SUSTAINABLE ACTINIDE MANAGEMENT STRATEGIES USING LWRS WITH CONFU ASSEMBLIES

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Abstract

The *CO*mbined *N*on-*F*ertile and *U*O_2 (CONFU) fuel system for sustainable actinide management has the potential to reduce accumulation of actinides in the next 50 years under the assumption of a growing worldwide nuclear energy power demand. The system, which is compatible with currently operating Light Water Reactors (LWRs), employs CONFU fuel assemblies where about 20% of the UO_2 fuel pins are replaced with fertile free fuel (FFF) hosting the TRU.

Over the next 50 years the CONFU is shown to allow reduction of the TRU stored inventory by 25% with respect to the reference once-through (OT) fuel cycle scheme. The CONFU assembly has a net TRU incineration rate equal to zero, which depletes the TRU inventory by displacing this mass from the spent fuel inventory into the CONFU cores to meet the growing power demand (only reprocessing losses of TRU proceed to repository). Additionally, further TRU reduction using a CONFU assembly that achieves a net TRU destruction with each cycle appears possible.

Introduction

A number of system analysis studies carried out in the past have shown that utilization of the existing Light Water Reactor fleet as part of Pu and minor actinides (MA) transmutation strategies may significantly reduce the overall cost of the transmutation system. The more efficient the LWR part of TRU transmutation task, the greater are the benefits [1, 2].

As an example, Table 1 compares TRU and Pu transmutation performance of various fuel options under typical PWR operating conditions and fuel assembly geometry for the full Pu or TRU core loading. A standard mixed oxide (MOX), Thorium, and fertile free fuel (FFF) options are considered. The initial Pu/TRU loading corresponds to a standard 18 months fuel cycle.

All fuel options exhibit a negative TRU generation rate. However, a full FFF core, if proved to be feasible, is capable of achieving the highest TRU destruction rate as well as fractional TRU burnup per pass through the core. MOX and Th fuels are less effective because of the generation of additional TRU (or U233) from the fertile part of the fuel and their competition for neutron absorption with the original TRU.

Although all the PWR based recycle fuel options can reduce the amount of TRU, none of them by itself is capable of reducing significantly the long-term radiotoxicity of the spent fuel as illustrated by Figure 1. As a result, to avert long-term radiotoxicity, TRU transmutation mandates introduction of multirecycling in reactor systems in order to destroy the residual TRU and achieve the goal of waste radiotoxicity reduction to the level equivalent to that of the original natural uranium in less than 1 000 years. Proposal for a second tier of reactor systems relying on advanced fast reactor and accelerator technologies, which have yet to be proven economically, is often made.

An alternative solution might be a closed LWR fuel cycle with continuous multiple recycling of TRU where generation and production of TRU is balanced by combining a standard UO_2 fuel with TRU hosting fuel in the same reactor core. In such schemes, only the losses from TRU recycling and refabrication activities would be transferred to the repository reducing the fuel cycle long term radiotoxicity by several orders of magnitude. Degradation of the TRU isotopic vector with multiple recycles is compensated by a slight increase in enrichment of the uranium part of the core.

The feasibility of constraining Pu inventories in PWRs was shown through multi recycling of Pu either in Advanced Pu Assembly (APA) or in Combustible Recyclage A Ilot (CORAIL) assembly [3] recently studied at CEA in France and at Argonne National Lab in the US.

The APA combines large internally cooled annular (or cruciform-shaped) fertile free fuel pins containing Pu with standard UO_2 fuel pins. Such a configuration allows effective Pu consumption through high moderator to fuel volume ratio in the region of the Pu bearing fertile free pins. The annular geometry also helps to accommodate high power peaking in Pu pins. However, APA cannot be combined with conventional assemblies in the same PWR core because of the differences in thermal hydraulic designs.

On the other hand, in the CORAIL assembly, all fuel pins have identical geometry. The pins on the assembly periphery contain Pu or TRU in the MOX form. The availability of existing technology for reprocessing and fabrication of MOX fuel is the main advantage of the CORAIL concept. The equilibrium TRU concentrations in the CORAIL fuel cycle are relatively high due to the presence of fertile U238, which results in additional TRU generation and therefore deteriorates TRU destruction efficiency.

The presence of TRU in the LWR fuel cycle complicates fuel reprocessing, handling, and fabrication beyond the level involved in Pu recycle alone. Therefore, it is desirable to minimize the total TRU inventory. This goal can be achieved by designing the fuel for high efficiency of TRU destruction (therefore, small TRU inventory) and more economic reprocessing. In light of this consideration, fertile free fuels (FFF) are the most attractive candidates for recycling of the TRU in a sustainable LWR fuel cycle.

A *Co*mbined *N*on-*F*ertile and *U*ranium (CONFU) fuel assembly concept proposed in Reference 4 may offer some advantages as compared to APA and CORAIL concepts. The proposed concept also assumes a heterogeneous fuel assembly structure where most of the fuel pins are of the conventional UO_2 fuel type while some of the pins (about 20%) are replaced by FFF pins containing TRU. Each time the CONFU-type assembly is discharged from the core, the residual TRU from the FFF pins and the TRU generated in the UO_2 pins are separated and refabricated into a new CONFU assembly with "fresh" enriched uranium pins and FFF pins that include all the TRU from the previous cycle.

The unique features of the CONFU assembly are:

- The use of fertile free fuel pins allowing efficient destruction of TRU and therefore minimal TRU inventory required to balance TRU generation and destruction, which, in turn, implies minimal deviation of the core neutronic characteristics from the standard UO_2 core values. MOX based TRU multi recycling options would require much higher TRU inventory to achieve equilibrium because of additional production of TRU from U238 in TRU hosting pins.

- A small TRU inventory also reduces the number of TRU hosting pins, which minimizes the more expensive handling and manufacturing of such pins.

- The assembly mechanical and thermal hydraulic design is identical to a standard UO_2 fuel assembly design. This feature is more likely to allow co-existence of the conventional UO_2 assemblies and CONFU assemblies in the same core and, therefore, simple transition of the existing PWRs to CONFU fuel.

- Similar to the CORAIL concept, the TRU loss from the recycling activities is the only waste stream requiring permanent storage, which reduces spent fuel in-situ radiotoxicity by orders of magnitude, thus, eliminating the long term radiological threat.

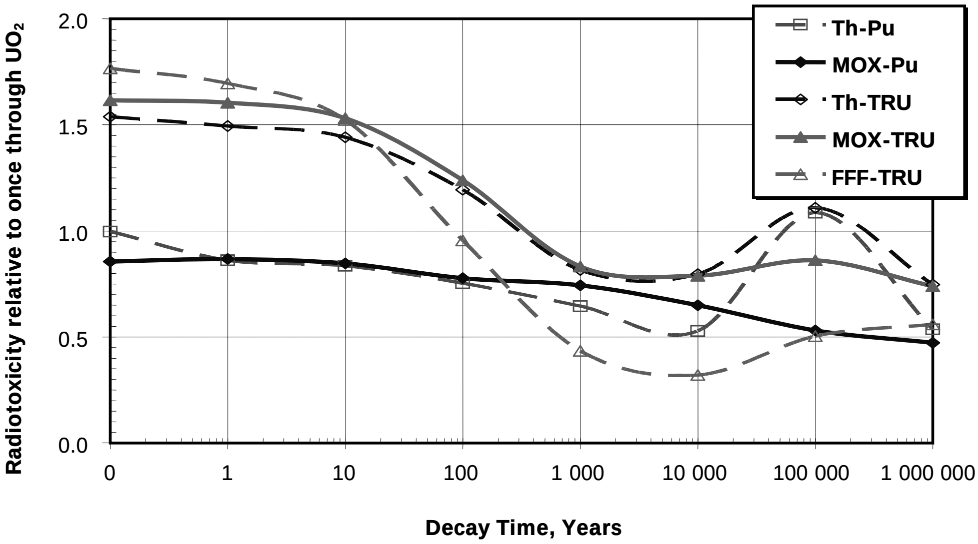
The rate of CONFU fueled LWRs deployment will determine the rate of existing TRU stockpile depletion because once fueled with CONFU assemblies, a reactor would operate in a TRU sustainable manner without requiring an external feed of TRU. In this study, we explore the possibility of achieving the negative TRU generation in the CONFU type fuel assembly for faster reduction of the existing TRU stockpile.

Table 1. **Comparison of fuel options for once-through burndown scenario**

	Standard UO_2	MOX-Pu	MOX-TRU	Th-Pu	Th-TRU	FFF-TRU
Discharge Burnup, MWd/kg	51	46	52	54	55	541
TRU generation rate, kg/GWe-Y	+260	-310	-480	-686	-793	-1150
Initial TRU, kg/assembly	0.0	33	75	43	101	48
Fractional burnup: TRU*	-	0.22	0.15	0.25	0.14	0.56
Discharged TRU, kg/assembly	5.5	25.3	63.6	26.8	82.0	21.4
Discharged Pu, kg/assembly	5.0	23.8	55.2	24.5	70.4	17.1

***** Including U233***

Figure 1. **Spent fuel radiotoxicity relative to once-through UO_2 fuel cycle**

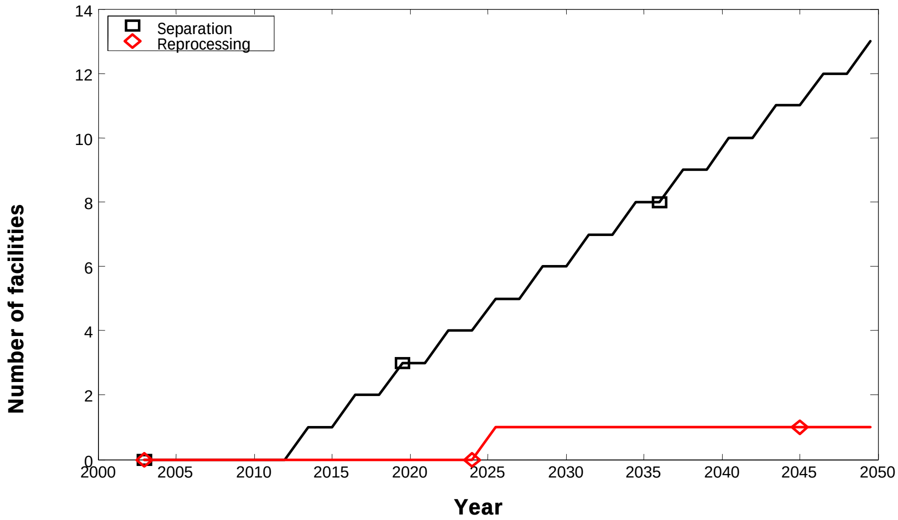


A CONFU strategy for long-term TRU management

A recent study [5] analyzed a long-term strategy for minimizing TRU using CONFU assemblies. The scenario assessed in this study assumed an increasing worldwide power demand over the next 50 years. This power demand is partially satisfied by nuclear power, beginning with 352 GWe in 2003, rising to 1 000 GWe in 2053. This represents an increase in the share of nuclear power worldwide increasing from 17% to 19% and is necessary to avoid 25% of the increase in global carbon emissions expected from a business-as-usual case.

The FFF pins in CONFU assemblies are initially fueled with the TRU from spent LWR fuel assemblies. Subsequent FFF pins are fueled with a mixture of TRU from both spent UO_2 pins and spent FFF pins. A cooling time of 6 years after discharge is allowed before the fuel is recycled. There are two types of facilities that support this recycling strategy. Separation plants are used to remove TRU from discharged UO_2 pins while reprocessing plants remove the TRU from discharged FFF pins. The analysis assumes that separation and reprocessing plants are built at a maximum rate of one every 36 months, as long as there is sufficient spent fuel to justify the additional capacity. Figure 2 shows the number of these facilities[1] in operation over time.

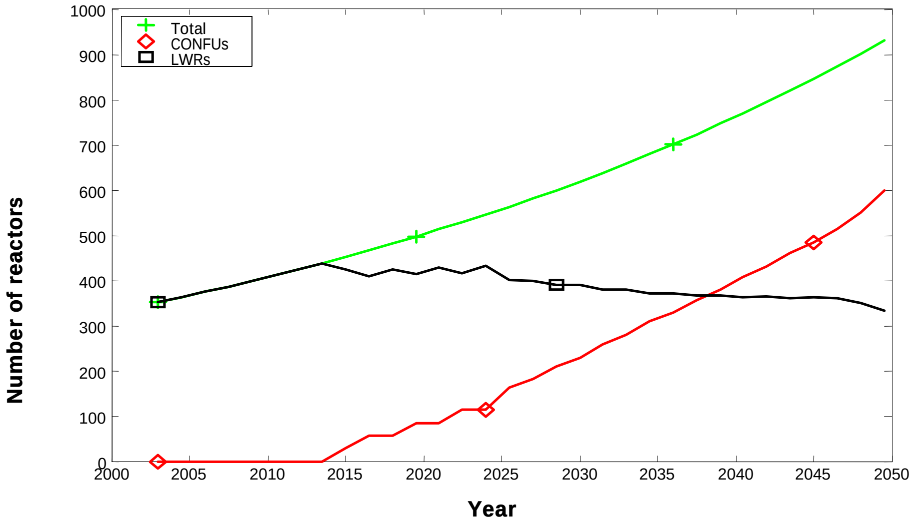
Figure 2. **Number of reprocessing and separation plants built to support the CONFU strategy**



Reactors are built to satisfy the power demand, and all reactors are taken to have 1 GWe capacity. These reactors are designated CONFU if they have one or more CONFU batches and are designated LWR if they contain all standard UO_2 batches. The number of FFF pins that can be produced is the only limit to the number of reactors that can contain CONFU assemblies. Figure 3 shows the number and types of reactors built to satisfy the power demand.

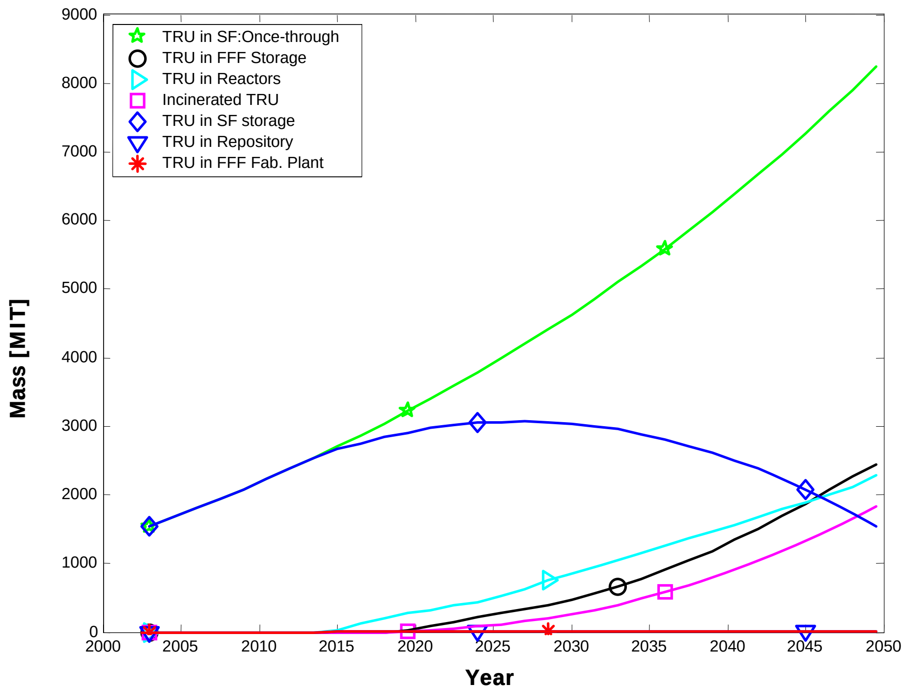
1. Capacity of separation and reprocessing plant was assumed 2 000 MT/yr and 250 MT/yr, respectively.

Figure 3. **Number of reactors with a least one CONFU batch and those with standard UO_2**



Based on this strategy, all the TRU from LWRs and CONFU reactors is recycled into FFF pins. There are small (0.1%) amounts of unrecoverable TRU at the separation and reprocessing plants that appear in the waste stream to the repository. This is the only TRU that is sent to the repository. The largest portion of TRU is incinerated, and the remaining TRU is in temporary storage, being burned in operating CONFU reactors, or in reprocessing/separation. It has been shown that an equilibrium CONFU batch could achieve a net zero TRU balance [6]. In this study, a CONFU batch produces 0.245 MT/GWe-yr in its UO_2 pins, and incinerates the same amount in its FFF pins. Figure 4 shows the mass of TRU located in each stage of CONFU operation and recycling, and compares it to the total amount of TRU that would accumulate in the once-through cycle. It should also be noted that each time the TRU is recycled, the plutonium vector is degraded and thus becomes less of a proliferation risk.

Figure 4. **TRU Balance for once-through compared to CONFU strategy**



An important concern with multi-recycling is the accumulation of curium and californium isotopes with each recycle. This can be dealt with in two ways. The first is to remove the Cm and Cf with each reprocessing of FFF pins. This material can then be put into separate storage, where it will eventually decay to plutonium, and could be re-introduced to the recycling stream. Alternately, the CONFU assemblies that have been recycled multiple times (2 times in this study) could be put into longer term (20-year) temporary storage to allow for Cm decay so that neutron and gamma doses are low enough for reprocessing and fuel manufacturing.

Net TRU destruction utilizing CONFU strategy

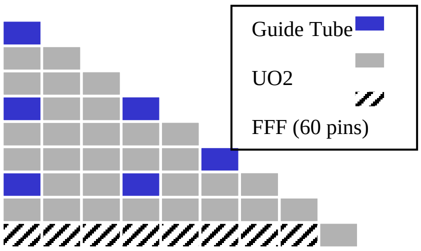
Additional analysis is being undertaken to determine if CONFU rectors can be designed to achieve a net destruction of TRU, while preserving acceptable operational performance and safety. This analysis uses CASMO4 for burnup and cooling calculations. CASMO4 is a multigroup two-dimensional transport theory code for burnup calculations on BWR and PWR assemblies or simple pin cells [7].

Previous work has conducted a baselining of CASMO4 [8]. This baselining evaluated the capability of CASMO4 to handle the non-conventional fuel designs with large loadings of TRU used in a CONFU assembly. The baselining established that CASMO4 could handle the heterogeneous nature of the FFF, although the fact that CASMO4 uses only 70 energy groups led to an underprediction of the number density of products of Pu-242 capture by about 10%.

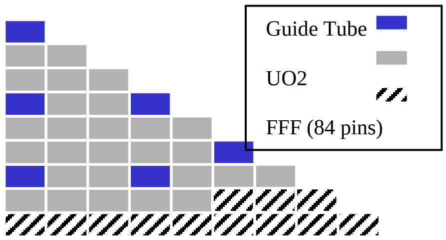
For this work, the following design constraints are used:

- Maximum UO_2 enrichment – 5 $^{w}/_{o}$
- Maximum TRU loading – 20 $^{v}/_{o}$ (This constraint was chosen so that the YSZ in the fuel particles is sufficient to minimise fission product damage to the surrounding matrix).
- Maximum allowable pin power peaking within an assembly – 1.25 (This constraint was chosen to give a reasonable assurance that the radial power peaking limit in the core remains within 1.587).

Under these constraints, four different assembly pin arrangements, shown below, are assessed.



Arrangement A



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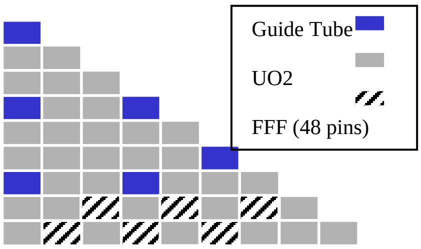
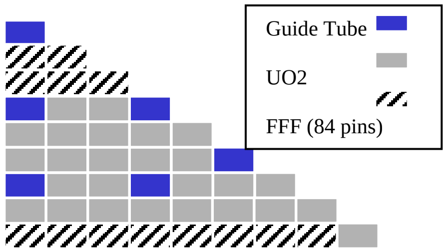


Arrangement B



Arrangement D

A series of five recycling depletions were run with the objective of achieving the highest possible net TRU destruction while remaining within the design constraints. The initial TRU vector used for loading the FFF pins comes from an ALWR spent fuel assembly (4.2 w/o UO2 enrichment, 50 GWd/t burnup) after 10 years cooling and 99.995% of the uranium and all fission products are removed [9].

A UO_2 enrichment of 5 $^{w}/_{o}$ was used for all CONFU assemblies. Each assembly burnup was followed by a 6-year cooling period. 99.995% of the uranium was removed, along with 99% of the curium and californium [10], and 0.1% TRU process losses were assumed. Fresh TRU was loaded at 15 $^{v}/_{o}$ in arrangement C for the first cycle. The TRU loading was increased to 20 $^{v}/_{o}$ and the pin arrangement was changed to D as power peaking limits allowed in order to maximize the net TRU destruction. The TRU destruction results are shown in Table 2.

These results show that a significant burndown in TRU mass can be achieved as the cycle moves towards equilibrium. Further recycle calculations are needed to see if these pin arrangements can achieve the desired net TRU destruction once equilibrium core concentration is reached. The larger TRU loading in these arrangements is expected to yield some level of net TRU destruction. Additionally, a more thorough thermal-hydraulic analysis needs to be performed and reactivity coefficients need to be calculated to ensure that proper operating margins are maintained. However, because of higher U content they are expected to be acceptable.

Table 2. **Results of TRU depletion per assembly**

	Cycle 1	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**
Fertile-free Matrix	35 v/o MgO 35 v/o ZrO2	35 v/o MgO 35 v/o ZrO2	35 v/o MgO 35 v/o ZrO2	35 v/o MgO 35 v/o ZrO2	35 v/o MgO 35 v/o ZrO2
Fuel particles	15 v/o TRU 15 v/o YSZ	15 v/o TRU 15 v/o YSZ	20 v/o TRU 10 v/o YSZ	20 v/o TRU 10 v/o YSZ	20 v/o TRU 10 v/o YSZ
# of TRU pins per assembly (arrangement)	84 (C)	84 (C)	84 (C)	84 (C)	84 (D)
TRU mass loaded per assembly (kg)	22.17	22.17	29.55	29.55	29.55
TRU after ~1500 EFPD (99.995% U removed) (kg)	17.19	18.07	25.14	25.47	25.12
TRU from UO_2 pins (kg)	4.49	4.54	4.67	4.67	4.85
TRU from FFF pins (kg)	12.70	13.53	20.47	20.80	20.27
Net TRU at EOL (kg)	-4.98	-4.10	-4.41	-4.08	-4.43
Pin power peaking within the assembly	1.196	1.187	1.205	1.218	1.232
Cm removed after 6-yr cooling (kg)	0.372	0.605	0.955	1.131	1.337
Cf removed after 6-yr cooling (g)	0.0005	0.0012	0.0018	0.0025	0.0040

Conclusions

It has been shown that introduction of CONFU assemblies, which attain a net zero balance of TRU while maintaining acceptable operational performance and safety features, into current LWRs can significantly reduce spent fuel inventory and incinerate appreciable amount of TRU in a nuclear energy growth scenario. The reduction of spent fuel inventory backlog is due to the loading of the first cores of new PWRs with TRU, hence a large portion of TRU from LWR spent fuel is transferred from storage into PWR cores. The multi-recycling of the TRU prevents all but a small fraction of the TRU from ever having to be stored in the repository. This strategy can achieve a 25% reduction (i.e. 25% of TRU is incinerated) in the peak TRU mass that would accumulate in the once-through option. This can be further increased for the case of a CONFU assembly designed for net TRU destruction. Work on such a CONFU assembly has been initiated and the first results reported here, show that for the case of 5 recycles, a 14-22% reduction in TRU per recycle is feasible. Further analyses will have to be performed to confirm that reactivity feedbacks and thermal hydraulic margins remain within acceptable bounds.

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