Assessment of Deep Burnup Concept Based on Graphite Moderated Gas-Cooled Thermal Reactor

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Abstract

A systematic assessment of the General Atomics (GA) proposed one-pass and two-pass deep-burn concepts based on the modular helium-cooled reactor design (DB-MHR) using non-uranium fuel has been performed. Sensitivity studies are done to investigate the impact of core design parameters and concept on the transmutation performance (maximum of 60% destruction). The repository loading benefits arising from the DB-MHR and LWR Inert Matrix Fuel (IMF) concepts are also estimated and compared (~2.0 and 1.6, respectively).

KEYWORDS: DB-MHR, deep-burn, transmutation, transuranics.

1. Introduction

The continued use of the once-through fuel cycle could lead to substantial increase in the number of geologic repository sites if nuclear power undergoes a significant resurgence. Technically, the repository capacity is determined by decay heat and regulatory limits for the released dose. Removing transuranics (TRU) and some fission products from the disposed material could provide significant benefits for effective repository loading. For the purpose of incinerating plutonium, neptunium, and americium nuclides, the Deep-Burn, Modular Helium-cooled Reactor (DB-MHR) concept has been proposed by General Atomics (GA). [1]

The objective of this study is to investigate the feasibility of this deep-burn transmutation concept by confirming the TRU consumption. A series of parametric and sensitivity studies has been performed to investigate the potential TRU consumption in the deep-burn concepts. These studies include (1) determination of optimum fuel design parameters to maximize the TRU consumption, (2) performance evaluations of the one-pass and two-pass concepts, and (3) estimation of the impacts of various design parameters and fuel management schemes such as initial TRU vector, operating temperature, power level, axial shuffling, etc. In addition, alternative deep-burn designs are introduced in this study.

In Section 2, the deep-burn concepts are briefly summarized. The computational methods are discussed in Section 3. The estimated performance parameters and sensitivity calculation results for the one-pass concept are presented in Section 4. The results for the two-pass concept are discussed in Section 5. The performance of the deep-burn concept is compared to conventional LWR systems employing non-uranium inert matrix (IMF) fuel forms in Section 6. [2] The conclusions of this study are provided in Section 7.

2. Overview of DB-MHR Concepts

The core design of the DB-MHR is based on the GT-MHR and prismatic modular Very High Temperature/Next Generation Nuclear Plant (VHTR/NGNP) designs. [3,4] The essential feature of the DB-MHR transmutation concept is the use of the coated fuel particles (TRISO) that are considered strong and highly resistant to irradiation, and potentially a durable waste form. The TRU material formed into TRISO particles can be irradiated for a long time in a thermal system, and thereby a very high TRU consumption (in particular fissile nuclides) would result. The geometry of the fuel element (i.e., graphite fuel block), and the core height and the annular core design, are identical to those of the VHTR/NGNP. However, the core configuration, fuel management scheme, and fuel kernel size are different in order to enhance the TRU consumption (see Table 1). These changes include the use of 144 fuel columns (versus 102) and a smaller kernel diameter for the reference DB-MHR core (~200 μm versus 425μm). The power density of the DB-MHR is about 30% smaller than that of the VHTR/NGNP because of the increased number of fuel columns with the same thermal power. The specific power density of the DB-MHR is however increased (2.5 to 17 times) due to the use of non-uranium fuel (lower mass) and smaller kernel size and packing fraction.

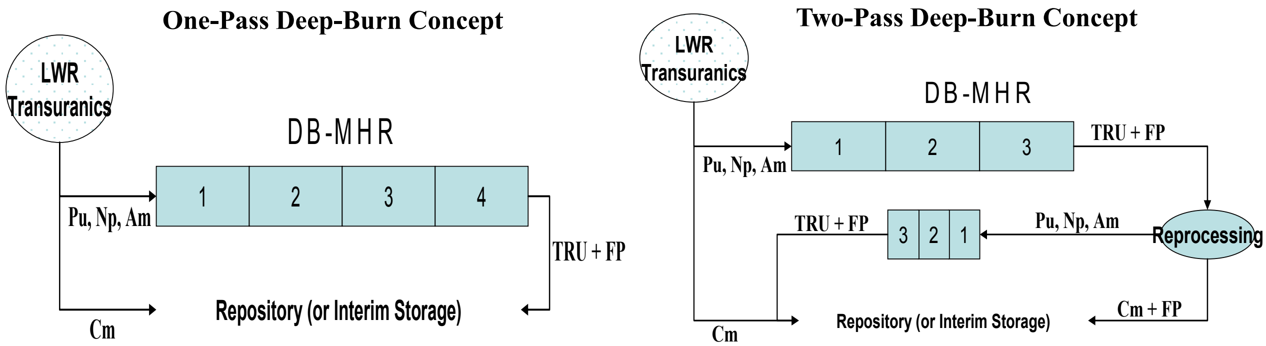
Table 1: Comparison of Design Parameters between DB-MHR and VHTR.

	VHTR (Gas-cooled)	DB-MHR
Core power, MWt	600	600 (or 800)
Number of fuel columns	102	144 (or 162)
Fuel management scheme	2-batch	4- or 3-batch
Core power density, W/cm^3	6.6	4.7 (or 4.2)
Specific power density, W/g	~100	250-1700
Kernel composition	Uranium (14%-U235)	LWR Spent TRU
Packing fraction, %	25	Determined (20%)
Kernel diameter, μm	425	Determined (200μm)

* Element data: Width across flats=36.0 cm; height=79.3 cm; Fuel rod channel OD=1.27 cm; Coolant channel OD=1.5875 cm; Pitch between holes=1.8796 cm; Active core height=793 cm. Average temperatures: Fuel=1273K, Graphite=1073K, Coolant=943K.

Two different approaches proposed by GA have been examined: one-pass and two-pass deep-burn concepts. For both concepts, Pu, Np, and Am isotopes of Light Water Reactor (LWR) spent fuel are fed into the DB-MHR, and Cm isotopes are sent to the repository or interim storage. (Separation of Cm from Am requires advanced elemental separation processes that are currently being developed.) Curium is excluded because it makes fuel fabrication difficult due to its high spontaneous fission rate and decay heat. Figure 1 illustrates the one-pass and two-pass concepts, respectively. In the one-pass concept, the fuel resides in the core for four cycles according to a four-batch fuel management scheme, and then the spent nuclear fuel is sent to the repository. In the two-pass concept, however, the Pu, Np, and Am isotopes discharged from the first pass are recycled into the second pass and only Cm isotopes are sent to the repository. In this latter approach, the total core volume is divided into four zones, and three-fourth are allocated for the first pass (fresh TRU recovered from LWR spent fuel) and one-fourth is allocated for the second pass (recycled TRU from DB-MHR discharge). The two-pass concept utilizes a three-batch scheme, and thus the fuel resides in the core for six cycles in total.

Figure 1: One-Pass and Two-Pass DB-MHR Concepts.



3. Computational Method

The double heterogeneity of DB-MHR fuel elements caused by the use of coated fuel particles is one of the most distinct characteristics that have to be properly treated in neutronics analysis. The choice of an annular core layout makes the neutron leakage into the inner and outer reflectors more important than in traditional light water reactors. To treat the neutron leakage effects properly, whole-core calculations are required. The performance of the DB-MHR concepts were evaluated with whole-core equilibrium cycle analyses using WIMS8/REBUS-3 calculations; burnup-dependent microscopic cross sections were generated from WIMS8 assembly calculations (with explicit particle modeling) and provided for whole-core REBUS-3 calculations. [5,6] In this study, an R-Z core model with finite-difference method was used for generating results for the one-pass concept and a Hex-Z core model with nodal expansion method was used for the two-pass concept.

The actinides from U-233 to Cm-245 were modeled in the REBUS-3 depletion calculations. About 100 fission products are traced in the WIMS8 lattice calculations. Although they can be modeled explicitly in the REBUS-3 calculations, this would be time-consuming because of the large size of the transmutation matrix. A simplified fission product model was used with a few nuclides (Xe-135, I-135, Sm-149, Pm-149 and parent-dependent lumped fission products) that does not degrade the solution accuracy significantly, but reduces the computation time substantially. Thermal feedback was not considered in this study, since this capability is not available in the current version of the REBUS-3 code used for the analysis.

To test the performance of the WIMS8/REBUS-3 coupled calculation procedure, Monte Carlo depletion calculations were also performed using the MONTEBURNS code. [7] This study indicated that the WIMS8/REBUS-3 methodology is applicable to the DB-MHR core analysis.

4. One-Pass Deep-Burn Transmutation

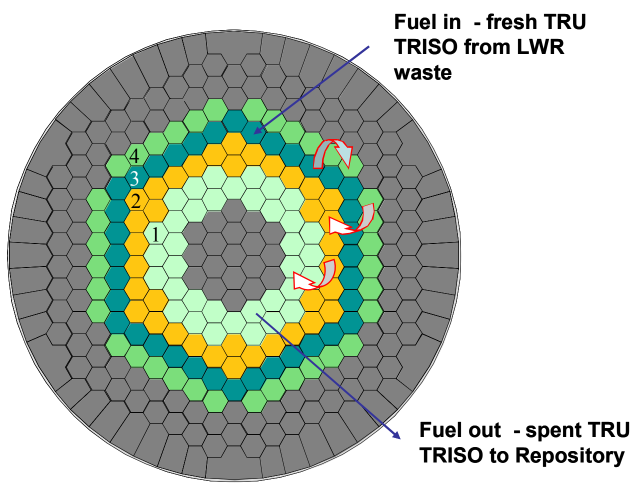
4.1 Fuel Shuffling in One-Pass DB-MHR

In the one-pass deep-burn concept, the active core is divided radially into four regions, each of which is composed of 36 fuel columns (see Fig. 2). Fresh TRU fuel is loaded into region 3 (dark green color), and moved sequentially into region 4 (green), region 2 (yellow), and region 1 (light-green) in the subsequent cycles. In this fuel management scheme, loading of fresh fuel near the inner and outer reflectors is avoided, to prevent excessive power peaking at the interface between the graphite reflectors and fuel blocks. An axial shuffling was additionally proposed to deplete TRU more effectively by achieving a flatter discharge burnup distribution. Consider a fuel column containing 10 blocks stacked axially. At each re-fueling, the fuel blocks located in the middle of the core are shuffled with those at the top and bottom of the core. Based on this axial shuffling strategy, the 5th and 6th axial fuel blocks are interchanged with the 1st and 10th axial fuel blocks, respectively, and the 4th and 7th axial fuel blocks are interchanged with the 2nd and 9th axial fuel blocks, respectively. The 3rd and 8th axial fuel blocks are not moved.

4.2 Optimum Fuel Data for DB-MHR Fuel

To determine the optimum fuel kernel size and packing fraction, whole-core depletion calculations were performed for a fuel design domain in which the kernel diameter and packing fraction are 150 μm to 300 μm and 15 % to 30 %, respectively. The ranges were selected based on initial scoping studies performed for the DB-MHR fuel element.

Figure 2: Radial Shuffling Scheme for One-Pass Deep-Burn Concept.



In Fig. 3 are displayed the TRU consumption (ΔM/M) and cycle length of the one-pass DB-MHR core as functions of the fuel-to-moderator ratio, obtained by varying the kernel size and packing fraction. Both the TRU consumption and the cycle length increase initially, attain peak values and then decrease. This trend is similar to the one observed for the multiplication factor (k-effective) at the beginning of cycle. As the fuel-to-moderator ratio (N_{TRU}/N_C) increases, the k-effective (burnup) increases, because of more fuel in the system (at the limit of zero fuel, the k-effective is zero). At higher fuel fraction, resonance capture becomes important and the k-effective (burnup) reaches a maximum and starts to decrease with further increase in fuel loading. The different curves for the cycle length and the burnup or TRU consumption (transmutation rate) are due to the different dependencies of the burnup and cycle length on the fuel mass.

It is attractive to choose the fuel-to-moderator ratio that maximizes the TRU consumption and the cycle length; but they correspond to different values. Since the primary purpose of the deep-burn concept is to transmute the LWR spent TRU, the fuel-to-moderator ratio corresponding to the maximum TRU consumption was selected (i.e., 0.00034). The kernel diameter and packing fraction corresponding to this ratio are 200 μm and 20%, respectively.

Figure 3: DB-MHR Performance as Function of Fuel-to-Moderator Ratio.

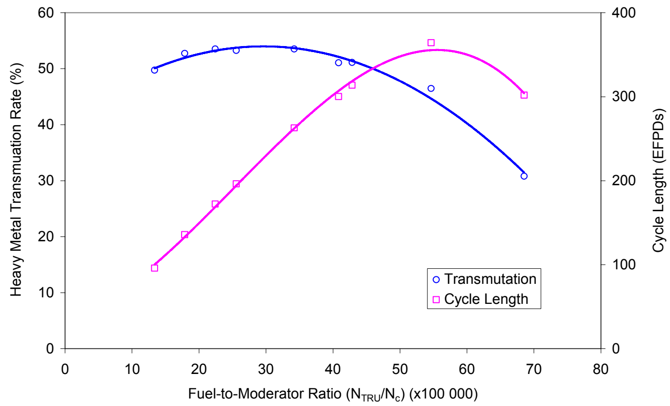


Table 2: Performance of 600 MWt One-Pass DB-MHR.

		Charge (by Region)				Discharge	Consumption (%)
		3	4	2	1		
Mass (kg)	Np-237	13.75	11.51	9.48	7.73	6.20	-54.9
	Np-239	0.00	0.00	0.00	0.00	0.00	
	Pu-238	3.99	8.70	14.58	18.84	20.33	409.1
	Pu-239	152.63	86.52	33.97	13.48	4.84	-96.8
	Pu-240	62.24	56.65	49.21	31.68	18.20	-70.8
	Pu-241	22.65	37.48	36.28	33.43	21.02	-7.2
	Pu-242	14.80	17.60	23.46	28.16	33.49	126.2
	Am-241	24.60	15.99	9.16	5.33	2.71	-89.0
	Am-242^m	0.09	0.38	0.21	0.13	0.05	-40.1
	Am-243	4.52	5.63	6.78	8.12	9.19	103.1
	Cm-242	0.00	4.11	4.64	3.52	2.54	
	Cm-243	0.00	0.05	0.11	0.14	0.13	
	Cm-244	0.00	1.47	2.88	4.57	6.06	
	Cm-245	0.00	0.07	0.19	0.37	0.43	
	Pu	256.3	206.9	157.5	125.6	97.9	-61.8
	HM	299.3	246.2	191.1	155.7	125.5	-58.1
Burnup (GWd/t)		0.0	167.4	340.7	451.6	546.1	
Power sharing (PS)		1.23	1.27	0.81	0.69		
Consumption (%)		-17.8	-18.4	-11.8	-10.1		

4.3 Performance of One-Pass DB-MHR Concept

Table 2 is a summary of the transmutation performance of the one-pass DB-MHR. In this table, the TRU consumption is defined as $(M-M_o)/M_o$, where M and M_o denote the discharged and charged masses, respectively. Thus, a negative value denotes consumption of the nuclide, while a positive value indicates net production of the nuclide. The discharge burnup of the one-pass DB-MHR is 546 GWd/t and the corresponding cycle length is 286 days (< 10 months). The initial fresh TRU mass is 299 kg and the discharge mass is about 126 kg. This indicates that the overall TRU consumption of the total heavy metal is 58%. The consumption of plutonium is 62%, including 97% Pu-239 depletion. About 55% of the Np-237 is destroyed in the

DB-MHR core. Regarding the power sharing (PS), the power in regions 3 and 4 is greater than the core average value while regions 2 and 1 are at lower power. This results in high power peaking factors in region 3 or 4. In particular, the power sharing of region 4 is greater than that of region 3 even though the region average burnup is higher. This effect is caused by the reflection of thermal neutrons to the outer region 4. At the bottom of Table 2, the regional TRU consumptions are provided. Generally, the regional TRU consumptions are proportional to the power sharing.

4.4 Sensitivity Studies on Core Parameters

The impacts of variation in the power, axial shuffling approach, initial TRU vector, and operating temperature on TRU consumption in the one-pass concept have been evaluated and are compared to that of the reference case discussed in Section 4.3; results are summarized below.

4.4.1 Impact of Power Level on DB-MHR TRU Consumption

The power density of the DB-MHR is significantly smaller than that of the VHTR/NGNP. The small power density will obviously have an adverse effect on plant economics. To obtain a similar power density as the GT-MHR, the power level of the DB-MHR was increased to 800 MWt and its performance was evaluated. All other data were retained.

Because of the higher specific power, the cycle length decreased to 222 days (compared to 286 days for the 600 MWt core). The discharge burnup of the 800 MWt core is, however, slightly increased compared to that of the 600 MWt core (561 GWd/t versus 546 GWd/t). This is because the higher power density (higher flux level) reduces the decay-to-fission rate ratio of Pu-241. Note that the Pu-241 decays to a neutron absorber, and the presence of this absorber reduces core reactivity over the irradiation time and hence the discharge burnup. Thus, the overall performance of the 800 MWt core is slightly better than for the 600 MWt core due to its higher discharge burnup; the TRU consumption is 60.1%.

4.4.2 Axial Shuffling Effect

The use of axial shuffling in the one-pass deep-burn concept was proposed for improved TRU consumption. However, axial shuffling might require increased effort during reloading because of its complexity. The effect of no axial shuffling on the DB-MHR performance has been evaluated in this study. The axial burnup distribution of the non-axial shuffling case is cosine shaped because neutron leakage at the top and bottom of the core reduces the power sharing at those locations. However, the axial burnup distribution of the axial shuffling case is depressed at the core center and the discharge burnup distribution is relatively flatter than that of the non-axial shuffling case. This flatter burnup distribution results in a higher discharge burnup and the TRU consumption for the case using axial shuffling is higher by about 0.9%. This trend is likely due to the effective utilization of all the fuel in the core (including the peripheral one) in the case with axial shuffling, which tends to increase the effective core reactivity. Conversely, however, the axial shuffling scheme increases the peak power. Since the fuel elements with low burnup are shuffled to the center of region 4, the axial power shape of the axial shuffling case is more skewed to the core center compared to the no-axial shuffling case.

4.4.3 Initial TRU Vector Effect

The impact of the initial TRU vector on the transmutation performance was evaluated. The reference calculation was done with a TRU vector obtained from GA (the pedigree of which is unknown); assessments indicated that the burnup is slightly greater than 33 GWd/t and the cooling time is slightly shorter than 20 years. The TRU vectors derived from the spent fuel of commercial PWR with medium burnup (33 GWd/t), cooled for 5 and 20 years (post-irradiation), were also considered in the study.

Because of a higher fissile content, the cycle length and the discharge burnup of the medium burnup case with 5-year cooling are higher (327 days and 628 GWd/t) than for the reference case, and the corresponding TRU consumption is 67%. The overall performance of the medium burnup case with 20-year cooling is however similar to that using the original TRU vector because of similar initial fissile content. The nuclide consumptions for the cases using the original TRU and the 20-year cooled TRU vector are quite similar except for Pu-241. The Pu-241 consumption is sensitive to its initial mass fraction in the TRU fuel. The Pu-241 mass produced from the (n,γ) reaction of Pu-240 are similar because both cores have similar spectrum and initial Pu-240 content. However, due to the high initial content of Pu-241 (7.57% versus 4.84%), the consumed Pu-241 mass (via decay and neutron absorption) in the reference case is higher than that of the case with 20-year cooling. Thus, the net mass Pu-241 change (i.e., production minus destruction) of the reference case becomes negative while it is positive in the 20-year cooling case. The produced Pu-241 mass decreases with increasing burnup because its precursors (i.e., Pu-240 & Pu-239) are depleted. Therefore, the consumption of Pu-241 becomes more negative for the case with 5-year cooling, due to its higher discharge burnup.

4.4.4 Operating Temperature Effect

The high operating temperature of the VHTR/NGNP ensures a higher plant efficiency than for LWRs (~47% compared to ~33%). High operating temperature is also attractive for hydrogen production, as is currently being considered for the NGNP. However, higher temperature typically implies a lower core reactivity state because of increased resonance absorption. This tends to reduce the core cycle length as the temperature is elevated. The temperature reactivity defect of the DB-MHR core was evaluated to be ~5%Δk, indicating that the DB-MHR core could have a longer cycle length (or higher TRU consumption) by decreasing the operating temperature. In addition, the core would gain operational safety margin because of the larger difference between the operating fuel temperature and the limiting fuel temperature; of course plant thermal efficiency would be degraded. To evaluate the performance of the low operating temperature core, the overall temperatures of the DB-MHR core were reduced by 200 K; thus, the temperatures of fuel, graphite and coolant are 1073, 873, and 743 K, respectively.

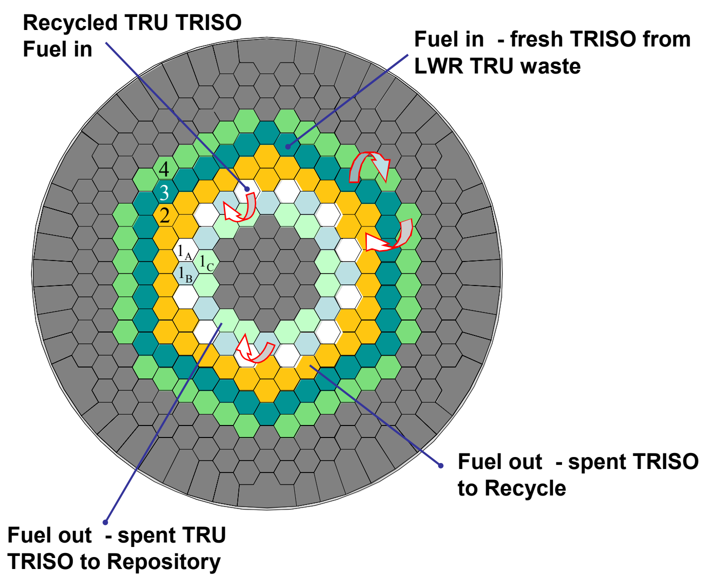
The cycle length and the corresponding discharge burnup increased to 312 days and 598 GWd/t. The TRU consumption also increased by ~ 5% (63.4 % versus 58.1 %).

5. Two-Pass Deep-Burn Transmutation

5.1 External Fuel Cycle and Fuel Shuffling in Two-Pass DB-MHR

The two-pass deep-burn concept has been proposed to increase the fuel consumption by significantly increasing the fuel residence time. The increased residence time is obtained by reprocessing the remnant TRU fuel (except for curium) from the first pass and reloading it in the core. The radial shuffling scheme for the two-pass deep-burn concept is illustrated in Fig. 4. The active core is divided into four zones similarly to the one-pass DB-MHR core. Three of the zones (regions 2, 3, and 4) are allocated for the first pass and one zone (region 1) for the second pass. Thus, the volume of the second pass is one-third of the first pass. The second pass zone is also divided into three sub-zones (i.e., regions 1A, 1B, and 1C). Based on this zoning structure of the active core, the two-pass deep-burn concept utilizes a three-batch fuel management scheme. In the first pass, the fresh TRU is loaded into region 3, and shuffled to regions 4 and 2, and then the fuel is discharged. After five-year cooling, the Pu, Np and Am are extracted in the reprocessing plant and delivered to the fabrication plant. The fission products and Cm are sent to the repository. After an additional 2-year cooling, the TRU is reloaded into the region 1A and then sequentially shuffled to regions 1B and 1C. The discharged fuel from the second pass is sent to the repository. A hexagonal-Z core model was developed for REBUS-3 depletion calculations.

Figure 4: Radial Shuffling Scheme for Two-Pass Concept.



In this study, the packing fraction of the first pass was fixed as 20% and the kernel diameters of the first and second passes were fixed as 200 μm. The packing fraction of the second pass was determined by preserving the TRU mass that remains following the reprocessing of the spent fuel TRU from the first pass. Based on this study, the packing fraction of the second pass was determined to be 29.7%.

5.2 Performance of Two-Pass DB-MHR

The heavy metal mass flow of the equilibrium two-pass DB-MHR core is summarized in Table 3. The cycle length and discharge burnup of the two-pass DB-MHR core are 267 days and 580 GWd/t, respectively (compared with 286 days and 546 GWd/t of the one-pass concept). A longer cycle length was expected in the two-pass concept because the fission products are removed from the second pass fuel. However, the cycle length of the two-pass concept is shorter than that of the one-pass DB-MHR. The reason for this behavior is the fissile-depleted composition of the second-pass fuel form. Compared to previous calculations by GA, this fissile depletion is exacerbated by the cooling interval between the discharge from the first pass and the charge of the second pass. The primary fissile nuclide in the second pass fuel is Pu-241 (because about 90% Pu-239 are destroyed in the first pass), but the content is significantly reduced during

7-year cooling time ($t_{½}$ = 14.4 years); in Table 3, the discharged Pu-241 mass is 33.1 kg (not shown), but decreases to 22.8 kg after 7-year cooling.

Because the cycle length decreases for the two-pass concept, the discharge burnup is also reduced. The total residence time of TRU in the two-pass DB-MHR core is much longer than that in the one-pass DB-MHR core (267×6 days versus 285×4 days), but the discharge burnup is not increased because the core uses a larger TRU mass than the one-pass core (30% higher).

The charge fresh TRU mass is 299 kg and the discharge TRU mass from the second pass is 136 kg, including 6.3 kg of Cm from the first pass. Thus, the overall TRU consumption is 55%.

Table 3: Mass Flow of Two-Pass DB-MHR (kg).

Nuclide	First pass (Fresh TRU)			Second pass (Reloaded TRU)				Consum (%)
	Charge mass (by Region)			Charge mass (By Region)			Discharge Mass	
	3	4	2	1A	1B	1C		
Np-237	13.7	11.5	9.3	7.8	7.1	6.5	6.0	-57
Pu-238	4.0	8.7	14.6	21.1	21.7	23.0	24.0	433
Pu-239	152.4	83.5	31.3	15.2	11.6	8.8	6.9	-96
Pu-240	62.2	56.4	47.9	34.2	28.4	23.7	20.6	-67
Pu-241	22.6	37.8	35.9	22.8	23.1	21.8	19.2	23
Pu-242	14.8	17.9	24.0	28.0	28.0	28.2	28.6	87
Am-241	24.6	15.6	8.6	14.6	11.8	9.6	8.0	-87
Am-243	4.5	5.6	6.9	8.5	9.4	10.2	10.6	127
Pu	256.0	204.3	153.6	121.3	112.8	105.5	99.3	-59
TRU	298.9	243.4	186.9	152.7	144.8	137.1	130.1	-55
PS (BOC/EOC)	0.33/0.35	0.39/0.30	0.16/0.18	0.04/0.06	0.04/0.06	0.04/0.05		
Burnup (GWd/t)	175	353	441	490	537	580		
TRU Cons. (%)	-18.6	-18.9	-9.4	-5.2	-5.0	-4.6		

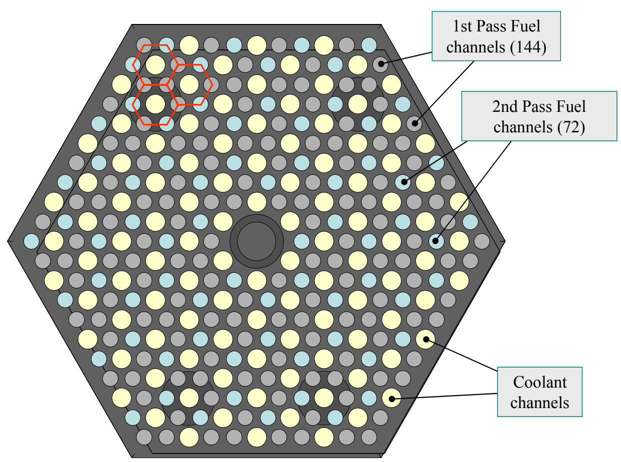
In order to understand the reason for the lower TRU consumption of the two-pass concept relative to the one-pass concept, a case with a zero cooling period between the first and second passes in the two-pass scheme was evaluated. In the study, the fuel data for the first and second passes were identical to those used for the reference two-pass case. For this zero-cooling period case, the cycle length and discharge burnup increased to 312 days and 716 GWd/t, respectively (compared to 267 days and 580 GWd/t for the 7-year cooling case). The high discharge burnup increases the TRU consumption of the first and second passes (50% and 26%, respectively). Consequently, the total TRU consumption is increased to 63.1% (compared to 55% for the 7-year cooling case). The primary reason of the high discharge burnup of the zero-cooling case is the relatively high Pu-241 content in the second pass fuel. The initial Pu-241 mass of the second pass fuel is 22.8 kg in the 7-year cooling case (see Table 3), but becomes 30.9 kg without cooling time. The high Pu-241 content of the second pass increases the power sharing and TRU consumption. The result indicates that the Pu-241 content of the second pass fuel plays an important role in improving the performance of the two-pass concept. However, due to its short half-life, the Pu-241 content is significantly deceased after 7-year cooling, and therefore the performance of the two-pass concept cannot be improved significantly with a reasonable cooling interval.

The use of a cylindrical core design (no inner graphite reflector zone) was also investigated. The same external fuel cycle and fuel management scheme of the original two-pass concept was utilized in the cylindrical DB-MHR core: i.e., 7-year cooling and 3-batch scheme. It was found that this configuration increased the power sharing in the inner region 1A by 3% (due to significantly lower leakage), resulting in increases in the cycle length and discharge burnup of the cylindrical core to 286 days and 630 GWd/t, respectively, compared to 267 days and 580 GWd/t of the original two-pass concept. TRU consumption was increased by 3%.

5.3 Heterogeneous Element in Two-Pass Concept

Because the transmutation performance of the two-pass concept using a homogeneous assembly is smaller than expected, a two-pass concept that flattens the power sharing between the passes was considered to investigate its impact on TRU consumption. This was done using a heterogeneous fuel element design. Figure 5 shows the heterogeneous fuel element, which consists of the first pass and the second pass fuels. The kernel size and packing fractions of both fuels were assumed to be same (i.e., 200 μm and 20%, respectively), but the number of fuel rods for the first and second passes are adjusted to ensure mass balance between the first and second passes. In this study, there are assumed to be 144 and 72 fuel rods containing the first and second pass fuels, respectively, in the fuel element.

Figure 5: Heterogeneous Fuel Element for Two-Pass DB-MHR.



The in-core fuel management scheme of the two-pass DB-MHR core using the heterogeneous fuel elements is identical to that for the one-pass DB-MHR core. A four-batch fuel management scheme is utilized and the radial and axial shuffling scheme used in the one-pass concept is employed for this core. Similarly to the other two-pass cores, the discharged first pass TRU is recycled in the second pass (except for the fission products and Cm) and the discharged second pass fuel is sent to the repository. A 7-year cooling time is also utilized in this concept. Because the second pass fuel exists with the first pass fuel in the same fuel element, the power sharing of the second pass is improved compared to the original two-pass DB-MHR core. Results indicated that the TRU consumption in the first pass is comparable to that for the other two-pass concepts. However, the TRU consumption in the second pass is much improved compared to the original two-pass DB-MHR core (30% versus 15%) because of the flat power sharing in the core; this is presumably because effective power sharing results in additional core reactivity over a core cycle. The overall TRU consumption of this core is 62.4%, which is about 8 % higher than that of the original two-pass DB-MHR core.

6. Comparison of DB-MHR and Conventional LWR IMF Concepts

The use of inert matrix fuel (IMF) has been considered for the transmutation of TRU in LWRs. This concept is very similar to that of the DB-MHR concepts because non-uranium fuels are utilized. The primary differences are the reactor type and the fuel form; the LWR IMF concept uses a LWR core and an inert-matrix (oxide solid solution) fuel. For a comparison of performance of the two systems, the LWR IMF concept has been evaluated using the same initial TRU vector utilized in the DB-MHR. It is noted that this is purely a neutronic comparison that has not evaluated the feasibility of the systems from a safety viewpoint. The specific power density of the DB-MHR core is about 670 W/g, while that for the LWR IMF concept is 360 W/g.

It was found that the discharge burnup of the DB-MHR core is very close to that of the IMF core (546 GWd/t versus 545 GWd/t), but the TRU consumption of the DB-MHR core is slightly higher than that of the IMF concept. This slightly higher TRU consumption (for about the same burnup) is attributed to the differences in contributions to fission from the nuclides during fuel irradiation and the resulting difference in energy released per fission (different for each nuclide). Furthermore, the higher thermal efficiency of the DB-MHR improves the energy generation for a given thermal energy production, resulting in a significant improvement in the repository benefit (1.6 to 2.0).

7. Conclusions

The TRU consumption in the one-pass and two-pass DB-MHR concepts proposed by General Atomics have been evaluated. The reference one-pass deep-burn core is a 600 MWt annular core with a power density of 4.7 MW/m^3. The estimated TRU consumption is 58% when an initial TRU vector having a fissile content of 58.6% is used. Using a power level of 800 MWt increased the TRU consumption to 60%. Additional sensitivity studies showed that the TRU consumption can be improved either by utilizing axial shuffling or decreasing the operating temperature. It was also observed that the transmutation performance is sensitive to the initial TRU vector; for a high-fissile-fraction (63%) TRU vector recovered from a medium-burnup (33.0 GWd/t) LWR fuel after 5-year cooling, the TRU consumption increased to 67%.

In the two-pass DB-MHR concept, the estimated TRU consumption of the two-pass DB-MHR was comparable to that of the one-pass DB-MHR, because of Pu-241 decay during the time lag between the first and second passes. It was found to be 54.7%, but increased to 63.1% when the time lag was neglected. An alternative cylindrical core design, which reduces the neutron leakage from the active core, gave a slightly improved TRU consumption (58.1 % versus 54.7%). Additionally, using a heterogeneous fuel element composed of the first and second pass fuels improved the TRU consumption to 62%, because of a flatter power sharing between the passes.

The repository loading benefits of the deep-burn and Inert Matrix Fuel (IMF) concepts were compared using the same initial TRU vector. The DB-MHR core gives a slightly better TRU consumption and repository loading benefit compared to the IMF concept (58.1% versus 55.1% for TRU consumption and 2.0 versus 1.6 for repository benefit). Whereas IMF has only been proposed for partial LWR cores, DB-MHR cores completely fueled with transuranics are considered possible.

Finally, this study has been focused on the transmutation performance of the DB-MHR. Future studies should be devoted to (1) use of burnable poison for controlling the burnup reactivity swing and reactivity coefficients and its penalty on performance, (2) reactor performance, (3) thermal performance and (4) transient behavior of the system. Additionally, the self-cleaning concept recently proposed by GA, in which low-enriched uranium fuel is used to extend the TRU burnup (increase destruction), should be evaluated in order to quantify its benefits, as well as the possibility of using the spent DB-MHR fuel as feed fuel for an advanced burner fast reactor.

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