Thorium as a Nuclear Fuel

Course 22.251

Fall 2005

Massachusetts Institute of Technology

Department of Nuclear Engineering

Earth Energy Resources

Commercial Energy Resources in India

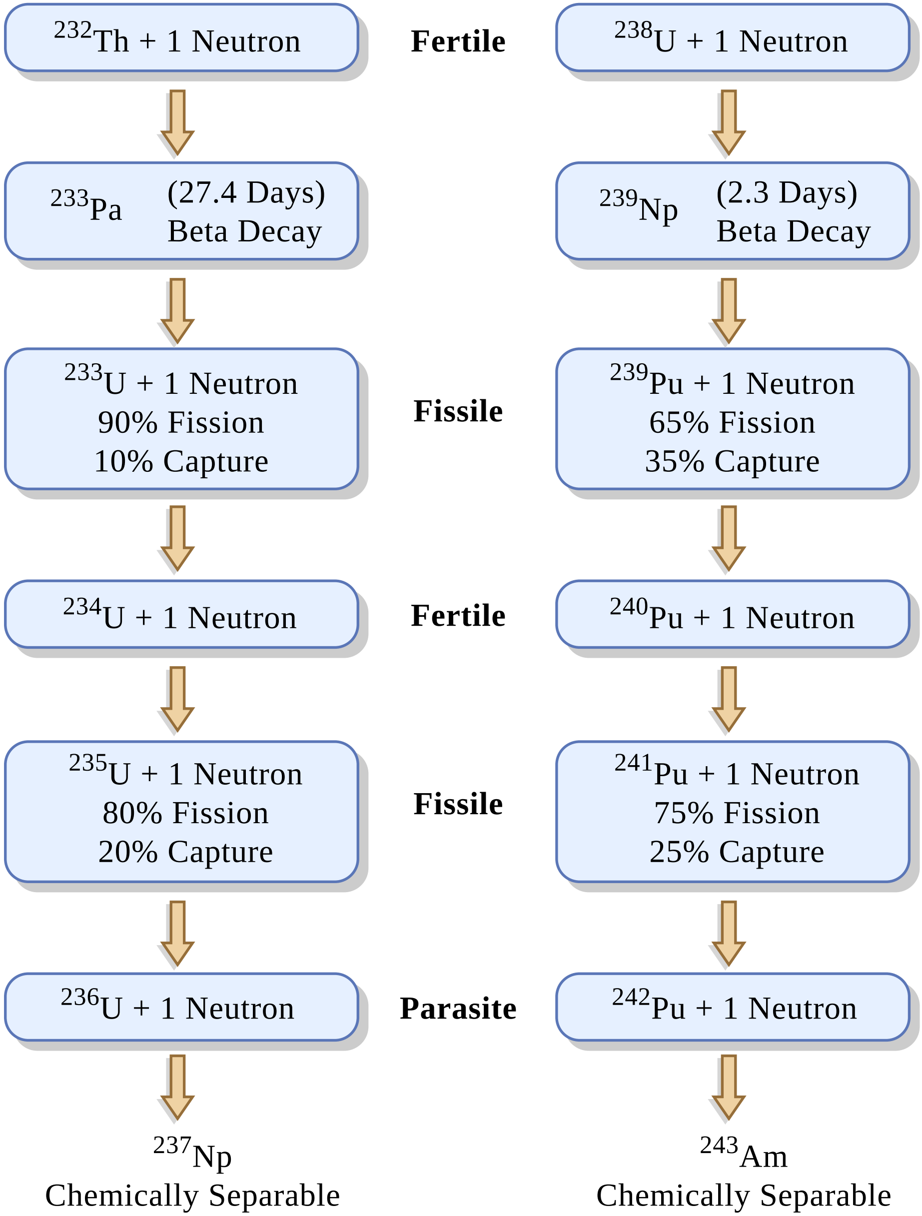
Electricity Generation Potential

Resources	Amount	Coal Equivalent in Billion T	GWe-Yr	Capacity GWe	No. of Years at CF 70%
Coal	190 bt	190	27,000*	350	110
Oil	0.6 bt	1.2	Not to be used for Power Generation		
Natural Gas	540 bm^3	1	280	10	40
Hydroelectricity	84 GWe at 60% CF	0.2/y	Renewable	84	Renewable (60% CF)
Uranium	60,000 t				
PHWR		1.2	340	15	30
FBR		195	16,000	350	65
Thorium	320,000 t				
Thermal Breeders		360	70,000	350	285
FBR		1,000	200,000	350	820

*50% Coal reserved for non electricity generation use

Figure by MIT OCW.

Breeding U233 and Pu239: Comparison



^{232}Th + 1 Neutron

Fertile

^{238}U + 1 Neutron

^{233}Pa (27.4 Days) Beta Decay

^{239}Np (2.3 Days) Beta Decay

^{233}U + 1 Neutron
90% Fission
10% Capture

Fissile

^{239}Pu + 1 Neutron
65% Fission
35% Capture

^{234}U + 1 Neutron

Fertile

^{240}Pu + 1 Neutron

^{235}U + 1 Neutron
80% Fission
20% Capture

Fissile

^{241}Pu + 1 Neutron
75% Fission
25% Capture

^{236}U + 1 Neutron

Parasite

^{242}Pu + 1 Neutron

^{237}Np
Chemically Separable

^{243}Am
Chemically Separable

Figure by MIT OCW.

η – Factor vs Neutron Energy

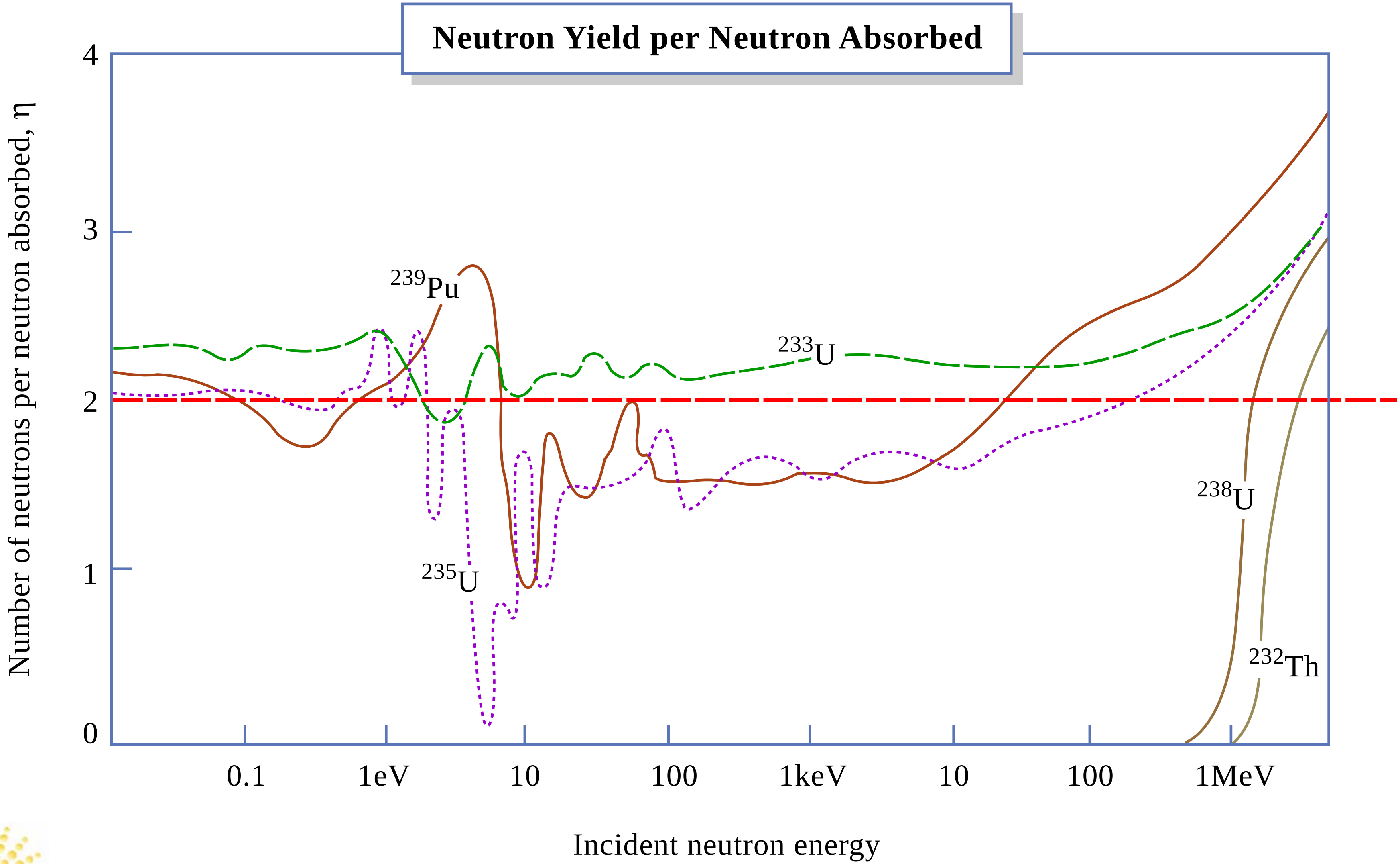


Figure by MIT OCW.

U233 as a Fissile Material

	^{233}U	^{235}U	^{239}Pu	^{241}Pu
$\sigma_{capture}$, barns	46	101	271	368
$\sigma_{fission}$, barns	525	577	742	1007
$\alpha = \sigma_c/\sigma_f$	0.088	0.175	0.365	0.365
$\eta = \nu\sigma_c/\sigma_f$	2.300	2.077	2.109	2.151
Effective β factor, pcm	270	650	210	490

Th232 vs. U238

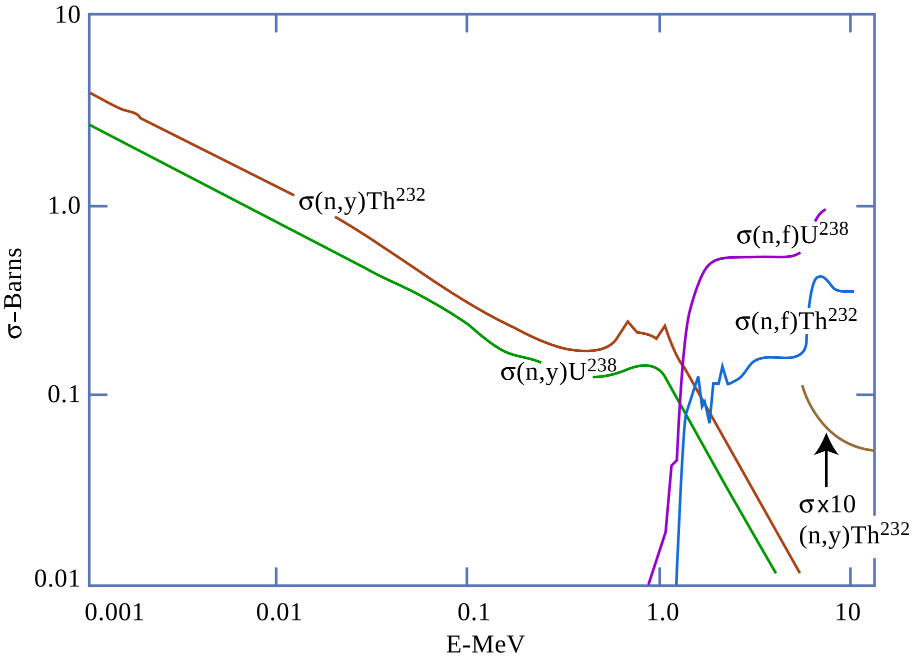


Figure by MIT OCW.

	^{232}Th	^{238}U
$\sigma_{capture}$, barns	7.40	2.73
$\sigma_{fission}$ (fast spectrum, 1-group), barns	0.01	0.05
IR (infinite dilution), barns	85	272
Fission cutoff, MeV	1.5	0.8
Neutrons per fission ($\nu_{average}$)	2.3	2.75
Effective β factor, pcm (fast fission)	2030	1480

MA Production Comparison

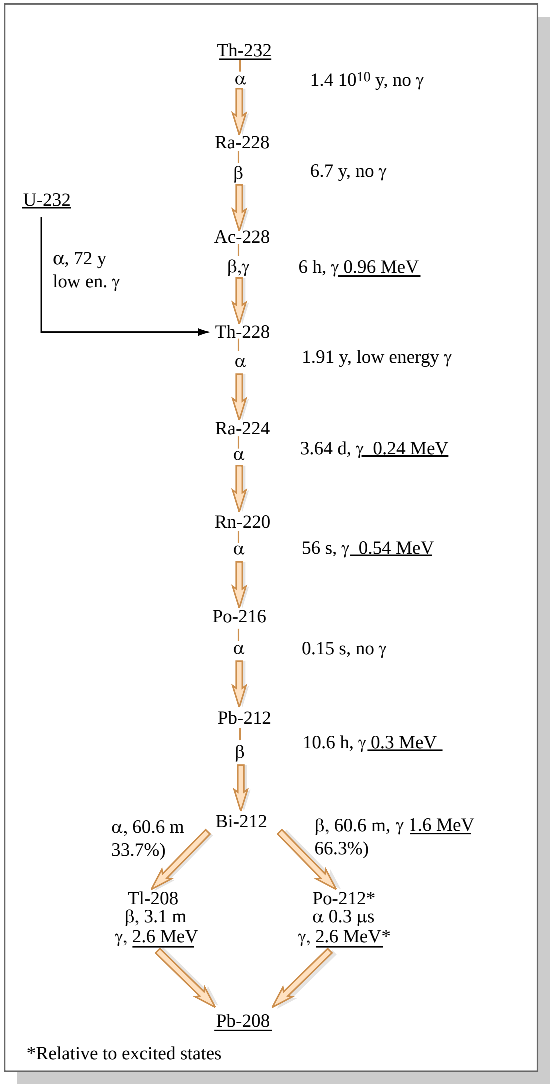
Relative Production of Minor Actinides in Diverse Cycles

Minor Actinides	**Diverse Fuel Cycles**			
	U5 + U8 (Reference cycle) (grams per ton HM)	U5 + Th2 (%)	U3 + U8 (%)	U3 + Th2 (%)
Np-237	360[a] 900[b]	92 107	20 13	1 3
Am (241+242+243)	160[a] 470[b]	0.04 0.28	106 117	$6.3\ 10^{-5}$ $1.8\ 10^{-3}$
Cm (243 to 246)	36 220	0.01 0.14	111 132	$1.68\ 10^{-5}$ $6.37\ 10^{-4}$

Key
[a]Discharge burn-up : 30 GW d/t
[b]Discharge burn-up : 60 GW d/t

Figure by MIT OCW.

U232 decay chain



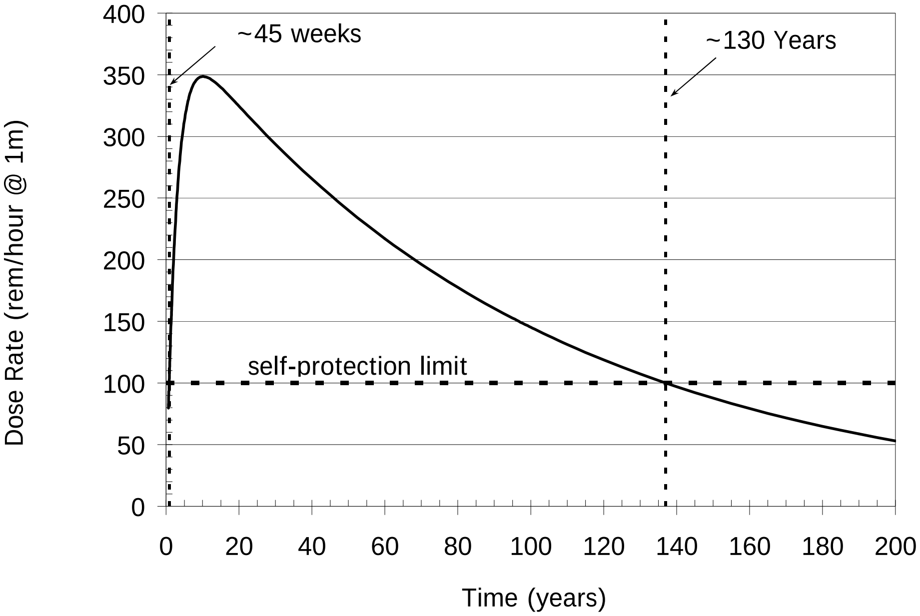


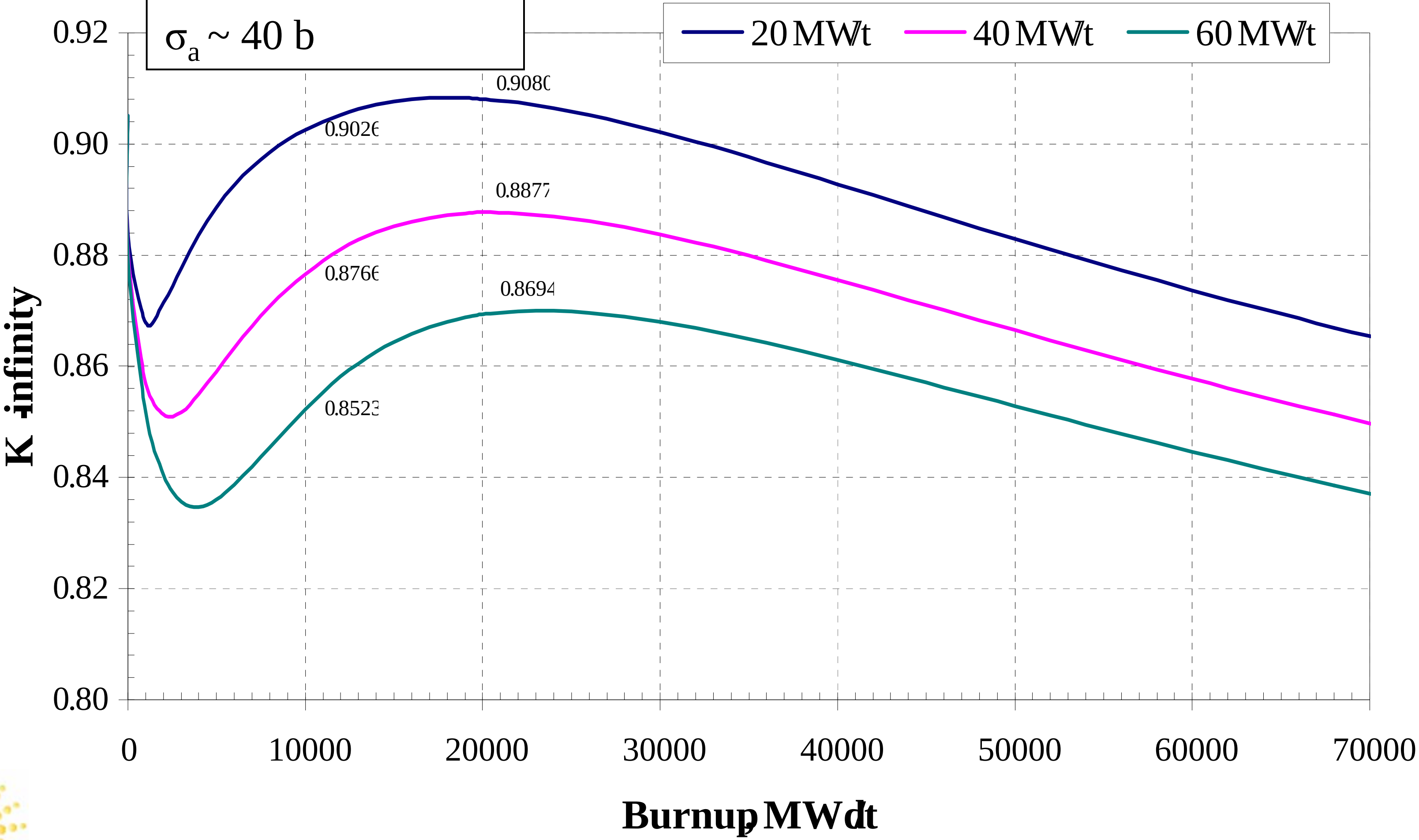
Figure by MIT OCW.

Power Density Effect

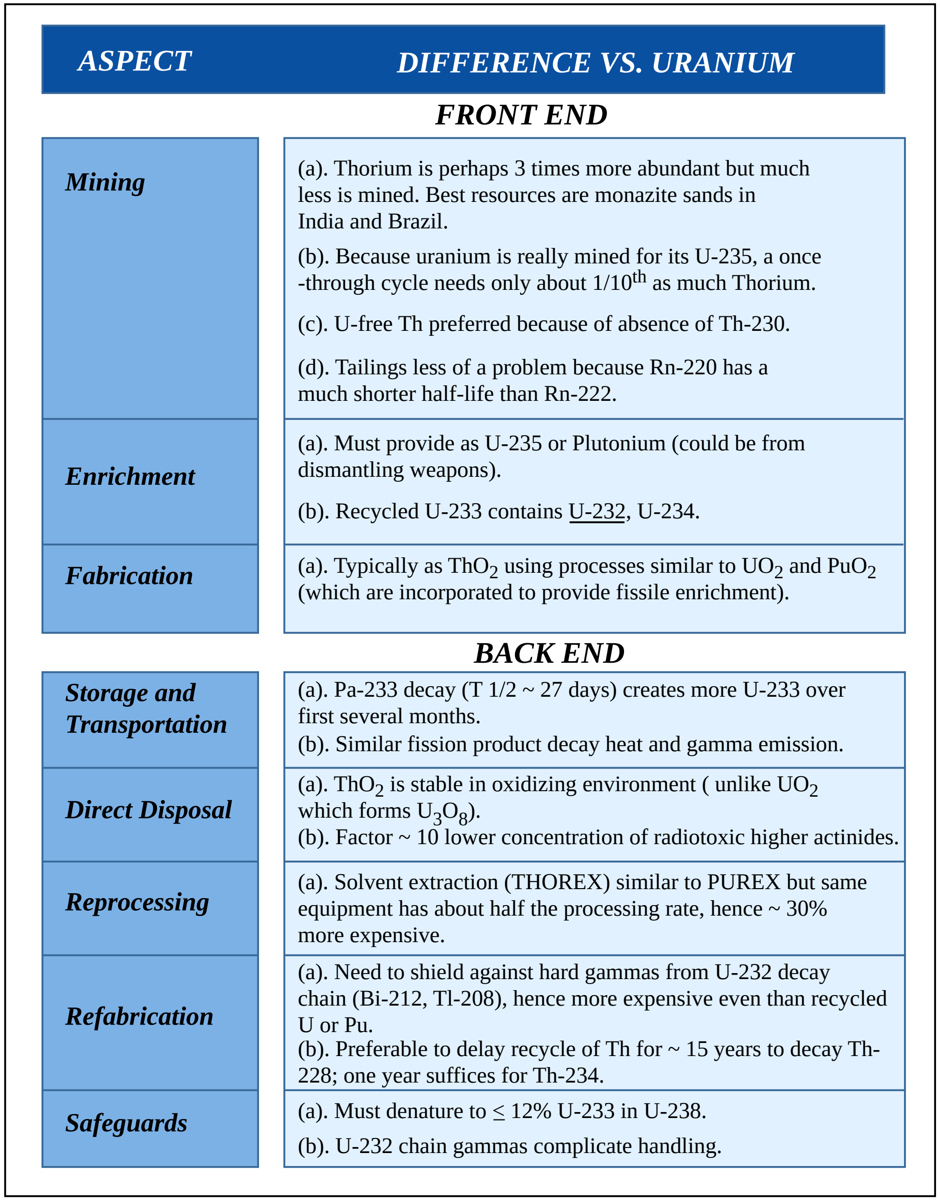
<u>Pa-233</u>

$T_{1/2}$ = 27.4 days

σ_a ~ 40 b



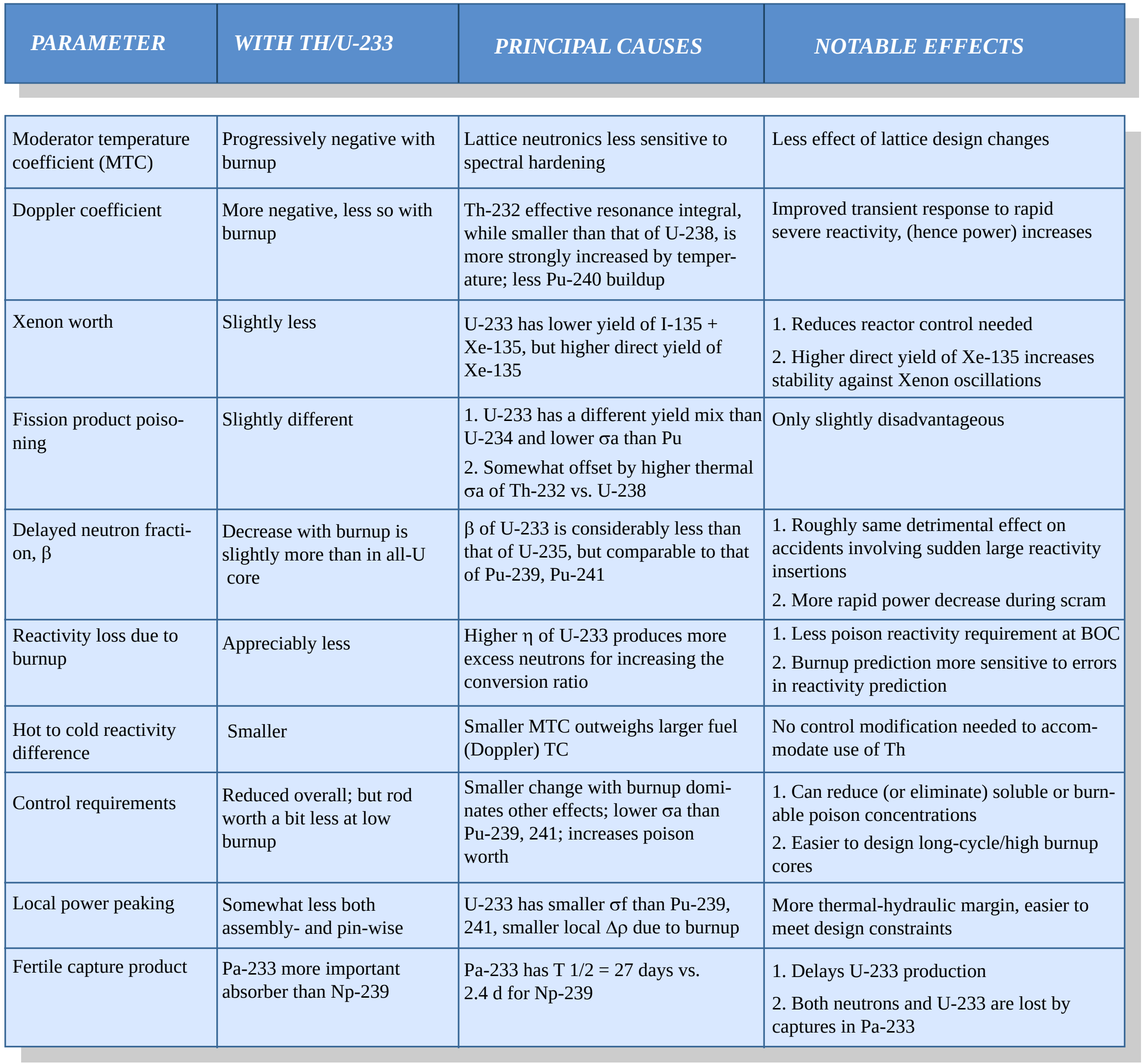
Th in LWRs: Front and Back End Fuel Cycle Effects



ASPECT	*DIFFERENCE VS. URANIUM*
	FRONT END
Mining	(a). Thorium is perhaps 3 times more abundant but much less is mined. Best resources are monazite sands in India and Brazil. (b). Because uranium is really mined for its U-235, a once -through cycle needs only about 1/10th as much Thorium. (c). U-free Th preferred because of absence of Th-230. (d). Tailings less of a problem because Rn-220 has a much shorter half-life than Rn-222.
Enrichment	(a). Must provide as U-235 or Plutonium (could be from dismantling weapons). (b). Recycled U-233 contains U-232, U-234.
Fabrication	(a). Typically as ThO_2 using processes similar to UO_2 and PuO_2 (which are incorporated to provide fissile enrichment).
	BACK END
Storage and Transportation	(a). Pa-233 decay (T 1/2 ~ 27 days) creates more U-233 over first several months. (b). Similar fission product decay heat and gamma emission.
Direct Disposal	(a). ThO_2 is stable in oxidizing environment (unlike UO_2 which forms U_3O_8). (b). Factor ~ 10 lower concentration of radiotoxic higher actinides.
Reprocessing	(a). Solvent extraction (THOREX) similar to PUREX but same equipment has about half the processing rate, hence ~ 30% more expensive.
Refabrication	(a). Need to shield against hard gammas from U-232 decay chain (Bi-212, Tl-208), hence more expensive even than recycled U or Pu. (b). Preferable to delay recycle of Th for ~ 15 years to decay Th-228; one year suffices for Th-234.
Safeguards	(a). Must denature to ≤ 12% U-233 in U-238. (b). U-232 chain gammas complicate handling.

Figure by MIT OCW.

Th in LWRs: Neutronic Effects



PARAMETER	WITH TH/U-233	PRINCIPAL CAUSES	NOTABLE EFFECTS
Moderator temperature coefficient (MTC)	Progressively negative with burnup	Lattice neutronics less sensitive to spectral hardening	Less effect of lattice design changes
Doppler coefficient	More negative, less so with burnup	Th-232 effective resonance integral, while smaller than that of U-238, is more strongly increased by temperature; less Pu-240 buildup	Improved transient response to rapid severe reactivity, (hence power) increases
Xenon worth	Slightly less	U-233 has lower yield of I-135 + Xe-135, but higher direct yield of Xe-135	1. Reduces reactor control needed 2. Higher direct yield of Xe-135 increases stability against Xenon oscillations
Fission product poisoning	Slightly different	1. U-233 has a different yield mix than U-234 and lower σ_a than Pu 2. Somewhat offset by higher thermal σ_a of Th-232 vs. U-238	Only slightly disadvantageous
Delayed neutron fraction, β	Decrease with burnup is slightly more than in all-U core	β of U-233 is considerably less than that of U-235, but comparable to that of Pu-239, Pu-241	1. Roughly same detrimental effect on accidents involving sudden large reactivity insertions 2. More rapid power decrease during scram
Reactivity loss due to burnup	Appreciably less	Higher η of U-233 produces more excess neutrons for increasing the conversion ratio	1. Less poison reactivity requirement at BOC 2. Burnup prediction more sensitive to errors in reactivity prediction
Hot to cold reactivity difference	Smaller	Smaller MTC outweighs larger fuel (Doppler) TC	No control modification needed to accommodate use of Th
Control requirements	Reduced overall; but rod worth a bit less at low burnup	Smaller change with burnup dominates other effects; lower σ_a than Pu-239, 241; increases poison worth	1. Can reduce (or eliminate) soluble or burnable poison concentrations 2. Easier to design long-cycle/high burnup cores
Local power peaking	Somewhat less both assembly- and pin-wise	U-233 has smaller σ_f than Pu-239, 241, smaller local $\Delta\rho$ due to burnup	More thermal-hydraulic margin, easier to meet design constraints
Fertile capture product	Pa-233 more important absorber than Np-239	Pa-233 has T 1/2 = 27 days vs. 2.4 d for Np-239	1. Delays U-233 production 2. Both neutrons and U-233 are lost by captures in Pa-233

Predicted Effects of Th/233U on Pressurized Water Neutronics Compared to All-U Fueling

Figure by MIT OCW.

Summary of Th Advantages and Drawbacks

Advantages

- Robust fuel and waste form
- Generates less Pu and higher actinides
- U233 has superior fissile properties
- Large resources

Drawbacks

- Requires initial investment of fissile material (U235/Pu)
- Pa considerations
- U232 issue and more complicated reprocessing
- U233 is weapons usable unless denatured

History of Using Thorium in Power Reactors

High Temperature Reactors

- PEACH BOTTOM (40 MWe) General Atomics, 1966 - 1972.
- DRAGON experimental reactor (20 MWt; 1966-73) OECD-EURATOM, England
- Pebble-bed AVR in Jülich (15 MWe) BBC-HRB (1967 and 1989), THTR (1984) 300MWe

Other Reactors

- ELK RIVER, is a 24 MWe BWR (1963–68)
- INDIAN POINT, a 285 MWe PWR (1962–1980)
- AHWR in India, plans to build 500MWe Fast Thorium Breeder Reactor
- SHIPPINGPORT Light Water Breeder Reactor

LWBR Shippingport

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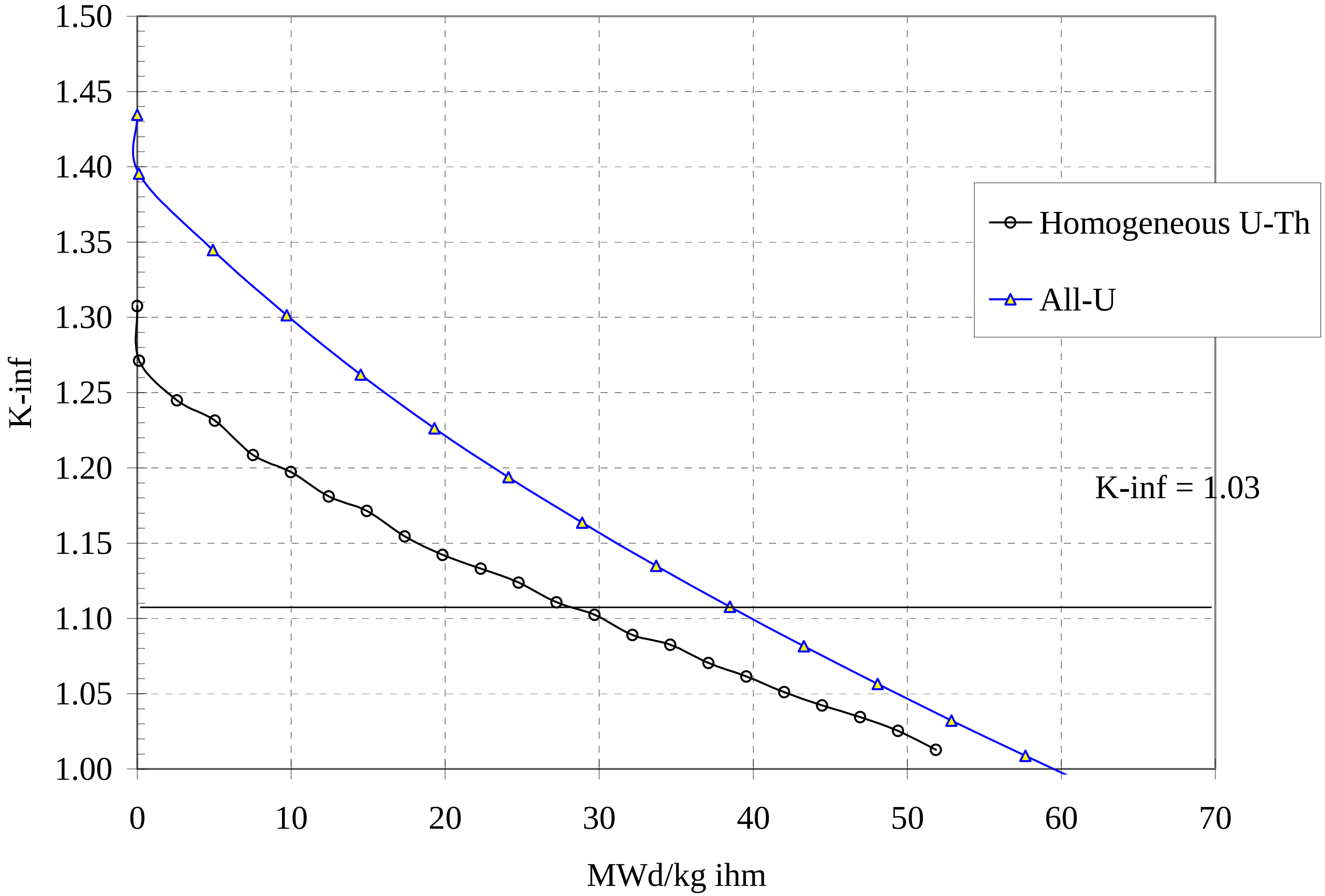
Thorium Based Fuel Design Options

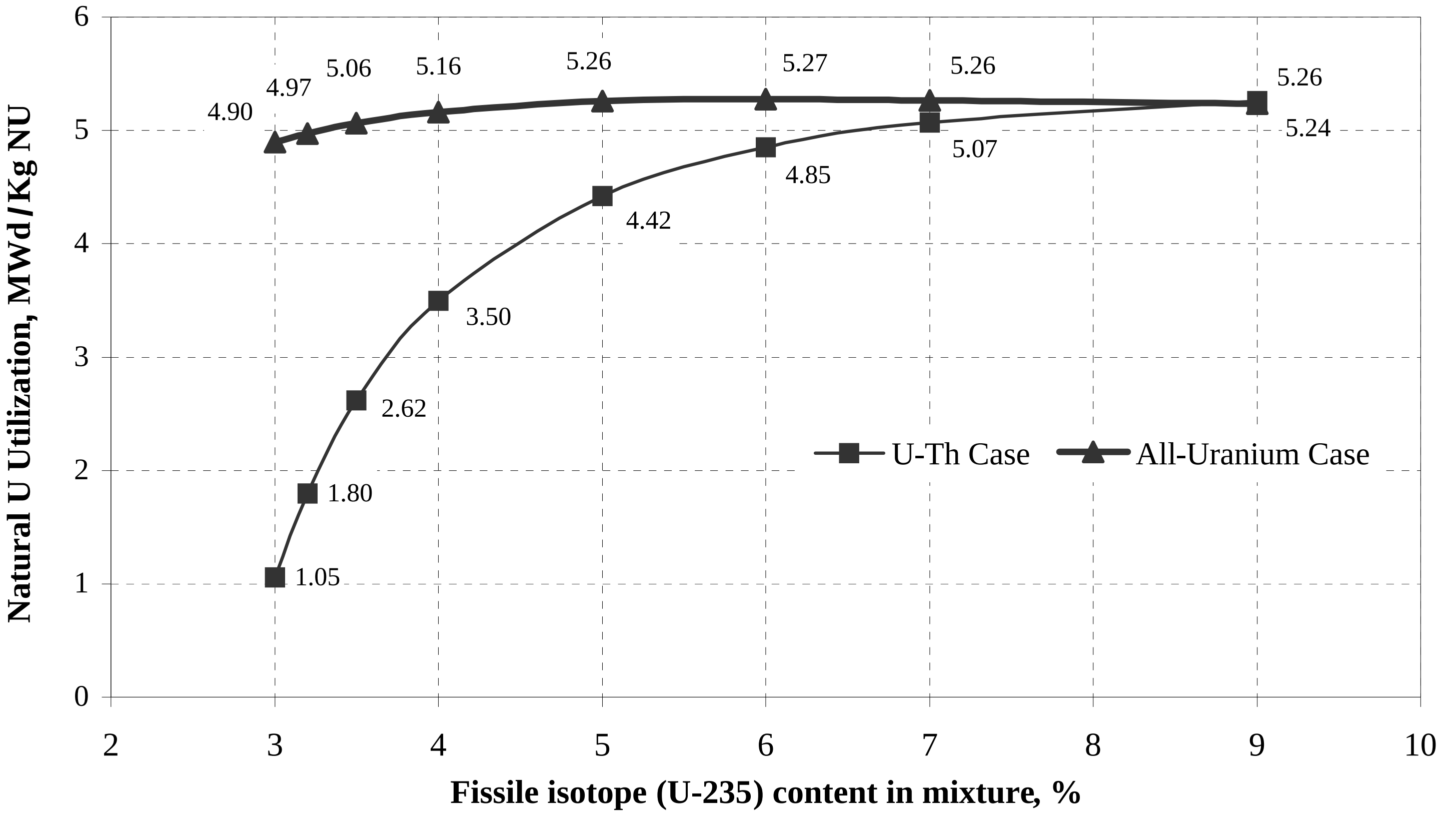
For once-through fuel cycle

- Homogeneously mixed UO_2 – ThO_2
- Micro-heterogeneous
  - *Small scale spatial separation*
  - *Minimal changes in core design*
- Macro-heterogeneous
  - *Large scale spatial separation*
  - *Different residence times for U and Th parts*

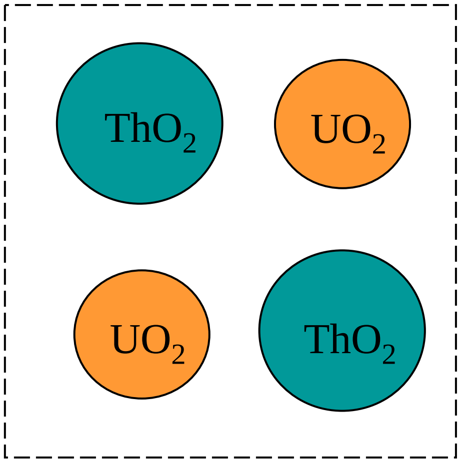
UO_2 vs. Homogeneously Mixed U-Th



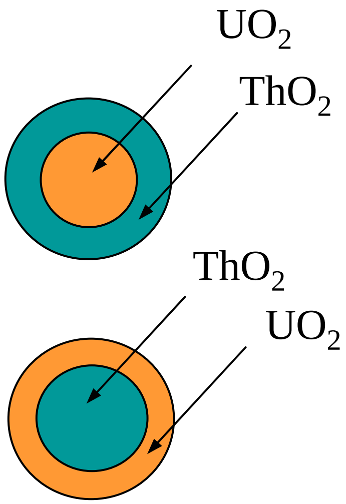
Homogeneous U-Th Fuel NU Utilization



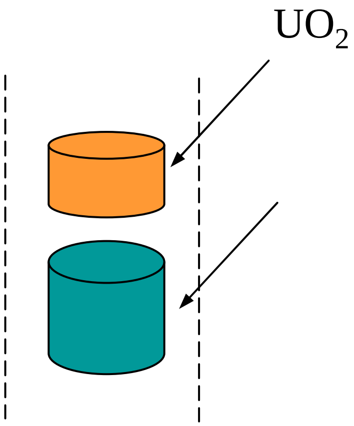
Micro-Heterogeneous U-Th Fuel



Checkerboard

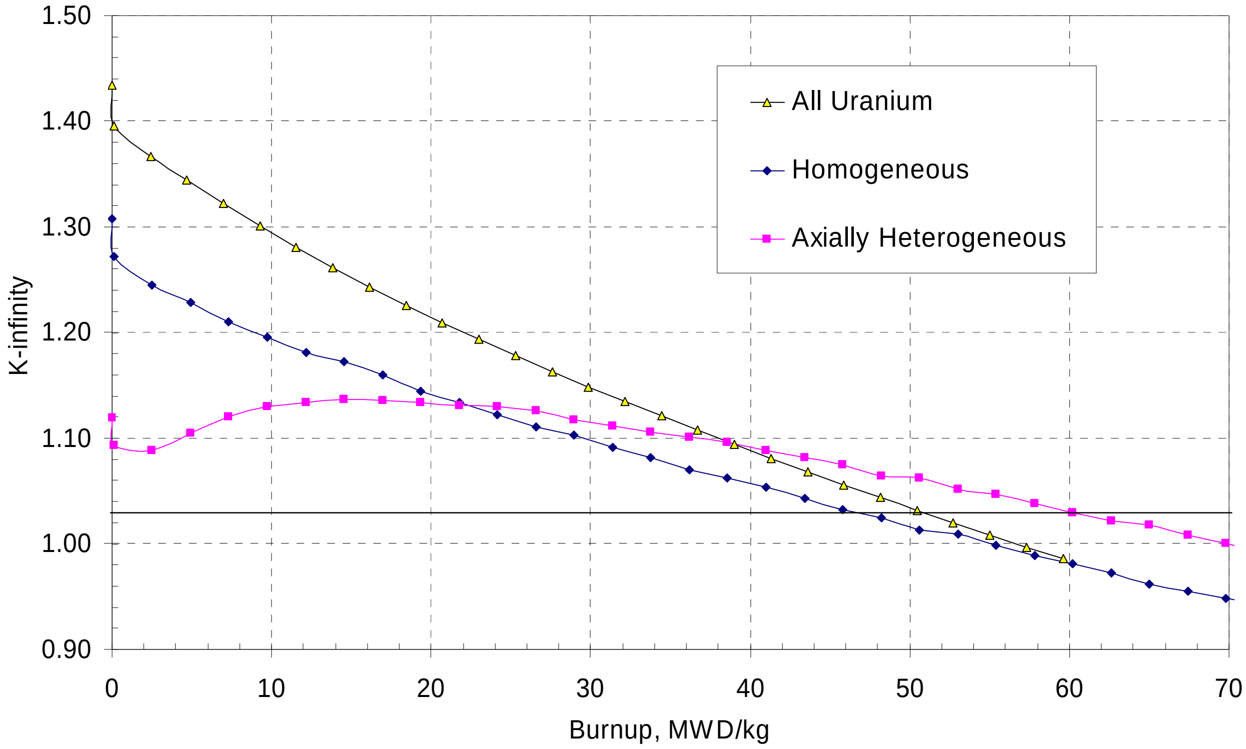


Duplex



Axial

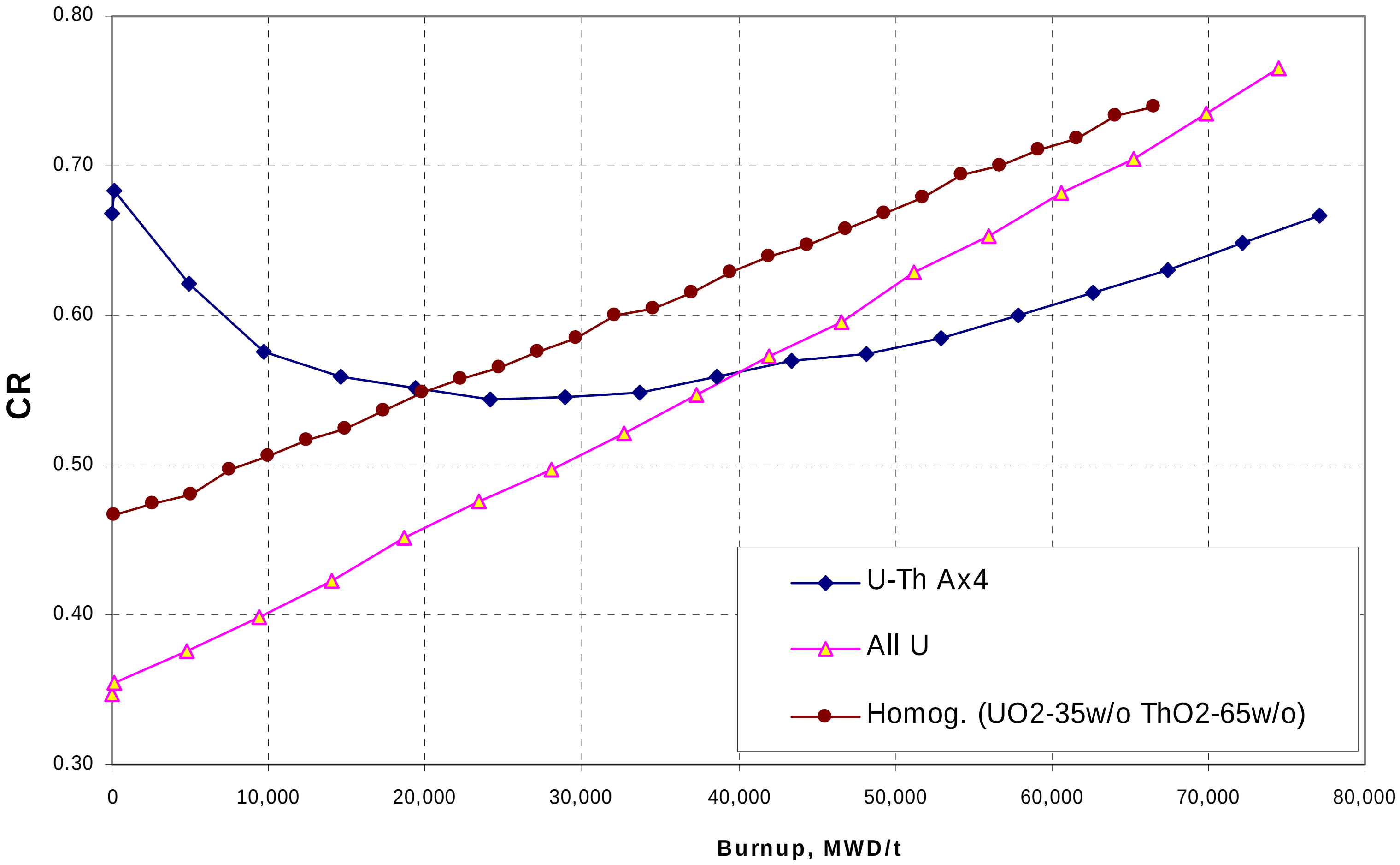
K_∞ vs. Burnup for Ax4 and Hom. Cases



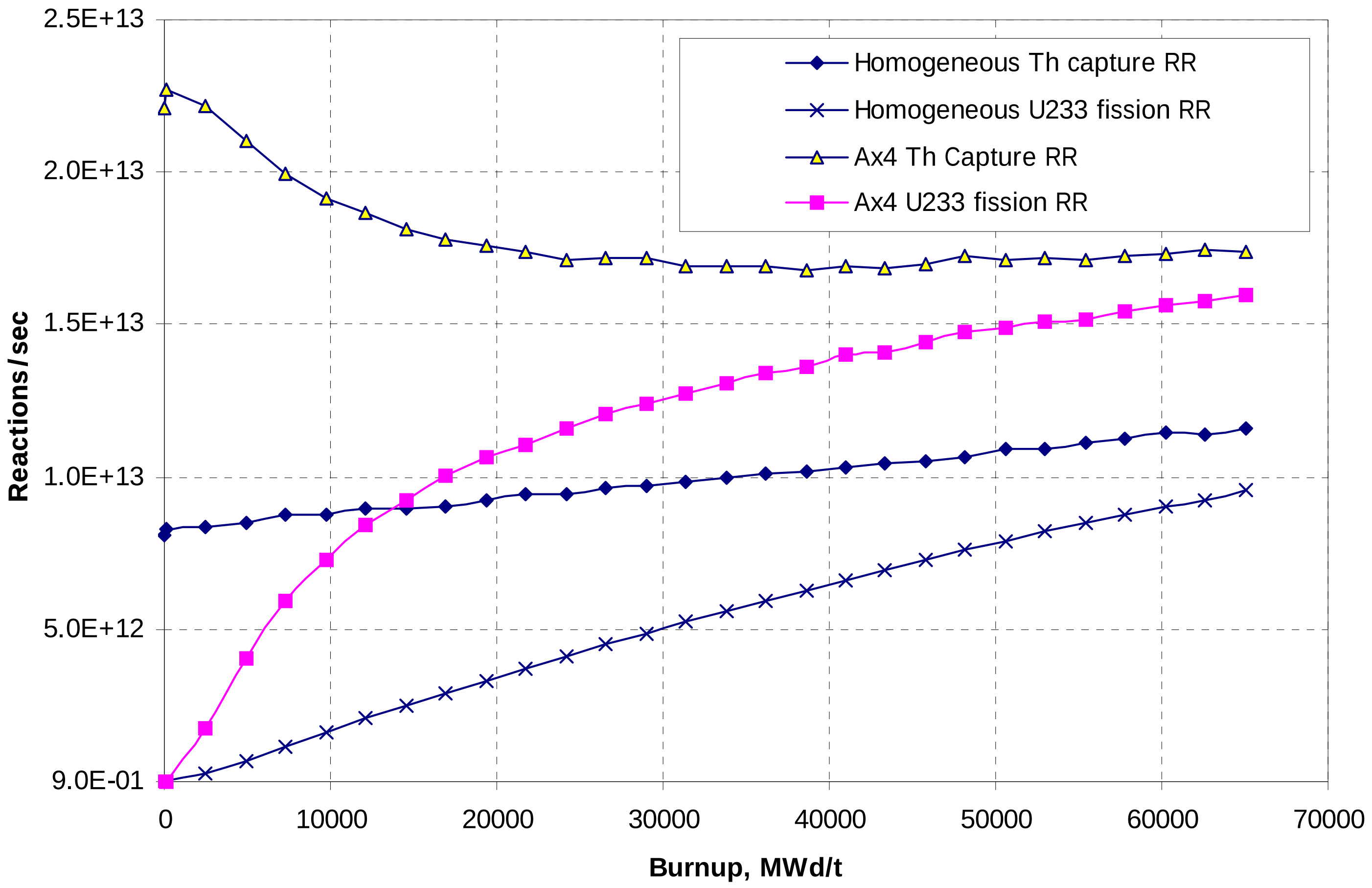
The effect is due to:

- **Spectral Shift**
- **Resonance Shielding**

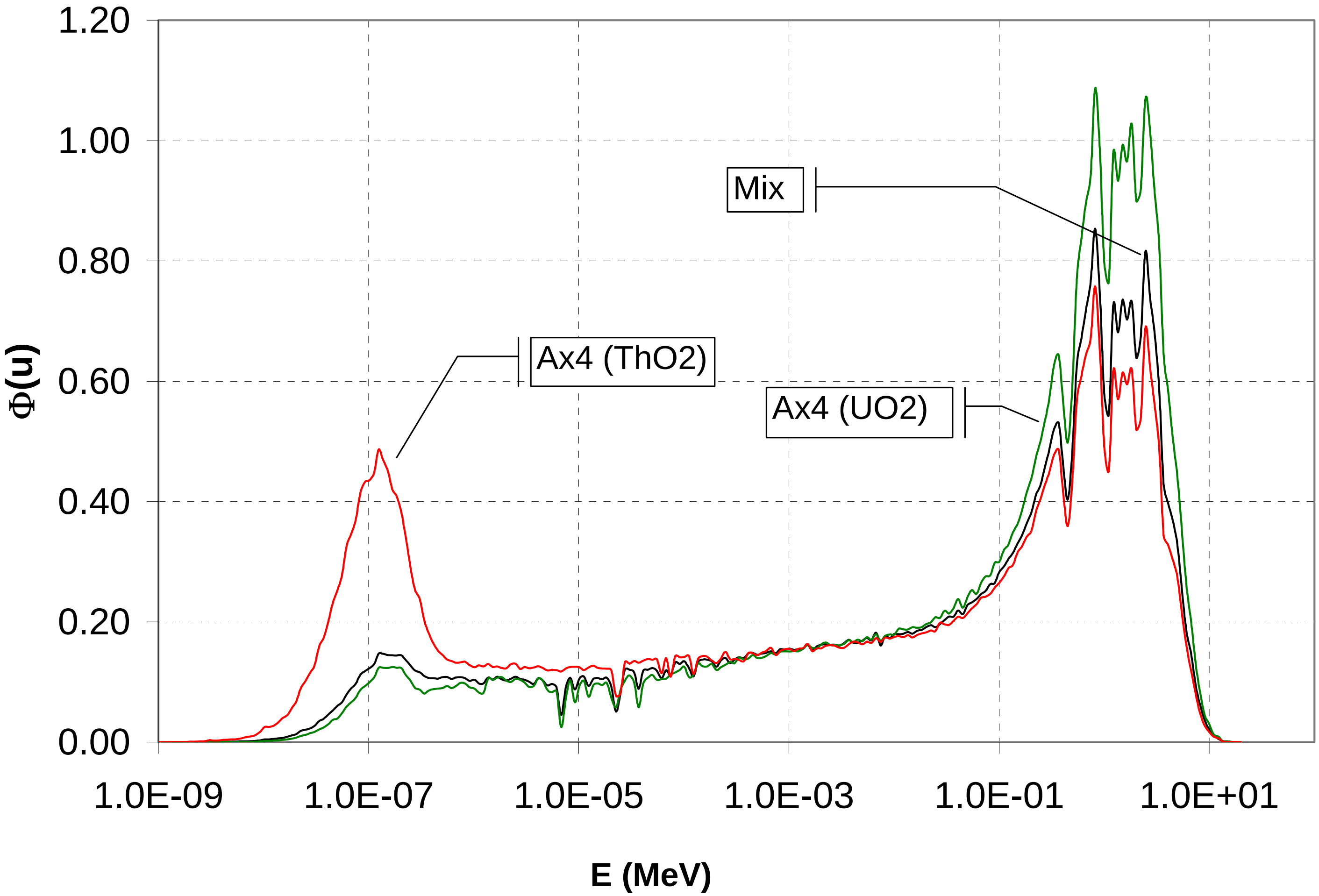
Breeding U233 (cont.)



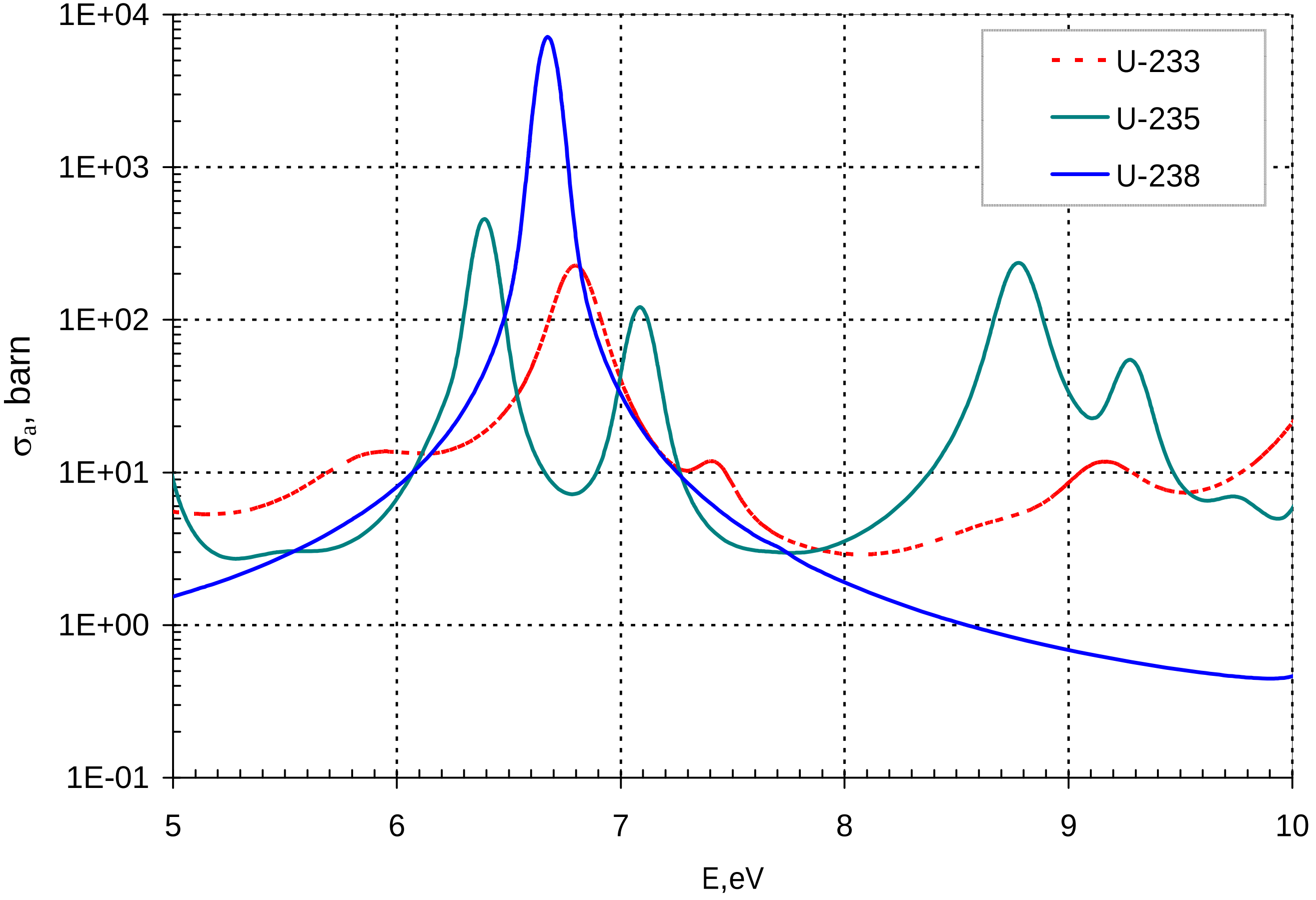
Breeding U233



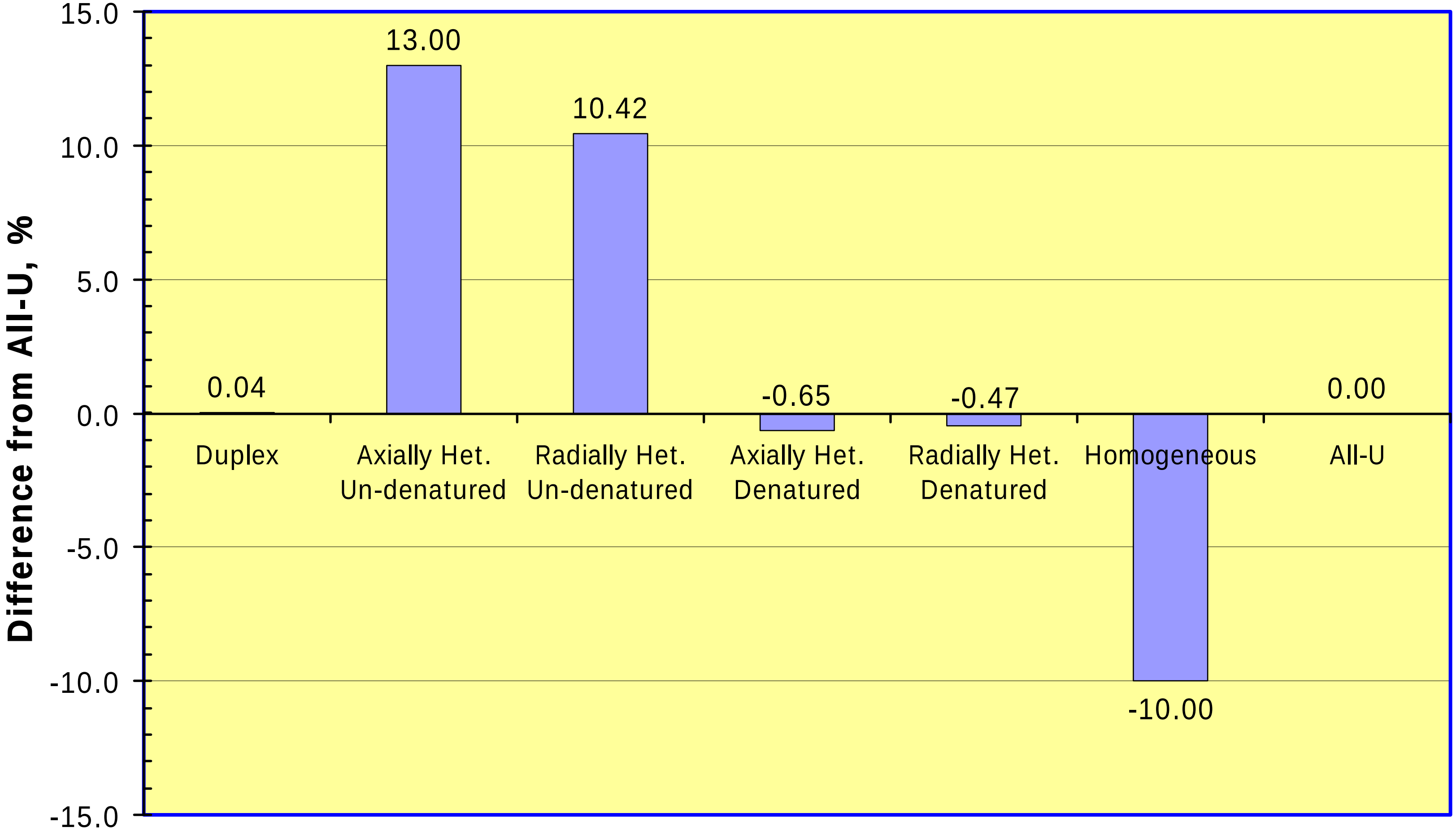
Spectral Shift



^{233}U, ^{235}U and ^{238}U Absorption Cross-Sections



Reactivity Limited Burnup Comparison

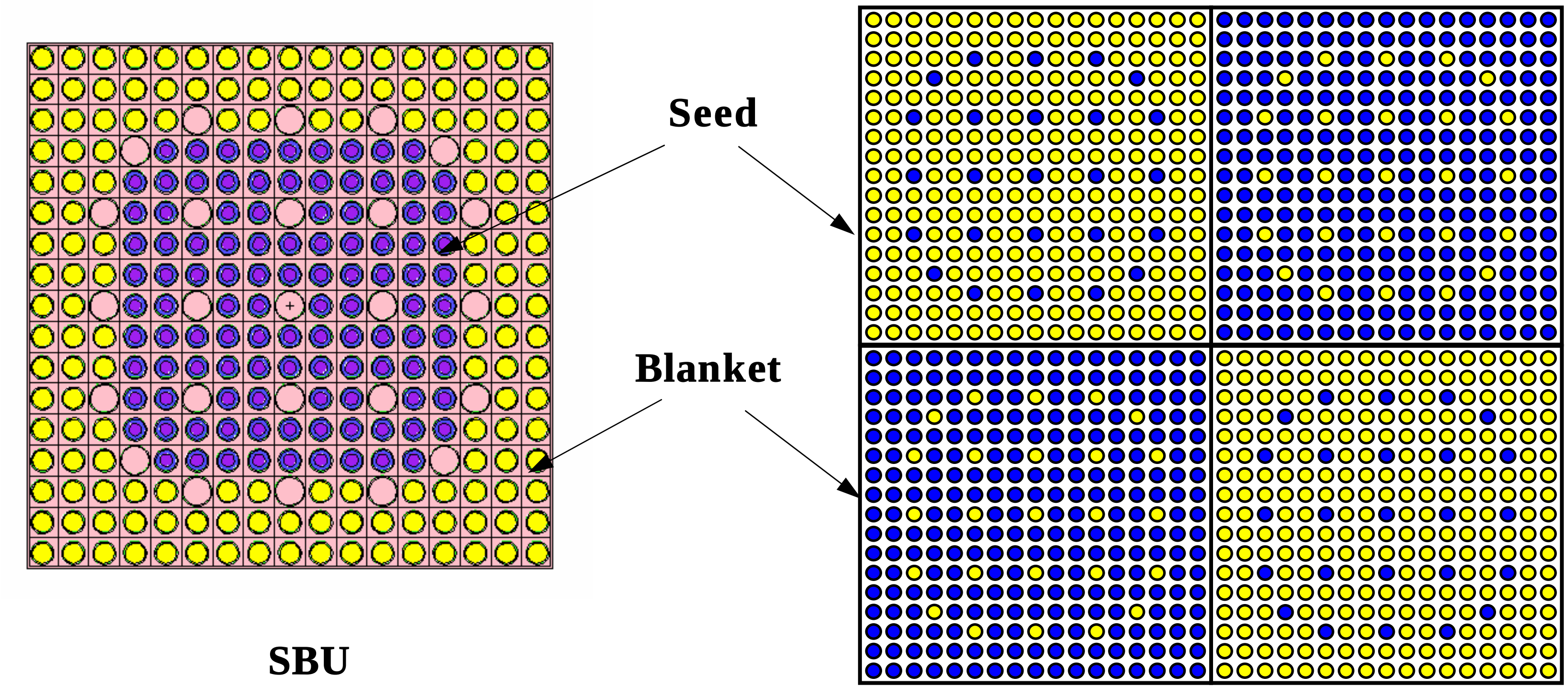


Proliferation Resistance

	Ax4	Ax4NU		Hom	All-U	Weapon Grade
	Seed Zone	Seed Zone	Blanket Zone			
Ratio of SFS to super grade Pu	29.29	24.2	22.2	22.5	23.0	2.9
Decay Heat (Watts/kg Pu)	59.6	48.4	13.4	38.6	33.9	2.4
Critical mass[a] (kg Pu)	21.2	20.5	22.4	21.25	21.4	16.45
Specific Activity (Curies/kg Pu)	1.87e4	1.79e4	2.04e4	2.05e4	1.76e4	4.39e2
Multiples of Critical Mass /GWe-year	3.3	3.9	1.3	5.2	10.8	--

[a] Calculated for un-reflected spherical geometry, Pu metal in δ-phase (ρ = 15.9 g/cm^3)

Macro Heterogeneous Th Fuel



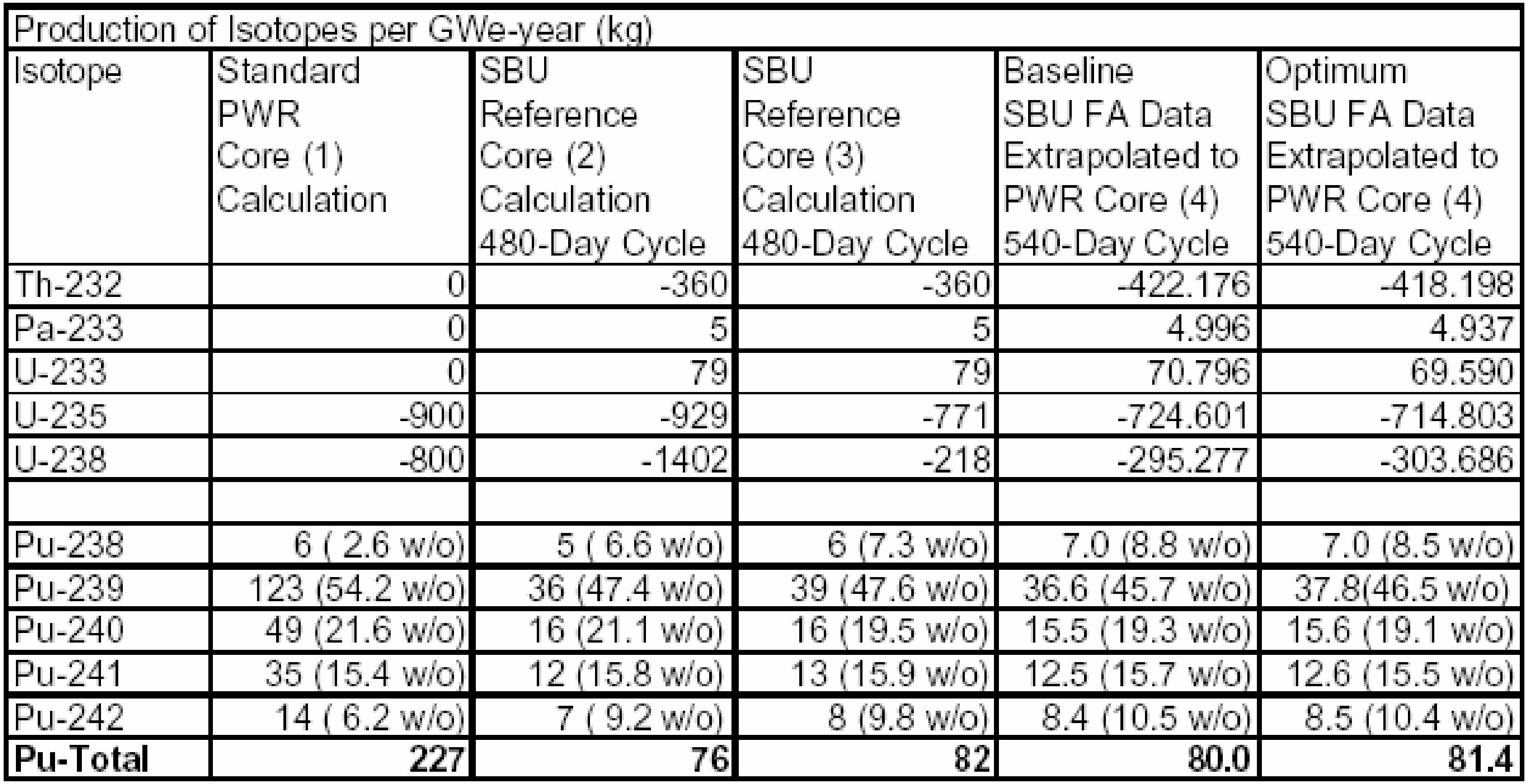
SBU

Radkowsky Seed-Blanket Concept

WASB

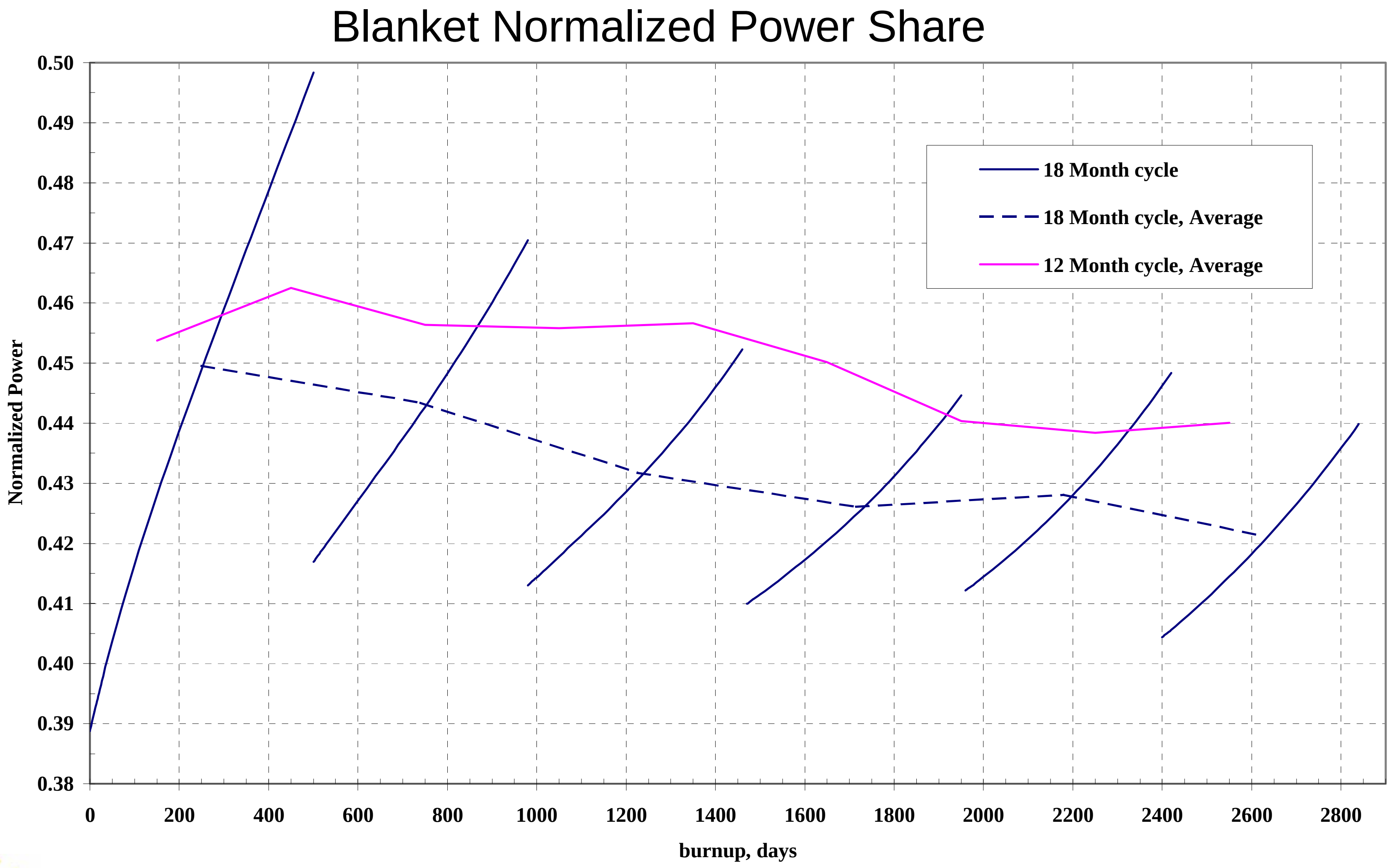
Whole Assembly Seed-Blanket Concept

Pu Production in Macro Het. U-Th Fuel



Production of Isotopes per GWe-year (kg)					
Isotope	Standard PWR Core (1) Calculation	SBU Reference Core (2) Calculation 480-Day Cycle	SBU Reference Core (3) Calculation 480-Day Cycle	Baseline SBU FA Data Extrapolated to PWR Core (4) 540-Day Cycle	Optimum SBU FA Data Extrapolated to PWR Core (4) 540-Day Cycle
Th-232	0	-360	-360	-422.176	-418.198
Pa-233	0	5	5	4.996	4.937
U-233	0	79	79	70.796	69.590
U-235	-900	-929	-771	-724.601	-714.803
U-238	-800	-1402	-218	-295.277	-303.686
Pu-238	6 (2.6 w/o)	5 (6.6 w/o)	6 (7.3 w/o)	7.0 (8.8 w/o)	7.0 (8.5 w/o)
Pu-239	123 (54.2 w/o)	36 (47.4 w/o)	39 (47.6 w/o)	36.6 (45.7 w/o)	37.8(46.5 w/o)
Pu-240	49 (21.6 w/o)	16 (21.1 w/o)	16 (19.5 w/o)	15.5 (19.3 w/o)	15.6 (19.1 w/o)
Pu-241	35 (15.4 w/o)	12 (15.8 w/o)	13 (15.9 w/o)	12.5 (15.7 w/o)	12.6 (15.5 w/o)
Pu-242	14 (6.2 w/o)	7 (9.2 w/o)	8 (9.8 w/o)	8.4 (10.5 w/o)	8.5 (10.4 w/o)
Pu-Total	**227**	**76**	**82**	**80.0**	**81.4**

Thorium Blanket Power Share



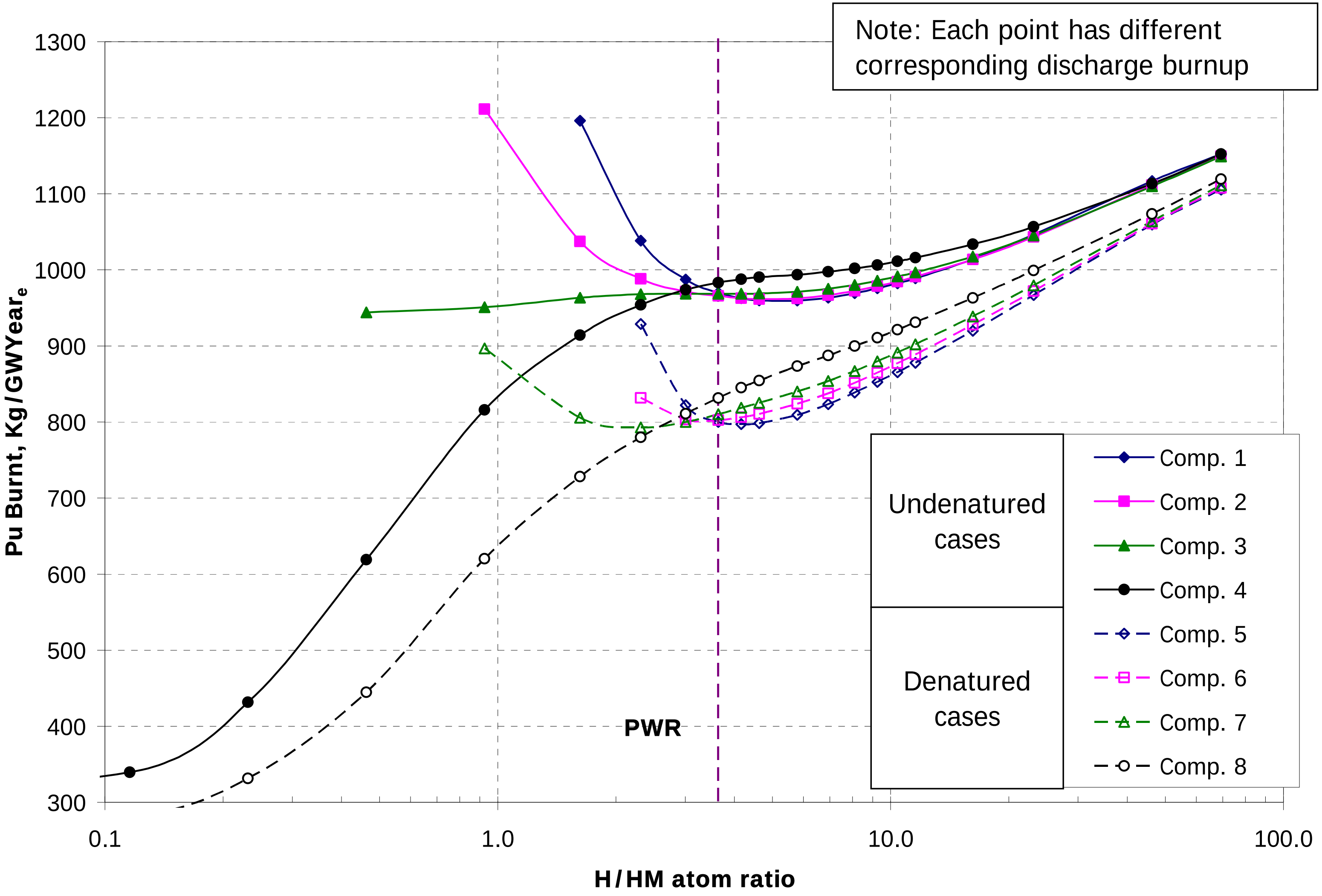
Economic Performance of Heterogeneous Once-Through Th Cycle

	PWR12	PWR18	RTF12 Metal Seed	RTF18 Metal Seed	RTF18 Oxide Seed
"equilibrium" enrichment, (%U235)	3.2	4.533	20	20	20
Average Cycle Length, FPD	300	454.5	300	473	482
NU Requirements, t NU/Gwe-Y	213.8	202.6	198.3	196.5	199.0
NU Utilization, GWd(th)/t NU	5.0475	5.3273	5.4418	5.4912	5.4234
SWU Requirements, t SWU/Gwe-Y	137.5	147.1	190.8	189.0	189.0
Direct Electricity Production, kWh(e)*10^6	74,520	75,265	74,520	78,328	79,819
PV Electricity Production	53,753	54,274	53,753	56,483	57,558
Levelized FCC, mills/kWh(e)	**3.8926**	**3.7955**	**3.8887**	**3.9768**	**4.0117**

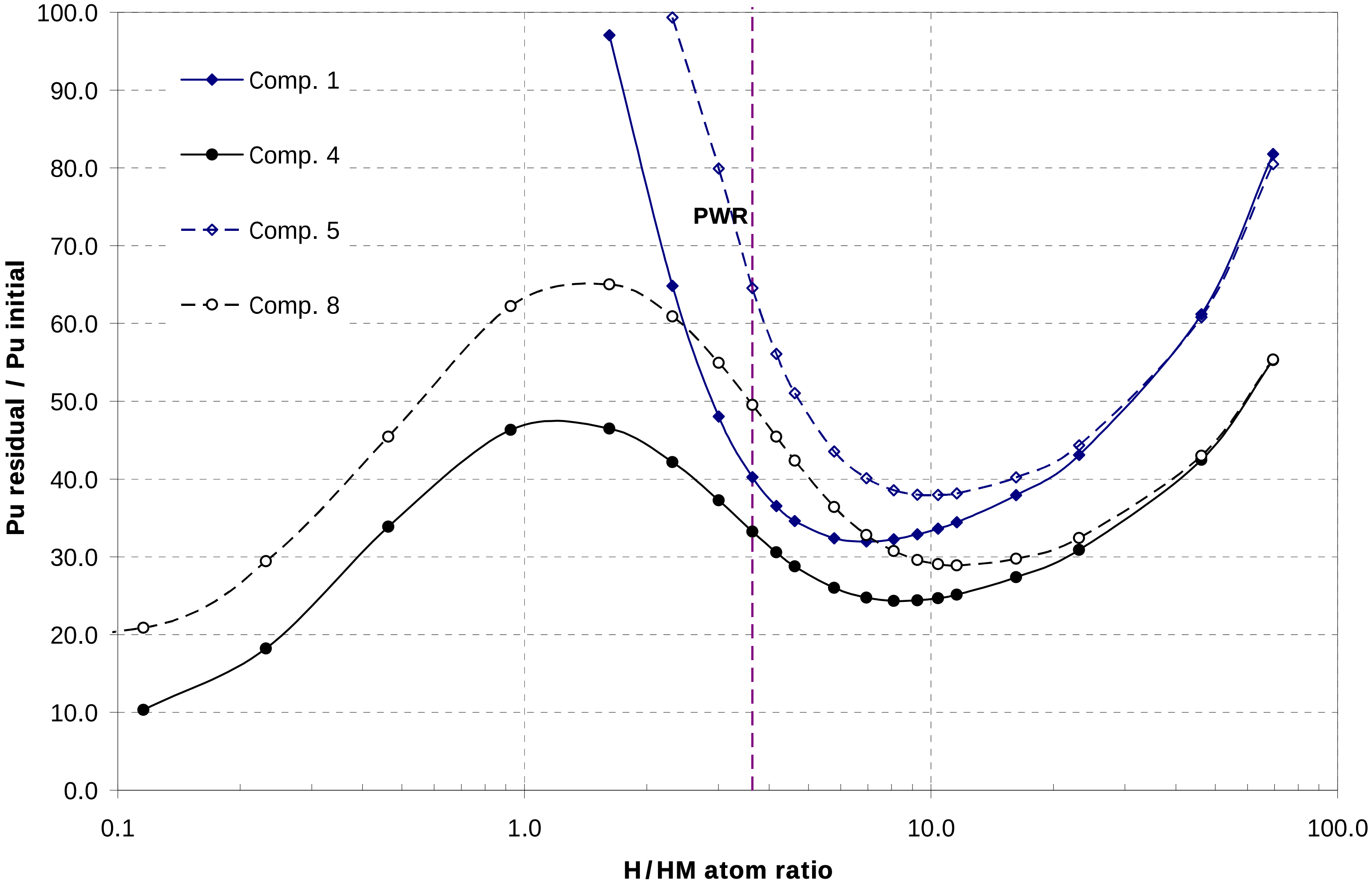
Pu Disposition in Th

- Possible in virtually any reactor type
- Pu destruction efficiency and destruction rate depend on neutron spectra
- Denaturing of Th with uranium is required in order to eliminate proliferation concerns about bred U233 – presence of U degrades Pu destruction efficiency and rates
- Compared to UO2, Pu-Th fuel has more negative Doppler and MTC but much smaller βeff and control materials worth

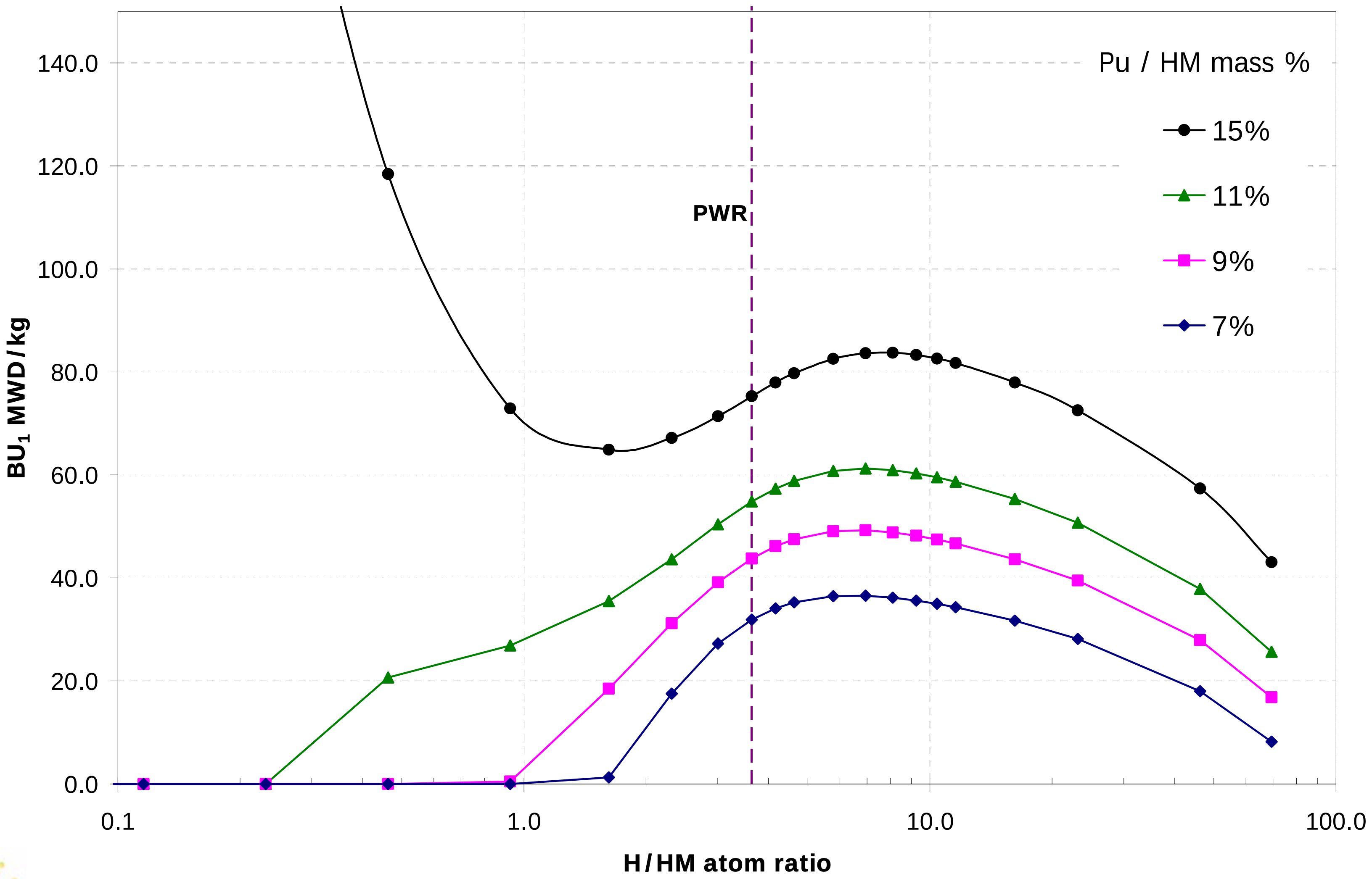
Pu Destruction Rates



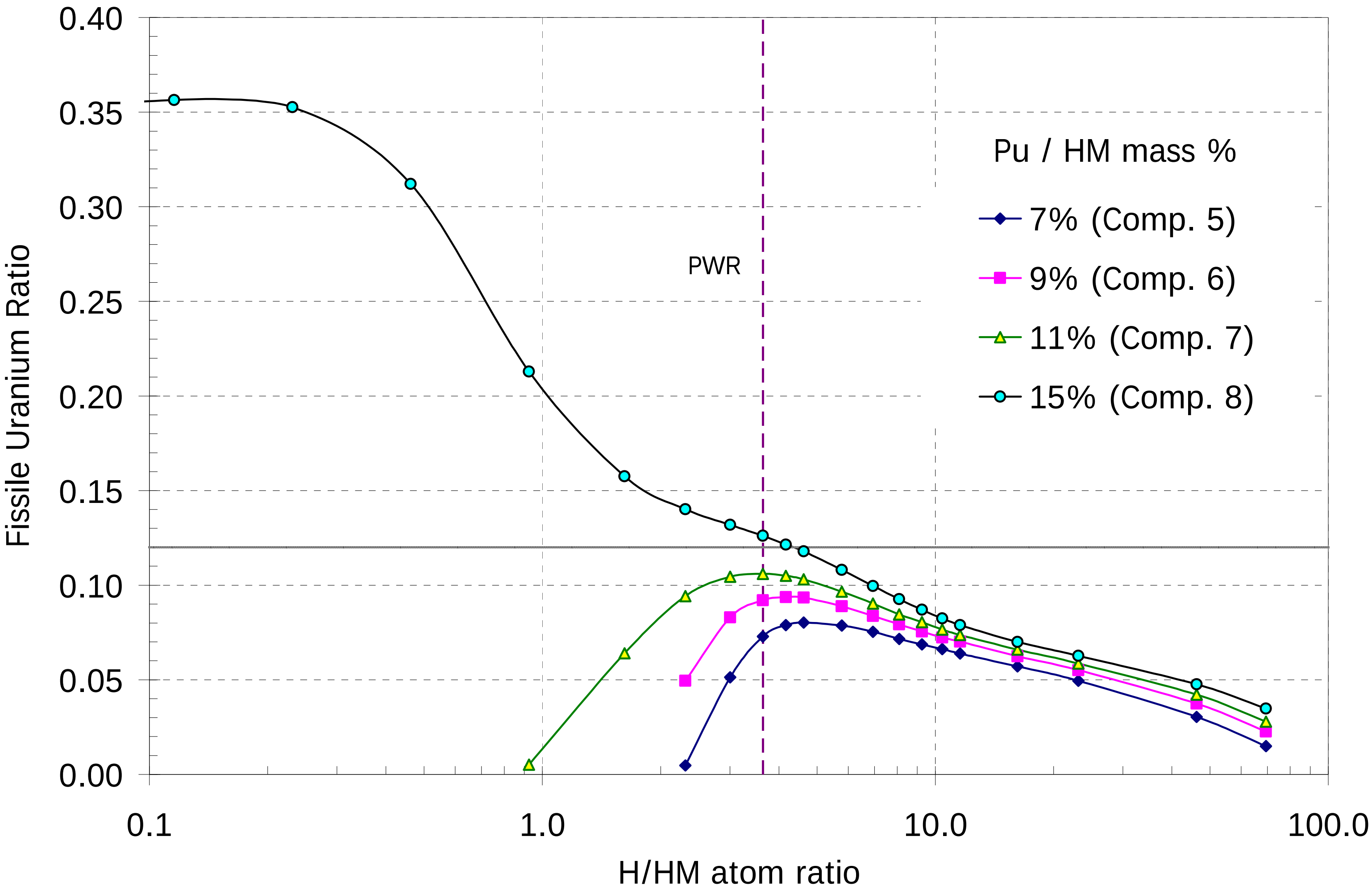
Residual Pu Fraction



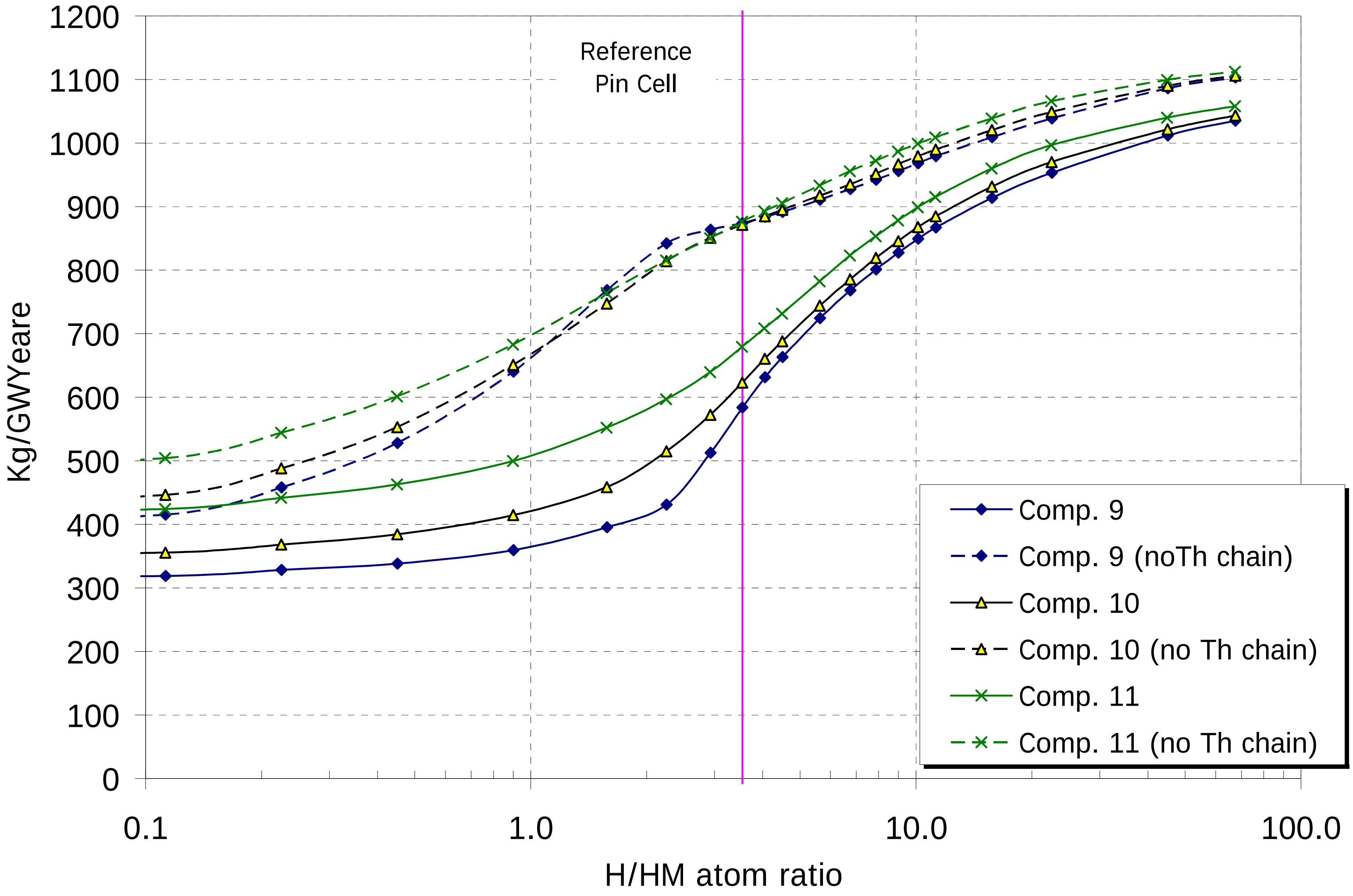
BU1 vs H/HM: Th-Pu Hom. mix



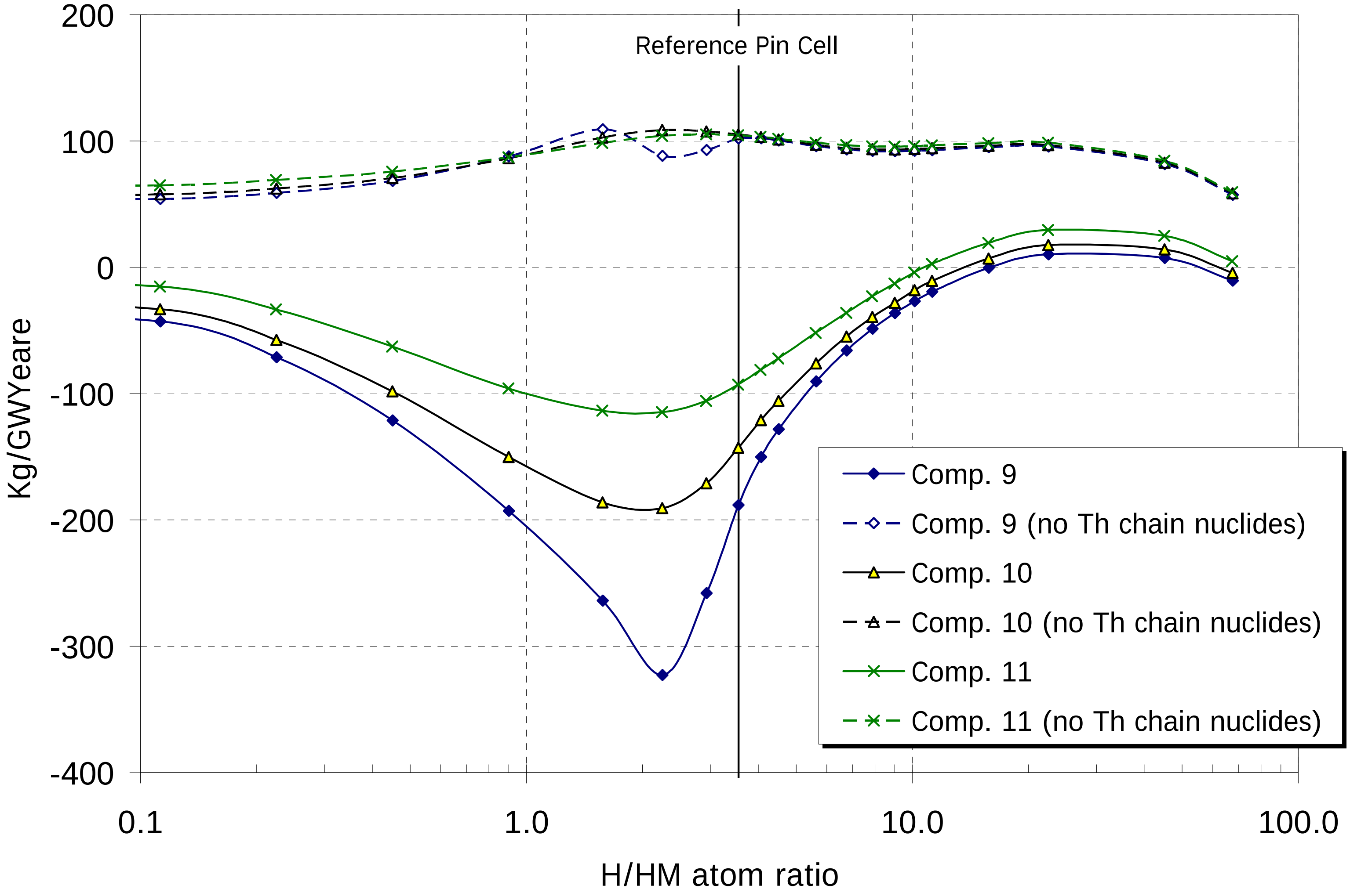
Fissile Uranium Ratio



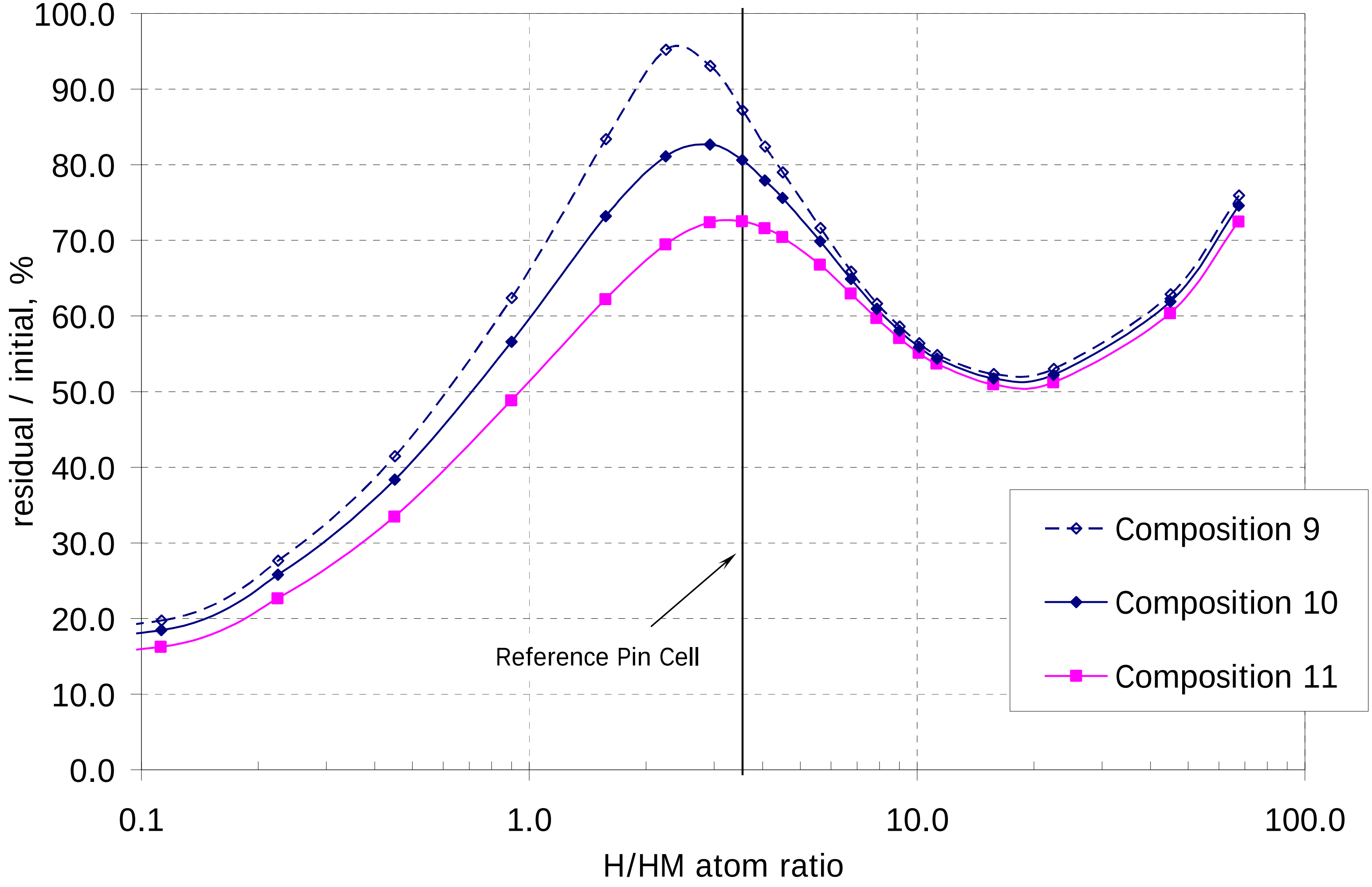
Homogeneous TRU-Th fuel: TRU Destruction Rate



Homogeneous TRU-Th fuel: MA Destruction Rate



Homogeneous TRU-Th fuel: Residual TRU Fraction



Pu-MA-Th Fuel: Reactivity Coefficients

DOPLER COEFFICIENT, pcm/K							
Comp. No.	Description	Reference H/HM			Reference + 40% H/HM		
		BOL	MOL	EOL	BOL	MOL	EOL
6	Pu-Th den.	-4.32	-4.65	-5.04	-3.43	-3.78	-4.22
9	Pu-MA-Th den.	-2.98	-3.02	-3.15	-2.63	-2.80	-3.02
12	MOX	-2.92	-3.09	-3.20	-2.36	-2.57	-2.70
13	All-U	-2.20	-2.93	-3.33	-1.82	-2.31	-2.75
MODERATOR TEMPERATURE COEFFICIENT, pcm/K							
6	Pu-Th den.	-49.05	-58.68	-73.47	-38.91	-50.40	-66.73
9	Pu-MA-Th den.	-18.53	-17.69	-23.40	-29.57	-33.17	-44.86
12	MOX	-40.63	-54.65	-73.78	-32.37	-46.92	-66.39
13	All-U	-22.17	-51.62	-77.79	-2.21	-26.00	-50.07
VOID COEFFICIENT, pcm/%void							
6	Pu-Th den.	-128.0	-156.8	-198.3	-104.8	-142.9	-190.4
9	Pu-MA-Th den.	-42.8	-41.4	-51.7	-70.8	-85.3	-115.8
12	MOX	-104.8	-145.3	-200.7	-86.0	-130.8	-190.8
13	All-U	-62.5	-145.7	-228.0	-10.8	-83.5	-164.8
SOLUBLE BORON WORTH, pcm/ppm							
6	Pu-Th den.	-1.95	-2.28	-3.02	-2.82	-3.60	-5.15
9	Pu-MA-Th den.	-1.05	-1.03	-1.24	-1.73	-1.90	-2.24
12	MOX	-1.96	-2.37	-2.76	-2.88	-3.70	-4.85
13	All-U	-4.80	-5.22	-6.23	-6.65	-8.15	-11.90

Homogeneous Pu-MA-Th Fuel: β_{eff} vs. Burnup