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Impact of Limited Reprocessing Capacity on Nuclear Material Utilization in Advanced Fuel Cycles

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ABSTRACT

A nuclear energy scenario study was performed using VISION 3.4; to analyze three different fuel cycles: once through (open) cycle (OTC), full recycle with a transition through a modified open cycle (MOC), and direct introduction of full recycle without transition (FuRe) in terms of their impact on uranium resource utilization on both the front- and back-end of these fuel cycles, Both the MOC and FuRe show significant improvement (reduction) in the amount of uranium ore required to generate the same amount of energy for a 150-year period when compared to the OTC. The same conclusion also holds for the amount of used nuclear fuel (UNF) in storage (wet, dry and monitored retrievable (MRS)) in the back-end of the fuel cycle.

Findings suggest that under the analyzed deployment scenarios, amount of separation capacity deployed have impact on resource utilization. There is no clear advantage of either MOC or FuRe over one another in the front end of the fuel cycle as far as material utilization under both separation capacities analyzed. However, due to its potential for earlier deployment, MOC offers better UNF management in the back end at 2 kT/yr separation capacity: the amount of UNF for storage is smaller compared to OTC and FuRe, this advantage is not evident when the capacity was doubled. In terms of transuranic (TRU) consumption, FuRe is the better choice compared to MOC, under the lower separation capacity scenario, however at doubled capacity, both cycles consumed about the same amount of TRU. It can be concluded that the choice of either MOC or FuRe depends on the fuel cycle objectives, however both are better compared to OTC, in terms of uranium resources utilization.

1 INTRODUCTION

Current US nuclear policy of the once-through cycle implies that UNF (estimated at 42,616 metric tons in 2000 [1] and growing at an annual rate of ~2,000 metric tons) will continue to sit in above-surface storage sites across the country, and the UNF will not be recycled for further use. However, there are on-going efforts to explore the possibility of deploying advanced nuclear fuel cycles in the US that may further increase the utilization of uranium resources. Most of these efforts suggest that a full recycling policy will be the most adequate, but full-scale commercial deployment of this technology may not occur until much later.

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Modified Open Fuel (MOC) cycle is a stop gap measure being proposed by the DOE. According to the DOE 2010 *Nuclear Energy Research Development Roadmap* [1], the MOC should achieve the following in terms of nuclear material utilization:

- *Improve uranium resource availability*
- *Improve uranium utilization*
- *Minimize waste generation, and*
- *Provide adequate capability and capacity to manage all waste produced.*

To investigate these requirements, nuclear energy scenario studies were defined and analyzed using VISION (VerifIable Fuel Cycle SimulatiON, version 3.4), which was benchmarked using data in [2, 3, 4], a dynamic nuclear fuel cycle analysis code developed for the Advanced Fuel Cycle Initiative (AFCI) studies through a collaboration between national laboratories and universities [5, 6]. The energy scenarios were setup using the information and parameters shown in Table 1.

Table 1: Nuclear Energy Scenario Parameters

Parameters	Unit	Values
General		
Introduction of first full-recycling reactor (i.e., fast reactor)	Year	2050
Electricity demand growth rate	% per year	1.0
U.S. nuclear electricity capacity in 2010	GWe	100
U.S. used nuclear fuel (UNF) inventory in 2010	ton HM	61482
U.S. TRU inventory in 2010	ton	600
LWR – LWRMOX		
Fuel form		UO_2, UO_2-MOX
Electrical Power	MWe	1000
Thermal Efficiency	%	34
Average discharge burnup	GWd/t	50
Average LEU enrichment	%	4.2
Reactor capacity factor	%	90
Life time	Years	60
Cooling time in interim wet storage	Years	5
SFR – Full-recycling reactor		
Fuel form		U-TRU-Zr alloy
Electrical Power	MWe	380
Thermal Efficiency	%	38
Average discharge burnup	GWd/t	70 – 100
Breeding ratio		1.0-1.2 (1.0 used in this study)
Reactor capacity factor	%	90
Life time	Years	60
Cooling time in interim storage	Years	1
Reprocessing		
Reprocessing start (depends on reactor)		Varied
TRU recovery factor in reprocessing	%	99.9
Reprocessing capacity	ton HM / year	Varied
Total reprocessing time (including fabrication, transportation)	Years	2

All current thermal reactors in the US are modeled as LWRs without distinction between BWR and PWR, and every LWR reactor built after 2010 is assumed to be capable of operating with a full core of mixed oxide (MOX) fuel. The fast reactors deployed in the study were modeled as sodium cooled fast reactors (SFR) with a break even breeding ratio.

2 FUEL CYCLE SCENARIO SETUP

Three nuclear fuel cycles were considered for this study:

- Once Through Cycle (OTC also known as open cycle; current US option),
- Full Recycling (FuRe) fuel cycle, introduced without a transition
- Full recycle introduced via a transitional Modified Open Cycle (MOC), where MOX-capable LWRs are deployed first. This option will be denoted as MOC, although it ultimately transitions to FuRe.

In terms of nuclear material utilization, the OTC is the least efficient; close to 95% of usable nuclear material remains in the UNF designated for storage and disposal. FuRe is the best cycle in terms of material utilization; almost all of the extractable energy can be extracted from the fuel, however the commercial infrastructure for large-scale FuRe deployment is not yet in place.

2.1 Once Through (Open) Cycle Scenario

For the OTC scenario, it was assumed that the LWR capacity increased to meet the 1% growth in nuclear energy demand. As shown in Fig. 2.1, there is no separation or reprocessing of UNF. Instead, the discharged fuel (DF) is sent to interim storage (wet, then dry) and later to a permanent disposal repository.

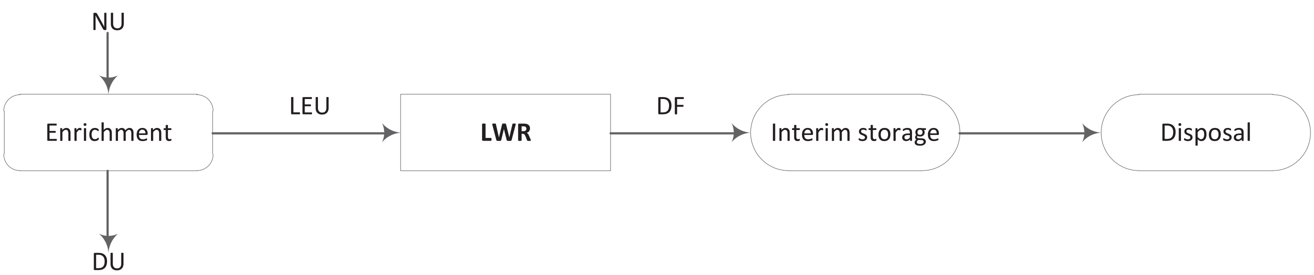

Figure 2.1: Once Through (Open) Cycle Scenario Setup

2.2 Full Recycling Cycle

In the FuRe scenario (Fig. 2.2), it was assumed that the LWR capacity increases until 2050 to fulfill the growing energy demand, after which only fast reactors are constructed. Consequently, all LWRs are out of service by 2110. Reprocessing of UNF inventory (legacy used fuel) and DF starts in 2048 using UREX+1 separation technology, while an electrochemical process is used for the separation of discharged SFR fuel. The recovered TRU from the UNF inventory is used for the startup SFR cores. The SFR breeding ratio (BR) is assumed to be break-even (BR = 1.0). This implies that there is no TRU limit to building new SFRs until the UNF inventory is completely exhausted. Except for the startup cycle, additional external TRU feed is not required due to the break-even breeding ratio. If TRU is not available for the new SFRs (due to exhausting of legacy UNF inventory), low-enriched uranium (LEU) was used as the contingent (or back-up) fuel for the SFRs. Otherwise, no SFRs will be built if there is insufficient TRU-based fuel.

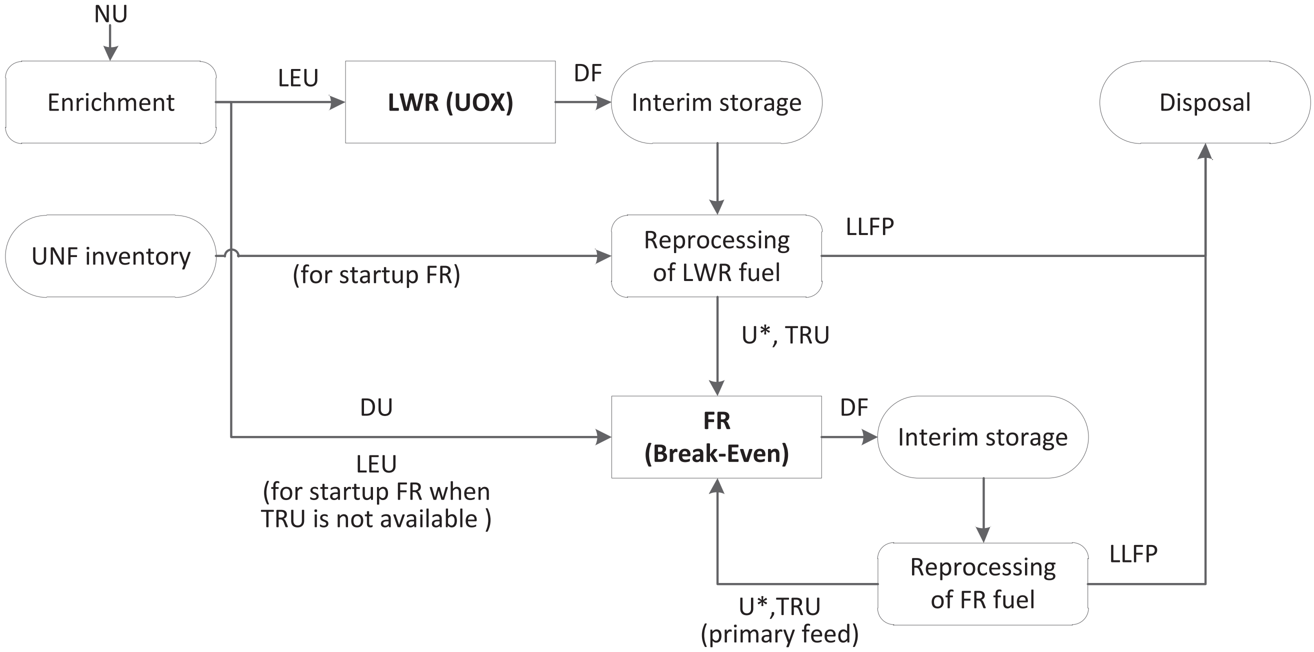

Figure 2.2: Full Recycling Cycle Scenario Setup

2.3 Modified Open Cycle (MOC: LWR-UOX / LWR-MOX / SFR) Scenario

In the MOC scenario (Fig. 2.3), a small amount of LWR-MOX reactors is introduced after 2025 along with the conventional LWR-UOX reactors, to meet the increasing energy demand.

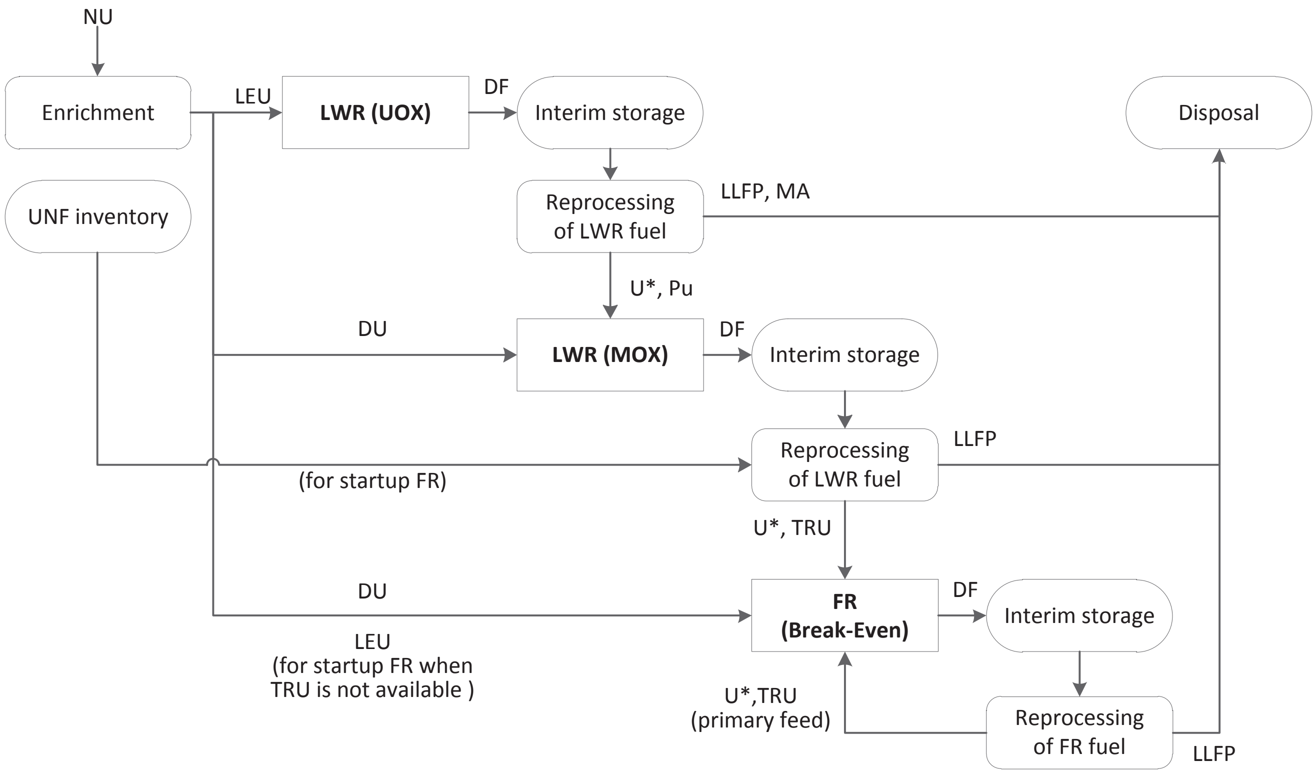

Figure 2.3: Modified Open Cycle Scenario Setup

Reprocessing of UNF inventory (legacy used fuel) and DF starts in 2020 by recycling U + Pu from discharged LWR-UOX fuel as well as from the legacy used fuel. Reprocessing of DF from LWR-MOX starts after the mandatory cooling time in temporary storage. After 2050, no new LWRs are constructed, only SFRs. Thus, all LWRs are completely replaced by full-recycling reactors after 2110. The recovered TRU/U from discharged LWR-MOX fuel is used as a makeup TRU feed for SFRs, if there is insufficient TRU/U from discharged LWR-UOX fuel. If there is insufficient TRU from any source, LEU is used to support FR deployment.

2.4 Other Scenario Parameters

All nuclear reactor types have a lifetime of 60 years with no assumed extensions. The separation capacity for LWR fuel is assumed to be 2000 metric ton per annum, the separation capacity for fast reactor DF is assumed to be unlimited, and all separation facilities have a lifetime of 40 years. LWR DFs (UOX and MOX) are recycled only once, while SFR DF is continuously-recycled.

3 RESULTS

As expected, both the FuRe and MOC scenarios showed better fuel utilization than the OTC scenario. The total amount of uranium ore consumed, shown in Figure 3.1, was reduced by about 45% (FuRe) and about 50% (MOC) at the end of the 150 years of simulation. The amount of energy generated is shown in Figure 3.2. The energy generated in the OTC and the advanced fuel cycles scenarios follows the energy demand. The assumptions for the analysis include a requirement that use of MOX fuel in LWR is limited to no more than 30%. The use of MOX fuel is limited by the LWR-UOX separation capacity, fixed at 2000 ton/yr; in reality this should increase as the number of LWRs increases. Although one may expect SFRs to counter this energy shortage starting from year 2050, this did not immediately happen because of the dependence of SFRs on reprocessed MOX fuel from LWR. It is important to note that there is no significant saving in required uranium ore until the deployment of SFRs in 2050, in both the FuRe and MOC. In the VISION model, both MOC and FuRe will operate on LEU (figures 2.2 and 2.3) if their primary fuels are not available (to run the reactor for their entire life cycle). Total separative work (in SWU units) required for uranium enrichment follows the same trends shown in Figure 3.1.

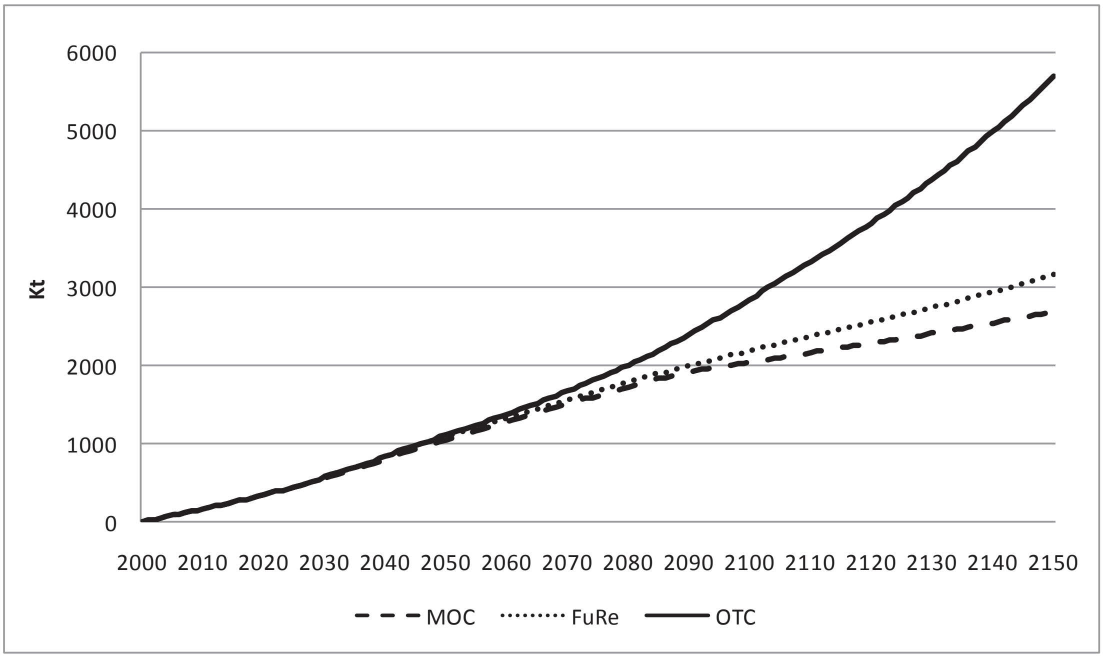

Figure 3.1a: Cumulative Uranium Ore Consumed in all Fuel Cycles @ 2 kT/yr Separation Capacity.

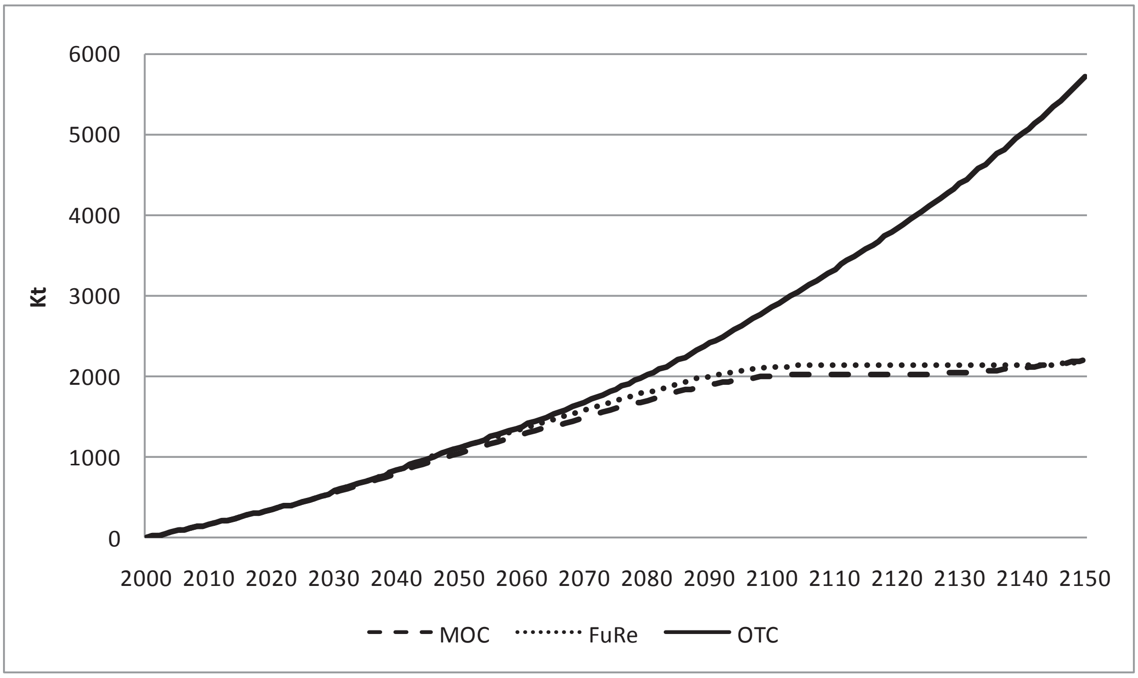

Figure 3.1b: Cumulative Uranium Ore Consumed in all Fuel Cycles @ 4 kT/yr Separation Capacity.

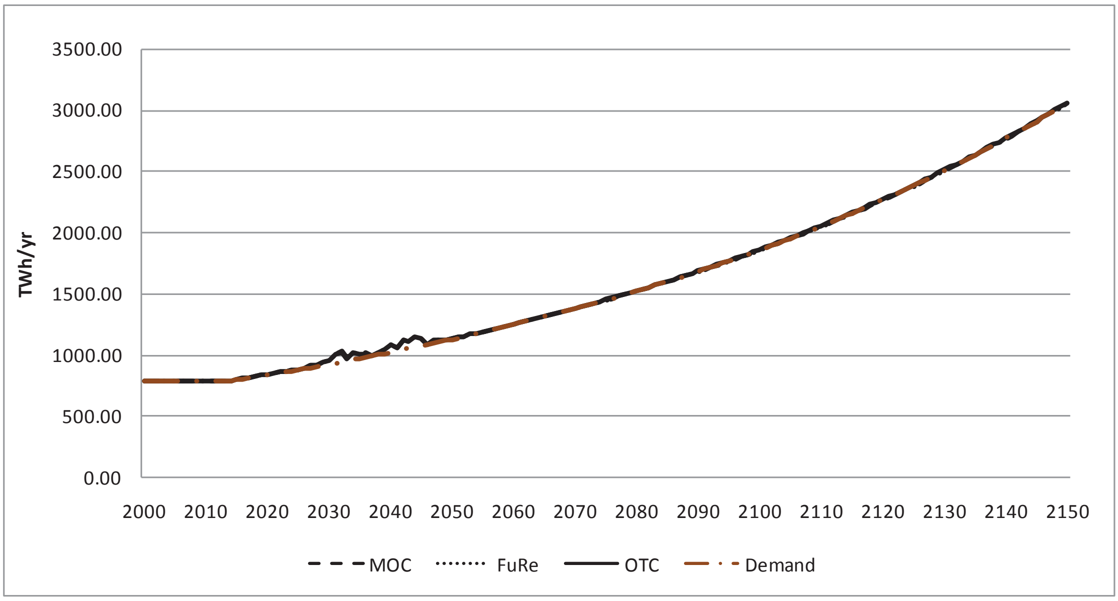

Figure 3.2a: Annual Energy Generated vs. Projected Demand @ 2kT/yr Separation Capacity.

The total reactor capacity (installed power) as a function of reactor type is shown in Figs. 3.3, 3.4 and 3.5 for the three scenarios considered. Most of the LWRs are out of service by the predicted year, 2110. Since the energy generated still meets the yearly predicted energy demand, it means LWRs can be phased out of MOC and FuRe scenarios. This may however be difficult to do in practice, when other factors and requirements are factored in. In Fig. 3.3 and 3.4, the LWR-MOX capacity only indicates that the reactors are capable of using MOX fuel, but no MOX fuel was actually used in either the OTC or FuRe scenarios. The impact of doubling the separation capacity is not noticeable in terms of installed reactor capacity as opposed to the impact shown on Uranium consumption (Fig. 3.1a and Fig. 3.1b) and in total amount of UNF in storage (Fig. 3.6a and Fig. 3.6b). Insufficient separation capacity will result in higher consumption of fuel resources and generate more UNF and other waste. Separation capacity should increase at approximately the same rate as UNF generation. Although one could expect that FuRe would show the best performance, the possibility to deploy MOC earlier makes it also attractive.

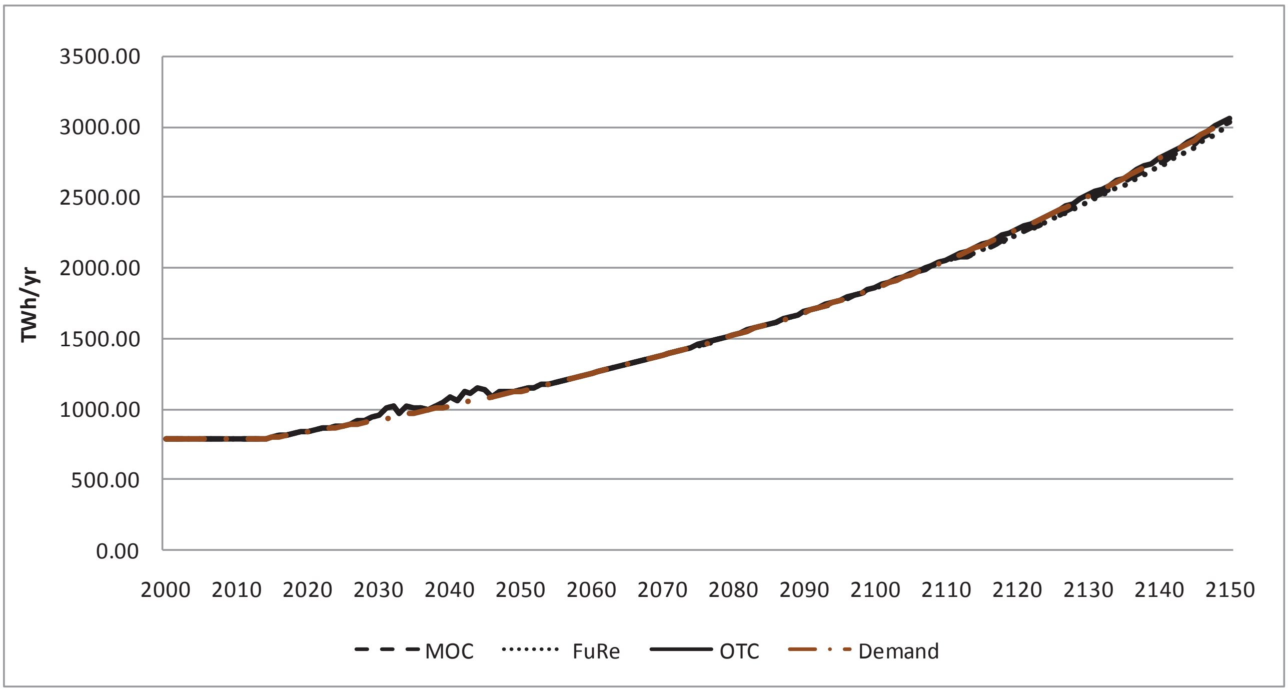

Figure 3.2b: Annual Energy Generated vs. Projected Demand @ 2kT/yr Separation Capacity.

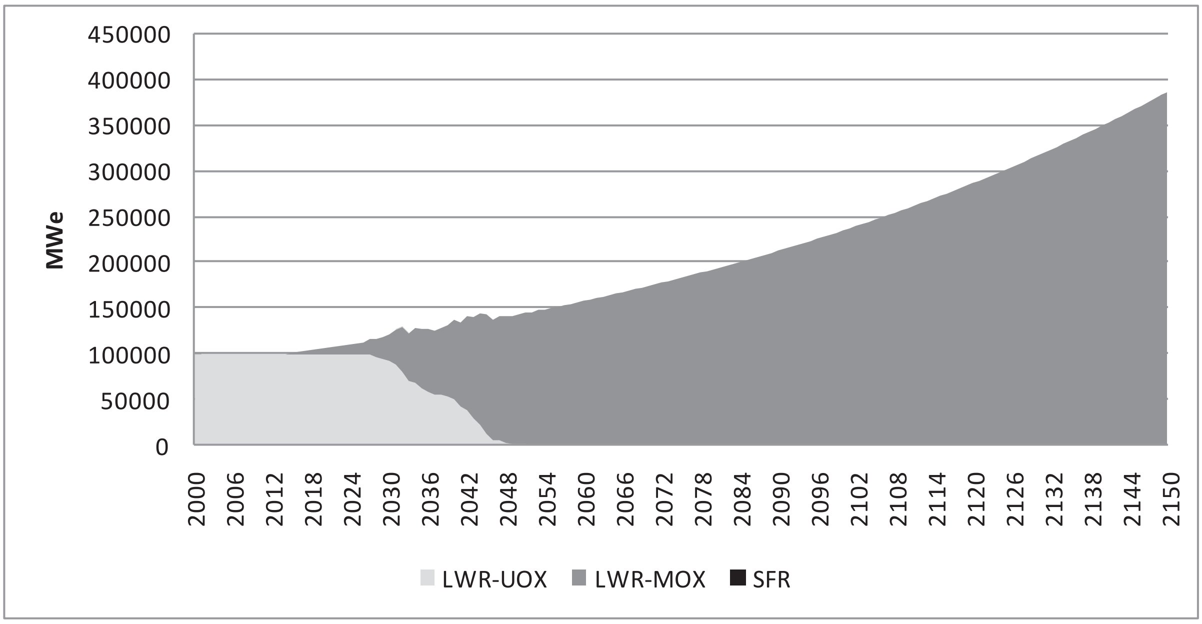

Figure 3.3: Reactor Capacity Deployed by Reactor Type in OTC

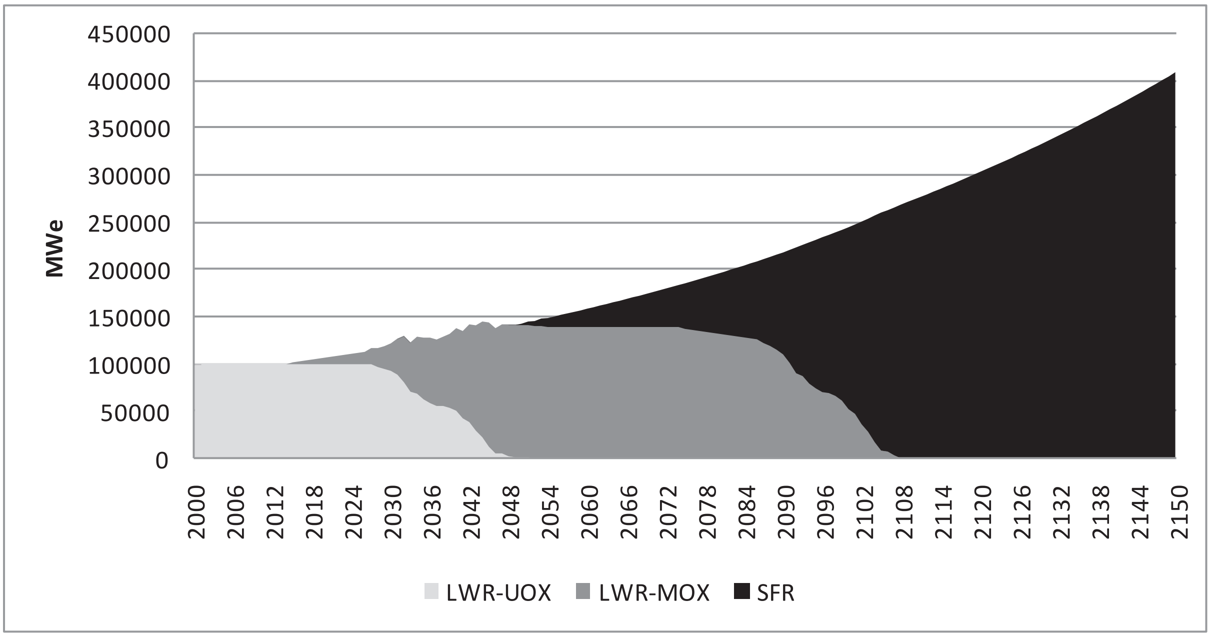

Figure 3.4a: Reactor Capacity Deployed by Reactor Type in FuRe @ 2 kT/yr Separation Capacity

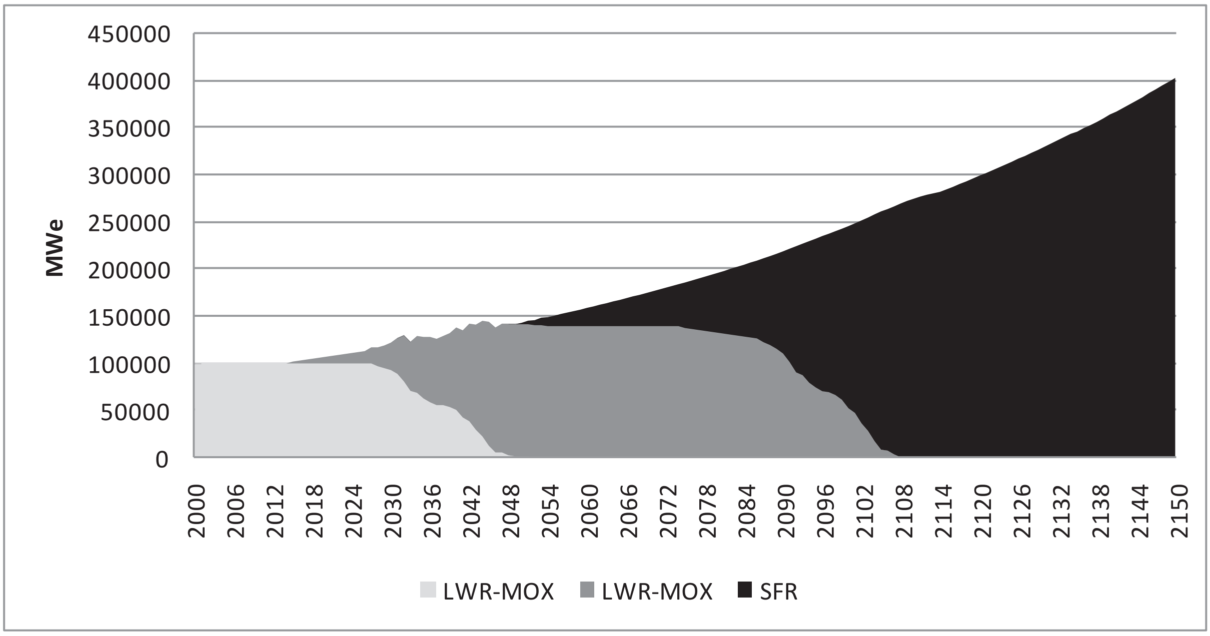

Figure 3.4b: Reactor Capacity Deployed by Reactor Type in FuRe @ 4 kT/yr Separation Capacity

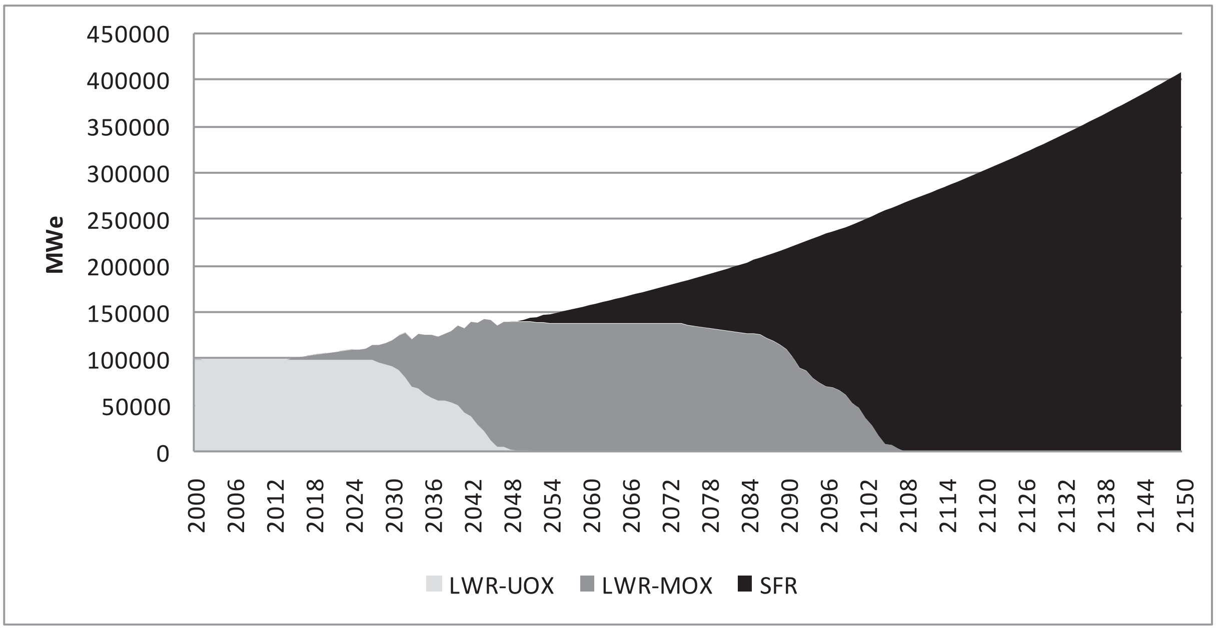

Figure 3.5a: Reactor Capacity Deployed by Reactor Type in MOC @ 2 kT/yr Separation Capacity

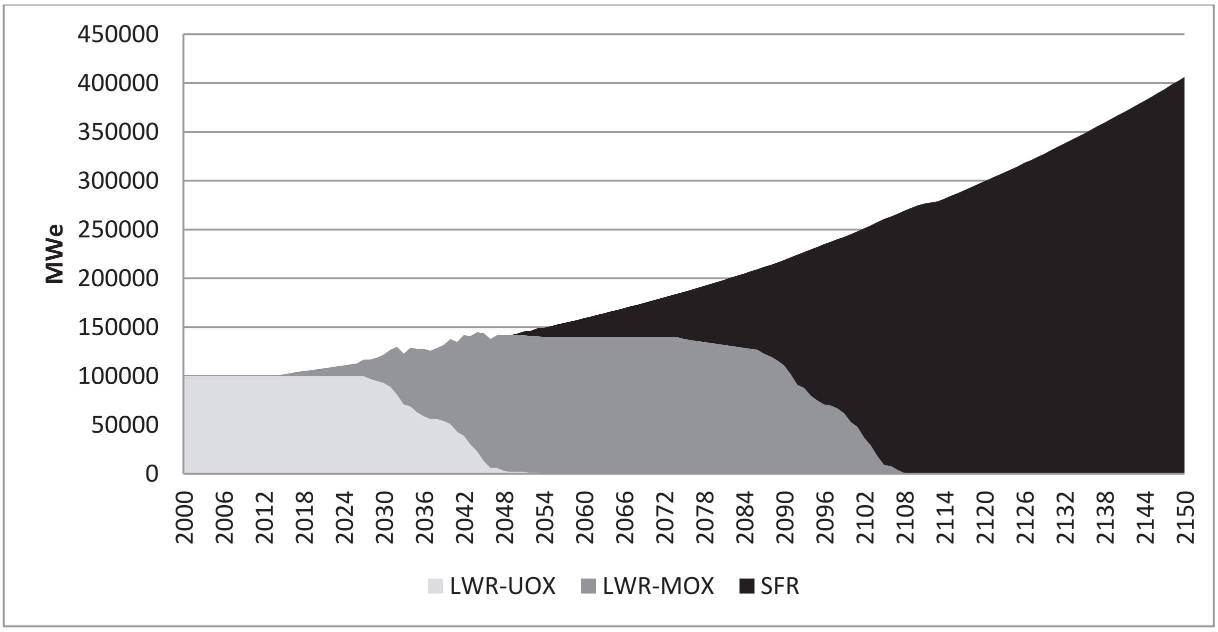

Figure 3.5b: Reactor Capacity Deployed by Reactor Type in MOC @ 4 kT/yr Separation Capacity

The results for the back end of fuel cycle did not give any clear superiority of either MOC or FuRe over one another. Figure 3.6 shows the amount of UNF in storage (wet, dry, and Monitored Retrievable Storage (MRS) in both MOC and FuRe, but defined as dry and wet in OTC): the decrease in trend after 2100 reflects phasing out of LWRs. The required energy demand is being met by break-even SFRs. There is a significant decline in the amount of UNF in storage. Note that un-used reprocessed uranium and fission products after separation are not included in this figure. Should these "separated elements" be included, the decline in total storage (used fuel and reprocessed fuel) is much more modest. The amount in storage is the same until reprocessing started in both MOC and FuRe, and the final amount in storage is about the same in both setup. Again, earlier deployment of MOC offsets the inherent theoretical advantage of FuRe.

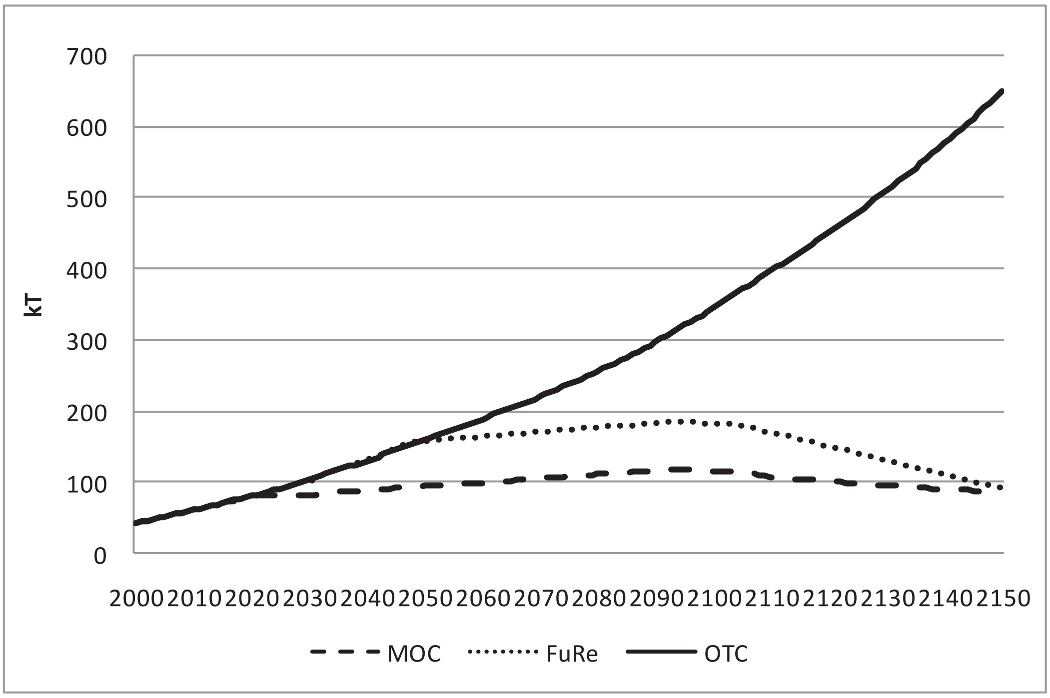

Figure 3.6a: Total Used Nuclear Fuel in Storage (Wet+ Dry + MRS) @ 2 kT/yr Separation Capacity

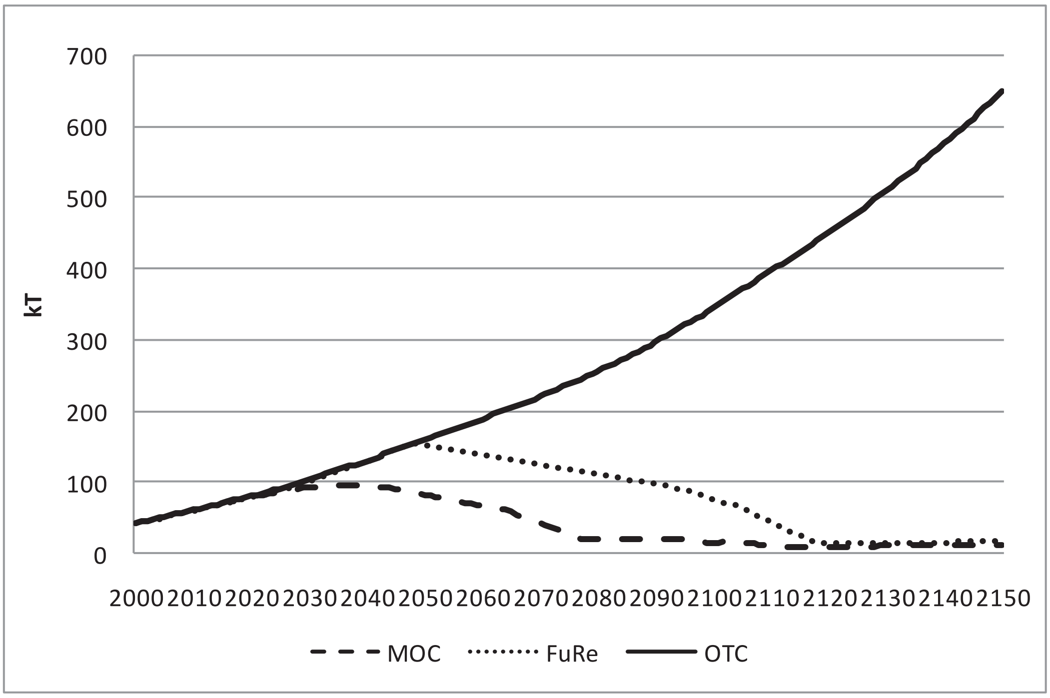

Figure 3.6b: Total Used Nuclear Fuel in Storage (Wet+ Dry + MRS) @ 4 kT/yr Separation Capacity

The total amount of TRU used in making new fuels in MOC and FuRe is shown in Figure 3.7a. The rate of TRU utilization is about the same for both of the advanced fuel cycles. However, because of the earlier deployment of reprocessing and recycling of UNF in MOC, the total TRU consumed is higher in MOC compared to FuRe at the end of the 150 years simulation. However under the 4 kT/yr separation capacity scenario (Fig. 3.7b), total TRU used was higher, and almost the same for both MOC and FuRe.

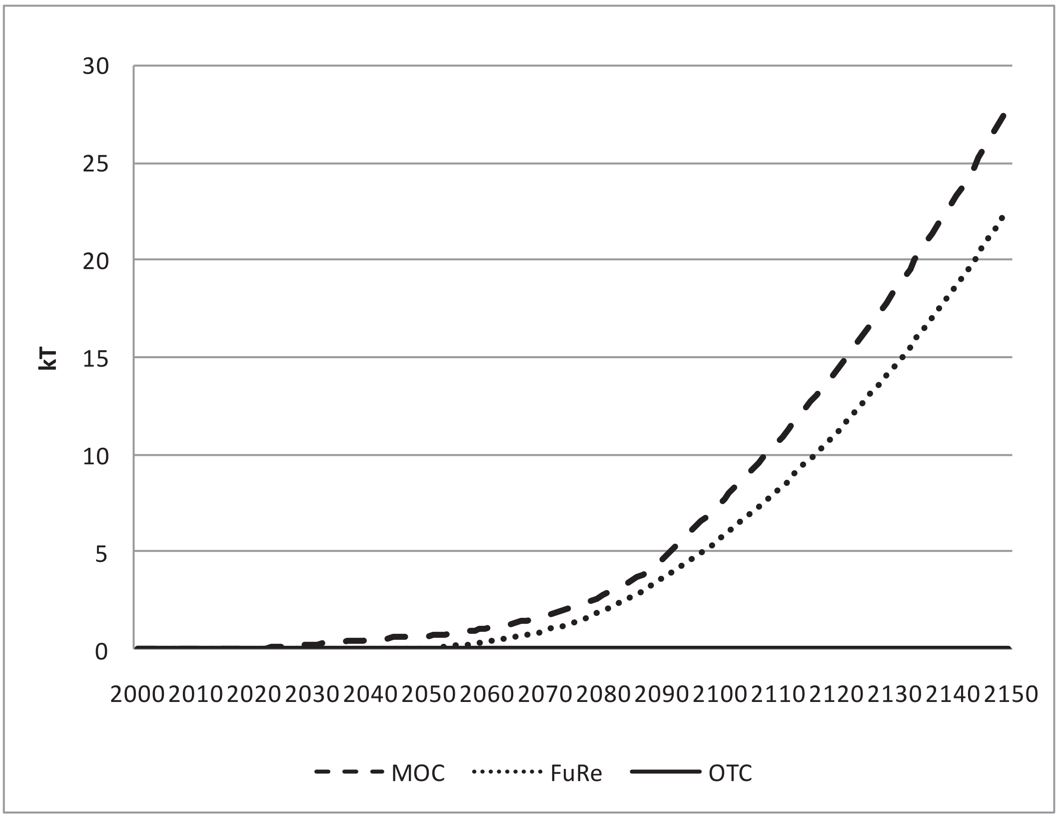

Figure 3.7a: Total Separated TRU Used for Fuel Fabrication (no TRU in OTC) @ 2 kT/yr Separation Capacity

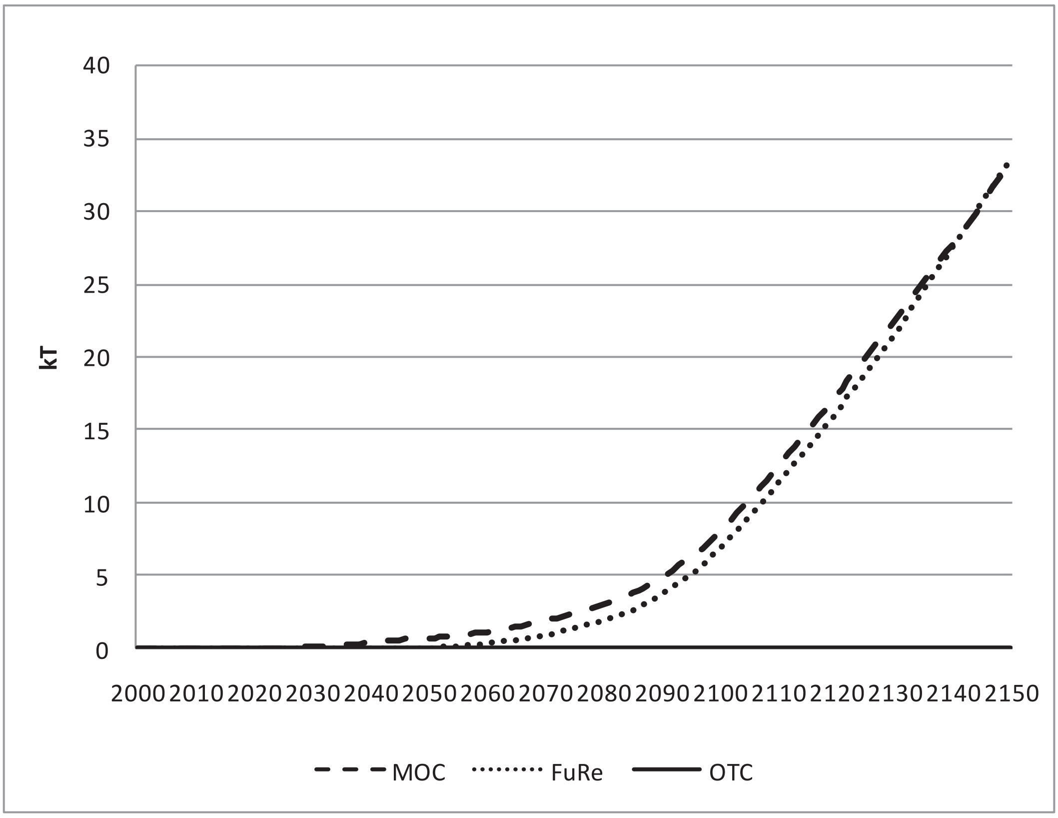

Figure 3.7b: Total Separated TRU Used for Fuel Fabrication (no TRU in OTC) @ 4 kT/yr Separation Capacity

4 CONCLUSIONS

A comparison study was performed on the OTC, MOC and FuRe scenarios with the constant external nuclear fuel cycle requirements and realistic deployment dates. From a nuclear material utilization perspective, the VISION results suggest that closing or modifying the OTC can greatly reduce the used fuel storage requirements. For a 2 kT/yr separation capacity, the MOC scenario results in a lower peak UNF storage requirement due to its earlier deployment of the recycling technology. When the separation capacity was doubled, there was about 30% improvement in the Uranium ore requirement in the FuRe scenario and about 18% in the MOC scenario (Fig. 3.1a and 3.1b). Also at this capacity, it is technically possible to eliminate all the UNF in storage (Fig.3.6a and 3.6b) because SFR dependence on LEU was eliminated (until after 2135 in MOC and 2145 in FuRe).

The amount of separation capacity deployed has a significant impact on the ability of any fuel cycle (as demonstrated above), to achieve any of the objective stated in the DOE 2010 *Nuclear Energy Research Development Roadmap*. Both the MOC and FuRe scenarios are better than OTC with respect to fuel cycle front and back end. This analysis underlines the importance of accounting for realistic, practical constraints, which may shift conclusions based on considering only inherent fuel cycle characteristics.

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