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Abstract – *This paper examines the time-dependent dynamics of transitioning from a once-through fuel cycle to a closed fuel cycle. The once-through system involves only Light Water Reactors (LWRs) operating on uranium oxide fuel UOX), while the closed cycle includes both LWRs and fast spectrum reactors (FRs) in either a single-tier system or two-tier fuel system. The single-tier system includes full transuranic recycle in FRs while the two-tier system adds one pass of mixed oxide uranium-plutonium (MOX U-Pu) fuel in the LWR. While the analysis primarily focuses on burner fast reactors, transuranic conversion ratios up to 1.0 are assessed and many of the findings apply to any fuel cycle transitioning from a thermal once-through system to a synergistic thermal-fast recycle system. These findings include uranium requirements for a range of nuclear electricity growth rates, the importance of back end fuel cycle facility timing and magnitude, the impact of employing a range of fast reactor conversion ratios, system sensitivity to used fuel cooling time prior to recycle, impacts on a range of waste management indicators, and projected electricity cost ranges for once-through, single-tier and two-tier systems.*

The study confirmed that significant waste management benefits can be realized as soon as recycling is initiated, but natural uranium savings are minimal in this century. The use of MOX in LWRs decouples the development of recycle facilities from fast reactor fielding, but also significantly delays and limits fast reactor deployment. In all cases, fast reactor deployment was significantly below than predicted by static equilibrium analyses.

I. INTRODUCTION

A number of nuclear fuel cycle studies have examined both open and closed fuel cycle systems in equilibrium. These studies miss dynamic behavior of significant importance in developing a strategy for transitioning from an existing fuel cycle with associated infrastructure to a new fuel cycle. This paper examines the transition from an open fuel cycle to both one-tier and two-tier closed fuel cycles with emphasis on the constraints and unique behavior that are revealed.

The information in this paper summarizes selected results of a comprehensive study[1] conducted in 2008 by the Systems Analysis campaign of the U. S. Department of Energy's Advanced Fuel Cycle Initiative. The study assessed a range of issues associated with the U.S. transitioning to a closed recycle system before mid-century. The study focused on the dynamic behavior of the system during the transition period, including introduction of initial fast reactors and recycle facilities, work-off of stores of used fuel and the eventual stabilization of the ratio of fast reactors to thermal reactors in a dynamic equilibrium by the end of the century. Sensitivity studies were used to increase understanding of the impact of several key assumptions. The scenario assessments in the study looked at a range of options for analysis purposes; these scenarios do not represent U.S. policy.

II. PROBLEM DESCRIPTION

The purpose of the study was to assess dynamic constraints which may impact the rate of transition from an open fuel cycle to an advanced fuel cycle with recycling of light water reactor (LWR) used uranium oxide (UOX) fuel. The two primary scenarios were based on recycling into either fast reactor fuel (one-tier) or first recycling uranium and plutonium into a one-pass mixed oxide (MOX-U/Pu) LWR fuel followed by fast reactor fuel (two-tier). A once-through scenario was also calculated for comparison. Fast reactor fuels included recycle of minor actinides, so were composed of a combination of uranium and transuranics (FR-TRU). The study primarily assumed burner fast reactors for consumption of the transuranics generated with a transuranic conversion ratio of 0.5[a]. The impact of

[a] The TRU conversion ratio is the ratio of transuranics created to transuranics destroyed during irradiation. It is similar to the breeding ratio, which measures fissile mass created to fissile mass destroyed.

this conversion ratio assumption was explored via sensitivity studies. Both oxide and metal fuel forms were considered for the fast reactors.

The transition analyses were all based on current U.S. fuel cycle and LWR infrastructure, including current inventories of used UOX fuel. Expansion of the current 100 GWe of installed reactor capacity started in 2015 based on 1.75% total annual compounded growth of nuclear-based electricity generation. This growth provided a doubling of nuclear electricity generation by 2060, redoubling by 2100. The impact of this growth rate assumption was assessed via sensitivity studies. Reactor retirements after 60 years of operation were included in the system dynamic analysis.

A geologic repository was assumed to open shortly after fleet expansion started, for receipt of used LWR fuel and high level waste. The initial repository capacity was limited to disposal of 63,000 metric tonnes of initial heavy metal per restrictions in the U.S. Nuclear Waste Policy Act[2]. For all scenarios, inventories of used UOX fuel accumulated through 2010 were assumed direct disposed to reach this limit with additional used fuel and high level waste allocated to "additional repository capacity". One key impact of this assumption was the disposal of all existing lower burn-up aged used fuels, simplifying the analysis. All used UOX fuels discharged after 2010 were assumed to have the same burnup of 51 MWth-days/kg-iHM. LWR MOX-U/Pu fuels were assumed to have similar burnup for compatibility in reactor reload cycles, while the FR-TRU fuel at CR = 0.5 had a burnup of 132 MWth-days/kg-iHM. Both LWR fuels were cooled a minimum of 10 years before separations or disposal, while the FR-TRU fuel was cooled 2 years for on-site recycling (primary assumption) and 10 years for centralized recycling (sensitivity analysis).

Reprocessing of used LWR fuel was assumed to begin in 2020 when the fuel discharged in 2010 reached the minimum cooling time. Reprocessing capacity was initially limited, restricting the production of MOX-U/Pu and FR-TRU fuels. The availability of fuel feedstock is a primary constraint on the rate of transition of the reactor infrastructure from only LWRs to a mixed fleet of LWRs and fast reactors. UOX reprocessing capacity was expanded during the scenario such that no excess of cooled fuel remained by 2100. MOX-U/Pu and FR-TRU fabrication and reprocessing capacities were not constrained. Natural uranium supply, conversion and enrichment were not constrained, so when the rate of construction of FRs was constrained by fuel availability below the overall rate of fleet growth and replacement, new UOX-fueled LWRs made up the deficit.

Fast reactor introduction began shortly after 2030 for the one-tier case. For the two-tier case, FRs were introduced when the first MOX-U/Pu used fuel had cooled and was available for reprocessing (~2037). In both cases, construction was limited for the first decade to 1 GWe/year new capacity for the first 5 years and 2 GWe/year for the second 5 years.

The analysis was performed using the dynamic fuel cycle simulation model VISION[3]. VISION calculates the mass flows of 81 isotopes and isotope groups of interest for fuel composition, shielding, decay heat, and radiotoxicity and includes decay calculations for isotopes with half lives greater than 0.5 years. The model provided facility and material information and annual data for total electricity output, reactor capacity by type, natural uranium and enrichment requirements, used fuel inventories, fresh fuel fabrication and used fuel separations rates, and a number of waste parameters.

III. FINDINGS

The primary results of the analyses include gradual growth of total nuclear output with a slow transition from all LWRs to a mixed fleet of LWRs and fast reactors in a ratio approaching dynamic equilibrium. Figure 1 shows the electricity generation by reactor type for the one- and two-tier systems. These graphs show the exponential growth pattern in all the analyses which is a reflection of using an annual compounded growth rate. In both cases, the amount of electricity generated by recycled materials is small compared to that generated by UOX. The two-tier system results in a slightly smaller amount of total electricity being generated by recycled materials. This is due to the time this material is sitting inactive in used LWR MOX fuel.

The two-tier system also results in significantly fewer fast reactors due to a number of factors. First, some of the Pu that contributes to fast reactor cores in the one-tier system is instead consumed during the LWR MOX pass. Second, the time spent in the MOX pass delays the construction of fast reactors, resulting in a lower dynamic equilibrium ratio.

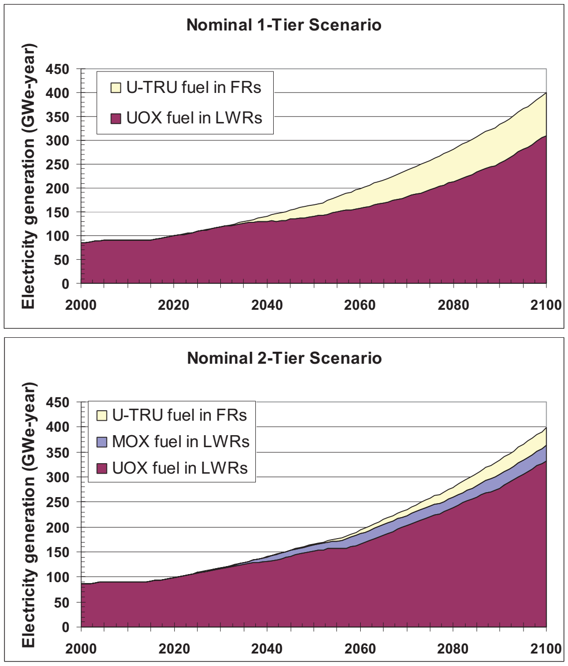

Fig. 1. Electricity generation for 1-tier (top) and 2-tier (bottom) scenarios as a function of fuel and reactor type.

Figure 2 shows the share of fast reactor electricity generation. Note the higher rate of market penetration in the one-tier case, reflecting the larger quantity of Pu available to the fast reactors in this case. Both cases approach an equilibrium point late in the century as the market share of fast reactors becomes sufficient to balance the net TRU production from the LWRs. The one-tier case slightly overshoots this equilibrium point while excess inventories of used UOX are worked off as the separations capacity catches up with discharge rates. The two-tier case slows less fluctuation because it is dampened by the intermediate MOX pass.

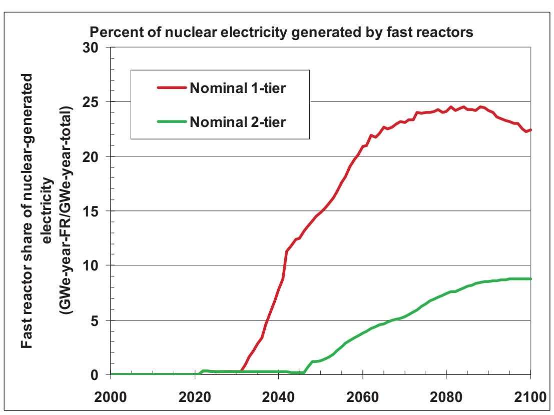

Fig. 2. Fast reactor electricity generation percentage for 1-tier and 2-tier scenarios.

III.A. Fast Reactor Equilibrium

One of the major findings of the study was the large difference in the equilibrium ratio of LWRs to fast reactors due to a number of dynamic features of the fuel cycle transition. Fast reactor share at equilibrium is an important economic driver for a closed fuel cycle because fast reactors are projected to have ~10% higher capital costs than LWRs when fielded in larger numbers[4]. (The first few fast reactors are projected to cost more, as with the first few copies of any new complex technology.)

At a TRU conversion ratio of 0.5, a static material balance analysis for the one-tier case indicates 36% of the fleet should be fast reactors. This is because the LWRs operating on UOX produce ~1/4th tonne of TRU per GWe-year of operation which the fast reactor consumes ~1/2 tonne and factors such as differences in thermal efficiency and capacity factor only slightly alter the ratio.

In the dynamic transition case several factors lower the fast reactor share. First, while each GWe of fast reactor capacity consumes ~1/2 tonne of TRU per full power year, nearly 10 tonnes is required for the initial cores to generate at this level. The greater the number of new cores needed, the lower the share of fast reactors at dynamic equilibrium. Figure 3 shows the impact of growth rate on fast reactor share, reflecting the requirement for more new cores as the total fleet growth rate increases.

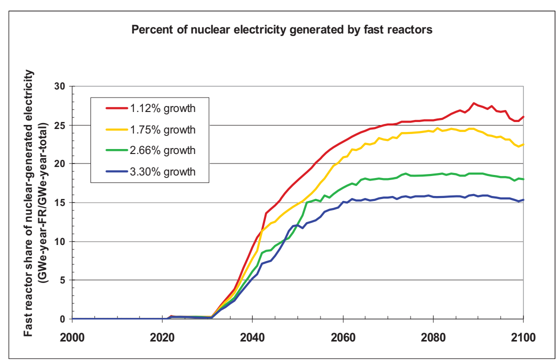

Fig. 3. Fast reactor electricity generation percentage for 1-tier scenario as a function of overall growth rate.

A second factor impacting fast reactor share is the reactor conversion ratio. The lower the conversion ratio, the more net consumption of TRU and therefore the larger the number of LWRs needed per fast reactor to provide feed material. Figure 4 shows the impact of conversion ratio on the dynamic equilibrium share of fast reactors for the nominal 1.75% growth rate scenario. While the sensitivity analysis considered conversion ratios down to

0, it is probably not practical to achieve a ratio much below 0.5 without considerable progress in inert matrix fuels[b].

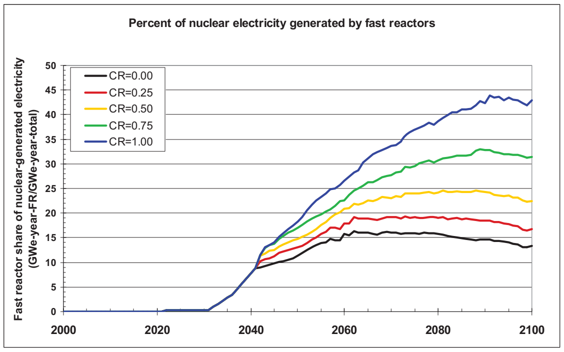

Fig. 4. Fast reactor share as a function of TRU conversion ratio.

The impacts of growth rate and conversion ratio are multiplicative, but are usually assumed to move in opposite directions in scenario development. As the growth rate increases, the demand for more natural uranium is usually assumed to result in higher prices. This trend can help reduce the cost difference between LWRs and fast reactors supporting economic adoption of higher conversion ratios. Higher conversion ratios result in more fast reactors, reducing natural uranium demand and stabilizing ore prices.

III.B. Infrastructure Considerations

Transitioning to a closed fuel cycle includes development of considerable fuel cycle infrastructure. This includes used UOX separations, fast reactor fuel fabrication, and used fast reactor fuel storage. The systems analyses included assessment of a number of infrastructure deployment assumptions.

UOX separations facilities are very large capital projects that can take a decade to plan and construct. A sensitivity study was performed to better understand the impact of different levels of separations construction. If separations construction is limited, the feed material for fast reactor fuel will be restricted and fewer fast reactors will be constructed. To make up for the shortage of fast reactors and still maintain overall generation growth, more LWRs are constructed and more UOX discharged. Figure 5 shows the impact of different levels of total separations capacity on used UOX inventories and fast reactor share.

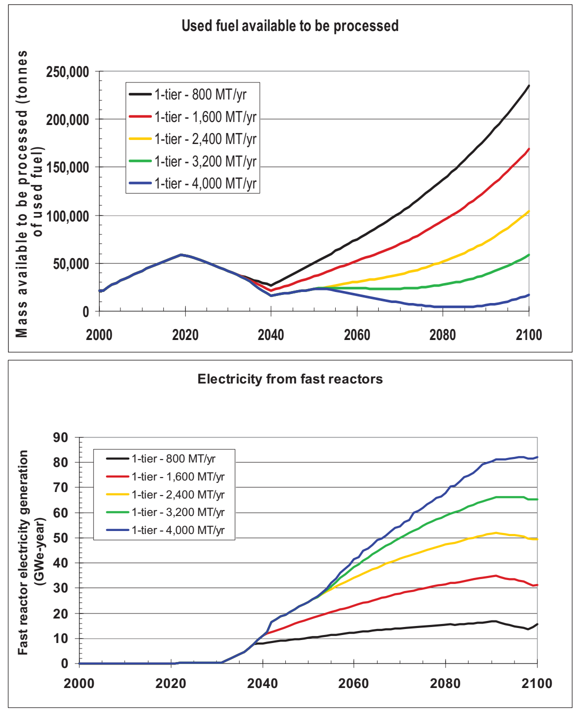

Fig. 5. Impact of varying UOX separations capacity on used fuel inventories (top) and electricity from fast reactors (bottom)

The location of fast reactor fuel recycle facilities impacts used fuel cooling time. If the fuel is recycled on-site, minimum cooling time is driven by the separations technology, while if it is recycled at a larger centralized facility then transportation constraints can require longer cooling to reduce decay heat management and shielding requirements. Figure 6 shows the impact of differences in cooling time for used fast reactor fuel on the total fast reactor share. Longer cooling times result in large amounts of TRU sitting in cooling fuel, just as was found for the MOX cycle.

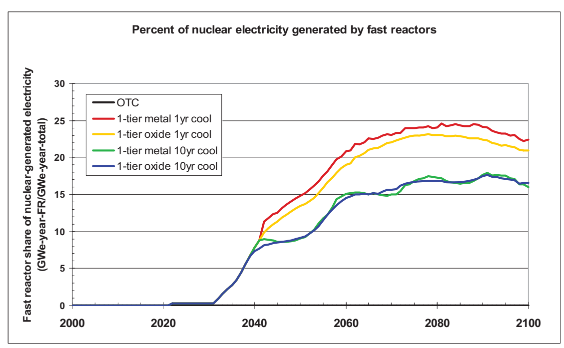

Fig. 6. Impact of cooling time on fast reactor share for both metal and oxide fuels.

Fuel cycle infrastructure deployment must also be coordinated with reactor deployment. For example, if large scale fast reactor construction is delayed due to technical or economic factors, then construction of UOX

[b] An inert matrix fuel contains no uranium, so has no transmutation of U-238 into Pu and other transuranics.

separations facilities also needs to be slowed. Figure 7 shows the impact of delay in fast reactor deployment assuming increases in separations capacity are also delayed. The initial share of fast reactors is reduced, resulting in more LWRs and more used UOX fuel. Later in the simulation when separations is increased to work off the accumulated UOX, the share of fast reactors is higher than the nominal scenario.

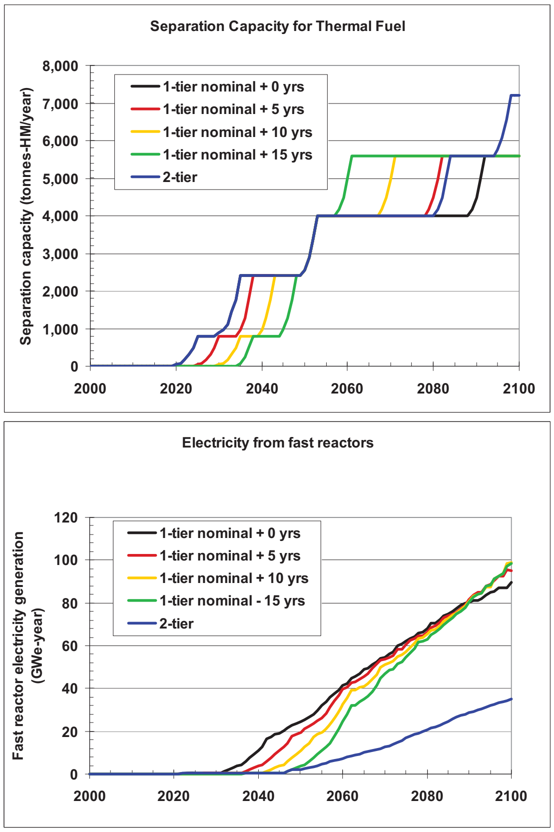

Fig. 7. Impact of later fast reactor introduction on UOX separations capacity (top) and fast reactor share (bottom).

Figure 8 shows the impact of not coordinating fast reactor deployment with UOX separations capacity in a one-tier system. If separations capacity is increased without simultaneous fast reactor construction then large inventories of separated TRU can accumulate very quickly. When fast reactors are subsequently fielded, these inventories are also worked off quickly due to the significant TRU requirements for initial cores. Storage of separated TRU involves significant expense due to shielding, decay heat, criticality, and security requirements. Storage of separated TRU can also be reduced by using a two-tier system with a MOX-TRU fuel in LWRs. Infrastructure coordination would still be needed between UOX separations and MOX-TRU fuel fabrication and between MOX fuel separations and fast reactor deployment.

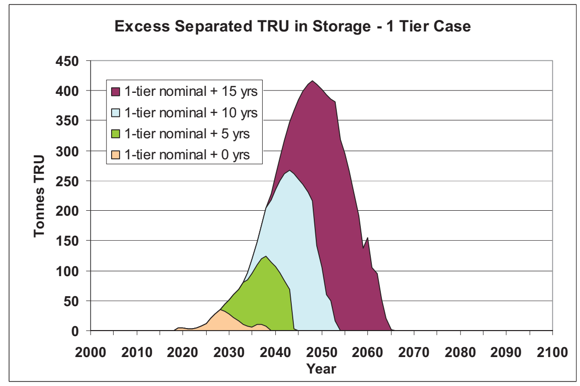

Fig. 8. Excess separated TRU as a function of fast reactor deployment timing

The reverse case of significant fast reactor deployment without large UOX separations capacity is not workable, as there is insufficient TRU to fuel initial cores, even if the first fast reactors are operating at conversion ratios of 1.0 or higher.

III.C. Sustainability

The systems analyses assessed a number of resource and waste parameters, three of which are presented here. Figure 9 shows the impact of transitioning to a closed fuel cycle on demand for uranium. The cumulative impact is quite small, even by the end of the century, which is to be expected given the small amount of electricity being generated by recycled materials (see Figure 1). Uranium demand can be reduced through application of a higher conversion ratio which could increase fast reactor share to near 50% by the end of the century (see Figure 4), but a large impact would still not occur until the following century.

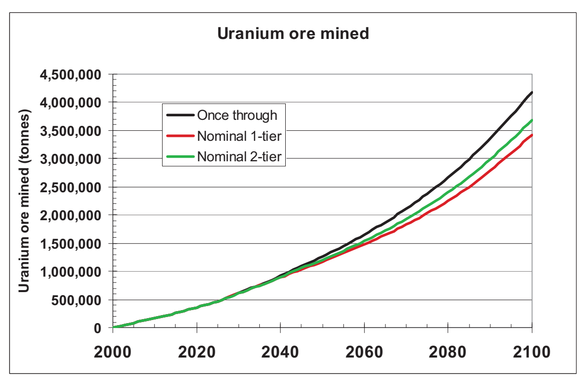

Fig. 9. Uranium ore requirements for once-through, one-tier and two-tier scenarios.

While the impact of transitioning to a close fuel cycle is limited for uranium demand, the impact on waste generation is immediate and significant. As soon as a decision is made to stop once-through and convert to recycle, the mass of radioactive material in the high level waste (HLW – mostly fission products) and greater-than-class-C low level waste (GTCC – mostly cladding) is limited only by the efficiency of the recycle process. Figure 10 shows the impact on total waste disposed, both as a function of radioactive material mass and projected waste volume. Between 2020 and 2040 the primary source of waste is the direct disposal of 63,000 tonnes of older low-burnup used fuel that was discharged by 2010. The additional waste disposed for the remainder of the century results from processing of over 350,000 tonnes of higher burnup used UOX discharged after 2010 as well as thousands of tonnes of very high burnup used fast reactor fuel.

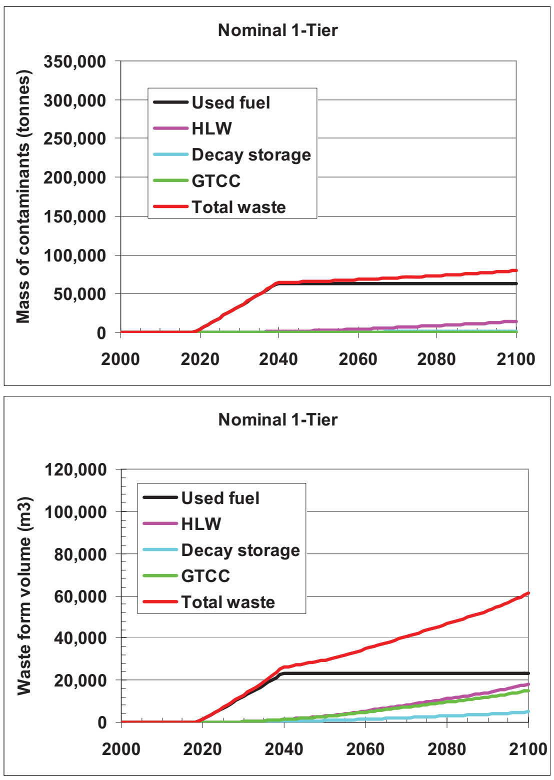

Fig. 10. Mass of radioactive material (top) and projected waste volume (bottom) for nominal one-tier scenario.

Long-term environmental impacts of radioactive waste disposal depend on a combination of the quantity and activity of the material disposed and the waste form, engineered barriers and geologic environment of the disposal repository. The first two factors determine how much hazard is present while the last three determine how mobile that hazard is in the environment. The design of a waste repository is outside of the scope of the fuel cycle systems studies, so only the quantity of hazard is calculated. The best indicator of the quantity of hazard is the long-term radiotoxicity of the material multiplied by the mass disposed. While Figure 10 showed the reduction in waste quantity after the start of recycling, Figure 11 shows the impact on long-term radiotoxicity, which is evaluated based on the isotopes (including decay products) 1000 years after discharge from the reactor. If the actinides are removed for recycle with less than 0.5% losses, then long-term radiotoxicity is reduced to less than 1% of that of direct disposed used UOX fuel, or by a factor of 100.

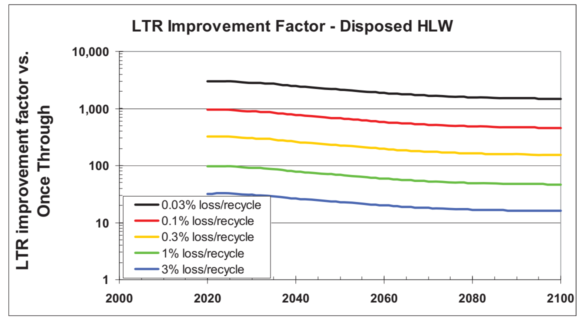

Fig. 11. Reduction in long-term radiotoxicity as a function of separations efficiency.

IV. CONCLUSIONS

The dynamic systems analyses discussed in this paper have highlighted a number of key findings associated with nuclear energy growth and fuel cycle transitioning.

Fast reactor deployment rates will be much lower than the levels predicted by simple "equilibrium" calculations due to multiple system constraints. Sensitivity studies have identified the most important constraints to be separations capacity and timing, nuclear growth rate, fast reactor TRU conversion ratio, used fuel cooling time, and fast reactor introduction timing. A 2-tier system with a MOX recycle stage imposes additional constraints that result in further reductions and delays.

The impact of a closed fuel cycle is highly dependent on the rate of deployment of fuel cycle facilities. The size and timing of UOX separations facilities is the primary driver behind the rate of deployment of TRU-burning fast reactors. The fast reactor deployment rate in turn impacts the amount of TRU both generated and consumed. Later fast reactor deployment can result in large inventories of separated TRU requiring secure storage, unless MOX is used in LWRs or separations is delayed. The location of used fast reactor fuel recycling facilities (onsite versus centralized) also has a significant impact on the rate of fast reactor deployment, impacting the amount of TRU tied up in used fuel.

A closed fuel cycle does little to reduce uranium needs in this century due to the constraints on fast reactor deployment. The use of higher conversion ratios does not significantly change this finding. However, the impact of continuous recycling of used fuel on waste management is large, with the mass radioactive material disposed reduced by more than an order of magnitude and the radiotoxicity reduced by two orders of magnitude.

ACKNOWLEDGMENTS

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NOMENCLATURE

FR – Fast spectrum Reactor
GTCC – Greater Than Class C low level waste
HLW – High Level Waste
LTR – Long Term Radiotoxicity
LWR – Light Water Reactor
MOX – Mixed Oxide Fuel
OTC – Once Through fuel Cycle
TRU – Transuranics (elements heavier than uranium)
UOX – Uranium Oxide Fuel

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