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Characteristics of TRU Fueled SFR Core during the Transition with Partially Loaded LEU Assemblies

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September 2019

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Characteristics of TRU-Fueled SFR Core with Partially Loaded HALEU Assemblies

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Fast Reactor Core and Fuel

- Traditionally in many cases, optimized for U/Pu or U/TRU fuels.
  - Designed for specific fuel-cycles (e.g. sustainable fuel-cycle (closed, breeders), minimizing transuranic (TRU) waste (once-through, burners), etc.).
  - More common in countries other than the US.

- Tend to have high enrichment (>20% of Pu/TRU content) due to:
  - Cross sections of the fissile isotopes are smaller relative to the fertile isotopes in the fast energy range.
  - High neutron leakage.

- Increases ***attractiveness*** of the fuel.

- It is possible to be optimized to use lower enriched fuel (e.g. 15-17% of Pu/TRU content for mid-sized (~400 MWe) Sodium-cooled Fast Reactor (SFR)) with relatively higher conversion ratio (CR ~ 1.0).

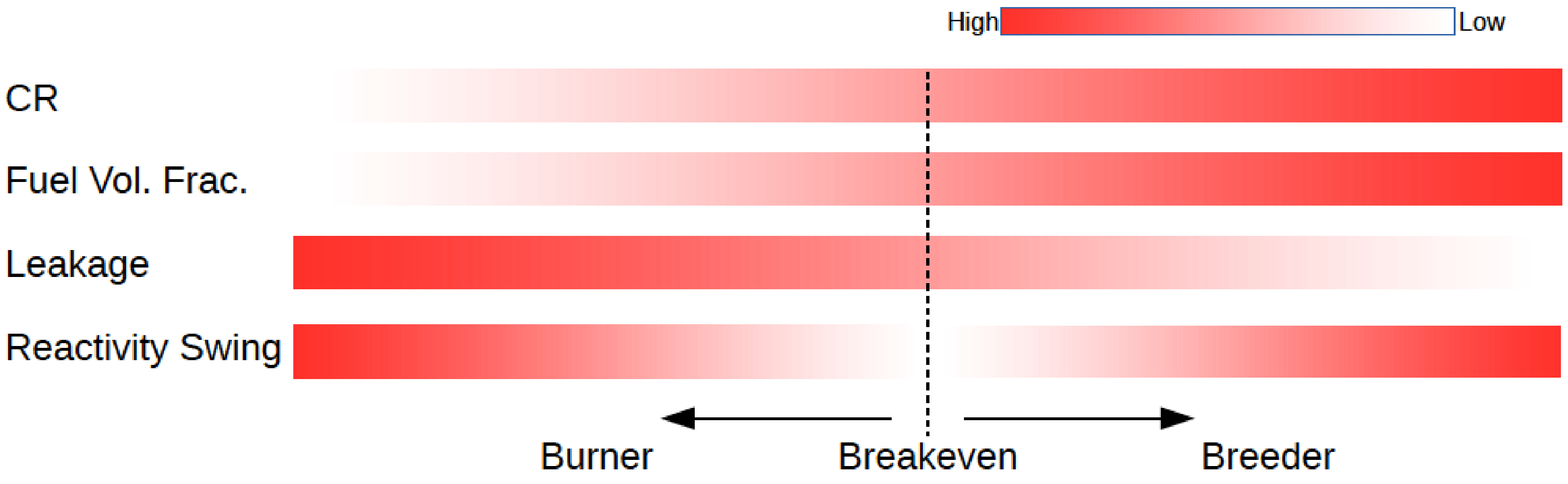
Fast Reactor Core and Fuel (Cont'd)

- Shortage or Inaccessibility to TRU based fuel need to be furnished with Low Enriched Uranium (LEU) with equivalent fissile (^{235}U) content.
  - Reactor startup.
  - Unavailability of Pu/TRU recycling/fuel fabrication facilities.
- High-assay LEU (HALEU). 5-20% of enrichment.

Conversion Ratio (CR) and SFR Core Characteristics

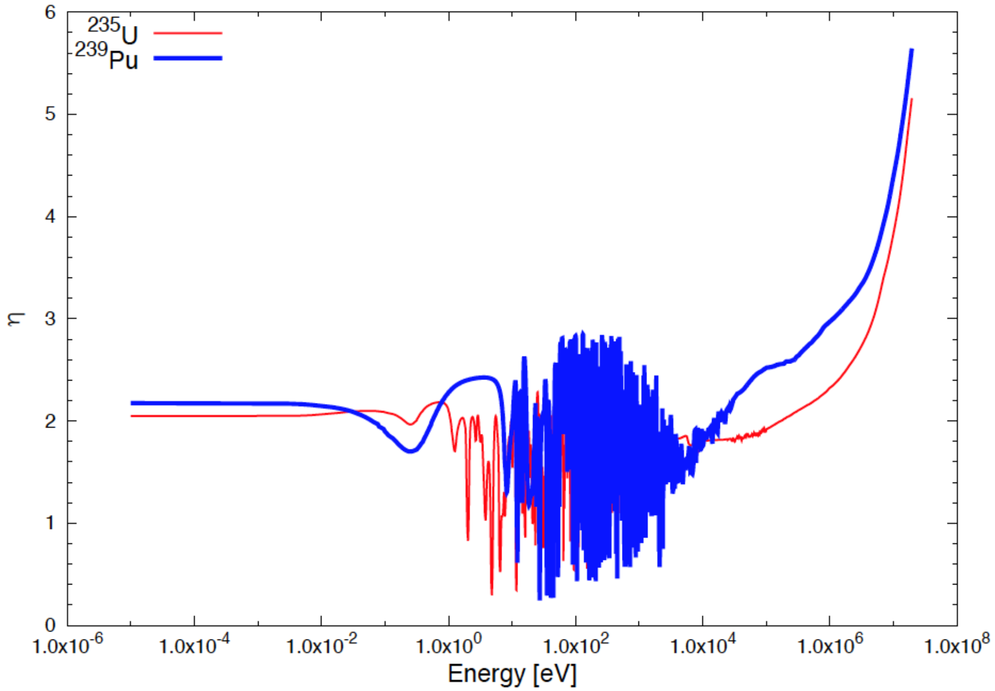
- Burner (CR < 1): Initially loaded with high excess reactivity, which decreases toward the end of cycle. Neutron absorbing materials (e.g. control rods) need to be inserted in order to offset the excess reactivity.
- Breakeven (CR ~ 1): Having the same amount of fissile in the discharged fuel as in the charged fuel. The reactivity swing is much smaller than other two conditions.

- Breeder (CR > 1): More fissile is produced than consumed. The reactivity increases toward EOC.
- Breakeven core needs less absorber.



Use of LEU in SFRs

- Some impact on important safety parameters needed to be quantified. (e.g. control rod worth).



- η of ^{235}U in the fast energy range (> 1e4 eV) is lower than that of ^{239}Pu.
  - Lead to the poor fissile conversion when LEU is used as a high-conversion FR fuel.
- The net fissile inventory in the core cannot be compensated with the LEU fuel.
  - It is necessary to load high excess reactivity when introducing LEU fuel assemblies next to TRU fuel assemblies.
- ^{235}U has a higher effective delayed neutron fraction, β_{eff}, than ^{239}Pu.
  - It may offset large reactivity swing caused by LEU loading.

Scope of This Study

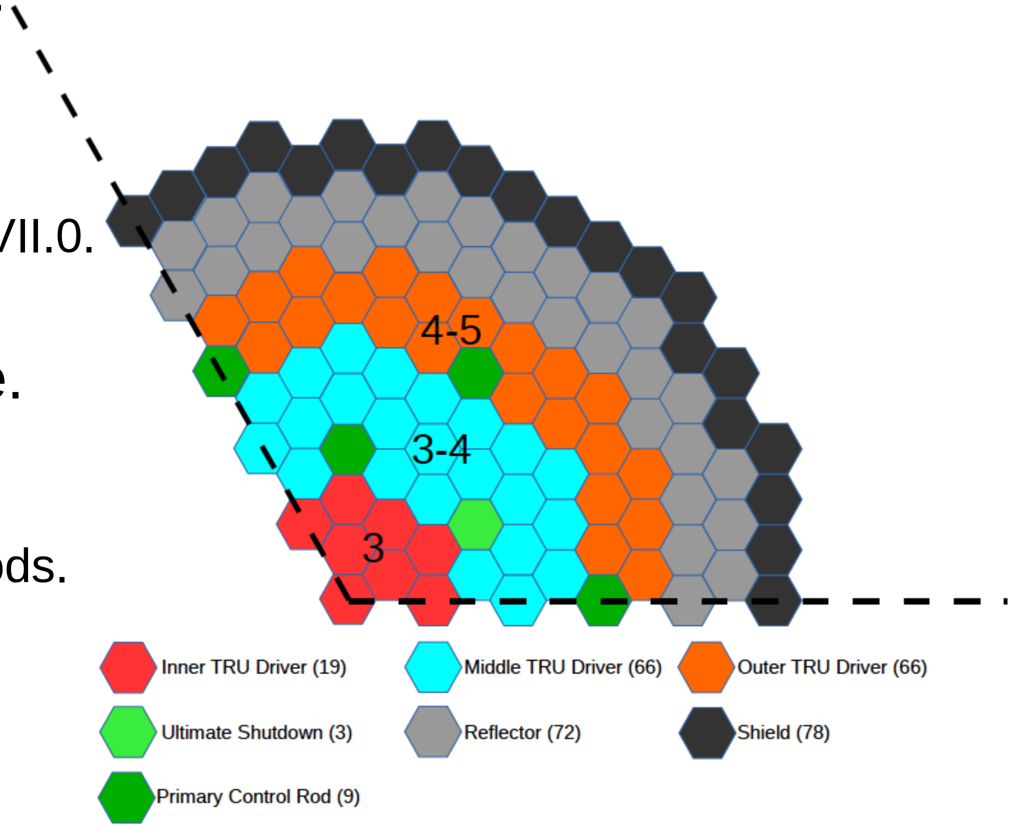
- Study the impact of partially loaded LEU fuels within TRU fueled **breakeven** SFR on fuel-cycle aspects:
  - Transition of nuclide evolutions.
  - Control rod requirement.
- Investigate how cycle lengths and power levels need to be sacrificed without insertion of control elements.

- For simplicity, the LEU fuel is assumed to be the pure mixture of ^{235}U and ^{238}U.

Breakeven SFR Core Model & Fuel Reloading Simulation

- MC^2-3/DIF3D/REBUS-3 for the SFR fuel reloading simulation.
  - REBUS-3
    - Depletion, fuel-reloading, ex-core fuel management.
  - DIF3D
    - 3D Finite Difference, **Nodal Method**, VARIANT.
  - MC^2-3
    - Generation of 33-group cross sections by ENDF/B-VII.0.

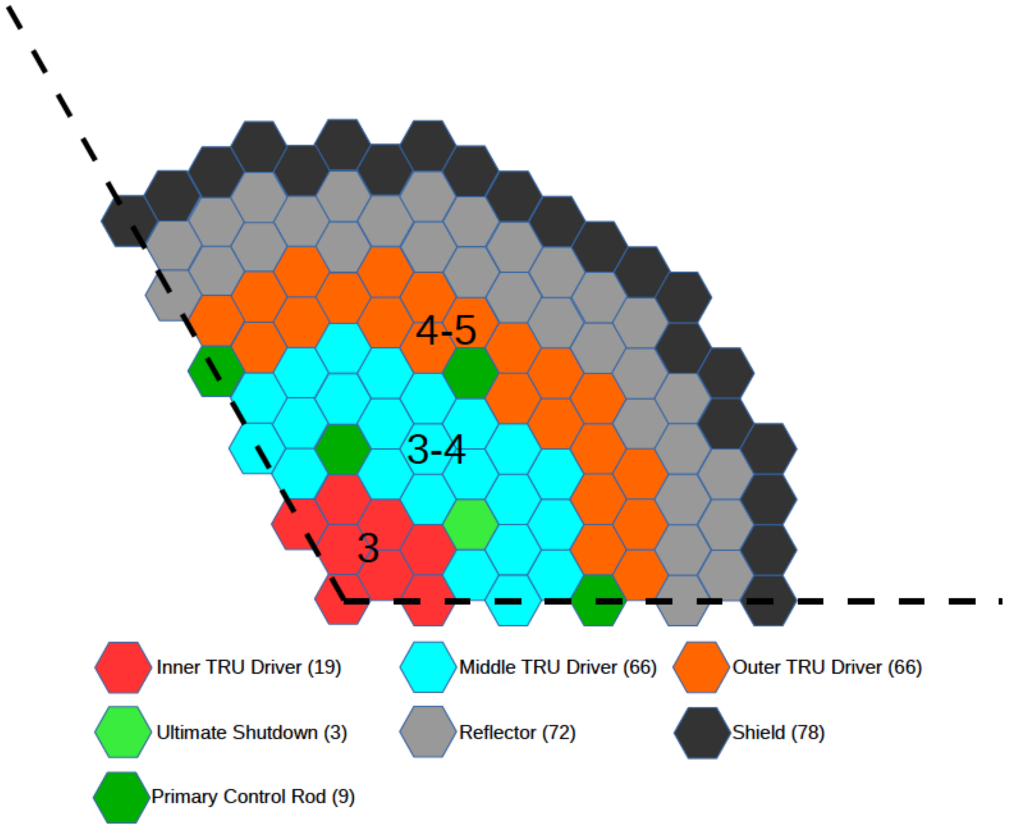
- 1000 MW_{th} blanket-free metallic-fuel breakeven core.
  - Similar to the model in ANL-177.
  - Hex-Z.
  - 151 fuel assemblies, 9 primary and 3 secondary control rods.
  - A third core rotational symmetry by periodic BCs.
  - 3 enrichment zones.
  - 41 axial nodes (12 nodes in the active fuel zone).
  - 40% of thermal efficiency for mass-flow calculations.
  - Cycle length = 370 EFPD.



Breakeven SFR Core Model & Fuel Reloading Simulation

- Non-equilibrium mode.
  - TRU feed composition was obtained by equilibrium mode in order to rapidly establish equilibrium condition (after 4-5 cycles).
  - 3 batches (Inner Core), 3-4 batches (Middle Core), 4-5 batches (Outer Core).
- Major Assumptions:
  - No outage period between cycles.
  - No batch-by-batch enrichment variation.
- Effective Delayed Neutron Fraction (by VARI3D):

$$\beta_{\text{eff}} = \sum_{i=1}^{6} \beta_i = \sum_{i=1}^{6} \frac{\langle \Phi_g^\dagger : \ \chi_{i,g}^d \sum_{g'=1}^{G} \nu_{d,i} \Sigma_{f,g'} \Phi_{g'} \rangle}{\langle \Phi_g^\dagger : \ \chi_g \sum_{g'=1}^{G} \nu \Sigma_{f,g'} \Phi_{g'} \rangle}$$



LEU Reloading Simulation

- A batch of LEU assemblies are loaded from the Cycle-7 for 1-5 consecutive cycles.
  - The enrichment was manually adjusted for the critical condition.
  - No batch-by-batch enrichment variation.

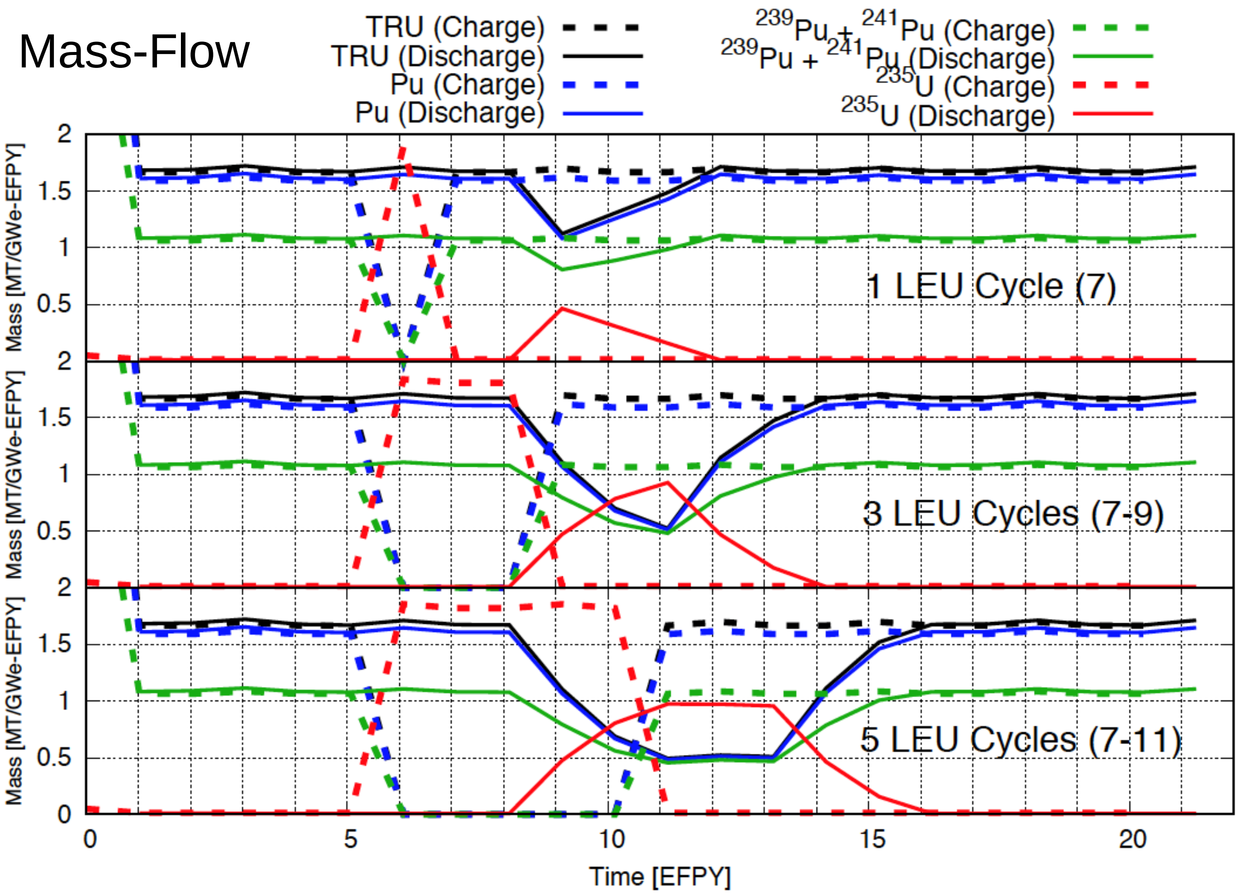
- The LEU enrichment is not strongly sensitive to the number of LEU cycles.

- But it tends to decrease as increasing the number of LEU cycles
  - The core approaches LEU equilibrium → no longer necessary to compensate TRU-LEU reactivity gap.

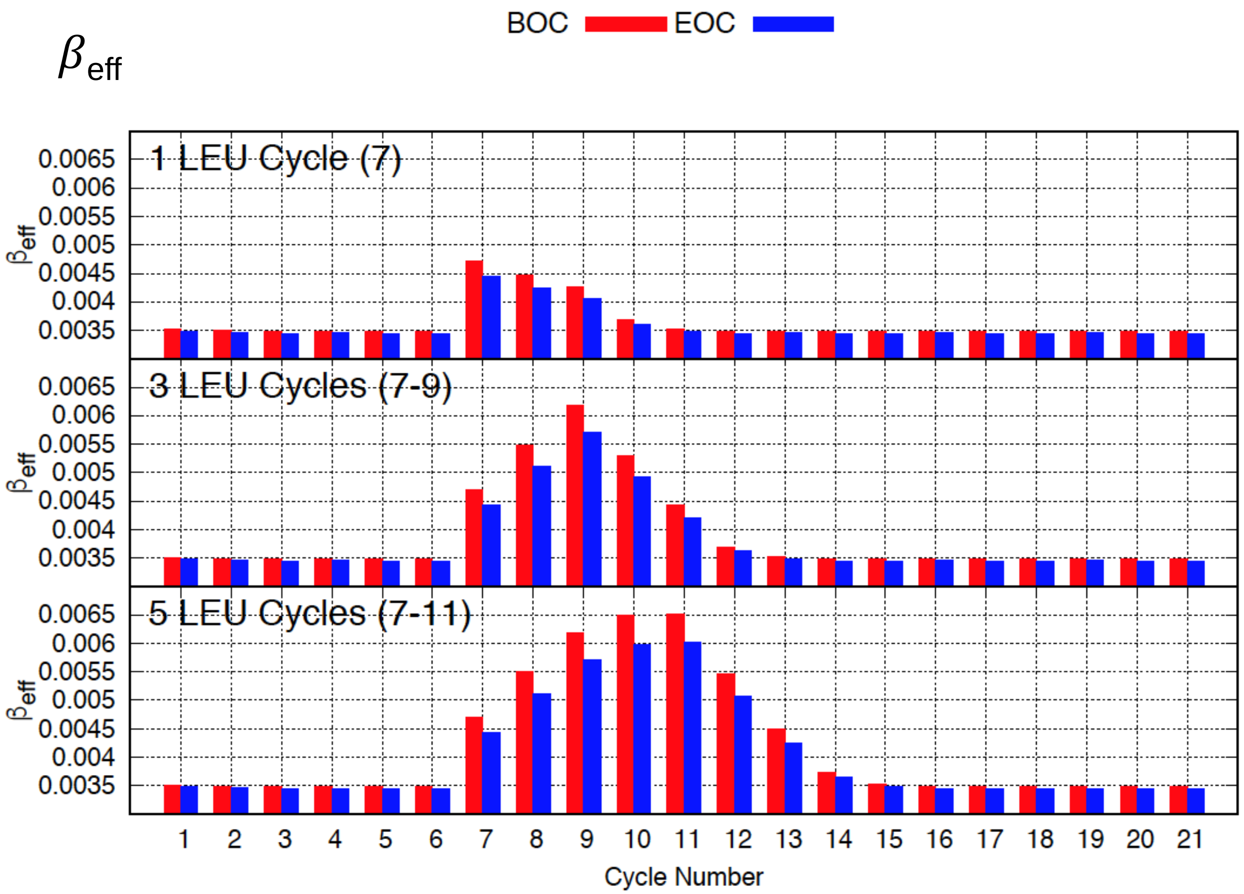
LEU Loading Cycles	Average [wt %]	Inner [wt %]	Middle [wt %]	Outer [wt %]
7	16.053	12.430	15.450	18.587
7, 8	15.851	12.241	15.216	18.304
7, 8, 9	15.647	12.073	15.007	18.053
7, 8, 9, 10	15.833	12.227	15.199	18.283
7, 8, 9, 10, 11	15.764	12.168	15.125	18.195

HM Mass-Flow and β_{eff} of Base Cases

Mass-Flow

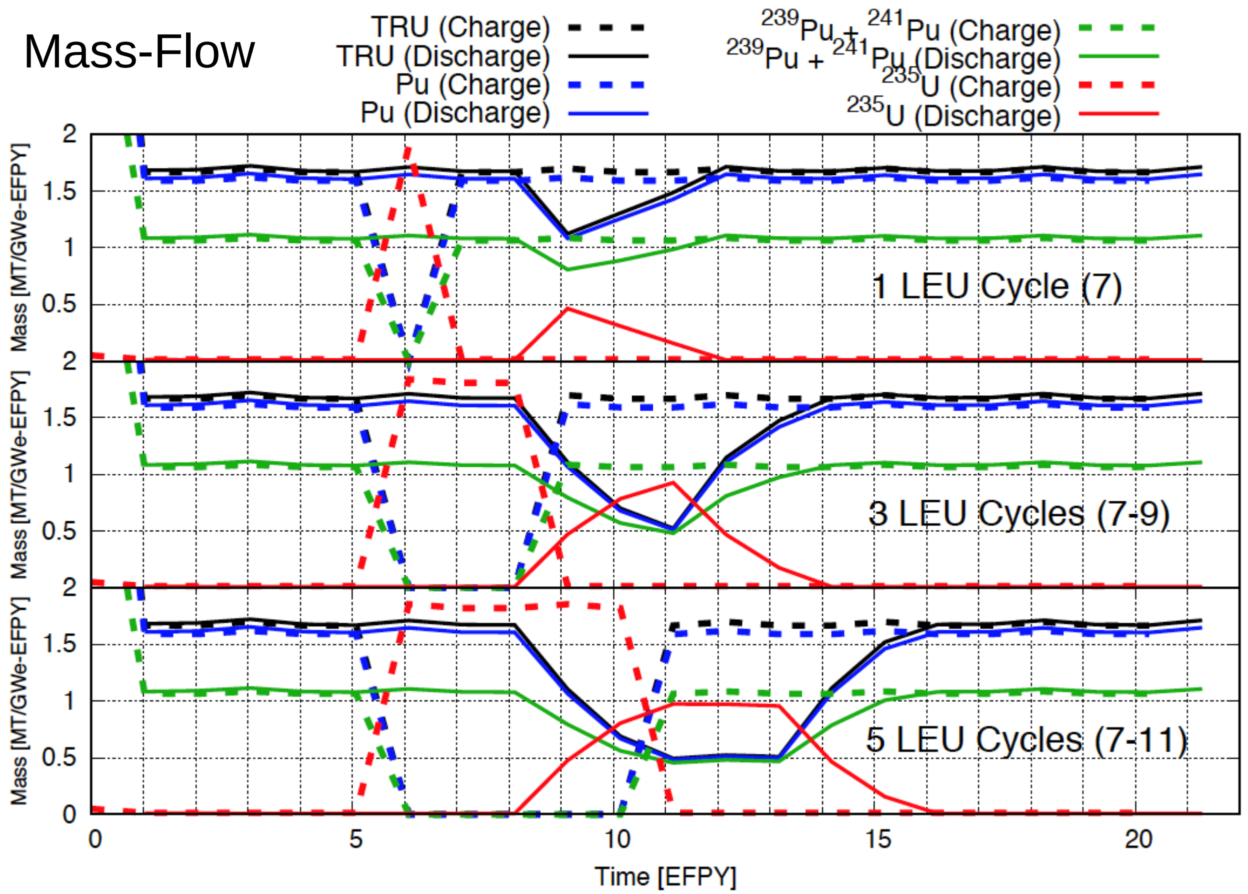


β_{eff}

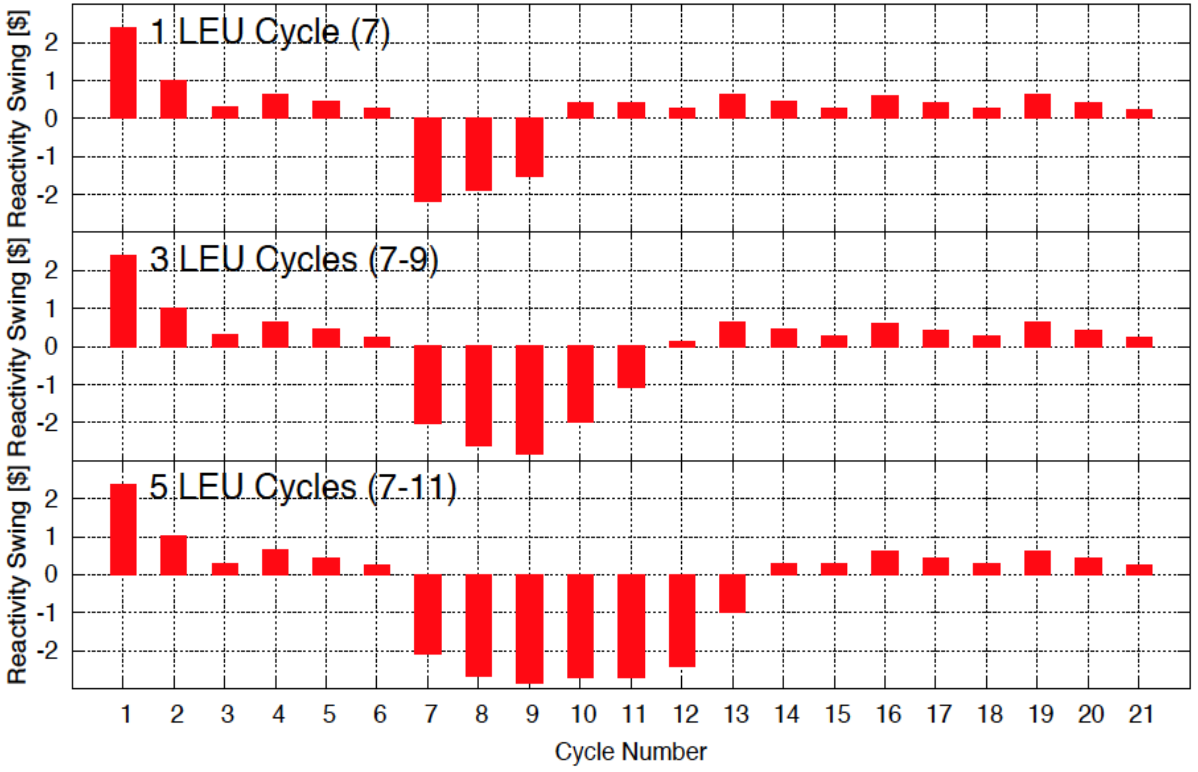


HM Mass-Flow and Uncontrolled Reactivity Swing of Base Cases

Mass-Flow



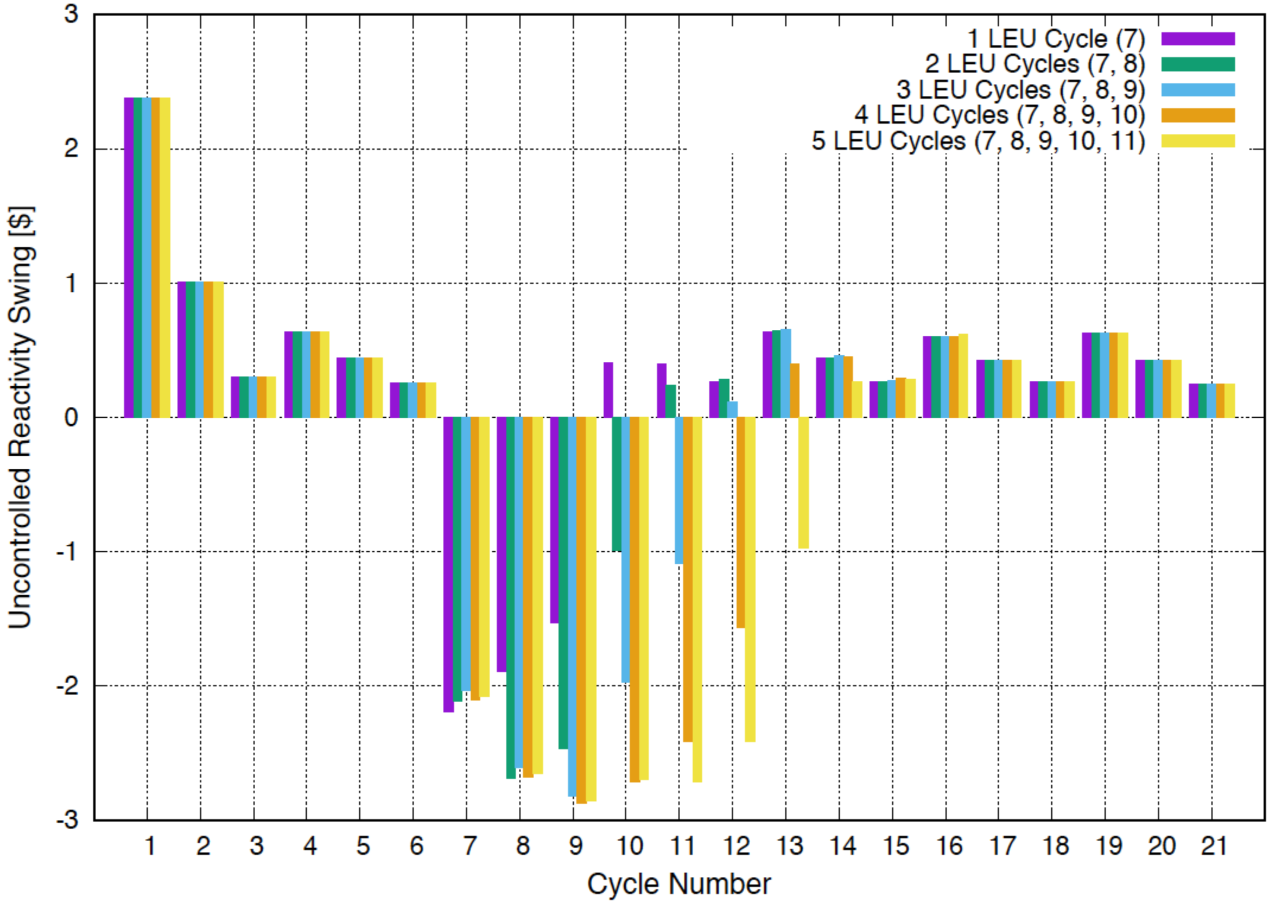
Uncontrolled Reactivity Swing



Estimated Average CR Requirement and Uncontrolled Reactivity Swing

- Small positive reactivity swing during equilibrium TRU cycles (< $0.7).
- Large negative reactivity swing during LEU cycles.
- The average control requirement: $0.3-0.7/rod during LEU cycles. (<$0.2/rod for TRU cycles).

LEU Loading Cycles	CR Requirement [$/rod]	
	BOC	EOC
7	0.670	0.426
7, 8	0.617	0.371
7, 8, 9	0.548	0.323
7, 8, 9, 10	0.610	0.367
7, 8, 9, 10, 11	0.583	0.350
TRU Cycles	0.110	0.137



Case: Reduced Cycle Length

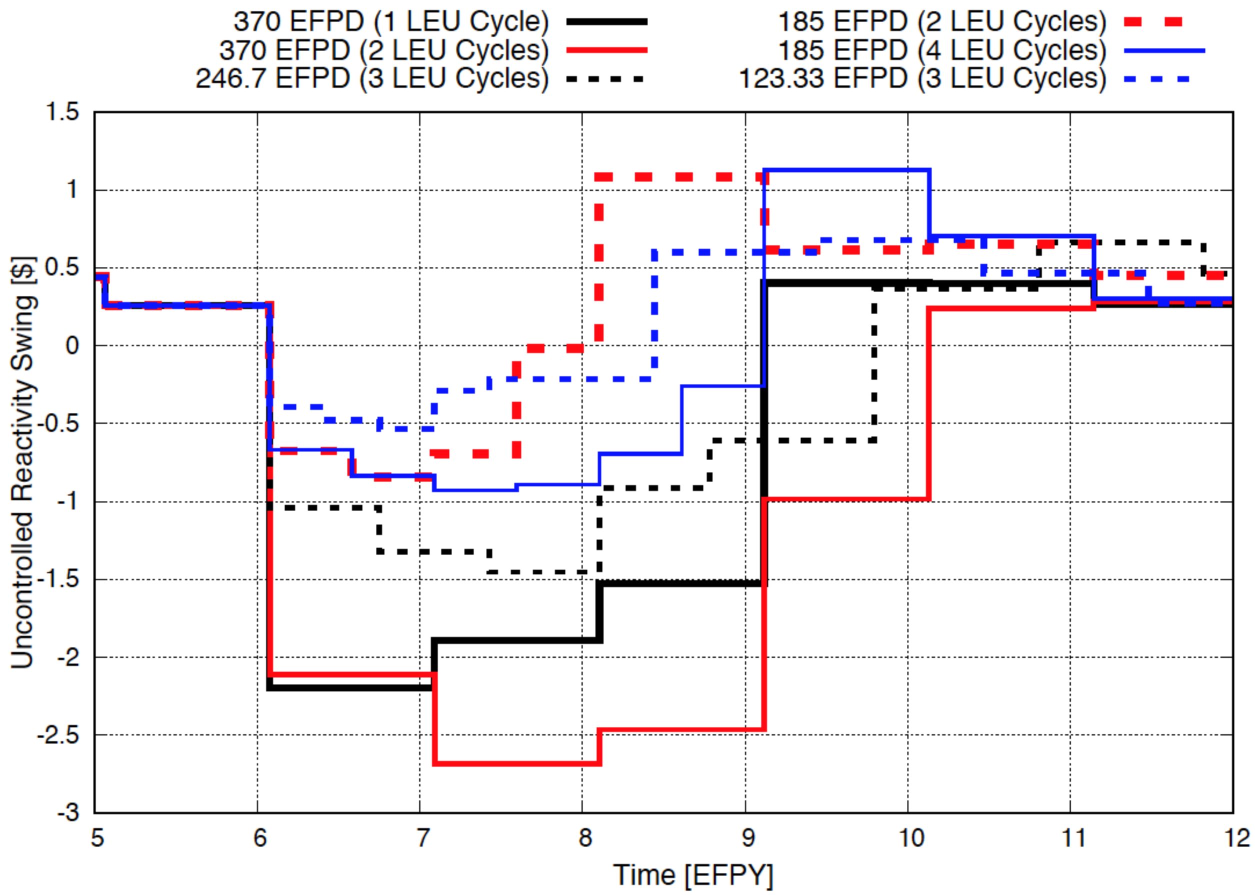
- Attempt to reduce high BOC excess reactivity/ reactivity swing equivalent to TRU cycles without changing core designs.
- Reduce the LEU enrichment.
- Disadvantages:
  - Increases the number of refueling.
  - Increase in fuel fabrication cost.
  - Decrease in capacity factor.
- Look at how cycle lengths and power levels need to be sacrificed without insertion of control elements.

LEU Loading Cycles	Cycle Length [EFPD]	Average [wt %]	Inner [wt %]	Middle [wt %]	Outer [wt %]
7	370	16.053	12.430	15.450	18.587
7, 8	370	15.851	12.241	15.216	18.304
7, 8, 9	246.7 (Cycles 7-10)	14.895	11.493	14.286	17.185
7, 8	185 (Cycles 7-12)	14.588	11.266	14.004	16.846
7, 8, 9, 10	185 (Cycles 7-12)	14.562	11.246	13.979	16.816
7, 8, 9	123.33 (Cycles 7-10)	14.426	11.131	13.836	16.644

Uncontrolled Reactivity Swing and Estimated Average CR Requirement

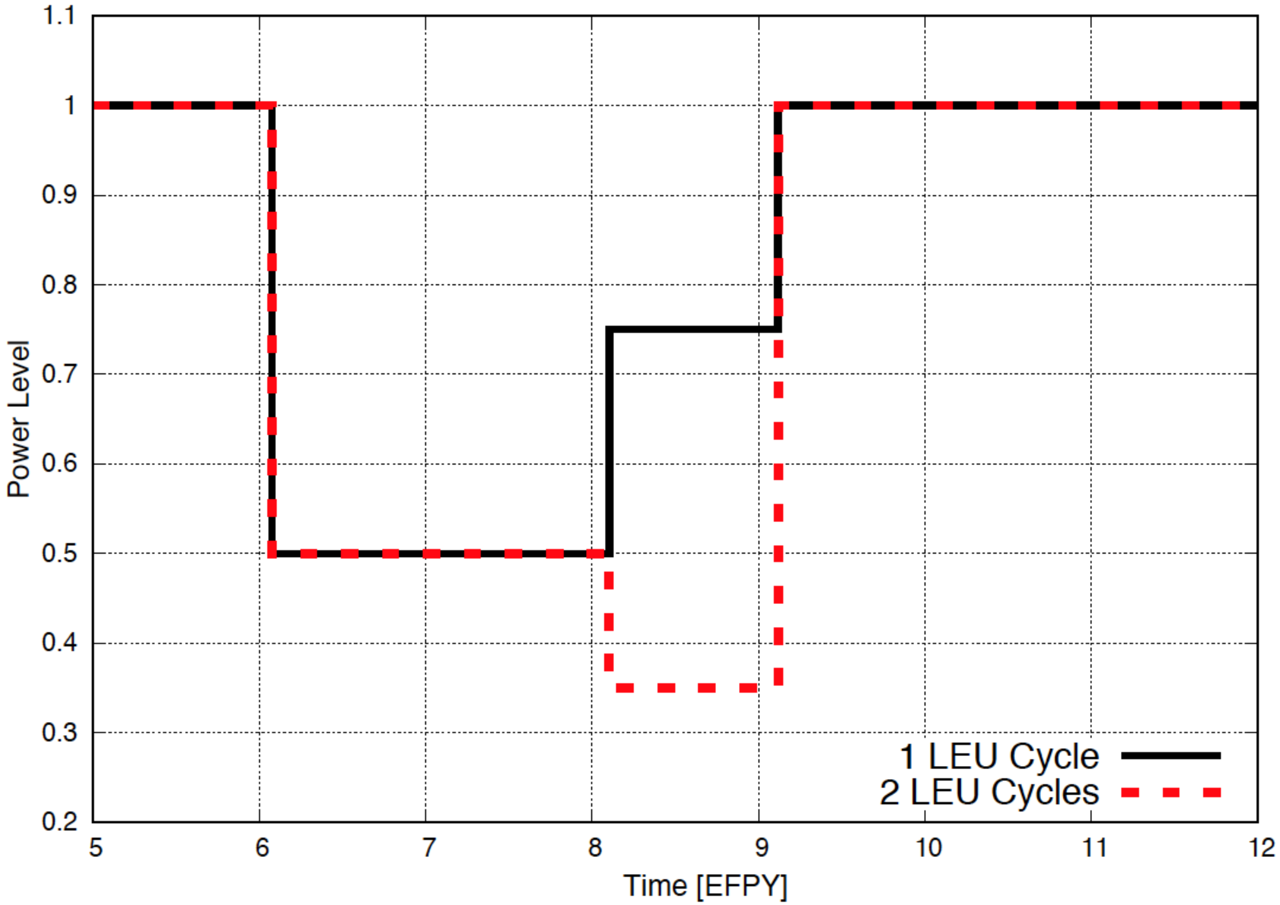
- In order to reduce the reactivity swing and CR requirement to the level of TRU cycles, the cycle length of 4-6 cycles from the first LEU cycle need to be reduced less than a third of the original length.

LEU Loading Cycles	Cycle Length [EFPD]	CR Requirement [$/rod]	
		BOC	EOC
7	370	0.670	0.426
7, 8	370	0.617	0.371
7, 8, 9	246.7 (Cycles 7-10)	0.343	0.227
7, 8	185 (Cycles 7-12)	0.261	0.185
7, 8, 9, 10	185 (Cycles 7-12)	0.253	0.179
7, 8, 9	123.33 (Cycles 7-10)	0.211	0.167
TRU Cycles		0.110	0.137



Case: Reduced Power Level

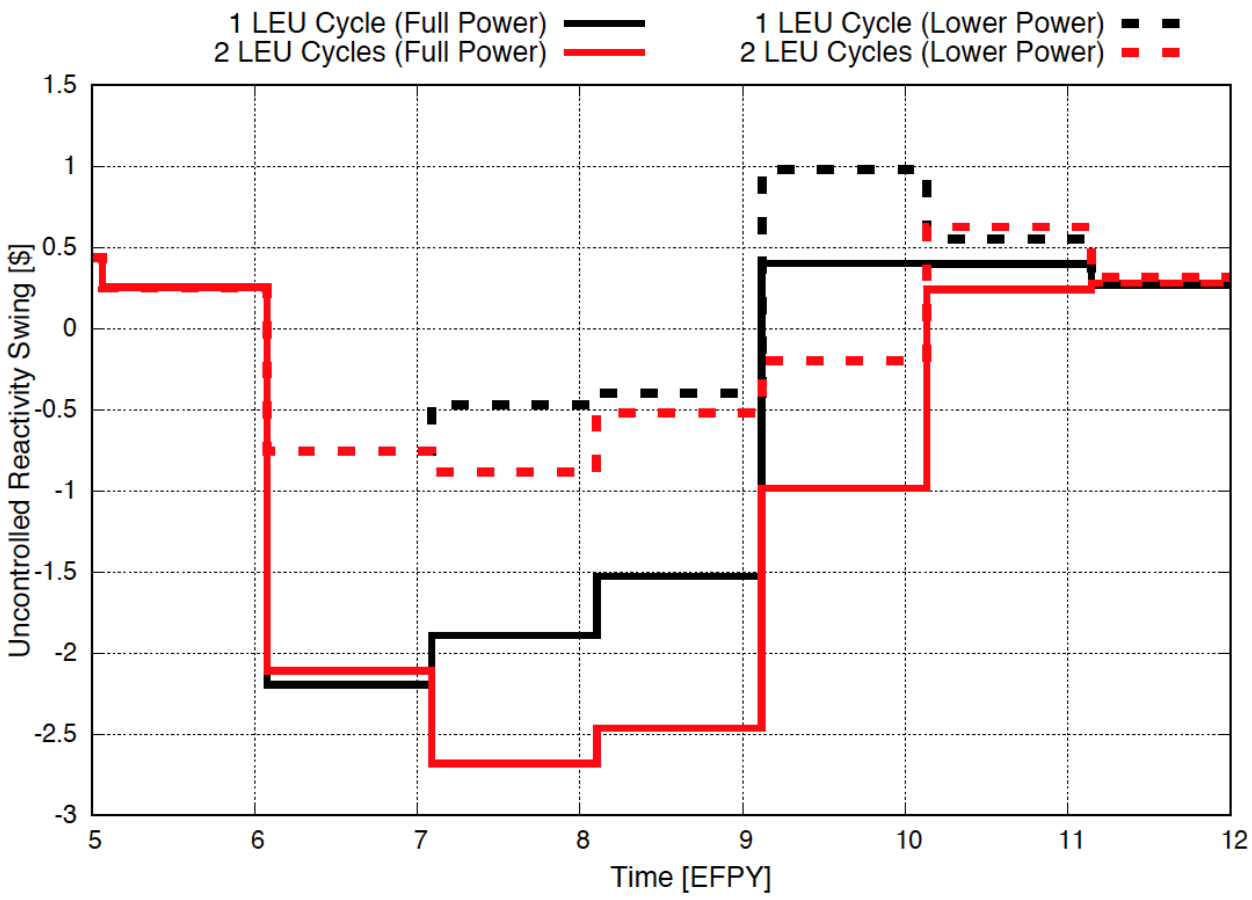
- LEU average enrichment = 14.588 %.
- The same cycle length (370 days).
- Two cases (1 LEU cycle & 2 LEU cycles).
- Power of Cycles 7 and 8 were lowered to 50% of original power level.
- The power of Cycle 9 was adjusted.



Uncontrolled Reactivity Swing and Estimated Average CR Requirement

- Significantly lowered power level (<50%) for equivalent reactivity swing and CR requirement.
- LEU cannot compensate TRU fuel by maintaining the same level of the excess reactivity and reactivity swing.

LEU Loading Cycles	CR Requirement [$/rod]	
	BOC	EOC
1 LEU Cycle (Full Power)	0.670	0.426
2 LEU Cycles (Full Power)	0.617	0.371
1 LEU Cycle (Lower Power)	0.261	0.177
2 LEU Cycles (Lower Power)	0.261	0.177
TRU Cycles	0.110	0.137



Summary/Conclusion

- While TRU equilibrium cycles exhibited small but positive reactivity swing, the reactivity swings of LEU cycles were significantly larger than those in TRU equilibrium cycles, and the core was acting like a burner reactor showing large negative reactivity swing over the cycle.
- In order to reduce larger control requirement during LEU cycles to the equivalent level to those of TRU cycles, either cycle length or power level needed to be significantly reduced, which potentially increases fuel-cycle cost per unit energy produced.
- Beside of increasing the number of control rods, SFR cores having slightly lower burnup could be the option for smoothly accommodating the TRU-LEU transition.
  - Small axial blanket.
  - Increase fuel volume fraction.