Systematic Evaluation of Uranium Utilization in Nuclear Systems

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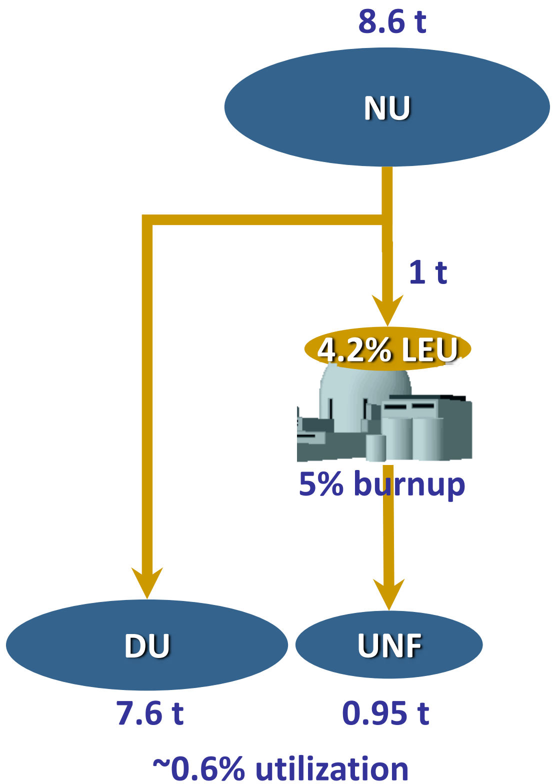
Background

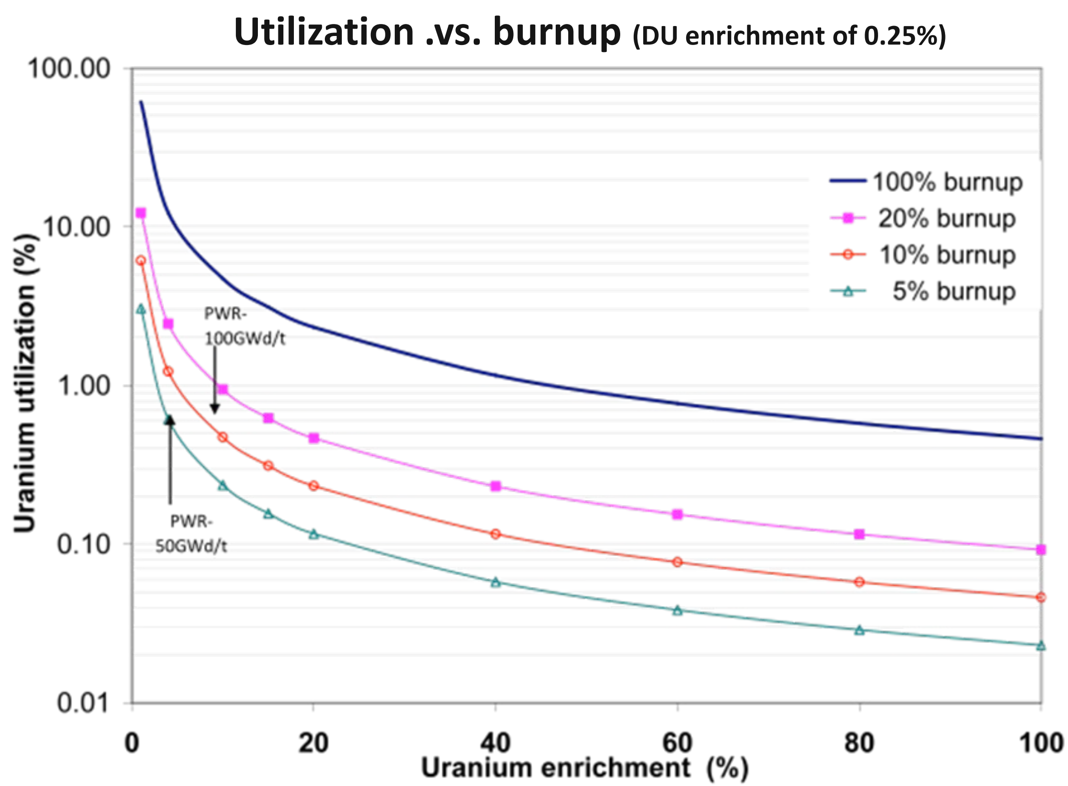
- **Uranium utilization is defined as ratio of heavy metal mass burned by fission to total uranium mass used for making fuel**
- **Current commercial nuclear system uses less than one-percent of energy available in mined uranium**
- **R&D objectives of US-DOE Nuclear Energy Office**

  Statement of Dr. Miller, Jr. Assistant Secretary of US-DOE before the Committee on Science and Technology U.S. House of Representatives, May 19, 2010)

  - **R&D OBJECTIVE 3: Develop Sustainable Nuclear Fuel Cycles**
    - Sustainable fuel cycle options are those that improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit proliferation risk
    - The key challenge is to develop a suite of options that will enable future decision makers to make informed choices about how best to manage the used fuel from reactors
    - DOE exploring once-through cycle, modified open cycle, full-recycling options
- **Primary objectives of this study are to provide information on once-through high uranium utilization systems proposed recently**
  - Performed scoping calculations to identify core performance parameters
  - Evaluated overall fuel cycle impacts (such as uranium utilization, etc)

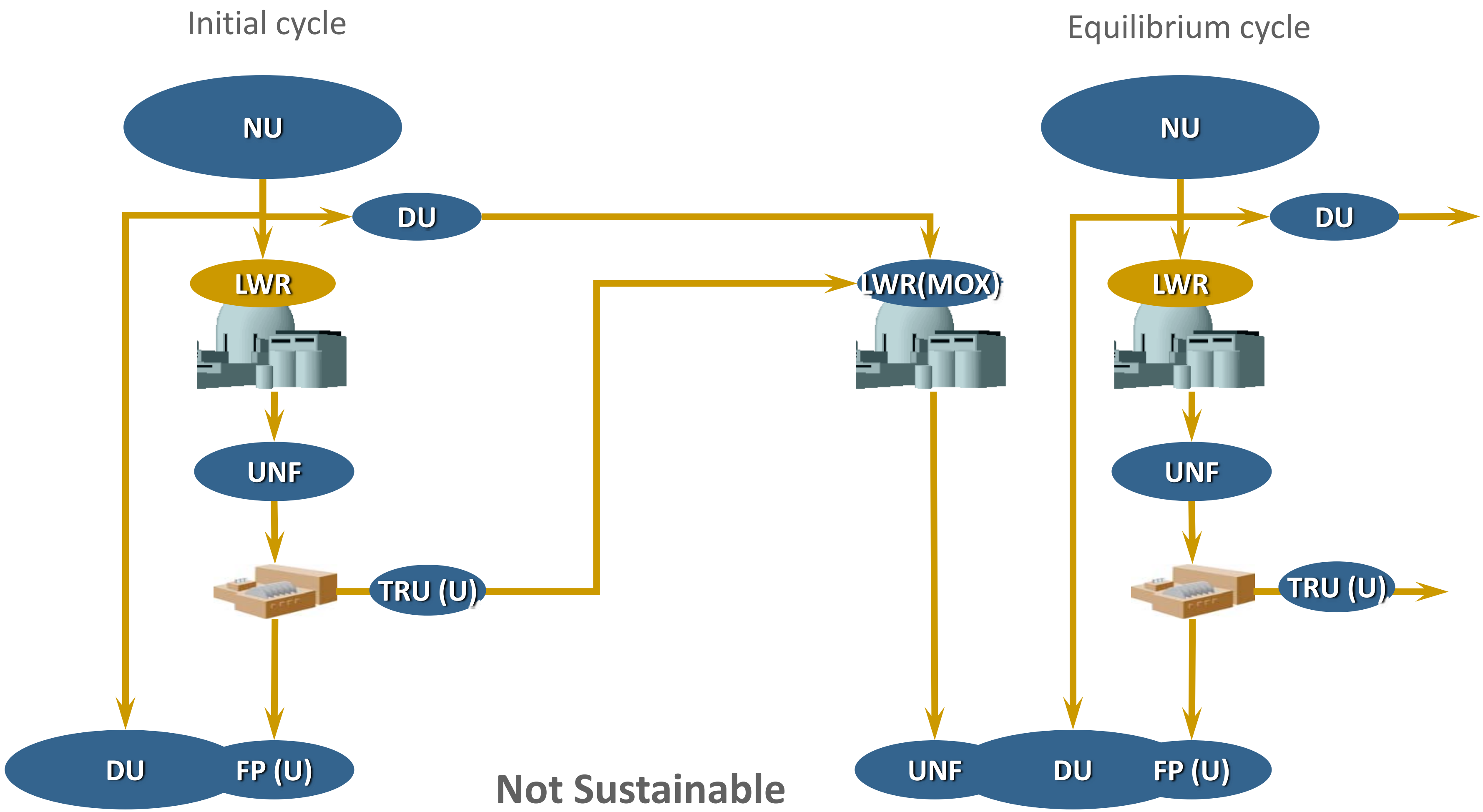
Uranium Utilization of Commercial Once-Through Systems





- **Low enrichment and high burnup is favorable to improve uranium utilization**
  - High burnup does not help because high enrichment is required
- **Generally, uranium utilization is less than 1%**

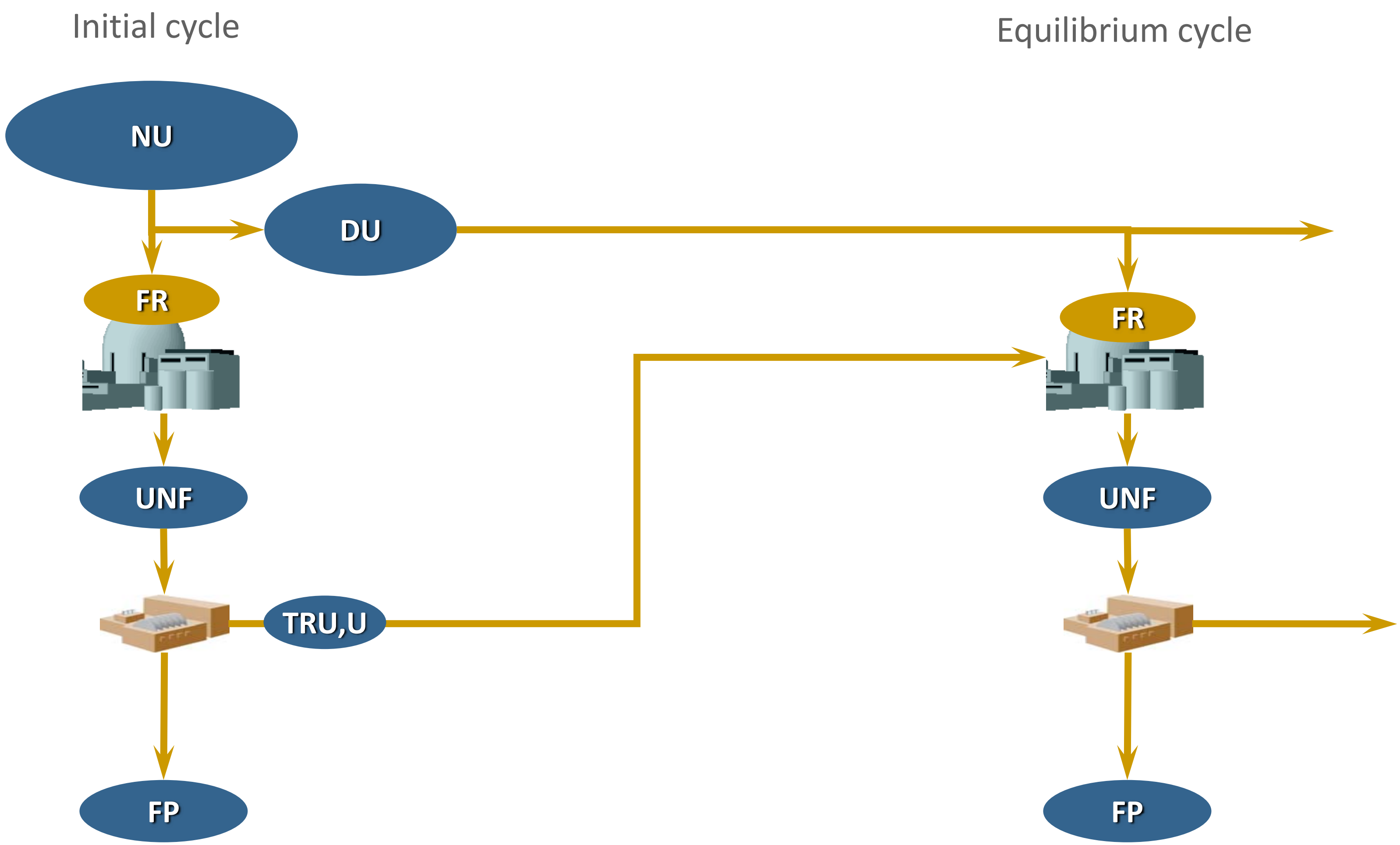
Recycling Option in Thermal Systems



Not Sustainable

Requires enriched uranium support

Recycling Option in Fast System



Sustainable due to breeding capability

Summary of Once-through and Recycling Options

- **Once-through systems**

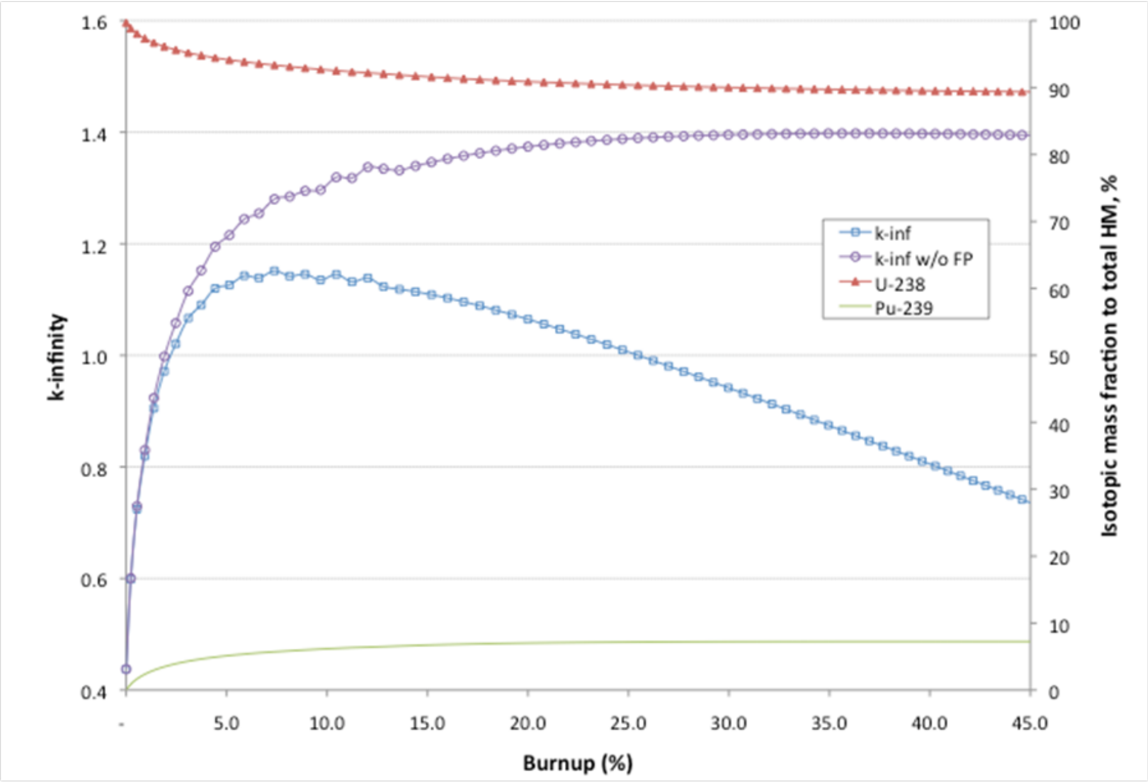
	PWR-50GWd/t	PWR-100GWd/t	VHTR	Fast Burner
Burnup, %	5	10	10.5	22.3
Enrichment, %	4.2	8.5	14.0	12.5
Utilization, %	0.6	0.6	0.4	0.8

- **Recycling options**

	Pure thermal		Thermal-fast hybrid		Pure fast
	LWR-UOX	LWR-MOX	LWR-UOX	Burner	Breeder
Power sharing, %	90	10	57	43	100
Burnup, %	5	10	5	9	-
Enrichment, %	4.2	-	4.2	12.5	-
Utilization, %	0.7		1.4		> 95

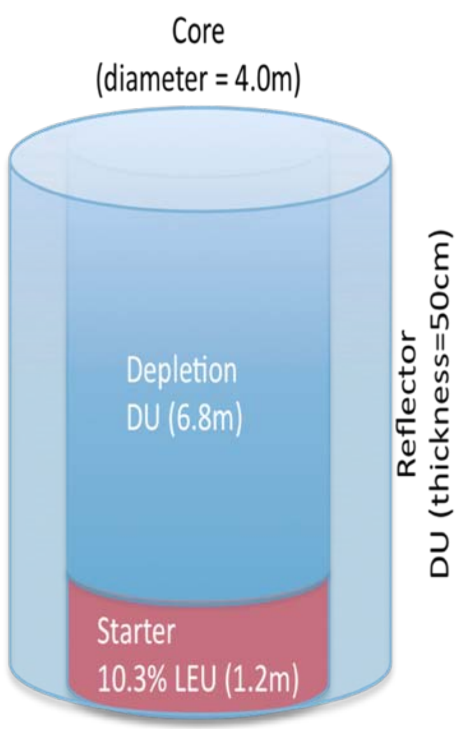
- **For non-sustainable once-through systems, uranium utilization is less than 1%**
- **For sustainable recycling systems, uranium utilization could be> 95% theoretically**
- **For non-sustainable recycling systems, however, improvement of uranium utilization is marginal because enriched uranium support is required**
- ***Sustainability is key to improve uranium utilization***

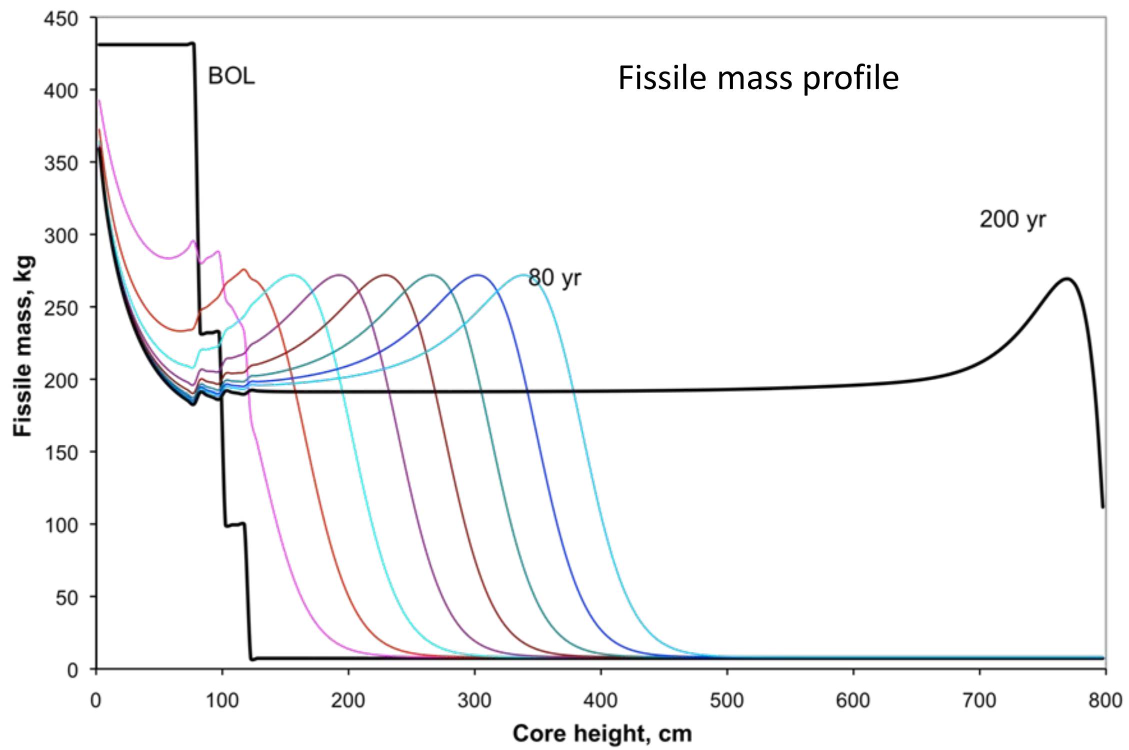
Sustainable w/o Recycling or Enrichment Support?



- **For sustainable fuel cycle with depleted uranium:**
  - Burnup should be reasonably high to breed sufficient plutonium, but adequately low to avoid fission product (FP) penalty
  - Escape from FP dominant zone (*traveling-wave)* or remove FP dominant fuel (*shuffling*)

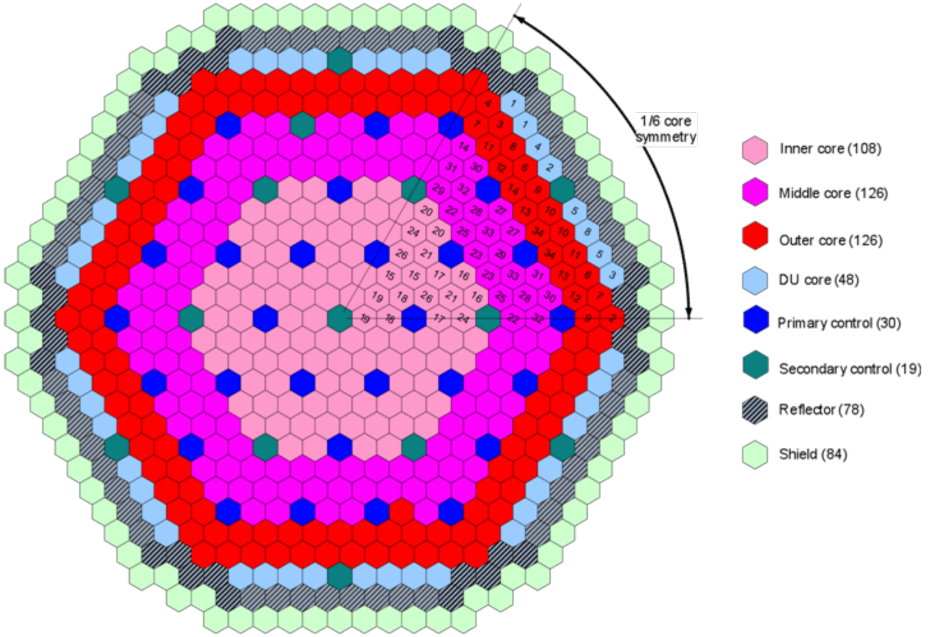
CANDLE

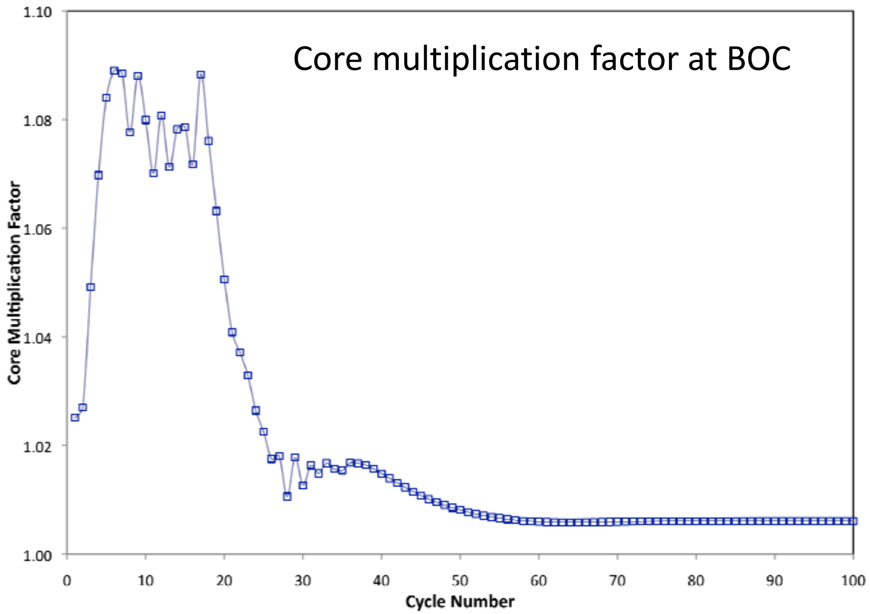




- **Burn-zone (power) propagates from starter region to depletion region**
- **Sustainable as long as depleted uranium is available**
  - Reactor operation time is dependent on height of depletion region

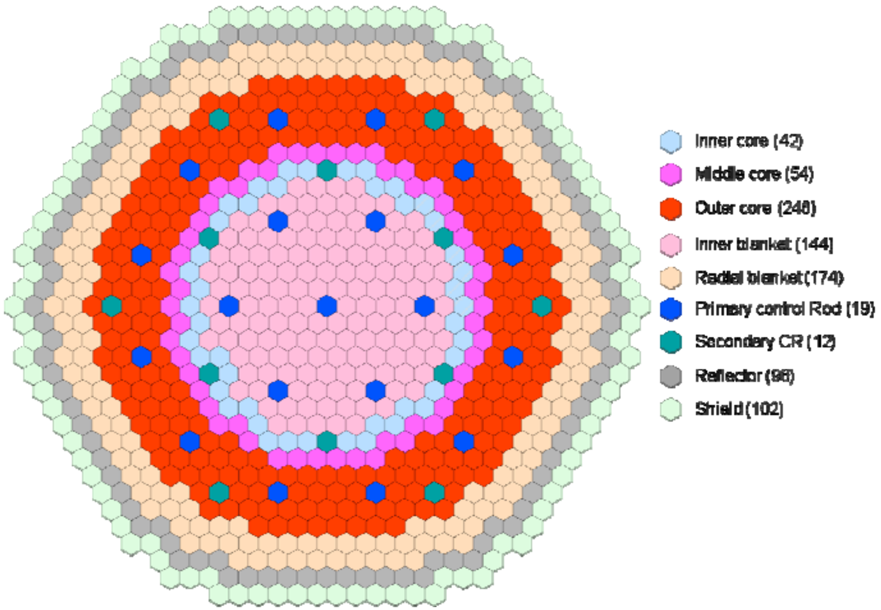
SSFR – Sustainable Sodium-cooled Fast Reactor



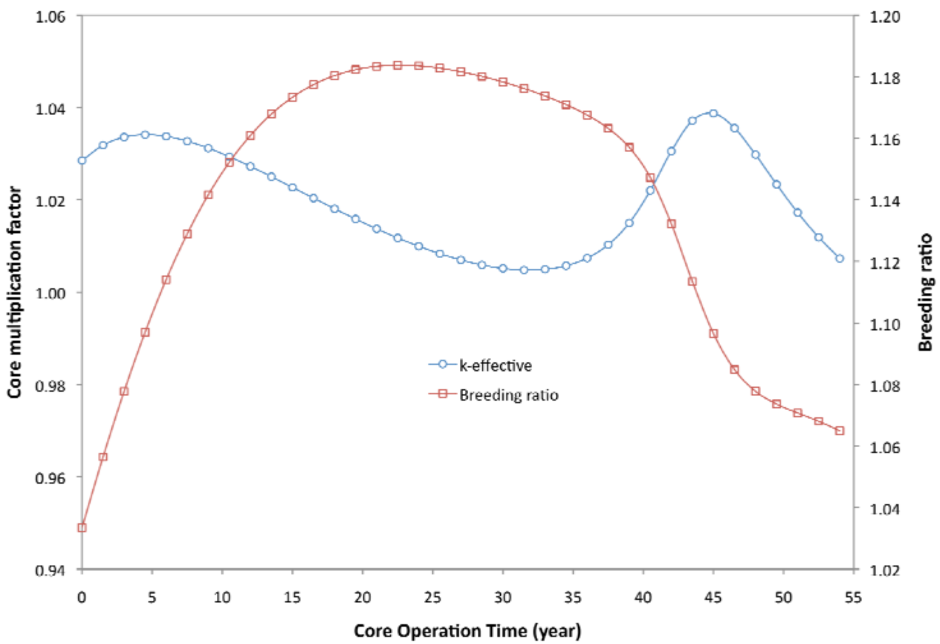


- **Sustainable by feeding depleted uranium assemblies except for initial core**
  - Enriched uranium fuel used as driver of initial core
  - 34 batch scheme with 1.5 year cycle length
  - Slowly converges to equilibrium cycle

ULFR – Ultra-long Life Fast Reactor



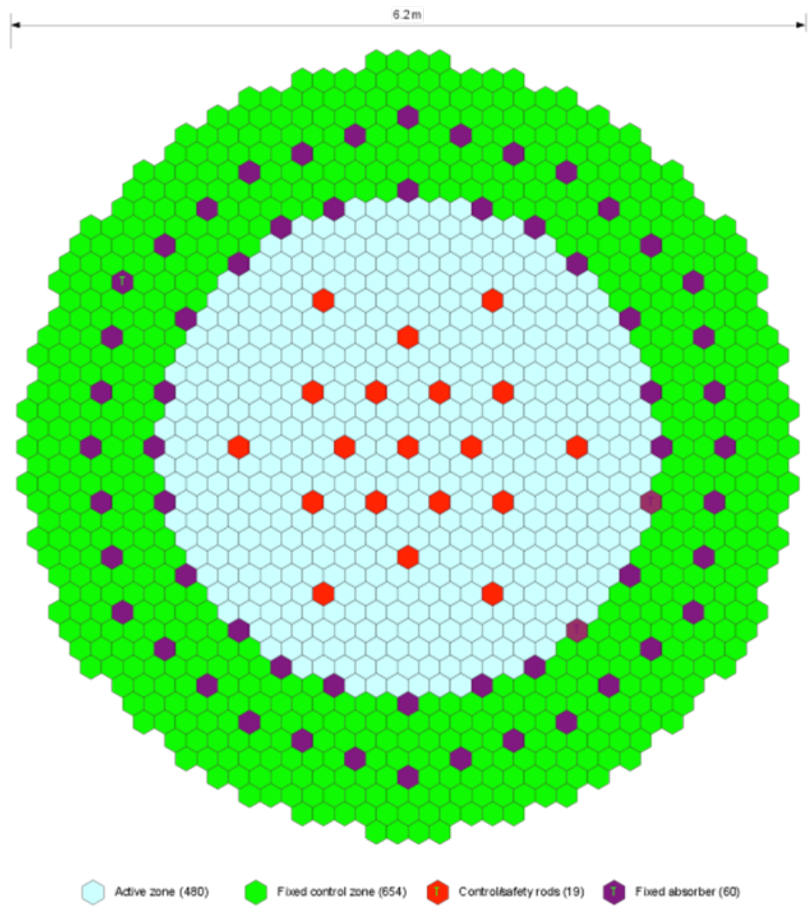
Core multiplication factor and breeding ratio



- **Burn-zone (power) propagates inwardly**
- **Sustainable as long as internal depleted uranium is available**
  - Reactor operation time is ~54 years without refueling

TWR – Traveling Wave Reactor

- **Original TWR core concept is similar to CANDLE concept**
  - Burn-zone propagates along natural or depleted uranium zone
  - TerraPower proposed a special case TWR core design: *standing wave* by periodically moving fuel in and out of breed-and-burn region
- **Sustainable as long as depleted uranium is available**
  - Reactor operation time of current 3000 MWth particular design is ~40 years



Core configuration may be different from recent TWR core concept of TerraPower because it was drawn using open literature

Summary of Sustainable Strategies of Advanced Once-Through Systems

	Fissile breeding	Treatment of FP
CANDLE/TWR (original)	Axial propagation of burn zone	Escape from FP dominant zone
ULFR	Radial (inward) propagation of burn zone	Escape from FP dominant zone
SSFR	Breeding Pu in blanket	Remove FP dominant fuel by shuffling
Breed-and-burn	Breeding Pu in blanket	Remove FP dominant fuel by shuffling and re-cladding

Reactor Performance Parameters

	PWR50/100	CANDLE	SSFR	ULFR	[a] TWR
Reactor power, MWt	3000	3000	3000	3000	3000
Thermal efficiency, %	33.3	40.0	40.0	40.0	37.8
Fuel Form	UO_2	U-Zr	U-Zr	U-Mo	U-Zr
Uranium enrichment, %	4.2 / 8.5	1.2	[b] 6.2 / 0.25	4.1	2.5
Number of batches	3	1	34	1	1
Burnup, GWd/t	50 / 100	258	277	166	93
Specific power density, MW/t	33.7	3.7	16.9	9.4	7.5
Cycle length per batch, yr	1.5 / 3.0	[c] 200	1.5	54	38
HM inventory, t	89	824	178	320	399
HM fission, t/yr	1.03	1.03	1.02	1.04	1.03

a) Scoping calculations were performed using open literature. Thus, some results may differ from values generated by TerraPower LLC.
b) First core and subsequent cores
c) Reactor operation time with 8 mactive core height

- **Compared to PWR systems, power density of advanced once-through fast reactor systems are significantly derated**
- **Due to long fuel residence time, however, average burnup higher than that of PWR**

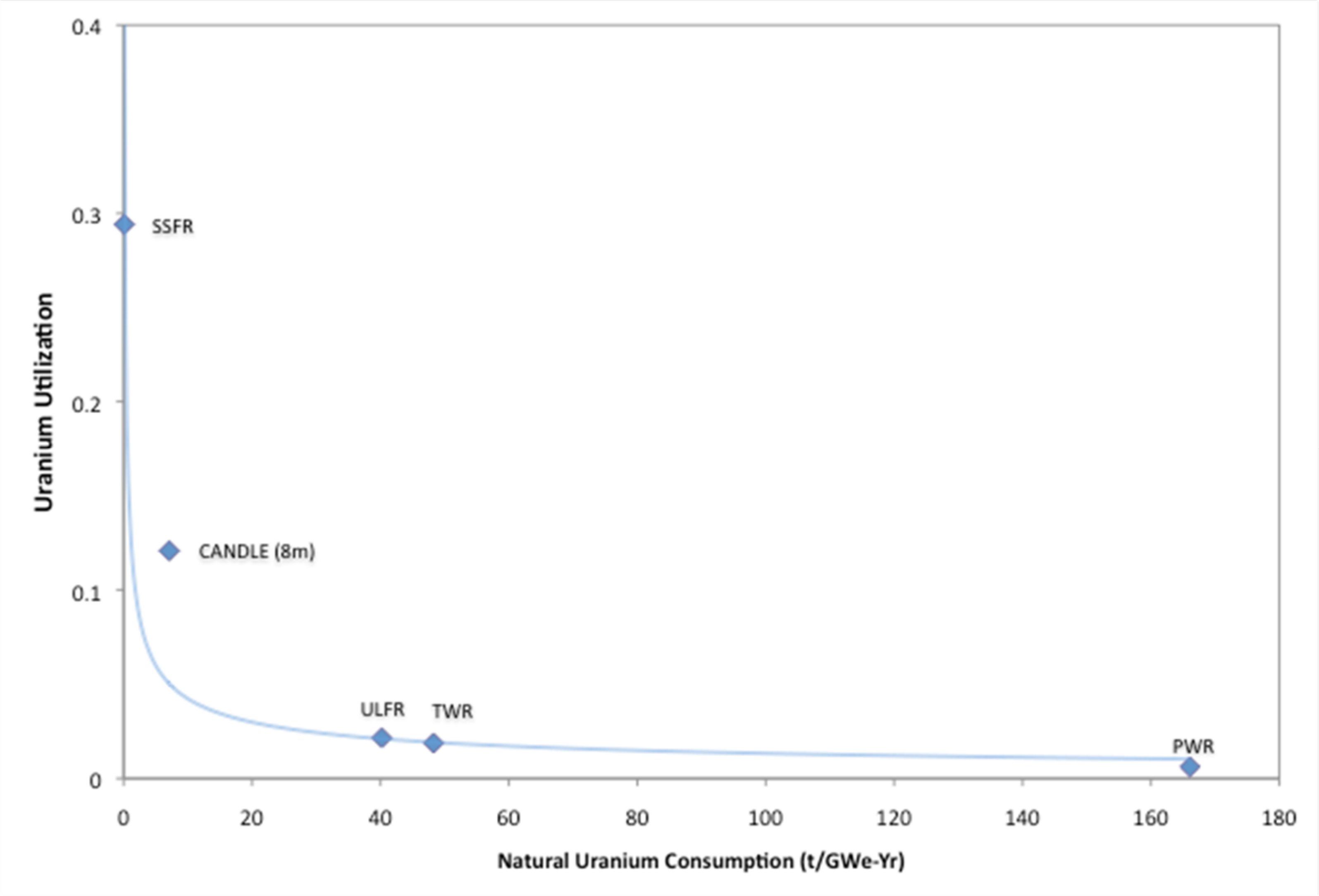
Uranium Utilization

	PWR50/100	CANDLE	a) SSFR	ULFR	TWR
Uranium enrichment, %	4.2 / 8.5	1.2	0.25	4.1	2.5
Tail Uranium enrichment, %	0.25	0.25	0.25	0.25	0.30
Required NU, t/GWe-yr	166.1	7.1	0.0	40.2	48.3
HM fission, t/GWe-yr	1.03	0.86	0.85	0.87	0.91
Uranium utilization, %	0.6	b) 12.1	29.4	2.2	c) 1.9

a) Equilibrium cycle.
b) Case for 8 m active core height. Theoretical maximum uranium utilization is ~25%.
c) TWR designers indicated that UNF could be used to start-up subsequent reactors. If such designs are possible, then higher utilization can be obtained.

- **For commercial once-through system (PWRs), uranium utilization is less than ~1% regardless of discharge burnup**
- **For sustainable once-through fast reactor systems, uranium utilization could be increased to average discharge burnup as long as depleted uranium is available, but attainable uranium utilization is dependent on design choices**

Uranium Utilization versus Natural Uranium Consumption Rate

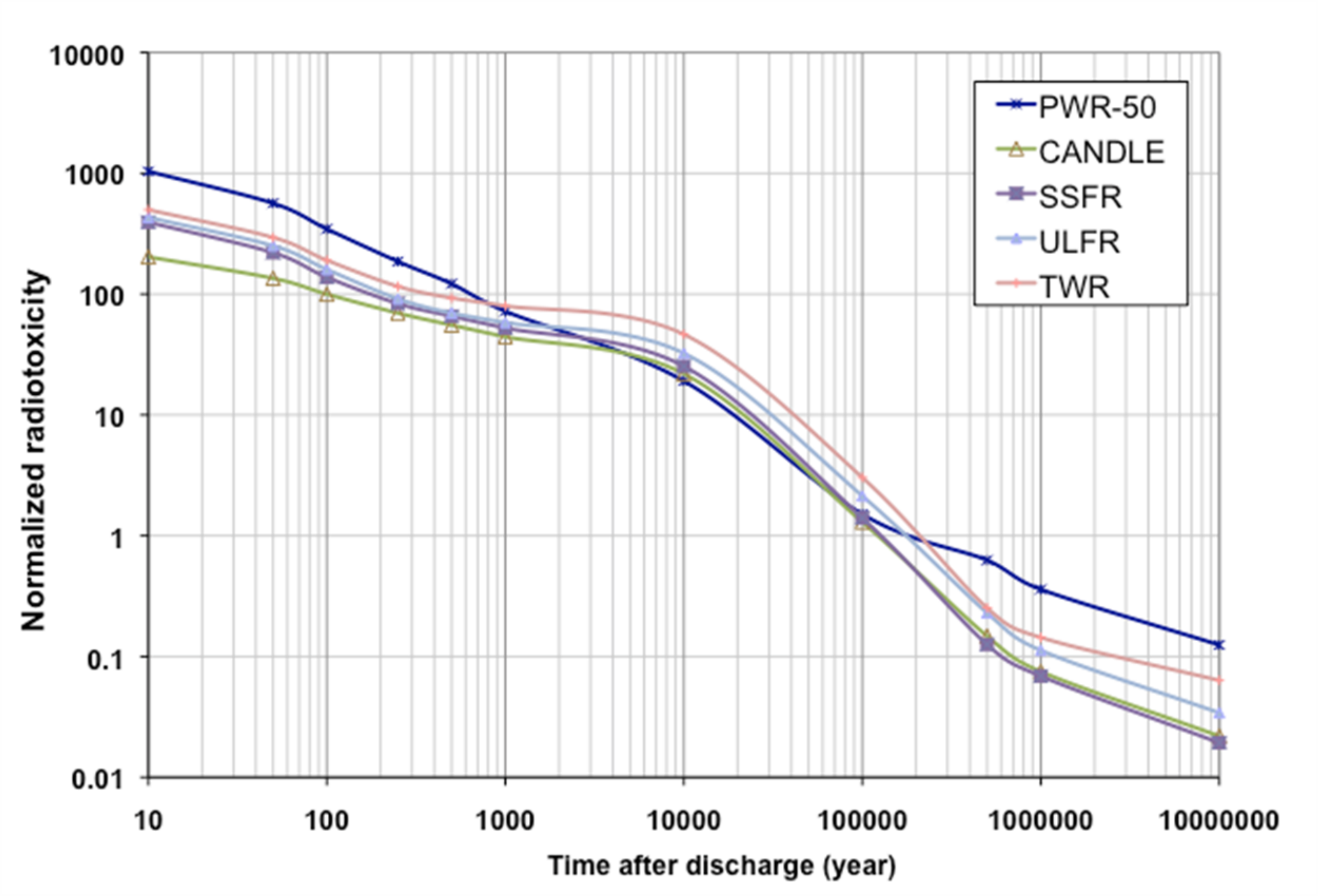


Characteristics of Used Nuclear Fuel

t/GWe-yr	PWR50	CANDLE	SSFR	ULFR	TWR
UNF total	19.71	3.42	2.90	4.93	9.26
Uranium	18.4	2.33	1.77	3.68	7.81
Plutonium	0.24	0.24	0.28	0.37	0.53
Minor Actinides	0.02	0.01	0.01	0.01	0.01
Fission products	1.03	0.84	0.85	0.87	0.91
Plutonium isotopic vector (%)					
Pu-238 ($T_{1/2}$ = 87.7yr)	2.5	0.6	0.6	1.0	0.9
Pu-239 ($T_{1/2}$ = 2.4 ξ 10^4 yr)	51.6	76.8	74.3	82.6	84.9
Pu-240 ($T_{1/2}$ = 6565 yr)	23.7	21.1	22.3	15.0	13.3
Pu-241 ($T_{1/2}$ = 14.4 yr)	14.9	0.7	2.1	1.1	0.9
Pu-242 ($T_{1/2}$ = 3.7 ξ 10^5 yr)	7.2	0.8	0.6	0.3	0.2

- **Compared to PWR system, normalized UNF production rates of fast reactor systems are lower but plutonium production rates are comparable (or higher)**
- **High Pu-239 content affects radiotoxicity and decay heat during 1.0×10^3 – 1.0×10^5 yrs**

Comparison Normalized Radiotoxicity



Conclusions

- **Sustainable fuel cycle is key to improve uranium utilization**
  - For commercial once-through systems, uranium utilization is less than 1% because most natural uranium becomes depleted uranium during enrichment process, rather than used for energy generation
  - For non-sustainable recycling systems, improvement of uranium utilization is marginal because enriched uranium support is required
  - For sustainable recycling systems, uranium utilization could be >95% theoretically
- **Uranium utilization of advanced once-through fast systems (CANDLE, SSFR, ULFR, TWR) is significantly improved by adopting sustainable fuel cycle strategies**
  - Common core performance characteristics are;
    - Derated power density with high burnup and long fuel residence time (breed-and-burn)
  - Theoretically, uranium utilization could be increased to discharge burnup of ~30%
  - Attainable uranium utilization is dependent on design choices
  - However, technical issues (long transient period, high neutron fluence, big core size, etc) would need to be resolved in order for these concepts to be practical