Synergistic Spent Nuclear Fuel Dynamics Within the European Union

Jin Whan Bae[1], Kathryn D. Huff[1], Clifford E. Singer[1]

[1] *Dept. of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana-Champaign*
Urbana, IL

Abstract

The French 2012-2015 Commission Nationale d'Evaluation Reports [1] emphasize preparation for a transition from Light Water Reactors (LWRs) to Sodium-Cooled Fast Reactors (SFRs). We used CYCLUS [2] 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 ran from 1950 to 2050 for EU nations to track the UNF mass and tails inventory. Another simulation ran to model the French transition to SFRs supported by reprocessing the UNF inventory accumulated by the EU nations. These simulations demonstrate that France can avoid deployment of additional LWRs by accepting UNF from other EU nations.

1 Introduction

We used CYCLUS [2] to analyze rt the EU and to model the French transition. CYCLUS is an agent-based extensible framework for modeling the flow of material through future nuclear cycles. We calculate the used fuel inventory in EU member states, and propose a potential collaborative strategy of used fuel management. A major focus of this paper is to determine the potential for France to utilize UNF from other EU nations to produce Mixed Oxide Fuel (MOX) for new SFRs. The MOX created will fuel French transition to a SFR fleet and allow France to avoid building additional LWRs.

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]. Other recent works implement partitioning and transmutation in a European context, with Accelerator-Driven Systemss (ADSs) and Gen-IV reactors [6], to reduce radiotoxicity for disposal. Little recent work considers synergistic international spent fuel arrangements. The present work finds that this collaborative strategy can reduce the need to construct additional LWRs in France.

2 Methodology

The EU nations' nuclear reactor operating history is modeled to the furthest foreseeable future. The UNF from EU nations is stored for later usage. France, on top of its historical operation with MOX production for its Pressurized Water Reactors (PWRs), transitions into a 66GWe SFR fleet starting from 2040. 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 in this paper are available in [8].

2.1 Cyclus

Cyclus is an agent-based fuel cycle simulation framework [2], meaning that each reactor, reprocessing plant, and fuel fabrication plant is modeled as an agent. At each timestep (one month), agents put out their bids for materials (supply and/or demand) and exchange with one another. A market-like mechanism called the dynamic resource exchange [9] governs the exchanges. Each material item has a quantity, composition, name, and a unique identifier for output analysis. A Cyclus input file 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 [10]. `DeployInst` is used as the institution archetype for this work, where the institution deploys agents in a user-defined time.

For example, 'France' would be a `Region` agent, that may contain two `Institution` agents LWRs and SFRs. The `Institution` agents would then deploy LWRs and SFRs agents, respectively, according to a pre-defined deployment scheme.

2.2 Nuclear Deployment in the EU

The International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database [11] contains reactor operation history. The database is imported as a csv file, to populate the simulation with deployment information, listing the country, reactor unit, type, net capacity (Mega Watt electric (MWe)), status, 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 input file from the csv file, which lists the individual reactor units as agents.

Projections of future reactor deployment in this simulation are based on assessment of analyses from references such as PRIS for reactors planned for

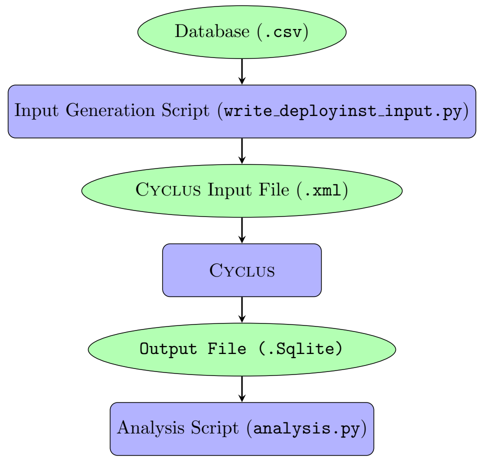

Figure 1: Computational Workflow for this work. The green circles represent files, and the blue boxes represent codes that process the files.

construction [11], the World Nuclear Association [12], and works on the future of nuclear power in a global [13] and European context [14]. The projections extend to 2050 at the latest. This allows the simulation to take place from 1970 to 2050. Later sections explain, in detail, the specific plans for each EU nation.

Section 2.2 lists the reactors that are currently planned or under construction. All planned constructions are completed without delay or failure and are assumed to reach a lifetime of 60 years.

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	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

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

For each EU nation, 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. A nation’s growth trajectory is categorized into five degrees depending on G, the growth trajectory metric.

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

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

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

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

Figure 2 displays the timeseries of installed capacity in EU nations.

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.

Table 2: Future Nuclear Programs of EU Nations [12]

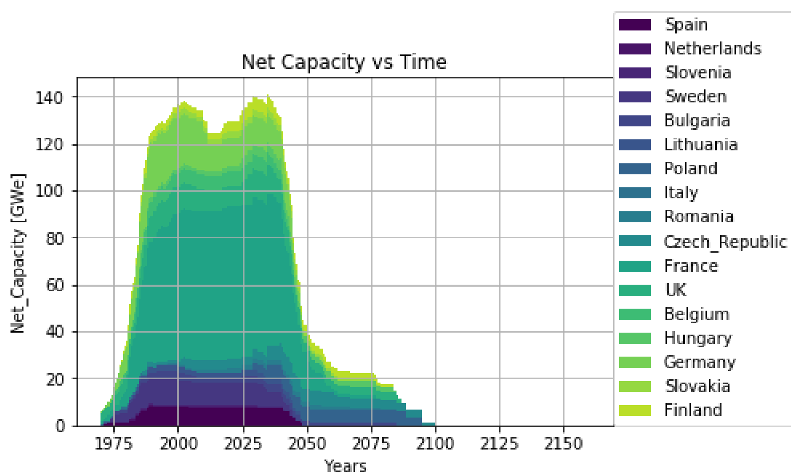

Figure 2: The timeseries of installed nuclear capacity in the EU is separated by `Regions` in Cyclus. The sudden drops in capacity are caused by nuclear phaseout plans by nations such as Germany and Belgium. The predictions into the future are made to the farthest planned future.

2.3 French SFR Deployment Schedule

From 2040, 600-MWe SFRs are deployed to make up for the decommissioned LWR capacities. This results in an installed SFR capacity of 66,000 MWe by 2076, when the last LWR decommissions.

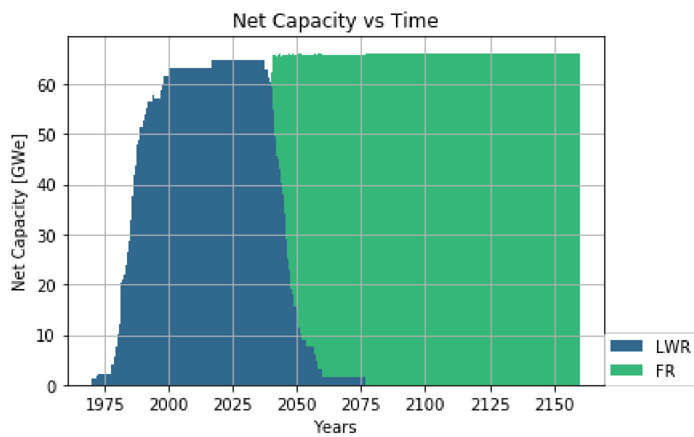

Figure 3: This plot shows the potential French transition from LWRs to SFRs. The aggressive growth of nuclear in the 1980s leads to a substantial shutdown of nuclear in the 2040s, which would be replaced by new SFRs. The net capacity is kept at a constant of 66 GWe.

Figure 3 and 4 display the French transition to SFRs over time. Figure 5 displays the total deployment scheme of the simulation. 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.

In reality, building five reactors every year is highly unrealistic. However, this analysis is to analyze material flow, claiming that, if such an aggressive deployment scheme was to take place, the SFRs would have enough fuel. More realistically, the deployment of new SFRs can be spread out by staggering scheduled decommissioning of LWRs through lifetime extensions. An analysis of the effect of LWR lifetime extension is shown in a later section.

2.4 Material Flow

The simulated fuel cycle is illustrated in fig. 6.

A source provides natural uranium, which is enriched by an enrichment facility to produce Uranium Oxide Fuel (UOX), while disposing enrichment waste (tails) to the sink. The enriched UOX fuels the LWRs and UOX waste is produced. The used fuel is sent to a pool to cool for at least 3 years [3].

The cooled fuel is then reprocessed to separate plutonium and uranium, or sent to a repository. The plutonium mixed with depleted uranium (tails) makes

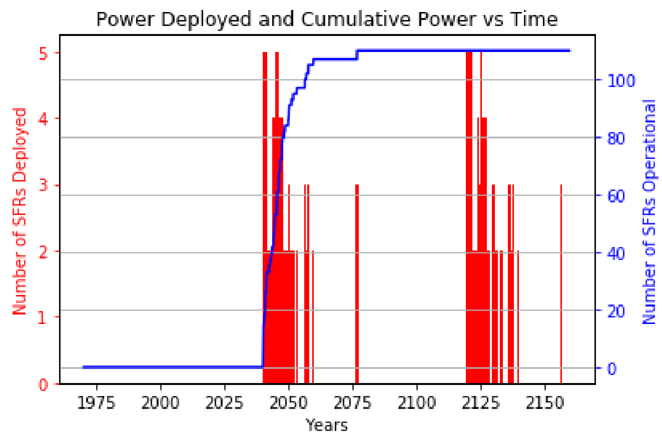

Figure 4: The deployment of SFRs in France is characterized by a period of aggressive building. An average of four reactors are built per year to make up for the decommissioned power plants built in the 1980s and 1990s. The second period of aggressive building occurs when the first generation of SFRs decommission after 80 years.

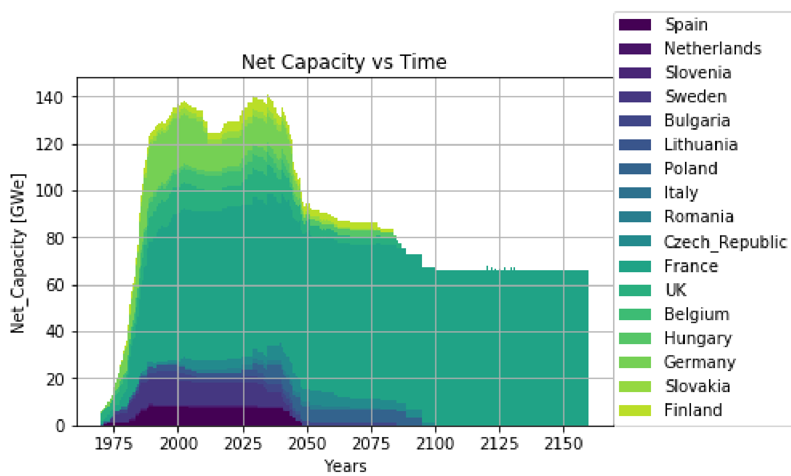

Figure 5: The total deployment scheme of the simulation. The historical operation EU reactors is followed by the French transition to SFRs.

MOX. 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 paper, reprocessed uranium may substitute depleted uranium for MOX production. In the simulations, sufficient depleted uranium existed that using reprocessed uranium was overlooked. However, further in the future where the depleted uranium inventory drains, reprocessed uranium (or, natural uranium) will need to be utilized.

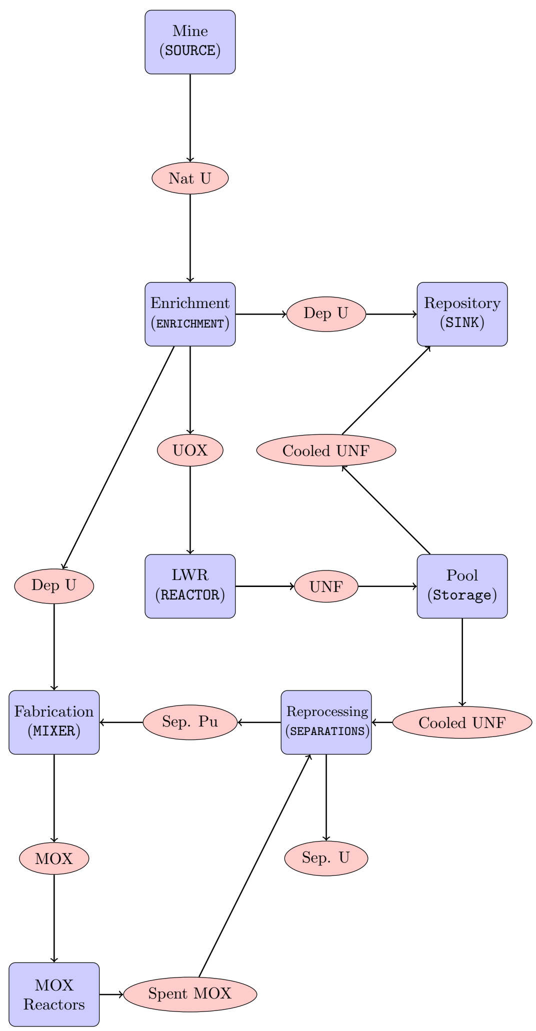

Figure 6: The blue boxes represent fuel cycle facilities, and the red ovals represent materials. The facility names in parenthesis are archetype names used in Cyclus. MOX Reactors include both French PWRs and SFRs.

3 Scenario Specifications

The scenario specifications are listed in tables 3, 4, and 5. The reprocessing and MOX fabrication capacity in France prior to 2020 is modeled after the French La Hague and MELOX site [15, 16].

Specification	**Value**
Simulation Time	1970-2160
Reprocessed Uranium Usage	None. Stockpile reprocessed U
Storage Residence Time	36 months
SFR available year	2040
Production of ASTRID fuel begins	2020

Table 3: General Simulation Specifications

Specification	**Value**
Reprocessing Capacity	91.6 MTHM of UNF per month [15]
Reprocessing Efficiency	99.8%
Reprocessing Streams	plutonium and uranium
MOX Fabrication Throughput	16.25 MTHM of MOX per month [16]
MOX Fuel Reprocessing Stage	Used MOX is not reprocessed.

Table 4: Specification for Historical Operation of EU

Specification	**Value**
Separation Efficiency	99.8 %
Reprocessing Streams	plutonium and uranium
ASTRID Fuel Reprocessing Stage	Used MOX gets reprocessed infinitely.

Table 5: Specification for French Transition to ASTRIDs

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 2 months to complete, during which the reactor is shut down. This value is acquired by averaging the historical refueling outage. The specifications are defined in Table 6 details the reactor specifications in this simulation.

Specification	**PWR [17]**	**BWR [18]**	**SFR** [7]
Lifetime [y] [1]	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 [2]	193	764	–
Batches per core	3	3	4
Initial Fissile Loading	3.1 t ^{235}U	4.2 t ^{235}U	4.9 t Pu
Fuel	UOX or MOX	UOX	MOX

Table 6: Model LWR and ASTRID specifications used for the simulations are listed, and LWRs are modified linearly for varying power capacity.

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 13). The recipe has also been used for [19].

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

[2] 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.

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

Table 7: Fresh fuel compositions used for the simulation [19, 7].

5 Results

5.1 Nuclear Material Inventory

Table 8 lists EU material inventory in 2050.

Category	**Value**	**Unit**	**Specifics**
UOX Usage	158,794	MTHM	
MOX Usage	6,671	MTHM	
Used UOX Stored	**95,161**	MTHM	UNF that is not reprocessed
Used UOX Stored (France)	**9,979**	MTHM	UNF that is not reprocessed
Tails	979,463	MTHM	
Natural U Used	1,141,916	MTHM	

Table 8: Nuclear material inventory in the EU in 2050 is summarized. The difference between total UOX usage and UOX stored is the amount that has been reprocessed for MOX. Only the stored UOX is used for ASTRID fuel production.

Figures 13 and 9 show the accumulation of tails and used fuel over time in 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 accumulate in 2050. Figure 8 shows the amount of fuel used in EU.

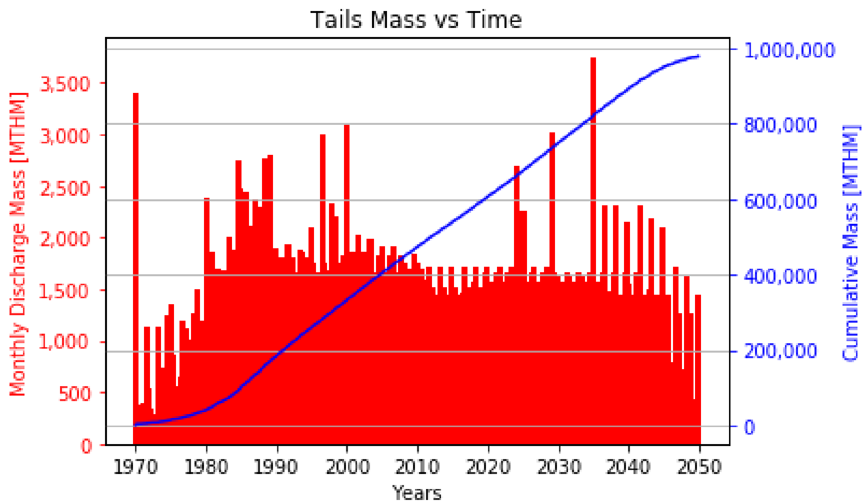

Figure 7: This plot shows the timeseries of tails mass accumulation and discharge in the EU nations. Tails mass accumulation is fairly steady, with peaks occurring when new reactors are deployed.

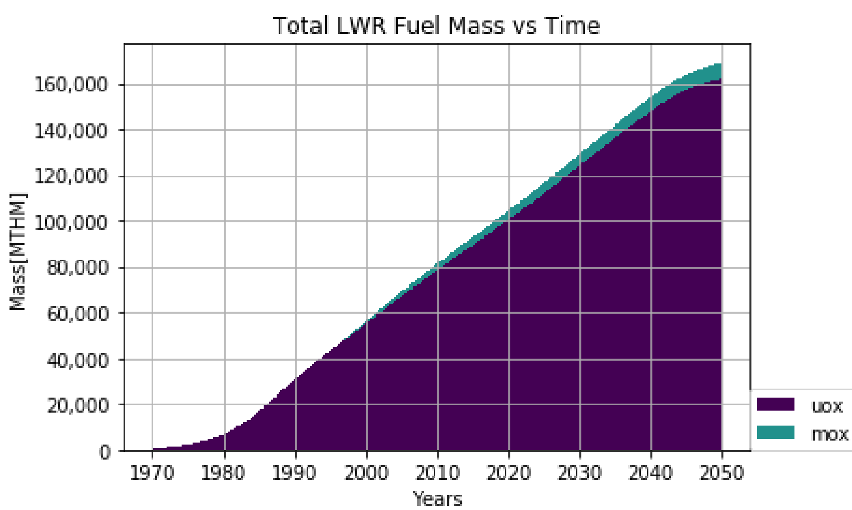

Figure 8: This plot shows the timeseries of total fuel usage in the EU nations.

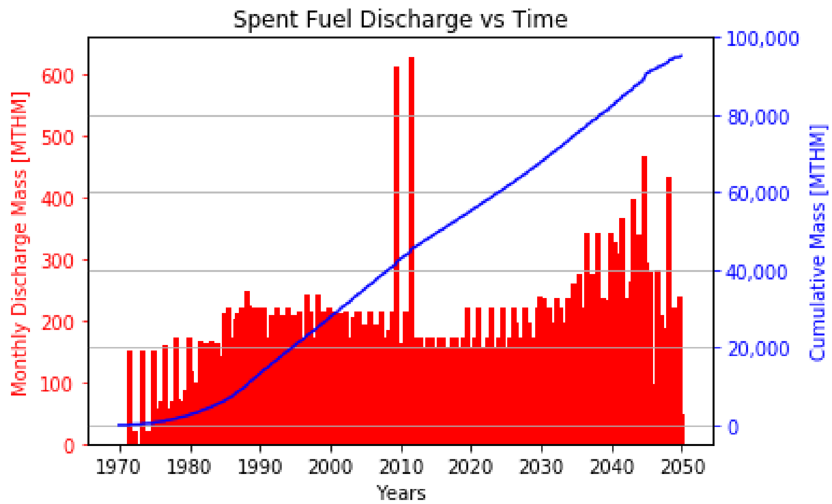

Figure 9: This plot displays the timeseries of UNF accumulation and discharge in the EU nations. The peaks are caused by decommissioning of reactors, where all the core is sent to the repository.

Isotope	Mass Fraction in Used Fuel [%]	Quantity [t]
Pu238	0.0111	10.5628
Pu239	0.518	492.93
Pu240	0.232	220.7
Pu241	0.126	119.9
Pu242	0.0487	46.3
Total	**0.9358**	**890.5**

Table 9: Plutonium From UNF Inventory. This table assumes no decay took place. The long half-life of the fissile Pu-239 (24,100 years) weakens the impact of decay on the usability of UNF.

Table 9 lists the isotope, mass fraction, and quantity of plutonium that can be obtained from the 2050 UNF inventory.

5.2 French SFR Deployment

Reprocessing UNF collected from all EU nations can start approximately 180 SFRs. With the SFR breeding ratio of over one, France can transition into a fully SFR fleet without extra construction of LWRs.

From Varaine et al. [7], a French ASTRID-type SFR of capacity 600 MWe needs 1.225 tons of plutonium a year, with an initial plutonium loading of 4.9 tons. Thus, the number of SFRs that can be loaded with the reprocessed plutonium from UNF can be estimated to $\frac{Pu\ from\ legacy\ UNF}{4.9} \approx 181$ SFRs, assuming infinite reprocessing and fabrication capacity as well as abundant depleted uranium supply.

Also, assuming that MOX can be recycled indefinitely, used MOX from an ASTRID reactor contains enough plutonium to produce a MOX fuel with the same mass, if mixed with depleted uranium. For example, used MOX from an ASTRID reactor is assumed to be 23.95% plutonium in this simulation (see table 13), whereas a fresh MOX is 22% plutonium. Separating plutonium from used MOX from an ASTRID reactor can create MOX of the mass of used MOX. The plutonium breeding ratio in this simulation is thus assumed to be ≈ 1.08.

Figure 10 shows MOX loaded in the SFRs per month. The spikes are due to initial fuel demand for new deployment of SFRs. The initial loading of new SFRs are done with the MOX created from legacy UNF. Once the deployed SFRs create enough amounts of extra plutonium, the legacy UNF is no longer used.

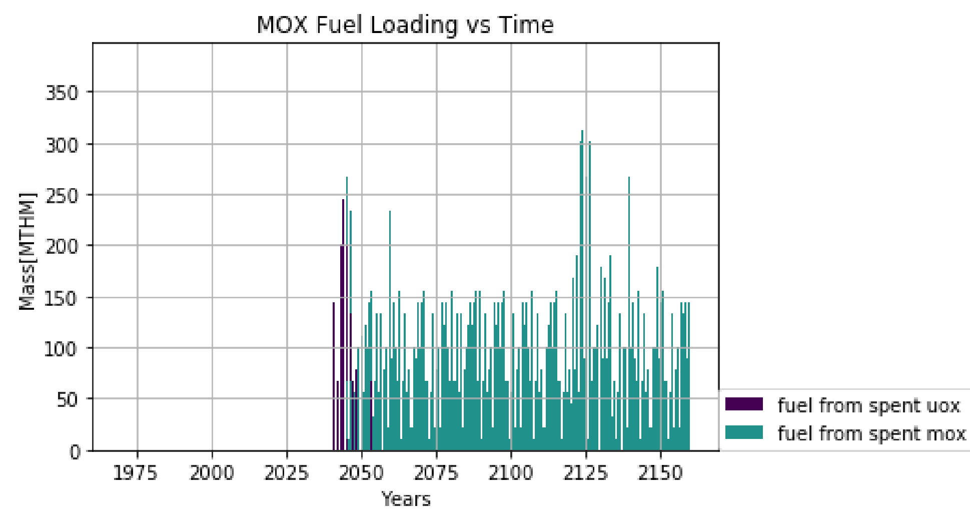

Figure 10: This plot shows the timeseries of fuel loaded into SFRs. The plot has peaks during a period of aggressive deployment of SFRs followed by an equilibrium at 150 metric ton of heavy metal (MTHM). The peaks reoccur with the deployment of the second generation of SFRs.

Figure 11 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. Table 10 lists metrics obtained from the second simulation.

Despite the large amount of initial plutonium that has to be reprocessed prior

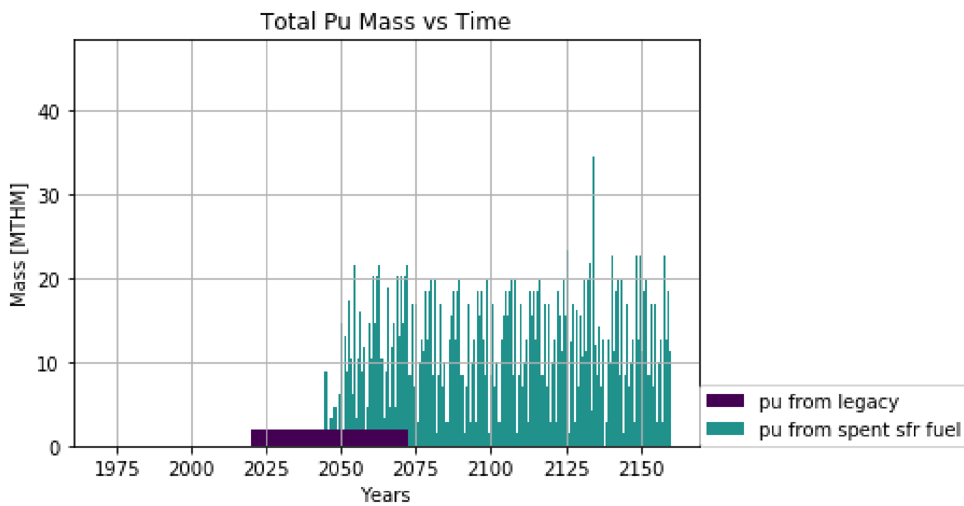

Figure 11: This plot shows the separated plutonium discharge from the reprocessing plant. The reprocessing demand for the first aggressive deployment of SFRs are lessened because the plutonium demand is met with plutonium separated from legacy UNF. The plutonium from reprocessing legacy fuel is a flat rectangle because the reprocessing throughput was set to 20 $\frac{tons}{month}$ to avoid reprocessing all the legacy in one timestep.

Category	Unit	Value
Total MOX used	MTHM	63,820
Average UOX Reprocessing	MTHM/month	**118.92**
Average Total Reprocessing	MTHM/month	**73.27**
Average Fuel Fabrication	MTHM/month	**45.2**
Total SFRs Deployed		220
Total Plutonium Reprocessed	MTHM	15,099
Total ASTRID fuel from UOX Waste	MTHM	2,923
Total ASTRID fuel from MOX Waste	MTHM	60,535
Total Tails used	MTHM	49,779
Total legacy UNF reprocessed	MTHM	**54,111**
Total Reprocessed Uranium Stockpile	MTHM	183,740
Total Raffinate	MTHM	33,806

Table 10: Listed are the metrics from the French transition to SFR scenario. The total legacy UNF reprocessed is the amount of UNF France would need for a transition into a fully SFR fleet. The tails used is around ninth of the original tails inventory from the previous simulation.

to ASTRID deployment, the 20 years of preparation of ASTRID fuel (2020-2040) 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 transition possible from the perspective of material availability, but the aggressive transition demands a significant increase in reprocessing capacity.

We varied two parameters, the lifetime of French LWRs and the breeding ratio of ASTRID reactors. The range over which we varies these parameters (table 11) sought to capture the full span of their uncertainty.

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

Table 11: Two parameters were varied for the sensitivity analysis - the lifetime of French LWRs and the breeding ratio of ASTRIDs. The parameters are increased to analyze their impact on the reprocessing demand for the transition.

6.1 Breeding Ratio

Increase in the breeding ratio of ASTRID reactors decreases the monthly average reprocessing up to five percent, as shown in fig. 12. However, average UOX reprocessing demand shows little change, because the time that reprocessed UOX is required decrease with increase in breeding ratio.

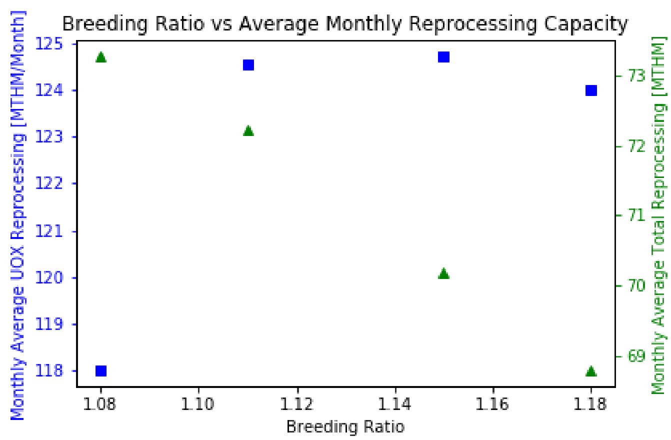

Figure 12: Increasing the breeding ratio decreases the average monthly reprocessing demand for all fuels, but the average monthly UOX reprocessing does not decrease due to a decrease in the time reprocess UOX is needed.

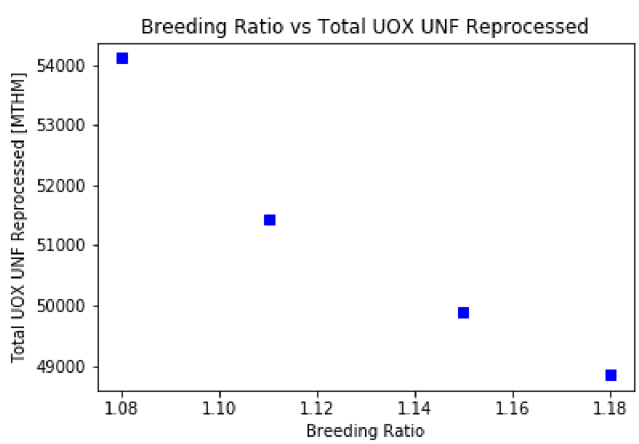

Figure 13: Increasing the breeding ratio decreases the number of total UOX UNF required. The ASTRIDs produce more plutonium, reducing the plutonium influx from reprocessed UOX.

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 less aggressive. The plutonium demand is delayed allowing the reprocessing plant more time to produce plutonium for ASTRID reactors. The extended deployment schemes are illustrated in figure 16.

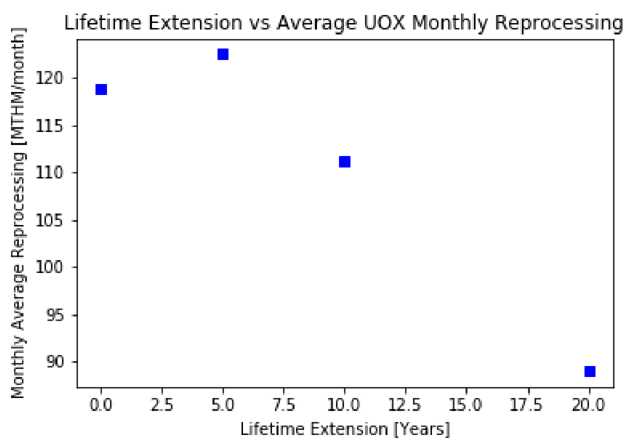

Figure 14: Increasing the lifetime of French LWRs decreases the monthly average UOX reprocessing demand.

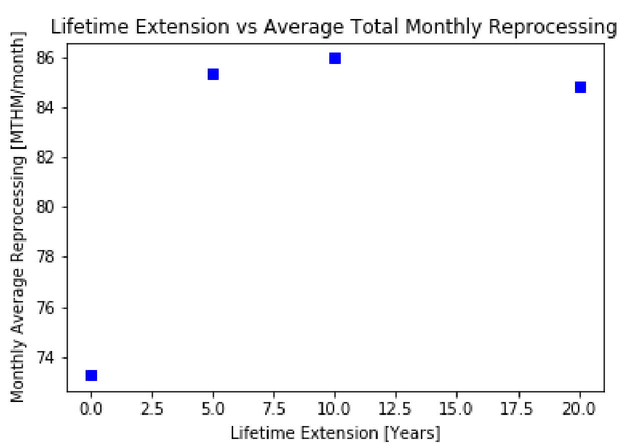

Figure 15: The shift in ASTRID deployment has little impact on the total monthly reprocessing demand.

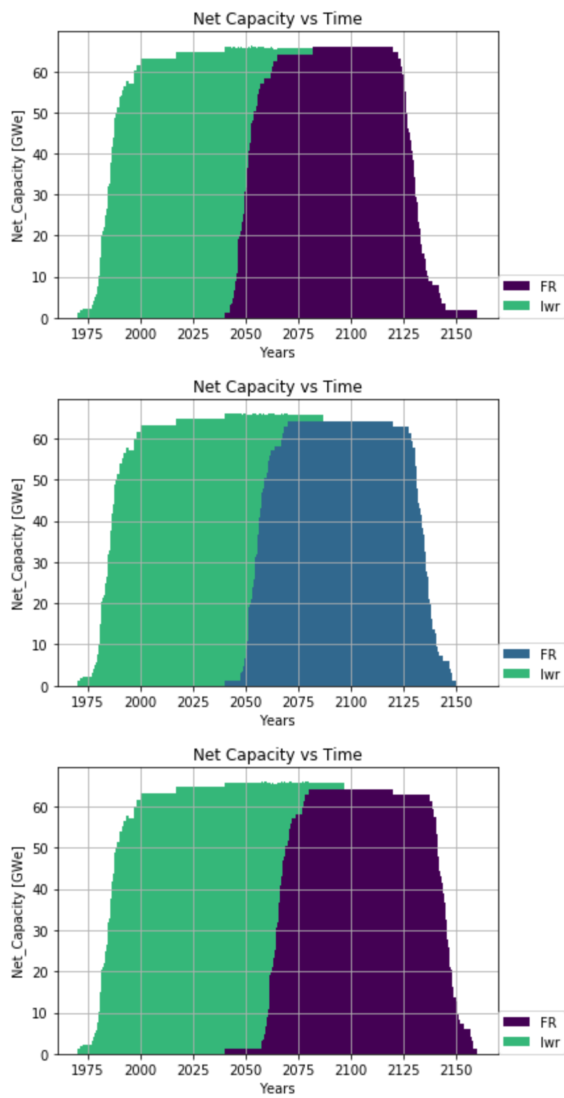

Figure 16: The shift in ASTRID deployment allows more time for the reprocessing plant to prepare the plutonium for ASTRID fuel production, lowering the average monthly reprocessing capacity.

The lifetime extension of French LWRs has little impact on the total monthly reprocessing capacity, since the amount of plutonium in the ASTRID used fuel remains the same.

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. The nations with 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 12 lists countries with the UNF inventory in 2050. We propose 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. Sweden is not considered because of its concrete waste management plan.

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**

Table 12: EU nations and their respective UNF inventory. The bolded countries' UNF inventory adds up to the required UNF amount for French SFR transition.

Though complex political and economic factors are overlooked, and various assumptions present for this scenario, this option may hold value for the EU as a nuclear community, and for France to advance into a closed fuel cycle.

References

[1] Reports of the CNE2. Technical report, Commission Nationae D'Evaluation, June 2015. URL https://www.cne2.fr/index.php/en/cne-2-2007-to-this-day.

[2] Kathryn D. Huff, Matthew J. Gidden, Robert W. Carlsen, Robert R. Flanagan, Meghan B. McGarry, Arrielle C. Opotowsky, Erich A. Schneider, Anthony M. Scopatz, and Paul P. H. Wilson. Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework. *Advances in Engineering Software*, 94:46–59, April 2016. ISSN 0965-9978. doi: 10.1016/j.advengsoft.2016.01.014. URL http://www.sciencedirect.com/science/article/pii/S0965997816300229.

[3] Frank Carre and Jean-Michel Delbecq. Overview on the French nuclear fuel cycle strategy and transition scenario studies. In *Proceedings of GLOBAL*, Paris, France, 2009. URL https://www.researchgate.net/profile/Frank_Carre/publication/273751217_Overview_on_the_French_Nuclear_Fuel_Cycle_Strategy_and_Transition_Scenario_Studies/links/55f6ace108ae07629dbae8ea.pdf.

[4] G. Martin and C. Coquelet-Pascal. Symbiotic equilibrium between Sodium Fast Reactors and Pressurized Water Reactors supplied with MOX fuel. *Annals of Nuclear Energy*, 103:356–362, May 2017. ISSN 0306-4549. doi: 10.1016/j.anucene.2017.01.041. URL http://www.sciencedirect.com/science/article/pii/S0306454916308076.

[5] David Freynet, Christine Coquelet-Pascal, Romain Eschbach, Guillaume Krivtchik, and Elsa Merle-Lucotte. Multiobjective optimization for nuclear fleet evolution scenarios using COSI. *EPJ Nuclear Sciences & Technologies*, 2:9, 2016. URL http://epjn.epj.org/articles/epjn/abs/2016/01/epjn150066/epjn150066.html.

[6] C Fazio. Study on partitioning and transmutation as a possible option for spent fuel management within a nuclear phase out scenario, October 2013. URL https://www.researchgate.net/publication/264479296_Study_on_partitioning_and_transmutation_as_a_possible_option_for_spent_fuel_management_within_a_nuclear_phase_out_scenario.

[7] Frederic Varaine, Marie-Sophie Chenaud, Philippe Marsault, Bruno Bernardin, Alain Conti, Pierre Sciora, Christophe Venard, Bruno Fontaine, Laurent Martin, and Gerard Mignot. Pre-conceptual design study of ASTRID core. June 2012. URL https://www.researchgate.net/profile/Frederic_Varaine/publication/282657288_Pre-conceptual_design_study_of_ASTRID_core/links/56166d1908ae37cfe4090bb7.pdf.

[8] Jin Whan Bae, Gyu Tae Park, and Kathryn Huff. arfc/transition-scenarios: Synergistic Spent Nuclear Fuel Dynamics Within the European Union,

August 2017. URL https://zenodo.org/record/858671#.WahAzHWGPdJ. DOI: 10.5281/zenodo.858671.

[9] Matthew J. Gidden. An agent-based modeling framework and application for the generic nuclear fuel cycle.

[10] Kathryn D. Huff, Massimiliano Fratoni, and Harris Greenberg. Extensions to the cyclus ecosystem in support of market-driven transition capability. In *Transactions of the American Nuclear Society*. American Nuclear Society.

[11] IAEA. PRIS - Home, September 2017. URL https://www.iaea.org/pris/.

[12] World Nuclear Association. Nuclear Power in the European Union - World Nuclear Association, February 2017. URL http://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx.

[13] Paul L. Joskow and John E. Parsons. The Future of Nuclear Power After Fukushima. Working Paper, MIT CEEPR, February 2012. URL http://dspace.mit.edu/handle/1721.1/70857.

[14] Michael T. Hatch. *Politics and Nuclear Power: Energy Policy in Western Europe*. University Press of Kentucky, January 2015. ISBN 978-0-8131-6307-9. Google-Books-ID: TrwfBgAAQBAJ.

[15] Mycle Schneider and Yves Marignac. *Spent nuclear fuel reprocessing in France*. 2008. URL http://www.psr.org/nuclear-bailout/resources/spent-nuclear-fuel.pdf.

[16] D. Hugelmann and D. Greneche. MELOX fuel fabrication plant: operational feedback and future prospects. In *MOX Fuel Cycle Technologies for Medium and Long Term Deployment (Proc. Symp. Vienna, 1999), C&S Papers Series No*, volume 3, pages 102–108, 1999. URL http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/31/062/31062323.pdf#page=110.

[17] Balendra Sutharshan, Meena Mutyala, Ronald P Vijuk, and Alok Mishra. The AP1000tm Reactor: Passive Safety and Modular Design. *Energy Procedia*, 7:293–302, January 2011. ISSN 1876-6102. doi: 10.1016/j.egypro.2011.06.038. URL http://www.sciencedirect.com/science/article/pii/S1876610211015475.

[18] David Hinds and Chris Maslak. Next-generation nuclear energy: The ESBWR. *Nuclear News*, 49(1):35–40, 2006.

[19] P. Wilson. The Adoption of Advanced Fuel Cycle Technology Under a Single Repository Policy. Technical report, University of Wisconsin – Madison, 2009.

8 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 13: Spent Fuel Compositions