Nuclear Waste Technical Review Board

Workshop on Evaluation of Waste Streams Associated with LWR Fuel Cycle Options

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Outline

- Introduction of CAFCA code
- Phase 1 Analysis Results
- Phase 2 Analysis Results
- Phase 3 Analysis Results
- Phase 4 Analysis Results
- Phase 5 Analysis Results

Code for Advanced Fuel Cycle Analysis

- **CAFCA** is a Nuclear Fuel Cycle Code developed at **MIT** coded in **System Dynamics-VENSIM** platform;
- **CAFCA** was the system analysis tool used to produce the results reported in '**The Future of Nuclear Fuel Cycle**' MIT Study**;**
- The **objective** of CAFCA is to **define**, **describe** and **assess** potentialities and impacts of **alternative nuclear fuel cycles** in the context of the **US energy scenario**;

CAFCA: Main Features

INPUT
Energy Scenario
Energy Growth Rate

+

INPUT
Fuel Cycle Strategy
Reactor Technologies

OUTPUT
Installed Capacities over Time
Nuclear Waste Streams
Uranium Consumption
Economics
...

CAFCA: Main Features

Currently Available Fuel Cycle Strategies

- Once Through Cycle
- Twice Through Cycle
- Two Tier Cycle
- Fast Burner Cycle
- Fast Breeder Cycle

Currently Available Reactor Technologies

- UO_2 Fueled LWR
- MOX Fueled LWR
- UO_2 Fueled RBWR
- Metal Fueled FRs*
- Oxide Fueled FRs*

* CAFCA currently includes Fast Reactor designs covering a wide range of Conversion Ratios, from pure burner (CR=0) to breeders (CR>1). For each conversion ratio two designs (metal and oxide fueled) are available in CAFCA

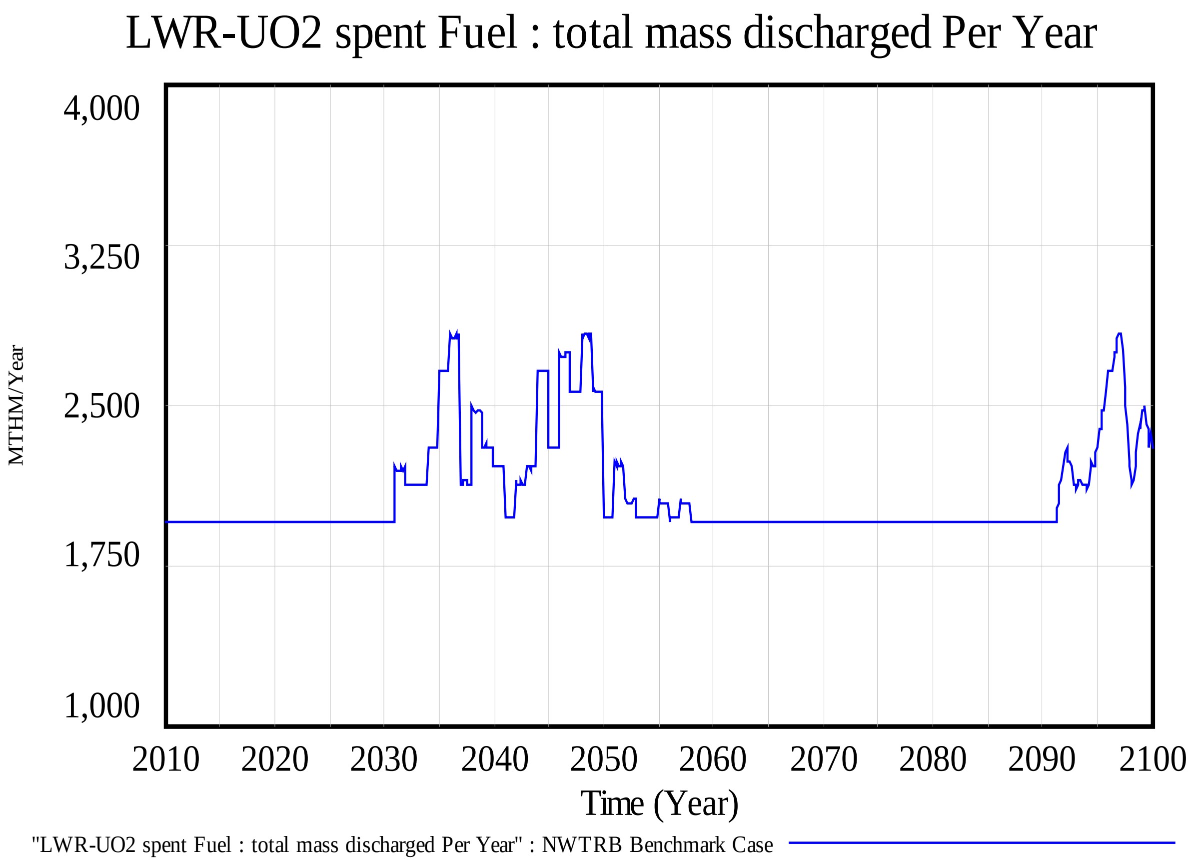
CAFCA: Main Assumptions (1)

- Discrete Time;
- Continuous Flow Code (no batches);
- Equilibrium Core;
- No Distinction between LWRs (PWRs and BWRs);
- 1000 MWe Reactor Size;
- No Isotope Tracking;
- Spent Fuel Composition is Fixed;

CAFCA: Main Assumptions (2)

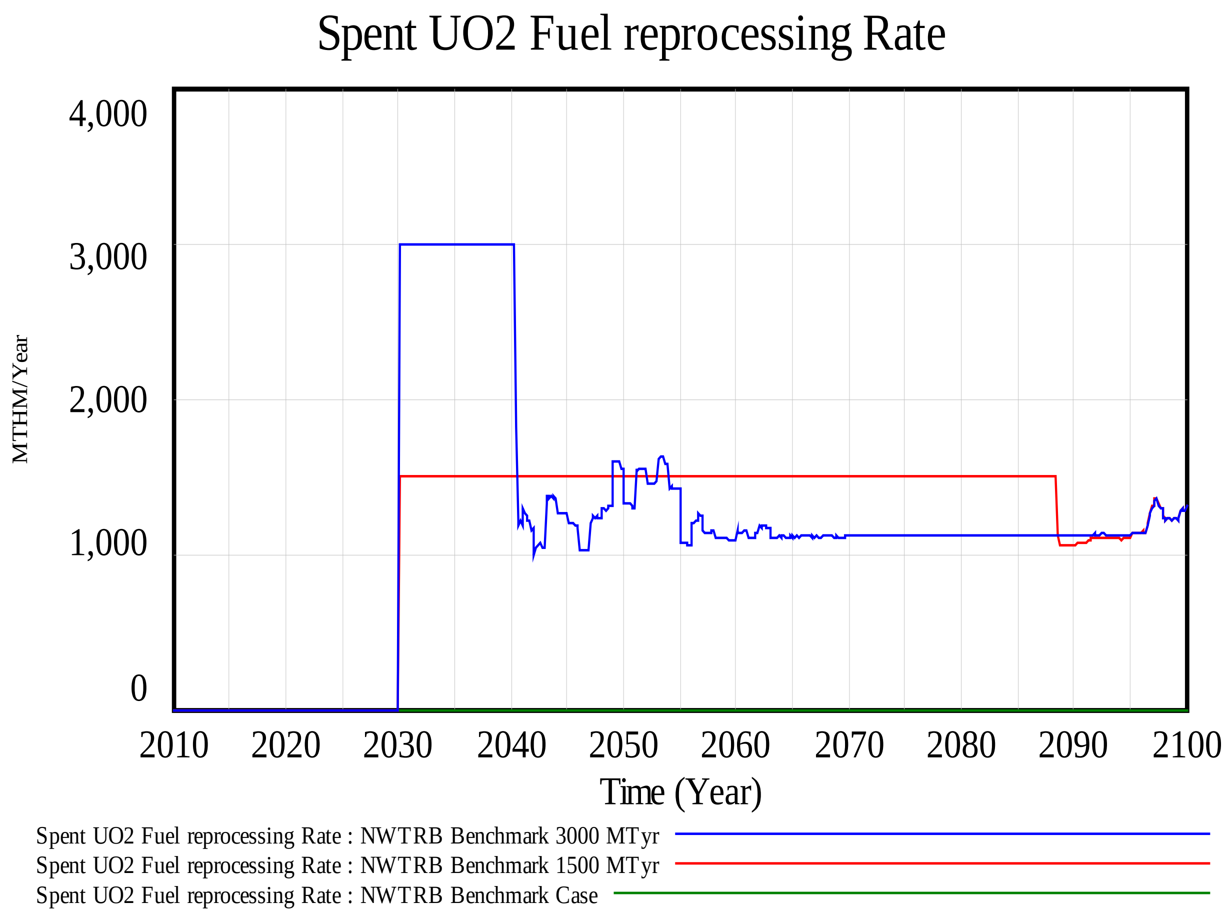
- The isotopic composition of the spent fuel was evaluated using the reactor physics code CASMO4, while Excel was used for numerical data analysis;
- CAFCA takes into account unit decommissioning;
- PWR and BWR # units assumed constant over time;
- PWR Fuel Assembly of reference: AP1000, 17x17;
- BWR Fuel Assembly of reference: ABWR, 10x10;

CAFCA Plots (1)



CAFCA takes into account also the spent fuel mass due to units decommissioning

CAFCA Plots (2)



The integral of the two reprocessing rate scenarios turns out to be almost the same

Phase 1 Analysis Results

Characteristic of U.S. Spent Fuel Inventory as of December 2009

Output Measure 1

Total Mass of Spent Fuel at the beginning of 2010

	Waste PWR	Waste BWR	Total MTU
Spent Fuel Pool [MT]	31,800	17,797	49,597
Dry Cask [MT]	8,817	3,307	12,125

	Waste PWR	Waste BWR	Total Elements
Spent Fuel Pool [# FA]	73,521	99,002	172,523
Dry Cask [# FA]	20,768	18,692	39,460

Phase 1 Analysis Results

Output Measure 2 and 3

Total Mass of ^{234}U, ^{235}U, ^{236}U, ^{238}U and ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu in spent fuel at the beginning of 2010

PWR VECTOR - 39 MWD/Kg		
NUCLIDE	**WT(%) HM**	**Metric Tons**
U-234	0.0148	6.01
U-235	0.7594	308.45
U-236	0.4465	181.36
U-238	93.6928	38,055.39
Pu-238	0.0184	7.47
Pu-239	0.5538	224.94
Pu-240	0.2425	98.50
Pu-241	0.1489	60.48
Pu-242	0.0626	25.43
Am-241	0.0061	2.48
TOT U	94.913	38,551.00
TOT PU	1.026	416.73
SUM	95.94	38,968.14

BWR VECTOR - 32 MWD/Kg		
NUCLIDE	**WT(%) HM**	**Metric Tons**
U-234	0.011	2.32
U-235	0.4544	95.90
U-236	0.3242	68.42
U-238	95.0671	20,063.06
Pu-238	0.0122	2.57
Pu-239	0.4144	87.46
Pu-240	0.2349	49.57
Pu-241	0.1063	22.43
Pu-242	0.0576	12.16
Am-241	0.0052	1.10
TOT U	95.857	20,229.76
TOT PU	0.825	174.11
SUM	96.682	20,403.87

The isotopic composition of the spent fuel was evaluated using CASMO4

Phase 1 Analysis Results

Output Measure 4

Total mass of fission products and minor actinides in spent fuel at the beginning of 2010

PWR	**WT (%) HM**	**Metric Tons**
MA	0.09	37.29
FP	3.98	1,614.59

BWR	**WT (%) HM**	**Metric Tons**
MA	0.08	15.83
FP	3.25	685.46

- Fission Products are in much larger quantity than Minor Actinides;
- PWR and BWR spent fuel composition is slightly different;

Phase 1 Analysis Results

Summary

- PWR fleet is about 66.44% of the total nuclear installed capacity;
- BWR fleet is about 33.56% of the total nuclear installed capacity;
- About 80% of the spent fuel is today stored in spent fuel pools;
- About 20% of the spent fuel is today stored in dry casks;

Phase 2 Analysis Results

Spent Fuel Discharged Through 2100

Output Measure 1

Total Number of PWR assemblies discharged

# of FA Discharged Through 2100	Fuel Type
194,326	**PWR**
467,887	BWR

NOTE: The PWR reference fuel assembly was AP1000 one. This means 17x17 pins PWR fuel assembly and 134 Fuel Assemblies per PWR core (value extrapolated from the 157 FA in a AP1000 core which is about 1117 MWe)

Phase 2 Analysis Results

Output Measure 2

Total Number of BWR assemblies discharged

# of FA Discharged Through 2100	Fuel Type
194,326	PWR
467,887	**BWR**

NOTE: The BWR reference fuel assembly was the ABWR one. This means and 10x10 pins BWR fuel assembly and 643 Fuel Assemblies per BWR core (value extrapolated from the 872 FA in a ABWR core which is about 1356 MWe).

Phase 2 Analysis Results

Output Measure 3 and 4

Total Mass of ^{234}U, ^{235}U, ^{236}U, ^{238}U and ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu discharged

PWR VECTOR - 55 MWD/Kg		
NUCLIDE	**WT(%) HM**	**Metric Tons**
U-234	0.0158	19.96
U-235	0.7005	884.81
U-236	0.612	773.02
U-238	91.7236	108,139.72
Pu-238	0.0378	44.57
Pu-239	0.599	706.21
Pu-240	0.2852	336.24
Pu-241	0.1843	217.28
Pu-242	0.0972	114.60
Am-241	0.0087	10.26
TOT U	93.052	109,705.87
TOT PU	1.203	1,418.31
SUM	94.255	111,124.18
100 days after discharge		

BWR VECTOR - 55 MWD/Kg		
NUCLIDE	**WT(%) HM**	**Metric Tons**
U-234	0.0152	9.70
U-235	0.5083	324.31
U-236	0.6029	384.67
U-238	92.1228	54,861.54
Pu-238	0.0342	20.37
Pu-239	0.4597	273.76
Pu-240	0.2876	171.27
Pu-241	0.1391	82.84
Pu-242	0.0987	58.78
Am-241	0.0085	5.06
TOT U	93.249	55,532.22
TOT PU	1.019	606.84
SUM	94.268	56,139.06
100 days after discharge		

The isotopic composition of the spent fuel was evaluated using CASMO4

Phase 2 Analysis Results

Output Measure 5

Total mass of fission products and minor actinides in spent fuel discharged through 2100

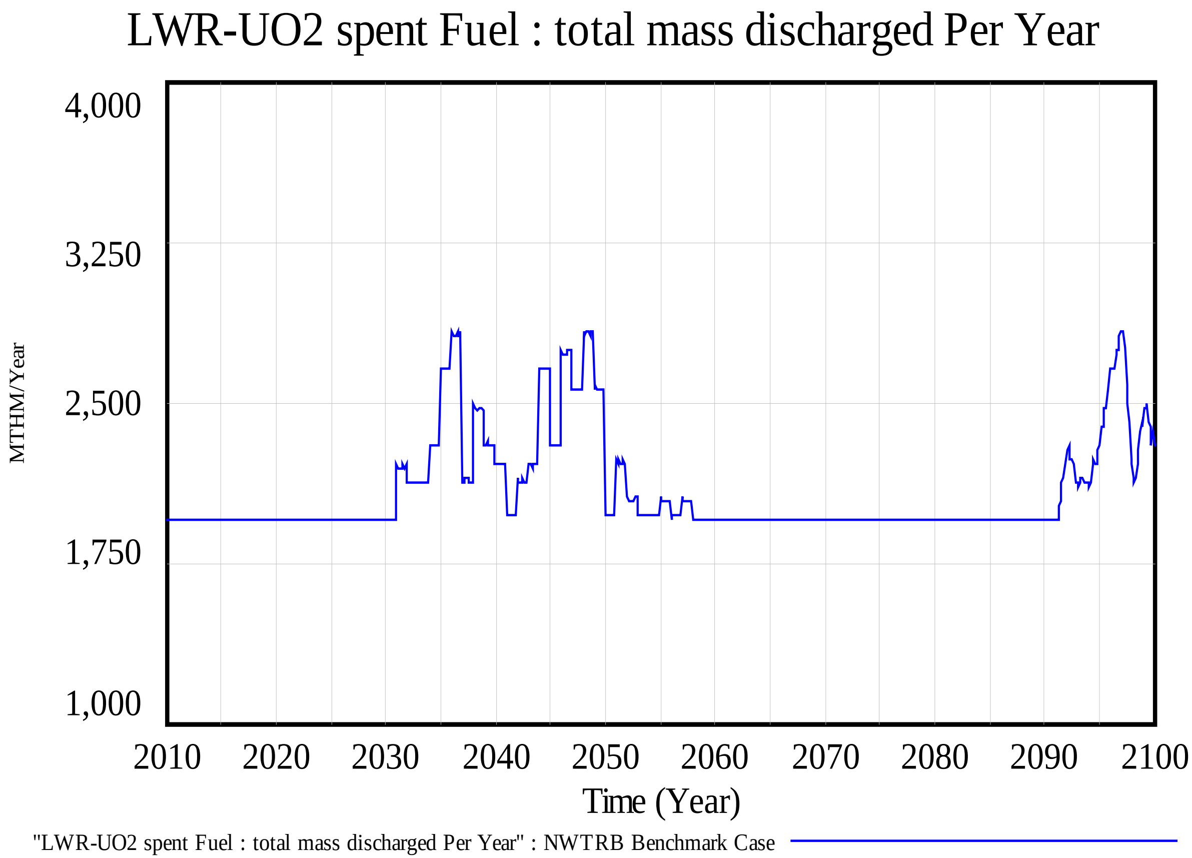
PWR	WT (%) HM	Metric Tons
MA	0.13	152.91
FP	5.62	6,620.29

BWR	WT (%) HM	Metric Tons
MA	0.13	77.06
FP	5.60	3,336.49

- Fission Products are in much larger quantity than Minor Actinides;
- PWR and BWR spent fuel have almost same composition;

Phase 2 Analysis Results

Summary



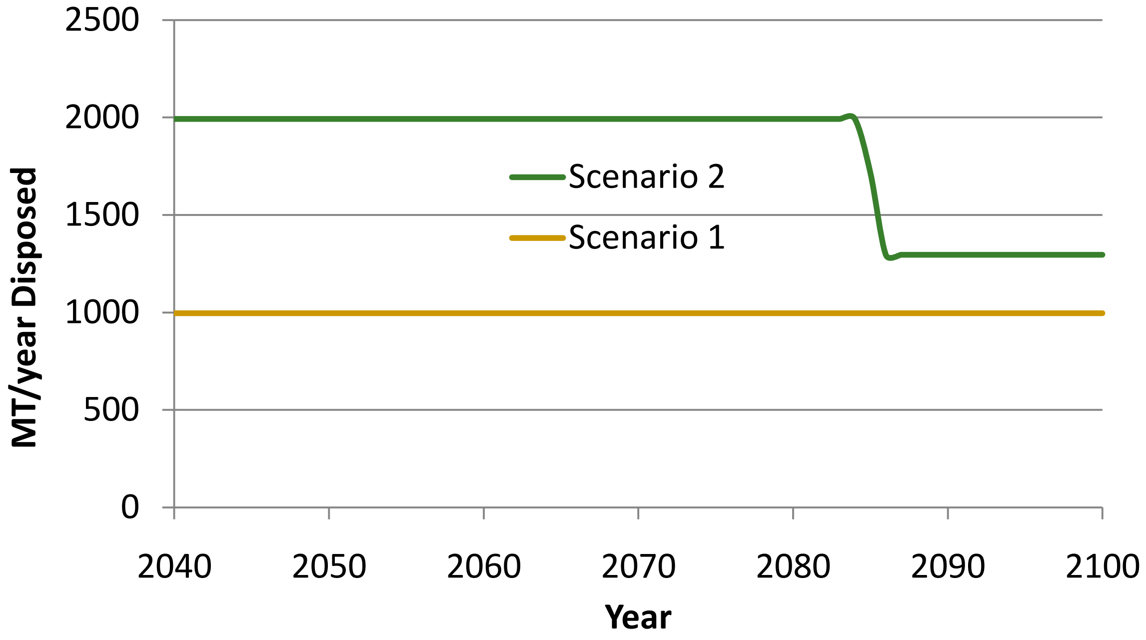
CAFCA takes into account also the spent fuel mass due to units decommissioning

Phase 3 Analysis Results

Impact of Repository Disposal

Output Measure 1

Total mass of PWR spent fuel disposed of each year through year 2100 for each scenario

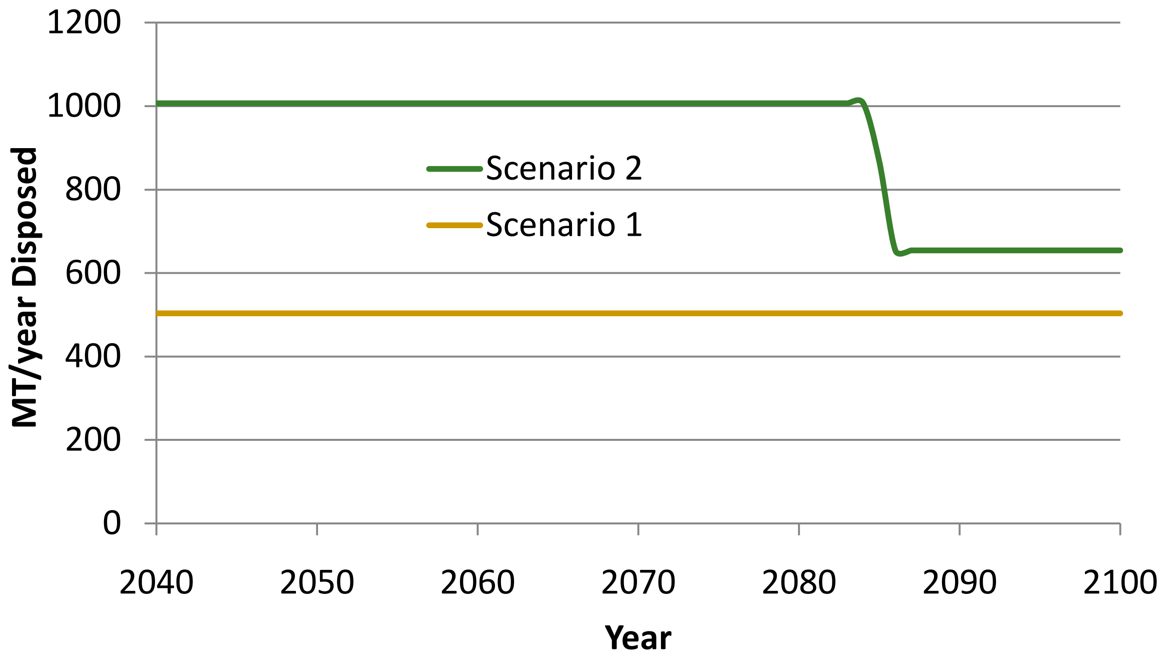


Scenario 2 is non constant due to complete disposal of spent fuel legacy

Phase 3 Analysis Results

Output Measure 2

Total mass of BWR spent fuel disposed of each year through year 2100 for each scenario



Scenario 2 is non constant due to complete disposal of spent fuel legacy

Phase 3 Analysis Results

Summary

- The annual spent fuel discharge for the entire fleet is about 1950 MT/year (excluding decommissioning)
- Spent fuel discharge rate saturates disposal capacity for Scenario 1;
- Spent fuel discharge rate does not saturate disposal capacity after 2085 for Scenario 2;

Phase 4 Analysis Results

Steady State Reprocessing and Fabrication of PWR MOX and Recycled UOX Fuel

Output Measure 1

Total mass of fission products and minor actinides separated by reprocessing

Output Measure 2

Percent Reduction in Natural Uranium Demand

Output Measure 3

Total mass of fuel assemblies fabricated (new PWR, new BWR, recycled UOX PWR, PWR MOX)

Output Measure 4

Mass of Uranium Tails Generated

Phase 4 Analysis Results

Steady State data taken from CAFCA were combined with CASMO. For **1950 MT/year** for a 100 GWe LWR fleet the Natural Uranium requirement is about **16,091 MT/year**.

The isotopic composition of the PWR reprocessed spent fuel (**4,4% U-235** initial enrichment, **55 GWd/MT** burnup) are listed below:

NUCLIDE	WT(%) HM
U-234	0.0172
U-235	0.7005
U-236	0.6122
U-238	91.7236
Pu-238	0.0382
Pu-239	0.599
Pu-240	0.2871
Pu-241	0.1467
Pu-242	0.0972
Am-241	0.0461
TOT U	93.054
TOT PU	1.168
SUM	94.222
5 YEARS OLD	

NUCLIDE	WT(%) HM
U-234	0.0227
U-235	0.7009
U-236	0.6128
U-238	91.7236
Pu-238	0.0326
Pu-239	0.5987
Pu-240	0.2921
Pu-241	0.0558
Pu-242	0.0972
Am-241	0.1338
TOT U	93.06
TOT PU	1.076
SUM	94.136
25 YEARS OLD	

NUCLIDE	WT(%) HM
U-234	0.0285
U-235	0.7013
U-236	0.6136
U-238	91.7236
Pu-238	0.0268
Pu-239	0.5983
Pu-240	0.2943
Pu-241	0.0167
Pu-242	0.0972
Am-241	0.1668
TOT U	93.067
TOT PU	1.033
SUM	94.1
50 YEARS Old	

Phase 4 Analysis Results

	Scenario 1 - 5 year old Spent Fuel	Scenario 2 - 25 year old Spent Fuel	Scenario 3 - 50 year old Spent Fuel
FP and MA separated [MT/year]	86.67	87.96	88.50
% Reduction in Nat U demand	-15.17	-14.67	-14.44
New U PWR Fuel [MT/year]	999.81	1,009.53	1,014.00
New U BWR Fuel [MT/year]	654.42	654.42	654.42
PWR recycled UOX Fuel [MT/year]	170.63	170.76	170.90
PWR MOX Fuel [MT/year]	125.14	115.29	110.68
New Uranium tails [MT/year]	11,996.15	12,066.65	12,099.07
Recycled Uranium tails [MT/year]	1,388.30	1,388.39	1,388.49
Uranium Tails for MOX Fuel [MT/year]	107.62	99.15	95.18

Phase 4 Analysis Results

	Scenario 4 - 5 year old Spent Fuel	Scenario 5 - 25 year old Spent Fuel	Scenario 6 - 50 year old Spent Fuel
FP and MA separated [MT/year]	173.34	175.92	177.00
% Reduction in Nat U demand	-30.34	-29.34	-28.88
New U PWR Fuel [MT/year]	704.04	723.48	732.42
New U BWR Fuel [MT/year]	654.42	654.42	654.42
PWR recycled UOX Fuel [MT/year]	341.25	341.52	341.80
PWR MOX Fuel [MT/year]	250.29	230.57	221.36
New Uranium tails [MT/year]	9,851.30	9,992.29	10,057.13
Recycled Uranium tails [MT/year]	2,776.61	2,776.77	2,776.97
Uranium Tails for MOX Fuel [MT/year]	215.25	198.29	190.37

Phase 4 Analysis Results

Summary

- The U demand is reduced by a factor of 2 when the reprocessing capacity is doubled;
- The older the fuel, the less Pu is available for reprocessing and therefore the smaller is the U saving;
- The total amount of U tails decreases for increasing reprocessing capacity (but with different distribution);

Phase 5 Analysis Results

Impacts of Reprocessing Combined with Recycling

Output Measure 1

Total mass of PWR spent fuel disposed in the repository

1500 MT/year Reprocessing Capacity Scenario
23,257 [MT]

3000 MT/year Reprocessing Capacity Scenario
22,704 [MT]

- No major difference between scenarios;
- Reprocessing capacity is under utilized in both cases

Phase 5 Analysis Results

Output Measure 2

Total mass of BWR spent fuel disposed in the repository

1500 MT/year Reprocessing Capacity Scenario
50,980 MT

3000 MT/year Reprocessing Capacity Scenario
51,176 MT

- Same amount should be expected (BWR fuel is not reprocessed);
- BWR/PWR distinguished trough fixed constant in Excel;
- This approximation brings just to 0.4% difference;

Phase 5 Analysis Results

Output Measure 3

Total mass of fission products and minor actinides disposed in the repository

	1500 MT/yr Scenario	3000 MT/yr Scenario
MA Mass Disposed [MT]	132.26	132.17
FP Mass Disposed [MT]	5,580	5,630

- No major difference between scenarios;
- Reprocessing capacity is under utilized in both cases;
- Fixed Vector to distinguish between MA and FP in spent fuel;

Phase 5 Analysis Results

Output Measure 4

Total Mass of PWR Spent Fuel Reprocessed

1500 MT/year Reprocessing Capacity Scenario
100,929 MT

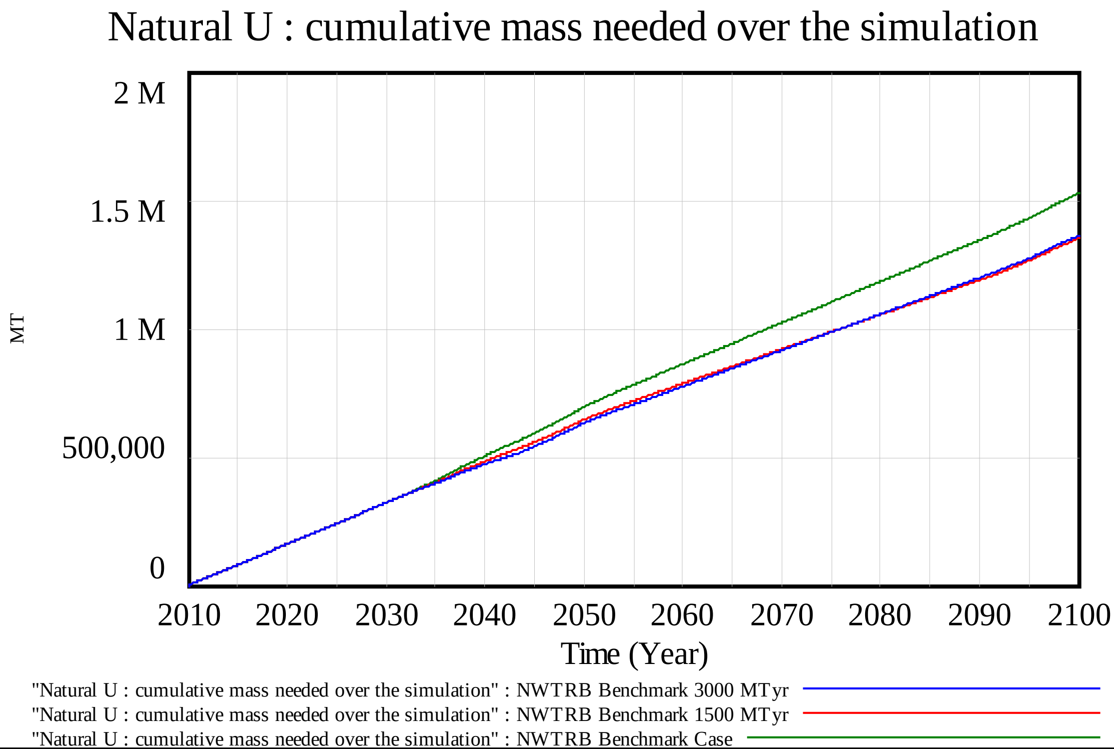
3000 MT/year Reprocessing Capacity Scenario
101,315 MT

- No major difference between scenarios;
- Reprocessing capacity is under utilized in both cases

Phase 5 Analysis Results

Output Measure 5

Percent Reduction in Total Natural Uranium Demand



	U Demand Difference compared to Base Case %
3000 MT/yr Scenario	-10.93
1500 MT/yr Scenario	-11.52

Phase 5 Analysis Results

Output Measure 6

Total mass of fuel assemblies fabricated (new PWR, new BWR, recycled UOX PWR, PWR MOX)

New U PWR	Mass of Fuel [MT]
3000 MT/yr Scenario	115,462
1500 MT/yr Scenario	114,486

New U BWR	Mass of Fuel [MT]
3000 MT/yr Scenario	58,322
1500 MT/yr Scenario	57,829

Recycled UOX PWR	Mass of Fuel [MT]
3000 MT/yr Scenario	10,854
1500 MT/yr Scenario	10,814

MOX PWR	Mass of Fuel [MT]
3000 MT/yr Scenario	11,376
1500 MT/yr Scenario	12,816

Phase 5 Analysis Results

Output Measure 6

Total mass of fuel assemblies fabricated (new PWR, new BWR, recycled UOX PWR, PWR MOX)

- The recycled UOX PWR assemblies are assumed to have a ^{235}U enrichment of 4.4%, as specified for Phase 4;
- The PWR MOX assemblies are 8.73% Pu enriched and 91.3% depleted Uranium; the MOX loading in the core is 30% and the rest of the core elements is made of 4.4% ^{235}U enriched UO;
- The Pu quality was assumed to be the one previously presented for 5 years old spent UO2 fuel, 55MWd/kg, 4.5% ^{235}U;

Phase 5 Analysis Results

Output Measure 7

Mass of Uranium Tails Generated

New Uranium Tails	Tails [MT]
3000 MT/yr Scenario	980,949
1500 MT/yr Scenario	945,743

Recycled U Tails	Tails [MT]
3000 MT/yr Scenario	80,752
1500 MT/yr Scenario	80,460

- No major difference between the two scenarios;
- Results different that the ones for Phase 4 because of different assumptions on saturation of reprocessing capacity;

Phase 5 Analysis Results

Summary

- The reprocessing capacity has almost no influence on the results because of the actual spent fuel discharge rate;
- The U demand decreases by about 11% compared to the nominal case (Phase 2);
- The obtained results are consistent and only slightly affected by the PWR/BWR distinction strategy used;

References

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