors of 7.9-8.5 versus the goal of 100. U and Pu constitute 94.6% of used UOX-51 or 99.89% of the heavy metal in used UOX-51. (Of used UOX-51, 0.1% is minor actinides and 5.3% is fission products.) Thus, even assuming complete recycle (no loss) of uranium and plutonium, which therefore achieves waste goal 1 (99.5% recovery), waste goal 4 (100x reduction in LTR-1000) is not met. Meeting waste goal 4 requires recycling most of the minor actinides. If 99%/99.5%/99.9%/100% of uranium, neptunium, plutonium, americium, curium, and californium are recycled, the LTR-1000 is reduced by factors of 100/200/950/20,000; and the time to reach uranium ore drops to 2100/900/500/300 years in fig. 3. A recent NEA study[9] shows similar trends.

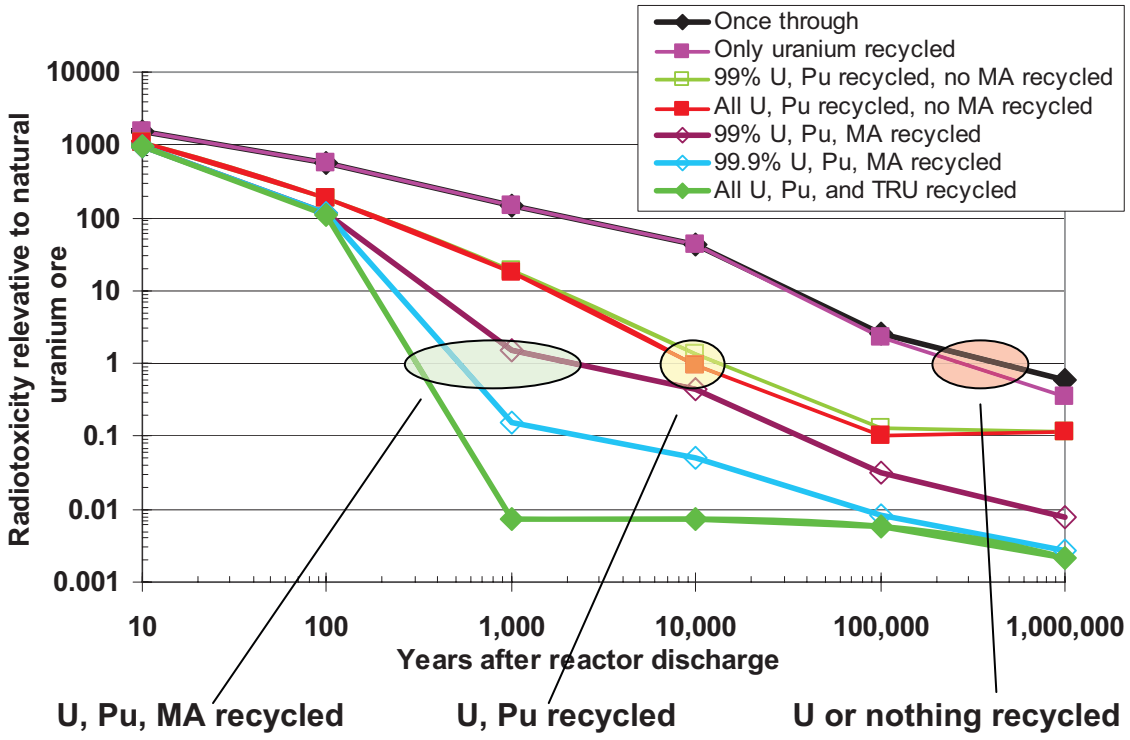

Fig. 3 Radiotoxicity of fission products from 5-year old UOX-51 as function of minor actinide (MA) recycling.

The fourth waste management observation is that significant material accumulates throughout the system during recycling; thus, achievement of high waste management benefits depends on continuation of recycling. Don't stop!

The metric is the long-term decay heat emitted by material from 50 to 1500 years; this is a rough approximation of the long-term thermal response in a repository.[10] It is the same concept as the "decay heat integral".[9] We call it a "commitment" because once emplaced, the energy that will be deposited has been committed; this is analogous to the concept of "dose commitment"; radioactivity taken into the human body commits the body to receiving a dose integrated over time. The heat units are energy (GWth-yr), heat rate (GWth) integrated over time (years). Fig. 4 shows the heat commitment in a 1-tier CR=0.50 case. The heat commitment in 2100 would be 86 GWth-yr with the once through fuel cycle; adoption of 1-tier CR=0.50 recycling reduces that to 47 GWth-yr. So, if recycling were to stop in 2100 and all the material in the system went to a repository, the heat-commitment improvement factor to the repository would be only 1.8=86/47.

There is nil heat commitment in depleted uranium (DU), recovered uranium (RU), low-level waste (LLW), or TRU waste. But, there is 7 GWth-yr in decay heat storage (CsSr). So, if recycling were to stop in 2100 and that material were not sent to a repository, the improvement factor would increase from 1.8 to 2.1 = 86/(47-7).

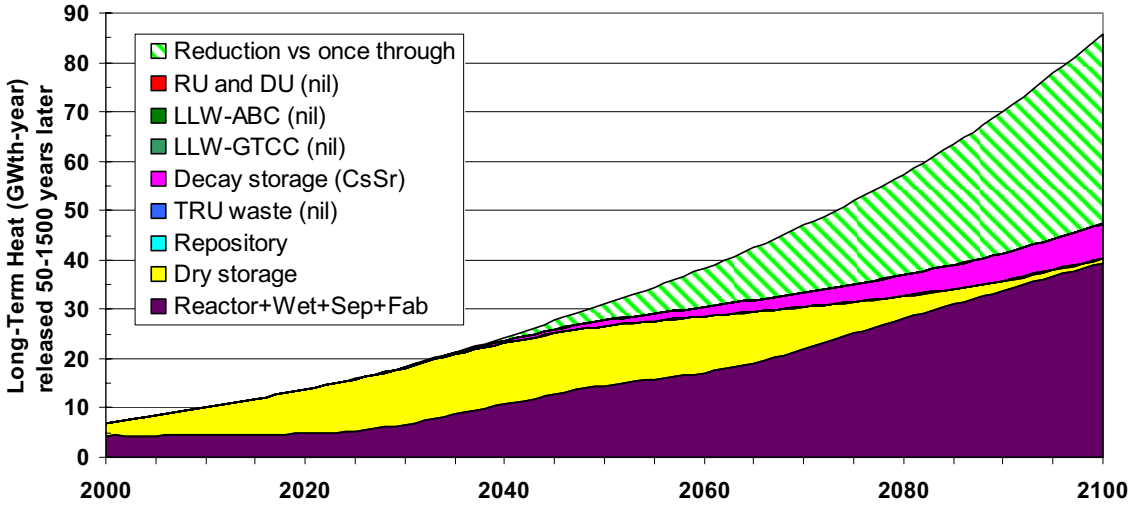

Fig. 4 Long-term heat commitment for 1-tier CR=0.50 fast reactor case.

If recycling continues beyond 2100, the 39 GWth-yr active in the system (reactor, wet storage, separation, fabrication) and 0.8 GWth-yr in dry storage avoid going to the repository. The repository only has 0.2 GWth-yr, so the maximum improvement factor could approach 430 = 86/0.2; this is an overestimate because some of the 40 GWth-yr (active, dry) will end up in the repository as recycling continues.

As a final observation based on fig. 4, consider if the material in decay storage is sent to a repository. Then, the repository heat commitment is 7.2 instead of 0.2. Then, the maximum improvement factor, even if recycling continues, would be 86/7.2 = 12. Again, this is an overestimate because some of the 40 GWth-yr in active systems would eventually go to the repository.

So, achieving high improvements in repository heat commitment requires continuation of recycling, recycle of Pu and MA, and use of decay storage for CsSr.

The fifth observation is that uranium dominates the mass of the system. Fig. 5 shows the mass in the system for a 1-tier case. The mass is dominated by DU and RU; the mass of fuel products and total waste is small. This case uses CR=0.50 fast reactors. To help understand this, consider the static equilibrium in fig. 6. At CR=0.50 only 1.3% of the RU and none of the DU is used as fuel. (Uranium in discharged fast reactor fuel is assumed recycled into new fast reactor fuel.) Use of RU increases to 4.2% at fast reactor CR=0.75. At CR=0.986, all of the RU is used. Above CR=0.986, some of the DU is used. Above TRU CR=0.9985, all of the RU and DU is used as fuel (other than processing losses). Dynamic simulations show somewhat worse results than fig. 6 because of the time lags involved in building and operating fast reactors in a growing system, i.e., LWRs are built first and their TRU is used to fuel later fast reactors.

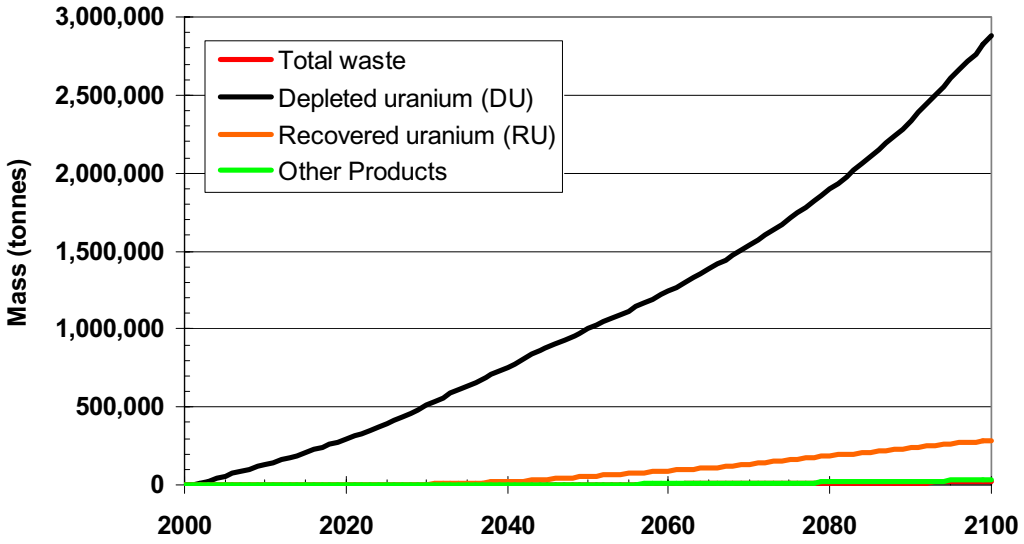

Fig. 5 Waste, uranium, and fuel product mass for a 1-tier recycle case, CR=0.50 fast reactors, no packing included.

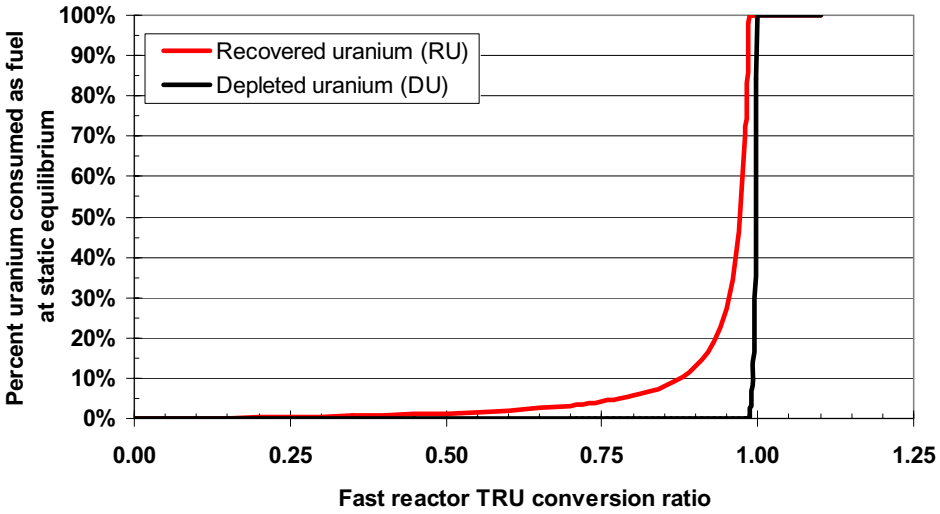

Fig. 6 Percent of RU and DU from LWRs used as fast reactor fuel with fast reactors and LWRs in static equilibrium.

The sixth and final waste management observation is that one must put TRU "in play" in order to reduce waste burdens. Use it to lose it. TRU that is sitting in storage does not help reduce waste burdens, except in so far as high-heat load isotopes decay; the notable example is Cs137 and Sr90 with ~30-year halflives. Similarly, the holdup of transuranic material in the system impacts system performance so that short time lags, e.g., when facilities are co-located instead of at different locations, can lead to faster waste management benefits via consumption and avoidance of TRU. Fig. 7 shows the impact of increasing the "wet" storage time from 1 to 10 years for a 1-tier CR=0.50 fast reactor case, approximating a shift from onsite to offsite separation and fuel fabrication. The total time from reactor discharge to reinsertion changes from 2 to 11 years.

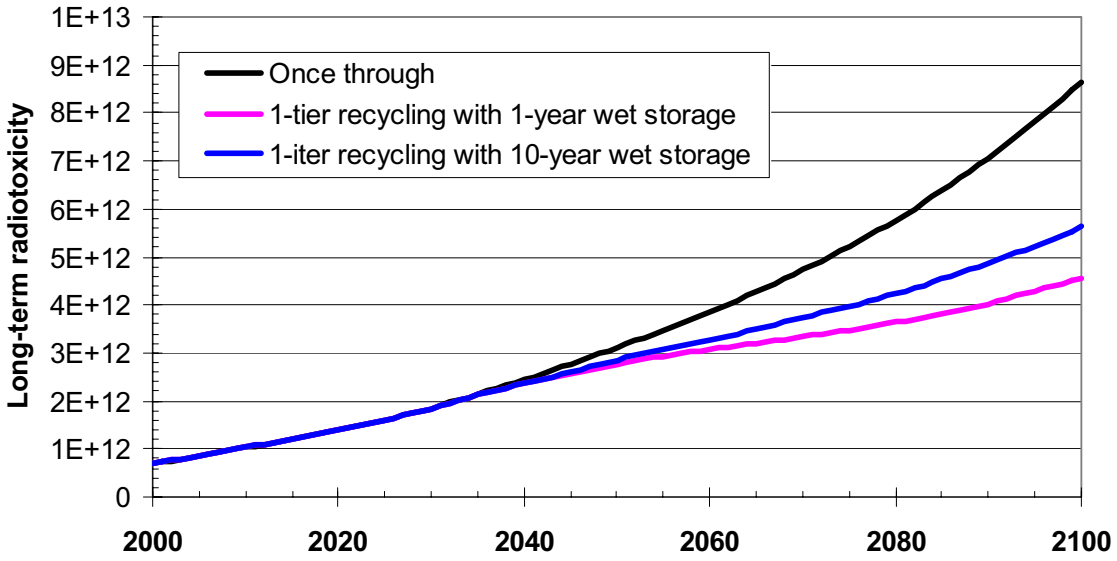

Fig. 7 Long-term radiotoxicity of 1-tier fast reactor CR=0.50 with either 1 or 10 year "wet" cooling before a year of separation and fuel fabrication.

4. PROGRAMMATIC OBJECTIVE 2 - PROLIFERATION RESISTANCE

The 2005 report states this objective as follows: "Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management."[1] Quantitative environmental goals that support this objective include:

1. "In the short-term, develop fuel cycle technologies that enhance the use of intrinsic[†] proliferation barriers."[1]

[†] Quoting from reference 1 - "Intrinsic" proliferation resistance features, as defined in the International Atomic Energy Agency Department of Safeguards STR-332, Proliferation Resistance Fundamentals for Future Nuclear Energy Systems, include (but are not limited to) technical features that:

- Reduce the attractiveness for nuclear weapons programs of nuclear material during production,
- Use, transport, storage and disposal;
- Prevent or inhibit the diversion of nuclear material;
- Prevent or inhibit the undeclared production of direct-use material; and
- Facilitate verification, including continuity of knowledge.

By contrast, examples of "Extrinsic Measures" as defined in STR-332 include:

2. "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."[1]

3. "In the long-term, stabilize the inventory of weapons-usable material in storage by consuming it for sustained energy production."[1]

First, observe that although there is significant reduction of TRU relative to once through (avoided and consumed), there remains significant TRU material throughout a fuel cycle system. The goals do not specify location-specific targets, other than the third goal is specific to material in storage. Fig. 8 illustrates that there is substantial reduction of TRU material relative to once-through (via avoidance and consumption) but also that there is substantial TRU in many parts of the system.

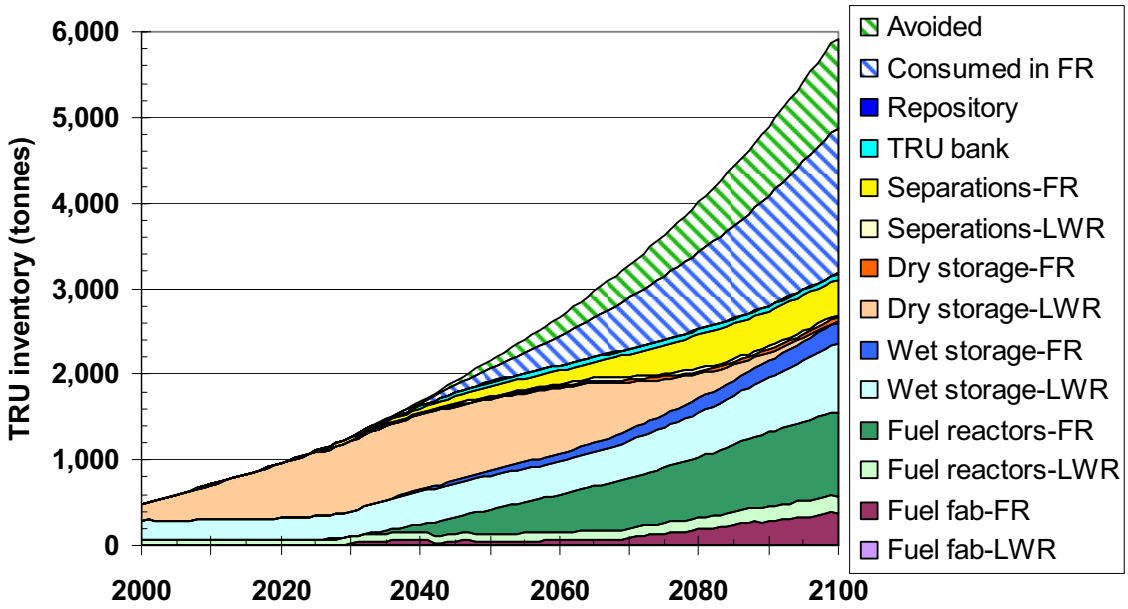

Fig. 8 Location of TRU material in a 1-tier recycle case.

The second proliferation resistance observation is that the mass flow of material through separations can vary significantly both quantitatively and by type of separation, independent of separation efficiency. Fig. 9 shows the total mass sent through separations (the sum of the flow tonnes-TRU/yr times the number of years) as a function

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- States' commitments, obligations and policies with regard to nuclear non-proliferation and disarmament;
- Agreements between exporting and importing states that nuclear energy systems would be used only for agreed purposes and subject to agreed limitations;
- Commercial, legal or institutional arrangements that control access to nuclear material and nuclear energy systems;
- Application of IAEA verification and, as appropriate, regional, bilateral and national measures to ensure that states and facilities comply with non-proliferation or peaceful-use undertakings; and
- Legal and/or institutional arrangements to address violations of nuclear non-proliferation or peaceful-use undertakings.

of fast reactor conversion ratio for a 1-tier simulation. As CR increases, there are fewer LWRs hence less processing of used LWR fuel; but there are more fast reactors and more fast reactor fuel processing. These may be of different technologies and the siting strategy could differ, e.g., large centrally located aqueous separation of used UOX fuel versus at-reactor electrochemical separation of used fast reactor metal fuel. In such cases, the proliferation risk posed by different technologies and locations would vary.

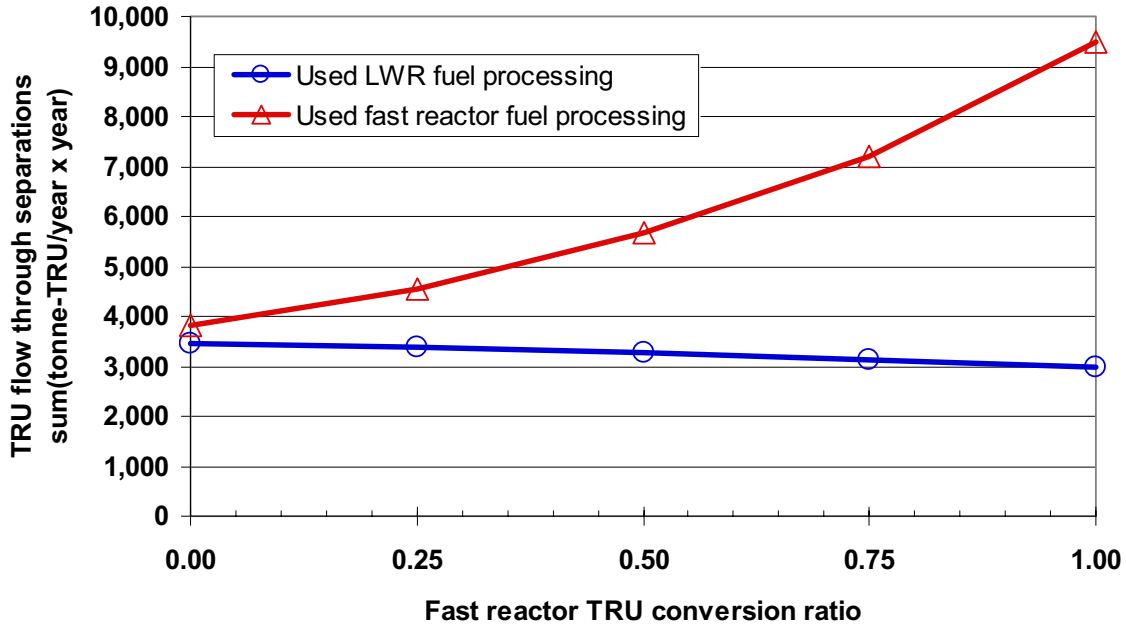

Fig. 9 Total mass of TRU material sent through separations in 1-tier recycle case as a function of fast reactor TRU conversion ratio.

The third proliferation resistance observation is that recycled material will change significantly with time. Figure 10 shows evolution of the recycle mix as TRU material is repeatedly recycled, in this case as inert matrix fuel in LWRs. This calculation uses heterogeneous IMF to keep the material actually fissile, i.e., each recycle is a mixture of fresh UOX and IMF made with TRU recovered from the previous recycle. The figure shows that the Cm and Cf isotopes, which emit high numbers of neutrons, increase three orders of magnitude between the first recycle and equilibrium.

The fourth and final proliferation resistance observation is that the quality of Pu does not change dramatically throughout the century. Fig. 11 shows the quality of Pu measured as the fraction of Pu-239 to total Pu in the system.

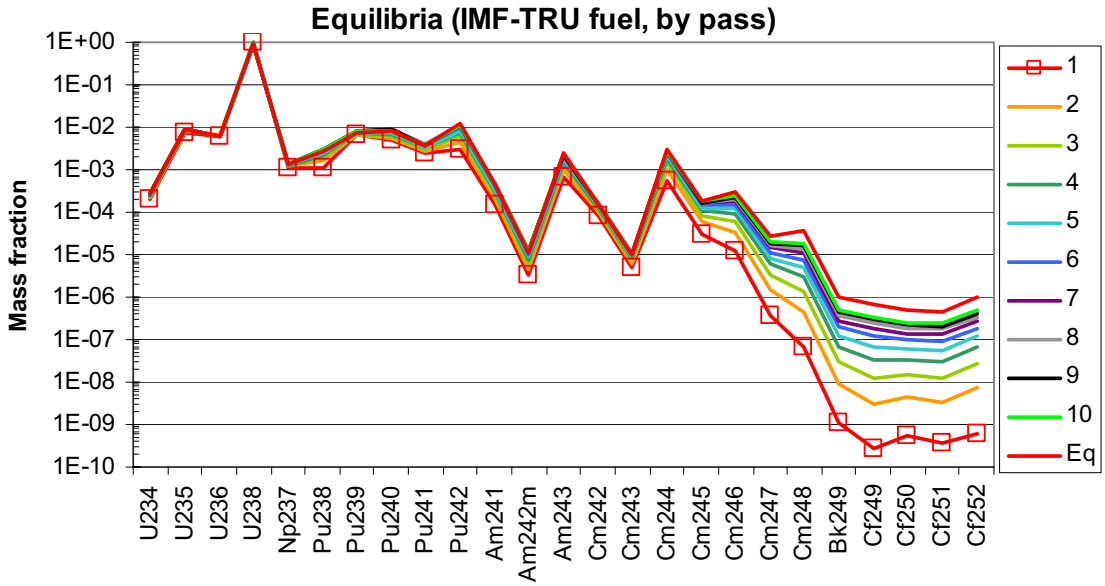

Fig. 10 Isotopic mix for IMF-TRU as a function of how many times transuranic material is recycled (1 to 10 recycles, equilibrium).

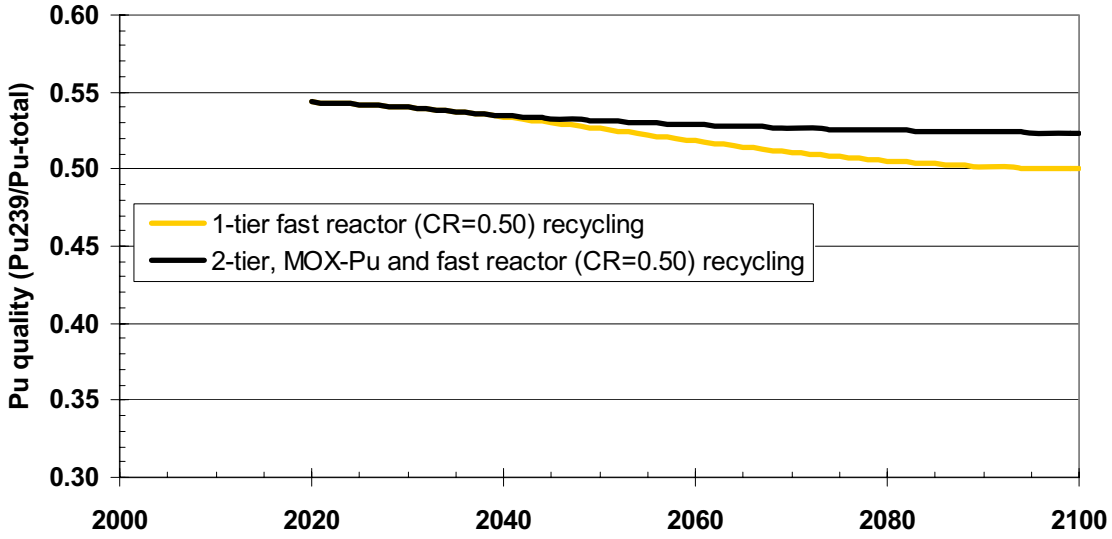

Fig. 11 The fraction of Pu that is Pu-239 as a function of time for 1-tier and 2-tier CR=0.50 examples.

5. PROGRAMMATIC OBJECTIVE 3 - URANIUM UTILIZATION

The third programmatic objective states, "Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting resource for nuclear power."[1] The goals are as follows:

1. "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."[1]

2. "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."[1]

To start, consider the range of estimates of world uranium resources in Table 1 relative to the 2006 production rate of 40,000 tonne-U. Without nuclear power growth, that production rate would exhaust total estimated conventional resources (16,000,000 tonnes-U) in 400 years. That time scale can drop to within a century with modest nuclear power growth, but extend many centuries if unconventional resources become practical.

Table 1 World Potential Uranium Resources.

Conventional resources	Reference	Tonnes U
Reasonably assured resource, at <$130/kg-U (<$50/lb U_3O_8)	Redbook[11]	3.3e6
Inferred resources, at <$130/kg-U (<$50/lb U_3O_8)	Redbook[11]	2.1e6
Prognosticated resources, at <$130/kg-U (<$50/lb U_3O_8)	Redbook[11]	2.8e6
Speculative resources, at <$130/kg-U (<$50/lb U_3O_8)	Redbook[11]	4.8e6
Total estimated conventional resources		
Above 4 categories, <$130/kg-U (<$50/lb U_3O_8)	Redbook[11]	1.3e7
Above 4 categories, plus "cost range unassigned"	Redbook[11]	1.6e7
Undiscovered + known < $130/kg-U ($50/lb-U_3O_8)	Herring[12]	1.5e7
Undiscovered + known < $130/kg-U ($50/lb-U_3O_8)	Steyn[13]	1.6e7
Unconventional resources	**Reference**	**Tonnes U**
Uranium in sandstone deposits	Herring[12]	1.8e8
Uranium in volcanic deposits	Herring[12]	2.0e9
Uranium from seawater	Herring[12]	4.2e9
Uranium in phosphate deposits	Herring[12]	8.0e11

The first uranium objective (15% increase) can be accomplished in thermal reactors, with most of the savings achieved in the first recycle of material.[10,14]

It has long been realized that far greater savings are possible with fast reactor operating in a breeder configuration. The limiting fuel isotope shifts from fissile U235 (0.71% of natural uranium) to fertile U238 (99.3% of natural uranium); theoretically increasing uranium utilization by ~100x, which motivates the second uranium objective. Note that the combination of the U235-to-U238 shift makes more expensive ore more practical as orders of magnitude more energy are derived from the same amount of ore.

Accomplishing 50-100x improvement in uranium utilization means near total replacement of LWRs (or other thermal reactors) with fast reactors. For example, if 10% of the reactor fleet remains LWRs with UOX fuel with 90% of the electricity from fast breeder reactors, the maximum uranium utilization improvement is 10x. Such substantial infrastructure change is notoriously difficult.[15] As most of the U.S. LWR fleet is moving toward a 60-year reactor lifetime, such a replacement of LWRs will take at least 6 decades from the operation of the last LWR. As an example, if fast breeder reactor deployment requires 2 decades from first deployment (in 2040 in uranium objective 2) to

100% market of new construction; it will be 2120 before the last LWR retires. Predicting uranium resources so far in advance is questionable.

The above example assumes that the fast breeder reactors can grow faster than nuclear power growth during its market penetration from 0 to 100%, followed by continued breeder growth at the nuclear power growth rate once it reaches 100% of new construction. The rate of breeder deployment is constrained by fuel supply, which we have tended to assume is transuranic material recycled from LWRs and fast reactors once operating, rather than high enriched uranium (~30% U235).

We have derived the required TRU conversion ratio, CR, such that LWR are not required to supply TRU to a growing fleet of fast reactors:

$$CR = e^{m(t_F + t_R)} \tag{1}$$

where m is the growth rate; t_F is the time for cooling, separation, and fuel fabrication; t_R is the time in reactor. Thus, $t_F + t_R$ is the total turnaround time. As an example, if $m = 0$, then $CR = 1$ and the system is in balance with no LWRs. Or, if one wants $m > 0$, then $CR > 1$. The higher the desired growth rate, the higher the required CR. In addition, because new fast reactors (growing at rate m) must have $t_R - 1$ additional years' worth of fuel to start up, equation 1 must be multiplied by another term.

$$CR = e^{m(t_F + t_R)} (1 + m(t_R - 1)) \tag{1}$$

At a nominal growth rate of 1.75%/yr, the time lags in the system are important.

If $t_F = 2$ (example for onsite recycling) and $t_R = 4$, then $CR = 1.17$ is required

If $t_F = 11$ (example for offsite recycling) and $t_R = 4$, then $CR = 1.36$ is required

Fig. 12 shows the required CR as function of desired growth rate and turnaround time. The minimum turnaround time is probably ~5 years (1-year cooling, separation, fabrication and 4 years in reactor).

The theoretical maximum CR is ~1.9 because Pu239 dominates fission in a fast reactor and it yields 2.9 neutrons/fission. One neutron must induce the next fission, leaving 1.9 to make more transuranic material from U238. Neutron yields vary slightly by isotope, e.g., 2.4 for U235, 2.9 for Pu241, and 3.2 for Am242m, so the exact theoretical maximum could be slightly different than 1.9. Of course, as neutron leakage and neutron capture by fuel and non-fuel core material is accounted for, the practical maximum conversion ratio will be significantly lower than 1.9. For example, if that maximum is considered to be 1.5, then the maximum rate of breeder reactor introduction can be 4.7% with 6-year turnaround (onsite recycling), but only 2.3% with 15-year turnaround (offsite recycling). The holdup of transuranic material in the system impacts system performance so that short time lags, e.g. when facilities are co-located instead of at different locations, can lead to faster system evolution.

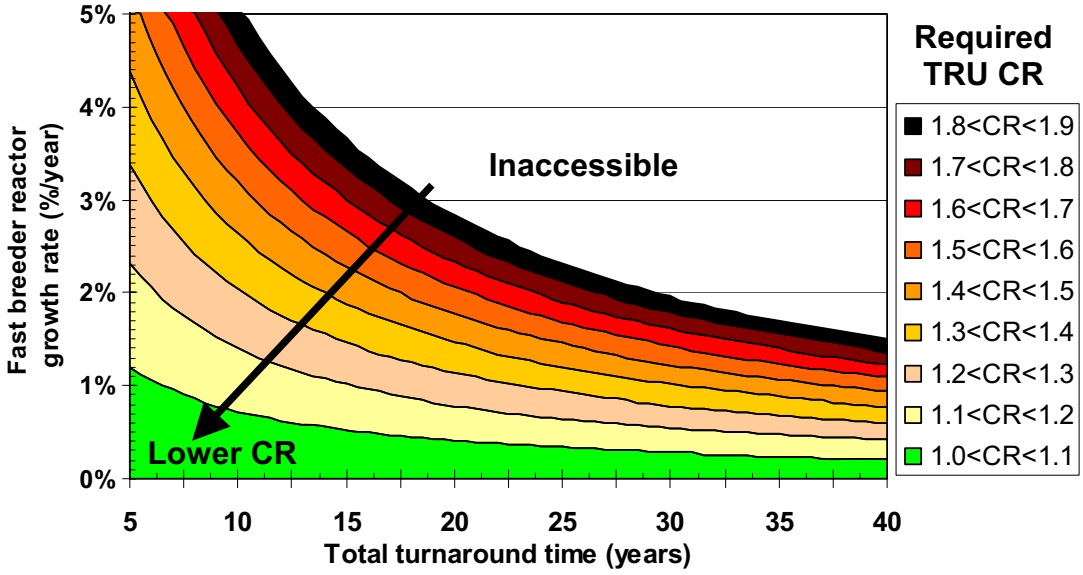

Fig. 12 Required fast reactor TRU conversion ratio, as a function of growth rate and turnaround, ignoring displacement of pre-existing LWRs or TRU stockpiles.

The dynamic equilibrium in fig. 12 depends on rates of fuel supply and usage, and includes filling up the fast reactor portion of the system. It ignores the additionally having to displace however many LWRs exist before fast reactor deployment and whatever TRU stockpile exists. These considerations will hinder (LWR displacement) or enable (stockpile) fast reactor deployment, see fig. 13. At low growth rates, the inventory of TRU material accumulated before fast reactor deployment allows the system to function through 2100 with a fast reactor TRU CR below that predicted by equation 2 (fig. 12). Over ~1% growth, the pre-existing inventory is not adequate and a higher TRU CR is required. The shape of the curve over 1%/yr growth depends on when FR deployment starts, when the last LWR is built, the retirement rate of current LWRs, etc.

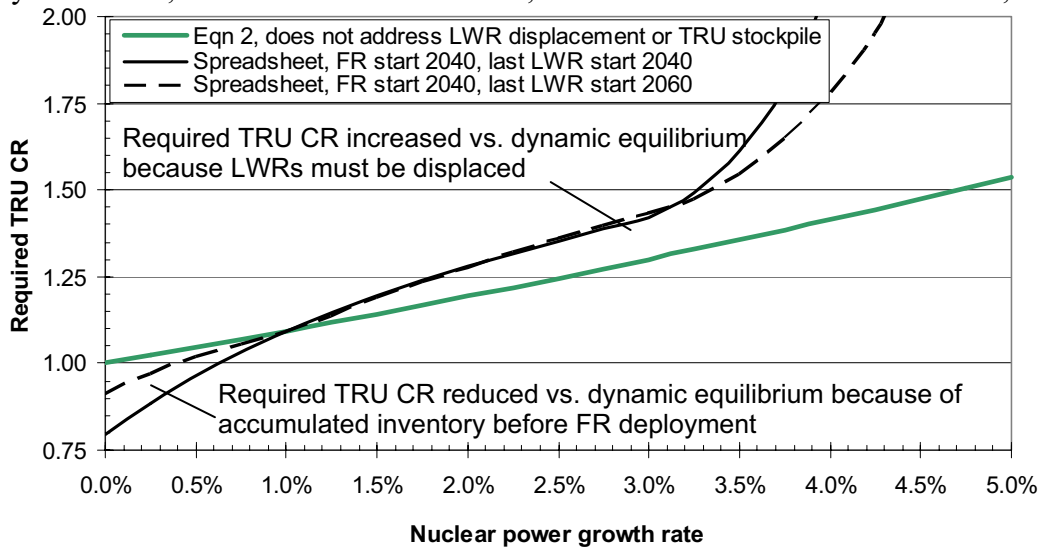

Fig. 13 Required fast reactor TRU conversion ratio to 2100 for onsite recycling (6 year turnaround from 2 years processing plus 4 years in reactor).

The situation gets more difficult if we desire an eventual mix of fast reactors and thermal reactors such as LWR and VHTR.[9]

Other studies[9] have similarly found constraints on fast reactor introduction and uranium utilization improvement along these lines. These dynamic effects occur whether the fast reactors are net TRU producers or consumers. The fraction of fast reactors will generally be lower than predicted by simple "static equilibrium" calculations. The higher the nuclear power growth, the higher the fast reactor TRU conversion ratio should be from the standpoint of uranium usage and the further the fast reactor fraction from static equilibrium. Fig. 14 and 15 show examples.

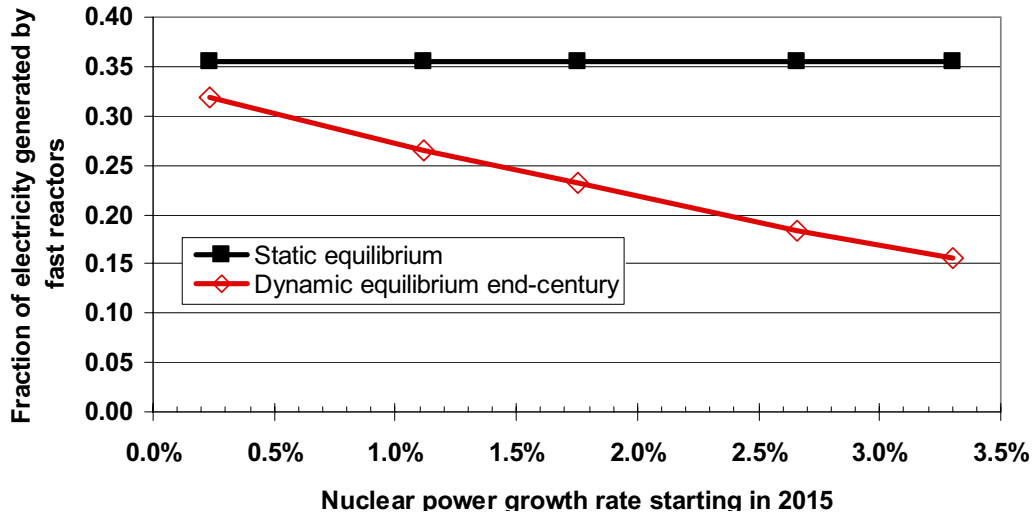

Fig. 14 Percent of 1-tier CR=0.50 fast reactors at 2100 based on either static equilibrium or dynamic simulations.

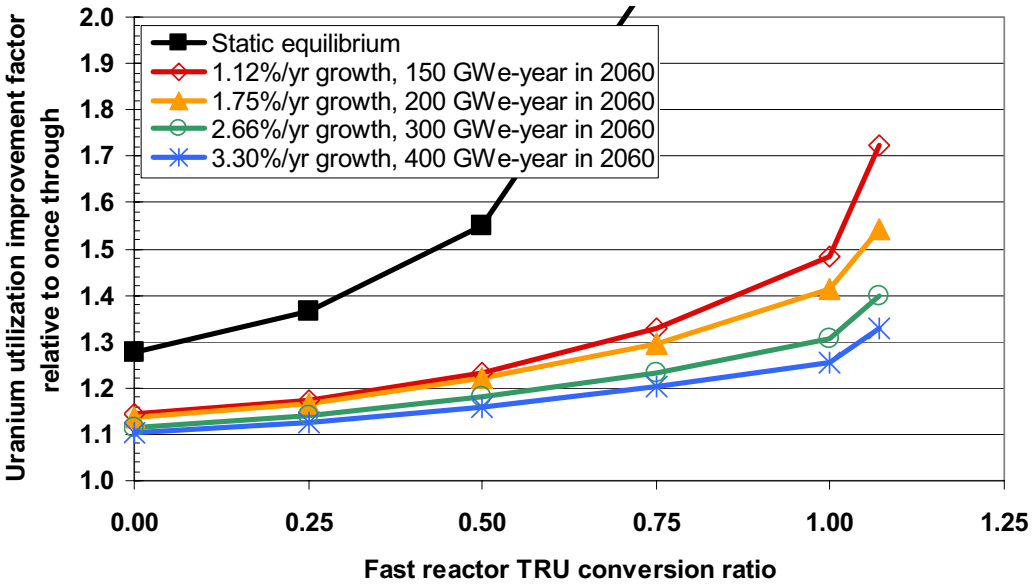

Fig. 15 Static and dynamic analysis of uranium improvement factors reactor to once-through as a function of growth rate and fast reactor conversion ratio.

6. PROGRAMMATIC OBJECTIVE 4 - FUEL CYCLE MANAGEMENT

The fourth objective is "Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system."[1] The corresponding goals are stated as follows:

1. "At all times, ensure that advanced fuel cycle technologies cause no significant decrease in the economic competitiveness of nuclear electricity."[1]

2. "At all times, maintain excellent safety performance of nuclear fuel cycle facilities and operations."[1]

3. For the long-term, improve spent fuel management to reduce on-site storage at nuclear power plants."[1]

Objective 4 is "catch-all"; most of the preceding examples and observations pertain to safety, economics, and on-site storage. For example, offsite fast reactor recycling versus onsite fast reactor recycling not only increases time lags and material storage while delaying reduction of radiotoxicity (waste management section), it also increases public transportation exposure. We offer three final observations.

The first is that dynamic versus static will impact economic assessments. A static equilibrium is appropriate when discount rates, the time value of money, and cash flows are not addressed. A dynamic equilibrium comes closer to cash flows if the time value of money is accounted for as costs that lead others are given greater weight; cash flows that lag others are given less weight. Table 2 lists key lead and lag items in dynamic equilibria. For example, one builds LWRs relatively early in the process of generating electricity; therefore, when time value of money is considered, the relative contribution of LWRs to total cost increases. Conversely, fast reactors and waste disposal are bought relatively late; therefore, their relative contribution to total cost decreases.

Table 2 Lead and Lag Items in Dynamic Equilibria

	Leading Pay for relatively soon	Lagging Pay for relatively late
Increase or decrease when shifting from static to dynamic equilibrium	Increase, hence factor might be more important than predicted by static equilibrium	Decrease, smaller impact than might be predicted by static equilibrium
Material inputs	Natural uranium (NU) Depleted uranium (DU) Enriched uranium (EU) Zirconium and steel	
Types of reactors	Number of thermal reactors using uranium oxide fuel	Number of fast reactors Thermal efficiency increases
Types of facilities	Fabrication plants	Separation plants
Material outputs		Waste disposal

The fraction of fast reactors in time will be much lower than predicted by simple "static equilibrium" calculations due to multiple system constraints that impact the amount of TRU available for fueling new reactors at startup. This is illustrated in fig. 16.

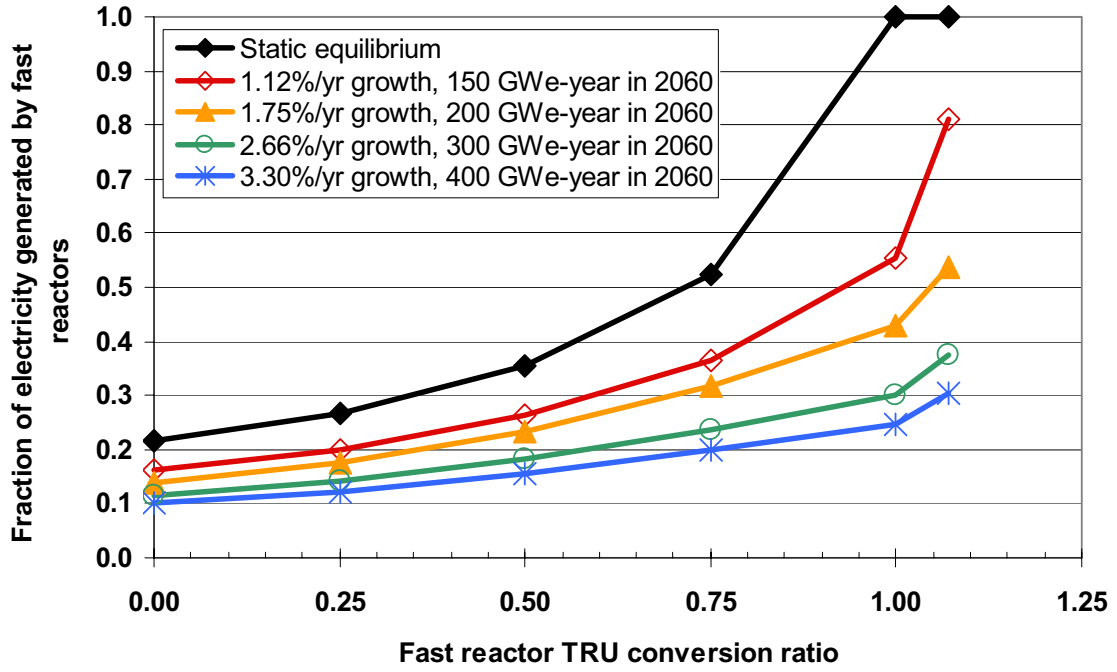

Fig. 16 Fraction of electricity generated by fast reactor at dynamic equilibrium (near 2100) as function of fast reactor TRU conversion rate and nuclear electricity power growth rate.

The final observation is that fuel and separation facilities must accommodate variation in fuel mixture elemental composition. This composition will vary as reactor type, fuel type, burnup, aging of used fuel, number of recycles, separation purity, etc.

7. CONCLUSIONS

The AFCI strategic objectives focus on the date of first deployment. Dynamic simulations also show the importance of the magnitude, timing, and rate of first deployments.

AFCI programmatic objective 1 is to reduce the waste management. Simulations show that often a sizable reduction of waste burden can be achieved by "avoidance", i.e., displacement of LWR-UOX by reactors producing less or no net TRU, even if such reactors do not themselves consume much TRU. TRU management needs to account for both the TRU consumed in fast reactors and the additional TRU generation avoided due to fast reactors replacing some LWRs. Waste goals may address either "per recycle" or cumulative impact targets. And, the isotopic mix can be important. Next, significant material accumulates throughout the system so that achievement of high waste management benefits depends on continuation of recycling. Another waste management observation is that uranium dominates the mass of the system. Finally, one must put TRU "in place" in order to reduce waste burdens. TRU in storage does not reduce waste

burdens, except in so far as 30-year halflife Cs137 and Sr90 decay. Similarly, the holdup of transuranic material in the system impacts system performance so that short time lags can lead to faster waste management benefits via consumption and avoidance of TRU.

AFCI programmatic objective 2 addresses proliferation resistance. The first observations are that the location and mass flow of weapon-usable transuranic material can vary significantly depending on the choice of technology, location of facilities (onsite versus offsite recycling), time lags, etc. We also observe that although the composition of recycled material changes significantly at the isotopic-level; the "quality" of Pu (Pu239/Pu-total) changes little.

AFCI programmatic objective 3 is uranium utilization. Achieving the stated objective of 50x improvement in uranium utilization relative to the current once-through fuel cycle requires fast breeder reactors. Dynamic simulations show that the fraction of fast reactors at any point in time will be much lower than predicted by static equilibrium calculations due to multiple system constraints that impact the amount of TRU available for fueling new reactors at startup. Longer storage time lags have a marked impact on the potential rate of FR introduction.

AFCI programmatic objective 4 is systematic fuel management, including economics. Economic analyses that consider the time value of money will increase the relative contribution of "lead" items such as LWR construction and decrease the relative contribution of "lag" items such as fast reactors and waste disposal. Fuel and separation facilities must accommodate variation in fuel mixture elemental composition.

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