VISION Contributions to DOE NWTRB Benchmark

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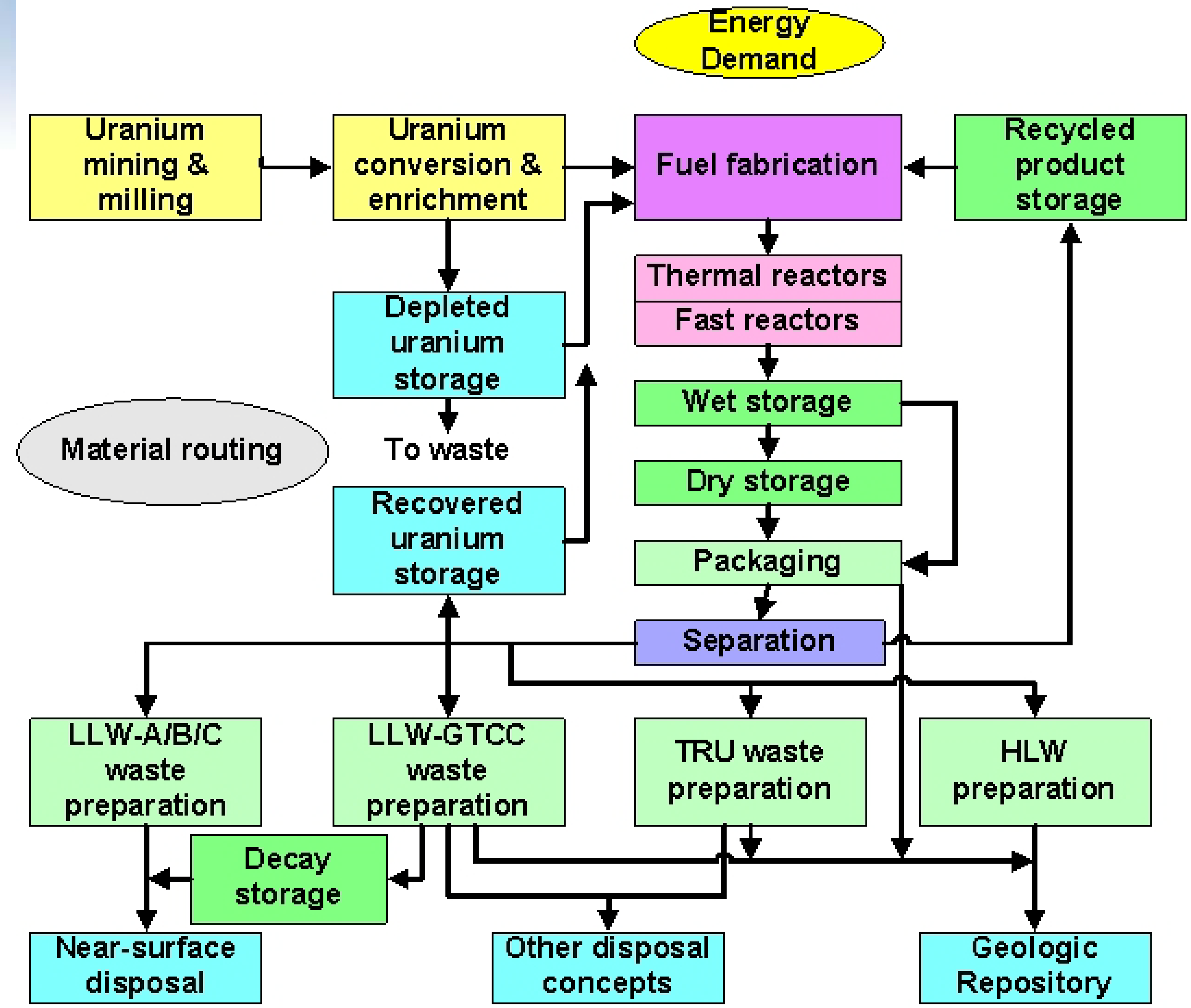
VISION is a tool for exploring advanced fuel cycle options

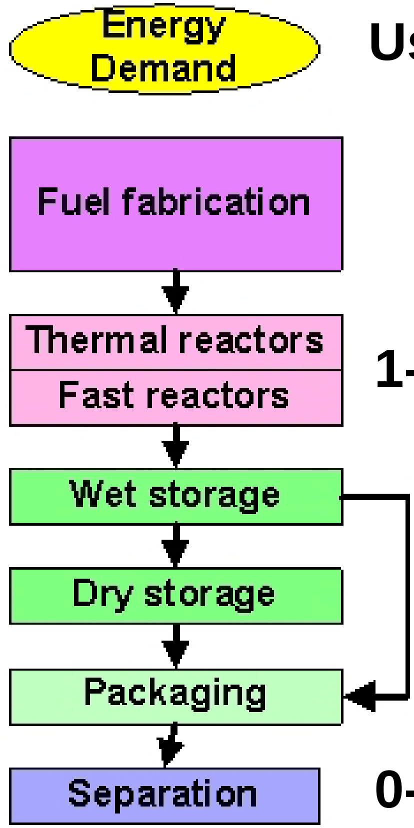
- Any U/TRU fuel cycle (probably Th/U in the future)
- Any U/TRU reactor
  - Models ***types*** of reactors, not individual reactors
- Any separation technology
- Technologies can be changed each year to study transitions
  - Nuclear electricity growth
  - Reactor mix
  - Fuel type and fuel fabrication capacity
  - Separation performance and capacity
  - Repository loading and receipt rate
  - Routing (reactor to separations, separations to fuel fab, etc.)
- 81 isotopes and groups of isotopes

VISION is a tool for exploring advanced fuel cycle options

NOTE: non-commercial wastes are not addressed



Some of VISION's capabilities



User specs for nuclear energy

1-10 reactor types

Each can be changed each year of the simulation

0-10 separation types

1-15 routing matrices from reactor to separations

0-40 separation matrices (how much of what goes where)

Benchmarks and comparisons

- Always take far longer and require far more iterations and specifications than anticipated.
  - Always start with general specs, then require additional iterations with more details to resolve differences in interpretations, etc.
- Cover only a portion of what a model requires as input.
- Cover only a portion of what a model provides.
  - Comparisons only possible on features common to all participating models
- Specifications often written to reflect the peculiarities of one of the models involved.
- Specifications never seem to be completely internally consistent, in part because real systems are more complex than any model.

Adjustments and interpretations

VISION	Adjustment to specifications
Does not model hundreds of reactors	Can model ≤ 10 reactor “types”, each with fixed lifetime. In this case: PWR-40, PWR-60, BWR-40, BWR-60
Has only one “legacy” retirement profile	Start calculations in 1960 so that existing reactors retire on time.
No true steady state develops (retirements, builds, isotope decay)	Obtain such results from as-stable-as-possible portion of a simulation
Does not do reactor physics, incorporates input/output fuel recipes. No recipes for re-enriched uranium.	Did not calculate re-enrichment cases.
Does not consider # of fuel assemblies	Did not calculate

Adjustments and interpretations (continued)

- No two models handle “routing” the same way
- VISION is separation-centric
  - User specifies order in which each separation type “pulls” from used fuel inventories (rather than define “push” from used fuel)
  - Separation type 1 goes first, then 2, etc.
  - Most attention to waste resulting from flow through separations
- If used fuel direct to repository, VISION simply draws on fuel in the order that reactor types are defined in the input deck, in this case …
  - PWR-40
  - PWR-60
  - BWR-40
  - BWR-60

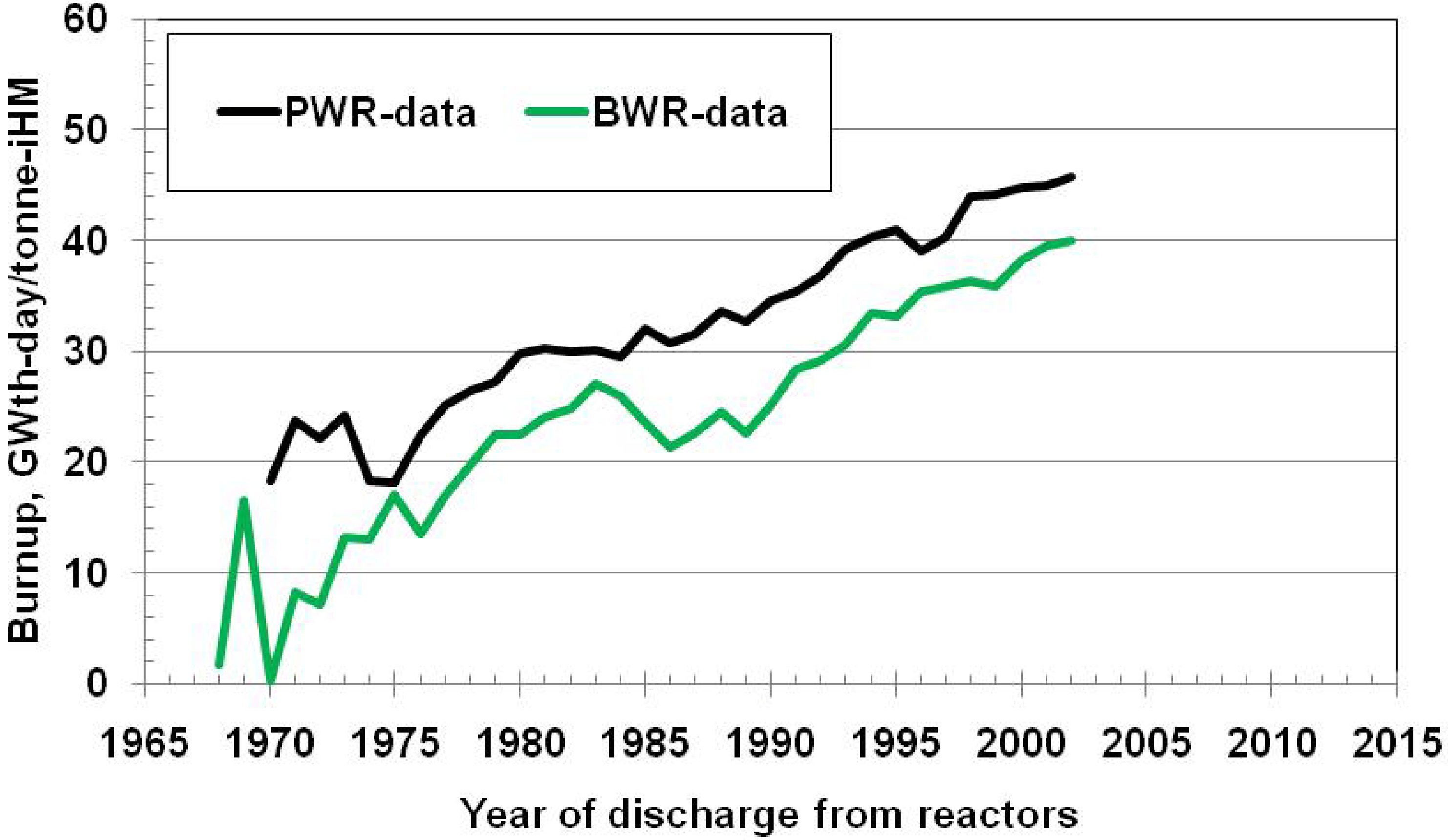
Adjustments and interpretations (continued)

- Can specify burnup or input enrichment, but not both
  - If LWR burnup, 4th order polynomial curve fit to PWR data provides input/output isotopic composition

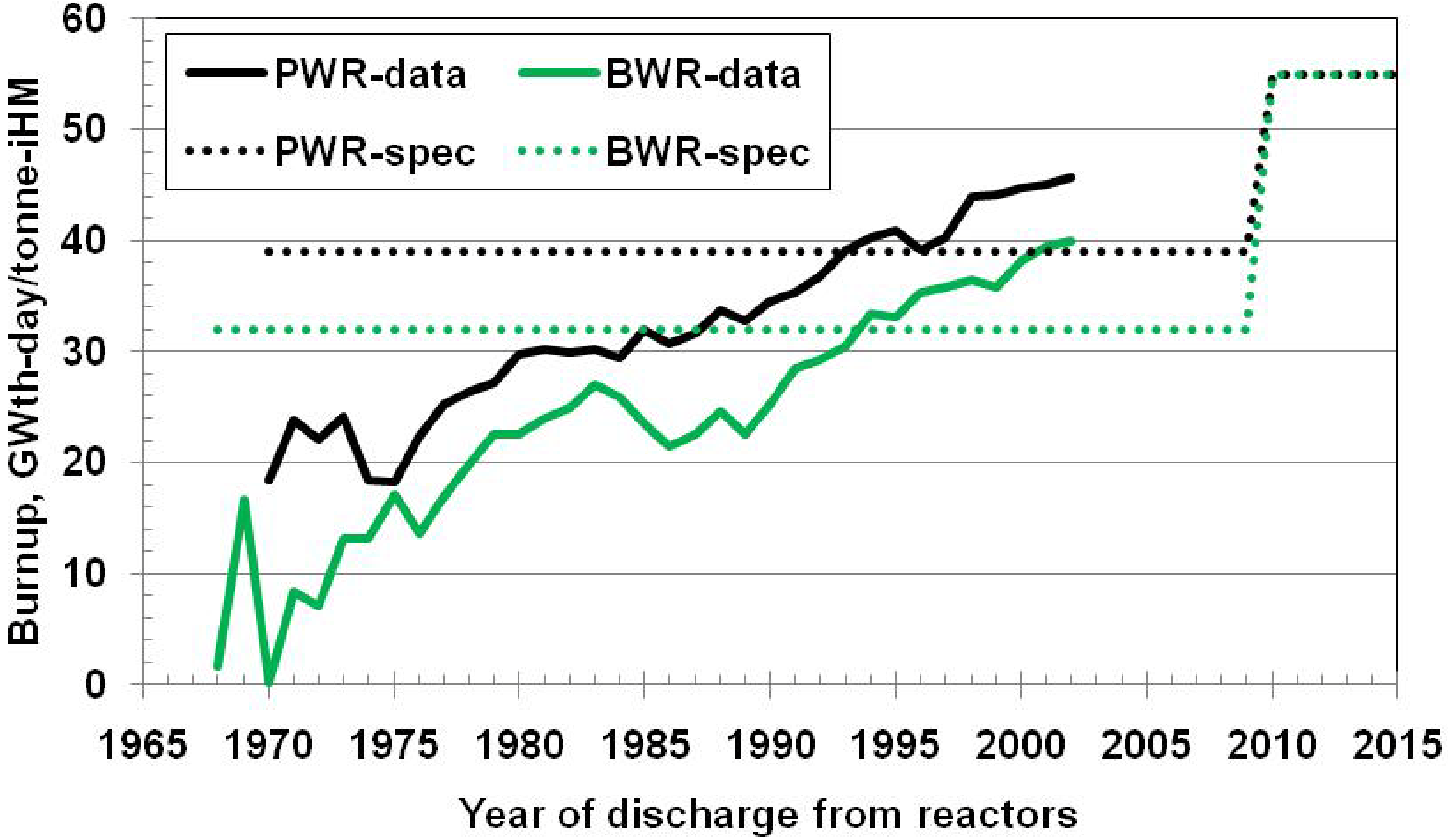
	PWR	BWR	PWR	BWR
Spec GWd/tonne	39	32	55	55
U235 spec	3.43%	2.39%	4.40%	4.35%
U235 VISION	3.38%	2.89%	4.59%	4.59%

- Known history of reactor start, constant 90% capacity factor, and specified constant burnup ("specs") lead to **50,800 tonnes-iHM** in 2000 versus historical data of **42,600 tonnes-iHM**.
  - Keep reactor start data, hence reactor retirement, 90% capacity factor after 2000, specified burnup after 2010
  - Adjust pre-2010 burnup and capacity factor to match 42,600 tonnes-iHM (and find it then matches the spec in 2010).

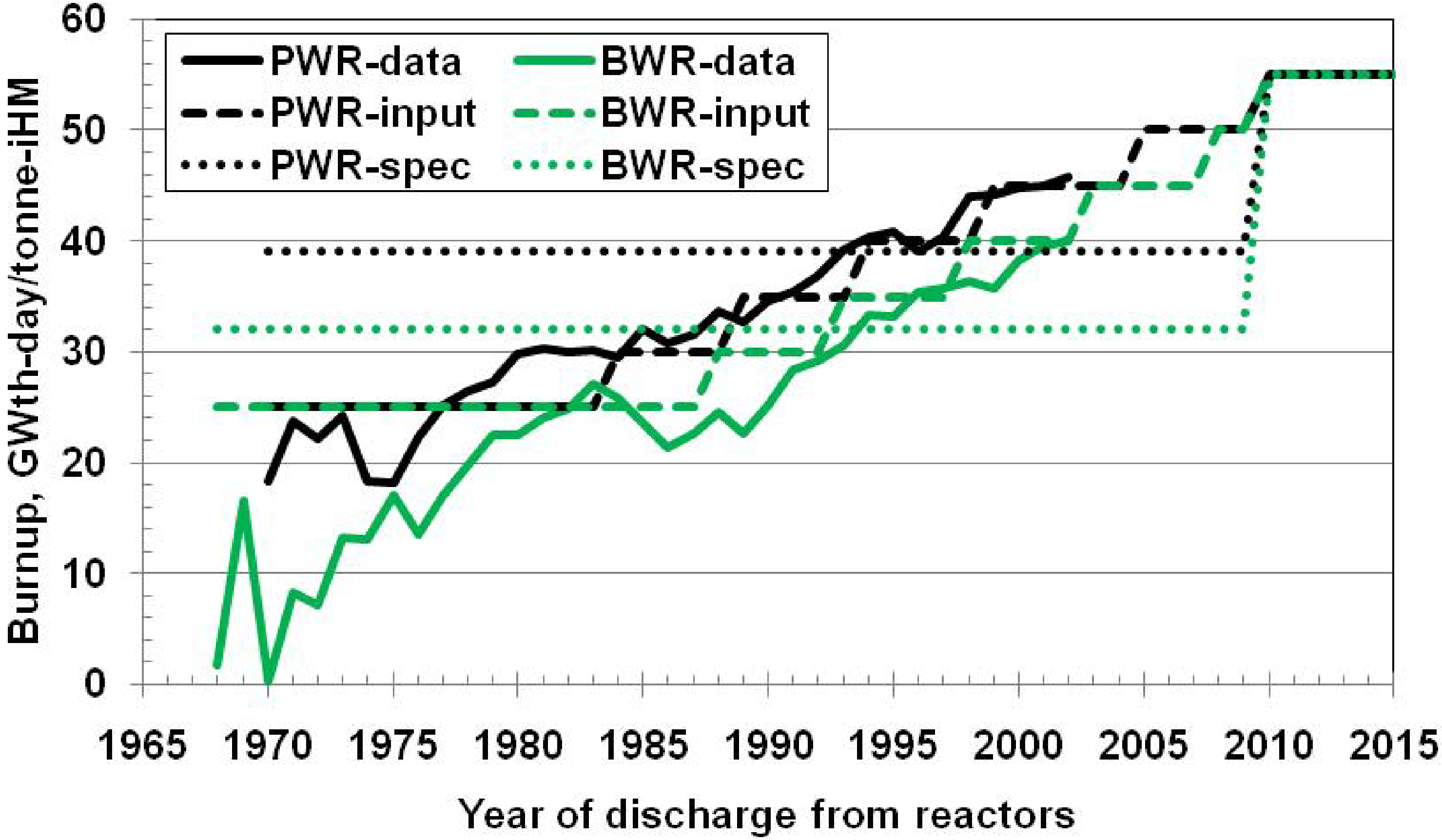
Adjusted burnup before 2010 to approximate the historical data



Adjusted burnup before 2010 to approximate the historical data



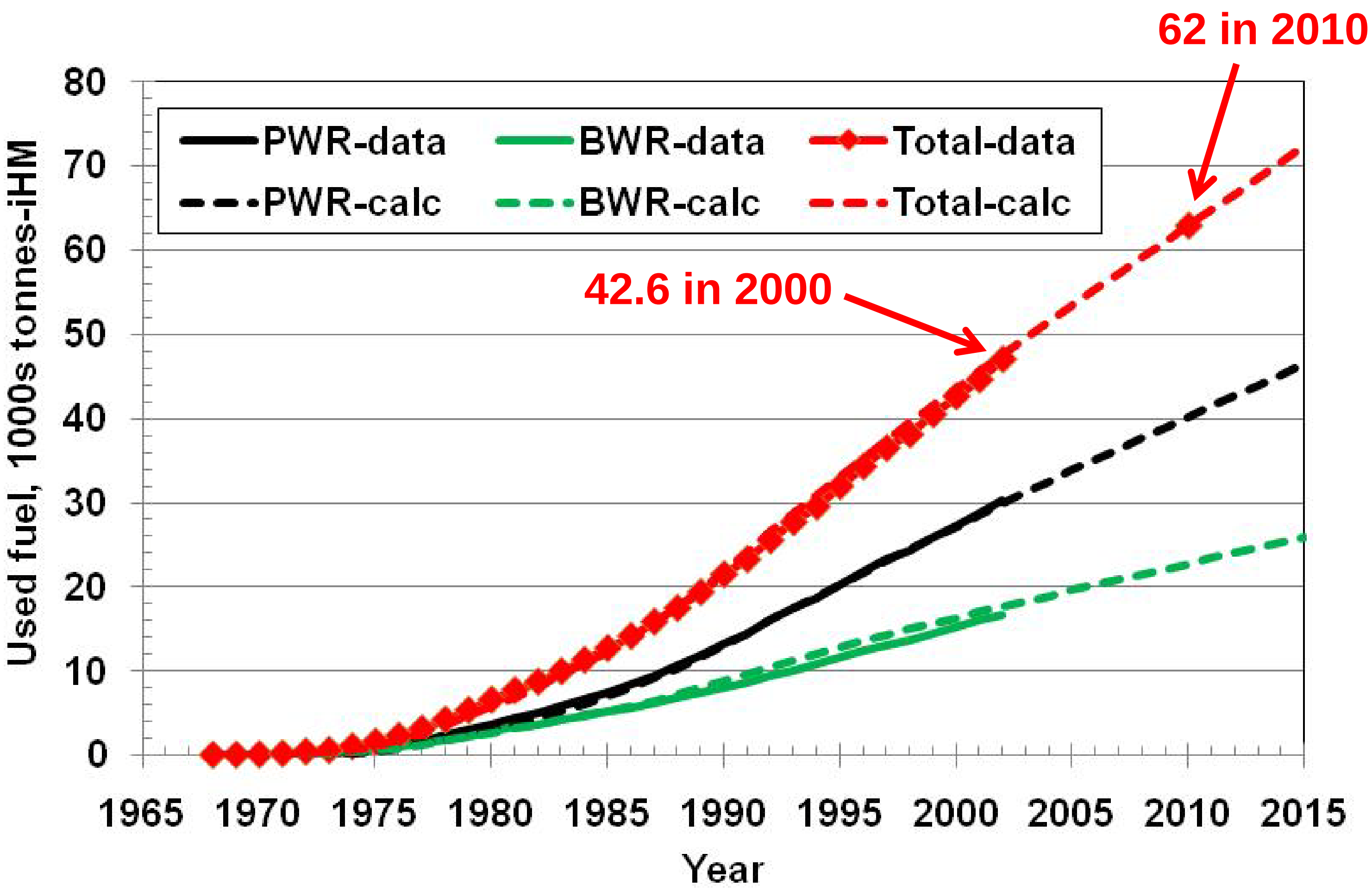
Adjusted burnup ("input") before 2010 to approximate the historical data



Burnup, enrichment, capacity factor

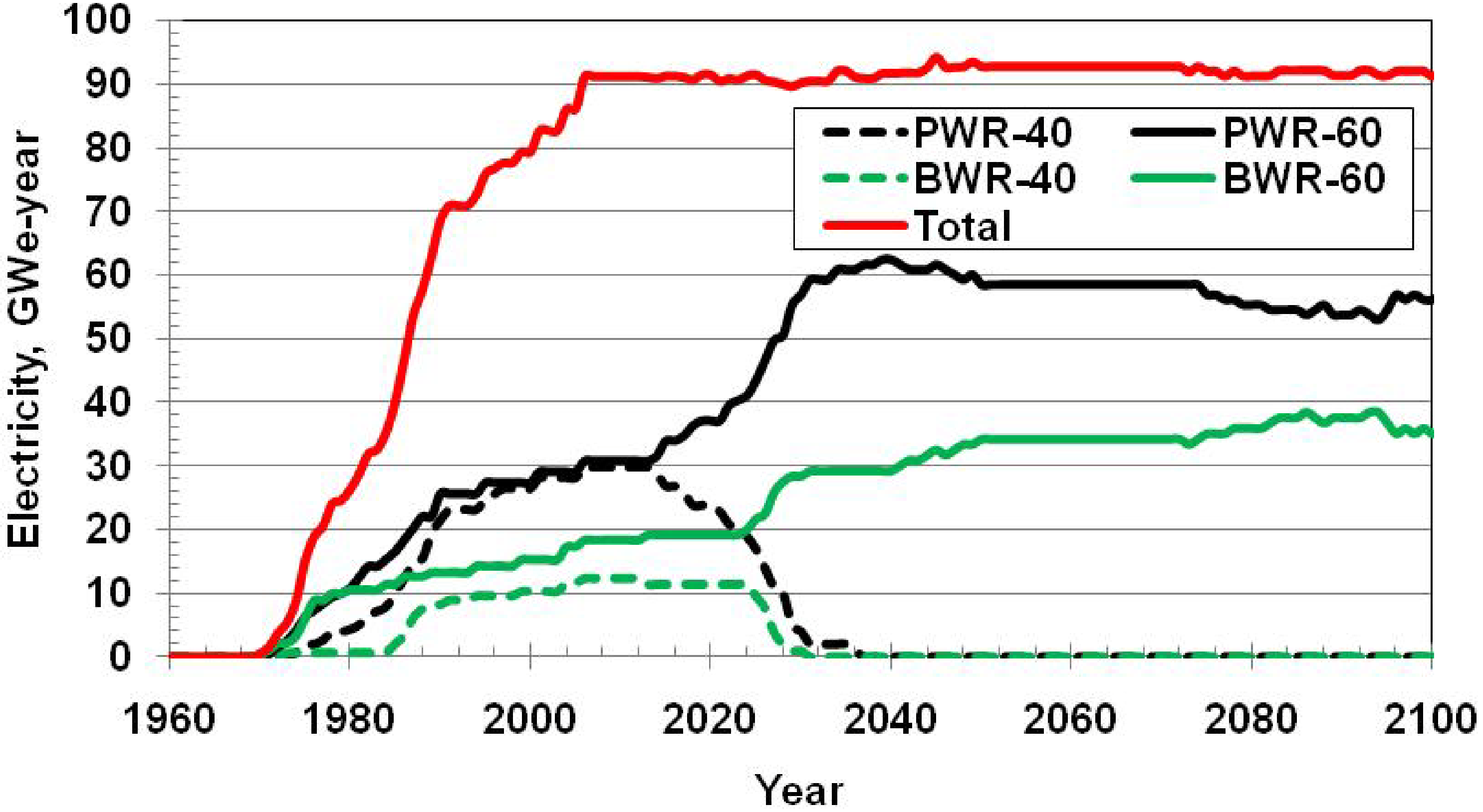
When start/PWR	1972	1984	1989	1994	1999	2005	2010
When start/BWR	1970	1988	1993	1998	2003	2008	
Burnup	25	30	35	40	45	50	55
% U235	2.43%	2.76%	3.10%	3.46%	3.82%	4.20%	4.59%
Capacity factor PWR	60%	65%	70%	75%	80%	85%	90%
Capacity factor BWR			65%	70%	75%		

Used fuel inventory



Electricity

Current fleet modeled as either 40 or 60-year lifetime. Per spec, all new reactors are 60-year lifetime.



Total electricity is not exactly constant as reactors are retiring and coming on line with differing unit sizes.

Phase 1 – End of 2009 used fuel inventory (tonnes)

	PWR	BWR	Total
Wet storage (≤10 years)	13,431	6,615	20,046
Dry storage (>10 years)	25,516	15,503	41,019
Total	38,948	22,118	61,065

Phase 1 – End of 2009 used fuel inventory (actinides, tonnes)

	U232	U233	U234	U235	U236	U238	U-total
PWR	0.0	0.0	0.5	267.3	157.8	36,622.8	37,048.4
BWR	0.0	0.0	0.2	151.8	79.5	20,921.1	21,152.7
	Pu238	Pu239	Pu240	Pu241	Pu242	Pu244	Pu-total
PWR	6.4	205.1	96.3	33.4	23.7	0.0	364.8
BWR	2.8	112.9	51.5	17.0	11.4	0.0	195.6
	Np237	Am	Cm	Bk-Cf	He	Other	MA-total
PWR	16.6	26.0	1.3	0.0	0.0	0.0	43.9
BWR	8.0	13.5	0.5	0.0	0.0	0.0	22.0

58,800 tonnes (>96% of used fuel) of recyclable material

Phase 1 – End of 2009 used fuel inventory (fission products, tonnes)

	H3	C14	C other	Kr81	Kr85	Inert gas-other					Subtotal	
PWR	0.00	0.00	0.00	0.00	0.55	244.38					244.93	**Volatiles**
BWR	0.00	0.00	0.00	0.00	0.27	121.54					121.81	
	Tc99	Tc other	I129	Halogen-other							Subtotal	
PWR	33.47	0.01	7.85	3.68							45.03	**Long-lived**
BWR	17.06	0.01	4.00	1.88							22.95	
	Rb	Sr90	Sr-other	Cs134	Cs135	Cs137	Cs-other	Ba			Subtotal	
PWR	15.05	17.91	15.96	0.82	16.57	41.60	48.05	76.80			232.75	**Heat**
BWR	7.57	8.94	8.09	0.36	9.00	20.71	24.65	38.34			117.68	
	Zr93	Zr95	Zr-other	Ru106	Pd107	Se79	Cd113m	Sn126	Sb125	TM-other	Subtotal	
PWR	30.92	0.08	123.68	0.39	10.18	0.25	0.01	1.21	0.09	351.54	518.35	**Transition metals (TM)**
BWR	15.56	0.04	62.03	0.19	5.07	0.13	0.00	0.61	0.05	175.75	259.43	
	Ce144	Pm147	Sm147	Sm151	Eu154	Eu155	Ho166m	LA-other			Subtotal	
PWR	0.54	0.72	2.63	0.61	0.81	0.19	0.00	443.94			449.44	**Lanthanides (LA)**
BWR	0.27	0.36	1.33	0.35	0.37	0.09	0.00	222.64			225.40	

2,238 tonnes of fission products

Phase 2 – 2010 to 2100 used fuel inventory (tonnes)

2100 inventory	PWR	BWR	Total
Wet storage (≤10 years)	13,405	9,141	22,546
Dry storage (>10 years)	143,031	79,542	222,573
Total	156,436	88,683	245,119

2010 to 2100	PWR	BWR	Total
Discharged	117,488	66,565	184,054

Discharge ~2000 tonnes/year

Phase 2 – 2010 to 2100 used fuel discharged (actinides, tonnes)

	U232	U233	U234	U235	U236	U238	U-total
PWR	0.0	0.0	5.2	846.7	712.2	107,736.8	109,301.0
BWR	0.0	0.0	2.9	479.7	403.6	61,039.5	61,925.7
	Pu238	Pu239	Pu240	Pu241	Pu242	Pu244	Pu-total
PWR	38.9	691.8	352.2	100.1	112.3	0.0	1,295.3
BWR	22.2	392.0	199.5	58.4	63.6	0.0	735.7
	Np237	Am	Cm	Bk-Cf	He	Other	MA-total
PWR	84.9	140.4	7.6	0.0	0.4	0.0	233.3
BWR	48.1	77.9	4.4	0.0	0.2	0.0	130.6

174,000 tonnes (>94% of used fuel) of recyclable material

Phase 2 – 2010 to 2100 used fuel discharged (fission products, tonnes)

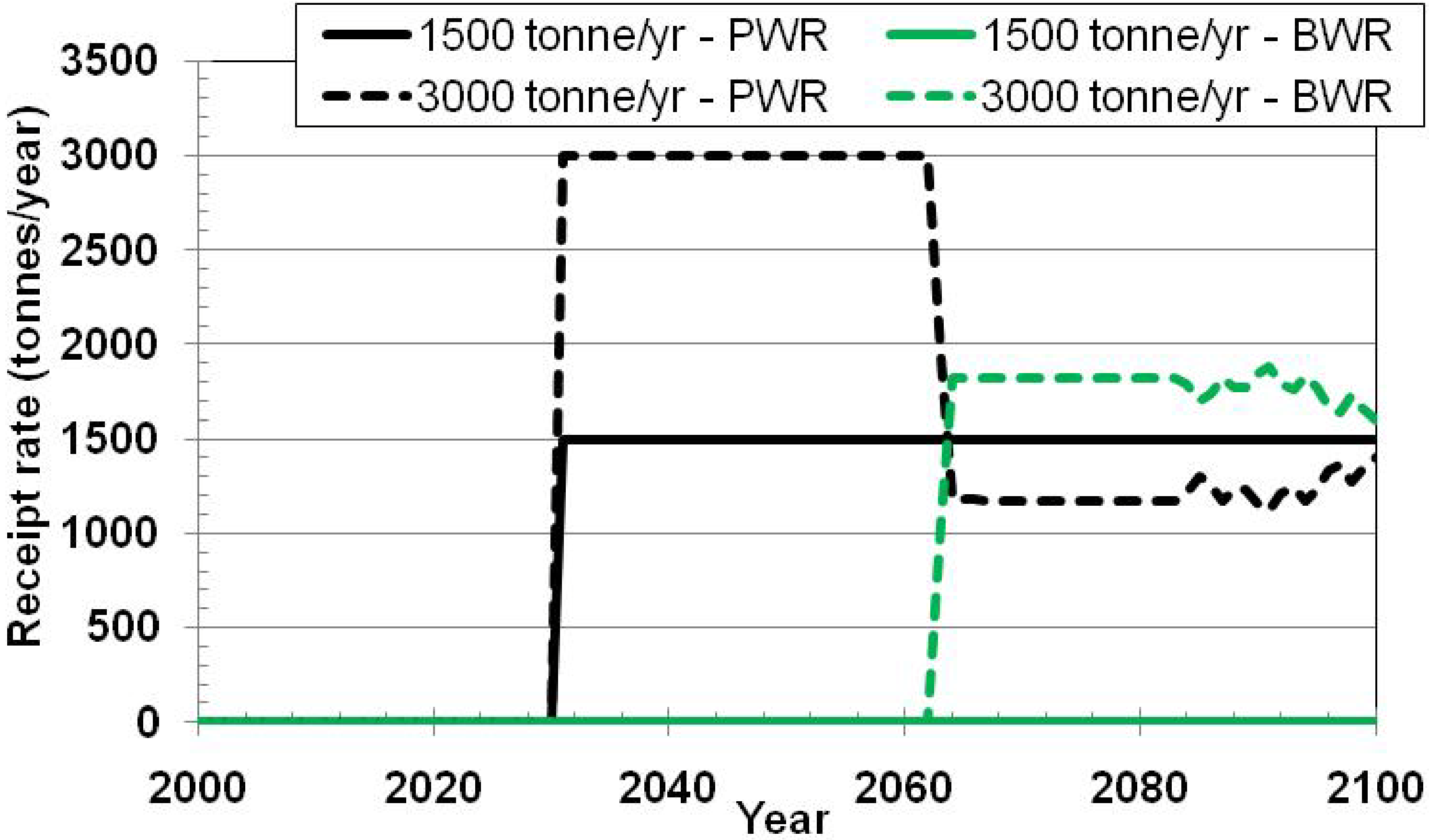
	H3	C14	C other	Kr81	Kr85	Inert gas-other					Subtotal	
PWR	0.00	0.00	0.01	0.00	1.62	1085.38					1,087.02	**Volatiles**
BWR	0.00	0.00	0.00	0.00	0.96	615.04					616.01	
	Tc99	Tc other	I129	Halogen-other							Subtotal	
PWR	143.35	0.04	34.11	15.49							192.99	**Long-lived**
BWR	81.23	0.02	19.33	8.78							109.36	
	Rb	Sr90	Sr-other	Cs134	Cs135	Cs137	Cs-other	Ba			Subtotal	
PWR	68.23	69.57	69.93	0.20	82.11	162.38	202.26	380.82			1,035.50	**Heat**
BWR	38.62	39.95	39.63	0.30	46.54	93.18	114.61	214.45			587.27	
	Zr93	Zr95	Zr-other	Ru106	Pd107	Se79	Cd113m	Sn126	Sb125	TM-other	Subtotal	
PWR	137.46	0.00	566.74	0.00	45.18	1.13	0.03	5.31	0.04	1576.57	2,332.46	**Transition metals (TM)**
BWR	77.90	0.01	320.63	0.07	25.60	0.64	0.02	3.01	0.04	893.29	1,321.20	
	Ce144	Pm147	Sm147	Sm151	Eu154	Eu155	Ho166m	LA-other			Subtotal	
PWR	-0.02	0.19	12.24	2.36	2.48	0.34	0.00	1,993.16			2,010.75	**Lanthanides (LA)**
BWR	0.08	0.23	6.93	1.34	1.50	0.23	0.00	1,129.12			1,139.42	

10,400 tonnes of fission products

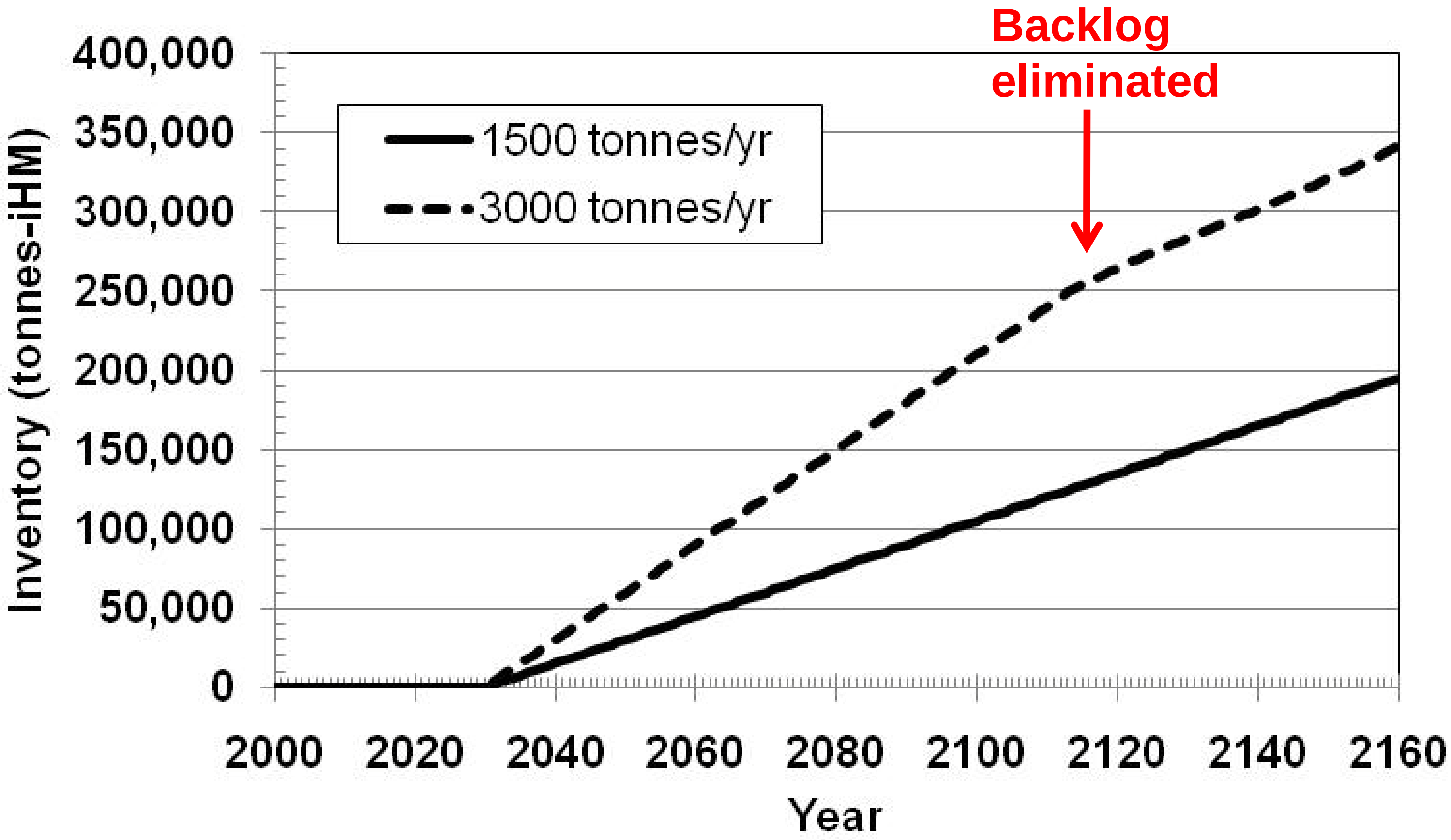
Phase 3 – Repository, but no recycling

- Cases specified, both start repository in 2030
  - 1500 tonnes/year – backlog continues to grow
  - 3000 tonnes/year – backlog eliminated in 2115
  - Per spec, there is no limit to repository capacity
- VISION sends waste (once old enough) to repository based on the order of reactors defined in the input file
  - In this case, takes PWR-40, then PWR-60, BWR-40, PWR-60
- Isotopic data in spreadsheet

Phase 3 – Repository receipt rate (tonnes/yr)



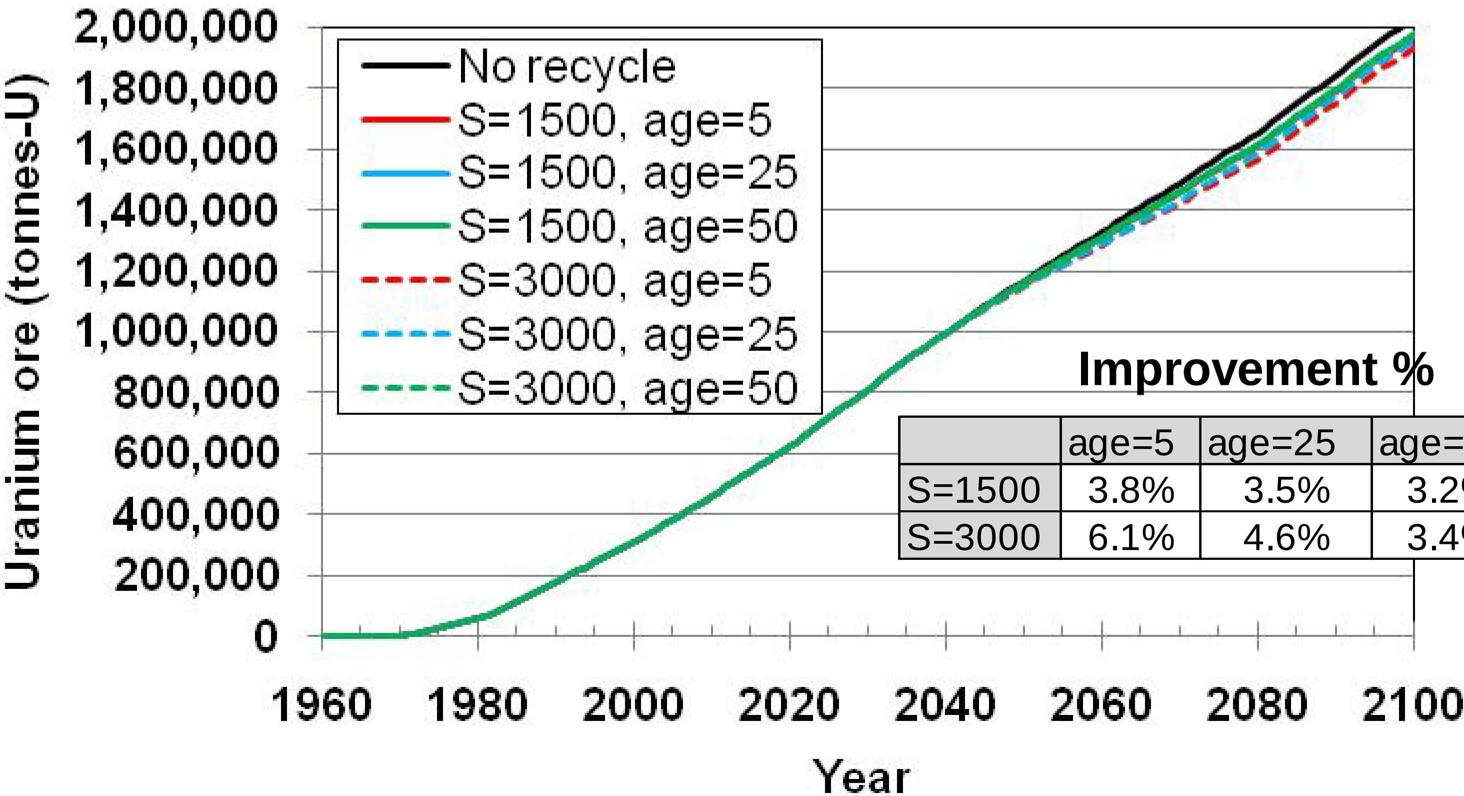
Phase 3 – repository inventory (tonnes)



Phase 4 – Recycling, but no repository

- MOX-RU-Pu, fuel recipe in Library has burnup of 50 GWth-day/tonne
  - Recycles RU from separated LWR UOX
  - Recycles Pu (11% of fresh MOX)
  - Best possible MOX-Pu uranium improvement (1 recycle) is 14%
    - x 64% of the fuel x 2/3 of the time (2010-2100) → **6.0%**
- Minimum aging before separation
  - **5 years, 25 years, 50 years**
- Separation cases specified, both start in 2040, tonnes-iHM
  - 1500 t/year – backlog grows, U savings **3.8%, 3.5%, 3.2%**
  - 3000 t/year – backlog gone in 2118, U savings **6.1%, 4.6%, 3.4%**
- Per spec, BWR fuel not recycled
- Isotopic data in spreadsheet

Phase 4 – Recycling – uranium ore consumption

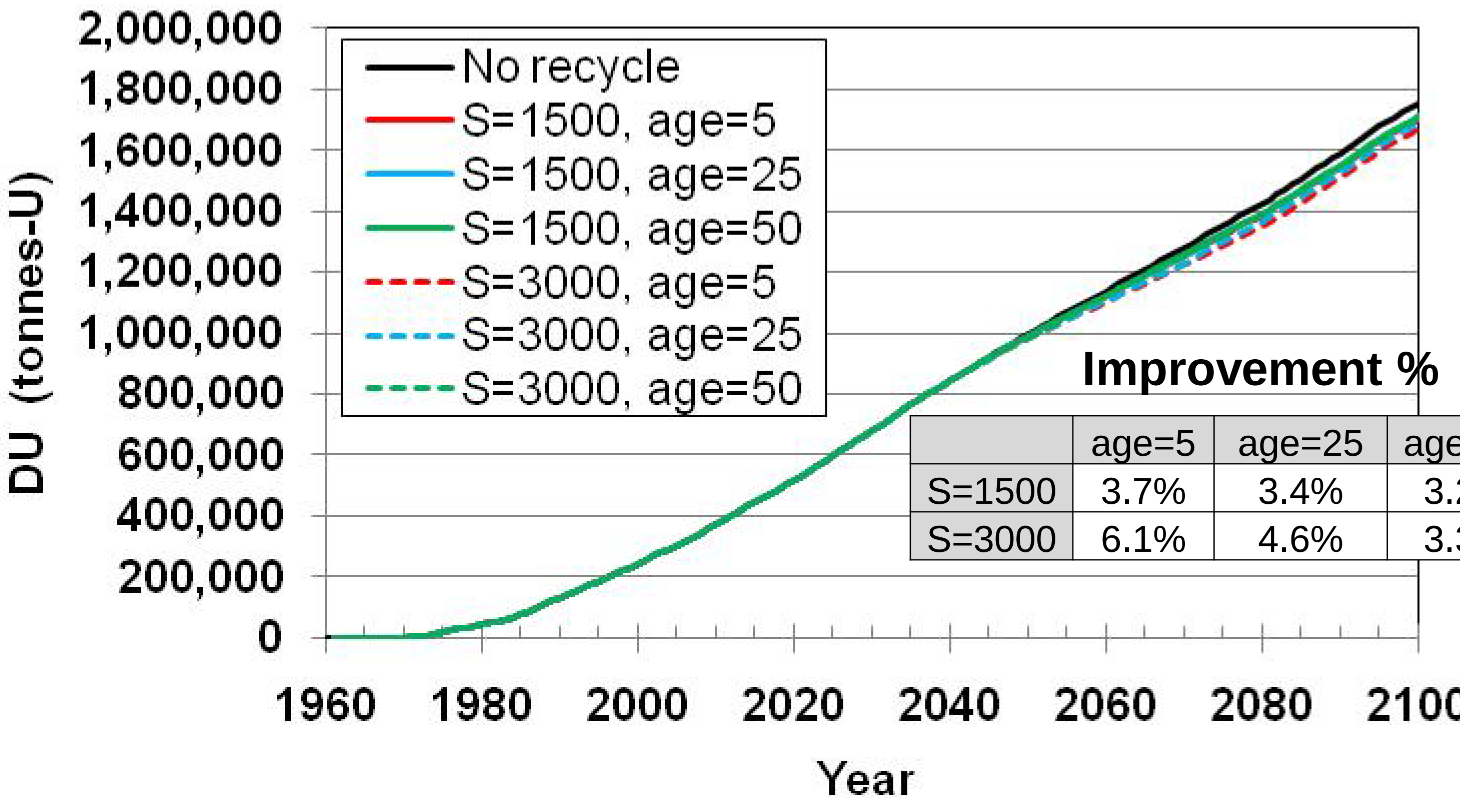


Improvement %

	age=5	age=25	age=50
S=1500	3.8%	3.5%	3.2%
S=3000	6.1%	4.6%	3.4%

Unit is tonnes of uranium metal in the ore

Phase 4 – Recycling – depleted uranium generated

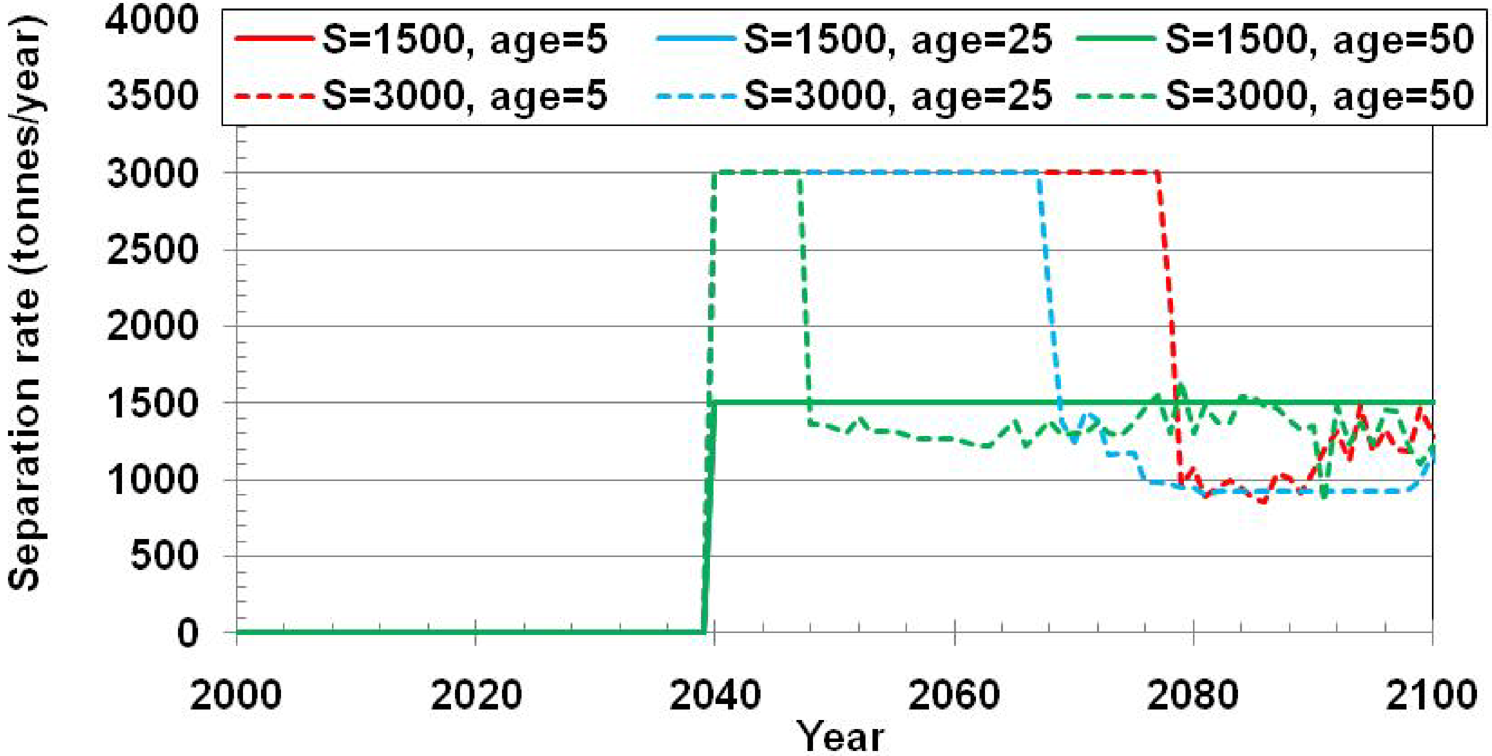


Improvement %

	age=5	age=25	age=50
S=1500	3.7%	3.4%	3.2%
S=3000	6.1%	4.6%	3.3%

Unit is tonnes of uranium metal in the ore

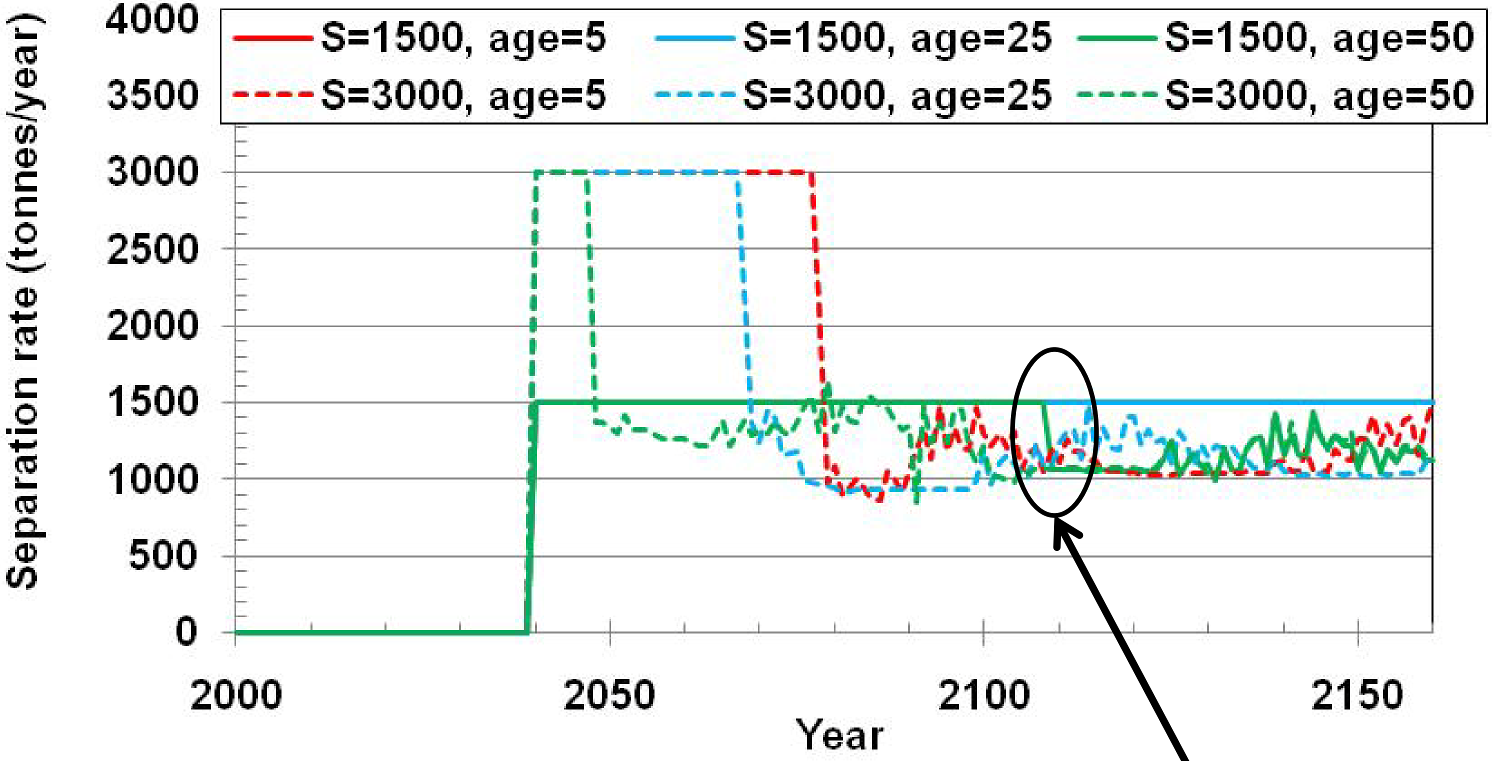
Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



At 1500 tonne/year, backlog continues

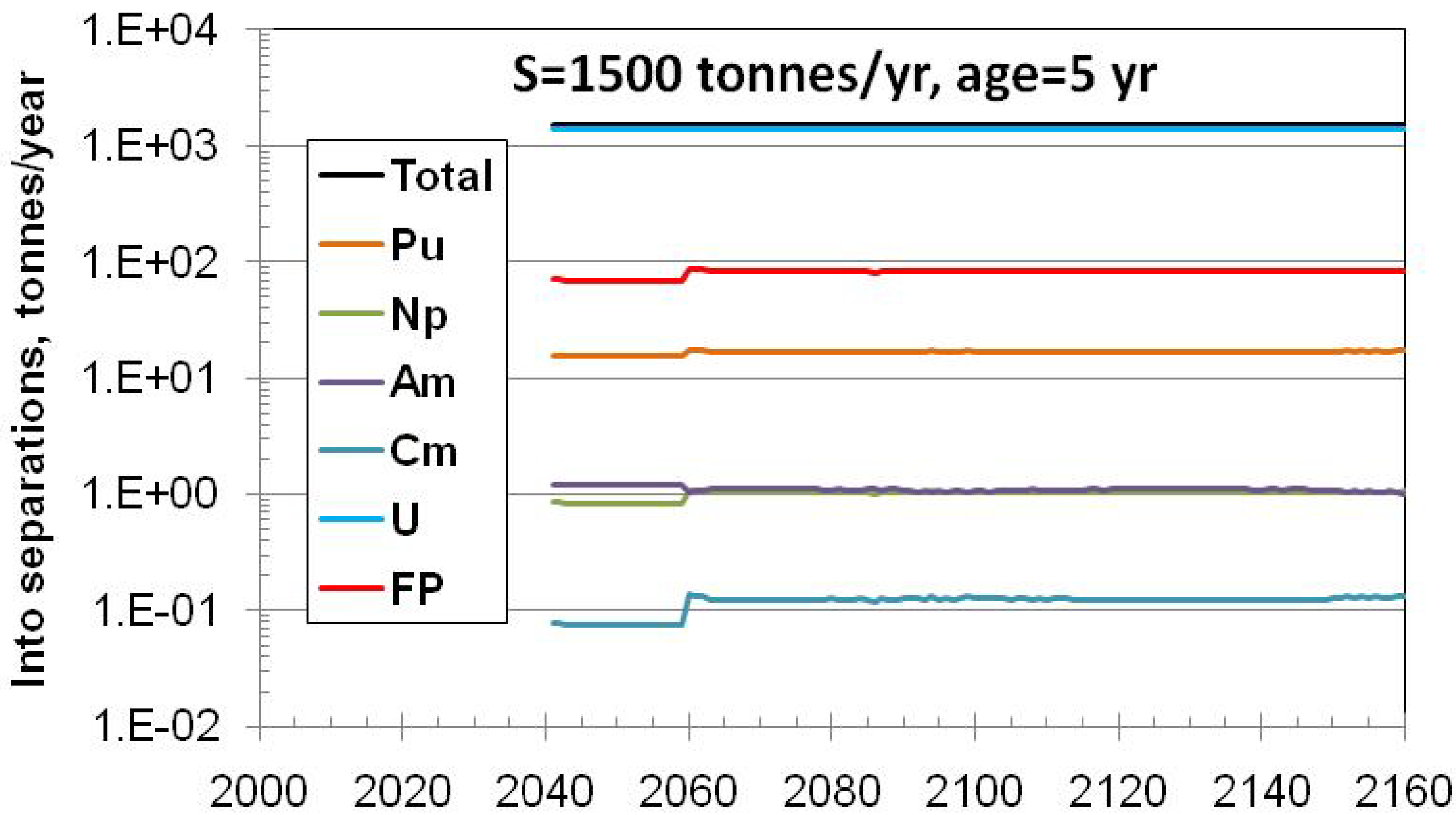
At 3000 tonne/year, backlog gone in 2048 (age=50), 2068 (age=25), 2078 (age=5)

Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



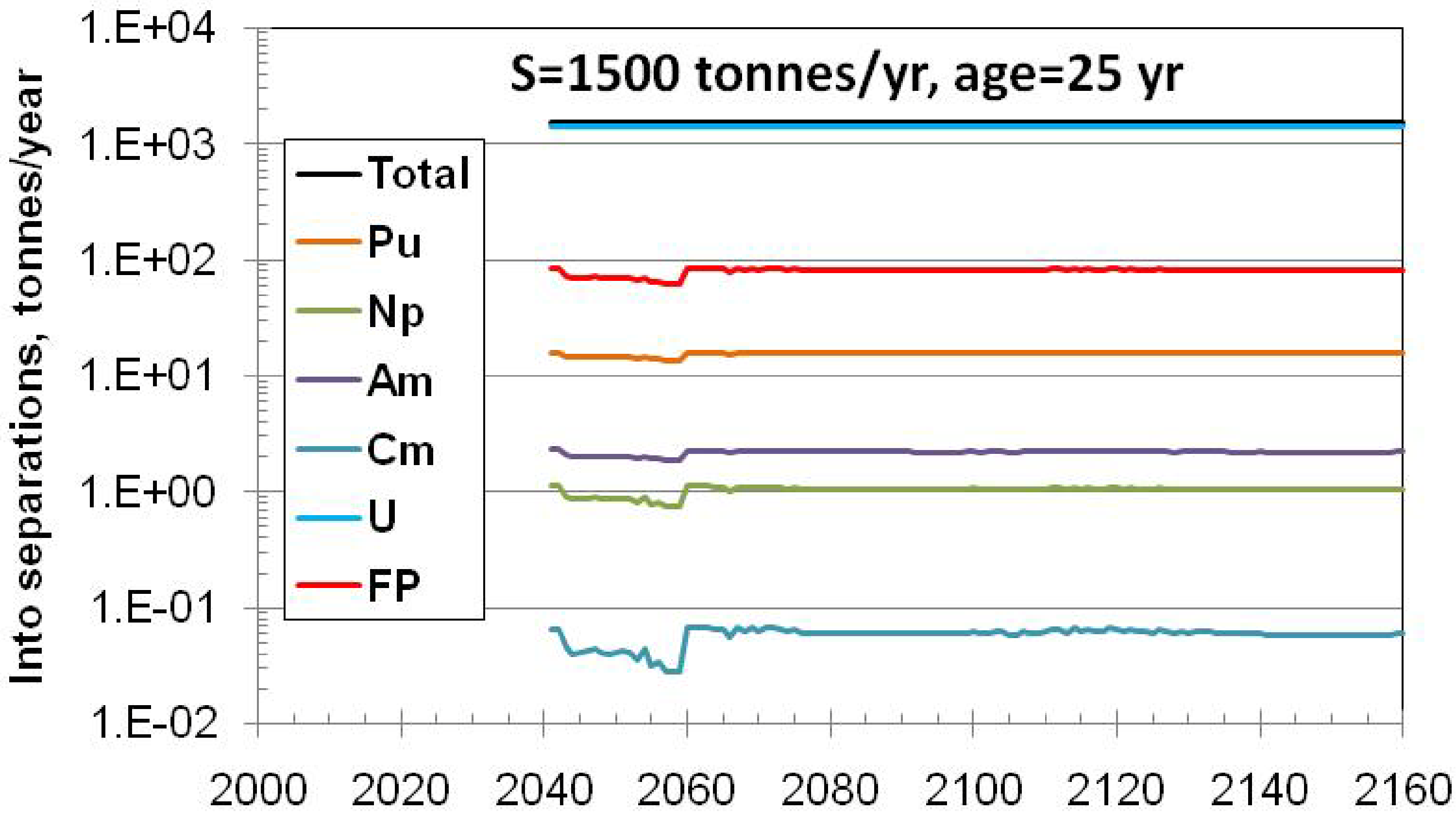
At 1500 tonne/year, age=50, backlog gone in 2109

Phase 4 – Recycling rate (tonnes/yr) of PWR fuel

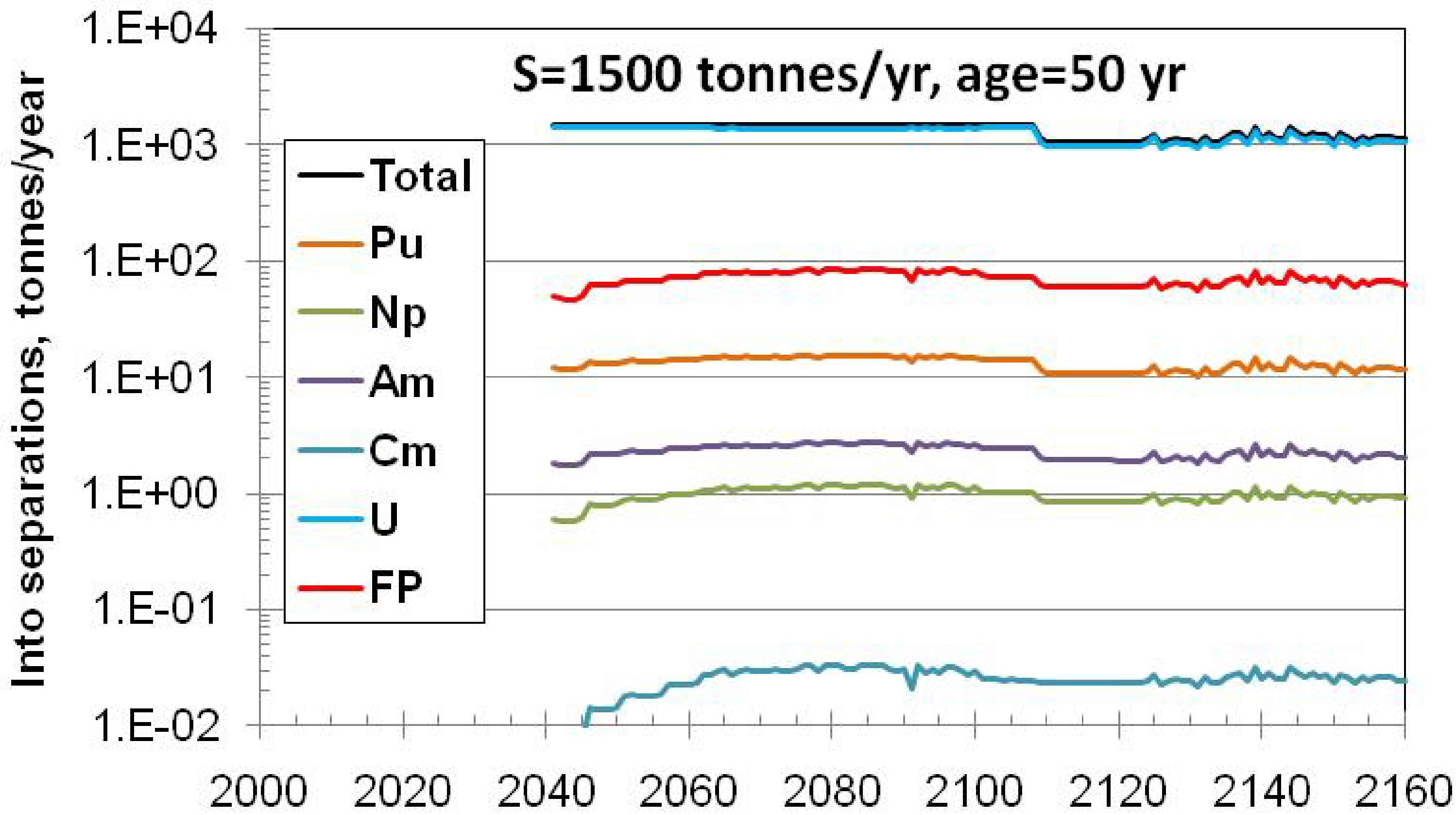


Two effects at work: isotope decay and different BU fuel used at different times

Phase 4 – Recycling rate (tonnes/yr) of PWR fuel

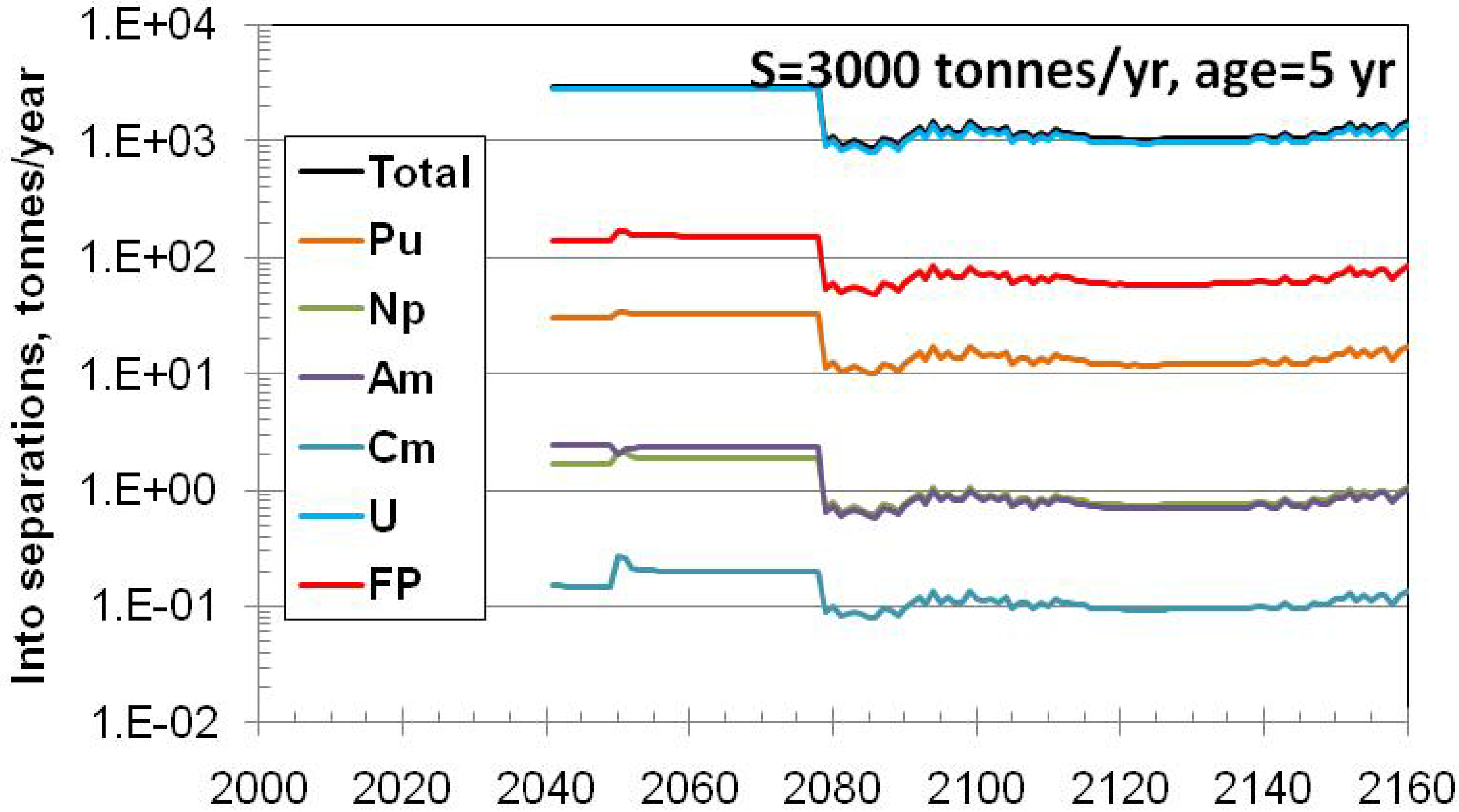


Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



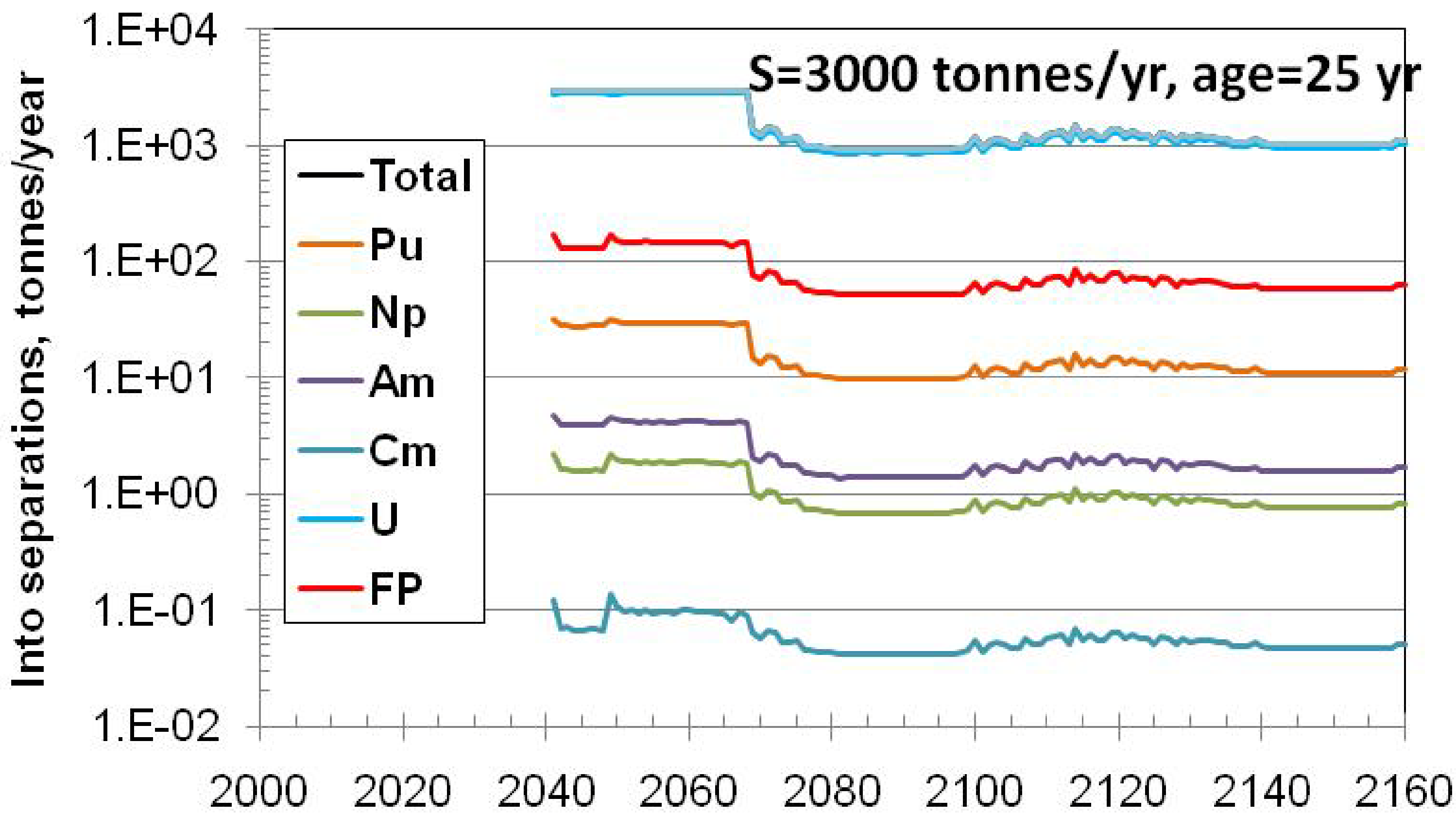
Dip in 2109 is when backlog worked off

Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



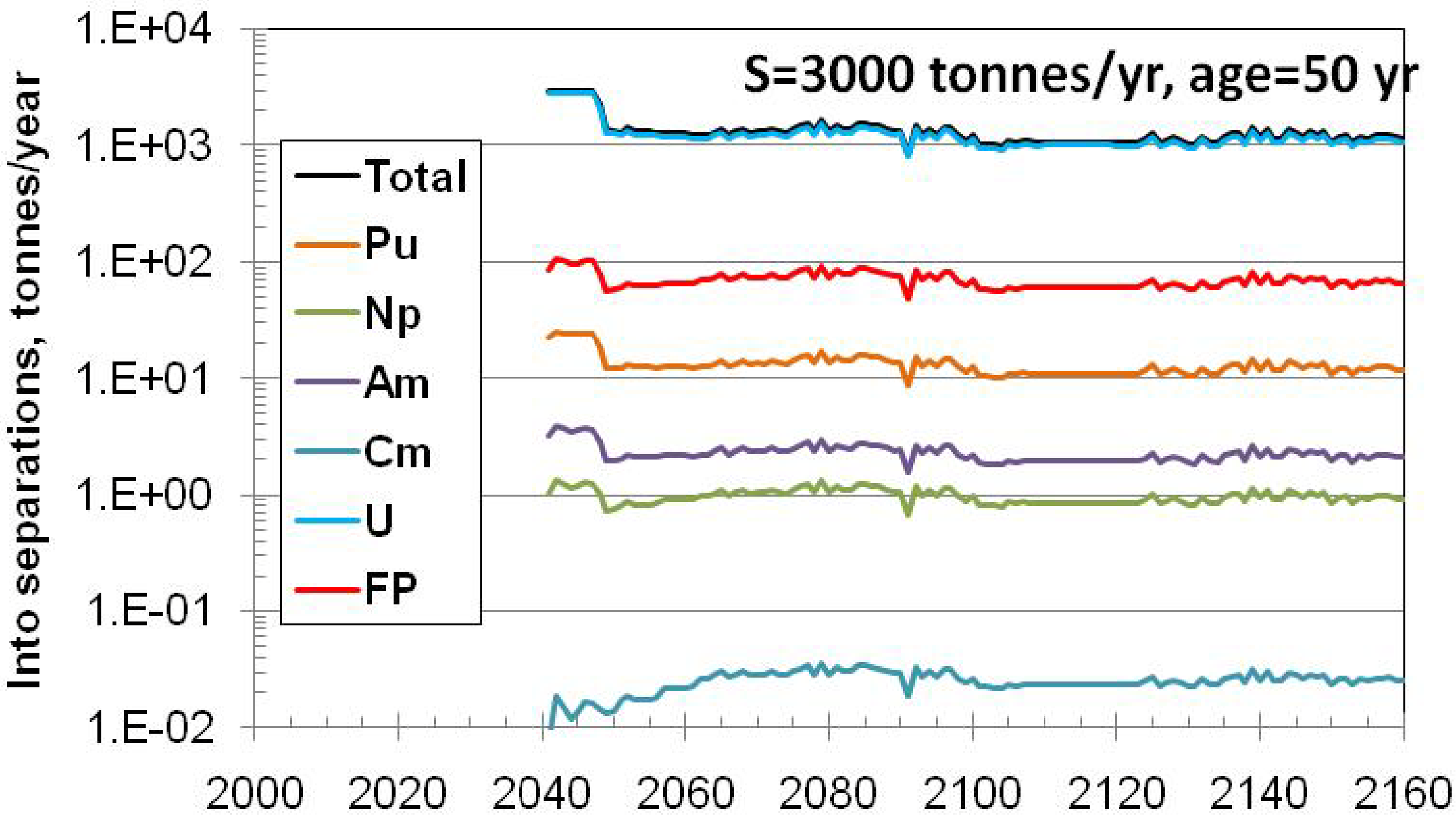
Dip in 2078 is when backlog worked off

Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



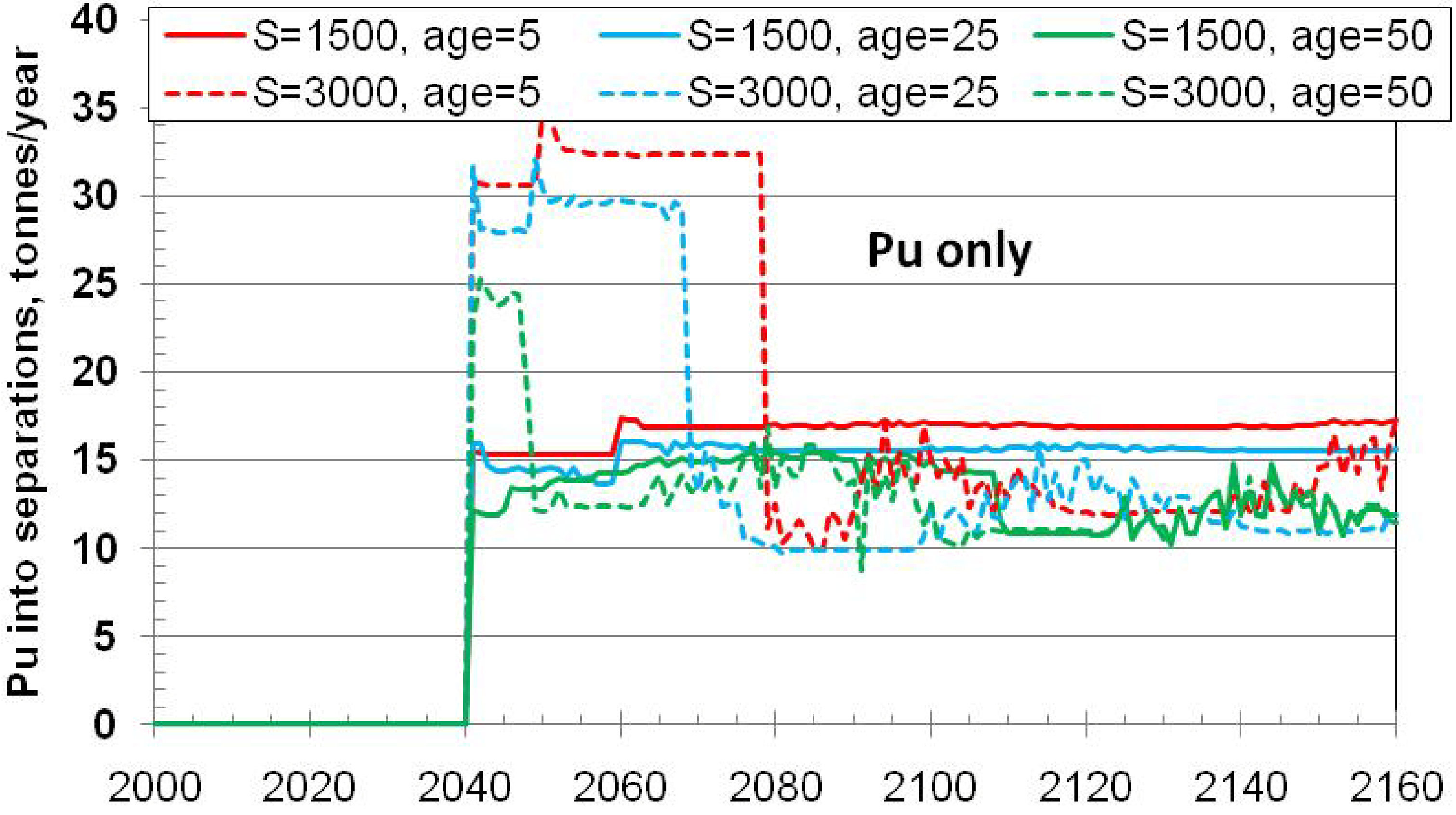
Dip in 2068 is when backlog worked off

Phase 4 – Recycling rate (tonnes/yr) of PWR fuel

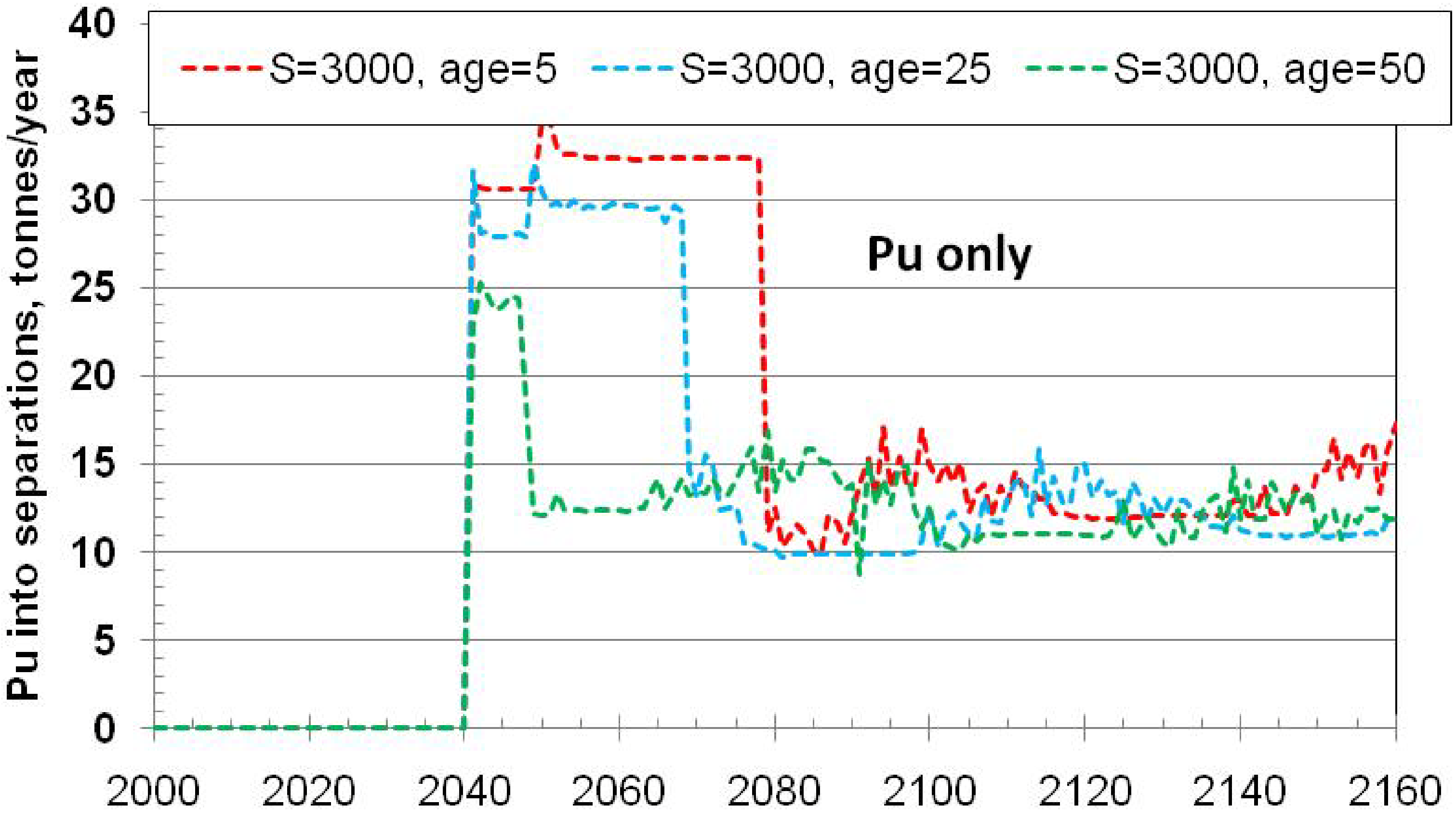


Dip in 2048 is when backlog worked off

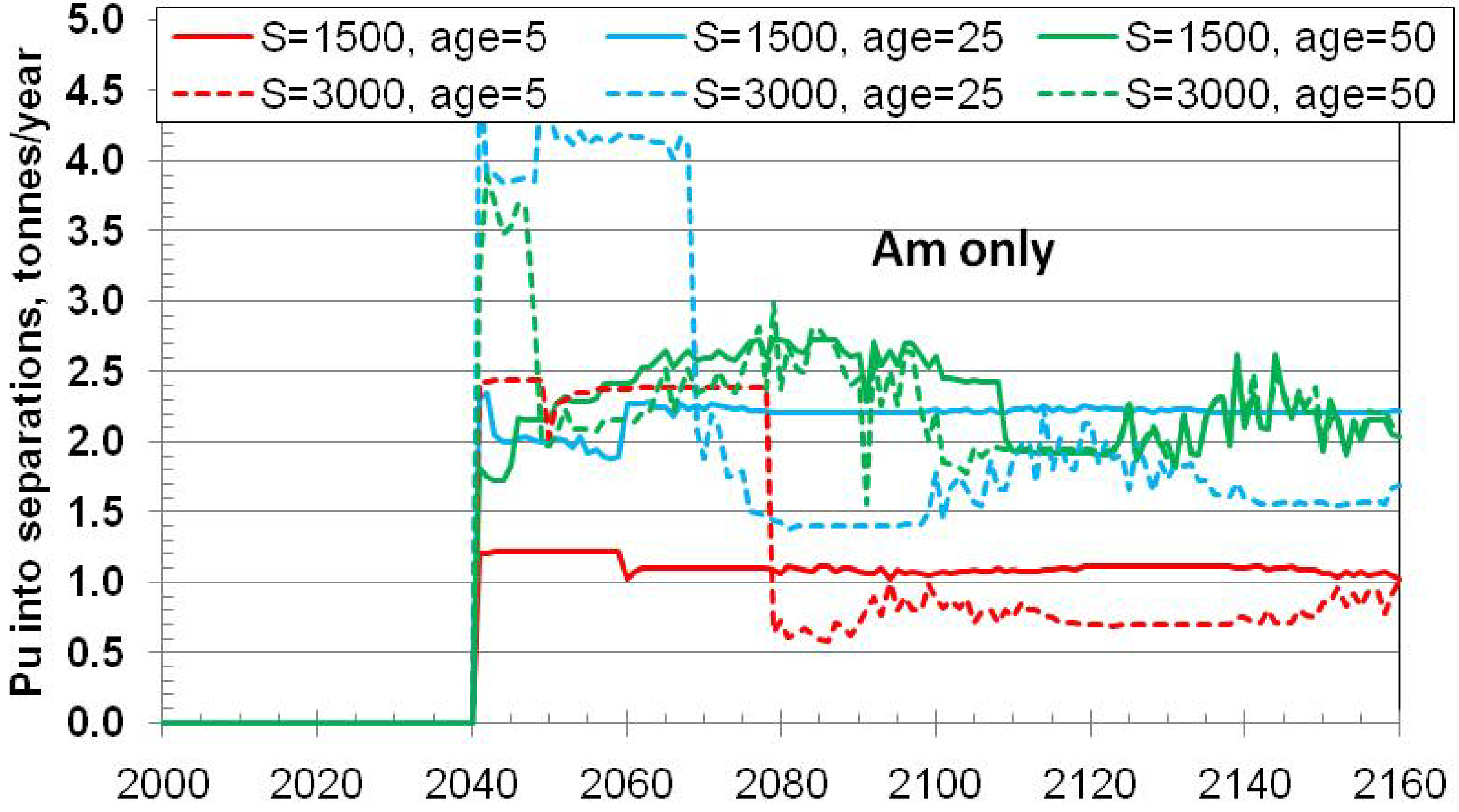
Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



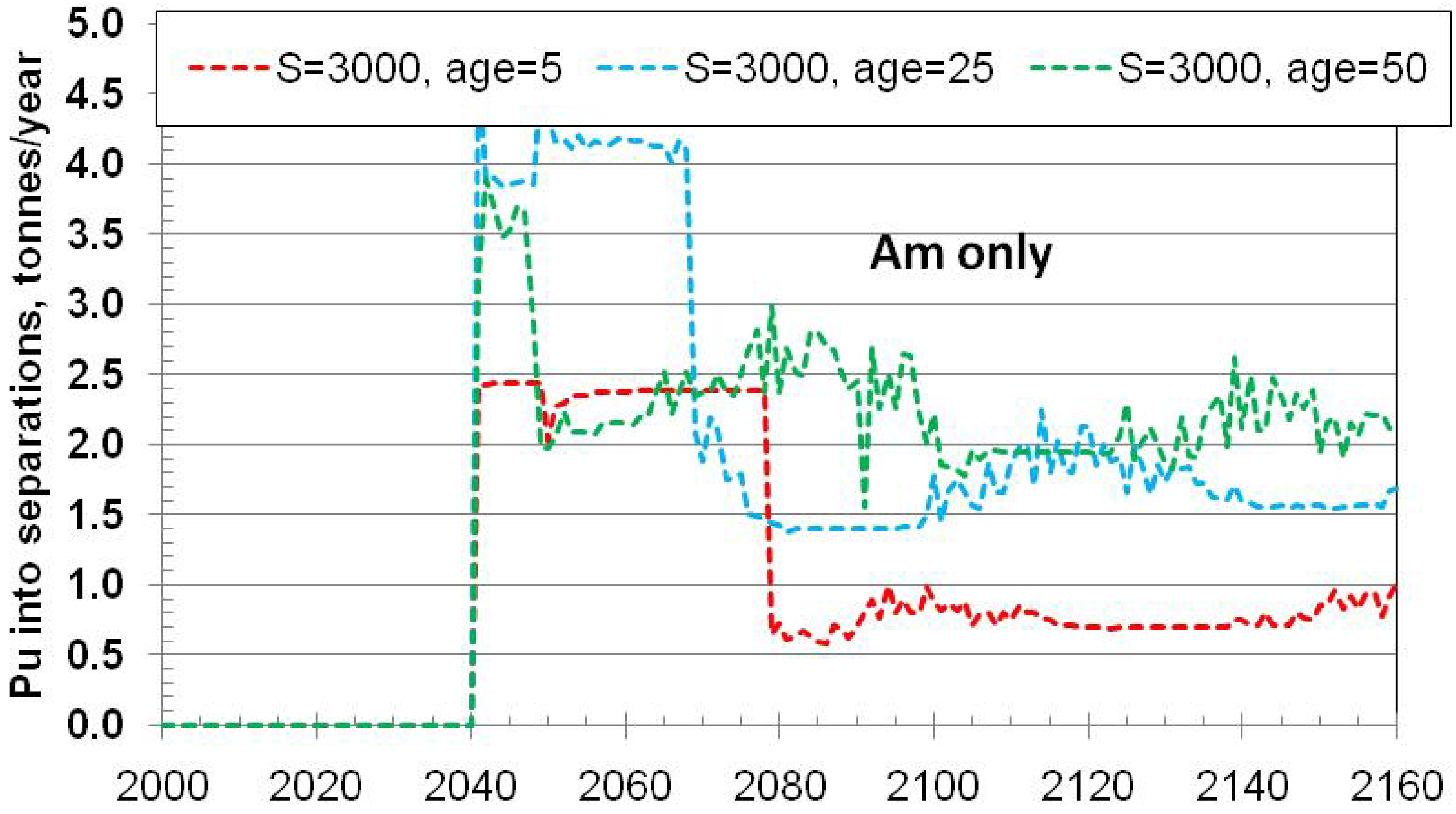
Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



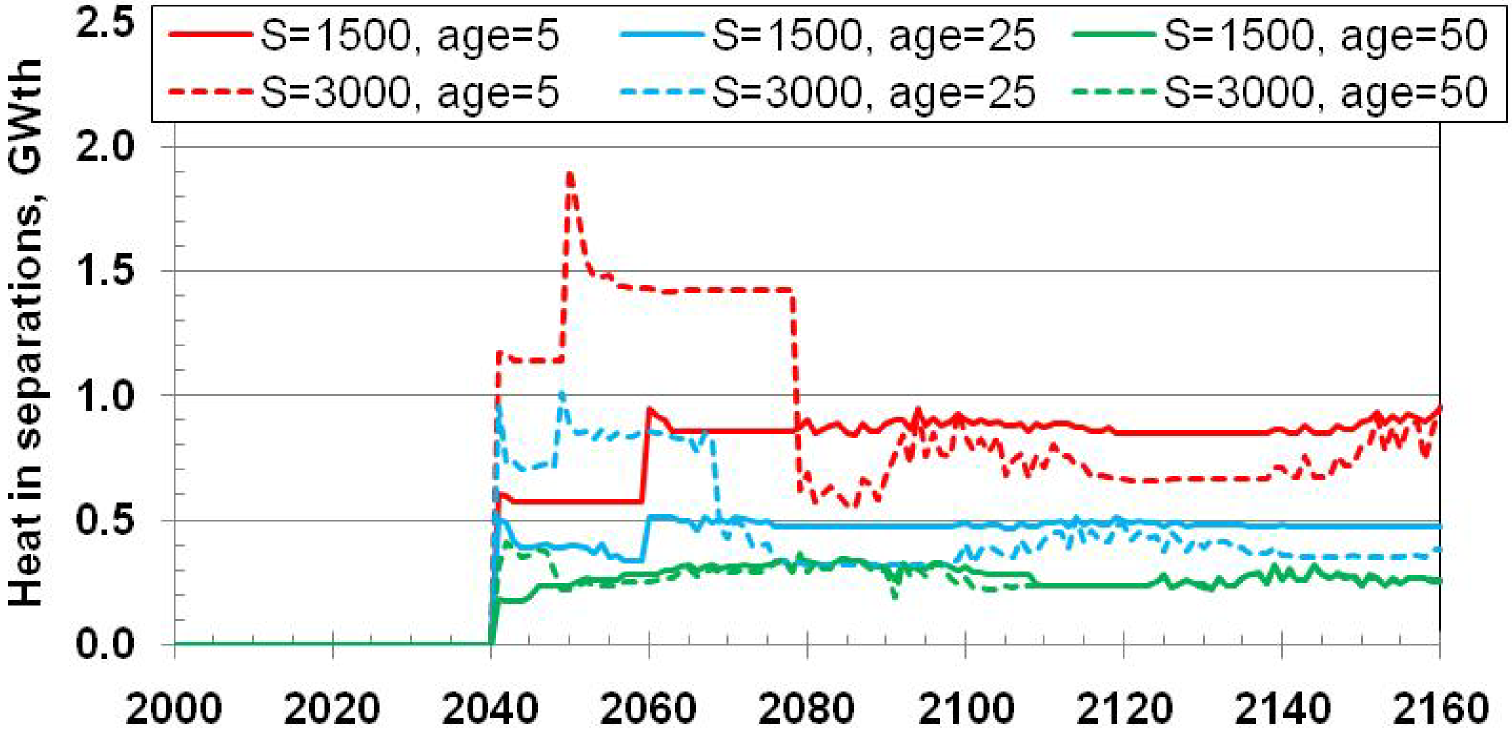
Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



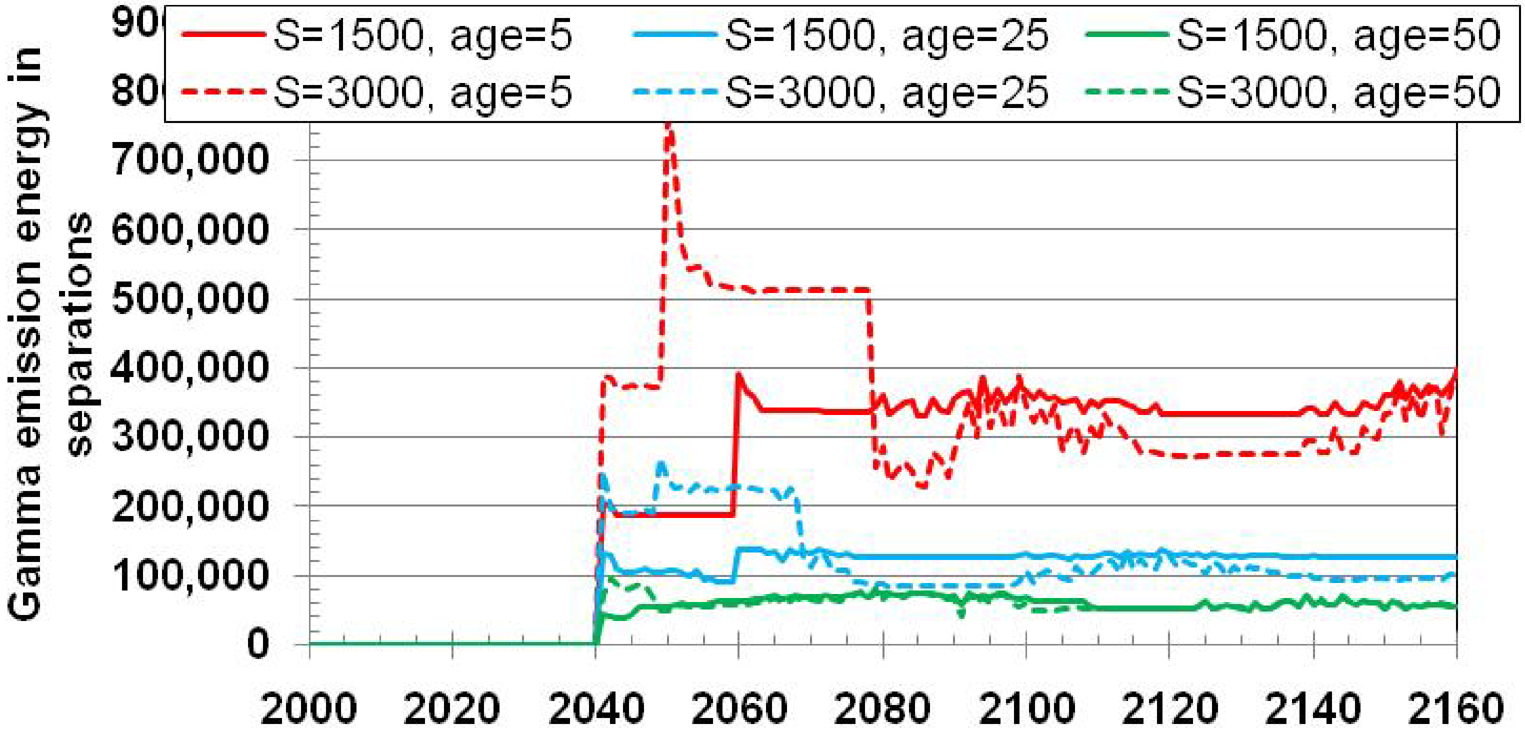
Phase 4 – Recycling rate (tonnes/yr) of PWR fuel



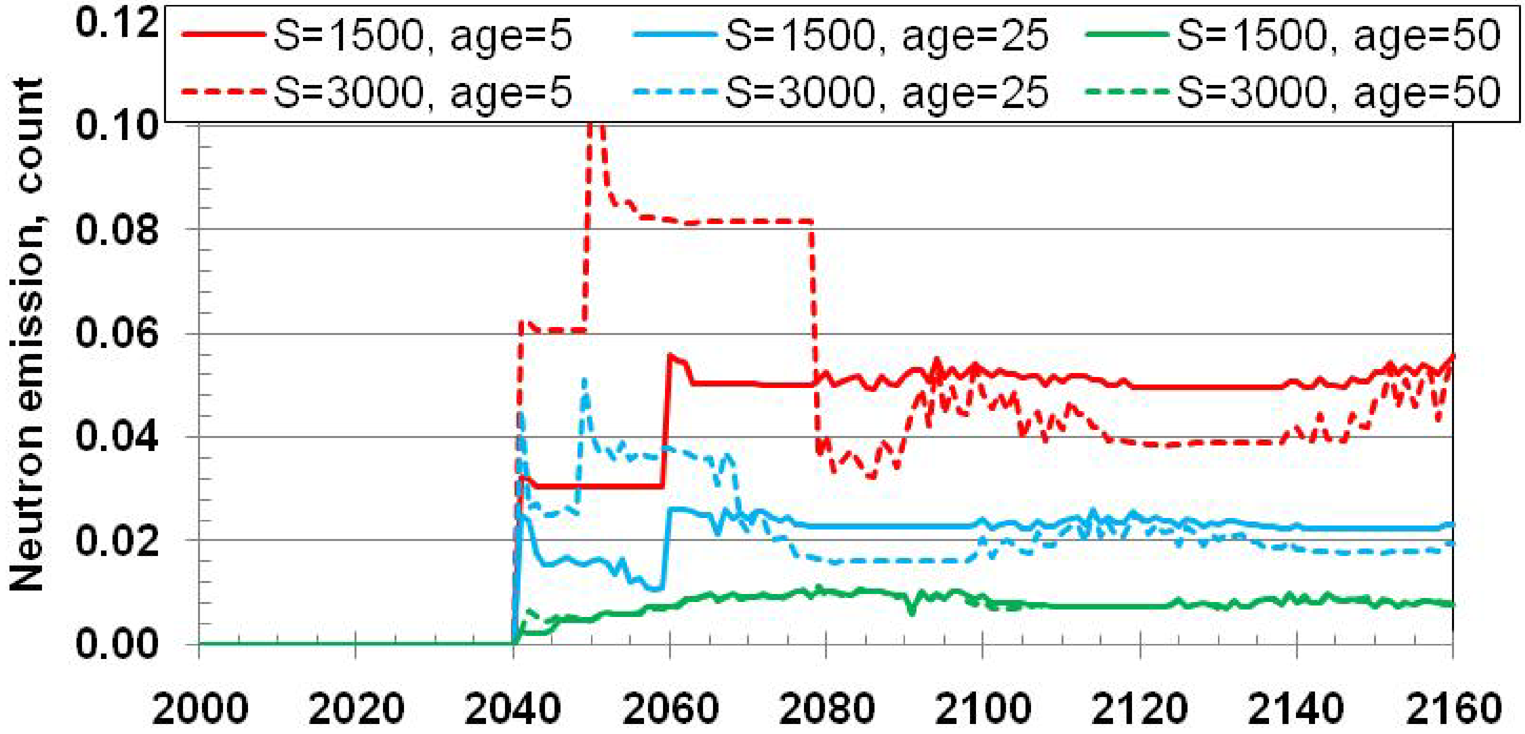
Phase 4 – Heat in separations (GWth) used fuel modeled as ¼ year in separations



Phase 4 – Gamma energy in separations used fuel modeled as ¼ year in separations



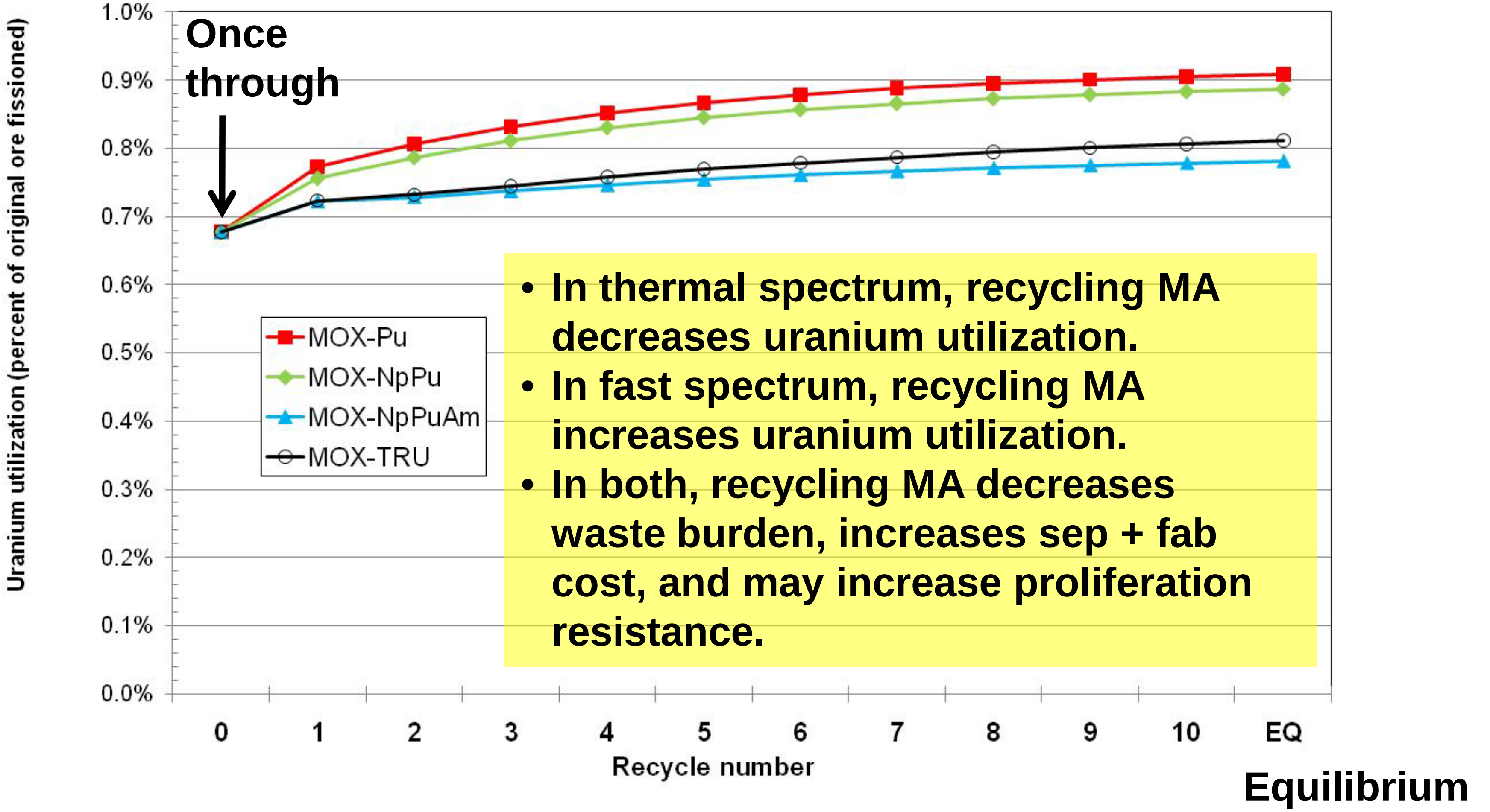
Phase 4 – Neutrons emitted in separations used fuel modeled as ¼ year in separations



Phase 5 – Recycling + repository (no PWR UOX to repository)

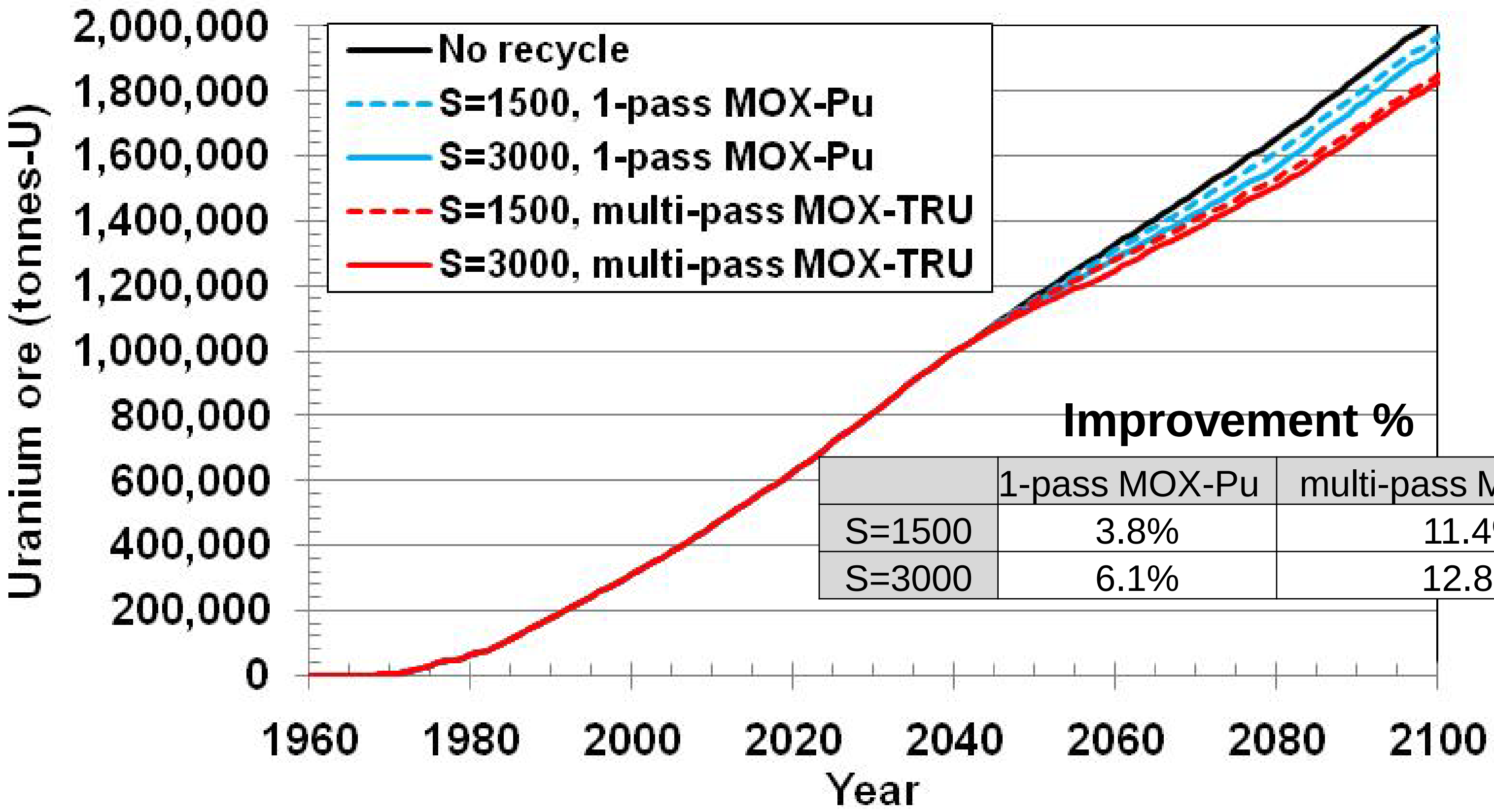
- MOX-RU-Pu (1 recycle) – same as phase 4
  - Used MOX goes to repository
- MOX-EU-TRU (indefinite recycles), burnup = 51 GWth-day/tonne
  - Recycles TRU (≤ 8% of fresh MOX, enrich U as needed)
  - Used MOX always recycled, never to repository
- Repository opens in 2030 at 1500 tonnes/year, infinite capacity
- Separation cases specified, both start in 2040, tonnes-iHM
  - 1500 tonnes/year – backlog continues to grow
  - 3000 tonnes/year – backlog eliminated in 2115
- Minimum aging before separation = 5 years
- Per spec, BWR fuel not recycled
- Isotopic data in spreadsheet

Repeated LWR recycle possible, modest uranium savings



- **In thermal spectrum, recycling MA decreases uranium utilization.**
- **In fast spectrum, recycling MA increases uranium utilization.**
- **In both, recycling MA decreases waste burden, increases sep + fab cost, and may increase proliferation resistance.**

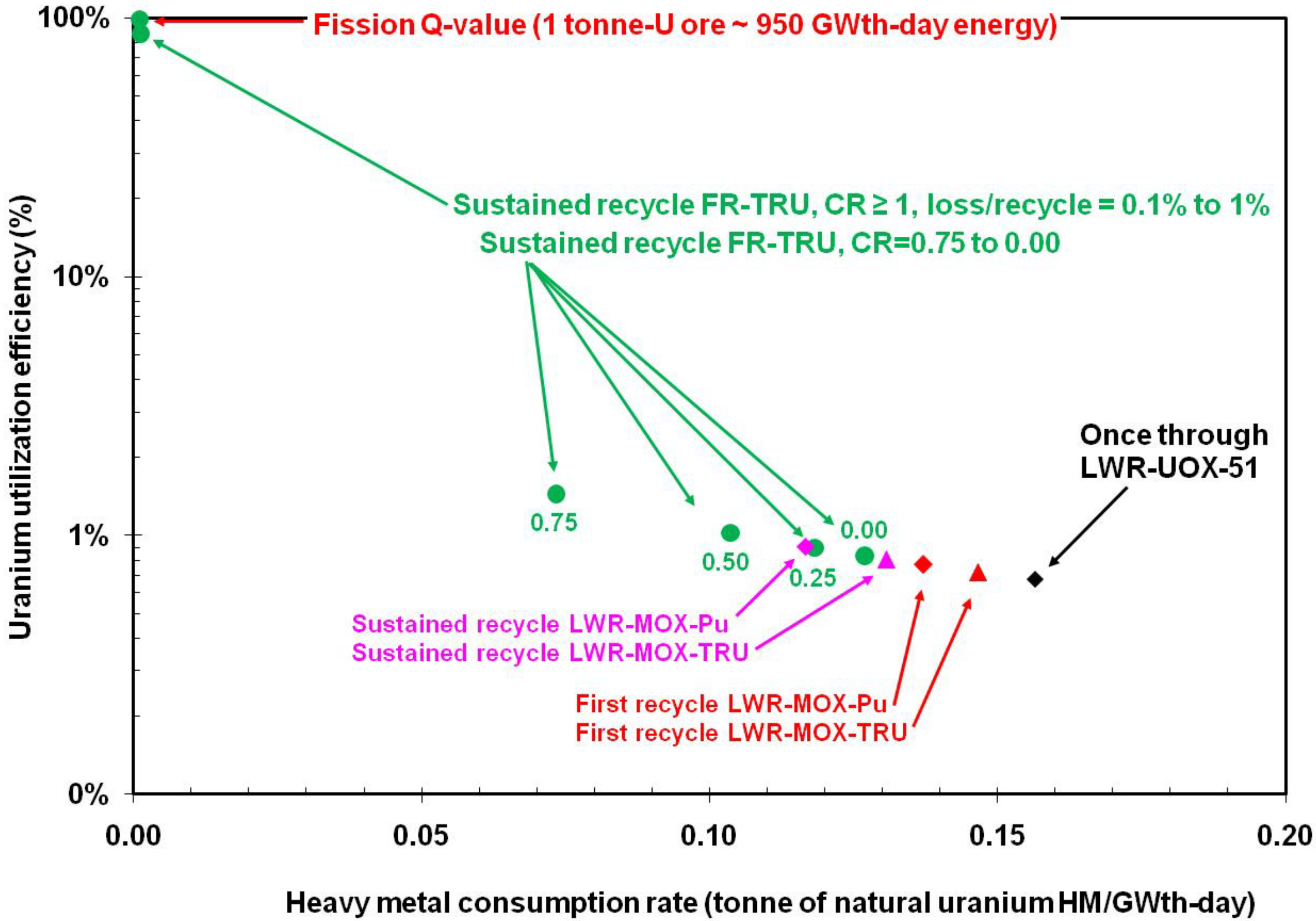
Phase 5 – Recycling – uranium ore



Improvement %

	1-pass MOX-Pu	multi-pass MOX-TRU
S=1500	3.8%	11.4%
S=3000	6.1%	12.8%

Phase 5 – Recycling
The broad picture on uranium



Phase 5 – Recycling – waste mass (1000s of tonnes, 2030-2100)

PWR+BWR	Pu	MA	FP	U	Total
No recycle	2.2	0.4	10.7	196.7	210.0
1-pass MOX-Pu	1.5	0.4	10.7	59.8	72.3
Multi-pass MOX-TRU	0.6	0.1	10.7	60.0	71.5

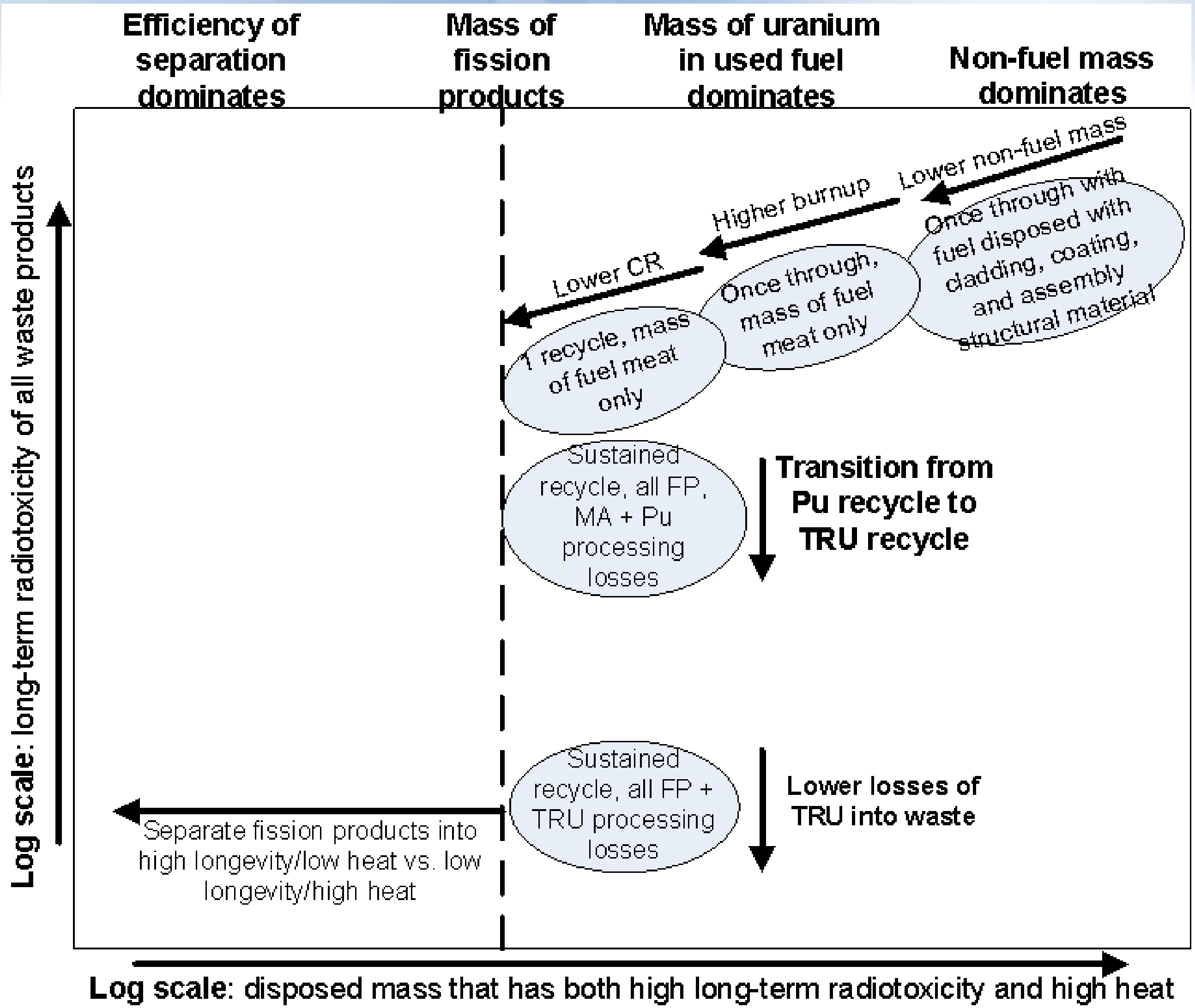
Not necessarily high heat/ high longevity waste

PWR only	Pu	MA	FP	U	Total
No recycle	1.5	0.3	7.4	133.6	142.7
1-pass MOX-Pu	1.0	0.3	7.4	10.6	19.2
Multi-pass MOX-TRU	0.0	0.0	7.4	0.0	7.4

Could have sent RU from UOX separation as waste, but didn't.

Phase 5 – Recycling

The broad picture on waste



Conclusions

- Benchmarks and comparisons are tricky.
- Timing
  - Improvement of most metrics (uranium, waste, etc.) inhibited by delaying implementation and by increasing UNF cooling time (hence increasing time lag in recycling)
  - Improvement inhibited if only recycle PWR (not BWR)
  - Of course, more recycling may increase cost.
- Uranium use
  - MOX achieves minor uranium savings
    - Higher if multi-recycle
  - If uranium savings is the goal, use a breeder reactor
- Waste management
  - If waste mgt savings is the goal, keep recycling