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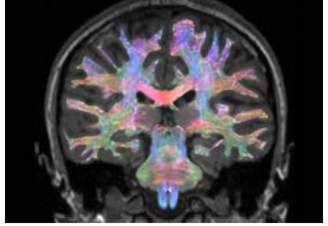






A LCOE Estimation on HALEU Fuels for Small Modular Reactors


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SMRs and Micro-Reactors (1/2)

- ***SMRs*** (<300 MWe)
  - Small Modular Reactors
  - Factory Manufactured Components
- ***Microreactors*** (<15 MWe)
  - Transportable as unit
- ***Unique Advantages:***
  - Modularity
  - Low Capital Cost
  - Passive Features
  - Reduced Risk of Outage
  - Geographic Benefits

Figure 1: Illustration of Rolls-Royce reactor module. Retrieved from IAEA website. https://www.iaea.org/newscenter/news/small-modular-reactors-a-challenge-for-spent-fuel-management

SMRs and Micro-Reactors (2/2)

Table 1. Development of Various SMR and Micro-Reactor Designs

Reactor	Capacity	Type	Developer	Nation	Project Status
CAREM-25	27 MWe	Integral PWR	CNEA & INVAP	Argentina	Under Construction
HTR-PM	210 MWe	Twin HTR	INET, CNEC & Huaneng	China	Under Construction
NuScale	45 MWe	Integral PWR	NuScale Power	USA	Near-Term Deployment
BWRX-300	300 MWe	BWR	GE Hitachi	USA	Near-Term Deployment
Integral MSR	192 MWe	MSR	Terrestrial Energy	Canada	Near-Term Deployment
Xe-100	75 MWe	HTR	X-energy	USA	Early Stages
Aurora	1.5 MWe	Heatpipe FNR	Oklo	USA	Early Stages
Sealer	3-10 MWe	Lead FNR	LeadCold	Sweden	Early Stages

HALEU Fuel

- ***Definition***
  - High-Assay Low-Enriched Uranium
  - Enrichment: 5-20 wt% U-235
  - Various chemical compounds
    - Oxide, carbide, nitride, etc…
- ***Benefits***
  - Increased capacity factor or power
  - Reduction in overall refueling costs
  - Marginal change in capital and O&M costs
- ***Costs***
  - Greater Fuel Cost
    - Mining & Milling, Conversion, Enrichment, Fabrication
  - No existing supply chain
  - Increased Transport Costs
  - Possible Reduction in Operation Lifetime

Figure 1: Illustration of Uranium Oxide Fuel. Retrieved from World Nuclear Association website. https://www.world-nuclear.org/nuclear-essentials/how-is-uranium-made-into-nuclear-fuel.aspx

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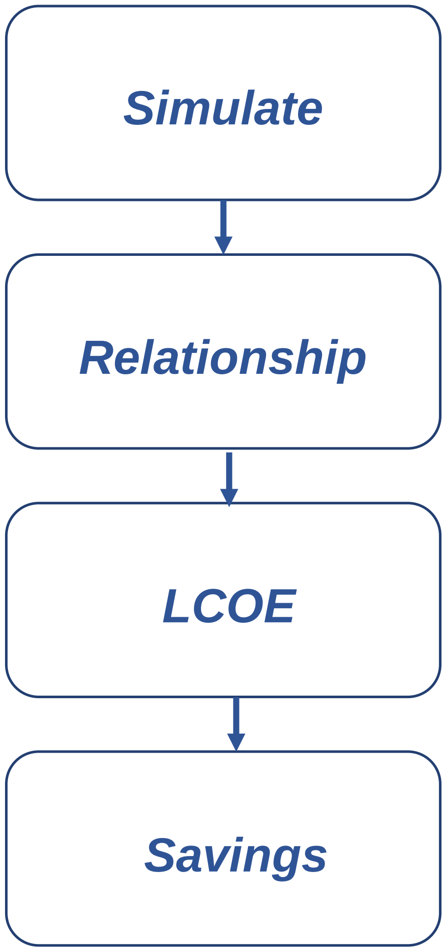
Overview

- ***Explain method for determining Levelized Cost of Electricity (LCOE) for higher enriched reactor designs***
  - *Case study of existing PWR type SMR design*
  - *Briefly discuss simulation of reactor and fuel enrichment optimization*
  - *Derive HALEU LCOE as function of reported LCOE of standard design*
- ***Analyze core loading cost of various enrichments (5-20 w/o)***
- ***Establish criteria for analyzing economic viability of HALEU fuel for the chosen reactor design***
- ***Report results for fuel enrichment, LCOE reduction, and total plant savings due to increased cycle time***

Method

Case Study:
- NuScale 160 MWth Reactor
- PWR type SMR

1. ***Simulate Reactor:*** Enrichment was optimized to increase cycle length from 24 months to 48 months
2. ***Establish Relationship:*** Linear reactivity model used to create relationship between fuel enrichment and reactor burnup
3. ***Find Levelized Cost of Electricity (LCOE):*** Optimal fuel enrichments used to estimate LCOE values with reported LCOE of standard design as input
4. ***Plant Savings:*** Estimation of total net benefit due to fuel enrichment increase



Simulation & Optimization

- ***Simulation***
  - ***Simulation***: CASMO/SIMULATE
  - ***Verification:*** MCNP
  - ***Enrichments:*** BRACC
- ***Optimization***
  - Fuel Enrichments adjusted to optimize pin peak power factors (PPPF) across each assembly
  - Core loading scheme unchanged

BP locations have smaller peaking factors.

Key:

- PPPF > 1.5
- 1.5 ≥ PPPF > 1.4
- 1.4 ≥ PPPF > 1.3
- 1.3 ≥ PPPF > 1.2
- 1.2 ≥ PPPF > 1.1
- 1.1 ≥ PPPF > 1.0
- 1.0 ≥ PPPF > 0.9
- 0.9 ≥ PPPF > 0.8
- 0.8 ≥ PPPF > 0.7
- 0.7 ≥ PPPF > 0.6
- 0.6 ≥ PPPF > 0.5
- 0.5 ≥ PPPF > 0.4
- 0.4 ≥ PPPF

BOC PPPF (0 GWd/MT), Homogenous Enrichment

IT								
0.854	0.346							
0.990	0.963	1.027						
GT	1.045	1.088	GT					
0.357	0.989	1.043	1.044	0.362				
1.021	1.012	0.998	1.067	1.064	GT			
GT	1.039	0.363	GT	1.122	1.057	0.365		
1.127	1.076	1.039	1.112	1.105	1.066	1.015	1.062	
1.124	1.115	1.109	1.122	1.121	1.111	1.103	1.120	1.153

Optimized BOC Pin Power Peaking Factor (0 GWd/MT)

IT								
0.906	0.354							
1.000	1.026	1.043						
GT	1.062	1.067	GT					
0.366	1.008	1.065	1.070	0.372				
1.045	1.035	1.023	1.059	1.062	GT			
GT	1.071	0.373	GT	1.081	1.060	0.375		
1.085	1.079	1.084	1.077	1.072	1.075	1.062	1.074	
1.091	1.082	1.076	1.092	1.092	1.082	1.073	1.095	1.087

EOC PPPF (25 GWd/MT), Homogenous Enrichment

IT								
0.914	0.574							
1.003	0.978	1.015						
GT	1.038	1.061	GT					
0.649	1.003	1.031	1.049	0.665				
1.030	1.015	1.012	1.061	1.067	GT			
GT	1.039	0.668	GT	1.086	1.047	0.638		
1.072	1.037	1.021	1.067	1.050	1.020	0.990	1.007	
1.055	1.050	1.048	1.054	1.049	1.041	1.034	1.041	1.063

Optimized EOC Pin Power Peaking Factor (25 GWd/MT)

IT								
0.969	0.639							
1.012	1.030	1.022						
GT	1.048	1.038	GT					
0.740	1.020	1.043	1.069	0.769				
1.050	1.032	1.034	1.051	1.062	GT			
GT	1.061	0.773	GT	1.043	1.043	0.738		
1.025	1.027	1.048	1.026	1.009	1.013	1.016	1.000	
1.012	1.008	1.006	1.013	1.009	1.000	0.994	1.001	0.992

BOC: Beginning of (fuel) cycle; **MOC**: Middle of (fuel) cycle; **EOC**: End of (fuel) cycle

Figure 3. Fuel Optimization Example

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LCOE Study Model (1/4)

- ***Levelized Cost of Electricity (LCOE)***
  - Price of electricity where revenues equal costs
  - Measure of economic efficiency
  - Represents total costs of a power plant divided by the total energy produced
- ***Assumptions***
  - Full Power during operation
    - No Peak Following
  - Zero power during refueling
  - Change in capital and O&M costs are marginal

$$\mathrm{LCOE} = \frac{C_{\mathrm{cc}} + C_{\mathrm{O\&M}} + C_U}{P \cdot \eta \cdot T_{cycle}}$$

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LCOE Study Model (2/4)

- LCOE is variable with capacity factor, fuel cost, and cycle time
- LCOE of higher enriched reactor may be estimated as function of the LCOE of the standard reactor design
- LCOF – Levelized Cost of Fuel

$$\mathrm{LCOE} = \frac{C_{\mathrm{cc}} + C_{\mathrm{O\&M}} + C_U}{P \cdot \eta \cdot T_{cycle}}$$

$$(\mathrm{LCOE})_E = \left[(\mathrm{LCOE})_O - (\mathrm{LCOF})_O\right]\frac{\eta_O}{\eta_E} + (\mathrm{LCOF})_E$$

$$\mathrm{LCOF} = \frac{C_U}{P \cdot \eta \cdot T_{cycle}}$$

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LCOE Study Model (3/4)

Cost of Fuel = Cost of Mining & Milling
+ Cost of conversion
+ Cost of Enrichment
+ Cost of Fuel Fabrication

Table 2. Fuel Prices Used for HALEU Economic Study

	Process	Cost	Unit
Fuel Prices	Mining & Milling	68	$/kgU3O8
	Conversion	105	$/kgU
	Enrichment	52	$/SWU
	Fuel Fabrication	300	$/kg

Prices are approximate and as of March 2017
(World Nuclear Association)

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LCOE Study Model (4/4)

- Cost of enrichment ($/kg)
- Not necessary to know feed or waste mass
  - Cost of fuel has significant dependence on tails enrichment
- Higher enriched fuel increases mining demands
- Tails enrichment
  - (0.2-0.3 w/o)
- Natural uranium enrichment
  - (0.711 w/o)

$$c_{UE} = C_{SWU}\left[\left(\frac{x_P - x_F}{x_F - x_W}\right)(2x_w - 1)\ln\left(\frac{x_w}{1 - x_w}\right) + (2x_P - 1)\ln\left(\frac{x_P}{1 - x_P}\right) - \left(\frac{x_P - x_W}{x_F - x_W}\right)(2x_F - 1)\ln\left(\frac{x_F}{1 - x_F}\right)\right]$$

$$\frac{M_F}{M_P} = \frac{x_P - x_W}{x_F - x_W}$$

Parameters Used for HALEU Economic Study

Table 3. Parameters Used for HALEU Economic Study

	Parameter	Value	Unit
NuScale Economic Parameters	Thermal Power, P_{th}	160	MWt
	Electric Power, P_e	45	MWe
	Cycle Burnup, B	12	MWd/kgU
	Cycle Length, T_{cycle}	24	months
	Capacity Factor, η_O	98.6	%
	Cycle Effective Full-Power Days, T_{EFPD}	720	days
	Fuel Loading Mass, M_P	9213	kg
	Average Fresh Load Enrichment, x_P	4.17	w/o
	Average Levelized Cost of Electricity, LCOE	86	$/MWh
	Estimated Levelized Cost of Fuel, LCOF	16.5-17.5	$/MWh

Results (1/4)

Table 4. Total Core Load Uranium Cost (Million USD}

		Product Enrichment {w/o}									NuScale Enr.
		5.0	7.0	9.0	11.0	13.0	15.0	17.0	19.0	20.0	4.17
Tails Enrichment {w/o}	0.20	15.2	20.8	26.5	32.3	38.0	43.8	49.6	55.4	58.3	12.8
	0.22	15.3	21.0	26.7	32.5	38.3	44.2	50.0	55.8	58.8	12.9
	0.24	15.4	21.2	27.0	32.9	38.8	44.7	50.6	56.5	59.4	13.0
	0.26	15.6	21.5	27.4	33.4	39.3	45.3	51.3	57.3	60.3	13.2
	0.28	15.8	21.8	27.9	33.9	40.0	46.1	52.2	58.3	61.4	13.4
	0.30	16.1	22.3	28.4	34.6	40.8	47.1	53.3	59.6	62.7	13.6

Results (2/4)

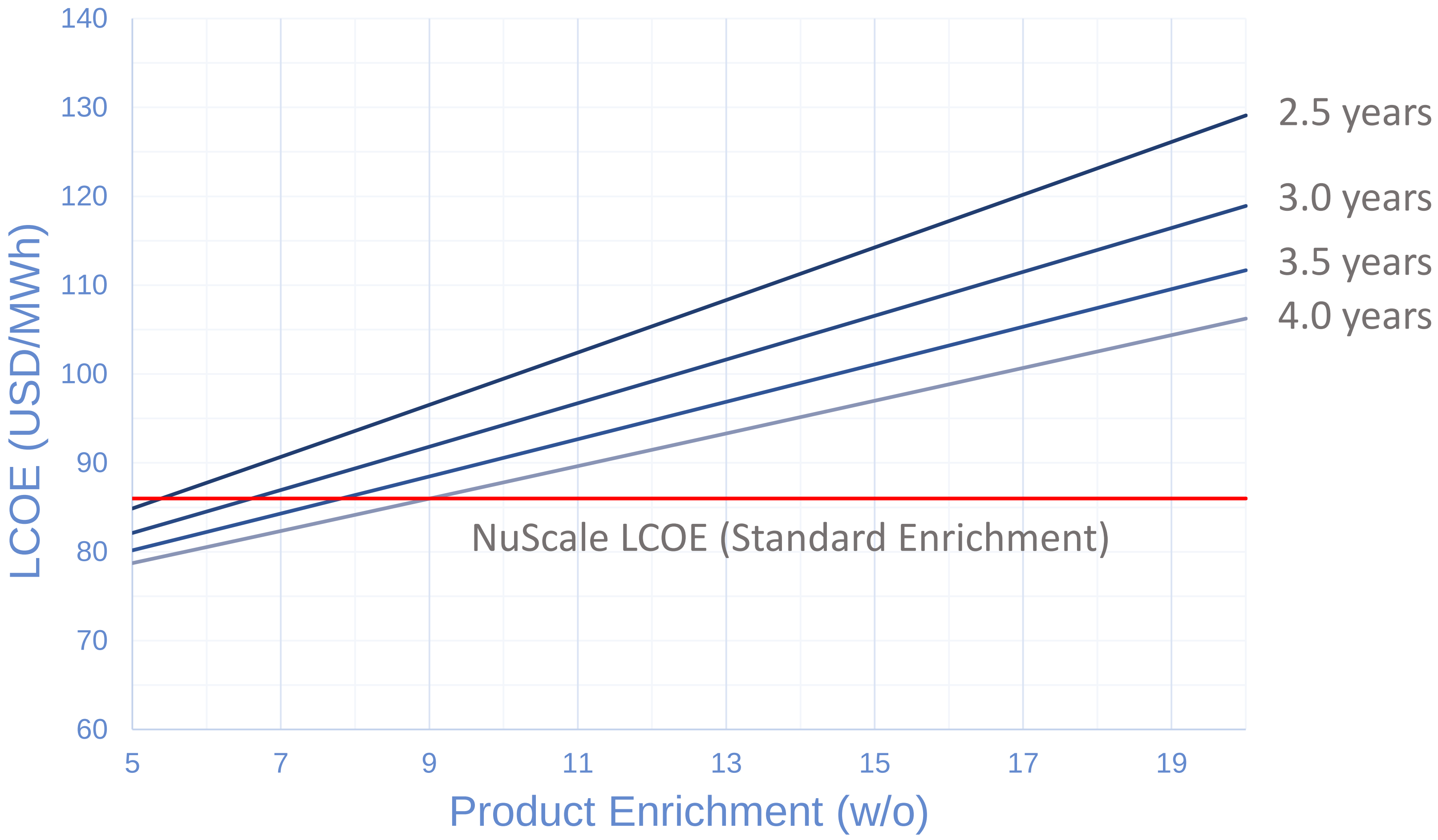

Figure 4. Projected LCOE of target enrichments and cycle lengths

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Results (3/4)

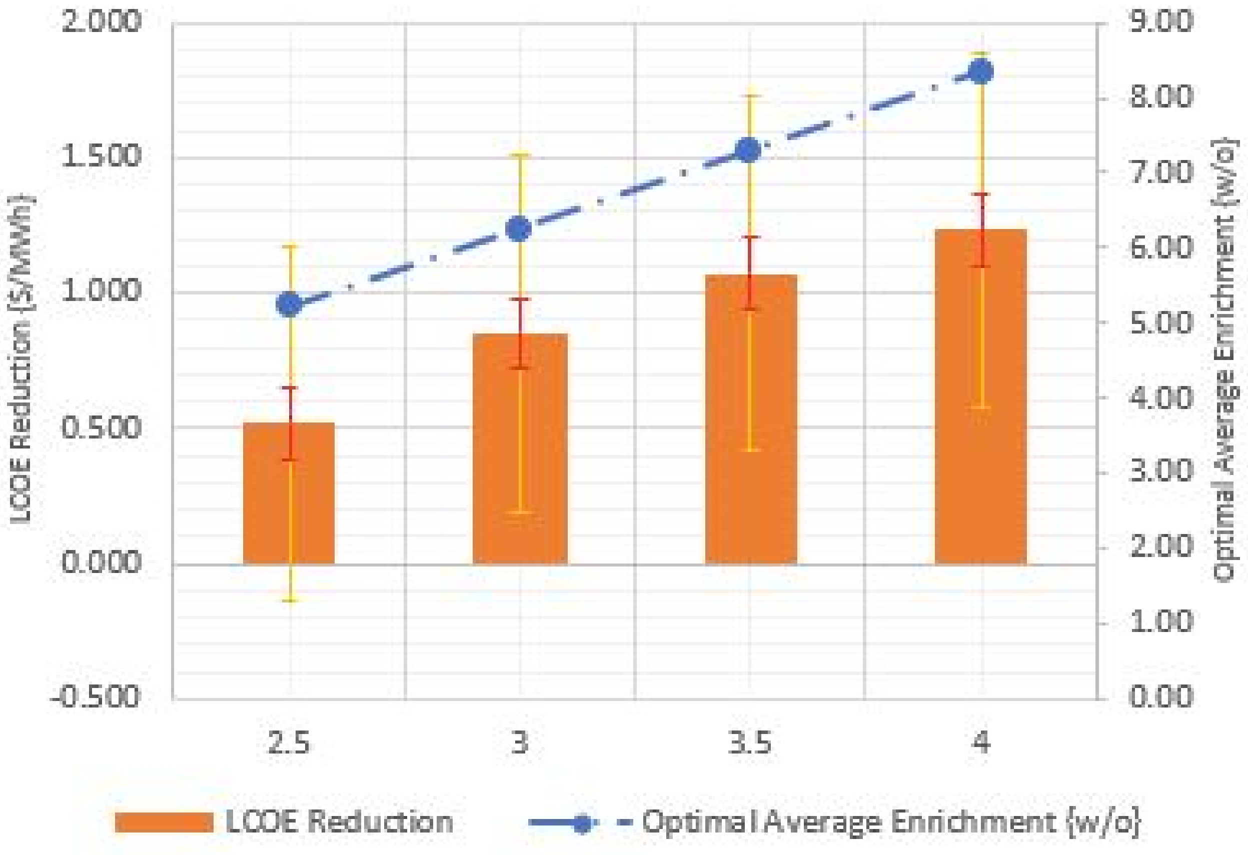

Figure 2. Optimized Enrichments and LCOE Reduction for SMR with Extended Cycle Length.

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Results (4/4)

Table 5. Savings of NuScale Reactor and Plant From Increasing Core Burnup

TIME {YR}	CORE-AVG. ENR. {W/O}	LCOE	LCOE REDUCTION {$/MWH}	REACTOR SAVINGS ($/YR)	12-MODULE PLANT SAVINGS ($/YR)
2	4.17	86	0	0	0
2.5	5.21	85.5	0.520	205,000	2,460,000
3	6.26	85.2	0.850	335,000	4,020,000
3.5	7.30	84.9	1.073	423,000	5,080,000
4	8.34	84.8	1.233	486,000	5,840,000

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