BENEFITS OF TRANSITIONING TO A THORIUM CYCLE

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Abstract

Projections of the total world nuclear electricity demand for the next century show that existing natural uranium (NU) resources will be severely challenged by 2070. One way to meet this challenge is to recycle spent plutonium from Light Water Reactors (LWRs) as starting fissile material in thorium-fuelled Heavy Water Reactors (HWRs). This arrangement obtains more total energy per unit of NU mined since no NU is required by the HWR fleet, which instead gets its fissile material from LWR spent fuel and from U-233 bred into the thorium. Modeling shows that world NU requirements up to the year 2130 can be reduced by 10% for a once-through Th-Pu fuel cycle and by almost 20% in a Th-Pu-U-233 fuel cycle where the U-233 in spent HWR fuel is recovered and used to top-up the initial fissile material. As an added benefit, the total decay heat of spent fuel in repositories, a limiting factor, is reduced by more than one third by the transmutation of LWR plutonium.

1. Introduction

Current known reserves of natural uranium are sufficient to fuel the world's nuclear capacity for many centuries at current levels, but assuming a significant decrease in fossil fuel use in the coming century (because of either resource depletion or ecological considerations), a significant expansion of nuclear capacity is likely. Figure 1 shows a recent compilation [1] of a large set of projections of the global primary energy demand (of which only part is nuclear) and a median reference line (in orange).

Currently, world energy demand from all sources is ~474 EJ/y and installed nuclear capacity is ~11.8 EJ/y (375 GWe). The median demand curve in Figure 1 corresponds to a total demand increase of ~4 times to 2000 EJ[1]/y. The share of this which will be nuclear is even more speculative, but it is reasonable to assume that increasing demand for emissions-free production will double the share of nuclear power, resulting in an eightfold increase in installed nuclear capacity relative to today. In this case, the installed nuclear capacity will be ~3000 GWe by 2100. The median demand curve is approximately the 'moderate'[2] scenario for electricity capacity[3] devised by the as GAINS[4] collaboration (Figure 2).

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[1] The exajoule (10^{18} J) is the preferred unit when talking about world energy. 1 EJ = 31.7 GW-y)
[2] The 'high' scenario forecasts another doubling of the nuclear power share.
[3] The actual GAINS scenario forecasts 2500 GWe of electrical demand. At an assumed availability factor of 85%, this requires 2941 GWe of electrical capacity to be built.

[4] http://www.iaea.org/INPRO/gains.html. GAINS[4] is an acronym for 'Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle'. The GAINS collaboration, a project under INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) at the IAEA was established to investigate nuclear fuel cycle options and the impact of available and foreseeable technologies in the next century against a backdrop of rising global energy demands.

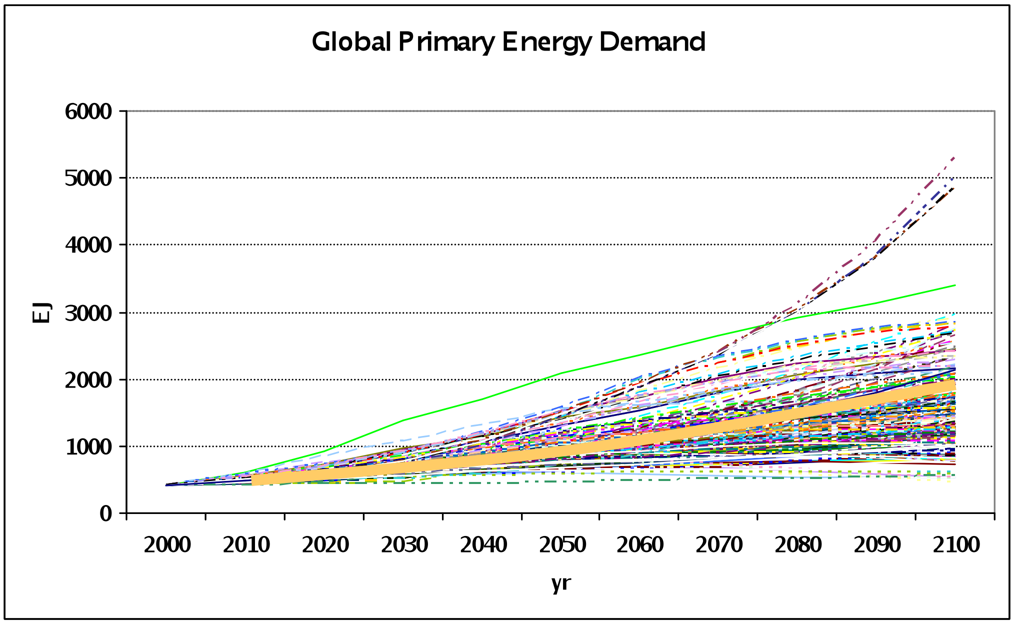

Figure 1: A Compilation of projections of the Increase in Primary Energy Demand, 2010 to 2100. The thick orange line is an approximate median reference line.

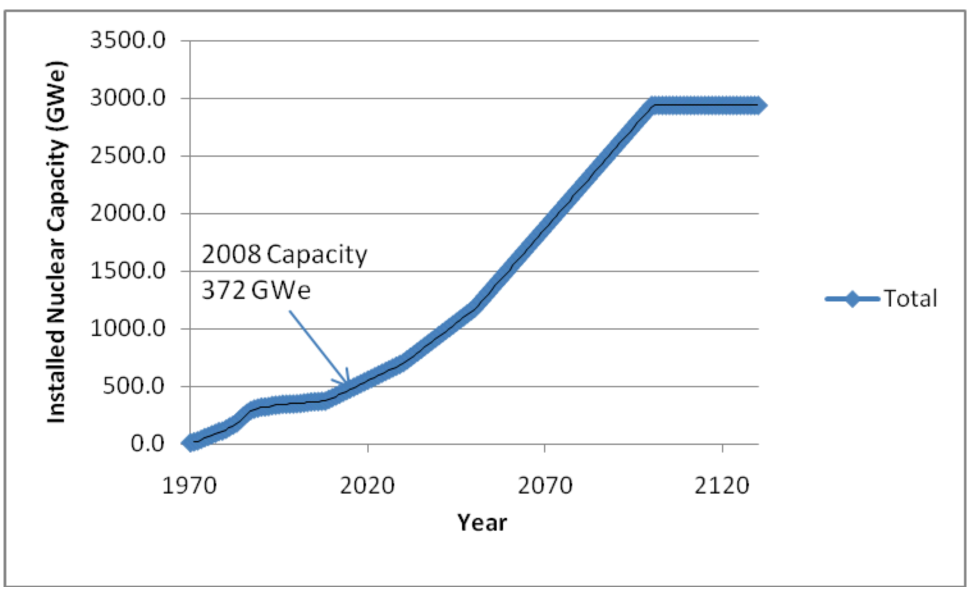

Figure 2: GAINS 'Moderate' Electricity Demand Forecast

In the context of such a significant expansion of nuclear capacity, once-through fuel cycles are no longer a sustainable option. An ideal solution would be the Self Sustaining Equilibrium Thorium (SSET) fuel cycle, which recycles U-233 from thorium-based fuel as the entire initial fissile charge in the next fuel load. A SSET based nuclear energy system would extract essentially all the available energy from Th-232, whose known reserves are ~4 times larger than those of natural uranium. Unfortunately, at present, this cycle is only self-sustaining when exit burnups are low, and, consequently, recycling rates prohibitively high [2]. In the meantime, we investigate here the effects on NU resource utilization (measured as total mined NU from 1970 to 2130) of two other thorium cycles, both of which require the initial fuel to be topped up with plutonium recycled from spent LWR fuel. The first cycle is a once-through cycle in which the initial fissile charge is only plutonium. In the second cycle, the U-233 which is bred into the thorium is recycled into the initial fuel and topped up with LWR-derived plutonium in order to raise the exit burnup of the fuel. Both of these cycles reduce NU requirements compared to a 'business-as-usual' scenario which maintains the current mix of LWRs and HWRs and the once through fuel cycle strategy. In addition, by re-irradiating the LWR plutonium, the total actinide decay heat in world spent fuel stocks is markedly reduced, easing the burden on repositories.

2. Method of Analysis

2.1 DESAE

The work presented here was done with a 'scenario' code. The input to a scenario code is an energy demand and reprocessing availability history for a mixture of reactor types over the period of interest as well as parameters specifying details of operation for each reactor (unit power, construction cost/time, availability factor, input and output fuel compositions etc.). The code then calculates the nuclear fuel cycle requirements, material balances and economic parameters. In particular, for this application, one can use a scenario code to confirm the availability of sufficient Pu-239 and U-233 from recycling as fuel for new and existing reactor cores. DESAE 2.2, the scenario code used for this analysis, is freely available from the IAEA. A Users Manual [3] has been written for DESAE and is distributed with the code. A conference paper [4] containing a high level overview of DESAE is also available.

2.2 Reactor Models

The parameters in Table 1 define the gross parameters for the reactors used in this study. For simplicity, both the initial core and final discharge cores were treated as if they had the same fuel composition as the equilibrium core.

Both of the thorium fuelled HWRs modeled used 'low-void' [5] 43-element CANFLEX® type fuel with a central pin containing a burnable neutron poison (in this case, Hafnium). These bundles are designed to limit the positive reactivity insertion accompanying coolant voiding. However, the presence of this poison limits the attainable exit burnup of the fuel.

Table 1: Characteristics of Nominal Reactors Used in this Study

	LWR	HWR	FR	ThPu	ThPuR
$P_{thermal}$ (GW)	3030	2000	2100	2064	2064
$P_{electrical}$ (GWe)	1000	600	870	668	668
Efficiency	33%	30%	41.43%	32.36%	32.36%
Availability	85%	85%	85%	85%	85%
Fuel residence time (EFPD[5])	1168	292	436	825	810
Exit burnup (MWd/t)	45000	7000	37677	20290	19850
Equilibrium loading (t)	78.7	83.4	24.3	71.4	71.4

Table 2 and Table 3 define the equilibrium input fuel characteristics and equilibrium output fuel characteristics.

Table 2: Input Fuel Isotopic Compositions

	LWR	HWR	FR	ThPu	ThPuR
Th-232				68707.00	69578.98
U-233					1031.25
U-234					
U-235	786.50	593.20	20.648		
U-236					
U-238	18880.00	82840.00	6861.938		
Np-237					
Pu-238			4.602	67.16	19.40
Pu-239			552.300	1456.00	420.62
Pu-240			225.522	639.35	184.70
Pu-241			100.334	338.48	97.78
Pu-242			37.740	182.67	52.77

Table 3: Output Fuel Isotopic Compositions

	LWR	HWR	FR	ThPu	ThPuR
Th-232				67766.92	68393.63
U-233				621.08	1031.28
U-234				36.06	108.08
U-235	156.60	198.20	19.317	2.78	10.71
U-236	102.00	59.33	1.695	0.15	0.90
U-238	18270.00	82250.00	6536.70		
Np-237	13.65	2.16	1.037	0.30	0.10
Pu-238	5.04	0.28	0.352	40.15	10.77
Pu-239	106.30	221.80	576.664	310.58	55.05
Pu-240	41.33	79.84	245.880	622.94	155.84

[5] Effective full power days.

Pu-241	36.45	15.13	74.101	155.84	43.95
Pu-242	15.38	3.28	40.065	264.04	83.45
Am-241	1.23	0.12	3.926	55.21	15.32
Am-242m	0.03	0.10	0.086	0.12	0.03
Am-243	3.60	0.04	2.960	39.57	14.17
Cm-242	0.43	0.01	0.269		2.32
Cm-244	1.26	602.10	0.309	6.46	0.10
Cm-245			0.010		
Total FP	912.20	198.20	299.710	1468.47	1459.93

2.3 Scenarios Analyzed

The following scenarios were analyzed to see the effect of the introduction of thorium fuelled HWRs. All scenarios assume the expansion of nuclear capacity outlined in Figure 2.

1. BAU (business-as-usual). This is the reference case against which NU resource conservation and spent fuel decay heat reduction was measured. This case idealized the world population of reactors as generic LWRs and HWRs. The proportion of HWRs was assumed to rise to 6% by 2008 and remain steady thereafter. No reprocessing of the spent fuel of any of the reactors is done.
2. BAU-FR (business-as-usual with fast reactors). In this case, it is assumed that fast reactors (FR) with a breeding ratio of 1.0 would be built starting in 2020, first to a specific schedule (10 GW by 2030, and 200 GW by 2050), then as rapidly thereafter as there is available plutonium for their initial MOX cores. HWR capacity stays at 6% of all nuclear. Only LWR and FR fuel is assumed to be reprocessed for plutonium.
3. ThPu (thorium-plutonium once-through fuel cycle). This scenario assumes that after 2008, plutonium from LWR reactors is recycled into thorium+plutonium fuelled HWRs (ThPu), with ThPu capacity limited only by plutonium availability. It is assumed that ThPu reactors will be built in preference to other HWR reactors (so that the production of new NU fuelled HWRs ceases after 2008 and all NU-HWRs are retired by 2068).
4. ThPuR (thorium-plutonium with U-233 recycling). As in case 3, plutonium from LWRs is used to build once-through ThPu reactors. However, in this case the U-233 from the ThPu reactors is reprocessed and then used to build as many ThPuR reactors as consistent with both U-233 and plutonium availability.

Some of the key parameters for each of the scenarios analyzed are summarized in Table 4.

Table 4: Summary of Scenarios Analyzed

Scenario	Scenario Name	Reactors	Fuel	Reprocessing
1	BAU	LWR HWR	4% enr. uranium NU	No No
2	BAU-FR	LWR HWR FR	4% enr. uranium NU DU+MOX	Yes No Yes (Pu)
3	ThPu	LWR HWR ThPu	4% enr. Uranium NU Th + Pu	Yes (Pu) No No
4	ThPuR	LWR HWR ThPu ThPuR	4% enr. Uranium NU Th + Pu Th + Pu +U-233	Yes (Pu) No Yes (U-233) Yes (U-233)

2.4 Simplifying Assumptions

A list of assumptions for the four scenarios is presented here. Some of these assumptions were made to either simplify the analysis or the comparison between scenarios (such as the assumption that all reactor types had the same availability). Others, such as the introduction rate for fast reactors, mimic the GAINS analyses and represent a best-guess of future trends and decisions.

- Nuclear power plant load factor and life time
    - All reactors; availability factor: 85%, plant life time: 60 years
    - U enrichment tails assay: 0.3 wt%
- Reprocessing
    - LWR: cooling + reprocessing time[6]: 6 years
    - FR; cooling + reprocessing time: 3 years
    - All reactors: initial core = equilibrium reload core. Final discharge core = equilibrium discharge core.
    - Reprocessing losses: 0%
    - Reprocessing availability: as required (no limit).
- Lead time
    - Lead times, such as mining, conversion and fabrication process time, were not taken into account in the analysis.
- Reactor introduction speed
    - NU-HWR

[6] Cooling+reprocessing time is the time between the time the fuel leaves the reactor and availability of the isotopes for fabrication of new fuel.

- Scenarios 1 and 2: attain 6% of all nuclear power at 2008 and remain a constant fraction thereafter.
- Scenarios 3 and 4: phased out after 2008 (thorium fuelled HWRs built instead)

- LWR
  - LWR are built to make up the overall required power capacity (after subtracting HWR, FR, ThPu and ThPuR share)
- FR introduction (scenario 2)
  - From 2021 to 2030 : 1 GWe FR demand growth a year (total demand 10 GWe at 2030)
  - From 2031 to 2050 : 9.5 GWe FR demand growth a year(total demand 200 GWe at 2050)
  - After 2051 : maximum FR introduction consistent with Pu availability
- ThPu introduction (scenario 3)
  - Once-though ThPu are introduced starting in 2008, and are built as there is available[7] Pu.
- ThPuR introduction (scenario 4)
  - Built when enough U-233 and plutonium is available[8].

2.5 Decay Heat

The DESAE calculation of decay heat was replaced by one calculated by ORIGEN-S, allowing the decay heat to be projected into the future after the end of the scenario at 2130. ORIGEN-S is an industry-standard isotope depletion code, part of the SCALE 5.1 [6] suite of codes, which can simulate irradiation and decay of nuclides from a comprehensive library. Only the decay heat from actinides, which dominates the decay heat of the fuel after ~200 years of cooling, was tracked. Scenarios were compared based on the actinide decay heat after 1000 years cooling.
The actinide decay heat was calculated by first running the program ORIGEN-S for nominal one tonne initial quantities of all the actinides tracked by DESAE 2.2, namely: U-234, U-235, U-236, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Am-241 and Cm-244. The ORIGEN-S results for heat output vs. time were used to develop conversion factors $C_N(t) = Q(t)/M_N^{t=0}$ for each nuclide '*N*' and various times *t*. These conversion factors related the heat output (*Q(t)*) of nuclide *N* (and its daughters) at time *t* to the total mass ($M_N^{t=0}$) of nuclide *N* present at *t=0*. The total actinide decay heat at time *t* (corresponding to *t* years after the end of the scenario, when the fuel is removed from the reactor) is then: $D(t) = \sum_N C_N(t) M_N^{t=0}$.

D(0), D(200), D(400) ... D(1000) were tabulated and are presented in Table 5. Integrated decay heat out to 1000 years has been found important in the design of long term repositories, as this is the timescale for the migration of heat away from the repository through the surrounding rock.

Table 5: ORIGEN-S Calculated Decay Heats for Uniform Initial Compositions

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[7] Pu must be available for the first core and for refueling throughout the reactor lifetime. This look-ahead (and the one for ThPuR) was done approximately by manually iterating on the reactor introduction history.
[8] See previous note for definition of 'available'.

Isotope 'N'	Relationship between the heat output (Q in Watts) of isotope 'N' and its daughters at time t and the initial quantity of isotope N in tonnes $Q(t) = \sum_N C_N(t) M_N^{t=0}$					
	$C_N(years)$ in Watts/initial tonne					
	$C_N(0)$	$C_N(200)$	$C_N(400)$	$C_N(600)$	$C_N(800)$	$C_N(1000)$
U-234	1.79E+02	1.79E+02	1.80E+02	1.81E+02	1.81E+02	1.82E+02
U-235	5.99E-02	6.41E-02	6.63E-02	6.84E-02	7.05E-02	7.26E-02
U-236	1.75E+00	1.75E+00	1.75E+00	1.75E+00	1.75E+00	1.75E+00
U-238	9.34E-03	1.03E-02	1.03E-02	1.03E-02	1.03E-02	1.03E-02
Np-237	2.01E+01	2.19E+01	2.20E+01	2.20E+01	2.20E+01	2.20E+01
Pu-238	5.68E+05	1.17E+05	2.42E+04	5.13E+03	1.20E+03	3.88E+02
Pu-239	1.93E+03	1.92E+03	1.91E+03	1.90E+03	1.89E+03	1.87E+03
Pu-240	7.07E+03	6.92E+03	6.78E+03	6.64E+03	6.50E+03	6.36E+03
Pu-241	3.29E+03	8.59E+04	6.24E+04	4.53E+04	3.29E+04	2.39E+04
Pu-242	1.17E+02	1.17E+02	1.17E+02	1.17E+02	1.17E+02	1.17E+02
Am-241	1.15E+05	8.31E+04	6.03E+04	4.38E+04	3.18E+04	2.31E+04
Cm-244	2.83E+06	8.16E+03	6.69E+03	6.55E+03	6.41E+03	6.28E+03
Total	3.53E+06	3.03E+05	1.63E+05	1.10E+05	8.10E+04	6.22E+04

3. Results

3.1 BAU (Business As Usual)

The division of electricity demand in this scenario is shown in Figure 3 and is defined by the assumptions (following Figure 2 and the assumption of a 94%:6% LWR:HWR division).

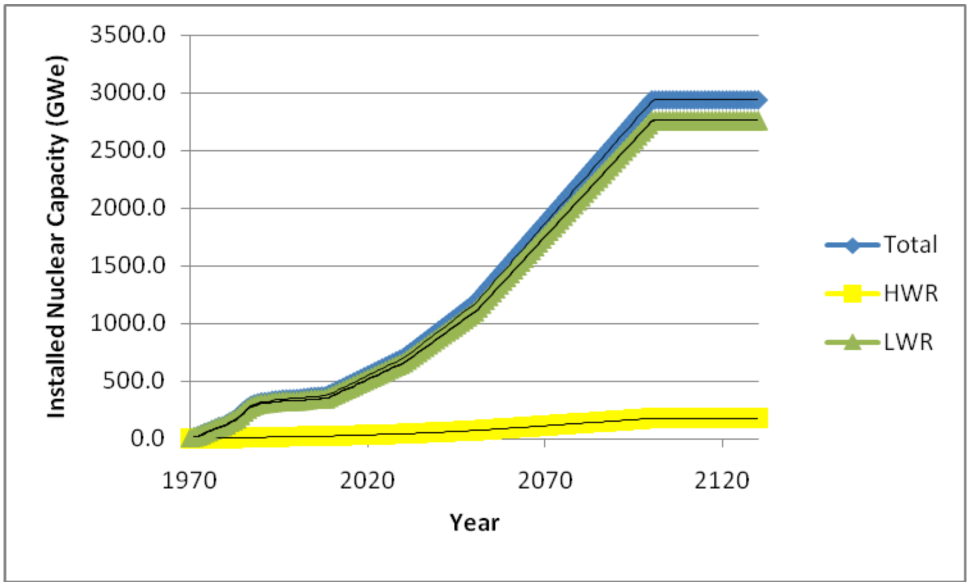

Figure 3: Electricity Production in BAU

The natural uranium requirements of this scenario are shown in Figure 4. Total uranium requirements are ~4.64x10^7 tonnes by 2130. Current resources are estimated[9] to be of 5.5x10^6 tonnes (known) and 10.5x10^6 tonnes (undiscovered). Together, these resources are termed here as 'easily mined' and are marked on Figure 4 as the red construction line. It is apparent that these NU resources will be exhausted at ~2075 in the BAU scenario. Adding in the potential of the extraction of an estimated 22x10^6 tonnes of uranium from higher cost sources, such as phosphates, gives an ultimate NU resource of 38 x10^6 tonnes (the green line on Figure 4), which will be exhausted by 2115.

HWRs consume about 2.07x10^6 tonnes of natural uranium in this scenario, or about 4.45% of the total. This is somewhat less than their 5.945% share[10] of the integrated electrical capacity because the HWRs have a higher neutron economy which leads to the extraction of more energy per unit of mined NU that LWRs.

The natural uranium requirements of the LWRs depends partly on the DU output ('tails') of the enrichment plants, the feed to product ratio being defined as: $\frac{F}{P} = \frac{x_p - x_t}{x_f - x_t}$, where x_f is the feed enrichment (0.711%), x_p is the product enrichment (4% for the LWRs) and x_t is the tails enrichment (0.3%). The natural uranium requirements of the LWRs[11] (the feed) decline to 82.6% (3.83 x10^7 tonnes) for a tails of 0.2% and to 70.9% (3.29 x10^{7}tonnes) for a tails of 0.1%,

[9] From the joint IAEA-OECD Red Book ("Uranium 2007: Resources, Production, Supply and Demand"). At $260/kg it becomes economic to extract uranium from seawater (http://www.wise-uranium.org/upusa.html#SEAWATER), with effectively infinite resources (billions of tonnes).
[10] Less than 6% since the HWR fraction of total nuclear capacity is less than 6% in the 1970 to 2008 period.
[11] Of course, to reduce the tails without impacting the reactor electrical efficiency, new technology is required to reduce the SWU cost. At present the electrical requirements of separation are about 5% of the nuclear output, a number small enough that it is ignored in the current analysis. This would not be the case if the tails were reduced without compensating factors.

at which point they are approximately as equivalent to those of HWRs. If the LWRs were replaced by GAINS-standard HWRs, their feed requirements would be 3.27×10^7 tonnes of natural uranium, or 3.48×10^7 tonnes for the whole scenario – a savings of 1.16×10^7 tonnes (25%) relative to the BAU. This scenario is marked on Figure 4 by the purple line.

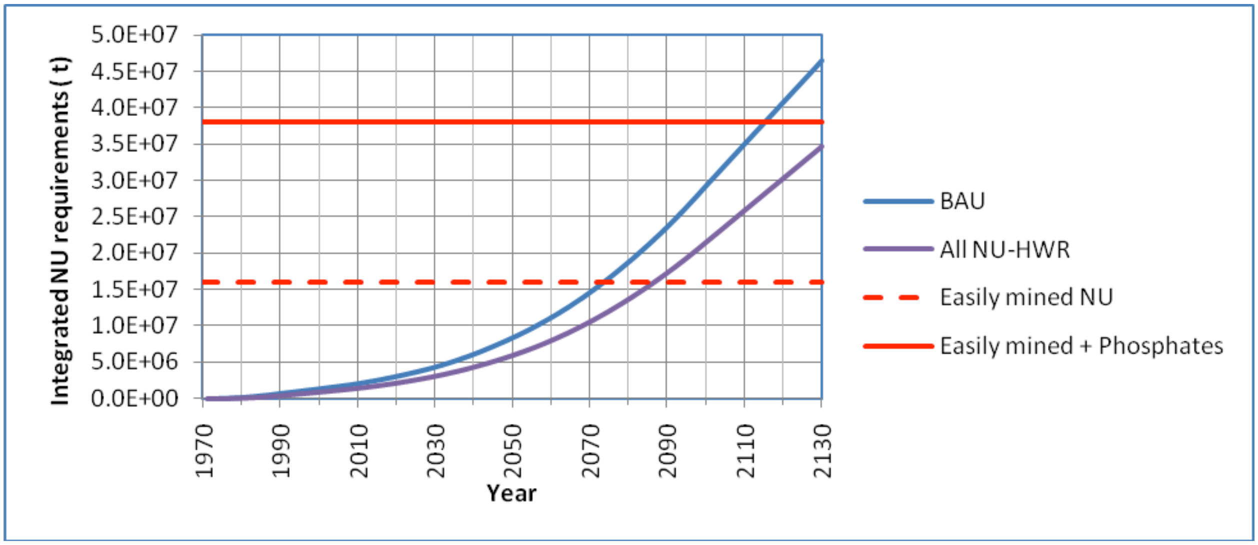

Figure 4: Natural Uranium Requirements for the BAU Scenario

Actinide decay heat was calculated using the method described in Section 2.5 and source terms which were the amounts of material left in the reprocessing facilities at the end of the scenario (2130). This method thus excludes from the calculation all fuel currently in the reactors or in the reactor cooling pools. The decay heat from spent HWR fuel was included separately. For the BAU scenario, the actinide decay heat at 1000 years after discharge is shown in Figure 5. After 1000 years decay, the total heat production is 0.304 GW.

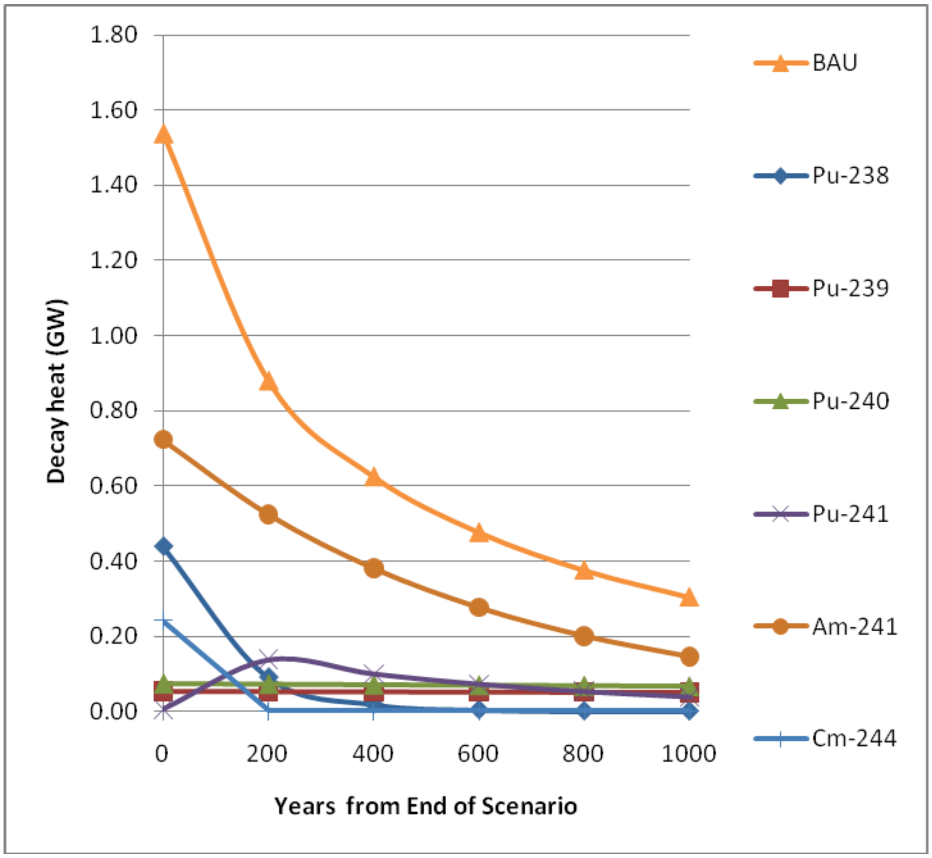

Figure 5: Decay Heat from Spent Fuel in the BAU Scenario

3.2 BAU-FR (Business As Usual with Fast Reactors)

Analysis via DESAE showed that a total capacity of 1500 GWe of nuclear capacity in fast reactors was possible by 2130, although the final situation is not an equilibrium one (plutonium stocks are small and decreasing and will go negative if the scenario is continued beyond this point) and therefore represents a slight overestimate. The electrical capacity of all three reactor types in this scenario is shown in Figure 6.

The natural uranium requirements to 2130 in this scenario are sharply reduced by more than 1/3rd (relative to the BAU scenario) to 3.05x10^{7} tonnes (Figure 7) due to the fact that the FRs use DU of the same enrichment as the already available enrichment plant tails (0.3%) and therefore require no new NU. However, even this large switchover to fast reactors as a limited effect on the point of exhaustion of the easily mined NU, delaying it by only 10 years.

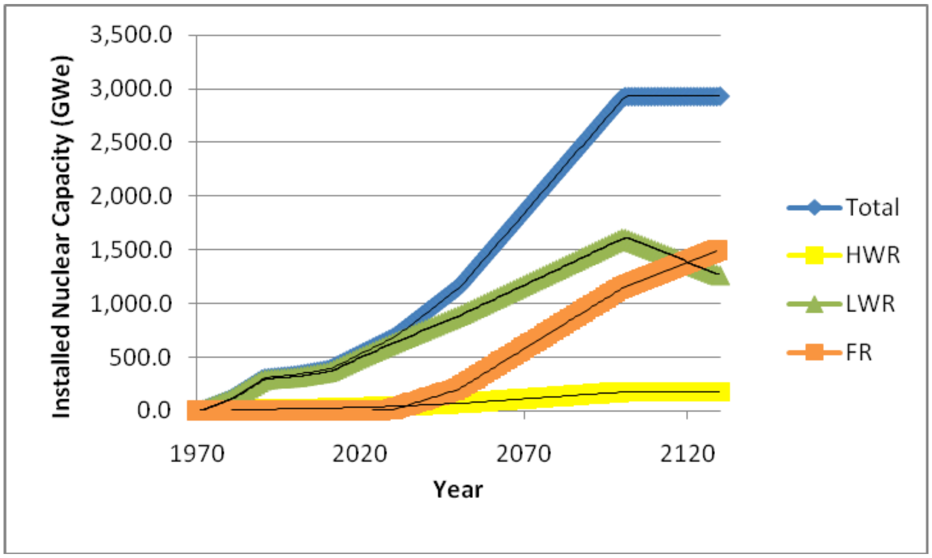

Figure 6: Electric Capacity of the BAU-FR Scenario

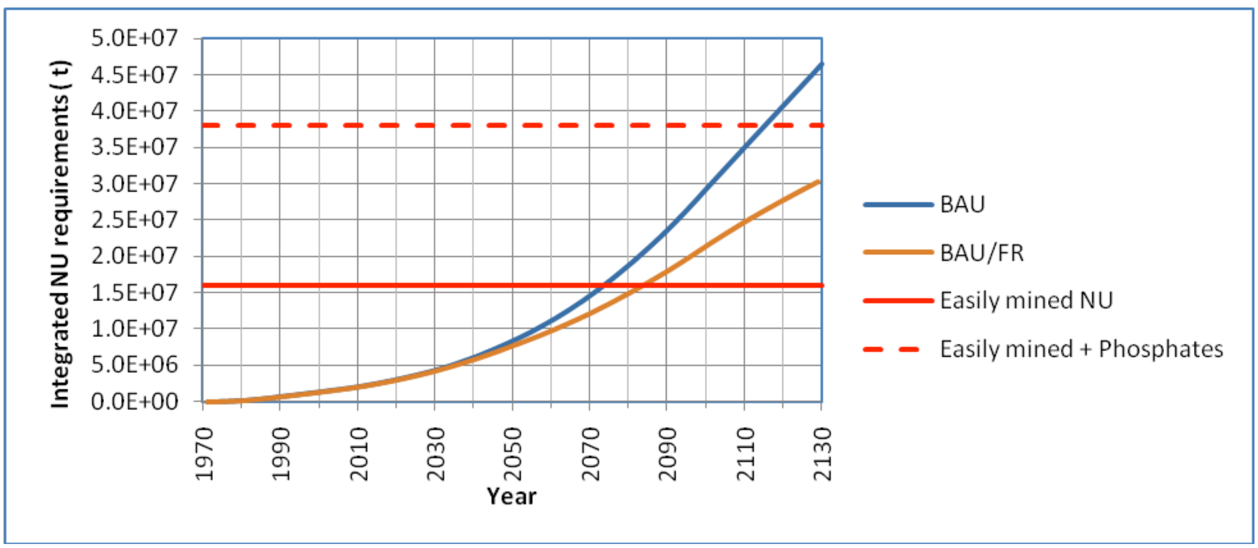

Figure 7: Natural Uranium Requirements in the BAU-FR Scenario

Spent fuel decay heat in this scenario is ~0.15 GW at 1000 years (Figure 8), about 50% of the BAU case. After 1000 years decay, 80% of the SNF decay heat in the BAU-FR scenario is from Am-241, which is not recycled into the FR fuel. The remaining 20% of the decay heat is from HWR fuel. There is virtually no decay heat from other sources since the plutonium in the FR exit fuel is continually recycled back into FRs and never appears in long term storage.

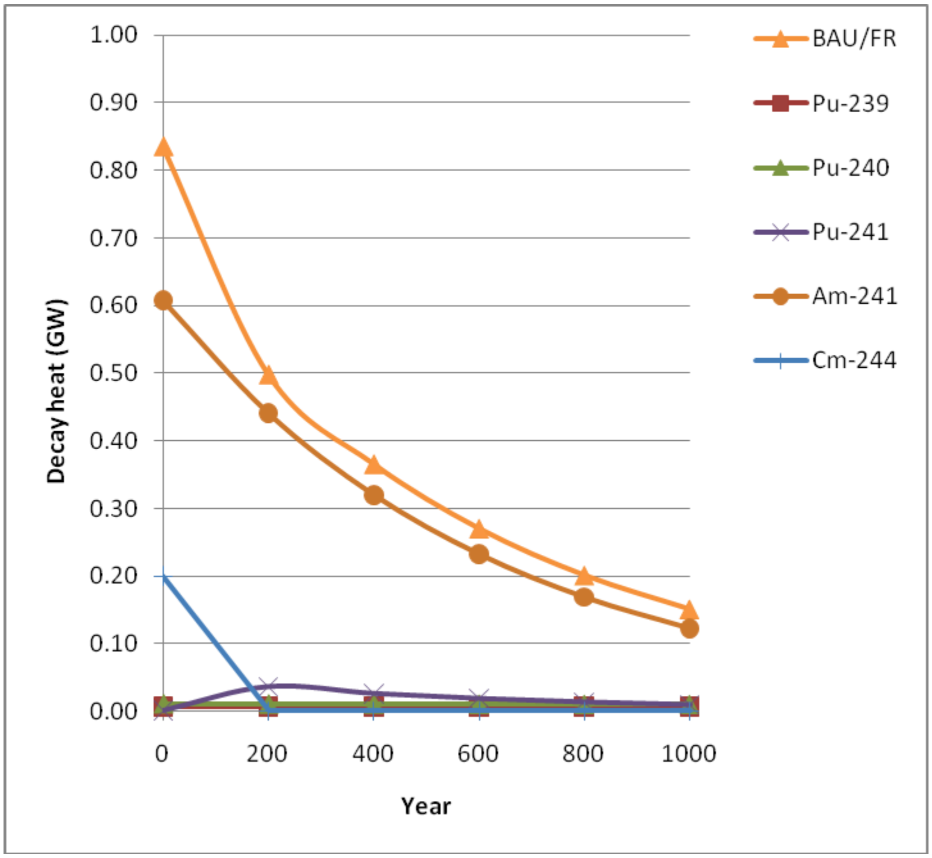

Figure 8: Decay Heat from Spent Fuel in the BAU-FR Scenario

3.3 Once Through Plutonium Driven Thorium Fuel (ThPu)

The division of electrical capacity amongst the various reactor types in this scenario is shown in Figure 9. The plutonium available from spent LWR fuel allows the electricity capacity of the ThPu HWRs to rise to 350 GWe by the end of the century – about 11.9% of the total capacity.

The integrated natural uranium requirements (Figure 10) for this scenario (41.9×10^6 tonnes at 2130) are reduced by 9.7% over the BAU case (46.4×10^6 tonnes). For comparison, the estimated NU requirements for a case introducing Breakeven FRs is also shown (30.5×10^6 tonnes, or 34.3% savings over the BAU at 2130). The ThPu case extends the limit on easily mined NU resources by about 5 years (relative to BAU, see the lower construction line on Figure 10). When unconventional NU resources (principally phosphates) are included, the exhaustion of resources is extended by about 10 years (from 2115 to 2125, see the higher construction line on Figure 10).

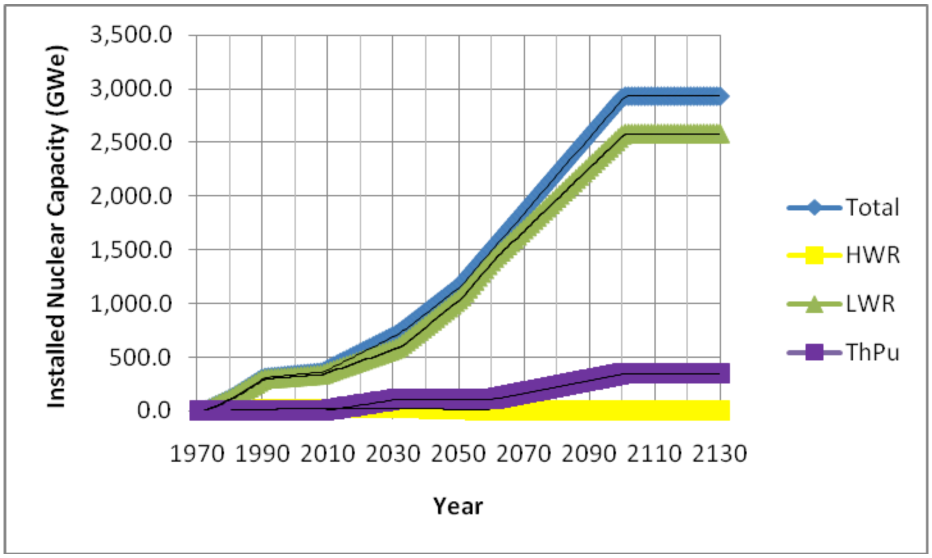

Figure 9: Electrical Capacity for the Scenario 3 (ThPu)

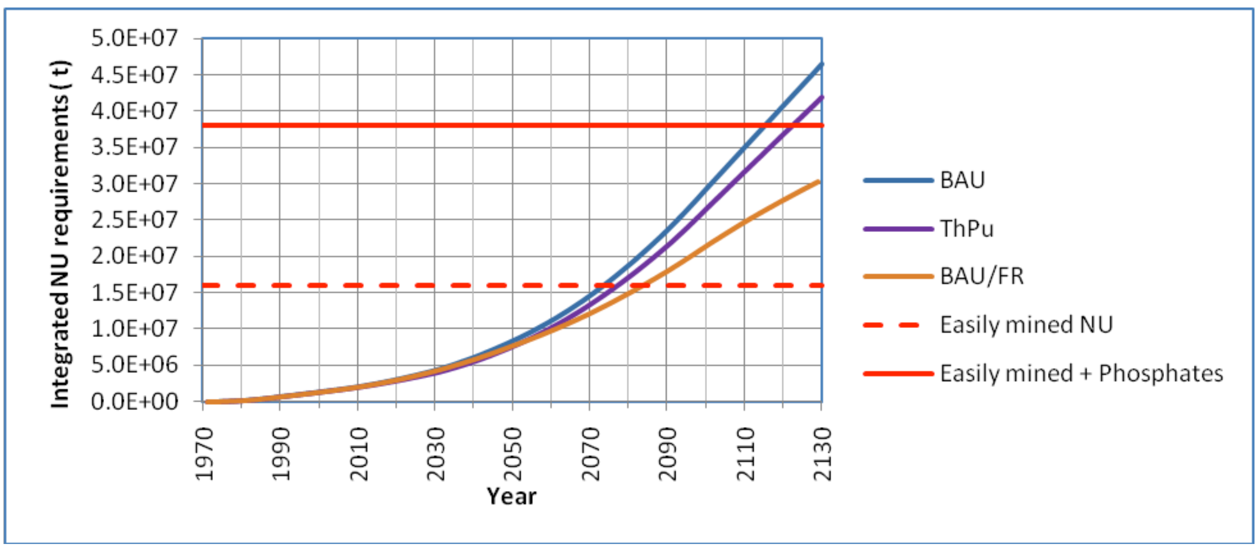

Figure 10: Integrated Natural Uranium Requirements for Scenario 3 (ThPu)

Actinide decay heat (Figure 11) was calculated and it was found that actinide decay heat at 1000 years has been reduced to 0.212 GWth, about 70% of the BAU case (0.304 GWth, see Figure 8). This is a result of a number of factors. In descending order of importance these are:

1) Pu-241 is re-irradiated and fissioned before it can decay into Am-241 – a major decay heat component.
2) The irradiation of thorium, which displaces 12% of the uranium based power production in the BAU case, produces essentially no new minor actinides with important decay heat contributions because there is no U-238 present.

3) The amount of spent NU-HWR fuel, containing the major decay heat components Pu-239 and Pu-240, and which is not reprocessed, is reduced relative to the BAU case because these reactors are phased out.

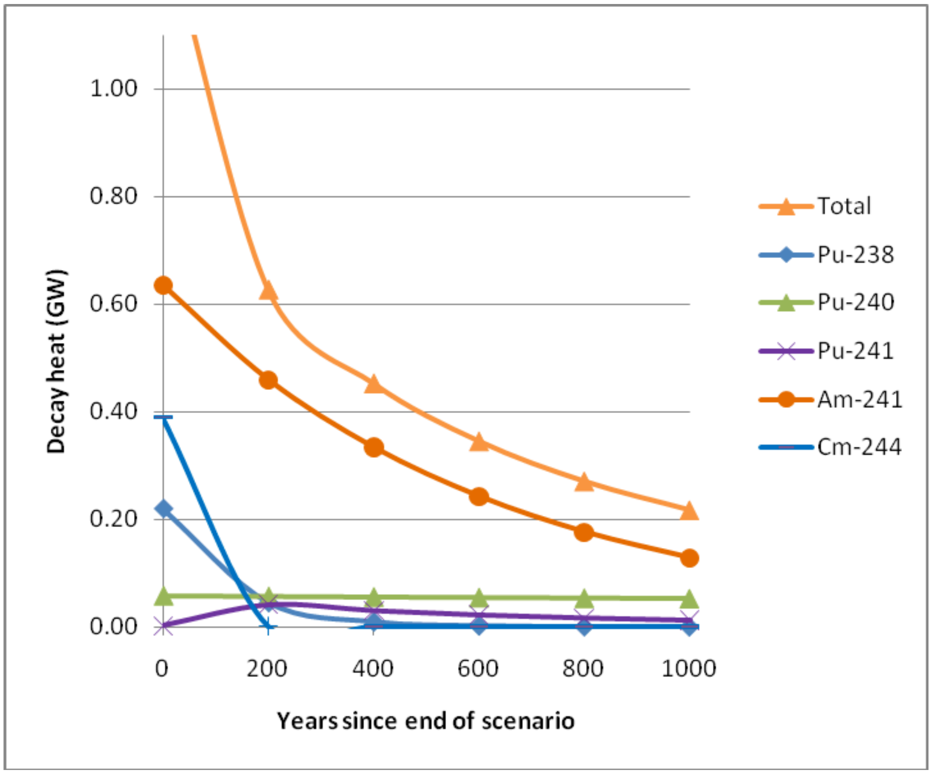

Figure 11: Decay Heat from the actinides (total spent fuel) for scenario 3 (ThPu)

3.4 Plutonium-Driven Thorium Fuel Scenario with U-233 and Pu Recycle (ThPuR)

The division of electrical capacity amongst the various reactor types in this scenario is shown in Figure 12. The division of electrical capacity at 2130 is: 130 GWe ThPu (4.4%), 610 GWe ThPuR (20.8%) and 2195 GWe LWR (74.8%). Plutonium generally restricts the construction of ThPuRs until ~2080 (Figure 13) when the LWRs built during the rapid expansion of nuclear capacity starting in 2020 are retired and their total inventories go to recycling. There exists a general upward pressure on U-233 inventories throughout the period because this isotope is created in ThPu reactors but not used by them. This upward pressure is periodically countered by the construction of ThPuR reactor cores, leading to an oscillatory final state (Figure 13).

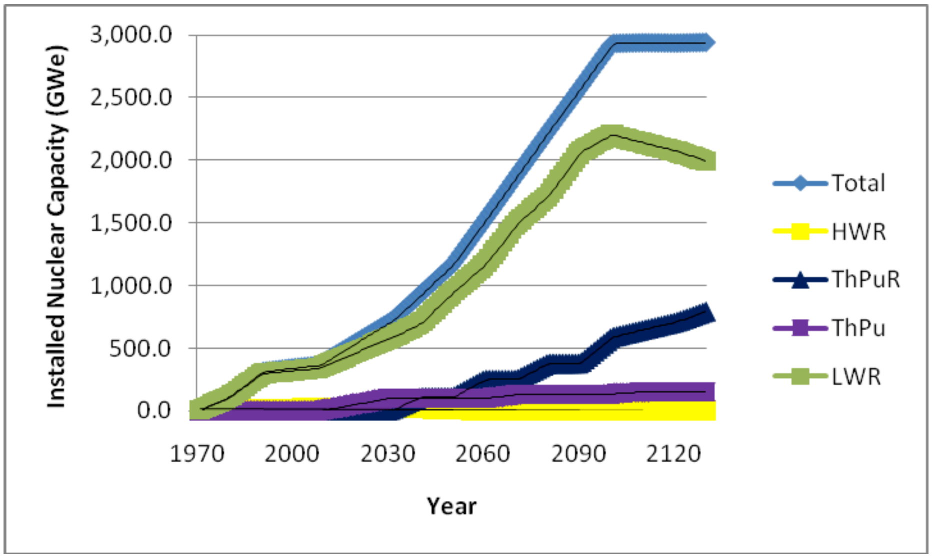

Figure 12: Electrical Capacity of Scenario 4 (ThPuR)

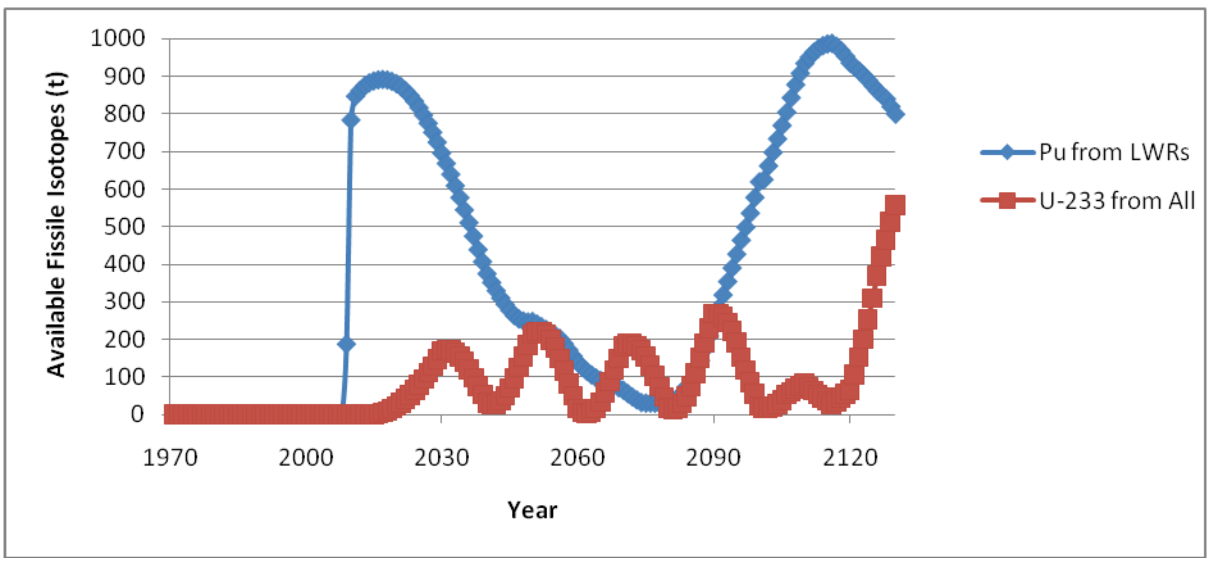

Figure 13: Fissile Isotopes Available After Reprocessing

The integrated natural uranium requirements (Figure 14) for this scenario (37.8x10^6 tonnes at 2130) are reduced by 18.7% over the BAU case (46.4 x10^6 tonnes). This is over half the potential savings of a full Breakeven FR introduction case. The ThPuR case extends the limit on easily mined NU resources by about 10 years (relative to BAU, see the lower construction line on Figure 14). When unconventional NU resources (principally phosphates) are included, the exhaustion of resources is extended by about 15 years (from 2115 to 2130, see the higher construction line on Figure 14).

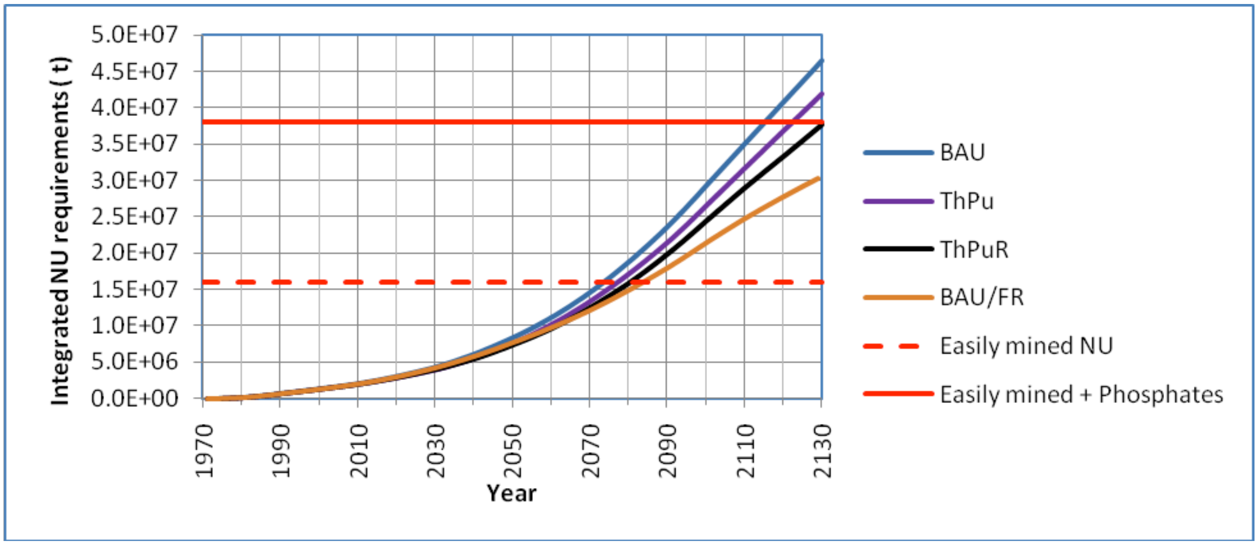

Figure 14: Integrated Natural Uranium Requirements ThPuR vs. BAU or BAU/FR

Actinide decay heat was calculated for this scenario to be ~0.182 GWth (Figure 15) at 1000 years, slightly less than the 0.212 GWth in the ThPu scenario, but more than the 0.15 GWth of the BAU-FR.

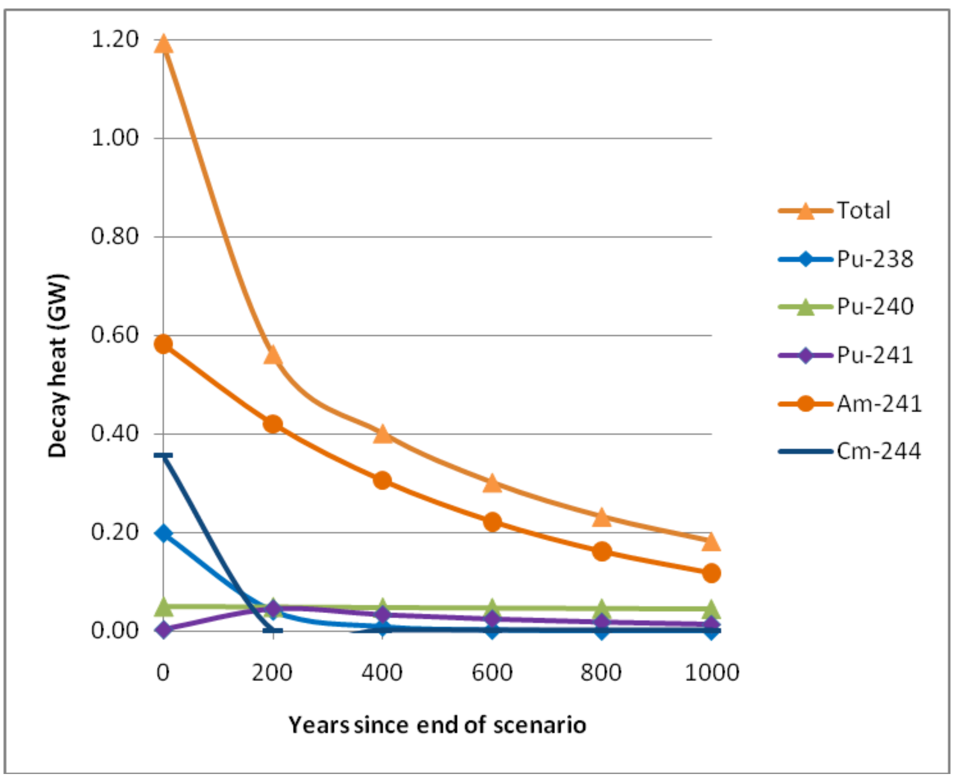

Figure 15: Actinide Decay Heat after 2130 of Scenario 4 (ThPuR)

4. Discussion

Two possibilities were considered to increase sustainability of the thorium scenarios.

a) the NU-HWR phaseout could be eliminated, keeping natural uranium fuelled HWRs as 6% of all capacity in the scenarios in which thorium fuelled HWRs are also built. This would replace some LWRs by HWRs and therefore lower the NU requirements per GWe produced.
b) HWR fuel could be recycled. This would increase the supply of plutonium for ThPu and ThPuR reactors.

Estimates were made of these effects for scenario 3 only and found to be ~1% for (a) and ~2% for (a)+(b), both in the direction of decreasing total NU requirements. These effects are small because of the rather low density of fissile plutonium in HWR fuel per unit mass (less than one third of that of LWR fuel) and the relatively small number of HWR reactors in total, diluting the effect of the extra efficiency of NU-HWRs (a) and of the extra plutonium for building ThPu HWRs (b).

5. Conclusions

Migrating to fast reactors over the next century is an ambitious undertaking which will require considerable investment to commercialize and which therefore may not be economically sensible. The potential savings of NU in such a scenario are about 34.3% of total NU requirements from here to 2130, assuming an eightfold increase in nuclear capacity, measured against a 'business-as-usual' scenario in which the current reactor types, and a once through fuel cycle, are maintained. However, building recycling thorium-plutonium reactors fuelled by plutonium from LWR SNF, a technology which requires much less research investment to achieve (on the reactor side – an efficient thorium reprocessing technique is still required, but this could be delayed a few decades), will manage slightly more than half the NU savings of the fast reactor case (18.7% vs. 34.3%) and also more than 80% of the reduction in SNF decay heat (0.182 GWth vs. 0.15 GWth compared to a BAU scenario with 0.304 GWth). This path may therefore be preferred by some jurisdictions without the capital to invest in the research to create fast reactors.

However, it should be noted that all the scenarios studied run out of cheap natural uranium between 2070 and 2090 and therefore none can really be termed sustainable. The establishment of a partially closed thorium fuel cycle, where U-233 alone is recycled, will mitigate the coming resource exhaustion but not avoid it. The creation of a viable SSET, or an inexpensive process for the extraction of NU from seawater, are the only apparent options for long term sustainability.

6. REFERENCES

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