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*Thermal recycle provides several potential benefits when used as **stop-gap, mixed,** or **backup** recycling to recycling in fast reactors. These three roles involve a mixture of thermal and fast recycling; fast reactors are required to some degree at some time. **Stop-gap** uses thermal reactors only until fast reactors are adequately deployed and until any thermal-recycle-only facilities have met their economic lifetime. **Mixed** uses thermal and fast reactors symbiotically for an extended period of time. **Backup** uses thermal reactors only if problems later develop in the fast reactor portion of a recycling system.*

*Thermal recycle can also provide benefits when used as **pure thermal recycling**, with no intention to use fast reactors. However, long term, the pure thermal recycling approach is inadequate to meet several objectives.*

I. INTRODUCTION

Recycling of used nuclear fuel transuranics in light water reactors (LWRs) can accomplish much, but with various costs and with the need to eventually transition to fast reactors for sustainability of uranium supplies. The report considers timing issues and benefits associated with thermal recycling. This requires identifying potential roles for thermal recycling, as opposed to the other two major classes of alternatives – no recycling of any kind (once-through fuel cycle) or recycling only in fast reactors.

In general, there are several possible roles for LWR recycling, as follows:

- Stop-gap recycling – One recycle pass in thermal reactors followed by subsequent recycle in fast reactors. This accommodates a theoretical delay in deployment of fast reactors.
- Mixed recycling – Recycling with a symbiotic mix of thermal and fast reactors for several decades.
- Backup recycling – Recycling in thermal reactors if economic or acceptance problems develop with fast reactor recycling. This allows recycling to continue if such a perturbation develops.
- Pure thermal - Thermal reactors as the only planned mechanism to recycle used fuel.

This study was requested to examine potential benefits of recycling in thermal reactors. It is not intended to create new specific recycling scenarios nor to address the status of required technologies.

II. OBJECTIVES

The fundamental objective of advanced nuclear fuel cycles is to provide technology options that would enable long-term growth of nuclear power to improve environmental sustainability and energy security.[1] The four top-level objectives address waste management, proliferation risk reduction, energy recovery, and economic and safe system management.[1,2,3,4]

III. CASE FOR COMPARISON (CC)

We established a case for comparison with the following parameters such that recycling occurs only in fast reactors:

- Test facility operational in 2016, supplying sufficient transuranic material (TRU) for the first advanced burner reactor (ABR).
- First separation facility for processing of used LWR fuel operational in 2020 at 2000 tonnes-used fuel/year.
- First fast reactor (Advanced Burner Reactor, ABR) operational in 2021 at 1 GWth (0.38 GWe)
- Subsequent ABRs built limited to 1 GWe/yr from 2030 to 2034, subject to the need for new nuclear power plants and TRU supply. Build rate increases to 2 GWe/yr from 2034 to 2044. Starting in 2045, fast reactor construction only limited by TRU supply and need for new nuclear power plants.
- Fast reactors at TRU conversion ratio of 0.50.
- Nuclear power grows at 2.25%/yr.

Calculations were done with the VISION model of the fuel cycle.[5]

IV. STOP-GAP RECYCLING

The Stop-gap recycling role involves one recycle pass in thermal reactors followed by subsequent

recycle in fast reactors. This accommodates potential delay of fast reactors by one or two decades, while still starting sustainable recycling of used fuel. Thereafter, the one recycle pass in thermal reactors would be phased out. Recycling can start to consume transuranic material (faster with inert matrix fuel (IMF) than with mixed oxide fuel (MOX)). The rate of consumption is controllable by the amount of IMF or MOX deployed. Implementing IMF approaches require solving difficult separation and fabrication issues, which are beyond the scope of this paper.

Figure 1 shows that "stop gap" recycling accommodates a hypothetically slower ABR program without increasing the separated TRU inventory. The CC curves are defined in the previous section. The "stop gap" curves assume fast reactors are delayed one decade (from 2030 to 2040) and MOX-NpPu is used from 2020 to 2050. Once facilities for backup MOX recycling are built, it is assumed they are used for at least thirty years to recover the investment.
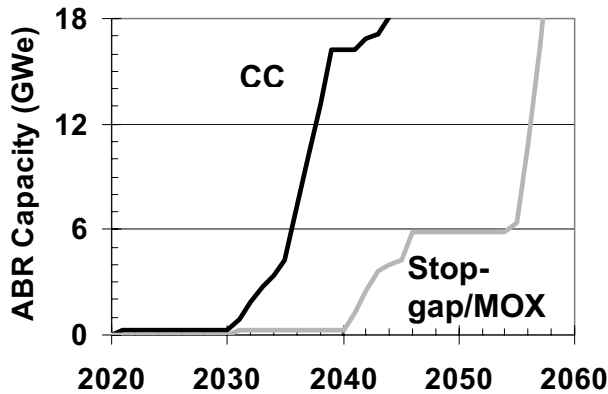

Figure 1. Fast reactor (ABR) capacity for baseline versus stop-gap recycling with MOX.

V. MIXED RECYCLING

The Mixed recycling role is defined as recycling with a symbiotic mix of thermal and fast reactors. This would reduce the fraction of fast reactors required for as long as the mix was continued. It also provides "buffer" recycling capability, where changes in transuranic supply from LWRs could be accommodated by changing the amount of recycling in thermal reactors, leaving the fast reactor portion of the fleet unaffected.

For example, at a fast reactor TRU conversion ratio[1] of 0.25, the static equilibrium fraction of fast

reactors would drop from 27% without thermal recycling to 19% with thermal recycling.

Figure 2 shows that "mixed" recycling reduces the number of fast reactors (more than in a static equilibrium analyses). The CC curve is the same as in figure 1. The "mixed" cases assume MOX or IMF start in 2020.
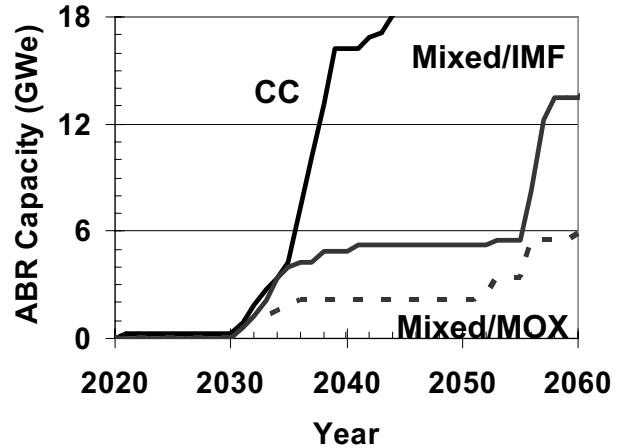

Figure 2. Fast reactor (ABR) capacity for baseline versus "mixed" thermal-fast recycling.

VI. BACKUP RECYCLING

The Backup recycling role is defined as recycling in thermal reactors if problems develop with fast reactor recycling. Section III indicates that the separation plant processing used LWR fuel is assumed to start before fast reactors to provide the fast reactors with fuel.[2] Thus, if economic or acceptance problems develop later with the fast reactor component of the program, the choice is among terminating the separation plant, thus incurring costs; accepting the accumulation of separated transuranic material; or recycling the material in thermal reactors. Backup recycling with either IMF or MOX could be continued for as long as needed, resuming recycle in fast reactors when possible.

Figure 3 shows that "Backup" recycling prevents a rush to rapidly build fast reactors to "catchup" with what would have been the drawdown of accumulated TRU. The CC curve is the same as in figure 1. The other two curves postulate that the first separation plant is operational in 2020 and the first ABR is indeed operational in 2021, but that subsequent fast reactors are delayed 2 decades (not dissimilar to past experience in France with fast reactors). Instead of subsequent fast reactors operational starting in 2030, the "backup" case uses backup MOX recycling in

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[1] The "conversion ratio" is used throughout this report to mean the TRU conversion ratio (CR), the production rate of transuranics divided by their destruction rate. CR <1 is a TRU consumer or burner; CR >1 is a TRU breeder.

[2] An alternative method to start the first fast reactors is to use excess weapons plutonium.

2030. The no-backup case merely allows TRU to accumulate. All cases are tuned so that used fuel inventories are processed by 2100. So, in the "no backup" case, the model builds fast reactors at a faster rate in the second half of the century.
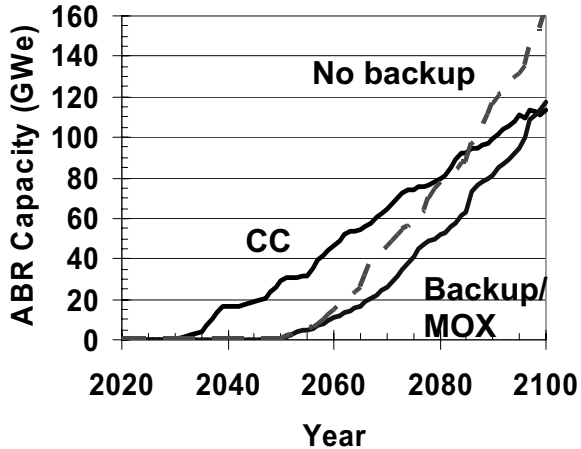

Figure 3. Fast reactor (ABR) capacity for baseline versus cases where subsequent fast reactors are delayed from 2030 to 2050, with and without backup MOX recycling.

VII. PURE THERMAL RECYCLING

This is recycling in thermal reactors with no intention to use fast reactors. One recycle pass in thermal reactors does not meet advanced fuel cycle objectives; many recycle passes are required.

Recycling in thermal reactors is sustainable provided two constraints are addressed. First, thermal reactors preferentially consume fissile isotopes versus fertile; thus, continued recycling requires a continuing source of fissile material. The most practical source of new fissile material is enriched uranium or new used LWR fuel.

The other constraint is that thermal reactor physics inherently promotes faster accumulation of higher transuranic elements. The higher transuranic elements are much more prone (orders of magnitude) to emit neutrons. The greater shift to higher transuranic elements in thermal reactors than in fast reactors can therefore lead to much higher neutron emissions. The thermal-to-fast penalty depends on many factors, but may be several orders of magnitude. Five approaches to this challenge have been proposed, as follows:

1. Only recycle in fast reactors.

2. Recycle the higher transuranic elements (curium and above) in fast reactors and the lower transuranic elements in thermal reactors.

3. Dispose of the curium (and above). This limits the equilibrium reduction in heat load to the repository to ~10x or less after many recycles, compared to ~100x for pure fast systems that do recycle Cm.[2,3,4,6]

4. Store the curium (and above) to let key isotopes decay.[7,8] Storage for several decades allows Cm244 (18.1 year halflife), Cf250 (13.1 year), and Cf252 (2.638 year) to substantially decay. These isotopes are responsible for 90% to 99% of the neutron emission when all transuranics are recycled in thermal reactors. While requiring relatively expensive facilities, such storage approaches appear capable of reducing the neutron emission for equilibrium fuel compositions by a few orders of magnitude.

5. Accept the penalties of accumulating higher transuranic elements in thermal reactors. The figures below show that compared to only recycling Pu, repeated recycle of all transuranics in **either** thermal or fast reactors results in higher heat, gamma, and neutron emission. In particular, in thermal reactors, the penalty for recycling all transuranics is 10,000x to 100,000x higher neutron emission than recycling only Pu (figure 4). In fast burner reactors, the penalty for recycling all transuranics is 100x to 1,000x higher neutron emission than recycling Pu to equilibrium (figure 4). Even fast breeder reactors with all-TRU recycling has higher neutron emission than thermal reactor recycling with only NpPuAm. These high-energy neutrons are difficult to shield. The issues associated with neutron-emitting fuels have been identified.[9,10] Additional analyses are recommended before serious consideration of such an approach.

Figures 4, 5, and 6 show neutron emission, gamma emission, and heat generation for potential recycle materials. The cases are UOX (LWR used fuel at 50 MW-day/kg-HM), pure thermal recycle cases (MOX or IMF), mixed recycle cases (MOX or IMF followed by a CR=0.25 fast reactor), and pure fast reactor cases for comparison (CR=0.25 and CR=1.0), Except as noted below, all compositions are for equilibrium recycle composition (i.e. after many recycles) based on reactor physics calculations.[11,12,13] Five years is assumed to elapse between reactor discharge and recycled fuel reinsertion into a reactor. The key observations are as follows:

- Recycle of Am increases gamma emission in either fast, thermal, or mixed by roughly an order of magnitude.
- Recycle of Cm increases neutron emission in either fast, thermal, or mixed by at least two orders of magnitude. The increase is substantially yet higher for pure thermal systems.
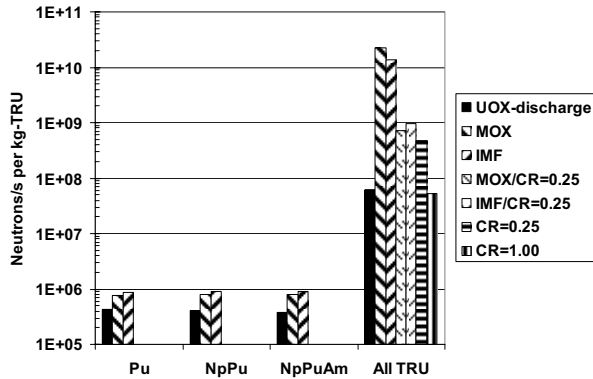

Figure 4. Neutron emission rate of several recycle options at equilibrium (except UOX-discharge), starting with 50 MW-day/kg-HM burnup UOX with 5 years between recycles.
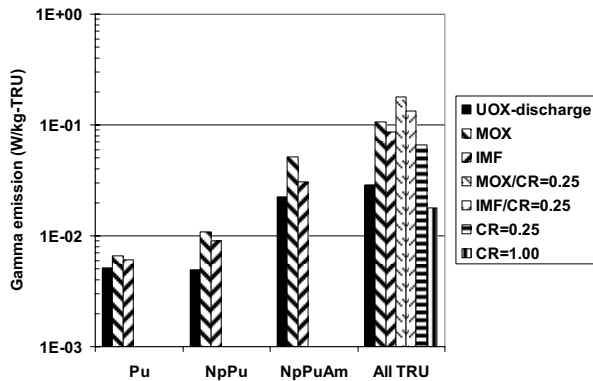

Figure 5. Gamma emission ratesof recycled materials at equilibrium (except UOX-discharge).
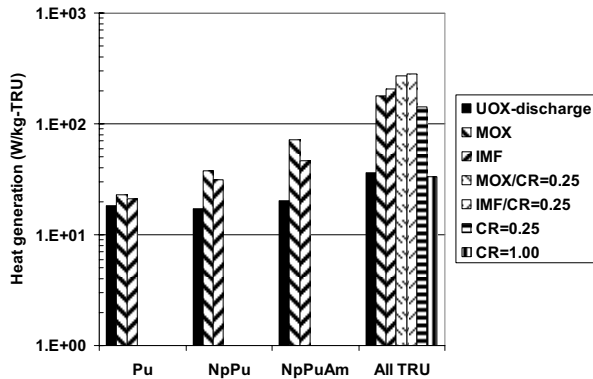

Figure 6. Gamma energy emission of recycled materials at equilibrium (except UOX-discharge).

The gamma and neutron increases associated with recycling Am or Cm are perhaps unnecessary if the only recycling objective is to recover the energy in used fuel. The large majority of the U+TRU mass (hence the hypothetical maximum energy release) is uranium and plutonium. Fast breeder reactors can achieve ~100x the energy recovery from original uranium ore as do current LWRs. Pure thermal systems appear limited to ~1.2x of current LWRs.[4] Thus, if or when uranium supply constraints warrant substantially increasing energy recovery, fast reactor systems are required that recycle uranium and plutonium for energy content.

But, if either waste management or proliferation resistance benefits are sought, recycle of Np, Am, and Cm are relevant.[3,4,14] Hence, the neutron and gamma emission increases become an issue. Heat, gamma, and neutron emission complicate weapon design: heat must be managed to prevent material from melting before detonation, chemical explosives must be protected from heat and radiation, and predetonation from neutrons must be prevented.

As with other recent U.S. advanced fuel studies, this paper uses heat load as a major metric to assess benefit to the geologic repository.[15,16,17,18] This factor is the increase in the amount of residual high-level waste that can be sent to the repository, assuming that repository capacity is based on temperature constraints rather than current statutory limits. (The calculations are always normalized to LWR once-through at 50 MW-year/kg-HM burnup and by the amount of energy produced from the fuel – assuming that the material is then disposed.)

Four clarifications are important to this paper. First, these factors are defined for a specific number of recycle passes assuming that the material is then disposed. The actual heat impact to the repository does not happen, of course, until the material is actually sent to the repository, which does not occur as long as recycle is sustained – hence the importance throughout this report given to sustainability of recycle. The exception is any materials deliberately sent to the repository each recycle such as processing losses (~0.1%) and (in some options) specified transuranics.

Second, for some concepts, there are blending effects. Thermal reactors require blending in an amount of new fissile material to sustain recycles, this is done in varying ways in different scenarios. The net effect is to adjust the "amount of energy generated" term, which always lowers that improvement factor for that recycle. Indeed, without blending, the thermal cases "dead end" after the second recycle; the fissile content is sufficiently

depleted it can no longer be used as fuel. With blending, the thermal cases "turn over" because of the dilution by fresh fissile material.

Third, one can estimate an equilibrium improvement factor (figure 7). These are calculated on the basis of the equilibrium fuel cycle composition – fuel is discharged, transuranic elements separated, mixed with any new material, fabricated into new fuel, and inserted into the reactor. The only material going to the repository is the processing losses, assumed here to be 0.2%/recycle pass. The heat load factors in figure 7 are approximations of the improvement in heat-limited repository capacity improvement. Note that recycle of NpPu is slightly worse than Pu because Np237 is a source of high-heat Pu238. Recycle of NpPuAm can achieve ~10x in a thermal reactor (and presumably at least as well in a fast reactor). Recycle of all-TRU can achieve ~100x in a fast reactor, subject to the neutron emission issues noted above. Recycle of all-TRU in a thermal reactor should achieve between 10x and 100x.

Based on current understanding, it appears that the equilibrium heat load improvement factor for a geologic repository can be ~100x if all transuranics are recycled and no blending of additional transuranic material is done each cycle. This combination can only occur with fast reactors in the system. All thermal systems require blending of additional transuranic material and thus cannot reach as high performance. If the Cm/Bk/Cf accumulation problem is resolved by disposal of these elements, the combination of such disposal and blending limits equilibrium performance to ~10x or less (higher for IMF than MOX). If Cm/Bk/Cf is not disposed, the equilibrium performance is intermediate between ~10x and ~100x
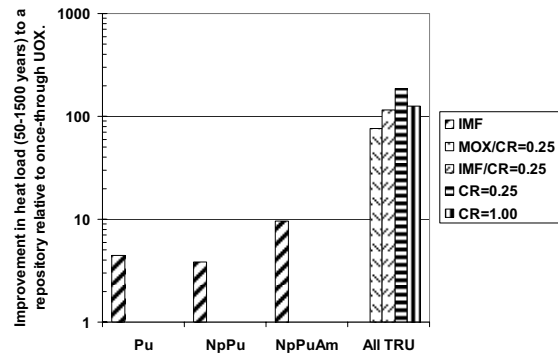

Figure 7. Improvement in heat load to repository (integrated from 50 to 1500 years) relative to used UOX at 50 MW-day/kg-HM burnup, at equilibrium. Fewer cases are shown than for figures 4, 5, and 6 because inadequate information is available for the missing cases.

Fourth, to achieve high improvement factors, more than recycle and consumption of transuranic elements is required. In particular, cesium-137 and strontium-90 must be removed and managed so that their heat is segregated from the residual long-term waste sent to the repository. The amount of cesium-137 and strontium-90 are only weak functions of which isotopes fission; so this component to the calculation does not vary significantly among the options considered here. High heat-load improvement factors are impossible without dealing with both transuranics and Cs-Sr.[15,16,17,18]

Fifth, the difference between thermal and fast reactors increases with the number of recycles. Note, for example, that the neutron emission of all-TRU from used UOX fuel is high in figure 4. Except for high TRU fast reactor conversion cases (breeder or near breeder), the neutron emission only increases thereafter in either thermal or fast reactor. The increases in a thermal reactor are faster and reach a higher equilibrium value.

Similarly, both thermal and fast reactors can achieve decent heat load improvement factors in the first few recycles. After one recycle, the actual calculated heat-limited repository improvement factors (assuming recycling continues thereafter) were recently estimated (0.1% processing loss). If Cm is recycled, both thermal and fast reactors start with high heat-limited repository capacity improvement factors. The advantage for fast reactors only manifests as additional fissile material is blended each recycle per the approximations in figure 7.

Table 1. Heat-Limited Repository Capacity
Improvement Factors [18]

Heat-limited repository capacity improvement factor	Case, all cases recycle all-TRU except as noted	Comment
238	UOX followed by CR=0.25	13094 GWd/m vs 55 GWd/m for UOX-50
235	UOX followed by CR=0.50	12950 GWd/m vs 55 GWd/m for UOX-50
182	UOX followed by CR=1.00	10000 GWd/m vs 55 GWd/m for UOX50
223	UOX followed by MOX	12917 GWd/m vs 58 GWd/m for UOX50
52	UOX followed by MOX (Cm disposal)	3025 GWd/m vs 58 GWd/m for UOX50

VIII. CONCLUSIONS

The approach of using only fast reactors to recycle separated transuranics requires coordination among the construction of capability for chemical separation of used LWR fuel, fabrication of new recycled fuel, and fast reactors. Adding some thermal recycling to this approach is a way to provide more latitude in the timing of when new reactors come on line. In this context, thermal recycle provides several potential benefits when used as **stop-gap, mixed,** or **backup** options to recycling to just recycling in fast reactors. These three roles involve a mixture of thermal and fast recycling; fast reactors are required to some degree at some time.

Thermal recycle can also provide benefits when used as **pure thermal recycling**, with no intention to use fast reactors for the foreseeable future. Both thermal and fast reactors start recycling with high potential repository heat-limited repository capacity improvement factors if Cm is recycled. The fast reactor advantage manifests itself as additional fissile material is blended in subsequent recycles, so that the equilibrium thermal reactor performance is expected to be less than the equilibrium fast reactor performance, which is ~100x. However, if Cm is recycled, both fast and thermal recycle start with 100x higher neutron emission in the recycled material; the fast reactor manifests itself in subsequent recycles as neutron emission increases faster and to a higher equilibrium in thermal systems.

If Cm is not recycled, the potential heat-limited repository improvement factors are significantly lower, ~10x for thermal systems and presumably somewhat higher for fast systems. However, the neutron emission is also reduced relative to all-TRU recycling.

Recycle of Am and Cm in either thermal or fast systems increases the heat, gamma, and neutron emission of recycled fuel. This will increase direct separation and fabrication costs but should improve proliferation resistance.

Thermal recycle does not eliminate the eventual need for fast reactors, a need driven by achieving highest repository benefits and eventually extending uranium supplies by shifting fast reactors to the breeder mode. The improvement in uranium ore utilization relative to the current once-through fuel cycle is limited to 20% improvement in thermal or low conversion fast reactors, whereas fast reactors in the breeder configuration can achieve a factor of one hundred improvement.

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