Investigation of Impacts of Deploying Reactors Fueled by High Assay Low Enriched Uranium

Final Defense

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Outline

The US is looking to develop supplies of HALEU

- Multiple new reactor designs require High Assay Low Enriched Uranium (HALEU) fuel, which allows for:
    - Longer cycle time
    - Increased capacity factor
    - Higher burnup

Table 1: Categories of uranium enrichment by weight fraction of ^{235}U.

Category	Weight fraction (%)
Depleted	$<$0.711
Natural	0.711
LEU	0.711-20
HALEU	5-20
HEU	$\geq$20

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- The US does not have any commercial supplies of HALEU
- There are two methods to produce HALEU:
  - Enrichment of natural uranium
  - Recovery and downblending of HEU

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The nuclear fuel cycle

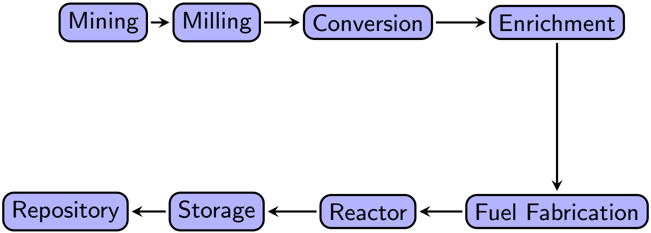

Figure 1: Overview of the Nuclear Fuel Cycle.

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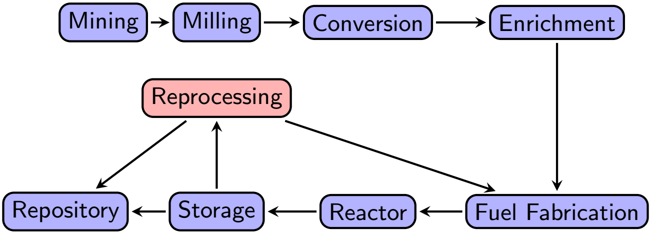

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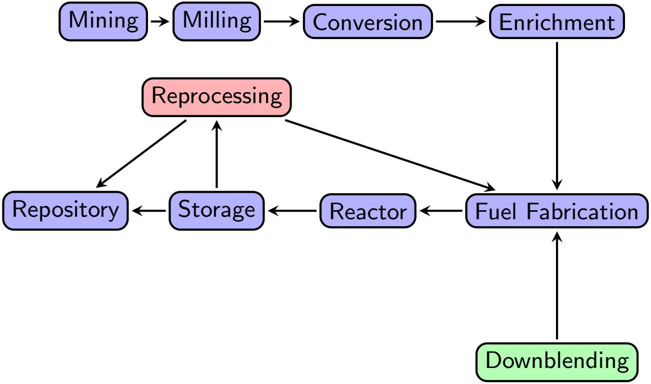

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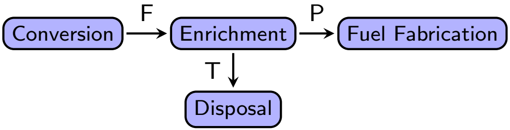

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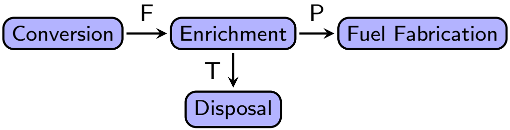

Variable	Definition
F	Feed mass
P	Product mass
T	Tails mass
x_i	Assay of material stream *i*
SWU	Separative work units
$V(x_i)$	Separation potential function
t	Time

$F = P + T$

$x_f F = x_p P + x_t T$

$SWU = [P \times V(x_p) + T * V(x_t) - F * V(x_f)] * t$

in which:

$$V(x_i) = (2x_i - 1) * \ln\left(\frac{x_i}{1 - x_i}\right)$$

Downblending HEU to produce HALEU

If we downblend HEU to produce HALEU:

- Spent fuel from Experimental Breeder Reactor II (EBR-II) can produce 10 MT of HALEU [12]
- HEU from Savannah River Site (SRS) can produce 4-20 MT of HALEU [12, 14]

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- HEU from SRS can produce 4-20 MT of HALEU [12, 14]
- The fuel will have uranium impurities that are not typically in enriched fuel or considered for reactor modeling [11, 18]

Efforts to estimate HALEU needs

Efforts are underway to estimate potential HALEU needs:

- Nuclear Energy Institute (NEI) surveyed multiple reactor design companies to estimate HALEU needs between now and 2035 [8, 12]
- National labs modeled the transition to some HALEU-fueled reactors to estimate HALEU needs to meet current net-zero carbon goals in 2050 [5]

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- Very prescriptive in reactor deployment

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Limitations of this previous work:

- All start from announced advanced reactor projects
- Very prescriptive in reactor deployment
- Mostly concerned with HALEU mass, don't consider other fuel cycle needs for HALEU-fueled reactors

Technical gaps & objectives

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- Understand changes to the US nuclear fuel cycle to commercially supply HALEU
- Understand limitations of using downblended HEU in advanced reactors

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Objectives

- Explore how the deployment of HALEU-fueled reactors affects the US nuclear fuel cycle
- Quantify potential material requirements for the transition from LWRs to advanced reactors in a once-through and recycling fuel cycle
- Understand the impacts of fuel cycle parameters on the material requirements and design optimized transition scenarios
- Identify potential limitations in using downblended HEU in advanced reactors

Outline

Transition analysis

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- Use Cyclus [7], a fuel cycle simulator, to model the transition
- Model the deployment and decommissioning of fuel cycle facilities
- Model material transactions between facilities
- Quantify material requirements for different fuel cycles

Transition analysis assumptions

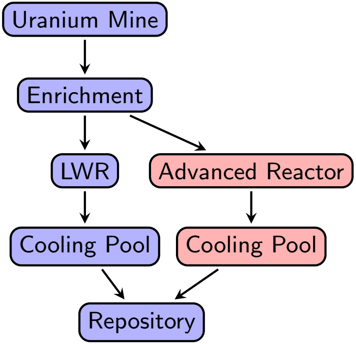

Figure 2: Fuel cycle facilities and material flow between facilities. Facilities in red are deployed at the start of the transition.

- Simulations model reactor deployment from 1965-2090
- Transitions begin in 2025

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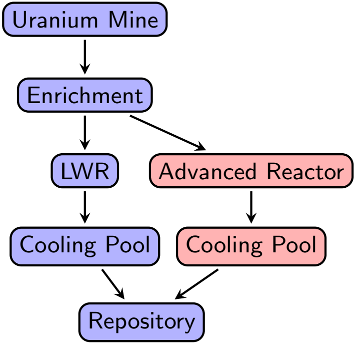

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- LWRs are assumed to operate until their current license expires

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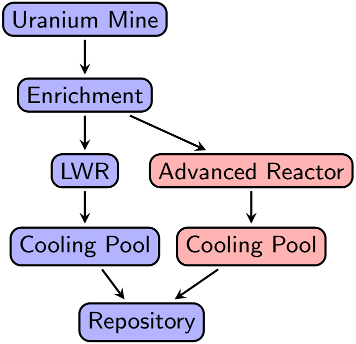

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- LWR commission dates are obtained from the IAEA PRIS database [1]
- LWRs are assumed to operate until their current license expires
- Assume natural uranium is enriched to produce all fuel
- Materials quantified include uranium mass, SWU capacity, feed uranium, and used nuclear fuel (UNF)

Advanced reactors

Table 2: Advanced reactor design specifications

Design Criteria	USNC MMR [2]	X-energy Xe-100 [10]	NuScale VOYGR [13, 15, 16]
Reactor type	HTGR	HTGR	SMR
Fuel form	UO_2 FCM	UCO TRISO	UO_2 pellets
Power (MWe)	5	80	77
Power (MWth)	15	200	250
Enrichment (% ^{235}U)	19.75	15.5	4.09
Cycle Length (yr)	20	Online	1.5
Number of cycles	1	6	3
Reactor Lifetime (yr)	20	60	60
Burnup ($\frac{MWd}{kgU}$)	82	168	45

$$\text{mass (kg)} = \frac{\text{Power (MWth) * cycle length (d)*number of cycles}}{\text{Burnup (MWd/kg)}}$$

Once-through scenario definitions

Table 3: Summary of the once-through fuel cycle transition scenarios. Energy growth is relative to energy from LWRs in 2025.

Scenario number	Reactors present	Energy demand
1	LWRs	N/A
2	LWRs and MMR	No growth
3	LWRs and Xe-100	No growth
4	LWRs, Xe-100, and MMR	No growth
5	LWRs, MMR, and VOYGR	No growth
6	LWRs, Xe-100, and VOYGR	No growth
7	LWRs, Xe-100, MMR, and VOYGR	No growth
8	LWRs and MMR	1% growth
9	LWRs and Xe-100	1% growth
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Table 4: Summary of the once-through fuel cycle transition scenarios. Energy growth is relative to energy from LWRs in 2025.

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4	LWRs, Xe-100, and MMR	No growth
5	LWRs, MMR, and VOYGR	No growth
6	LWRs, Xe-100, and VOYGR	No growth
7	LWRs, Xe-100, MMR, and VOYGR	No growth
8	LWRs and MMR	1% growth
9	LWRs and Xe-100	1% growth
10	LWRs, Xe-100, and MMR	1% growth
11	LWRs, MMR, and VOYGR	1% growth
12	LWRs, Xe-100, and VOYGR	1% growth
13	LWRs, Xe-100, MMR, and VOYGR	1% growth

Advanced reactor deployment scheme

Calculate the deployment scheme for advanced reactors outside CYCLUS

- Apply a modified greedy algorithm
- Deploy reactor with largest power output until an oversupply of power would be produced, deploy the next reactor until an oversupply of power, then deploy the last reactor until demand is met
- Deployment schedule is given to CYCLUS

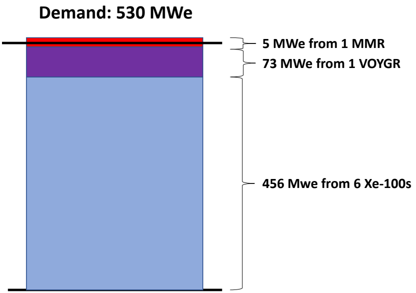

Figure 3: Example of how advanced reactors in Scenario 7 are deployed to meet a fictitious demand of 530 MWe.

Reactor numbers scales with the power output of the reactors

- Scenario 2 (MMR) deploys the most reactors
- Scenario 3 (Xe-100) deploys the fewest reactors
- Similar number of Xe-100s and VOYGRs are deployed
- Scenarios 4 (Xe-100+MMR), 6 (Xe-100+VOYGR), and 7 (Xe-100+VOYGR+MMR) mostly deploy Xe-100s
- Scenario 5 (MMR+VOYGR) mostly deploys VOYGRs

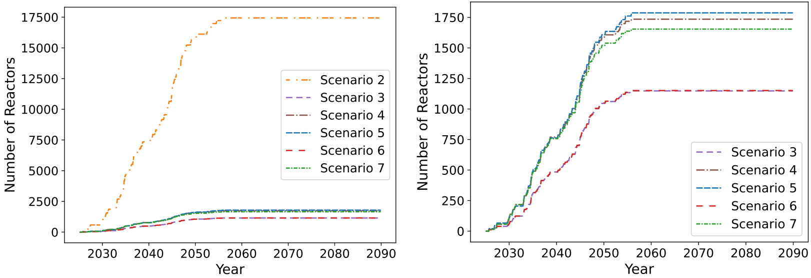

Figure 4: Number of advanced reactors deployed in Scenarios 2-7 (left) and Scenarios 3-7 (right).

Reactor designs drives the uranium mass required

- Scenario 5 (MMR + VOYGR) requires the largest average mass of enriched uranium
- Scenario 5 (MMR + VOYGR) requires the smallest mass of HALEU
- Scenario 2 (MMR) requires the largest mass of HALEU
- Scenario 3 (Xe-100) requires the smallest mass of enriched uranium

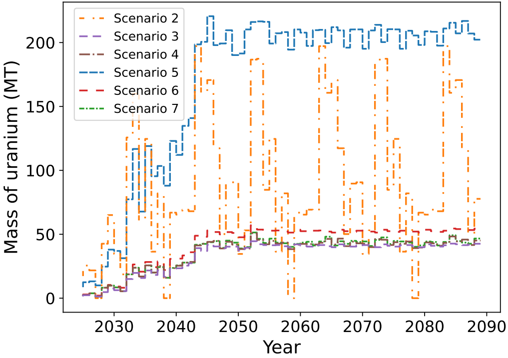

Figure 5: Annual average mass of enriched uranium required to fuel advanced reactors in Scenarios 2-7.

SWU capacity is a function of product mass and assay

- Scenario 2 (MMR) requires the largest average SWU
- The other scenarios are comparable for the average capacity they require
- Xe-100 and VOYGR differences in product mass and assay offset each other

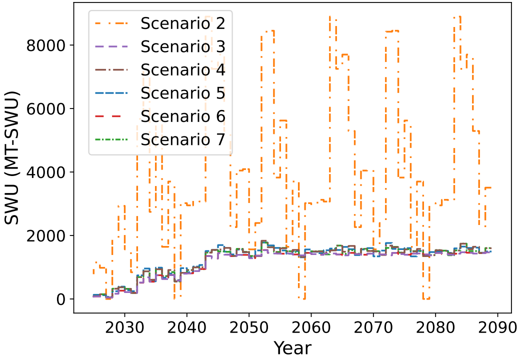

Figure 6: Annual average SWU capacity required to produce enriched uranium for and advanced reactors in Scenarios 2-7.

What about a different fuel cycle option?

What if we had a closed fuel cycle that required HALEU?

- How does the fuel cycle option impact the material requirements?
- How many resources does this save?

Reactor models account for fuel depletion

- CYCLUS uses archetypes to model reactors, and the physics of a reactor
- Different reactor archetypes use different methodologies to model fuel depletion

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- Other CYCLUS reactor archetypes can dynamically model fuel depletion, but they require export controlled software or are reactor design specific
- UNF compositions impact numerous fuel cycle considerations:
  - decay heat
  - criticality safety
  - amount of plutonium and transuranic elements

OpenMCyclus: an open source coupling with OpenMC

- Developed a reactor archetype that couples CYCLUS with stand-alone depletion solver in OpenMC
- Publicly available on GitHub [4]

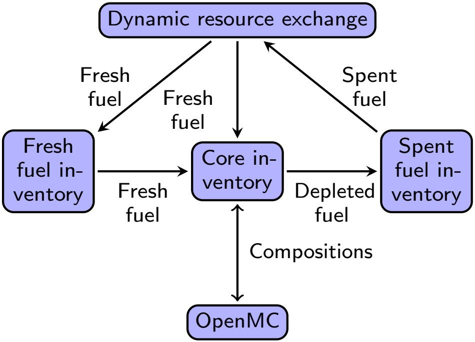
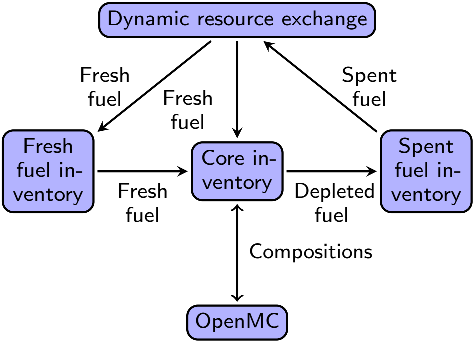


Figure 7: Material handling pathways between different material inventories in OpenMCyclus and the dynamic resource exchange (DRE) of CYCLUS.

OpenMCyclus: an open source coupling with OpenMC

- Developed a reactor archetype that couples CYCLUS with stand-alone depletion solver in OpenMC
- Publicly available on GitHub [4]
- Compared against the CYCAMORE `Reactor` in a simple closed fuel cycle



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- Closed fuel cycle with 1 reactor type, modeled with either CYCAMORE or OpenMCyclus
- Reactors prefer MOX over UOX

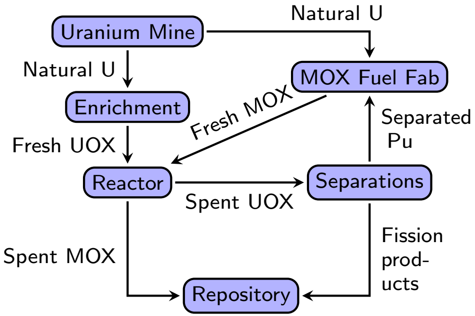

Figure 8: Fuel cycle facilities and material flow between facilities for the sample fuel cycle scenarios used to compare the results of the CYCAMORE Reactor and OpenMCyclus DepleteReactor archetypes.

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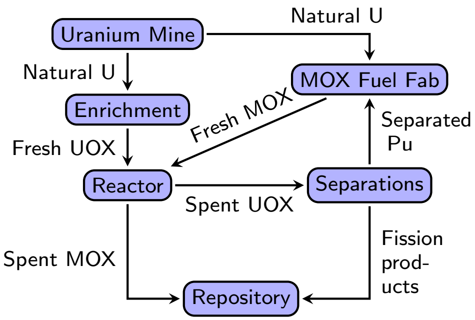

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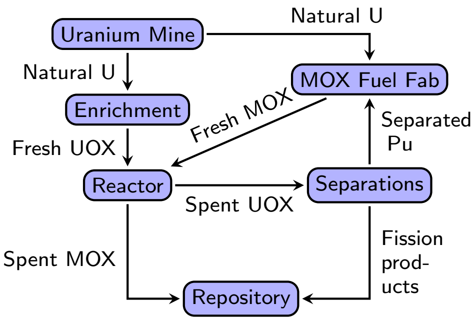
- Reactors have 60 time step lifetime
- Ran with CYCAMORE `Reactor` twice, toggling the `decom_transmute_all` setting



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Benchmark Results (I)

- Separated plutonium masses differ because of different depletion methodologies

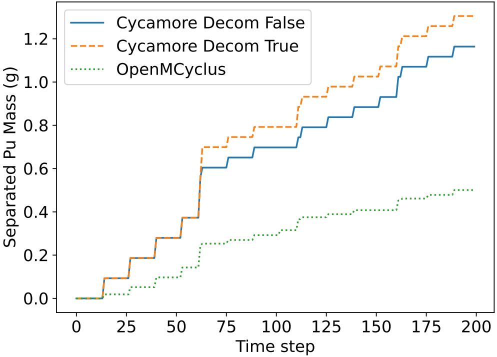

Figure 9: Comparison of cumulative separated plutonium in benchmark between OpenMCyclus and CYCAMORE `Reactor`.

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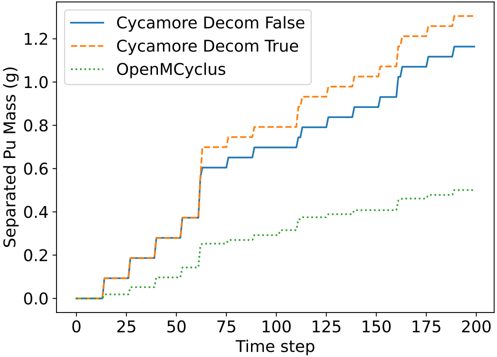

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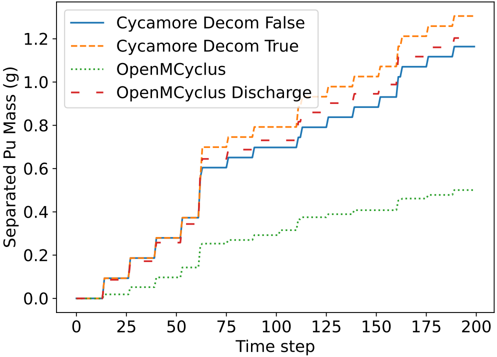

Figure 10: Comparison of cumulative separated plutonium in benchmark between OpenMCyclus and CYCAMORE `Reactor`.

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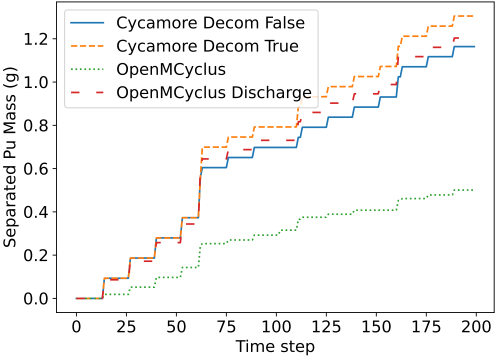
- Temporarily changing OpenMCyclus method shows better agreement
- Results suggests CYCAMORE Reactor overestimates separated plutonium inventory



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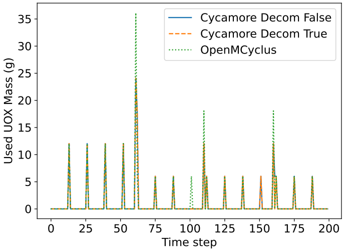
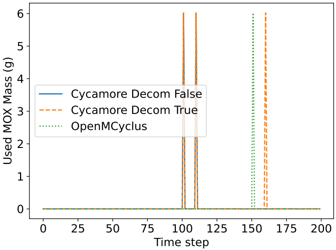
Benchmark Results (II)

- Differences in separated plutonium masses propagate into different fuel receipts
- Used fuel masses are mostly consistent, except when a reactor is decommissioned



(a) Comparison of used UOX fuel discharged.



(b) Comparison of used MOX fuel discharged.

Figure 11: Used fuel transactions in OpenMCyclus/Cycamore benchmark

Recycle scenario definitions

Table 5: Summary of the recycle fuel cycle transition scenarios. Energy growth is relative to energy from LWRs in 2025

Scenario	Advanced Reactors	Energy demand	Recycle scheme
14	Xe-100, MMR, VOYGR	No growth	Limited
15	Xe-100, MMR, VOYGR	No growth	Limited, no TRISO
16	Fast reactor	No growth	Continuous
17	Xe-100, MMR, VOYGR	1% growth	Limited
18	Xe-100, MMR, VOYGR	1% growth	Limited, no TRISO
19	Fast reactor	1% growth	Continuous

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Limited recycle fuel cycle assumptions

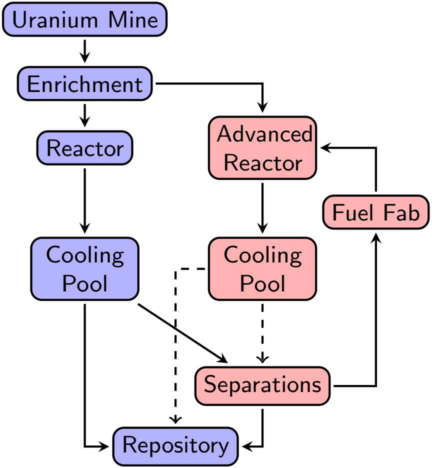

Figure 12: Fuel cycle facilities and material flow between facilities for the limited recycling scenarios.

- Reprocess uranium-based fuel, dispose plutonium-based fuel
- Reactors prefer plutonium-based fuel over uranium-based fuel
- Separations remove only plutonium (aqueous reprocessing)

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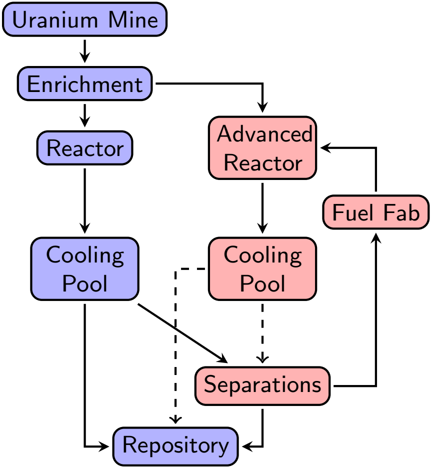

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- Modeled Xe-100 and VOYGR with OpenMCyclus

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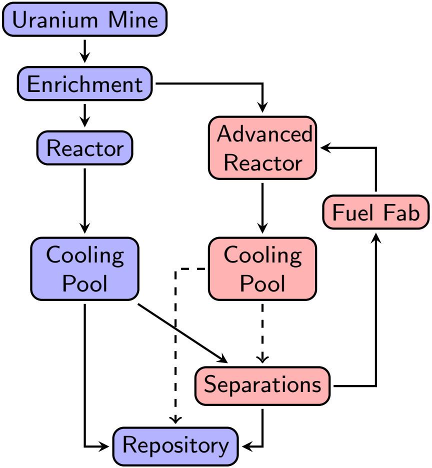

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- Use the same deployment schedule as Scenarios 7, 13
- Modeled Xe-100 and VOYGR with OpenMCyclus
- Separations start in 2020
- Vary if TRISO UNF is reprocessed

Continuous recycle fuel cycle assumptions

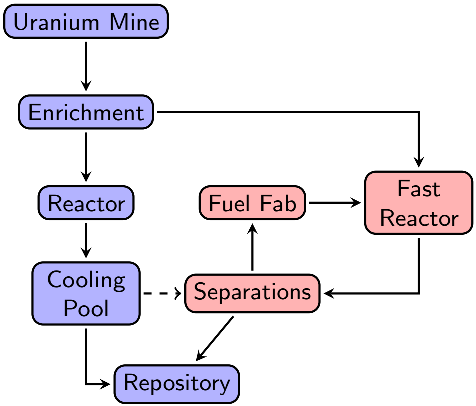


Figure 13: Fuel cycle facilities and material flow between facilities for the continuous recycling scenarios.

- Reprocess all UNF
- Introduce a fast reactor for transition, modeled through OpenMCyclus
- Separation start 2020
- Can accept plutonium-based fuel (preferred) or HALEU
- Separations remove U, Np, Pu, Am (electrochemical reprocessing)

Continuous recycle fuel cycle assumptions

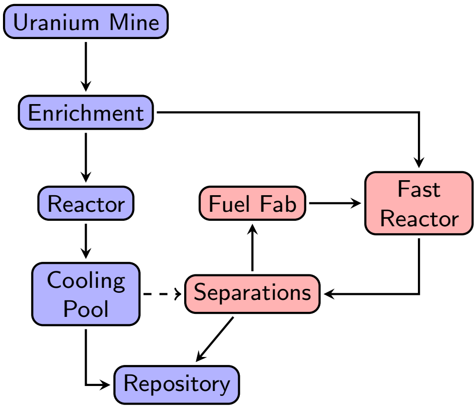


Figure 13: Fuel cycle facilities and material flow between facilities for the continuous recycling scenarios.

- Reprocess all UNF
- Introduce a fast reactor for transition, modeled through OpenMCyclus
- Separation start 2020
- Can accept plutonium-based fuel (preferred) or HALEU
- Separations remove U, Np, Pu, Am (electrochemical reprocessing)
- Use the same deployment scheme to determine how many fast reactors to deploy

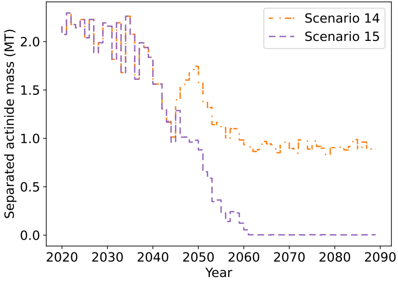
Advanced reactors

Table 7: Fast reactor design specification.

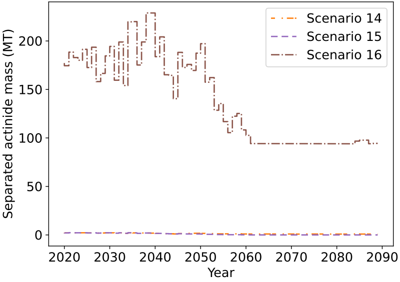
Design Criteria	Fast Reactor [6, 17]
Reactor type	Sodium-Cooled Fast Reactor (SFR)
Fuel form	Metallic
Power Output (MWe)	311
Power Output (MWth)	840
Enrichment (wt% fissile Pu)	11.3/13.5
Cycle Length (yrs)	1
Number of cycles	4
Reactor Lifetime (yrs)	60
Burnup (MWd/kg)	87.51

Recycling scheme dictates amount of separated material

- Scenario 16 (Continuous reprocessing) has the most separated material
- Scenario 15 (Limited, no TRISO) has the least separated material



(a) Annual average mass in Scenarios 14-15

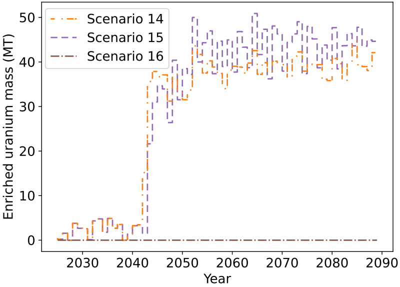


(b) Annual average mass in Scenarios 14-16

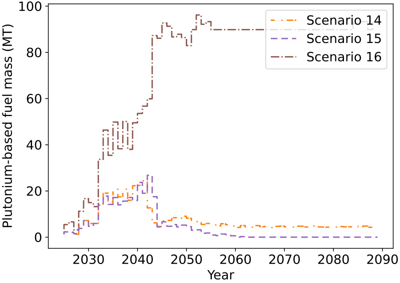
Figure 14: Separated actinide masses for advanced reactors in Scenarios 14-16

Recycling decreases HALEU needs

- Scenario 15 (Limited, no TRISO) requires the most enriched uranium, has least plutonium-based fuel
- Scenario 16 (Continuous reprocessing) doesn't require any enriched uranium, most plutonium-based fuel



(a) Uranium-based fuel mass



(b) Plutonium-based fuel mass

Figure 15: Fuel masses for advanced reactors in Scenarios 14-16

Transition analysis conclusions

- The advanced reactors deployed drive the materials required for each scenario
- Reprocessing decreases HALEU needs
- Decrease in HALEU needs is driven by the material available for reprocessing and the material separated from UNF

Transition analysis conclusions

- The advanced reactors deployed drive the materials required for each scenario
- Reprocessing decreases HALEU needs
- Decrease in HALEU needs is driven by the material available for reprocessing and the material separated from UNF
- These scenarios consider large changes in the transition. What about small changes?

Outline

Sensitivity analysis provides more insight into the fuel cycles.

To meet the third objective, I performed sensitivity analysis on Scenario 7 (once-through, no growth, Xe-100 + VOYGR + MMR), comparing the impact of different model parameters

- Couple Cyclus with Dakota [3]

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- Couple CYCLUS with Dakota [3]
- Input parameters include:
  - Transition start time
  - Percent of LWRs operating for 80 years
  - Build share of Xe-100, VOYGR, MMR
  - Discharge burnup of Xe-100 and MMR

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  - Total enriched uranium mass
  - HALEU mass
  - Total SWU capacity
  - SWU capacity to produce HALEU
  - Feed uranium to produce HALEU
  - UNF mass

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  - Total enriched uranium mass
  - HALEU mass
  - Total SWU capacity
  - SWU capacity to produce HALEU
  - Feed uranium to produce HALEU
  - UNF mass
- Varied parameters individually and multiple combinations
- Modify deployment scheme to prioritize reactor with specified build share, then deploy others in the same manner as before

Increasing MMR build share increases all metrics

- All of the materials increase
- Enrichment-related metrics increase the most

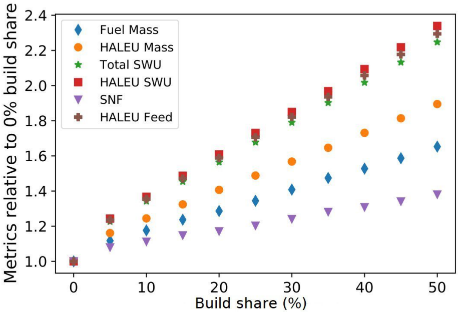

Figure 16: Relative effect of varying MMR build share

Increasing MMR build share increases all metrics

- All of the materials increase
- Enrichment-related metrics increase the most
- Results are a function of the number of each advanced reactor deployed

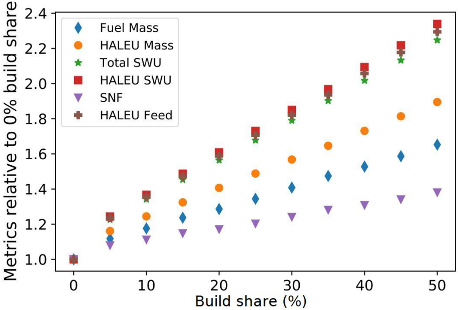

Figure 16: Relative effect of varying MMR build share

Effects of varying MMR build share

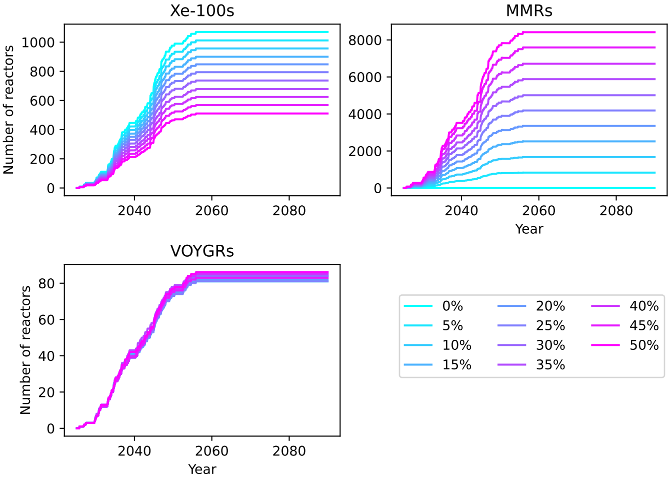

Figure 17: Number of Xe-100s (top left), MMRs (top right), and VOYGRs (bottom left) as a function of MMR build share.

Effects of varying Xe-100 burnup and MMR build share

- Non-uniform relationship
- At smaller Xe-100 burnup values, increasing MMR share decreases the HALEU mass
- At larger Xe-100 burnup values, increasing MMR share increases the HALEU mass
- Comparison of how much fuel each reactor needs

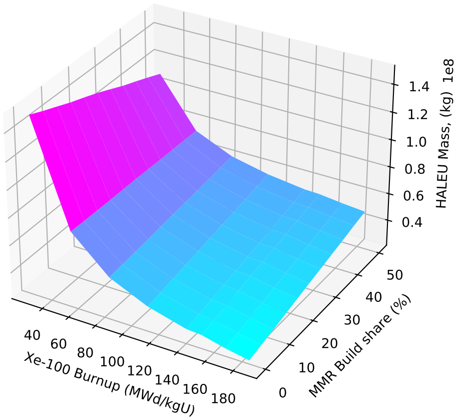

Figure 18: Effects of varying the Xe-100 burnup and MMR build share on HALEU mass requirements.

Varying multiple parameters shows importance of the Xe-100 burnup

Table 8: Sobol' indices for the Gaussian model when varying the MMR build share. Highlighted values indicate a total Sobol' indices of above 0.5.

	Output Metric					
Parameter	Fuel	HALEU	SWU	HALEU SWU	Feed	UNF
Transition Start	0.006	0.004	0.001	0.001	0.001	0.006
LWR Lifetime	0.068	0.063	0.071	0.069	0.069	0.071
MMR Share	0.107	0.107	0.203	0.204	0.193	0.055
Xe-100 Burnup	0.846	0.858	0.732	0.734	0.747	0.900
MMR Burnup	0.049	0.050	0.071	0.071	0.069	0.053

Use the CYCLUS-Dakota coupling to optimize the transition

- Use the genetic algorithms in Dakota to perform optimization
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- Use the genetic algorithms in Dakota to perform optimization
- Consider the same input parameters as the sensitivity analysis, except the transition start time
- Apply a linear constraint for the advanced reactor build shares
- Goal is to minimize the SWU capacity needed to produce HALEU, the mass of UNF, or both in a multi-objective problem

Single-objective optimization isn't perfect

- Maximize Xe-100 build share, LWR lifetimes, and Xe-100 burnup to minimize UNF mass
- Find a solution that has less UNF mass than the transition scenarios and the OAT analysis

Table 9: Values resulting in a minimum waste mass disposed of for a once-through transition scenario.

Variable	Value
LWR Lifetime	50%
Xe-100 build share	100%
MMR build share	7%
VOYGR build share	11%
Xe-100 burnup	185 MWd/kgU
MMR burnup	90 MWd/kgU
UNF mass	1,736 MT

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Outline

Downblending HEU is a potential source of HALEU

To meet the fourth objective, I modeled the neutronics of different HALEU compositions in the Xe-100 and MMR

- Consider pure HALEU (^{235}U and ^{238}U only) and HALEU from downblended EBR-II [18] and Y-12 [11] HEU inventories
- Create models in Serpent [9] for these two reactors
- Compare the performance of the fuels with respect to:
  - k_{eff}
  - β_{eff}
  - Energy- and spatially-dependent flux
  - Fuel, coolant, moderator, and total reactivity temperature feedback coefficients

k_{eff} and β_{eff} of Xe-100

- Impurities increase k_{eff}, larger η value ($\frac{\nu\sigma_f}{\sigma_a}$) of the fuel

Table 10: k_{eff} values for the Xe-100-like reactor model using each fuel type.

Fuel type	k_{eff}
Pure	1.06663 ± 0.00016
EBR-II	1.08086 ± 0.00016
Y-12	1.08016 ± 0.00014

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- Impurities decrease β_{eff} because non-^{235}U isotopes have a smaller β_{eff} than ^{235}U

Table 11: β_{eff} value for the Xe-100-like reactor mode using each fuel type.

Fuel type	β_{eff}
Pure	0.00617 ± 0.00003
EBR-II	0.00604 ± 0.00003
Y-12	0.00598 ± 0.00003

Energy dependent neutron flux in Xe-100

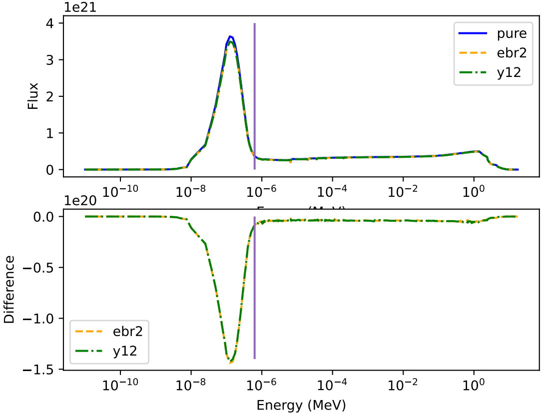

Figure 19: Energy-dependent flux through the active region of the Xe-100 core. The purple line is the delineation between fast and thermal neutrons for this work.

Spatitally-dependent neutron flux in Xe-100

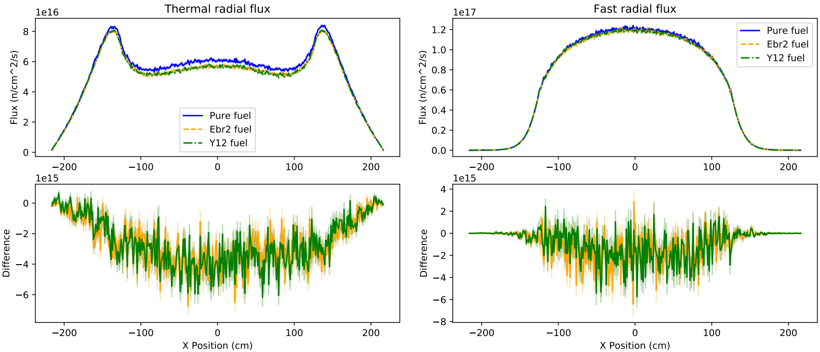

Figure 20: Radial fluxes through Xe-100.

Outline

Conclusions

- This work investigates the impacts of deploying HALEU-fueled reactors on the nuclear fuel cycle

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- This work investigates the impacts of deploying HALEU-fueled reactors on the nuclear fuel cycle
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- Sensitivity analysis highlighted how the advanced reactor characteristics affect the material requirements, and the importance of the Xe-100 burnup
- Found transitions to minimize HALEU SWU and SNF mass, but other algorithms should be used when using a linear constraint
- The impurities from downblending HEU affect reactor parameters, but won't necessarily prevent key design parameters from being met

A methodology for comprehensive fuel cycle analysis

- Develop and demonstrate how to expand transition analysis with sensitivity analysis and optimization
- Develop a reactor-agnostic archetype to dynamically model depletion in CYCLUS, without needing an export-controlled code

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A methodology for comprehensive fuel cycle analysis

- Develop and demonstrate how to expand transition analysis with sensitivity analysis and optimization
- Develop a reactor-agnostic archetype to dynamically model depletion in CYCLUS, without needing an export-controlled code
- Provide a detailed insight on how parameters and decisions affect fuel cycle needs and their relative impact
- Deployment scheme is an important facet of this work and greatly impacts the results, but can be replaced

Limitations and Future Work

- Transition analysis provided a macroscopic view of material needs

Limitations and Future Work

- Transition analysis provided a macroscopic view of material needs
  - Break up the material needs into time periods or reactor-specific quantities
  - Determine and model facility capacities
  - Design enrichment centrifuge cascades
  - Account for processing time
  - Model the needs of non-fuel materials, like reactor-grade graphite

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- ARFC Group members
- RFCA members, Drs. Bo Feng and Scott Richards
- CYCLUS and OpenMC communities
- Kyle and Little R

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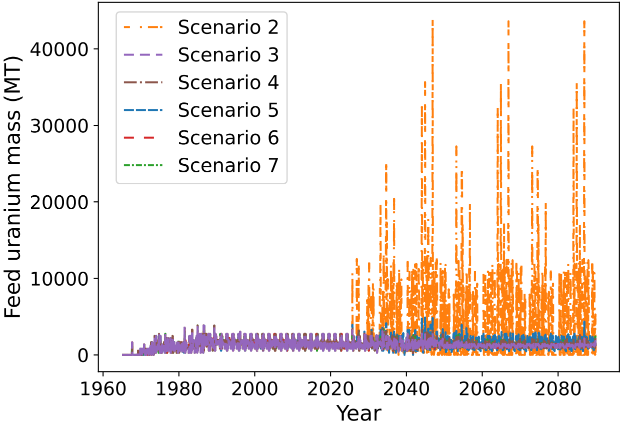
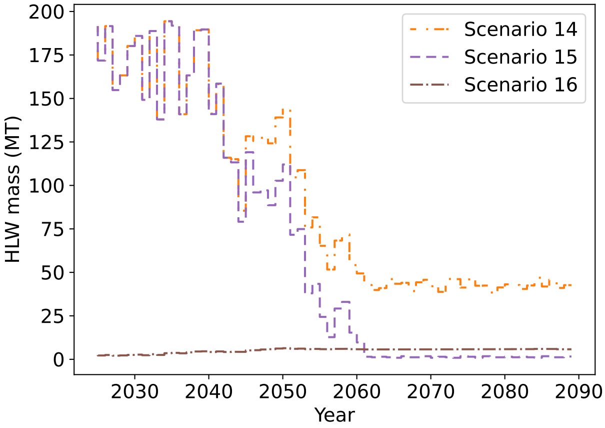
More limitations and future work

- Ignores other externalities, like nonproliferation safeguards
  - Incorporate potential safeguards measures into models
  - Account for construction time and/or licensing
- Expand analysis on impurities in HALEU
  - Consider power-peaking factors
  - Model burnable poisons and control rods
  - Model core in non-isothermal state

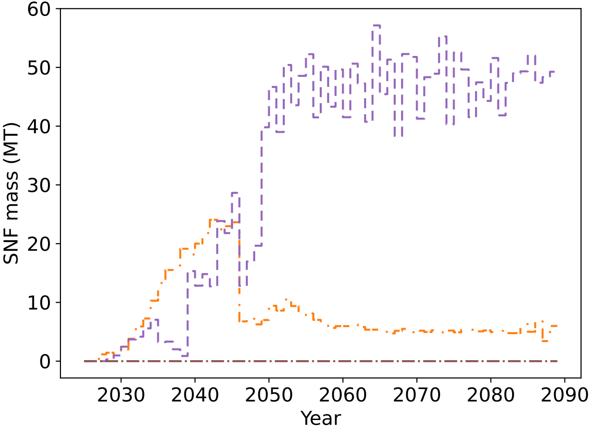
Once-through feed uranium



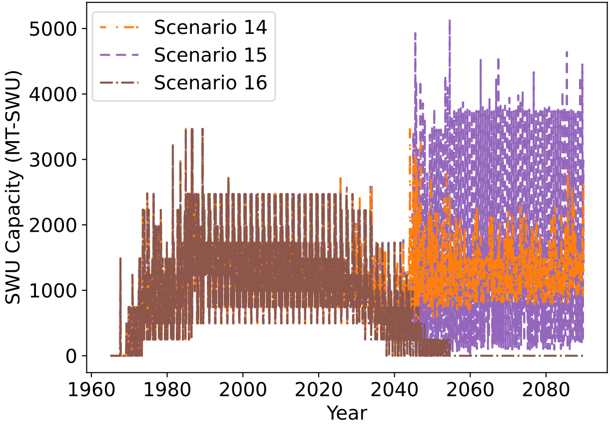
Recycle HLW


Scenario 14
Scenario 15
Scenario 16
HLW mass (MT)
Year
0
25
50
75
100
125
150
175
200
2030
2040
2050
2060
2070
2080
2090

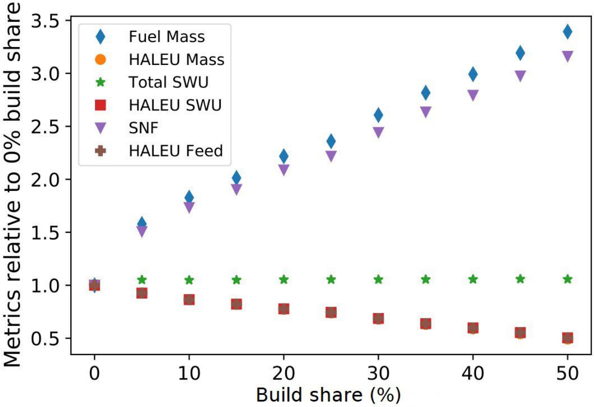
Recycle SNF


60
50
40
30
20
10
0
SNF mass (MT)
2030
2040
2050
2060
2070
2080
2090
Year

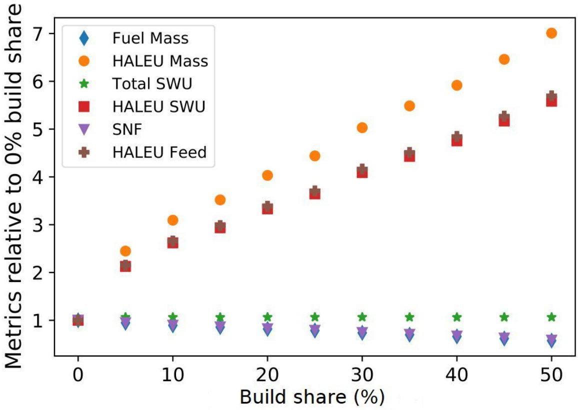
Recycle SWU


Scenario 14
Scenario 15
Scenario 16
SWU Capacity (MT-SWU)
0
1000
2000
3000
4000
5000
1960
1980
2000
2020
2040
2060
2080
Year

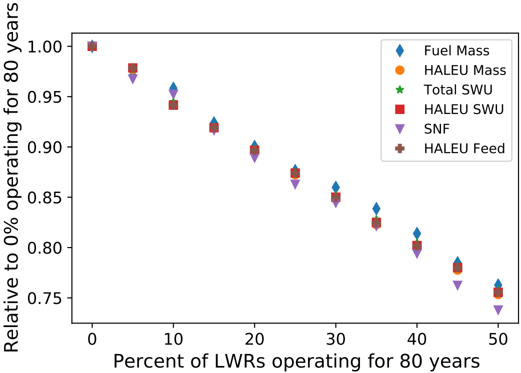
Effects of varying VOYGR build share



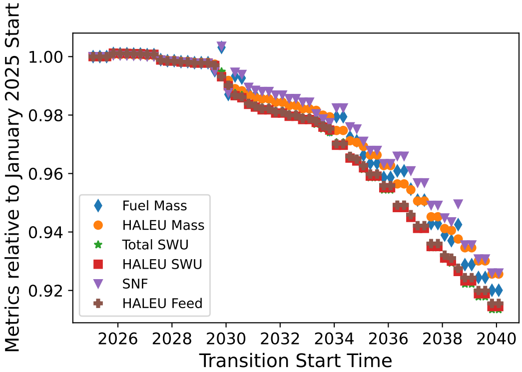
Effects of varying Xe-100 build share



Effects of varying LWR lifetimes



Effects of varying transition start time



HALEU SWU Optimization

Table 12: Values resulting in a minimum HALEU SWU capacity for a once-through transition scenario.

Variable	Value
LWR Lifetime	36%
Xe-100 build share	0%
MMR build share	2%
VOYGR build share	100%
Xe-100 burnup	151 MWd/kgU
MMR burnup	90 MWd/kgU
HALEU SWU	4.812×10^7 kg-SWU

Axial flux through Xe-100

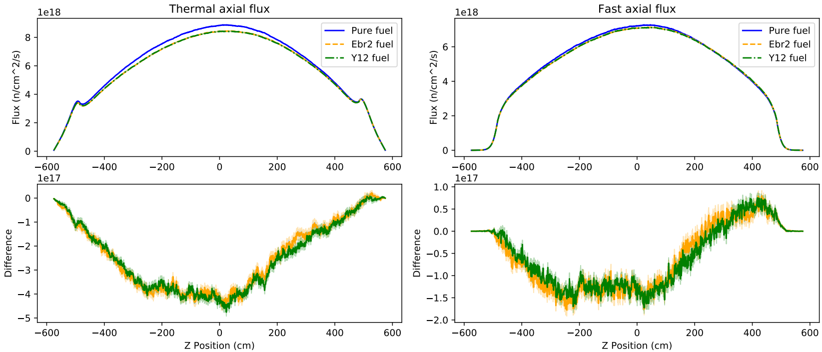


Figure 21: Axial fluxes through Xe-100.

Reactivity feedback coefficients for Xe-100

Table 13: Reactivity temperature feedback coefficients for each material type in the Xe-100-like model for each fuel type.

	Material feedback coefficient (pcm/K)			
Fuel Type	Fuel	Coolant	Moderator	Total
Pure	-3.875 $\pm$ 0.094	-0.044 $\pm$ 0.112	-0.071 $\pm$ 0.459	-4.216 $\pm$ 0.502
EBR-II	-3.759 $\pm$ 0.138	-0.433 $\pm$ 0.048	-0.708 $\pm$ 0.404	-4.817 $\pm$ 0.438
Y-12	-3.797 $\pm$ 0.157	-0.351 $\pm$ 0.092	-0.728 $\pm$ 0.469	-4.700 $\pm$ 0.349