WM2013 Conference, February 24 – 28, 2013, Phoenix, Arizona, USA

Transmutation, Burn-Up and Fuel Fabrication Trade-Offs in Reduced-Moderation Water Reactor Thorium Fuel Cycles – 13502

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ABSTRACT

Multiple recycle of long-lived actinides has the potential to greatly reduce the required storage time for spent nuclear fuel or high level nuclear waste. This is generally thought to require fast reactors as most transuranic (TRU) isotopes have low fission probabilities in thermal reactors. Reduced-moderation LWRs are a potential alternative to fast reactors with reduced time to deployment as they are based on commercially mature LWR technology. Thorium (Th) fuel is neutronically advantageous for TRU multiple recycle in LWRs due to a large improvement in the void coefficient. If Th fuel is used in reduced-moderation LWRs, it appears neutronically feasible to achieve full actinide recycle while burning an external supply of TRU, with related potential improvements in waste management and fuel utilization. In this paper, the fuel cycle of TRU-bearing Th fuel is analysed for reduced-moderation PWRs and BWRs (RMPWRs and RBWRs). RMPWRs have the advantage of relatively rapid implementation and intrinsically low conversion ratios. However, it is challenging to simultaneously satisfy operational and fuel cycle constraints. An RBWR may potentially take longer to implement than an RMPWR due to more extensive changes from current BWR technology. However, the harder neutron spectrum can lead to favourable fuel cycle performance. A two-stage fuel cycle, where the first pass is Th-Pu MOX, is a technically reasonable implementation of either concept. The first stage of the fuel cycle can therefore be implemented at relatively low cost as a Pu disposal option, with a further policy option of full recycle in the medium term.

INTRODUCTION

Multiple recycle of long-lived actinides has the potential to greatly reduce the required storage time for spent nuclear fuel or high level nuclear waste. This is difficult, if not impossible, to achieve in conventional thermal reactors due to a build-up of TRU isotopes (Am, Cm etc.) with low fission probability in the thermal spectrum. However, thanks to the reduced moderation, the neutron spectrum of RMPWRs and RBWRs is shifted towards higher energies compared to current LWRs. This facilitates implementation of the full recycle strategy. While still requiring considerable technology development and infrastructure, RMPWRs and RBWRs are an evolution of current LWRs which should reduce the time and cost to licensing and deployment compared to fast reactors (FRs). In addition, some reactors in the US fleet could be converted to the reduced moderation mode of operation, thus reducing the economic penalty of the implementation. While use of Th may enhance the transmutation performance of various burner

designs and help limit the Am, Cm and higher actinide populations, its principal advantage in LWRs is in ensuring a negative moderator temperature coefficient (MTC) or void coefficient (VC). If confirmed in further studies, this feature could provide a compelling case for considering the introduction of Th in the nuclear fuel cycle if nuclear waste reduction becomes a key objective.

If a Th-TRU cycle was implemented, it could be necessary, and from a life-cycle point of view advantageous, to implement the first stage as Th-Pu MOX in an unmodified or slightly modified PWR, using Pu recovered via reprocessing of commercial spent fuel or weapons decommissioning programs, and current (glove-box) fuel manufacturing technology. This would allow effective reduction of the Pu supply, relatively rapid deployment and licensing, potentially with existing stockpiles of Pu, which would postpone the need for further reprocessing. A final decision regarding full recycle could then be delayed without economic penalty.

METHOD

Lattice calculations were performed using WIMS 9 and a development version of WIMS 10 [1]. WIMS is a thermal reactor code and therefore some errors are incurred for reduced-moderation designs [2]. The JEF-2.2 data library was used. The TRU feed was PWR discharge, burned to 52 GWd/tiHM and cooled for 10 years. This isotope vector is given in Table I.

The RMPWR model consisted of a standard 17×17 square-lattice fuel assembly with pin pitch of 12.6 mm but with pin diameter increased from the 9.5 mm of standard 17×17 fuel to a 11-11.5 mm range considered for the RMPWR, corresponding to a reduction in the hydrogen to heavy metal (H/HM) volumetric ratio from 1.98 to respectively 1.09-0.87.

The RBWR model consisted of $1/6^{th}$ of a hexagonal 217 pin assembly based on [3]. The pitch was 15 mm, the pin diameter was 13.7 mm and the pellet radius was 5.865 mm (Figure 1). The average void fraction was 53%. The H/HM of this configuration is 0.50, reduced to 0.26 when weighted for the difference in water density compared to the RMPWR. The RBWR assembly design is generally not fixed and various flow qualities, fuel volume fractions and assembly geometries have been proposed [3]. The RBWR plant was specified as 3926 MWth, with a 720 assembly core and 200 cm active fuel height. It appears unfeasible to retro-fit an operating BWR to an RBWR.

Full-core analyses and thermal-hydraulic studies are being performed to determine the operational feasibility of the cases under consideration and will be discussed in future work. An 11 mm pin diameter may be achievable within thermal-hydraulic constraints in a Westinghouse 4-loop PWR but a further increase in pin diameter is likely to require a new PWR core or de-rating.

Table I: Reload isotope vectors (at%)

Isotope	Single Tier	Multi-Tier (Cases 5 & 9)	Isotope	Single Tier	Multi-Tier (Cases 5 & 9)
Am-241	5.77	10.22	Np-237	4.94	6.38
Am-242m	7.15E-03	3.70E-02	Pu-238	2.74	3.42
Am-243	1.60	4.39	Pu-239	48.45	14.64
Cm-242	2.99E-07	3.30E-04	Pu-240	21.03	21.41
Cm-243	5.73E-03	1.79E-02	Pu-241	8.45	9.59
Cm-244	0.50	1.53	Pu-242	6.46	9.21
Cm-245	0.06	0.24	U-233	0.00	16.83
Cm-246	6.46E-03	2.06E-02	U-234	0.00	1.76
Cm-247	9.34E-05	3.45E-04	U-235	0.00	0.27
Cm-248	7.04E-06	2.09E-05	U-236	0.00	2.21E-02

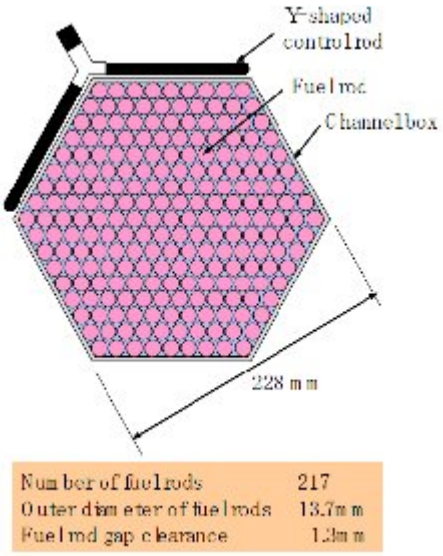

Figure 1: 217 pin fuel assembly design. Figure taken from ([3] pp 421)

While all the considered RMPWR cases can achieve a negative MTC over the cycle, this is not sufficient to ensure the neutronic feasibility of the core. The reactor must be controlled and power peaks need to be kept within acceptable limits. In addition, the behaviour during transients and accidents needs to be ascertained. Reactivity hold-down and power shaping can be achieved by adding integral fuel burnable absorbers in synergy with control rods movement (the option of avoiding chemical shim is being considered). The use of fuel burnable absorbers generally deteriorates the MTC, while control rods with sufficiently high worth improve the MTC. The mechanisms for this behaviour derive from the energy and spatial dependency of cross-sections and neutron flux for the two absorber types and will be discussed in future work. Extensive use of control rods erodes the shutdown margin, which is already a problem due to lower worth in a hard neutron spectrum. It is possible to design a core which satisfies both these constraints, but has positive reactivity when fully voided with the rods out. This condition corresponds to a large break loss of coolant accident without trip. At this stage, it is unclear if this constraint must be satisfied or if a full or partial trip can be assumed. Balancing all these constraints requires careful core design.

The full-core RBWR analyses indicate that the 2D average void fraction model presented here is sufficient for a top-level feasibility study and evaluation of the fuel cycle.

WIMS models the isotopes which are relevant to the reactor physics. These include isotopes of Cm up to Cm-248, Th-232 and Pa-233, but not other isotopes of Th, Pa or U-232. There is therefore no implicit assumption of the treatment of Pa in the WIMS analysis. WIMS 9 was interfaced with the inventory code FISPIN [4] to evaluate full inventories, activities and decay heat for a larger set of nuclides, assuming all actinides are recycled in the fuel.

DISCUSSION OF FUEL CYCLE CASES

Nine fuel cycle cases are considered. An equilibrium isotope vector was evaluated for each by multiple recycle at an estimated average discharge burn-up, with 5 years assumed between recycles to account for post-irradiation cooling, reprocessing and re-manufacturing. The performance is sensitive to the recycle time due to Pu-241 decay into Am-241, and a recycle time shorter than 5 years is not realistic with current aqueous reprocessing technology. A longer decay time than the assumed 5 years would degrade the neutronic performance, although the extent and feasibility need to be determined in future work.

Case 1

RMPWR with 11.5 mm 95% theoretical density (TD) fuel, homogeneous assembly design. An 11.5 mm pin diameter is approximately the minimum for acceptable neutronic performance (negative MTC and adequate cycle length) in an RMPWR with homogeneous Th oxide fuel. The MTC for this case is approximately zero without considering reactivity control and the core has

slightly positive reactivity when fully voided.

Case 2

RMPWR with 11.5 mm, 95% TD fuel, heterogeneous assembly design, 132 Th-TRU pins placed at the centre of the assembly and 132 Th-U3 at the periphery (TCUP) (Figure 2). This configuration improves the MTC, and therefore the achievable enrichment and burn-up. Preliminary full-core calculations indicate that a negative MTC is achievable throughout the cycle and the core has negative reactivity when fully voided. Also, an acceptable shutdown margin appears achievable.

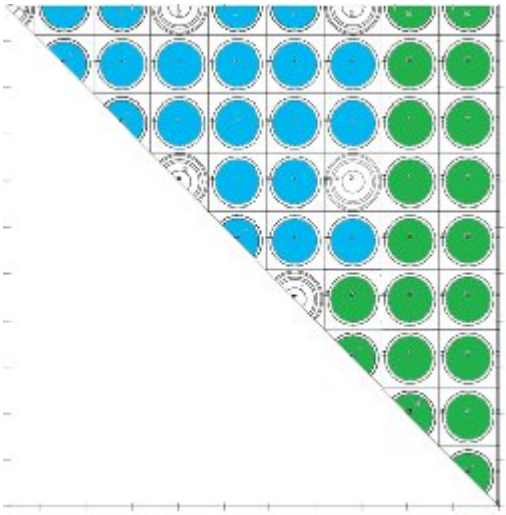

Figure 2: Case 2 and Case 3 TCUP assembly with 132 Th-U3 pins (green) and 132 Th-TRU pins (blue)

Case 3

As Case 2 but with 11 mm pin instead of 11.5 mm. The design and performance is very similar to Case 2, except that the reactivity is slightly positive when the core is fully voided.

Case 4

As Case 3, but the fuel density of Th-U3 pins is reduced to 85% TD. In addition, Np/Am/Cm (minor actinides, MAs) are placed in separate pins, modelled as low density MAO_2. In practice, an inert matrix (e.g. ZrO_2) may be used (e.g. [5]). In the unrodded assemblies, these low density pins can replace the guide tube positions, as burnable absorber inserts are not foreseen in the RMPWR (they are ineffective as the spectrum is too hard). As the pins are low power, the radius is increased to almost the lattice pitch. These extra rod positions should allow the thermal-hydraulic conditions to be satisfied with some of the conventional fuel rods also displaced. This

is necessary to satisfy mass flow considerations while minimizing the required MA density. The density of MAs assumed in this study for the target pins is ~3.4 g/cc HM. This is required to satisfy the mass balance constraints of this fuel assembly. Previous studies have considered a wide range of densities ([5] considered a Am/Cm/Ln mixture occupying 5-60% of the total pin volume). The pins are ~65 wt% Am, 21 wt% Cm and 14 wt% Np. The power of the MA target pins is ~70% that of normal rods.

The lattice calculation model assumed rod cluster control assemblies positioned in a checkerboard configuration. The MA-bearing pins should be distributed within the Th-Pu pins so as to favour more even power distribution in the assembly by lowering the thermal flux impinging on the MA-bearing pins. However, if the design of the assembly containing MAs is not compatible with the MA absorbers being removed and redistributed between cycles, the fuel management scheme is constrained. This is a problem as the 1st and 2nd batches are often deployed in a checkerboard for power peaking reasons, so if one type of assembly is only compatible with alternate positions in the core, they cannot be shuffled from the usual batch 1 positions to the adjacent batch 2 positions. It should be possible to reconcile these objectives with careful core design.

In addition, it is difficult to maintain an acceptable form factor as the rodded assembly is significantly more thermal. The assembly must be designed so that when it is in a hot position in the core (e.g. near the centre), the assembly power peaking is low. It is usually not a problem if the assembly power peaking is high due to a different rod/MA configuration when the assembly is in a low power region of the core. The core design will be challenging and a full-core analysis is required to identify a feasible configuration and demonstrate concept viability. The MA pins take the place of some of the rods – as well as allowing movement of the assembly from the rodded to the unrodded position, it is desired that these can be removed at the end of the cycle and shuffled round the core on their own loading scheme. As the MA pins should be placed near the Th-Pu pins to maximise spectral hardening, this means the Th-Pu pins should be positioned at the centre of the assembly. This does, however, incur a thermalisation penalty from the guide tubes (Figure 3). There were 132 Th-TRU pins and 120 Th-U3 pins per assembly, with 12 MA pins in rodded assemblies and 36 MA pins in unrodded assemblies.

While it is possible to achieve a negative MTC throughout the equilibrium cycle, there is a penalty compared to Case 3. This is primarily attributable to the reduction in density of the Th-U3 pins and the flux dip in MA pins. An increase in reload enrichment is necessary to maintain a cycle length of ~40 GWd/tiHM, which increases the incineration rate but makes the MTC less negative. A full-core analysis is necessary to determine if an acceptable core configuration can be achieved with an 11 mm pin diameter, or if a larger pin is required.

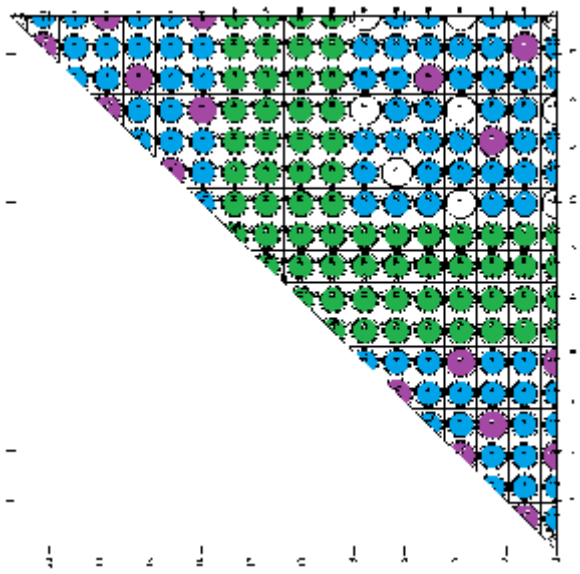

Figure 3: Case 4 TCUP model with Th-U3 pins (green), Th-TRU pins (blue) and MA pins (purple) centred on where 4 assemblies meet

Case 5

As Case 3, but the feed is the discharge from a previous stage Th-Pu fuelled PWR with standard (9.5 mm) pin diameter. The discharge from this previous stage is reprocessed with 5 years between stages; the MAs from the initial UO_2 LWR stage are added back to the actinide feed to the RMPWR (see Multi-Tier in Table I) so that the overall actinide balance across stages is preserved with only reprocessing losses and fission products being disposed of. This multi-tier implementation may allow more rapid implementation than straight full TRU recycle: the first stage homogeneous Th-Pu fuel could be implemented with existing Pu stockpiles and glove box fuel fabrication (Figure 4). However, it also introduces specific challenges, including increased higher actinide content in the RMPWR fuel inventory and separate management requirements for the Pu and MAs from the UO_2 LWR stage. The equilibrium cycle inventory contains more U3 than the previous cases as the feed contains U3 from the discharge of the intermediate Th-Pu PWR stage. As a result the number of Th-U3 pins is increased from 120-132 of Cases 2-4 to 156 (Figure 5).

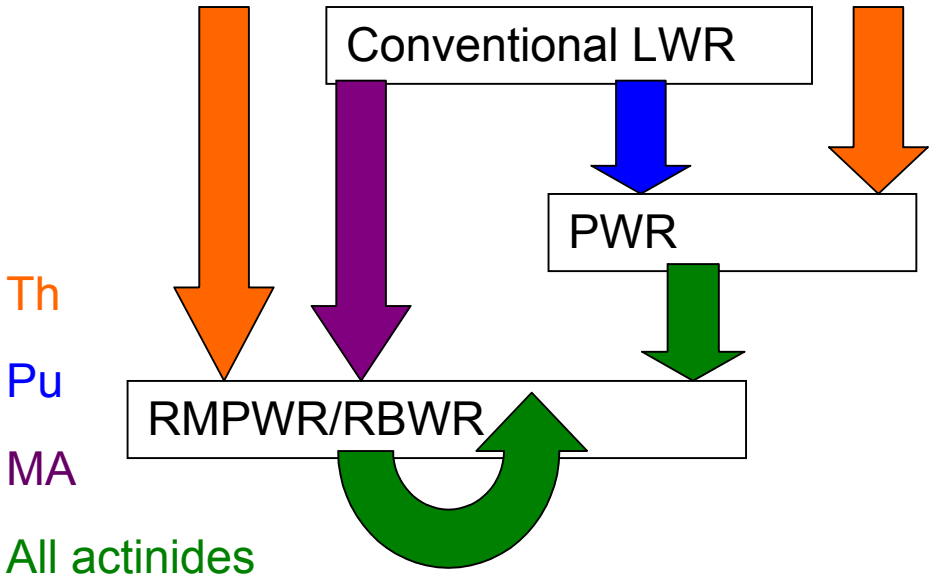

Figure 4: Multi-tier fuel cycle implementation for existing Pu stockpile

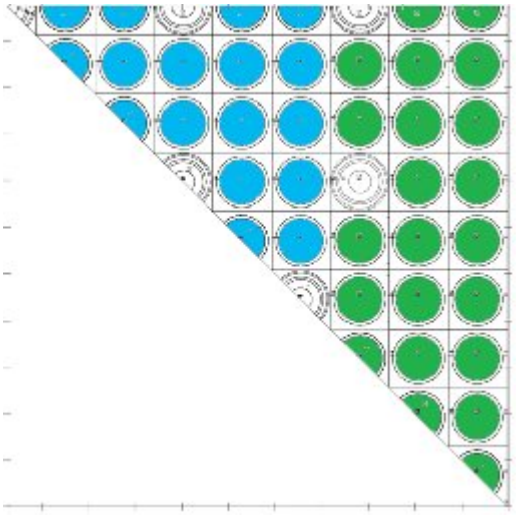

Figure 5: Case 5 TCUP pin assembly with 108 Th-TRU pins (blue) and 156 Th-U3 pins (green)

The feed to the equilibrium cycle has lower fissile quality than the single tier cases, and therefore a higher reload proportion than in the geometrical single-tier counterpart (Case 3) is required. (Note that the reload proportion is counted here as the total incineration liability, i.e. everything except Th-232.) However, the presence of in-bred U3 leads to a comparable MTC to Case 3. The resultant achievable burn-up for a given MTC is slightly superior to Case 3. This is beneficial but warranting further investigation. It appears that in the heterogeneous configuration the increase

in the number of Th-U3 pins offsets the deterioration in the Pu fissile quality and the increase in higher actinide content of the TRU pins.

Case 6

RBWR with 85% TD homogeneous fuel. This has a relatively low incineration rate but excellent burn-up potential. However, MAs cannot be added until a first Th-Pu pass is completed and U3 is bred in to ensure a negative VC and negative reactivity when the core is fully voided.

Case 7

As Case 6 but with a heterogeneous TCUP assembly with 91 85% TD Th-TRU pins and 126 85% TD Th-U3 pins per assembly (Figure 6). This approach is neutronically extremely effective, improving the VC and therefore allowing the reload enrichment to be substantially increased. If a suitable clad could be found, the burn-up would be competitive with an FR.

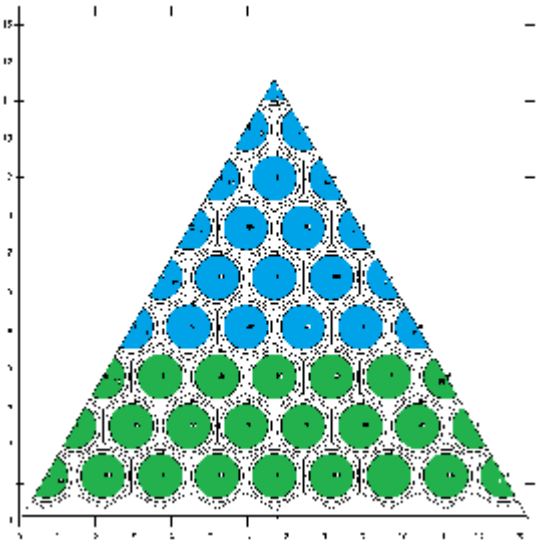

Figure 6: RBWR TCUP assembly with 91 Th-TRU pins (blue) and 126 Th-U3 pins (green) (Case 7)

Case 8

The RBWR does not require heterogeneous fuel, although spatial separation of TRU and U3 is advantageous. Positioning the MAs in the Th-Pu pins is neutronically preferable, but segregating MA from Pu in the U3 pins reduces remote fuel fabrication requirements. Therefore a micro-heterogeneous 'checkerboard' of 78 95% TD Th-Pu pins and 139 85% TD Th-U3-MA pins is considered (Figure 7). Assembly calculations indicate a slightly reduced reload proportion is appropriate and a slightly higher burn-up is achievable relative to Case 6. An average void

fraction assembly calculation is not sufficient to accurately calculate the full-core burn-up, so the same burn-up as Case 6 was assumed. The Case 6 burn-up was calculated using a coupled neutronic-thermal-hydraulic full-core calculation using a coupled PARCS-RELAP5 model based on one developed at the University of Michigan [6].

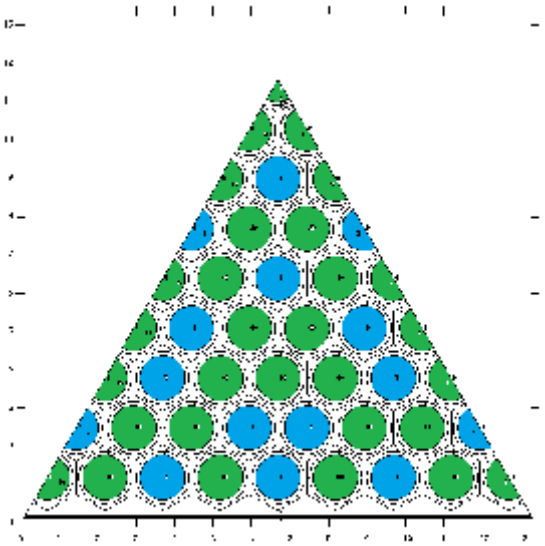

Figure 7: Micro-heterogeneous RBWR fuel design with 78 Th-Pu pins and MAs in the 139 Th-U3 pins (green) (Case 8)

Case 9

As Case 8, but the feed is from a Th-Pu fuelled PWR with standard (9.5 mm) pin diameter with MAs added from the initial UO_2 LWR stage (same as Case 5). This multi-tier approach again allows more rapid implementation than straight full TRU recycle, which is particularly relevant to a strategy in which the transmutation starts in current PWRs while an RBWR is licensed and the reprocessing and fabrication technologies for TRU fuel are developed. A similar reload proportion to Case 6 is appropriate to give the same VC, corresponding to a lower Pu enrichment. The cycle incineration rate and burn-up is evaluated as a weighted average of the Th-Pu stage and the RBWR, based on the relative proportions incinerated at each stage, with the U3 in the feed to the RBWR counted as a liability to be incinerated.

There is a substantial burn-up penalty compared to Case 7, but discharge burn-ups of ~78 GWd/tiHM should be possible. In addition, the incineration rate in the first stage is very high so the overall incineration performance is good.

Indeed, this trade-off appears highly favourable as the burn-up in the RBWR is likely to be constrained by materials considerations. Therefore trading burn-up in the equilibrium cycle for

incineration rate in the first stage is not unreasonable. With the added bonus of postponing RBWR deployment, this result is encouraging.

Implementation of Case 9 with heterogeneous fuel is also an option. At this stage, this was omitted for simplicity. With a micro-heterogeneous implementation the number of Th-Pu or Th-TRU pins in the RBWR would be small, as the Pu enrichment is only ~5%.

The RMPWR cases (1-5) are all not ideal, as they all stretch the limits of neutronic, thermal-hydraulic or fuel fabrication feasibility, and it is not clear which compromise, if any, is preferable.

In contrast the RBWR cases (6-9) have more favourable neutronic, thermal-hydraulic and fabrication feasibilities. However, an RBWR is an unlicensed design with a radically different core configuration to current BWRs. In addition, the achievable incineration rate is low without axially heterogeneous fuel. This makes the multi-tier options of considerable interest as they delay the time before an RBWR is required.

These cases were selected to cover a range of combinations of reactor, fuel design and fuel cycle options and therefore allow the key trade-offs and performance measures to be identified. This essentially covers: homogeneous recycle; heterogeneous fuel for improved neutronic performance (TCUP); heterogeneous fuel for reduced remote fuel fabrication requirements (also discussed in [7] in this session); and multi-tier fuel cycles for RMPWRs and RBWRs. The effect of varying the RMPWR pin diameter is also covered. Table II summarises the objectives and scope of each case.

Table II: Summary of objectives and scope of considered fuel cycle case

Scope of fuel cycle case	**RMPWR case**	**RBWR case**
Homogeneous fuel ‘reference’ case.	1	6
Neutronically superior ‘TCUP’ fuel configuration.	2	7
Effect of changing pin diameter (reduced pin diameter possible due to TCUP fuel in RMPWR).	3	N/A
Investigate potential heterogeneous recycle methods to minimise remote fuel fabrication requirements.	4	8
Multi-tier fuel cycle.	5	9

Fuel Cycle Performance

The equilibrium isotope vectors for all the cases are given in Table III. The RMPWR generally has significantly higher content of TRU and lower U3 and Th-232 contents. Cm-246 and above take a very long time to converge to their equilibrium values, so the compositions of these isotopes may not have fully converged.

Table IV summarizes the fuel cycle performance of each case (although note that some of the cases have positive reactivity when fully voided). Unlike multi-tier fast FR approaches (e.g. [8]) the reactor support ratio is not the primary concern from a standpoint of cost minimization. Once the sunk costs on licensing have been met, an RBWR (or non-retro-fit RMPWR) is expected to have similar cost to conventional LWRs, except for the fuel cycle costs. Minimizing the fuel cycle costs, which essentially corresponds to limiting the reprocessing volumes and the number of pins which must be fabricated remotely, is then a key objective. We therefore consider kg burned/t reprocessed to be our primary figure-of-merit. This will be slightly influenced by the proportion of fuel pins which are fabricated remotely, but this will depend upon the relative costs of fabrication and reprocessing.

Table III: Equilibrium isotope vectors at start of cycle (at%, assembly-averaged)

Case	1	2	3	4	5	6	7	8	9
Am-241	0.882	1.191	1.423	2.102	1.992	0.701	1.225	0.656	0.776
Am-242m	0.023	0.035	0.038	0.058	0.053	0.027	0.052	0.024	0.028
Am-243	0.613	0.671	0.770	1.043	1.137	0.365	0.533	0.332	0.506
Cm-243	0.005	0.004	0.005	0.006	0.007	0.002	0.003	0.002	0.003
Cm-244	0.453	0.456	0.515	0.627	0.701	0.203	0.248	0.184	0.287
Cm-245	0.232	0.202	0.218	0.201	0.267	0.113	0.105	0.101	0.152
Cm-246	0.195	0.188	0.207	0.131	0.152	0.084	0.118	0.080	0.114
Cm-247	0.036	0.046	0.048	0.026	0.028	0.019	0.032	0.017	0.026
Cm-248	0.018	0.021	0.023	0.014	0.008	0.008	0.013	0.008	0.010
Np-237	0.427	0.487	0.583	0.699	0.846	0.366	0.549	0.354	0.462
Pu-238	1.743	2.059	2.409	2.471	3.039	1.113	1.424	0.982	1.154
Pu-239	2.297	2.786	3.520	3.587	1.834	1.797	3.127	1.660	0.739
Pu-240	2.831	4.683	5.427	5.867	5.802	2.312	5.106	2.373	1.880
Pu-241	0.883	0.906	1.073	1.170	1.090	0.513	0.642	0.466	0.476
Pu-242	1.688	2.461	2.871	3.100	3.841	0.966	1.928	1.042	1.177
Th-232	80.592	77.136	74.803	73.284	72.315	82.580	76.616	82.457	82.182
U-233	3.804	3.025	2.555	2.571	3.151	5.588	4.709	5.603	6.107
U-234	1.935	2.301	2.211	1.968	2.523	1.983	2.287	2.298	2.446
U-235	0.831	0.684	0.641	0.570	0.706	0.722	0.699	0.740	0.837
U-236	0.511	0.656	0.658	0.503	0.505	0.538	0.586	0.619	0.637
TRU	**12.326**	**16.197**	**19.130**	**21.103**	**20.798**	**8.590**	**15.104**	**8.283**	**7.790**
U3	**7.080**	**6.666**	**6.065**	**5.612**	**6.886**	**8.830**	**8.280**	**9.259**	**10.027**

Table IV: Fuel cycle performance

Case	Reload proportion (at%)	Incineration (kg/GWth yr)	Burn-up (GWd/tiHM)	kg burned/t reprocessed	Th-Pu pins?	Reactivity when fully voided
1	45%	172.9	34.9	16.5	No	Positive
2	40%	156.1	41.2	17.6	No	Negative
3	50%	191.9	42.7	22.4	No	Positive
4	55%	217.6	40.5	24.1	Yes	Positive
5	60%	223.1	39.9	24.4	Stage 1	Positive
6	26%	101.3	94.3	26.2	No	Negative
7	35%	135.7	152.5	56.7	No	Negative
8	24%	93.5	94.3	24.1	Yes	Negative
9	26%	112.1	78.1	24.0	Stage 1	Negative

Implementation in an RMPWR is a delicate compromise between neutronic, thermal-hydraulic and fuel fabrication constraints. It may not be possible to satisfy these constraints in a retro-fit core design. Implementation in a new LWR design gives flexibility to optimise the performance. If a new PWR plant can be designed with satisfactory thermal-hydraulic performance at an H/HM ratio equal to or less than the 11.5 mm pin diameter design, then the neutronic (negative reactivity at full voiding) and possible fuel fabrication constraints (e.g. lower fuel density) are easier to meet. Case 1 has the worst fuel cycle performance and also the least negative MTC, so if an RMPWR is selected heterogeneous fuel should be used. Reducing Th-U3 pin density and using MA target pins improves the fuel fabrication case but makes the MTC less negative, so for this strategy to be pursued it needs to be established that (1) this does not affect feasibility and (2) fabrication advantages are enough to compensate for any burn-up penalty.

The RBWR has the neutronic potential to reach very high burn-ups. In particular, the performance of Case 7 (TCUP) far exceeds the performance of the other cases due to the neutronic capability of achieving a very high burn-up. However, no cladding yet exists which can survive these burn-ups. A lower burn-up RBWR is less competitive relative to an RMPWR due to its lower incineration rate – leading to increased reprocessing costs. It is possible to increase the RBWR incineration rate by increasing the enrichment and decreasing the core height

(to keep the VC negative by increasing leakage). Overall the achievable kg burned/t reprocessed from a neutronic perspective is worse relative to a low leakage RBWR, but with current clad licensing limits this approach may have merit. A high leakage version of Case 7 could be expected to have superior performance and a lower, more realistic burn-up. The number of pins which require remote fabrication can be reduced significantly without substantial burn-up penalty by implementing Case 8.

The RBWR yields a significant further reduction in moderation compared to the considered RMPWR core configurations (Table V). Therefore, a core can be specified with an H/HM ratio between the RBWR and the 11.5 mm RMPWR, by designing an RBWR with a less tight lattice or an RMPWR with a tighter lattice. A tighter lattice RMPWR would require a new design, probably with a lower core height and more control rods, to satisfy shutdown margin and thermal-hydraulic constraints.

Table V: H/HM ratios of considered cases

PWR 9.5 mm pin diameter	1.98	Reference case.
PWR 11 mm pin diameter	1.09	Depending on the fuel configuration and fully voided reactivity constraint, the maximum H/HM ratio for neutronic feasibility lies in this range.
PWR 11.5 mm pin diameter	0.87	
RBWR	0.26[i]	Design from [4], low H/HM gives a 'bounding case'.

[i] Volumetric H/HM weighted by reduced water density compared to PWR, i.e. 0.3655 g/cc in RBWR, 0.707 g/cc in RMPWR, weighted by 0.517.

The multi-tier cases both achieve comparable performance to the single tier cases – with the added advantages of more rapid implementation and no need for remote fuel fabrication at the first Th-Pu stage. For the RMPWR, this gives comparable burn-up performance so appears a favourable implementation. For the RBWR, this allows the fuel cycle performance to be realised with achievable burn-ups, whereas the single tier RBWR is only competitive at high burn-ups which may not be achievable. Therefore, Case 5 appears to be the 'best' RMPWR case, with the possibility of using separate MA pins or Th-U3 pins (like Case 4), and possibly increasing the fuel pin diameter to ensure the fully voided core has negative reactivity (like Case 2). Case 9 appears favourable for the RBWR. This could be combined with the heterogeneous implementations of Cases 7 or 8, but the number of Th-Pu pins would be relatively low so these approaches can be expected to foster smaller improvements in the multi-tier case.

MOST SIGNIFICANT SOURCES FOR FUEL FABRICATION

The closed Th fuel cycle results in major challenges for fabrication and reprocessing technology. The most significant problem with fuel fabrication is the high energy gamma emitter Tl-208 in the decay chain of U-232. This necessitates remote fuel fabrication. Similarly, a major obstacle to MA transmutation is the need to fabricate fuel remotely, primarily due to a large spontaneous neutron (SN) source and, to a lesser extent, gamma source. Therefore multi-recycle and burn of Pu with Th is economically disadvantageous compared to using U-238, unless MA transmutation is also pursued, in which case there is little disadvantage relative to using U-238, especially if a homogeneous recycle scheme is pursued. For heterogeneous configurations, MA incineration in U-238 systems greatly reduces remote fabrication requirements compared to Th. However, for RMPWRs, and RBWRs, use of U may be precluded, or greatly complicated, by MTC and VC constraints.

The inventories for Cases 3 and 9 were calculated by generating burn-up-dependent 3-group cross-sections for the key actinides in WIMS and using these in FISPIN. Case 3 is the single tier TCUP RMPWR and has a relatively high incineration rate. Case 9 is the multi-tier RBWR, and hence has a relatively low TRU population. These are therefore representative cases at each end of the design region, giving examples of the representative trends for different moderations and different fuel cycle implementations.

The cross-sections of less significant actinides (e.g. higher than Cm-245) were calculated assuming they were evenly distributed across the assembly. This is not accurate for the heterogeneous RMPWR assembly, where essentially all the TRU is in the Th-TRU pins. These isotopes are therefore within a significantly harder neutron spectrum than that assumed in the FISPIN calculation. Notably, this will lead to an overestimate in the SN source, which is acceptable as a conservative first approximation.

The assumed burn-up is 40.5 GWd/tiHM for the RMPWR and 62 GWd/tiHM for the RBWR. The reactor residence time is ~4 and 11 years for the RMPWR and RBWR respectively. The RBWR has a very large inventory leading to a low MW/tiHM. The long residence time in this case may lead to unacceptable clad performance (e.g. clad oxidation). 25 recycles were evaluated assuming constant reload enrichment for simplicity. This corresponds to over 200 and 400 years of recycling for the RMPWR and RBWR respectively, including cooling time. This is obviously far longer than is relevant, but it is instructive to observe the full transition to equilibrium.

[9] reported neutron sources at fabrication of around 10^{10} and 10^{11} n/s/tiHM for a fast breeder reactor and a fast TRU incinerator respectively. The build-up in Cf-252 is expected to be markedly more severe in more thermal RM reactors. The SN source shows a similar initial increase in an RMPWR and RBWR (first recycles in Figure 8), as the higher fluence over the RBWR cycle somewhat offsets the lower MA capture cross-sections, but the harder spectrum of

the RBWR results in saturation at a much lower value (~25% after 5 years cooling). In addition, the RBWR TRU fuel content is significantly less (Table II). The U gamma source of a Th-fuelled FR is 40 times greater than the SN source [8], so a significant increase in SN source is needed before it becomes the limiting factor.

The SN source at saturation is high in both cases, but this does not appear to be a relevant factor due to the long time (centuries) required to arrive at saturation (the RMPWR is still not converged). The SN values at fabrication over a realistic number of recycles are substantially larger than for the FR, but still within the range where U-232 is expected to be a larger contributor to shielding requirements.

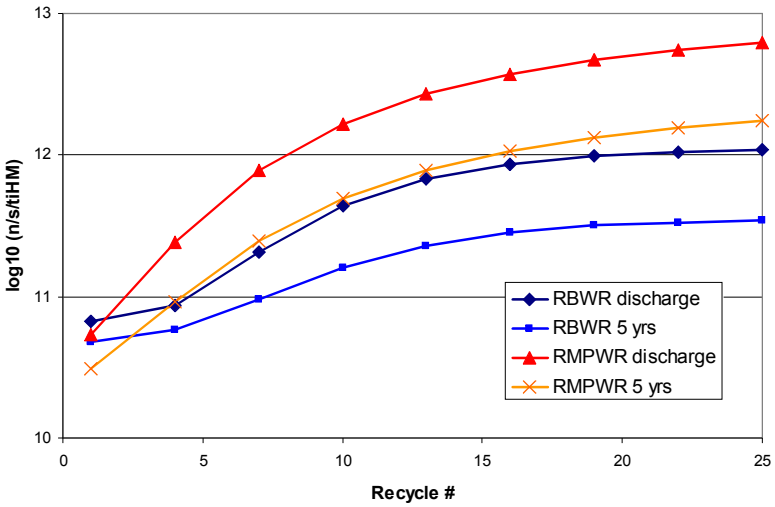

Figure 8: SN source at discharge and 5 years cooling

The U-232 concentration in the U3 is relatively high, which is typical of hard spectrum LWRs [10]. The RMPWR has a higher U-232 ppm in the U3 but a nearly identical ppm in the reactor due to lower U3 enrichment. The population varies little after the first few cycles and equilibrium is essentially reached by the 3rd recycle for the RMPWR and the 8th recycle for the RBWR (Figure 9). The drop in U-232 population for the RBWR is possibly attributable to an observed drop in the Pa-231 population, itself potentially due to a lower Th-232 (n,2n) cross-section in the RBWR compared to the RMPWR, but this requires further investigation.

Decay heat

The build-up of MAs over multiple recycles results in a significant decay heat increase at discharge (although fission products still dominate) and during fuel fabrication. At fabrication, the dominant decay heat contributions come from Pu-238 and Cm-244. There is also a

contribution from Am-241.

In the one-stage RMPWR analysed, the Pu-238 and Cm-244 populations increase with recycle number, while the Am-241 population is approximately constant (Figure 10). Therefore, the decay heat is higher for the equilibrium cycle than the first cycle. In the two-stage RBWR case analysed, the Pu-238 and Cm-244 populations are initially higher due to the impact of the first stage and then remain approximately constant due to the low TRU reload enrichment. By similar mechanisms, the Am-241 population reduces significantly over the first 10 recycles (Figure 10). Therefore, the decay heat is lower at the equilibrium cycle than the first cycle.

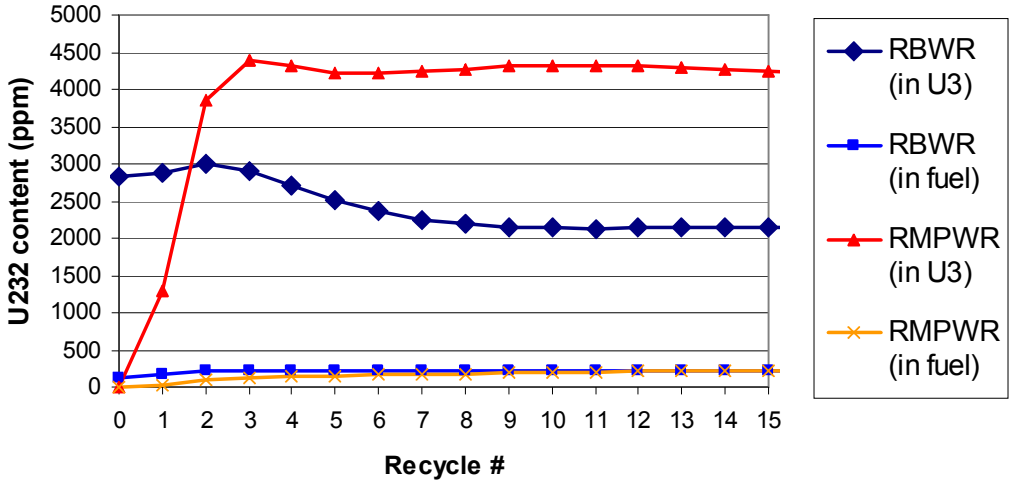

Figure 9: U-232 population after 5 years cooling

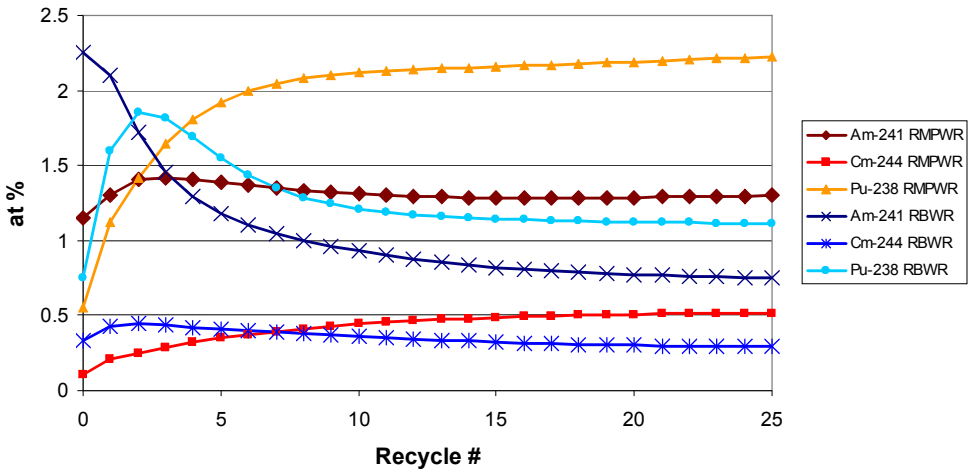

Figure 10: Relative content (at%) at start-of-cycle for the main contributors to actinide decay heat

The result is that the maximum decay heat for both cycles is similar, although it will depend on exactly how the recycle scheme is implemented (Table VI). The concerns from decay heat appear comparable for RMPWRs, RBWRs and FRs operating a similar fuel cycle.

Table VI: Actinide decay heat 5 years after discharge (W/kg)

	Reload proportion	Recycle 1	Recycle 25
RMPWR	50%	14.9	26.3
RBWR multi-tier	26%	32.1	16.9
FR (breakeven)[i]	0%	0.6	3.4
FR (TRU burner)[i]	64%	20.2	42.7

[i] [private communication with C Fiorina, 2012].

CONCLUSIONS

Reduced-moderation LWRs are a potential alternative to fast reactors for full transuranic recycle, with the compelling advantages that the reactor cost is similar to existing plants, the reactor technology is widely established and familiar to utilities and regulators, and the time for deployment can be greatly reduced. On the other hand, reprocessing and manufacturing rates will probably be higher for RM reactors, especially RMPWRs, compared to FRs. Neutronically, Th-232 is a far superior carrier to U-238 for this fuel cycle to the point of making it possibly the only practical option, at least for RMPWRs. However, the Th fuel cycle is much less technically

mature than the U fuel cycle. Industrial reprocessing of Th irradiated fuel needs to be developed and appears more challenging than U-based fuel. Remote handling is required for multiple recycle of Th-232, which is required in any case for MA recycle, but relative amounts vary and are lower in U assuming heterogeneous recycle is acceptable and pursued.

RMPWRs have the advantage of a potentially relatively rapid first-stage implementation and intrinsically low conversion ratios, especially if the reduction in moderation occurs through a larger pin diameter. However, it is challenging to simultaneously satisfy operational and fuel cycle constraints. A homogeneous fuel RMPWR requires a large reduction in moderation, which is not achievable in a retro-fit plant design, and would require a very different core design. In a retro-fit plant, intra-assembly fuel zoning is necessary to achieve an acceptable trade-off, and sufficiently reduced moderation may not be possible without a new plant design.

An RBWR may potentially take longer to implement than an RMPWR as a new plant is required, although much of the design is based on current technology. However, the harder neutron spectrum leads to more favourable fuel cycle performance. Homogeneous, micro-heterogeneous and macro-heterogeneous fuel configurations all have their merits.

A two-stage fuel cycle, where the first pass is Th-Pu MOX, is a technically reasonable implementation for either concept; it would reduce the number of reactors operating in reduced moderation mode, and delay and reduce the amount of fuel to be made remotely. Use of an unmodified PWR is reasonable, giving additional time for the RMPWR or RBWR to be designed and licensed. The first stage of the fuel cycle can therefore be implemented at relatively low cost as a Pu disposal option, maintaining flexibility for introducing a further policy option of full recycle in the medium term utilizing RMPWRs or RBWRs. This is a potential advantage of Th-Pu MOX over U MOX.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of Prof. Paul Smith and the rest of the ANSWERS team at AMEC for providing access and guidance on the use of WIMS and FISPIN. The first author would like to acknowledge the Institution of Mechanical Engineers and the UK Engineering and Physical Sciences Research Council (EPSRC) for providing funding towards this work.

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