Key Parameters and Metrics of Fuel Cycle Transitions

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Abstract

This work identifies important metrics and parameters in nuclear fuel cycle transition scenarios. First, the agent-based fuel cycle simulator CYCLUS is benchmarked against ORION (ORION). Second, important fuel cycle transition metrics are identified by extensive literature review. Third, I run sensitivity studies on two regional fuel cycle transition scenarios (U.S. and France) to identify important parameters and how they affect the metrics. [results]

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Background

Nuclear energy provides the largest amount of carbon-free energy in the United States. However, several problems remain with nuclear energy, such as nuclear waste. From the 1950s, the United States have been trying to commission a geological waste disposal site for its 'spent' fuel. However, even after 60 years, this endeavor has yet to accomplish of substantial value.

Recent advances in nuclear technology produced a multitude of new reactor designs which experiment with new forms of fuel that deviate from an enriched uranium oxide fuel. Noble designs such as fast reactors and molten salt reactors allow various types of fuel forms and fuel cycles to be considered. These advances in new technology fueled the dream of a 'closed' fuel cycle, where little to no supply of natural material is required, that 'used' fuel from one reactor, after processing, could fuel another reactor.

However, transitioning the nuclear fuel cycle requires great investment, from constructing new reactors to new fuel processing infrastructure. Thus, it seems highly unlikely that, given the current circumstances such as the economic competitiveness of nuclear, uprising of natural gas, an administration unenthusiastic towards sustainability, that this transition will happen soon.

In 2017, American Nuclear Society (ANS) announced closing the fuel cycle as one of its grand challenge, stating that doing so will allow the U.S. to 'obtain maximum value and minimizing environmental impact from using nuclear fuel' [1]. The report also says that identifying the 'most promising' fuel cycles based on clear evaluation metrics is crucial towards this effort, as it was done in the Fuel Cycle Evaluation and Screening Study report [2].

However, the Fuel Cycle Evaluation and Screening Study report evaluates fuel cycles in static conditions rather than in a dynamic fuel cycle transition scenario. Thus, it is important to question the important metrics when considering a nuclear fuel cycle transition - what will 'nudge'[**?**] the public to support such a great effort ? What incentives do we have to 'close' the fuel cycle?

Additionally, we need to identify important parameters in fuel cycle transition, so that resources can be focused on the more important parameters, such as reprocessing research or advanced reactor development.

These series of studies attempts to answer those questions with a combination of literature review, fuel cycle simulations and sensitivity studies.

Chapter 4

Introduction

The goal of this paper is to identify and quantify the importance of key parameters in fuel cycle transition scenarios and their impacts on important fuel cycle transition metrics. I follow several steps to accomplish this goal.

First, I benchmark CYCLUS, the fuel cycle simulator that is used for this study, against ORION [**?**] with the Used Nuclear Fuel Storage Transportation and Disposal Analysis Resource and Data System (UNF-ST&DARDS) database [**?**]. The UNF-ST&DARDS database contains detailed data on the U.S. legacy nuclear fuel assemblies, and contains the assemblies' burnup and composition. This allows me to check the fidelity of CYCLUS with a previously-benchmarked code like ORION.

Then, key metrics for fuel cycle transition is identified through literature review and discussion. I then extract important metrics in the perspective of the general public.

Then, I identify important fuel cycle parameters by performing a parameter sweep on two real scenarios to visualize the sensitivity of the parameters on the key metrics.

In a glance, this study sounds very similar to the OECD-NEA study in 2015 by Hyland et al. [3], but this study provides unique insight in that it explores the sensitivity of incentives to transition, not just fuel cycle metrics.

Also, this study attempts to apply the similar sensitivity study in real-world regional scenarios, such as France and the U.S. Note that the purpose of this study is to identify important parameters, not to make a suggestion as to what any government should do.

Chapter 5

Literature Review

Since the scope of this study is broad and interdisciplinary, I read through numerous literature to gain insight into the general consensus of advanced fuel cycles and completed studies.

5.1 Metrics and Parameters

An evaluation of a complex system like the nuclear fuel cycle requires clear, quantitative metrics. There have been many honest efforts by expert groups to identify and quantify the key metrics of fuel cycles, such as the Evaluation and Screening Study [2]. However, the metrics from the E&S study are not quite appropriate for transition scenarios, for the evaluation and simulation were done in static fuel cycles. This work intends to find important metrics in a transition scenario. For reference, the metrics identified in the Evaluation and Screening study is listed in table 5.1.

While metrics are the outputs of a fuel cycle transition, the parameters are inputs to a fuel cycle transition scenario, and are subject to variability. The varying parameters impacts the metrics, which causes the uncertainty in the outcome of a fuel cycle. Key parameters in fuel cycle transitions have been identified by the OECD-NEA study on uncertainty [3]. In this study, some of these parameters (organized in table 5.1) are swept over a range to quantify its effect on the metrics. As mentioned in the introduction, the correlations are with static metrics, not what parameters are important for incentivizing transition.

Publications from MIT, while taking a more reluctant stance on the need to transition into a 'closed' fuel cycle, provides broader metrics like economics, safety, waste management, or energy independence. The report's criteria to compare fuel cycles is replicated in table 5.1.

Table 5.1: Metrics considered in Evaluation and Screening Study [2].

Category	**Parameter**
Nuclear Waste Management (per energy)	Mass of UNF + high level waste (HLW)
	Activity of UNF + HLW at 100 years
	Activity of UNF + HLW at 100,000 years
	Mass of depleted uranium (DU) + reprocessed uranium (RU)
	Volume of Low Level Waste (LLW)
Proliferation Risk / Material Security	Material Attractiveness
	Targets for Malevolent Use
Environmental Impact (per energy)	Land use
	Water use
	CO2 released
	Radiological exposure - worker dose
Resource Utilization (per energy)	Natural U required
Others	Safety
	Development and Deployment Risk
	Institutional Issues
	Financial Risk and Economics

Table 5.2: Parameters considered in uncertainties study in OECD-NEA study [3].

Category	**Parameter**
Fissile Inventory and Consumption	Fissile Burnup
	Fresh fuel composition
	Cycle length
	Breeding Grain
Waste	Initial minor actinide (MA) content in fuel
	Recuperation Rate (MA)
	Reprocessing Efficiency
	Enrichment Tail
Fabrication and Reprocessing	Minimum cooling time
	Fabrication Time
	Reprocessing begin time
	Reprocessing capacity
General	Reactor Lifetime
	Nuclear Energy Demand
	FR introduction time
	Rate of transition

Table 5.3: Criteria to Compare Fuel Cycles from the MIT report [4]

Criteria	**Technical**	**Institutional**
Economics	Overnight Capital Costs	Financing, Regulation
Safety	Risk Assessment	Regulatory structure
Waste Management	Waste form, time of storage	Regulation, Societal view
Environment	Water / land consumption	Greenhouse gas regulation
Resource utilization	Uranium costs	Security of supply
Nonproliferation	Separated plutonium	Institutional arrangements for fuel

5.2 Economics

Currently, most fuel cycles in the world are once-through, with the exception of France's Mixed Oxide Fuel (MOX) reprocessing for its LWRs. Because there has not been a commercial advanced fuel cycle, with large-scale reprocessing and fast reactor operation,there are large cost uncertainties are associated with fuel cycle strategies [5].

Also, with the now abundant uranium resources and a possibility of uranium seawater extraction, prospective uranium fuel costs are relatively low. This led to a general consensus that 'closed' cycles are more expensive than once-through-cycles [5**?** , 6].

With a high risk and uncertainty associated with advanced fuel cycles, and the fact that taking the risk to transition may cost more, economics does not seem to be a dominant incentive for transitioning into an advanced fuel cycle.

Chapter 6

CYCLUS

CYCLUS is an agent-based fuel cycle simulation framework [?], 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 [?]. `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 [?] 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.

Chapter 7

Method

To quantify the important metrics for incentives to transition into a closed fuel cycle, I take the following steps:

1. Benchmark CYCLUS against ORION and UNF-ST&DARDS
2. Identify key fuel cycle transition metrics
3. Identify key fuel cycle parameters
4. Perform parameter sweep on key parameters on real scenarios
   (a) United States transition scenario
   (b) France transition scenario
5. Analyze sensitivity of parameters on key metrics
6. Visualization and discussion

7.0.1 Material Flow

The fuel cycle is represented by a series of facility agents whose material flow is illustrated in figure 7.1, along with the CYCLUS archetypes that were used to model each facility. In this diagram, MOX Reactors include both French Pressurized Water Reactors (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. [**?**].

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

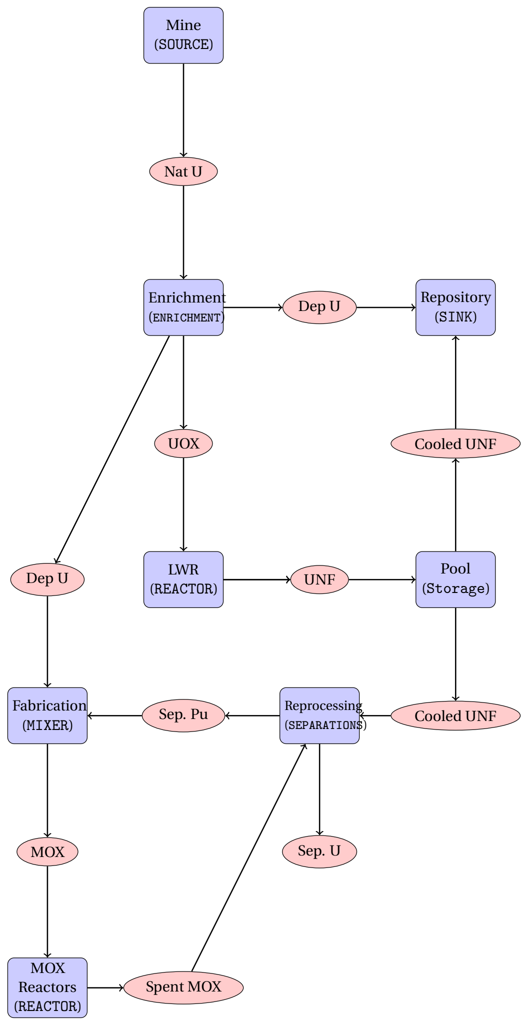

Figure 7.1: Fuel cycle facilities (blue boxes) represented by CYCLUS archetypes (in parentheses) pass materials (red ovals) around the simulation.

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.

Chapter 8

France

The stated long term plan for nuclear deployment in France targets a technology transition to SFRs[**?**]. However, the current inventory of French UNF is insufficient to fuel that transition without building new LWRs.

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

To simulate this cooperative scenario, I simulated the entire EU region and all its nuclear reactor operating history and UNF accumulation up to the nearest foreseeable future. Then, France would take as much UNF it needs to transition into a fully SFR fleet without building additional LWRs.

This chapter includes the results and comparison of two simulations:

1. France transitions into a fully SFR fleet by taking other EU nations' UNF

2. France maintains its current fuel cycle with LWR MOX reprocessing.

8.0.1 EU Deployment Schedule

The International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database [**?**] contains worldwide reactor operation history. The computational workflow in this work, shown in Figure 8.1, 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 (Megawatt 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 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 [**?**], the World Nuclear Association [**?**], and literature concerning the

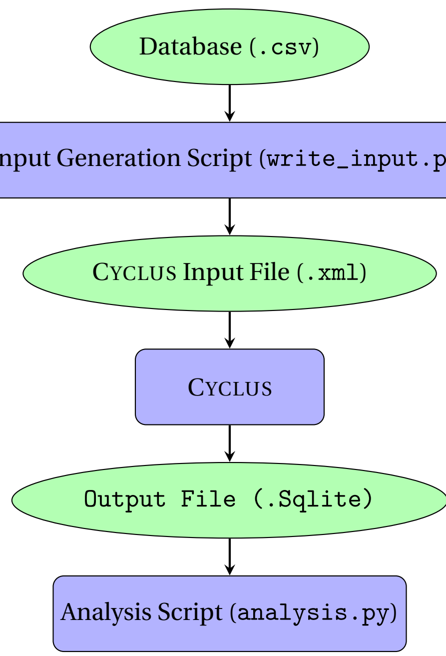

Figure 8.1: Green circles and blue boxes represent files and software processes, respectively, in the computational workflow.

future of nuclear power in a global [?] and European context [?]. Existing projections extend to 2050.

Table 8.1 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 8.1: Power reactors under construction and planned. Replicated from [**?**].

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:

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

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

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

The growth trajectory and specific plan of each nation in the EU is listed in Table 8.2.

[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 PWRs in the simulation.

Table 8.2: Projected nuclear power strategies of 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.

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. 8.2 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.

8.0.2 French SFR Deployment Schedule

Figure 8.3 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 8.4 shows the deployment required to support the transition in fig. 8.3. 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 8.5 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.

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

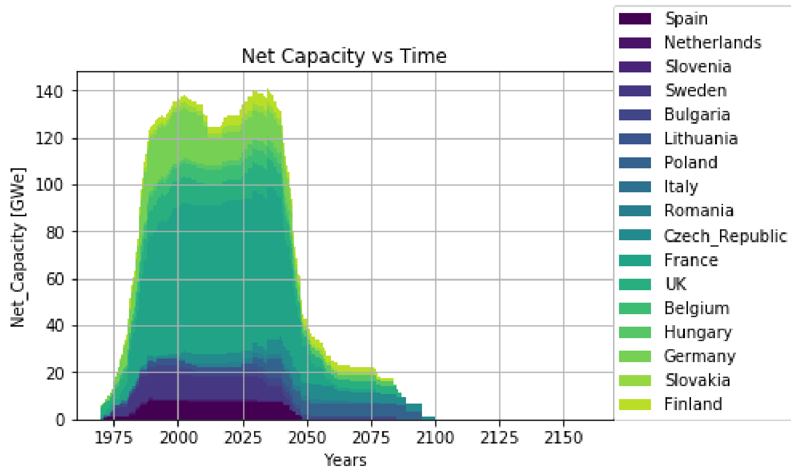

Figure 8.2: Installed nuclear capacity in the EU is distinguished by `Regions` in CYCLUS.

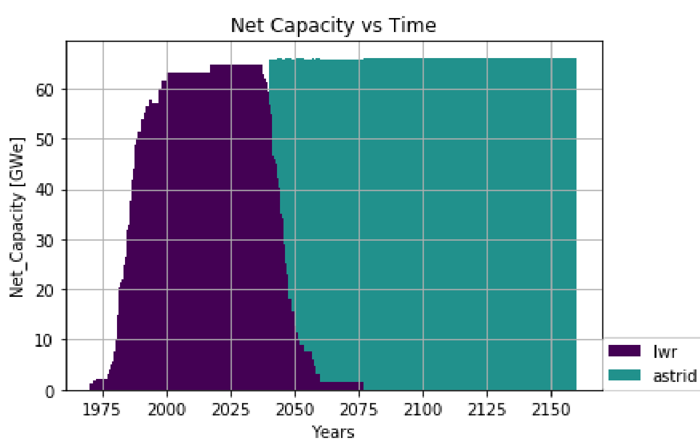

Figure 8.3: The potential French transition from LWRs to SFRs when assisted by UNF from other EU nations.

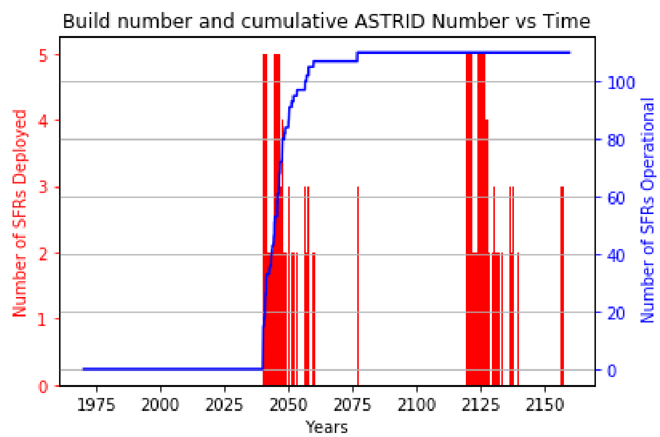

Figure 8.4: The deployment of SFRs in France is characterized by a period of aggressive building.

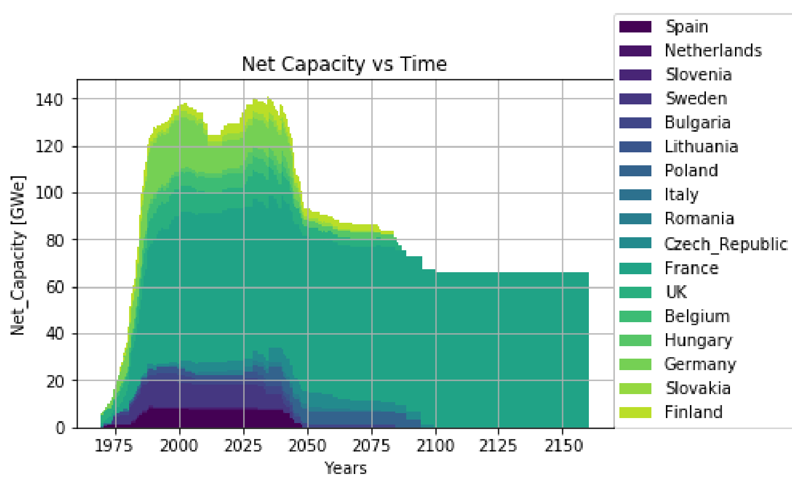

Figure 8.5: The total deployment scheme we simulated relies on UNF collaboration among nations.

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.

8.0.3 Scenario Specification

The scenario specifications defining the simulations presented in this work are listed in table 8.3. The reprocessing and MOX fabrication capacity in France prior to 2020 is modeled after the French La Hague and MELOX sites [**?** **?**].

Table 8.3: 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 [**?**]	$\frac{\text{metric tons of UNF}}{month}$
Reprocessing capacity after 2020	183.2	$\frac{\text{metric tons of UNF}}{month}$
LWR MOX fabrication throughput	16.25 [**?**]	$\frac{\text{metric tons of MOX}}{month}$
ASTRID MOX fabrication throughput	No limit (∞)	$\frac{\text{metric tons of MOX}}{month}$
LWR MOX recycling	Not reprocessed	-
ASTRID MOX recycling	∞-pass	-

8.1 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 8.4 which details the reactor specifications in this simulation. LWR specifications are modified linearly for varying power capacity.

Table 8.4: Baseline LWR and ASTRID simulation specifications.

Specification	**PWR [?]**	**BWR [?]**	**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

8.1.1 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 **??**). ORIGEN calculates buildup, decay, and processing of radioactive materials [**?**]. This recipe recipe has also been used for repository performance modeling [**?**].

Table 8.5: Fresh fuel compositions in the simulation [**?** 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

[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.

8.1.2 Results - Transition Scenario

This section displays the simulation results if France utilized UNF from other EU nations to fuel the transition into a fully ASTRIDs fleet.

Nuclear Fuel Material Inventory

Table 8.6 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 8.6 distinguishes the UOX in the simulation either stored or reprocessed to create MOX.

Table 8.6: 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 8.6 and 8.8 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 8.7 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. 8.8, the peaks are caused by reactor decommissioning which triggers all the batches in the final reactor core to be sent to the repository.

French SFR Deployment

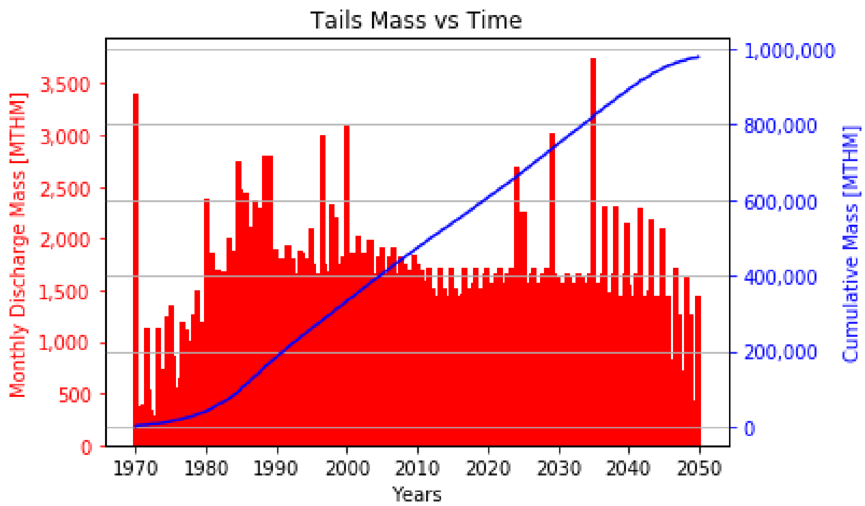

Figure 8.6: Simulated accumulation of tails in the EU is shown as a function of time.

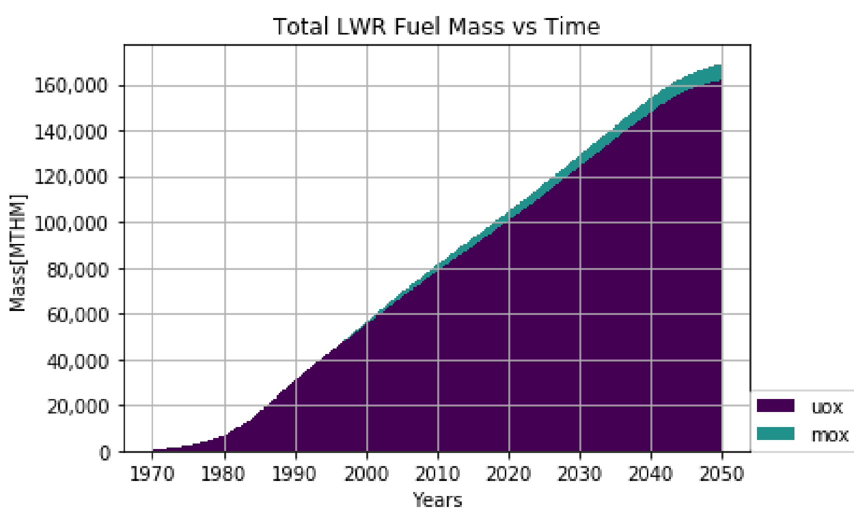

Figure 8.7: Simulated total EU fuel useage is shown as a function of time.

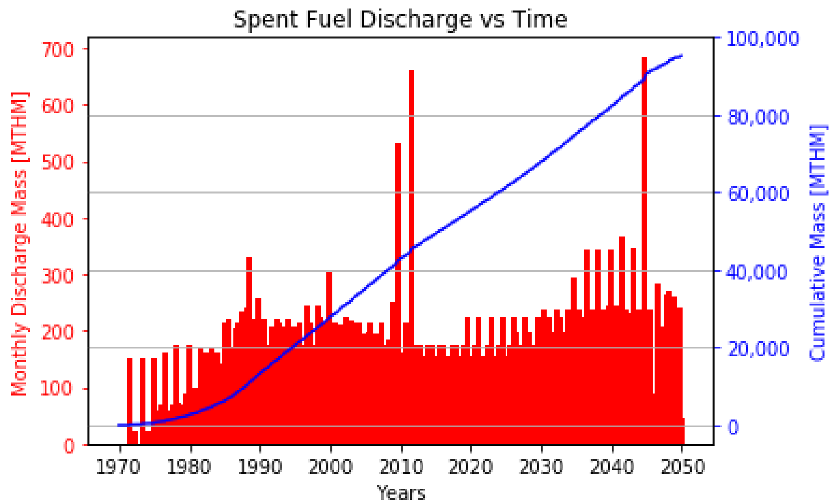

Figure 8.8: Simulated EU UNF accumulation and discharge is shown as a function of time.

Reprocessing the UNF collected from all EU nations can provide the initial cores for approximately 180 SFRs. Table 8.7 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 8.7: 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 **??**), whereas fresh MOX is 22% plutonium. The plutonium breeding ratio in this simulation is thus assumed to be ≈ 1.08.

Figure 8.9 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 [**?**].

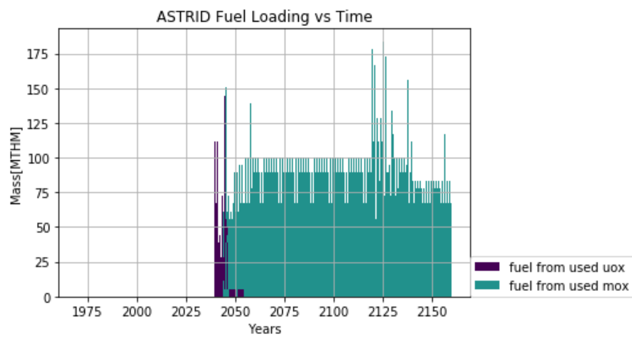

Figure 8.9: Fuel loaded into SFRs was simulated in discrete batches.

Figure 8.10 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.

Table 8.8 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.

Conclusion

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.

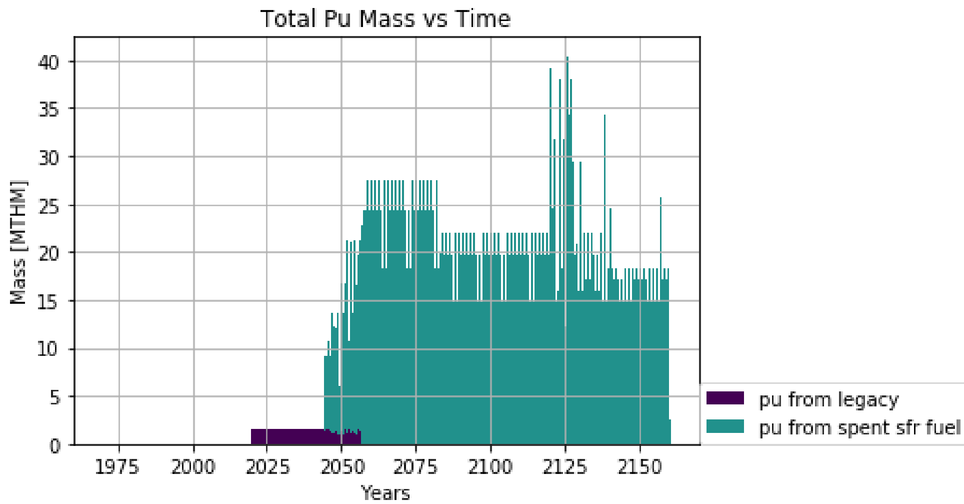

Figure 8.10: The separated plutonium discharge from the reprocessing plant in $\frac{\text{MTHM}}{\text{month}}$.

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 8.9 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 8.9. 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 [**?**], 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 8.8: 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

Table 8.9: 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**

8.1.3 Results - Parameter Sweep

8.1.4 Results - Sensitivity Study

Chapter 9

United States

The United States have been the forerunner of nuclear energy, with a current installed capacity of about 100 GWe. With its size and long history of nuclear energy, the United States have accumulated about $70,000$ MTHM of UNF. The United States' historical nuclear operation and inventory is tracked using CYCLUS and is compared with benchmarked results from ORION and the UNF-ST&DARDS database. The UNF-ST&DARDS database is a comprehensive, controlled source of UNF information, including dry cask attributes, assembly data, and economic attributes [**?**]. With the successful benchmark, the simulation is be extrapolated to the future. Two separate simulations, one with transition into a 'closed' fuel cycle, and the other once-through, is run.

The problem with modeling the U.S. transition scenario is that the U.S. does not have a defined advanced reactor, whereas France has a solid plan to transition into ASTRIDs.

This chapter includes the results and comparison of two simulations:

1. The United States transitions into a 'closed' fuel cycle with breeder reactors and reprocessing.

2. The United States maintains once-through cycle.

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