Synergistic Spent Nuclear Fuel Dynamics Within the European Union

French Transition into SFRs

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Outline

Background

- France
    - Preparation for a transition from Light Water Reactors (LWRs) to Sodium-Cooled Fast Reactors (SFRs) [1]
    - Additional LWR construction to supply Plutonium for SFR transition
- Most EU nations do not have a repository for Used Nuclear Fuel (UNF)

Summary

By taking UNF from other EU nations, France can transition into a fully SFR fleet (66 GWe capacity) without additional construction of LWRs.

- Transition to 110 Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID)-type SFRs (Capacity 66 GWe)
- Collaborative approach benefits both sides

Literature Review

Past research is mostly on:

- French transition to SFRs after additional construction of European Pressurized Reactors (EPRs) [3, 12, 5]
- partitioning and transmutation in a regional (European) context [4]

There is little research on managing UNF in a cooperative manner in advanced fuel cycles.

Cyclus

CYCLUS is the next generation agent-based nuclear [8] fuel cycle simulator.

- Flexibility to users and developers through a dynamic resource exchange solver
- user-developed agent framework
- low barrier to entry for new users and developers
- expanding ecosystem

Deployment Timeline for EU historical operation

Historical operation and predictions are made using references such as International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) [10], World Nuclear Association [2] and papers on the future of nuclear power [11, 6].

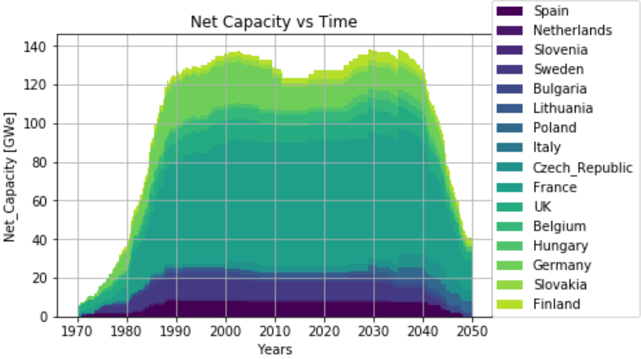

Figure 1: Timeseries of installed nuclear capacity in European Union (EU).

Simulated European Deployment

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 1: Future Nuclear Programs of EU Nations [2]

Deployment Timeline for French Transition

110 SFRs (66 GWe) are deployed by 2076.

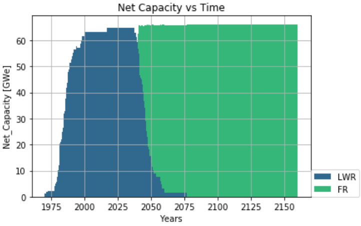

Figure 2: French Transition into an SFR Fleet

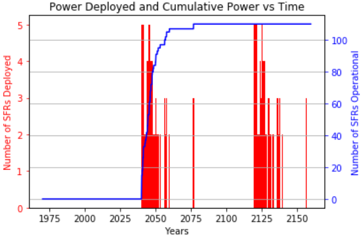

Figure 3: Deployment of French SFRs and total installed capacity

Method

CYCLUS simulation of EU nations (1970 - 2160) with French Transition into an SFR fleet from 2040.

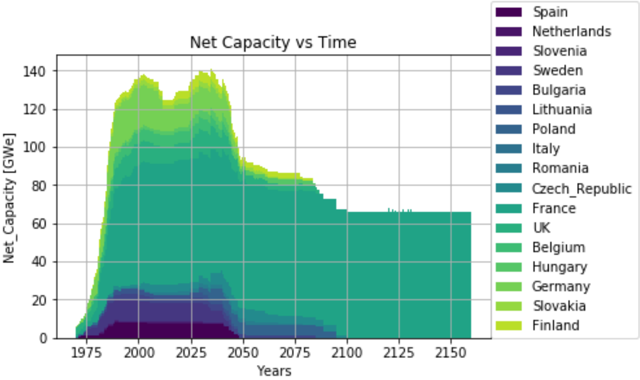

Figure 4: Total Deployment Scheme of EU nations

Outline

Assumptions

- Fuel cycle facility parameters (throughput, availability)
- Compositions of fresh and spent fuel
- Material flow

Assumptions

- SFR technology available for deployment in 2040.
- Reactor construction is always completed on time.
- Separated uranium is unused and stockpiled.
- LWRs have a lifetime of 60 years, unless shut down prematurely.
- SFRs have a lifetime of 80 years.

For the French Transition:

- Reprocessing and fabrication begins 2020
- French nuclear capacity remains constant at 66,000 MWe

Material Flow

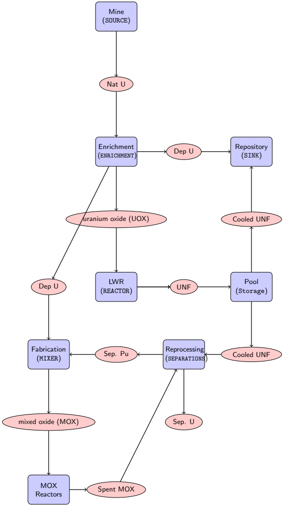

Figure 5: Model Fuel Cycle with MOX Reprocessing

EU Nuclear Opearations ˜2050

Deployment and Reactor data from IAEA PRIS. Reprocessing plant and fabrication plant modeled after French La Hague and MELOX site [13, 9].

Parameter	Value
Simulation Start Year	1970
Simulation End Year	2160
Reprocessing Capacity	91.6 [MTHM UNF per month] [13]
Reprocessing Efficiency	99.8 [%]
Reprocessing Streams	Plutonium and Uranium
MOX Fabrication	9% Reprocessed Pu + 91% Depleted U
MOX Fabrication Throughput	16.25 [MTHM MOX per month] [9]
MOX Fuel Reprocessing Stage	Used MOX is not reprocessed.
Reprocessed Uranium Usage	None. Stockpile reprocessed U

Table 2: Parameter for Historical Operation of EU Case (˜2040)

French Transition to SFRs ˜2160

Parameter	Value
SFR Available Year	2040
Reprocessing and Fabrication Begins	2020
Separation Efficiency	99.8 [%]
Reprocessing Streams	plutonium and uranium
ASTRID fuel Fabrication	22% Reprocessed Pu + 78% Depleted U
ASTRID Fuel Reprocessing Stage	Used fuel gets reprocessed infinitely.
Reprocessed Uranium Usage	None. Stockpile reprocessed U.

Table 3: Parameter for French Transition to SFR

Reactor Parameters - LWRs

Number of assemblies are linearly adjusted from a model 1,000 MWe reactor.

Parameter	Units	PWR [14]	BWR [7]
cycle time	months	18	
refueling outage	months	2	
Fuel mass per assembly	kg	446	180
Burnup	GWd/MTHM	51	
Num. of assem. per core	(for 1,000 MWe)	193	764
Num. of assem. per batch	(for 1,000 MWe)	62	254
Fuel		UOX, MOX	UOX

Table 4: LWR Parameters

Reactor Parameters - ASTRID-type SFRs

Parameter	Value
SFR Cycle Time	12 months
SFR Refueling Outage	2 months
Fuel Mass per Batch	5,568 kg
Initial Pu Loading	4.9 Tons
Breeding Ratio	1.08
Batch per Core	4
Power Output	600 MWe
lifetime	80 years
Fuel	MOX (78% Tails, 22% Separated Pu)

Table 5: SFR ASTRID Parameters [15]

Outline

1. Background
    - Motivation
    - Method and Specfications
    - Future Projections
2. Scenario Specification
    - Assumptions
    - Simulation Parameters
3. Results
    - EU Nuclear Operation until 2050
    - French Transition Scenario 2160
4. Conclusion

Historical Operation of EU Reactors

Category	**Value**	**Unit**	**Specifics**
Total UOX Usage	176,600	MTHM	
Total MOX Usage	6,953	MTHM	
Total Used UOX Stored	110,013	MTHM	UNF that is not reprocessed
Total Used UOX Stored (France)	12,943	MTHM	UNF that is not reprocessed
Total Tails	1,059,210	MTHM	
Total Natural U Used	1,235,810	MTHM	

Table 6: Simulation Results for Historical Nuclear Operation of EU Nations

Tails and UNF Inventory

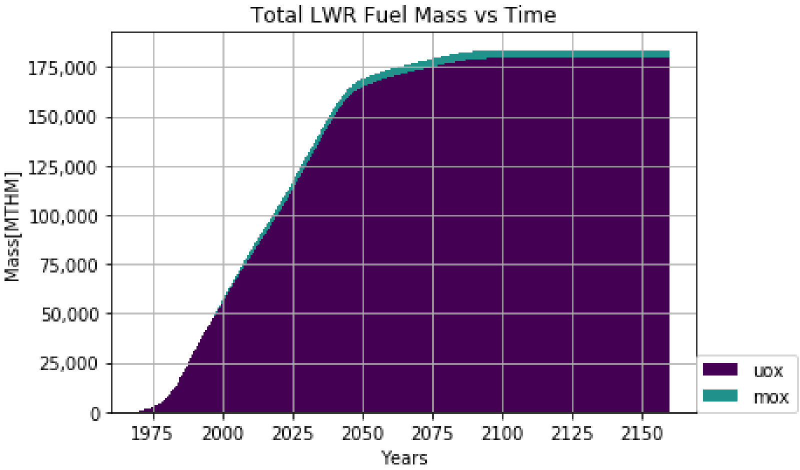

Figure 6: Timeseries of Total Fuel Usage in EU.

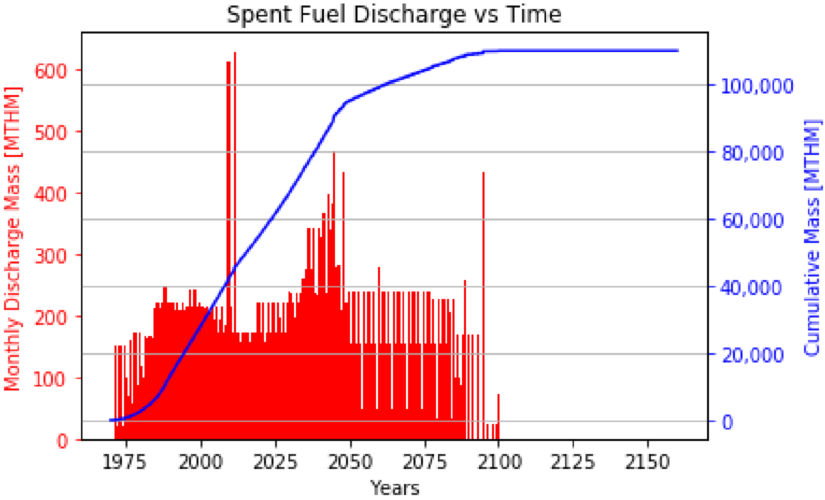

Figure 7: Timeseries of Used Nuclear Fuel in EU.

SFR Deployment with Legacy UNF

- Reprocessing UNF from all EU nations can start approx. 202 SFRs. (UOX UNF has about 0.9% pu)
- $\frac{Pu\ \ from\ \ legacy\ \ UNF}{4.9} \approx 202$
- Initial Pu loading of 4.9 tons for ASTRID-type SFR [15].
- Two generations of 66GWe SFRs $=$ 220 SFRs

Frech Transition Results

Category	**Unit**	**Value**
Total MOX used	MTHM	63,820
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 7: SFR Simulation Results

Material Flow in French Transition Scenario

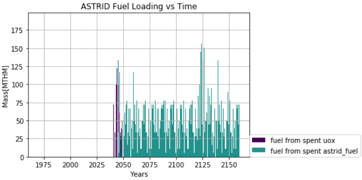

Figure 8: Timeseries of fuel loaded into SFRs, separated by origin

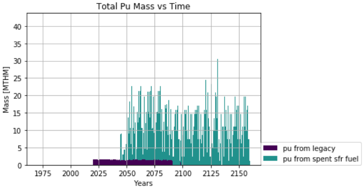

Figure 9: Separated plutonium discharge from Reprocessing Plant

Material Flow in French Transition Scenario

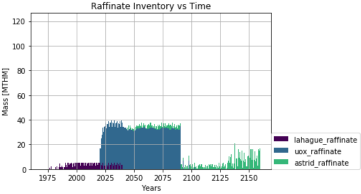

Figure 10: Timeseries of raffinate discharge from reprocessing plants

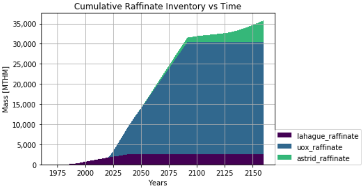

Figure 11: Cumulative raffinate inventory separated by origin

Outline

Conclusion

France can transition into a fully SFR fleet with installed capacity of 66GWe by 2076.

- Reprocessing Capacity : $\approx 140 \frac{MTHM}{month}$
- Fabrication Throughput: $\approx 150 \frac{MTHM}{month}$

Discussion

Total Legacy UNF reprocessed: **54,111 MTHM**
France + Spain + Italy + Belgium + Germany = 53,809 MTHM

Nation	**Growth Trajectory**	**UNF in 2050 [MTHM]**
UK	Aggressive Growth	53,188
Poland	Aggressive Growth	6,714
Hungary	Aggressive Growth	4,768
Finland	Modest Growth	7,528
Slovakia	Modest Growth	3,446
Bulgaria	Modest Growth	3,930
Czech Rep.	Modest Growth	7,583
Slovenia	Modest Reduction	765
Netherlands	Modest Reduction	539
Lithuania	Modest Reduction	2,644
France	**Modest Reduction**	**12,943**
Spain	**Modest Reduction**	**9,771**
Italy	**Modest Reduction**	**583**
Belgium	**Aggressive Reduction**	**6,644**
Sweden	Aggressive Reduction	16,035
Germany	**Aggressive Reduction**	**23,868**

Table 8: Growth Trajectory and UNF Inventory of EU Nations.

Discussion

- Most EU nations do not have an operating repository or management plan
- Some nations need a repository for complete decommission & nuclear phase-out
- Strong incentive for collaboration

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University Programs

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