Synergistic Spent Nuclear Fuel Dynamics Within the European Union

Jin Whan Bae, Kathryn Huff, Clifford Singer[1]

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

1 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 using Used Nuclear Fuel (UNF) from other EU nations for French transition into a SFR fleet without additional construction of LWRs. A Cyclus simulation ran from 1950 to 2050 for EU 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 European Union (EU) nations. These simulations demonstrate that France can avoid deployment of additional LWRs by accepting UNF from other EU nations.

reorder:
... feasibility of enabling a French transition to an SFR fleet by using ...

?

2 Introduction

We used Cyclus to analyze the future nuclear inventory in the European Union. 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 in 2050, and propose a potential collaborative strategy of used fuel management. A major focus of this paper is to determine the extent to which France has an incentive to receive all the UNF from EU nations to create Mixed Oxide Fuel (MOX). The MOX created will fuel French transition to a SFR fleet and allow France to avoid building additional LWRs.

Past research, focused solely on France, typically assumes that additional LWRs, namely European Pressurized Reactors (EPRs) supply the UNF required to produce MOX [3, 4, 5]. Studies also exist on implementation of partitioning and transmutation in a regional (European) context, with Accelerator-Driven Systemss (ADSs) and Gen-IV reactors [6]. There is little attention paid to reprocessing legacy UNF from other EU nations to produce MOX for the newly

ambiguous. is all past research focused on france or is all of the research that focuses on france also making these assumptions?

To clarify move the commas...

...little recent work considers...

This sentence is too long.

Just say synergistic international spent fuel arrangements.

This is a strange way to phrase it...

Usually:
- "Other recent work implements"
- "Implementation of P&T has also been considered..."

deployed SFRs. The present work finds that this collaborative strategy can reduce the need to construct additional LWRs in France.

3 Methodology

sounds weird
they didn't
run themselves

present tense, but this happened in the past.

Two Cyclus simulations ran for this paper. The first simulation calculates the mass and composition of used fuel and tails accumulated by EU nations from 1970 to 2050. All EU nations with the exception of France adopts a once-through fuel cycle. France can reprocess used Uranium Oxide Fuel (UOX) and MOX to produce MOX from reprocessed plutonium and depleted uranium (tails).

This was pointed out in #36. Verb-subject plurality mismatch.

After obtaining the UNF inventory of all EU in 2050, the second simulation runs. ~~where~~ In it, the UNF inventory is reprocessed and fabricated as fuel for the newly deployed SFR reactors. SFRs are modeled after the ASTRID breeder reactor [7]. The ASTRID-type SFRs make up for the decommissioned capacity of LWRs in France, to remain a constant installed capacity of 66,000 MWe up to 2160. Eventually, the MOX created from recycled MOX fuels the entire fleet of 110 SFRs.

"all of the EU" might sound better

again, a diagram would improve this.

I think you mean "maintain" or "retain" or "preserve"

All scripts and data used in this paper are available in [8].

3.1 Cyclus

Cyclus is an agent-based fuel cycle simulation framework, meaning that each reactor, reprocessing plant, and fuel fabrication plant is modeled as agents. At each timestep (one month), agents put out their bids for materials (supply and/or demand) and exchange with one another. This is done using a market-like mechanism called the dynamic resource exchange [9]. Each material item has a quantity, composition, name, and a unique identifier for output analysis. A Cyclus input file contains archetypes, which are fuel cycle facilities with pre-defined parameters, that are deployed in the simulation as `facility` agents. An `Institution` agent deploys `facility` agents according to a user-defined deployment scheme at pre-defined timesteps. The `Institution` agent is part of a `Region` agent, which can contain multiple `Institution` agents.

subject verb plurality mismatch

here, a figure of the computational workflow is appropriate

there is probably a more exciting verb.
What happens if the DRE is the subject rather than the object?

nope. not all archetypes become facility agents. some are Inst, Region...

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.

3.2 EU Historical Deployment Scheme

history is not based on PRIS. PRIS is based on history.
I think you're trying to say the PRIS database informed simulation deployment.

The historical nuclear operation of EU nations is based on the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database [10]. The database is imported as a csv file, to populate the simulation with deployment information, listing the country, reactor unit, type, net capacity (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 wrote up a python script to generate a Cyclus input file from the csv file, which lists the individual reactor units as agents.

again, if the workflow is going to be discussed in detail, create a diagram.

"wrote up" "written up" are COLLOQUIAL. One wonders "up where?" Instead, say implemented, developed, scripted, etc...

Projections of future reactor deployment in this simulation is based on assessment of analyses from references such as PRIS for reactors planned for construction [10], the World Nuclear Association and two other papers for future plans in EU nations [11, 12, 13]. 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.

I have mentioned this before.

Figure 1 displays the timeseries of installed capacity in EU nations.

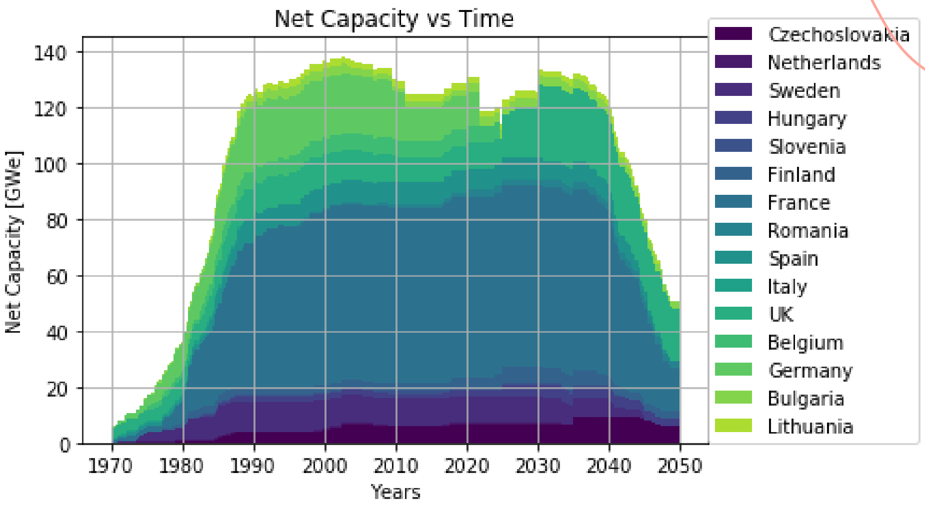

Figure 1: The timeseries of installed nuclear capacity in the EU are separated by `Regions` in Cyclus. The sudden drops in capacity are caused by nuclear phaseout plans by nations like Germany and Belgium.

3.3 French SFR Deployment Schedule

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

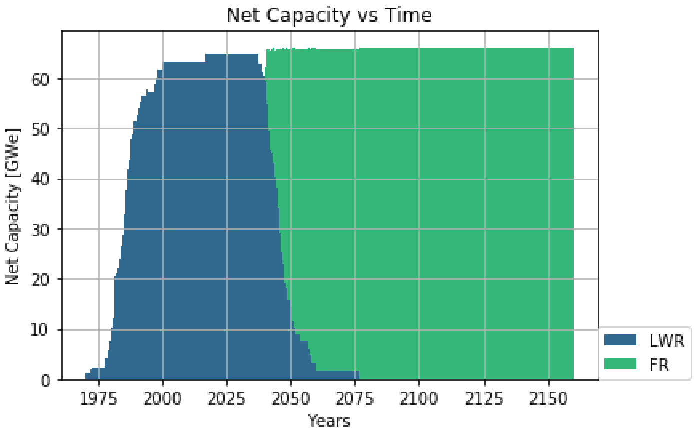

Figure 2: This plot shows the potential French transition from LWRs to SFRs. The aggressive growth of nuclear in the 1980s leads to a substantial shutdown of nuclear in the 2040s, which would be replaced by new SFRs. The net capacity is kept at a constant of 66 GWe.

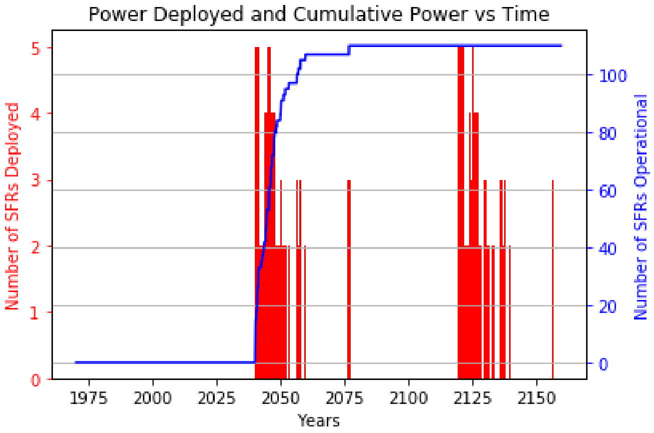

Figure 3: The deployment of SFRs in France is characterized by a period of aggressive building. An average of four reactors are built per year to make up for the decommissioned power plants built in the 1980s and 1990s. The second period of aggressive building occurs when the first generation of SFRs decommission after 80 years.

Figure 2 and fig. 3 display the French transition to SFRs over time. 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.

3.4 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 fuel, a reference depletion calculation from ORIGEN is used (see table 10). The recipe has also been used for [14].

3.5 Material Flow

The simulation follows the model fuel cycle, illustrated in fig. 4, where a source provides natural uranium, which is enriched by an enrichment facility to produce UOX, while disposing enrichment waste (tails) to the sink facility. The enriched UOX fuels the LWRs and UOX waste is produced. The used fuel is sent to a pool to cool for 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 MOX. The 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.

4 Scenario Specifications

This paper shows results from two separate simulations. The first simulation is a historical operation of EU reactors, with a realistic reprocessing and MOX fabrication capacity, modeled after the French La Hague and MELOX site [15, 16]. The second simulation is an ideal French Transition scenario to SFR, where an ASTRID-type SFR replaces the decommissioned capacity of LWRs in France. The specifications of the simulations are listed in tables 1 and 2.

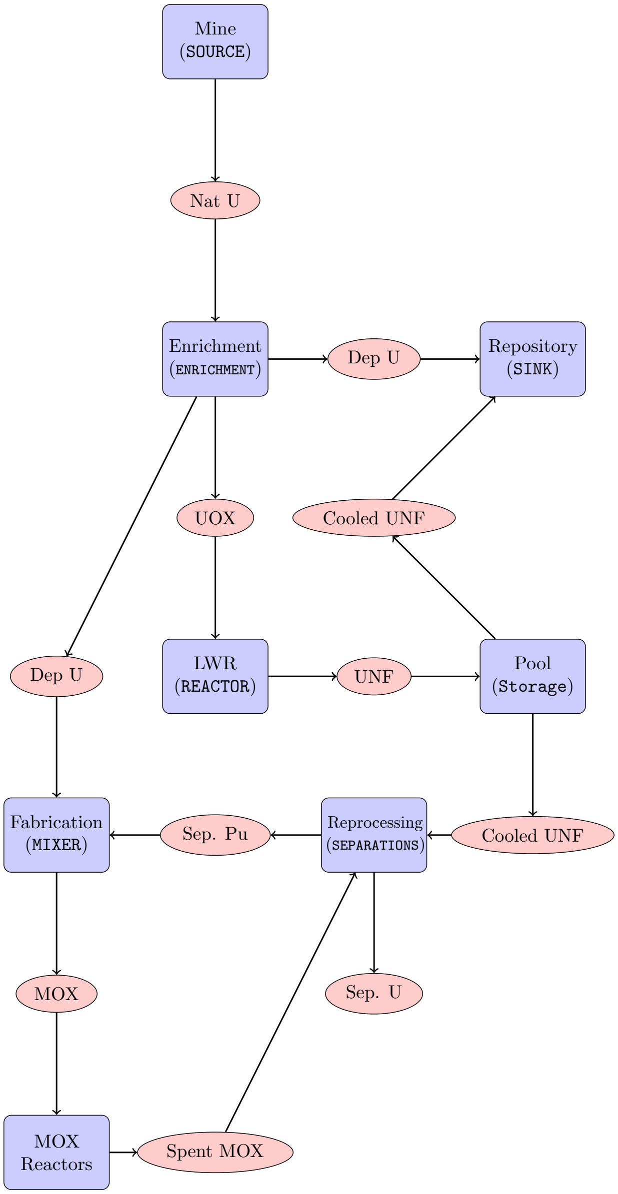

Figure 4: The blue boxes represent fuel cycle facilities, and the red ovals represent materials. The facility names in parenthesis are archetype names used in Cyclus. MOX Reactors include both MOX LWRs and SFRs.

Specification	**Value**
Simulation Time	1970-2050
Reprocessing Capacity	91.6 MTHM of UNF per month [15]
Reprocessing Efficiency	99.8%
Reprocessing Streams	Plutonium and Uranium
MOX Fabrication	9% Reprocessed Pu + 91% Depleted U
MOX Fabrication Throughput	16.25 MTHM of MOX per month [16]
MOX Fuel Reprocessing Stage	Used MOX gets reprocessed infinitely.
Reprocessed Uranium Usage	None. Stockpile reprocessed U

Table 1: Specification for Historical Operation of EU Case

Specification	**Value**
Simulation Time	1970-2160
SFR Available Year	2040
UOX Reprocessing Capacity	20 tons per timestep
MOX Reprocessing Capacity	∞
Reprocessing and Fabrication Begins	2020
Separation Efficiency	99.8 %
Reprocessing Streams	plutonium and uranium
Used UOX and Depleted U Inventory	125,453 MTHM (From first simulation)
Additional Used UOX or Depleted U	None
MOX Fabrication	11% Reprocessed Pu + 89% Depleted U
MOX Fabrication Throughput	infinite
MOX Fuel Reprocessing Stage	Used MOX gets reprocessed infinitely.
Reprocessed Uranium Usage	None. Stockpile reprocessed U.

Table 2: Specification for French Transition to SFR Case

5 Reactor Specifications

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

For LWRs, a linear core size model was assumed 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) discharge. 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 3.

For the SFR, a model design is adopted from Marsault-Marie-Sophie et al. [7]. The specifications are defined in table 4.

Specification	**PWR**	**BWR**
Lifetime	60 years unless shutdown prematurely	
PWR Cycle Time	18 months	
PWR Refueling Outage	2 months	
Fuel Mass per Assembly	523.4 kg	180 kg
Burnup	51 GWd/tons	
Assembly per Core	193 for 1,000 MWe	764 for 1,000 MWe
Assembly per Batch	1/3 of the core	
Fuel	UOX, MOX	UOX

Table 3: LWR Specifications

Specification	**Value**
SFR Cycle Time	12 months
SFR Refueling Outage	2 months
Fuel Mass per Batch	11,136 kg
Batch per Core	4
Power Output	600 MWe
Lifetime	80 years
Fuel	MOX (89% Tailings, 11% Separated Pu)

Table 4: SFR ASTRID Specifications [7]

6 Future Nuclear Projections

The future of nuclear energy in EU nations is organized in the table by the World Nuclear Association [11]. We assumed that all the planned constructions are completed without delay or failure. Also, the newly constructed LWRs are assumed to have a lifetime of 60 years.

Section 6 lists the reactors that are currently planned or under construction.

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 5: Power Reactors under construction and planned. Replicated from [11].

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 6.

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.
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.
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 6: Future Nuclear Programs of EU Nations [11]

7 Results

7.1 Historical Operation of EU Reactors

Table 7 lists the metrics obtained from the first simulation. The following values are the EU inventory and history at year 2050, and will be reprocessed in the second simulation.

Category	**Unit**	**Value**	**Specifics**
Total UOX Usage	MTHM	163,826	
Total MOX Usage	MTHM	6,560	
Total Used UOX Stored	MTHM	125,453	UNF that is not reprocessed
Total Used MOX Stored	MTHM	3,438	UNF that is not reprocessed
Total Tailings	MTHM	975,938	
Total Natural U Used	MTHM	1,146,420	

Table 7: Listed are the metrics from the historical nuclear operation of EU nations. The difference between total UOX usage and UOX stored is the amount that has been reprocessed for MOX. Only the stored UOX is used in the second simulation.

Figures 5 and 7 show the timeseries of tails and used fuel inventory accumulation in EU. Figure 6 shows the amount of fuel used in EU.

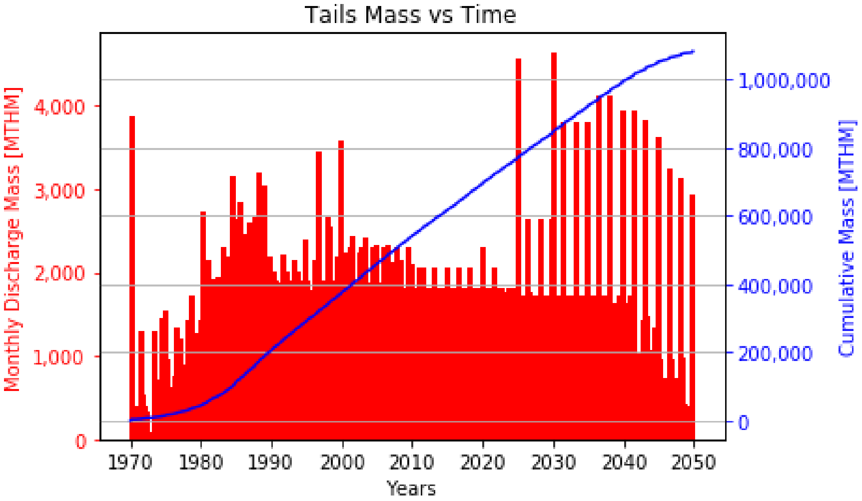

Figure 5: This plot shows the timeseries of tails mass accumulation and discharge in the EU nations. Tails mass accumulation is fairly steady, with peaks occurring when new reactors are deployed.

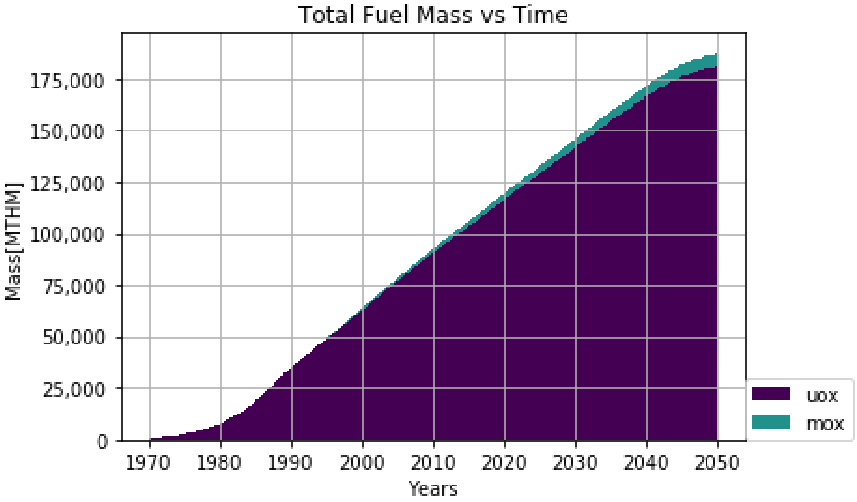

Figure 6: This plot shows the timeseries of total fuel usage in the EU nations.

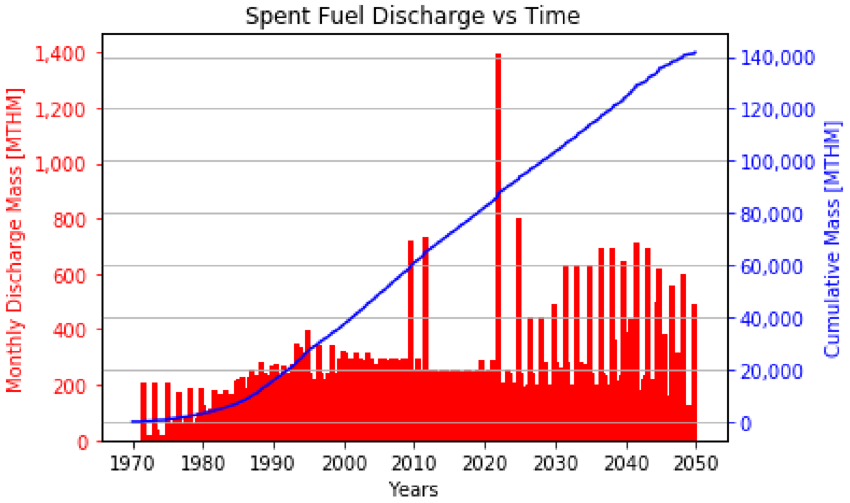

Figure 7: This plot displays the timeseries of UNF accumulation and discharge in the EU nations. The peaks are caused by decommissioning of reactors, where all the core is sent to the repository.

Isotope	**Mass Fraction in Used Fuel** [%]	**Quantity** [t]
Total	0.9358	1,173
Pu238	0.0111	13.9
Pu239	0.518	649.8
Pu240	0.232	291.05
Pu241	0.126	158.07
Pu242	0.0487	61.09

Table 8: 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 8 lists the isotope, mass fraction, and quantity of plutonium that can be obtained from the 2050 UNF inventory.

7.2 French SFR Transition Scenario

Reprocessing UNF collected from all EU nations can start approximately 240 SFRs, which is more than enough for two generations of 66GWe SFR fleet. 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 $\frac{Pu\ from\ legacy\ UNF}{4.9} \approx 240$ 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 12.6% plutonium in this simulation (see table 10), whereas a fresh MOX is 11% 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 ≈ 1.145.

Figure 8 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.

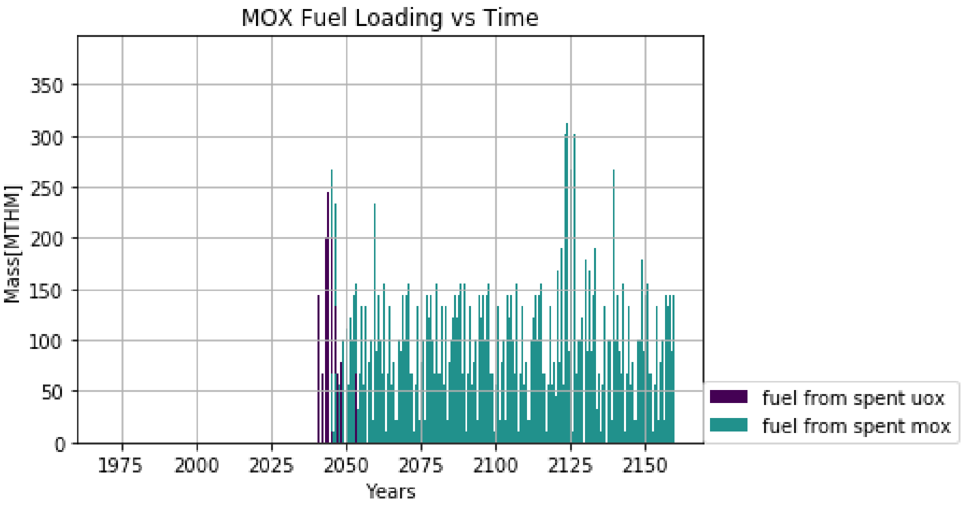

Figure 8: This plot displays the timeseries of fuel loaded into SFRs. The initial purple bars denote that the fuel is from reprocessing the previously used UOX inventory. The peaks coincide with the new deployment of SFRs.

Figure 10 shows the amount of raffinate (minor actinides, fission products) over time. The spikes in the waste discharge is due to large influx of used fuel from decommissioned SFRs. Figure 9 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. Table 9 lists metrics obtained from the second simulation.

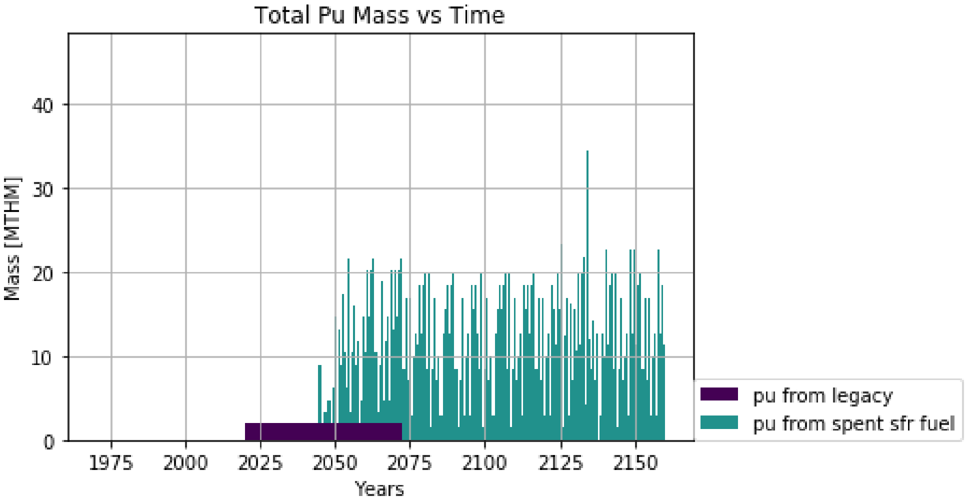

Figure 9: This plot shows the separated plutonium discharge from the reprocessing plant. The plutonium from reprocessing legacy fuel is a flat rectangle because the reprocessing throughput was set to 20 $\frac{tons}{month}$ to avoid reprocessing all the legacy in one timestep.

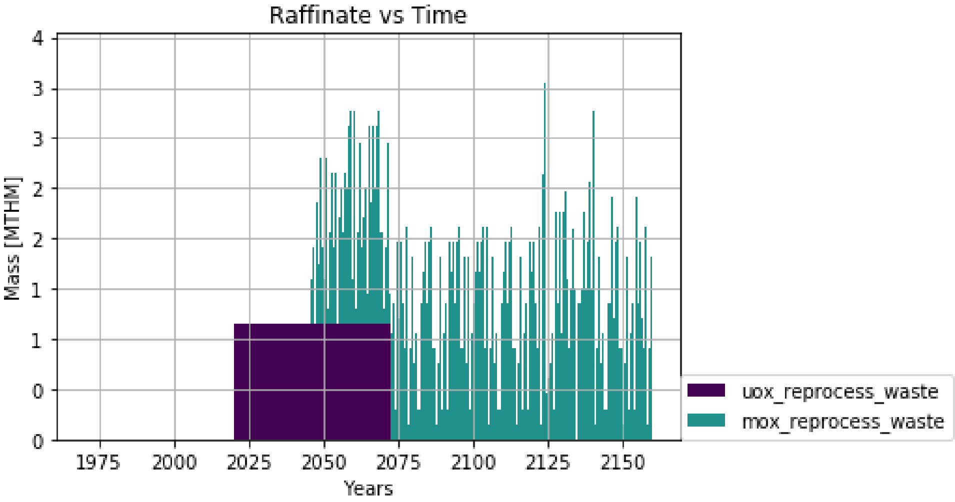

Figure 10: This plot displays raffinate discharge from each reprocessing plant. The plutonium from reprocessing legacy fuel is a flat rectangle because the reprocessing throughput was set to 20 $\frac{tons}{month}$ to avoid reprocessing all the legacy in one timestep.

Category	Unit	Value
Total MOX used	MTHM	127,200
Total SFRs Deployed		220
Total Plutonium Reprocessed	MTHM	16,200
Total MOX from UOX Waste	MTHM	6,570
Total MOX from MOX Waste	MTHM	121,070
Total Tails used	MTHM	116,153
Total legacy UNF reprocessed	MTHM	77,082
Total Reprocessed Uranium Stockpile	MTHM	226,197
Total Reprocess Waste	MTHM	16,352

Table 9: 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.

8 Discussion

This work demonstrated that France can transition into a fully SFR fleet with installed capacity of 66,000 MWe by 2076, if France receives UNF from other EU nations. Supporting the SFR fleet would require a reprocessing capacity of 250 MTHM per month, and a fabrication capacity of 300 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 all 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 reuse of used fuel from other nations will allow France to meet their MOX demand without new construction of LWRs.

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] CNE2. 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 Gidden, Robert Carlsen, Arrielle Opotowsky, Olzhas Rakhimov, Anthony M. Scopatz, and Paul P. H. Wilson. Agent-based dynamic resource exchange in CYCLUS. Kyoto, Japan, 2015. JAEA. doi: 10.11484/jaea-conf-2014-003. URL `http://inis.iaea.org/Search/search.aspx?orig_q=RN:47042686`.

[10] PRIS IAEA. *Nuclear Power Reactors in the World.* Number 2 in Reference Data Series. IAEA, Vienna, Austria, 2017. URL `http://www-pub.iaea.org/books/IAEABooks/12237/Nuclear-Power-Reactors-in-the-World`.

[11] 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`.

[12] 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`.

[13] 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.

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

[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`.

9 Fresh and Used Fuel Composition

Isotope	Fresh UOX Fuel	Spent UOX Fuel (BU: 51 $\frac{GWdth}{MTHM}$)	Fresh SFR Fuel	Spent SFR Fuel
He4		9.474E-07		7.827E-06
Ra226		9.788E-14		5.151E-14
Ra228		2.750E-20		4.904E-21
Pb206		5.574E-18		1.210E-18
Pb207		1.685E-15		1.892E-16
Pb208		3.688E-12		5.875E-11
Pb210		3.023E-19		8.143E-18
Th228		8.475E-12		1.004E-10
Th229		2.727E-12		4.065E-12
Th230		2.625E-09		2.139E-09
Th232		4.174E-10		4.425E-11
Bi209		6.607E-16		2.600E-14
Ac227		3.096E-14		4.840E-15
Pa231		9.246E-10		1.300E-10
U232		0.000		0.000
U233		2.213E-09		5.528E-09
U234	0.000	0.000		0.000
U235	0.032	0.007	0.002	0.000
U236		0.005		0.000
U238	0.968	0.920	0.887	0.808
Np237		0.000		0.000
Pu238		0.000	0.001	0.001
Pu239		0.006	0.060	0.085
Pu240		0.002	0.027	0.027
Pu241		0.001	0.014	0.003
Pu242		0.000	0.005	0.001
Pu244		2.864E-08	1.508E-07	5.461E-09
Am241		6.442E-05		0.001
Am242m		8.533E-07		7.961E-05
Am243		0.000		0.000
Cm242		2.589E-05		5.331E-05
Cm243		0.000		3.242E-06
Cm244		8.561E-05		0.000
Cm245		5.721E-06		3.936E-05
Cm246		7.295E-07		1.434E-05
Cm247		0.000		5.317E-07
Cm248		7.691E-10		0.000
Cm250		4.280E-18		6.407E-15
Cf249		1.649E-12		6.446E-10
Cf250		2.041E-12		6.703E-11
Cf251		9.865E-13		1.903E-12
Cf 252		6.579E-13		4.014E-14
H3		8.584E-08		1.747E-07
C14		4.057E-11		
C Other				
Kr81		4.216E-11		8.038E-12
Kr85		3.444E-05		2.950E-05
Kr Other		0.000		0.000
Sr90		0.001		0.001
Sr Other		0.000		0.000
Tc99		0.000		5.391E-05
Tc Other		0.000		0.002

Table 10: Fresh and Spent Fuel Compositions