Synergistic Spent Nuclear Fuel Dynamics Within the European Union

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Abstract

The French 2012-2015 *Commission Nationale d'Evaluation Reports* emphasize preparation for a transition from Light Water Reactors (LWRs) to Sodium-Cooled Fast Reactors (SFRs). We used the Cyclus nuclear fuel cycle simulator to explore the feasibility of enabling a French transition to an SFR fleet by using Used Nuclear Fuel (UNF) from other European Union (EU) nations. A Cyclus simulation captured nuclear power deployment in the EU from 1970 to 2160. In this simulation, France begins its planned transition to SFRs as existing LWRs are decommissioned. These SFRs are fuelled with UNF accumulated by other EU nations and reprocessed in France. The impact of reactor lifetime extensions and SFR breeding ratios on time-to-transition were investigated with additional simulations. These simulations demonstrate that France can avoid deployment of additional LWRs by accepting UNF from other EU nations, that lifetime extensions delay time-to-transition, and improved breeding ratios are not particularly impactful.

Keywords: nuclear fuel cycle, european union, transition, agent-based, simulation, spent nuclear fuel

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Preprint submitted to Progress in Nuclear Energy *April 11, 2018*

1. Introduction

The stated long term plan for nuclear deployment in France targets a technology transition to Sodium-Cooled Fast Reactors (SFRs)[1]. However, the current inventory of French Used Nuclear Fuel (UNF) is insufficient to fuel that transition without building new Light Water Reactors (LWRs).

If instead, France accepted UNF from other European Union (EU) nations and used it to produce Mixed Oxide Fuel (MOX) for new SFRs, the MOX created will fuel a French transition to an SFR fleet and allow France to avoid building additional LWRs.

We used the CYCLUS nuclear fuel cycle simulator [2] to simulate EU spent nuclear material inventory accumulation and to model the proposed French technology transition from LWRs to SFRs. CYCLUS is an agent-based extensible framework for modeling the flow of material through future nuclear fuel cycles. We calculated the used fuel inventory in EU member states and propose a potential collaborative strategy of used fuel management.

Past research focuses solely on France and typically assumes that additional LWRs, namely European Pressurized Reactors (EPRs), supply the UNF required to produce MOX [3, 4, 5]. The strategies in these works estimate full SFR transition in 2100. However, little recent work considers synergistic international spent fuel arrangements. This work finds that a collaborative strategy can reduce the need to construct additional LWRs in France, if the SFRs are as commercially competitive as recent work suggests they may be [6].

2. Methodology

We simulated the nuclear reactor operating history in the EU beginning in 1970 including MOX production and use in France. The simulation captured all discrete regions, reactor facilities, and materials involved in EU historical reactor operation using CYCLUS fuel cycle simulation framework and CYCAMORE agents. In this simulation, the UNF from EU nations is stored for later use in French SFRs and France begins production of fuel for SFRs in 2020 by recycling the stored UNF. The SFRs are modeled after the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) breeder reactor [7]. All scripts and data used for the simulations in this article are available in [8].

2.1. Cyclus

Cyclus is an agent-based fuel cycle simulation framework [2], which means that each reactor, reprocessing plant, and fuel fabrication plant is modeled as an agent. A Cyclus simulation contains prototypes, which are fuel cycle facilities with pre-defined parameters, that are deployed in the simulation as `facility` agents. Encapsulating the `facility` agents are the `Institution` and `Region`. A `Region` agent holds a set of `Institutions`. An `Institution` agent can deploy or decommission `facility` agents. The `Institution` agent is part of a `Region` agent, which can contain multiple `Institution` agents. Several versions of `Institution` and `Region` exist, varying in complexity and functions [9]. `DeployInst` is used as the institution archetype for this work, where the institution deploys agents at user-defined timesteps.

At each timestep (one month), agents make requests for materials or bid to supply them and exchange with one another. A market-like mechanism called the dynamic resource exchange [10] governs the exchanges. Each material resource has a quantity, composition, name, and a unique identifier for output analysis.

In this work, each nation is represented as a distinct `Region` agent, that contains `Institution` agents, each deploying `Facility` agents. The `Institution` agents then deploy agents according to a user-defined deployment scheme.

2.2. Nuclear Deployment in the EU

The International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database [11] contains worldwide reactor operation history. The computational workflow in this work, shown in Figure 1, automates data extraction from the PRIS database. We import this database directly as a `csv` file to populate the simulation with deployment information, listing the country, reactor unit, type, net capacity (Mega Watt electric (MWe)), status,

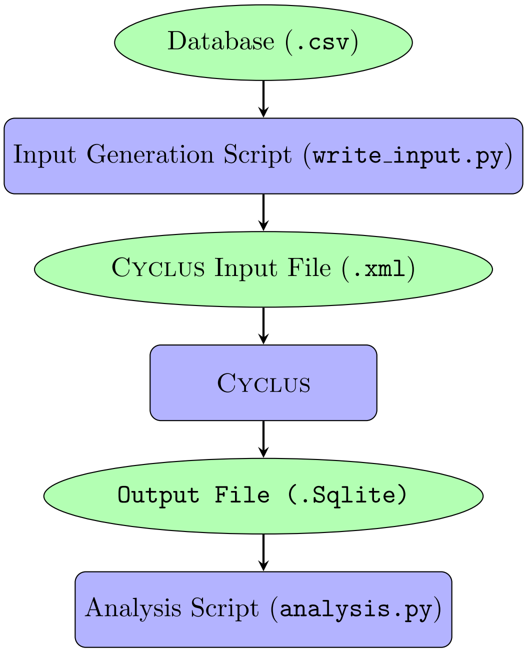

Figure 1: Green circles and blue boxes represent files and software processes, respectively, in the computational workflow.

operator, construction date, first criticality date, first grid date, commercial date, shutdown date (if applicable), and unit capacity factor for 2013. Then only the EU countries are extracted from the `csv` file. We developed a python script to generate a Cyclus compatible input file accordingly, which lists the individual reactor units as agents.

Projections of future reactor deployment in this simulation are based on assessment of analyses from references, for instance PRIS, for reactors planned for construction [11], the World Nuclear Association [12], and literature concerning the future of nuclear power in a global [13] and European context [14]. Existing projections extend to 2050.

Table 1 lists the reactors that are currently planned or under construction in the EU. In the simulation, all planned constructions are completed without delay or failure and reach a lifetime of 60 years.

Table 1: Power reactors under construction and planned. Replicated from [12].

Exp. Operational	Country	Reactor	Type	Gross MWe
2018	Slovakia	Mochovce 3	PWR	440
2018	Slovakia	Mochovce 4	PWR	440
2018	France	Flamanville 3	PWR	1600
2018	Finland	Olkilouto 3	PWR	1720
2019	Romania	Cernavoda 3	PHWR	720
2020	Romania	Cernavoda 4	PHWR	720
2024	Finland	Hanhikivi	VVER1200	1200
2024	Hungary	Paks 5	VVER1200	1200
2025	Hungary	Paks 6	VVER1200	1200
2025	Bulgaria	Kozloduy 7	[1]AP1000	950
2026	UK	Hinkley Point C1	EPR	1670
2027	UK	Hinkley Point C2	EPR	1670
2029	Poland	Choczewo	N/A	3000
2035	Poland	N/A	N/A	3000
2035	Czech Rep	Dukovany 5	N/A	1200
2035	Czech Rep	Temelin 3	AP1000	1200
2040	Czech Rep	Temelin 4	AP1000	1200

For each EU nation, we categorize the growth trajectory is categorized from “Aggressive Growth” to “Aggressive Shutdown”. “Aggressive growth” is characterized by a rigorous expansion of nuclear power, while “Aggressive Shutdown” is characterized as a transition to rapidly de-nuclearize the nation’s electric grid. We categorize each nation’s growth trajectory into five degrees depending on G, the growth trajectory metric:

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[1] The fate of many planned reactors is uncertain. The proposed reactor types are also unclear. The ones marked ‘N/A’ for type are assumed to the Pressurized Water Reactors (PWRs) in the simulation.

$$G = \left\{ \begin{array}{ll} \text{Aggressive Growth,} & \text{for } G \geq 2 \\ \text{Modest Growth,} & \text{for } 1.2 \leq G < 2 \\ \text{Maintanence,} & \text{for } 0.8 \leq G < 1.2 \\ \text{Modest Reduction,} & \text{for } 0.5 \leq G < 0.8 \\ \text{Aggressive Reduction,} & \text{for } G \leq 0.5 \end{array} \right\} = \frac{C_{2040}}{C_{2017}}$$

$$G = \text{Growth Trajectory } [-]$$

$$C_i = \text{Nuclear Capacity in Year i } [MWe].$$

The growth trajectory and specific plan of each nation in the EU is listed in Table 2.

Table 2: Projected nuclear power strategies of EU nations [12]

Nation	**Growth Trajectory**	**Specific Plan**
UK	Aggressive Growth	13 units (17,900 MWe) by 2030.
Poland	Aggressive Growth	Additional 6,000 MWe by 2035.
Hungary	Aggressive Growth	Additional 2,400 MWe by 2025.
Finland	Modest Growth	Additional 2,920 MWe by 2024.
Slovakia	Modest Growth	Additional 942 MWe by 2025.
Bulgaria	Modest Growth	Additional 1,000 MWe by 2035.
Romania	Modest Growth	Additional 1,440 MWe by 2020.
Czech Rep.	Modest Growth	Additional 2,400 MWe by 2035.
France	Modest Reduction	No expansion or early shutdown.
Slovenia	Modest Reduction	No expansion or early shutdown.
Netherlands	Modest Reduction	No expansion or early shutdown.
Lithuania	Modest Reduction	No expansion or early shutdown.
Spain	Modest Reduction	No expansion or early shutdown.
Italy	Modest Reduction	No expansion or early shutdown.
Belgium	Aggressive Reduction	All shut down 2025.
Sweden	Aggressive Reduction	All shut down 2050.
Germany	Aggressive Reduction	All shut down by 2022.

Using this categorization to drive facility deployment, the simulation captures regional differences in reactor power capacity and UNF production as a function of time. Accordingly, fig. 2 shows the resulting simulated installed capacity in EU nations. Sudden capacity reductions seen in the 2040s result from end-of-license reactor retirements and nuclear phaseout plans in nations such as Germany and Belgium.

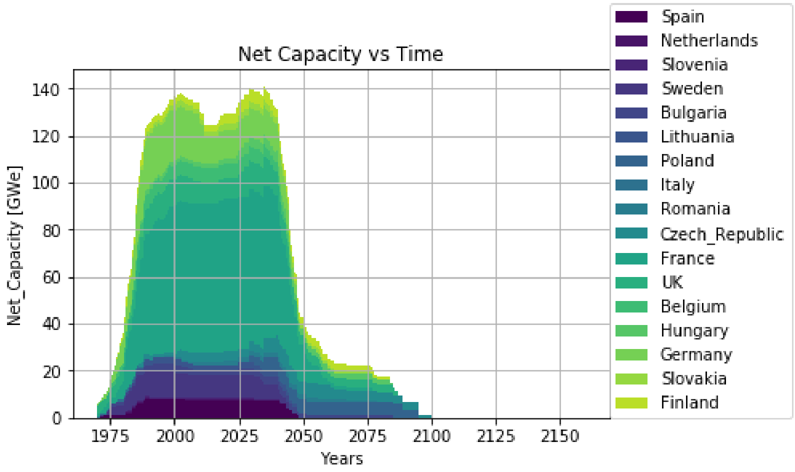

Figure 2: Installed nuclear capacity in the EU is distinguished by `Regions` in Cyclus.

2.3. French SFR Deployment Schedule

Figure 3 shows the French transition to SFRs modeled in this simulation. Historically aggressive growth of nuclear in the 1980s leads to a substantial shutdown of nuclear in the 2040s, which, in the simulation, are replaced by new SFRs. The net capacity is kept constant at 66 GWe.

Figure 4 shows the deployment required to support the transition in fig. 3. France must build four reactors per year, on average, to make up for the end-of-license decommissioning of power plants built in the 1980s and 1990s. The second period of aggressive building occurs when the first generation of SFRs decommission after 80 years. Starting in 2040, France deploys 600-MWe SFRs to make up for decommissioned French LWR capacity. This results in an installed SFR capacity of 66,000 MWe by 2078 when the final LWR is decommissioned.

Finally, Figure 5 shows the total deployment scheme we simulated. The French transition to SFRs couples with the historical and projected operation of EU reactors. The steep transition from 2040 to 2060 reflects the scheduled decommissioning of reactors built in the 1975-2000 era of aggressive nuclear growth in France.

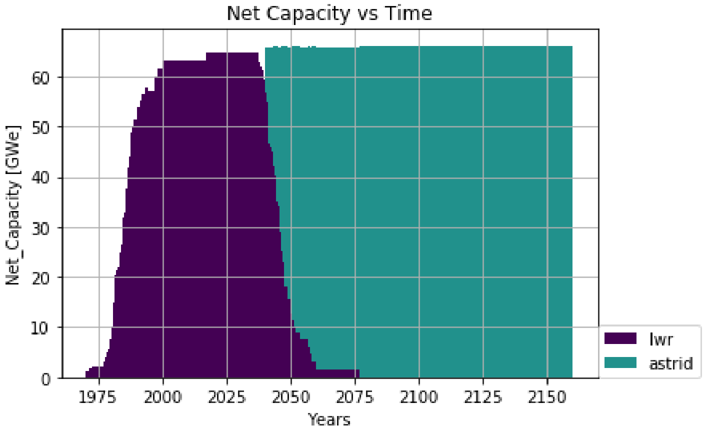

Figure 3: The potential French transition from LWRs to SFRs when assisted by UNF from other EU nations.

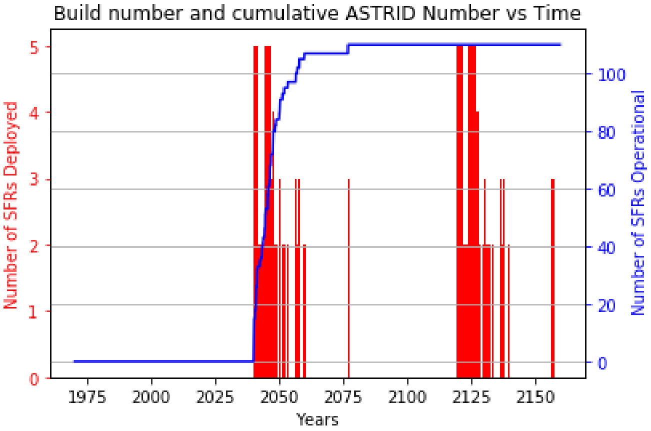

Figure 4: The deployment of SFRs in France is characterized by a period of aggressive building.

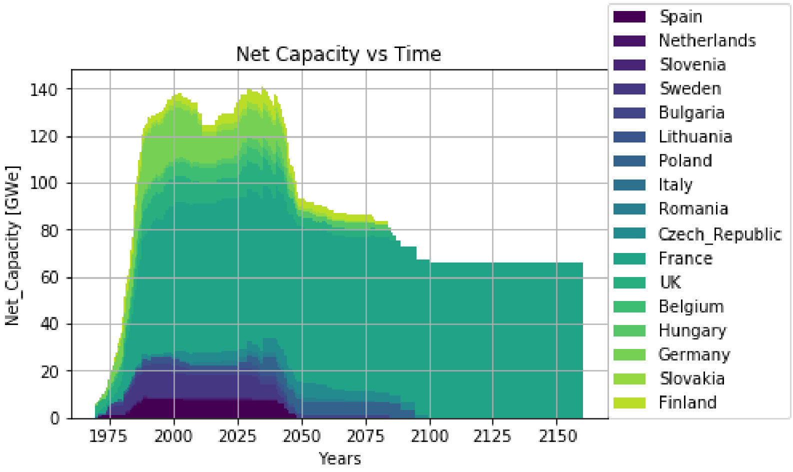

Figure 5: The total deployment scheme we simulated relies on UNF collaboration among nations.

These figures reflect that, for the given assumptions, bursts of construction are necessary to maintain capacity. In reality, a construction rate of five reactors every year is ambitious, but might have the advantage of larger scale production of components and more modular assembly and construction if major components can mostly be built off site.

This analysis establishes a multi-national material flow and demonstrates that, if such an aggressive deployment scheme took place, the SFRs would have enough fuel. Alternatively, the deployment of new SFRs can be spread out by staggering scheduled decommissioning of LWRs through lifetime extensions. For example, we increased the original lifetime of French LWRs (60 years) randomly by sampling from a uniform distribution of lifetime extension magnitudes between 0 and 25 years. This results in a more gradual transition and ASTRID construction burden, as shown in figure 6 and 7. The effect of LWR lifetime extension is discussed in Section 6.2.

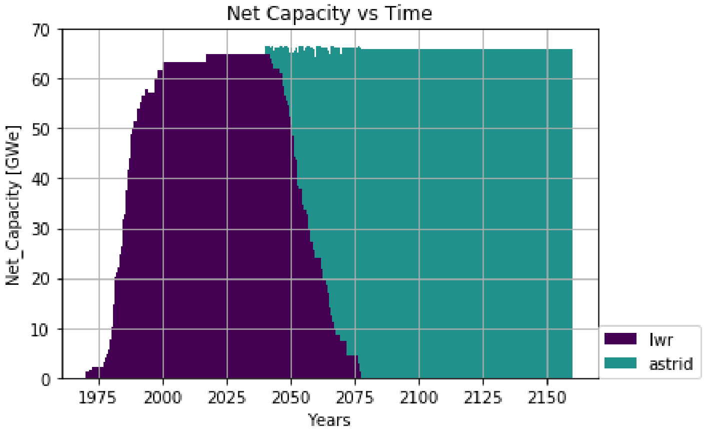

Figure 6: The transition to ASTRIDs becomes more gradual if the French LWRs lifetime extensions are sampled from a uniform distribution ∈ $[0, 25]$ years.

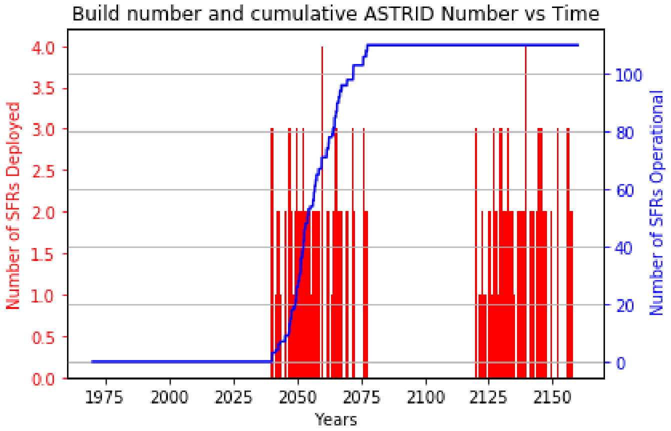

Figure 7: The acute construction burden lessens if the French LWRs lifetime extensions are sampled from a uniform distribution ∈ $[0, 25]$ years.

2.4. Material Flow

The fuel cycle is represented by a series of facility agents whose material flow is illustrated in figure 8, along with the CYCLUS archetypes that were used to model each facility. In this diagram, MOX Reactors include both French PWRs and SFRs.

A mine facility provides natural uranium, which is enriched by an enrichment facility to produce Uranium Oxide Fuel (UOX). Enrichment wastes (tails) are disposed of to a sink facility representing ultimate disposal. The enriched UOX fuels the LWRs which in turn produce spent UOX. The used fuel is sent to a wet storage facility for a minimum of 72 months. [3].

The cooled fuel is then reprocessed to separate plutonium and uranium, or sent to the repository. The plutonium mixed with depleted uranium (tails) makes MOX (Both for French LWRs and ASTRIDs). Reprocessed uranium is unused and stockpiled. Uranium is reprocessed in order to separate the raffinate (minor actinides and fission products) from usable material. Though neglected in this work, reprocessed uranium may substitute depleted uranium for MOX production. In the simulations, sufficient depleted uranium existed that the complication of preparing reprocessed uranium for incorporation into reactor fuel was not included. However, further in the future where the depleted uranium inventory drains, reprocessed uranium (or, natural uranium) will need to be utilized.

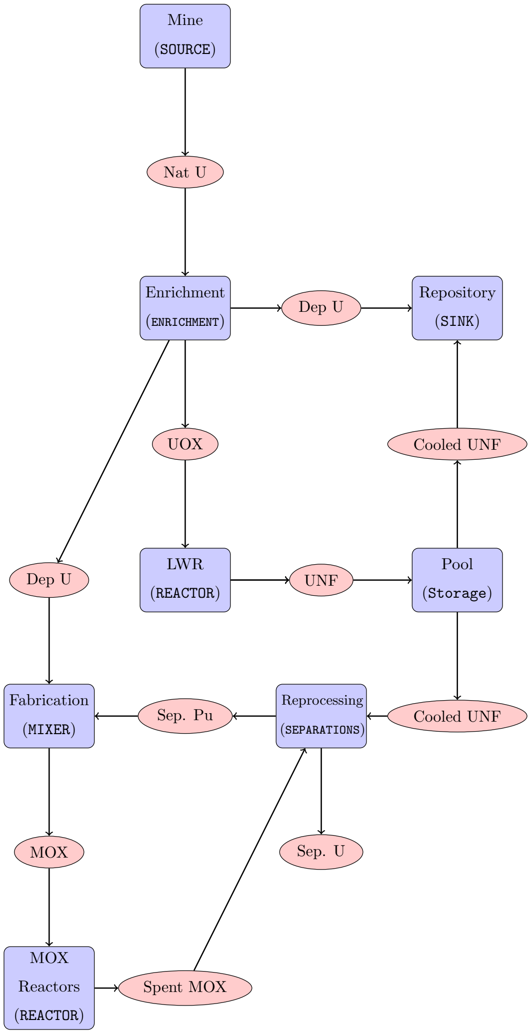

Figure 8: Fuel cycle facilities (blue boxes) represented by CYCLUS archetypes (in parentheses) pass materials (red ovals) around the simulation.

3. Scenario Specifications

are listed in table 3. The scenario specifications defining the simulations presented in this work The reprocessing and MOX fabrication capacity in France prior to 2020 is modeled after the French La Hague and MELOX sites [15, 16].

Table 3: Simulation Specifications

Specification	**Value**	**Units**
Simulation Starts	1970	year
Simulation Ends	2160	year
Production of ASTRID fuel begins	2020	year
SFRs become available	2040	year
Reprocessed uranium usage	Not used anywhere	-
Minimum UNF cooling time	36	months
Separation efficiency of U and Pu	99.8	%
Reprocessing streams	Pu and U	-
Reprocessing capacity before 2020	91.6 [15]	$\frac{\text{metric tons of UNF}}{month}$
Reprocessing capacity after 2020	183.2	$\frac{\text{metric tons of UNF}}{month}$
LWR MOX fabrication throughput	16.25 [16]	$\frac{\text{metric tons of MOX}}{month}$
ASTRID MOX fabrication throughput	No limit (∞)	$\frac{\text{metric tons of MOX}}{month}$
LWR MOX recycling	Not reprocessed	-
ASTRID MOX recycling	∞-pass	-

4. Reactor Specifications

Three major reactors are used in the simulation, PWR, Boiling Water Reactor (BWR), and ASTRID-type SFR reactors.

For LWRs, we used a linear core size model to capture varying reactor capacity. For example, a 1,200 MWe PWR has $193 * \frac{1{,}200}{1{,}000} = 232$ UOX assemblies, each weighing 523.4 kg. After each 18 month cycle, one-third of the core (77 assemblies) discharges. Refueling is assumed to take two months to complete, during which the reactor is shut down. The specifications are defined in table 4 which details the reactor specifications in this simulation. LWR specifications are modified linearly for varying power capacity.

Table 4: Baseline LWR and ASTRID simulation specifications.

Specification	**PWR** [17]	**BWR** [18]	**SFR** [7]
Lifetime [y] [2]	60	60	80
Cycle Time [mos.]	18	18	12
Refueling Outage [mos.]	2	2	2
Rated Power [MWe]	1000	1000	600
Assembly mass [kg]	523.4	180	–
Batch mass [kg]	–	–	5,568
Discharge Burnup [GWd/tHM]	51	51	105
Assemblies per core [3]	193	764	–
Batches per core	3	3	4
Initial Fissile Loading [t]	3.1 ^{235}U	4.2 ^{235}U	4.9 Pu
Fuel	UOX or MOX	UOX	MOX

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[2] The simulated reactor lifetime reaches the licensed lifetime unless the reactor is shut down prematurely.

[3] Number of assemblies and corresponding LWR core masses are reported for a 1000-MWe core. Reactors with different core powers are modeled with a linear mass assumption.

4.1. Material Definitions

Depletion calculations of the nuclear fuel are recipe-based, such that a fresh and used fuel recipe is defined for each reactor type. For the compositions of the used fuel, a reference depletion calculation from ORIGEN is used (see table A.11). ORIGEN calculates buildup, decay, and processing of radioactive materials [19]. This recipe recipe has also been used for repository performance modeling [20].

Table 5: Fresh fuel compositions in the simulation [20, 7].

	Composition [%]		
Recipe	U-235	U-238	Pu
Fresh UOX Fuel	3.1	96.9	-
Fresh LWR MOX Fuel	0.2	90.7	9.1
Fresh ASTRID Fuel	0.2	77.7	22

5. Results

5.1. Nuclear Material Inventory

Table 6 lists EU material inventory in 2050. The materials continue to accumulate after 2050, but the UNF France receives before 2050 is most impactful for the feasibility of the transition. Note that table 6 distinguishes the UOX in the simulation either stored or reprocessed to create MOX.

Table 6: EU nuclear material inventory in 2050.

Category	**Value [MTHM]**	Specifics
UOX Loaded	161,894	UOX used in EU (minus France) reactors 1970-2050
MOX Loaded	6,945	MOX used in French reactors 1970-2050
Available used UOX (EU)	95,193	Used EU (minus France) UOX in storage for future ASTRID MOX production
Available used UOX (France)	10,029	Used French UOX stored for future ASTRID MOX production.
Reprocessed UOX (France)	53,590	Used French UOX already reprocessed for the production of LWR MOX
Tails	980,294	(Tails generated) − (Tails used for production of LWR MOX)
Natural U Used	1,142,189	

Figures 9 and 11 show the accumulation of tails and used fuel over time in the EU. Tails accumulate as a by-product of uranium enrichment. For every ton of UOX fuel, about nine times of tails is produced. Spent fuel is discharged from reactors every refueling period. The entire core is discharged when the reactor decommissions. A total of about $1,000,000$ MTHM of tails and $100,000$ MTHM of UNF have accumulated by 2050. Figure 10 shows the amount of fuel used in the EU. The tails mass accumulation rate is fairly steady, with peaks occurring when new reactors are deployed. In fig. 11, the peaks are caused by reactor decommissioning which triggers all the batches in the final reactor core to be sent to the repository.

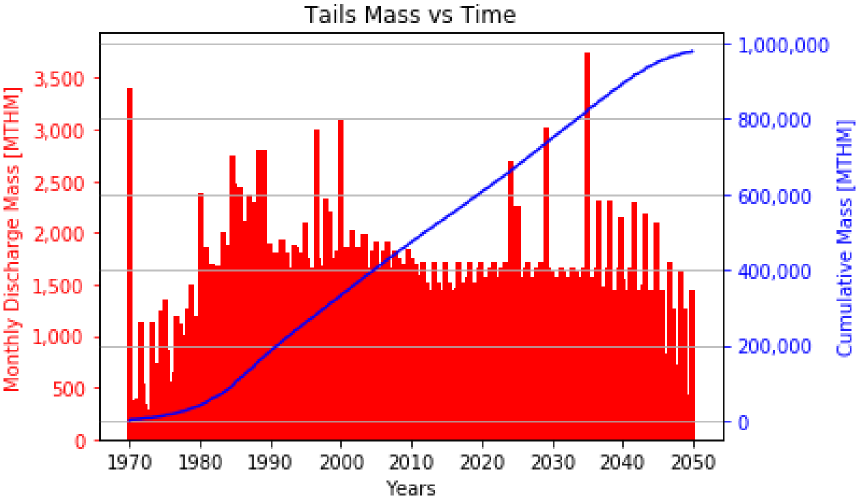

Figure 9: Simulated accumulation of tails in the EU is shown as a function of time.

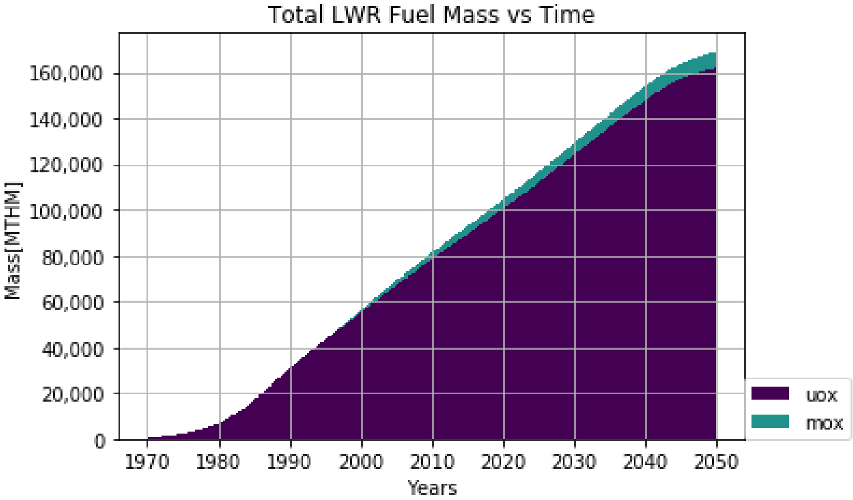

Figure 10: Simulated total EU fuel useage is shown as a function of time.

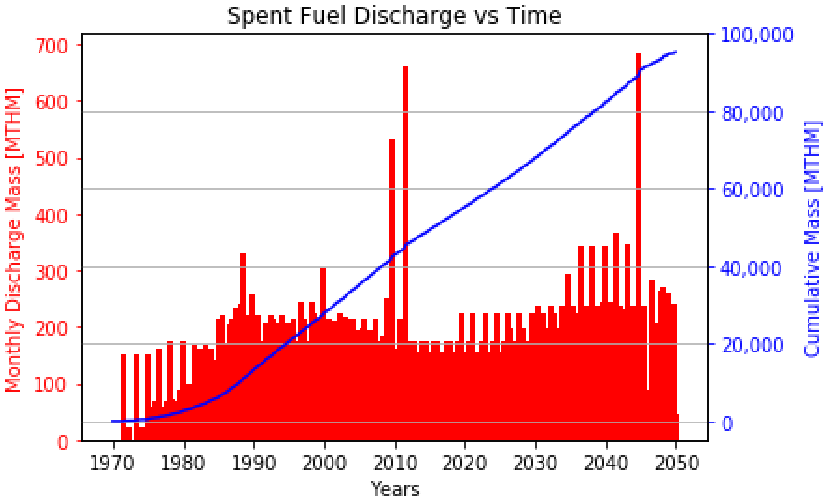

Figure 11: Simulated EU UNF accumulation and discharge is shown as a function of time.

5.2. French SFR Deployment

Reprocessing the UNF collected from all EU nations can provide the initial cores for approximately 180 SFRs. Table 7 lists the isotope, mass fraction, and quantity of plutonium that can be obtained from the 2050 UNF inventory. With the SFR breeding ratio above one, France can transition into a fully SFR fleet without extra construction of LWRs.

Table 7: Plutonium in the UNF inventory.

Isotope	**Mass Fraction in Used Fuel [%]**	**Quantity [t]**
Pu238	0.0111	10.52
Pu239	0.518	545.05
Pu240	0.232	244.11
Pu241	0.126	132.58
Pu242	0.0487	51.24
Total	**0.9358**	**983.52**

From Varaine et al. [7], a French ASTRID-type 600MWe SFR consumes

1.225 metric tons of plutonium a year, with an initial plutonium loading of 4.9 metric tons. Thus, the number of SFRs that can be loaded with the reprocessed plutonium from UNF can be estimated to be 200, assuming adequate reprocessing and fabrication capacity as well as abundant depleted uranium supply.

Used MOX from an ASTRID reactor is 23.95% plutonium in this simulation (see table A.11), whereas fresh MOX is 22% plutonium. The plutonium breeding ratio in this simulation is thus assumed to be ≈ 1.08.

Figure 12 shows MOX loaded in the SFRs per month. The plot has peaks during a period of aggressive deployment of SFRs followed by an equilibrium at 100 metric ton of heavy metal (MTHM). The peaks reoccur with the deployment of the second generation of SFRs. The spikes are due to initial fuel demand correspoding to these new deployments. The initial cores loaded into new SFRs rely on the MOX created from legacy UNF. Once the deployed SFRs create enough extra plutonium, the legacy UNF is no longer used. Notably, this switch from a less preferred fuel origin to a more preferred fuel origin is handled automatically within Cyclus via user-defined preferences within its dynamic resource exchange algorithm [21].

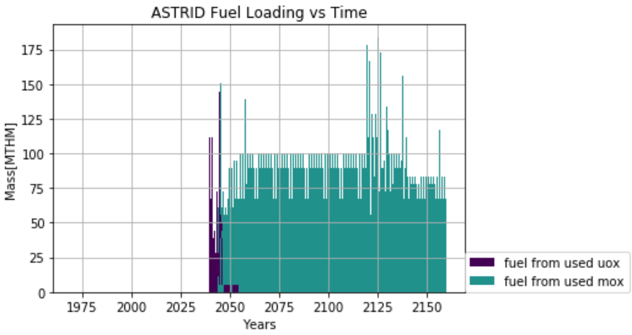

Figure 12: Fuel loaded into SFRs was simulated in discrete batches.

Figure 13 shows the separated plutonium discharge per month from the reprocessing plant. The plutonium outflux does not precisely follow the fuel demand because Cyclus agents have material buffers that store commodity fuel for later usage. The reprocessed plutonium from legacy UNF is stored for the initial loading of SFRs. Plutonium separated from legacy UNF meets plutonium demans sufficiently to reduce the reprocessing demand for the first aggressive deployment of SFRs. The plutonium from reprocessing legacy fuel is a flat rectangle because the reprocessing throughput was set to 183.2 $\frac{MTHM}{month}$ to avoid reprocessing all the legacy in one timestep.

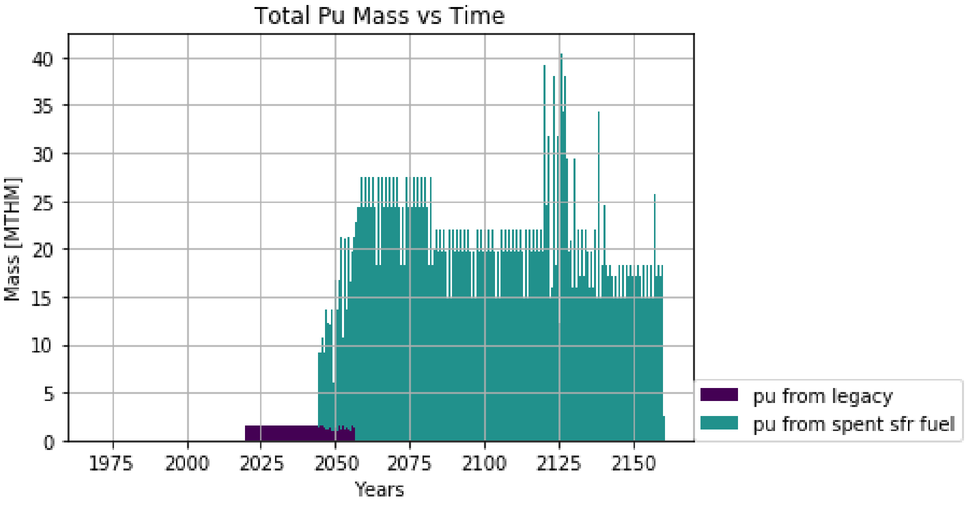

Figure 13: The separated plutonium discharge from the reprocessing plant in $\frac{\text{MTHM}}{\text{month}}$.

Table 8 lists metrics obtained from the second simulation.

These results demonstrate that despite the large amount of initial plutonium that has to be reprocessed prior to ASTRID deployment, the 20 years (2020-2040) of ASTRID fuel preparation allows a reasonable level of average UOX reprocessing capacity demand. UOX reprocessing continues until 2057, when the ASTRID spent fuel can supply the plutonium for its own fuel.

6. Sensitivity Analysis

An important aspect of any fuel cycle transition scenario is the accrual of fissile materials for new reactor deployment. The collaborative strategy makes a

Table 8: In the French transition to SFRs, the total legacy UNF reprocessed is the amount of UNF France needs for a transition into a fully SFR fleet.

Category	**Unit**	**Value**
Total ASTRID MOX used	MTHM	63,447
Average UOX Reprocessing	MTHM/month	**123.27**
Average Total Reprocessing	MTHM/month	**63.23**
Average Fuel Fabrication	MTHM/month	**74.31**
Total SFRs Deployed		220
Total Plutonium Reprocessed	MTHM	14,831
Total ASTRID fuel from UOX Waste	MTHM	2,895
Total ASTRID fuel from MOX Waste	MTHM	60,552
Total Tails used	MTHM	49,488
Total legacy UNF reprocessed	MTHM	**53,595**
Total Reprocessed Uranium Stockpile	MTHM	159,383
Total Raffinate	MTHM	24,789

transition possible from the perspective of material availability, but the aggressive transition demands a significant increase in reprocessing capacity.

We explored the impact of two key variables, the lifetime of French LWRs and the breeding ratio of ASTRID reactors. The range over which we varied these parameters (table 9) sought to capture the full span of their uncertainty.

Table 9: Both LWR lifetime and ASTRID breeding ratio impact transitional reprocessing demand.

Parameter	**Default**	**Values**
Breeding Ratio of ASTRIDs	1.08	1.11, 1.15, 1.18
Lifetime of French LWRs [years]	60	65, 70, 80

6.1. Breeding Ratio

Increase in the breeding ratio of ASTRID reactors decreases the monthly LWR UNF reprocessing demand, as shown in figure 14. An increase in breeding ratio also reduces the number of total UOX UNF required for the transition, because the ASTRID creates more plutonium. The demand previous to 2050 is unaffected by the breeding ratio because only UOX UNF is reprocessed.

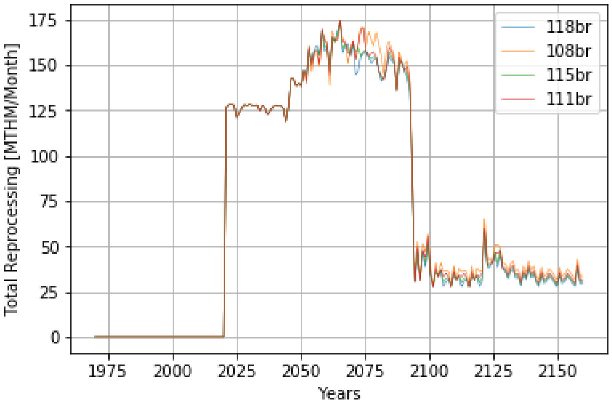

Figure 14: Increasing the breeding ratio decreases the monthly reprocessing demand.

The sensitivity analysis also shows, as demonstrated in fig. 15 that increasing the breeding ratio decreases the mass of UOX UNF required for the transition. The ASTRIDs produce more plutonium, reducing the plutonium demand from reprocessed UOX.

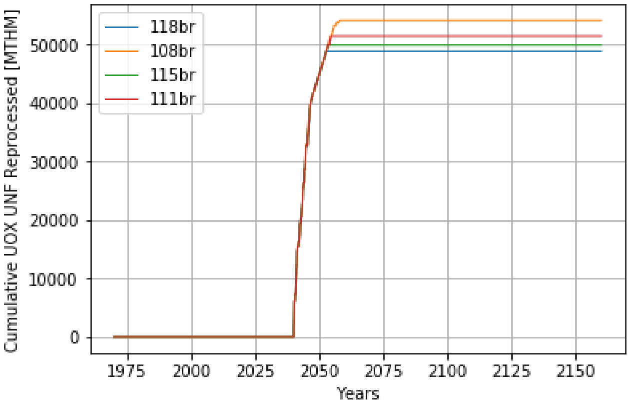

Figure 15: Sensitivity analysis demonstrates that increasing the breeding ratio decreases the required UOX UNF.

6.2. Lifetime Extension of French LWRs

Extending the lifetime of French LWRs dramatically lowers the average monthly UOX reprocessing demand, since the ASTRID deployment becomes delayed (shown in figure 16). The plutonium demand is delayed, allowing the reprocessing plant more time to prepare plutonium for ASTRID reactors.

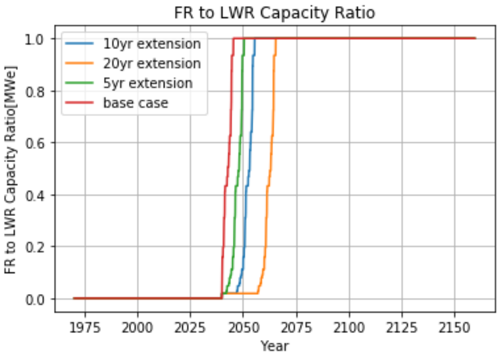

Figure 16: The ratio of ASTRIDs to LWRs in France demarcates the transition period.

Increasing LWR lifetimes also enables a less aggressive transition to ASTRIDs. Figure 17 shows the decrease in the average monthly UOX reprocessing burden with increased LWR lifetimes, which reduces to the current capacity of the La Hague site if all the French LWRs extended their operation for 20 years. However, figure 18 shows that lifetime extension has little effect on the average total monthly reprocessing demand, because the amount of plutonium in the ASTRID used fuel remains the same. The initial increase is caused by the delay of ASTRID deployment delaying the first ASTRID UNF reprocessing. The period of which ASTRID UNF is reprocessed decreases, which increases the average.

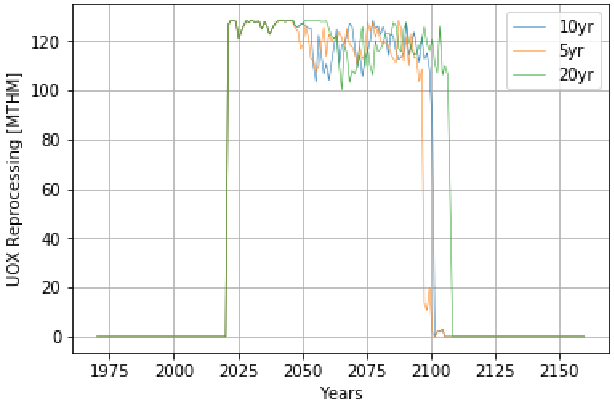

Figure 17: Increasing the lifetime of French LWRs decreases the monthly UOX reprocessing demand.

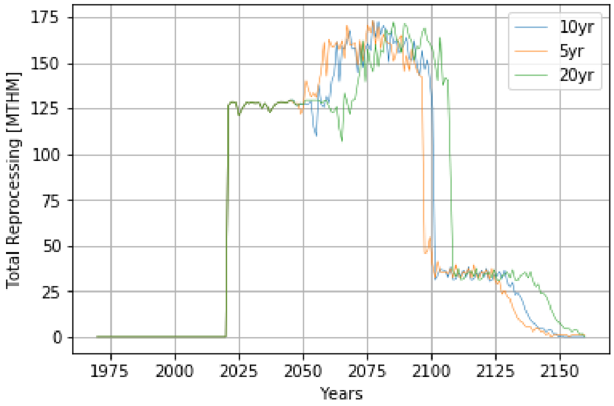

Figure 18: Increasing the lifetime of French LWRs simply delays the reprocessing demand, and has little impact on the total reprocessing capacity required.

7. Conclusion

This work demonstrates that France can transition into a fully SFR fleet with installed capacity of 66,000 MWe without building additional LWRs if France receives UNF from other EU nations. Supporting the SFR fleet requires an average reprocessing capacity of 73.27 MTHM per month, and an average fabrication capacity of 45.29 MTHM per month.

Since most EU nations do not have an operating UNF repository or a management plan, they have a strong incentive to send their UNF to France. In particular, the nations planning aggressive nuclear reduction will be able phase out nuclear without constructing a permanent repository. France has an incentive to take this fuel, since recycling used fuel from other nations will allow France to meet their MOX demand without new construction of LWRs.

Table 10 lists EU nations and their UNF inventory in 2050. We analyzed a strategy in which the nations reducing their nuclear fleet send their UNF to France. The sum of UNF from Italy, Slovenia, Belgium, Spain and Germany provides enough UNF for the simulated transition ($\approx 54,000$ MTHM). These nations are shown in bold in table 10. Sweden is not considered because of its concrete waste management plan.

On the other hand, in these simulations, some complex political and economic factors were not incorporated and various assumptions were present in this scenario. For example, Germany's current policy is to not reprocess its LWR fuel [22], and this policy would create a shortage in the supply of LWR UNF for ASTRID MOX production. Continuation of that German policy would not, however, be incompatible with a change in EU policy that frees EU countries from creating their high level waste repositories, since France could still agree to take in Germany's UNF for direct disposal. The analysis method described herein could readily be adapted to account for such possibilities. The collaborative option explored here may hold value for the EU nuclear community, and may enable France to advance more rapidly into a closed fuel cycle.

Table 10: EU nations and their respective UNF inventory.

Nation	Growth Trajectory	UNF in 2050 [MTHM]
Poland	Aggressive Growth	1,807
Hungary	Aggressive Growth	3,119
UK	Aggressive Growth	13,268
Slovakia	Modest Growth	2,746
Bulgaria	Modest Growth	3,237
Czech Rep.	Modest Growth	4,413
Finland	Modest Growth	5,713
Netherlands	Modest Reduction	539
Italy	**Modest Reduction**	**583**
Slovenia	**Modest Reduction**	**765**
Lithuania	**Modest Reduction**	**2,644**
Belgium	**Aggressive Reduction**	**6,644**
Spain	**Modest Reduction**	**9,771**
France	**Modest Reduction**	**9,979**
Sweden	Aggressive Reduction	16,035
Germany	**Aggressive Reduction**	**23,868**

8. Acknowledgments

This research is being performed using funding received from the DOE Office of Nuclear Energy's Nuclear Energy University Program via NEUP Project 16-10512: Demand-Driven Cycamore Archetypes. Additionally, early conception of this work was supported by The Program in Arms Control & Domestic and International Security (ACDIS), an interdisciplinary venture at the University of Illinois at Urbana-Champaign that facilitates objective research, academics, and outreach about international security issues within the academic and policy-making communities.

The authors would like to thank members of Advanced Reactors and Fuel Cycles research group (ARFC) at the University of Illinois - Urbana Champaign, in particular Gyu Tae Park, who provided valuable code reviews and proofreading. We also thank our colleagues from the Cyclus community, particularly those in the University of Wisconsin Computational Nuclear Engineering Research Group (CNERG) and the University of South Carolina Energy Research Group: Scopatz (ERGS) who provided collaborative support in the core software, Cyclus, enabling this work although they may not agree with all of the interpretations/conclusions of this paper.

The authors contributed to this work as described below. Jin Whan Bae conceived and designed the simulations, wrote the paper, prepared figures and/or tables, performed the computation work, contributed to the software product, and reviewed drafts of the paper. Clifford E. Singer conceived and designed the simulations and reviewed drafts of the paper. Kathryn D. Huff directed and supervised the work, conceived and designed the simulations, wrote the paper, prepared figures and/or tables, contributed to the software product, and reviewed drafts of the paper.

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Appendix A. Fresh and Used Fuel Composition

Isotope	Used ASTRID Fuel	Used UOX Fuel	Used MOX Fuel
He4	8.2631E-05	9.4745E-07	2.5108E-05
Ra226	2.306EE-13	9.7885E-14	6.8586E-14
Ra228	6.029EE-21	2.7508E-20	1.0769E-19
Pb206	5.2269E-18	5.5747E-18	3.6378E-18
Pb207	1.0722E-15	1.6859E-15	1.0589E-15
Pb208	4.4347E-10	3.6888E-12	2.0018E-12
Pb210	1.3841E-16	3.0238E-19	1.1829E-19
Th228	7.7910E-10	8.4756E-12	4.9017E-12
Th229	3.5259E-11	2.7278E-12	1.4379E-12
Th230	1.1419E-08	2.6258E-09	2.3998E-09
Th232	6.3415E-11	4.1748E-10	8.7655E-10
Bi209	2.5042E-13	6.6077E-16	2.6878E-16
Ac227	2.8317E-14	3.0968E-14	2.4608E-14
Pa231	8.8076E-10	9.2465E-10	7.0696E-10
U232	1.4693E-07	0.0000	5.9336E-10
U233	4.0461E-08	2.2139E-09	1.0359E-08
U234	0.0010	0.0001	0.0002
U235	0.0003	0.0076	0.0043
U236	0.0005	0.0057	0.0051
U238	0.5864	0.9208	0.8283
Np237	0.0038	0.0006	0.0043
Pu238	0.0096	0.0002	0.0060
Pu239	0.0981	0.0060	0.0410
Pu240	0.0890	0.0029	0.0283
Pu241	0.0155	0.0017	0.0146
Pu242	0.0273	0.0008	0.0098
Pu244	1.779EE-07	2.8648E-08	2.1888E-07
Am241	0.0077	6.4427E-05	0.0021
Am242m	0.0005	8.5336E-07	5.0357E-05
Am243	0.0091	0.0001	0.0020
Cm242	0.0004	2.5898E-05	0.0002
Cm243	0.0000	0.0000	1.2639E-05
Cm244	0.0067	8.5616E-05	0.0010
Cm245	0.0017	5.7217E-06	0.0001
Cm246	0.0009	7.2956E-07	6.1406E-06
Cm247	0.0000	0.0000	1.2059E-07
Cm248	4.0265E-06	7.6916E-10	9.1585E-09
Cm250	1.076EE-12	4.2808E-18	3.7338E-17
Cf249	1.6590E-07	1.6499E-12	4.0567E-11
Cf250	9.5219E-09	2.0419E-12	2.9328E-11
Cf251	3.2032E-10	9.8655E-13	1.4479E-11
Cf 252	8.3754E-12	6.5797E-13	7.5346E-12
H3	3.1829E-07	8.5846E-08	1.0269E-07
Kr81	1.5156E-11	4.2168E-11	7.3446E-11
Kr85	0.0000	3.4448E-05	2.0548E-05
Sr90	0.0009	0.0007	0.0004
Tc99	0.0029	0.0011	0.0011
I129	0.0009	0.0002	0.0003
Cs134	0.0001	0.0002	0.0002
Cs135	0.0051	0.0006	0.0009

Table A.11: Spent Fuel Compositions