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Multiple recycling of fuel in prototype fast breeder reactor in a closed fuel cycle with pressurized heavy-water reactor external feed

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Abstract. A fast breeder reactor (FBR) closed fuel cycle involves recycling of the discharged fuel, after reprocessing and refabrication, in order to utilize the unburnt fuel and the bred fissile material. Our previous study in this regard for the prototype fast breeder reactor (PFBR) indicated the possibility of multiple recycling with self-sufficiency. It was found that the change in Pu composition becomes negligible (less than 1%) after a few cycles. The core-1 Pu increases by 3% from the beginning of cycle-0 to that of recycle-1, the Pu increase from the beginning of the 9th cycle to that of the 10th by only 0.3%. In this work, the possibility of multiple recycling of PFBR fuel with external plutonium feed from pressurized heavy-water reactor (PHWR) is examined. Modified in-core cooling and reprocessing periods are considered. The impact of multiple recycling on PFBR core physics parameters due to the changes in the fuel composition has been brought out. Instead of separate recovery considered for the core and axial blankets in the earlier studies, combined fuel recovery is considered in this study. With these modifications and also with PHWR Pu as external feed, the study on PFBR fuel recycling is repeated. It is observed that the core-1 initial Pu inventory increases by 3.5% from cycle-0 to that of recycle-1, the Pu increase from the beginning of the 9th cycle to that of the 10th is only 0.35%. A comparison of the studies done with different external plutonium options viz., PHWR and PFBR radial blanket has also been made.

Keywords. Fast breeder reactors; closed fuel cycle; fuel production and depletion; Pu^{239} equivalence; multiple recycling; fuel reactivity effects.

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1. Introduction

A study on the possibility of multiple recycling of fuel in the Indian prototype fast breeder reactor (PFBR) was done recently [1]. Fuel compositions were estimated for 10 refueling cycles involving cooling, fuel recovery and refabrication, by taking into account the mandatory requirements on fuel quality and mass. The concept of Pu^{239} reactivity equivalence was used to assess its quality [2]. The nuclide evolution computations were performed using the code ORIGEN2 [3]. With efficient fuel recovery ($\sim$99%) assumed, the study showed the possibility of multiple recycling with self-sufficiency. It was found that the variation in Pu composition becomes negligible from 6th recycle onwards. In a subsequent study [4], more refined estimations were carried out with (i) PFBR reactor spectrum-averaged self-shielded one-group cross-sections from ENDF/B-VII.0 [5], (ii) burn-up-dependent cross-sections modified to suit PFBR, (iii) uranium recovery and (iv) present PFBR beginning-of-life inventory [6]. While self-shielded averages lead to realistic predictions, unshielded averages significantly overpredict breeding in the blankets and underpredict loss in the cores. The unshielded averages overpredict Pu production in the (axial and radial) blankets by a factor of 2 compared to the self-shielded averages. Plutonium bred in the blankets was about 1.5 times more than that required to make up for the depletion in the cores.

In the earlier studies, plutonium bred in (axial and radial) blankets was considered as the external plutonium feed, for compensating the plutonium loss due to burn-up in the core. In this study, the external plutonium feed is from the Indian pressurized heavy-water reactors (PHWRs). As the qualities of plutonium bred in PFBR blankets and that produced in PHWR are different, percentage addition in each fuel recycle is different. This study aims at finding the feasibility of multiple recycling of PFBR fuel with external plutonium feed from PHWR. The following modifications are also included in the present calculations.

(i) The cooling period of the irradiated fuel subassembly (SA) at the storage location of PFBR is increased from 240 to 480 days. This modification is necessitated from the fuel handling aspects.
(ii) The reprocessing period is extended from 120 to 240 days.
(iii) In the earlier study, it was assumed that, while reprocessing the spent fuel, the unburnt fuel (U and Pu) remaining in the core region alone is processed separately and recovered. But in the actual scenario, the fuel in the axial blanket region is reprocessed together with the fuel in the core region and, U and Pu are recovered. So, the plutonium bred in axial blankets mixes with the core plutonium.

This paper discusses the results of this improved analysis on the multiple fuel recycling in PFBR.

2. Revised calculations for recycling

2.1 *Sequence of operations in one cycle*

Prototype fast breeder reactor (PFBR) is a 500 MWe pool-type mixed oxide fueled fast breeder reactor having liquid sodium as the coolant and boron carbide as the control material. The fuel consists of PuO_2 and UO_2 in two zones of enrichment, inner core (core-1) having fuel in the ratio 20.7 : 79.3 and the outer core (core-2) in the ratio 27.7 : 72.3. The beginning-of-life (BOL) (fractional) composition of PFBR fuel in the cores and blankets are given in table 1. BOL corresponds to the initial start-up of PFBR. A schematic view of the important regions of PFBR, along with the number of SA in each region, are given in figure 1. Plutonium for PFBR is obtained from PHWR discharge.

In a cycle, core-1 SA of PFBR undergoes irradiation up to an average burnup of 70 GWd/t, which corresponds to an irradiation time of 540 full power days (fpd) at a specific power of about 130 MW/t. Similarly, the core-2 SA undergoes irradiation for 540 fpd at a specific power of about 120 MW/t and reaches an average burnup of ∼65 GWd/t. Before discharge, the SA is given an in-core cooling at the storage location for 480 calendar days. A period of 240 calendar days for reprocessing and 120 calendar days for refabrication and reloading are considered in this study. The sequence of operation for one cycle is schematically shown in figure 2.

2.2 *Method for estimating the BOC composition*

During irradiation of the fuel, the relative isotopic composition of Pu changes, leading to a decrease in reactivity worth per unit mass of Pu. To compensate the reactivity worth reduction, Pu enrichment is increased in subsequent recycles. The basis for arriving at the enrichment is that the reactivity worth of the refabricated fuel has to be the same as that of the BOL fuel. The concept of 'Pu^{239} equivalence' method is used to compute the total worth of fuel for the next cycle, given its composition. However, in the present calculations, Pu^{239} equivalence of U fuel is not considered and the total mass of the fuel (U+Pu) is kept constant by decreasing the mass of U in the refabricated fuel.

The Pu^{239} equivalences of the nuclides relevant for this study are given in table 2. To illustrate the change in composition during one cycle, the composition of (i) BOL plutonium vector, (ii) plutonium vector of the spent fuel of the core region and (iii) the

Table 1. Initial (BOL) fuel composition in different regions.

	Inventory (kg)						
	Core-1			Core-2			
Nuclide	Core	LAB	UAB	Core	LAB	UAB	RB
U^{234}	3.96E-3	4.99E-3	4.99E-3	3.61E-3	4.99E-3	4.99E-3	5.00E-3
U^{235}	0.20	0.25	0.25	0.18	0.25	0.25	0.25
U^{236}	5.55E-2	7.00E-2	7.00E-2	5.06E-2	7.00E-2	7.00E-2	7.00E-2
U^{238}	79.04	99.67	99.67	72.04	99.67	99.67	99.68
U-total	79.30	100.00	100.00	72.28	100.00	100.00	100.00
Pu^{238}	2.07E-2			2.77E-2			
Pu^{239}	14.24			19.07			
Pu^{240}	5.09			6.82			
Pu^{241}	1.04			1.39			
Pu^{242}	0.25			0.33			
Am^{241}	6.21E-2			8.32E-2			
Pu-total	20.70			27.72			
Net	100.00	100.00	100.00	100.00	100.00	100.00	100.00

LAB: lower axial blanket; UAB: upper axial blanket; RB: radial blanket.

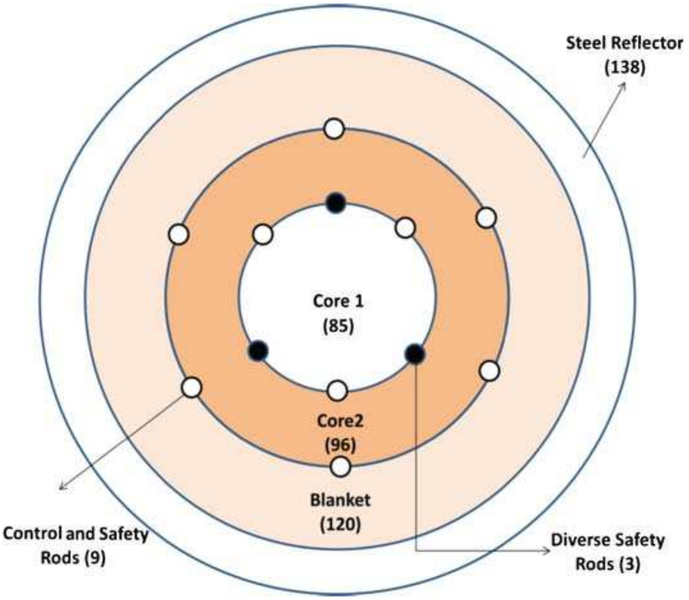
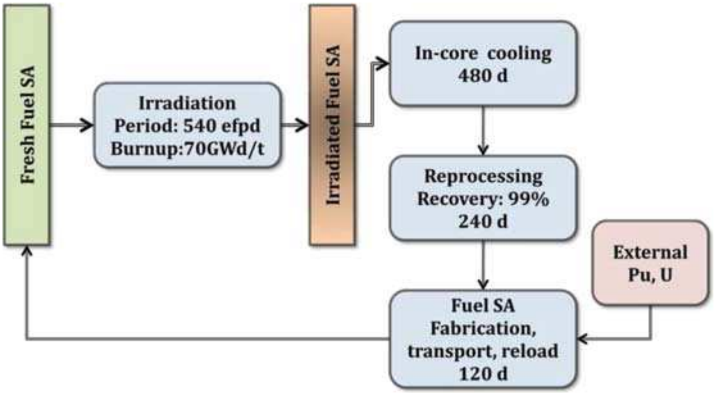


Figure 1. Schematic of PFBR homogenized radial core configuration.

plutonium vector of the spent fuel in the core region and the axial blanket taken together are given for cycle-0 in table 3. Pu^{239} equivalence % computed for these three cases are given in the last column of table 3.

It can be seen from the table that, due to higher production of fertile components (Pu^{240} and Pu^{242}) during irradiation, Case (ii) has the lowest reactivity worth compared to



Irradiation Period	In-core Storage	Reprocessing	Fabrication and Reload
720 d (540 efpd)	480 d	240 d	120 d

Figure 2. Flow chart of the fuel cycle for a fuel subassembly.

Table 2. Pu^{239} equivalences for PFBR.

Nuclide	Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}	Am^{241}
Pu^{239} Equivalence	0.58	1.0	0.1	1.5	0.04	−0.24

Table 3. Pu composition.

Case	Nuclide	Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}	Am^{241}	Pu^{239} eq. %†
(i)	Fresh core (BOL)*	0.10	68.80	24.60	5.00	1.20	0.30	78.79
(ii)	Spent fuel-core	0.21	64.79	28.96	4.38	1.59	0.07	74.42
(iii)	Spent fuel (core + axial)	0.20	67.17	27.05	4.05	1.47	0.06	76.11

*PFBR initial Pu from PHWR discharge. †Pu^{239} equivalence.

other cases. However, compared to Case (ii), the reactivity worth of Case (iii) is slightly improved due to the presence of higher quality Pu from axial blankets. In a kilogram of depleted uranium loaded in axial blankets, about 25.6 g and 18.1 g of plutonium are bred in core-1 and -2 axial blankets, respectively. This Pu has more than 95% of fissile component. This higher grade plutonium mixes with the unburnt plutonium remaining in the spent fuel core region and hence the reactivity worth of Case (iii) is better than Case (ii).

In the earlier study, spent fuel from the core (Case (ii)) was recycled with the external feed from PFBR blankets. In the present study, Case (iii) Pu is considered for recycling. For refabrication, the Pu lost in a cycle is compensated for, from that produced in PHWR taking care to conserve fuel worth as at BOL. This results in increased Pu inventory requirement at every BOC, as the fissile component needs to be marginally increased in each cycle to compensate for the reactivity reduction due to accumulation of non-fissile Pu nuclides viz., Pu^{240} and Pu^{242}.

The inventories of fuel recovered (calculated using ORIGEN-2), fuel lost during a cycle and the external feed required are estimated for core-1 and -2 for every recycle. The computational procedure followed in this study is similar to that followed in [1,2].

3. Results and discussions

In the previous study, multiple recycling of PFBR fuel showed the possibility of recycling with the high-quality plutonium from PFBR blankets as external feed. Compared to the radial blanket-bred Pu, the quality of PHWR plutonium is low, which might have an impact on recycling study. The following discussions bring out the salient observations made:

The estimated BOC inventories for all the 10 cycles are presented in tables 4 and 5 for core-1 and -2, respectively. In tables, recycle number ‘0’ indicates the BOL composition and 1–10 indicate the refabricated fuel composition for each BOC. The results are normalized to the total BOC inventory of 1000 kg (BOL inventory for cycle ‘0’).

Table 4. BOC fuel composition for core-1 per 1000 kg of fuel: PHWR external Pu feed.

	Inventory (kg) against recycle number										
Nuclide	0	1	2	3	4	5	6	7	8	9	10
Pu^{238}	0.21	0.41	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.51	0.51
Pu^{239}	142.45	143.92	143.79	143.11	142.47	141.56	140.89	140.36	139.93	139.58	139.35
Pu^{240}	50.94	57.74	63.12	67.34	70.70	73.14	75.09	76.59	77.77	78.68	79.40
Pu^{241}	10.35	8.75	8.45	8.64	8.98	9.30	9.60	9.84	10.04	10.19	10.32
Pu^{242}	2.48	3.12	3.55	3.91	4.23	4.53	4.82	5.09	5.34	5.57	5.77
Am^{241}	0.62	0.16	0.15	0.15	0.16	0.16	0.16	0.17	0.17	0.17	0.17
Pu-total	207.07	214.11	219.49	223.59	227.00	229.16	231.04	232.54	233.74	234.71	235.52
Pu^{239} eq.	163.14	163.14	163.14	163.19	163.40	163.26	163.23	163.23	163.23	163.20	163.25
U^{232}	0.0	2.E-6	3.E-6	5.E-6	5.E-6	5.E-6	5.E-6	5.E-6	5.E-6	5.E-6	5.E-6
U^{235}	1.98	1.30	0.91	0.69	0.57	0.49	0.45	0.43	0.42	0.41	0.41
U^{236}	0.55	0.73	0.82	0.86	0.89	0.90	0.90	0.91	0.91	0.90	0.90
U^{238}	790.42	783.73	778.64	774.83	772.92	769.42	767.54	765.93	764.86	763.79	763.19
U-total	793.09	785.87	780.51	776.44	774.26	770.76	768.88	767.27	766.20	765.13	764.53
Total	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Pu%	20.7	21.41	21.95	22.36	22.7	22.92	23.1	23.26	23.37	23.47	23.55
Fissile%	15.48	15.4	15.32	15.24	15.2	15.14	15.09	15.06	15.04	15.02	15.01
Pu^{239} eq.%	78.79	76.2	74.33	72.98	71.99	71.23	70.65	70.19	69.83	69.54	69.31

Table 5. BOC fuel composition for core-2 per 1000 kg of fuel: PHWR external Pu feed.

	Inventory (kg) against recycle number										
Nuclide	0	1	2	3	4	5	6	7	8	9	10
Pu^{238}	0.28	0.50	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.69
Pu^{239}	190.72	191.16	190.42	189.16	187.67	186.60	185.34	184.29	183.34	182.52	181.87
Pu^{240}	68.20	79.51	88.86	96.63	103.00	108.45	112.87	116.57	119.64	122.18	124.32
Pu^{241}	13.86	12.60	12.44	12.77	13.28	13.85	14.36	14.84	15.25	15.59	15.89
Pu^{242}	3.33	4.23	4.94	5.57	6.14	6.69	7.20	7.68	8.13	8.56	8.95
Am^{241}	0.83	0.17	0.17	0.18	0.19	0.20	0.20	0.21	0.22	0.22	0.23
Pu-total	277.27	288.21	297.28	304.79	310.77	316.43	320.61	324.18	327.21	329.76	331.94
Pu^{239} eq.	218.42	218.42	218.45	218.47	218.42	218.78	218.78	218.83	218.83	218.80	218.85
U^{232}	0.E+00	1.E-06	2.E-06	5.E-06	5.E-06	5.E-06	5.E-06	5.E-06	5.E-06	5.E-06	5.E-06
U^{235}	1.81	1.31	0.98	0.77	0.62	0.53	0.47	0.43	0.40	0.39	0.38
U^{236}	0.51	0.63	0.72	0.77	0.82	0.85	0.87	0.89	0.91	0.92	0.94
U^{238}	720.40	709.93	700.86	693.58	687.60	682.18	677.99	674.42	671.40	668.84	666.67
U-total	722.73	712.03	702.72	695.21	689.00	683.57	679.39	675.82	672.79	670.24	668.06
Total	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Pu%	27.72	28.81	29.74	30.48	31.09	31.64	32.06	32.42	32.72	32.98	33.19
Fissile%	20.64	20.51	20.38	20.27	20.16	20.1	20.02	19.95	19.9	19.85	19.81
Pu^{239} eq.%	78.79	75.8	73.46	71.67	70.26	69.15	68.24	67.49	66.87	66.36	65.92

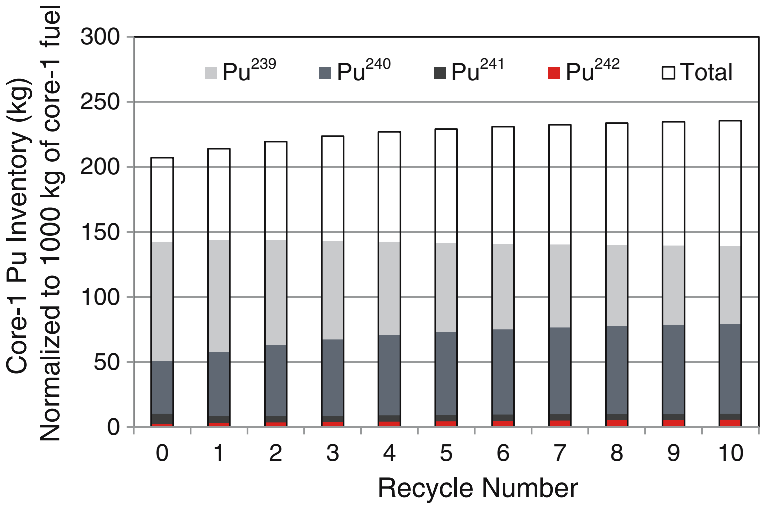


Figure 3. Core-1 Pu inventory over consecutive cycles.

The following observations are made for the multiple recycling of PFBR fuel:

(a) The total Pu^{239} equivalent mass at the start of every cycle was kept constant to preserve the fuel worth.
(b) The total Pu inventory (and the enrichment) required at the start of every cycle shows a gradual increase over that at the start of the previous cycle. This was due to the buildup of non-fissile nuclides and consequent loss in the reactivity worth of the recovered Pu.
(c) The total uranium mass (U-tot) was decreased to compensate for the increase in Pu inventory to maintain total mass constant at the start of every cycle.

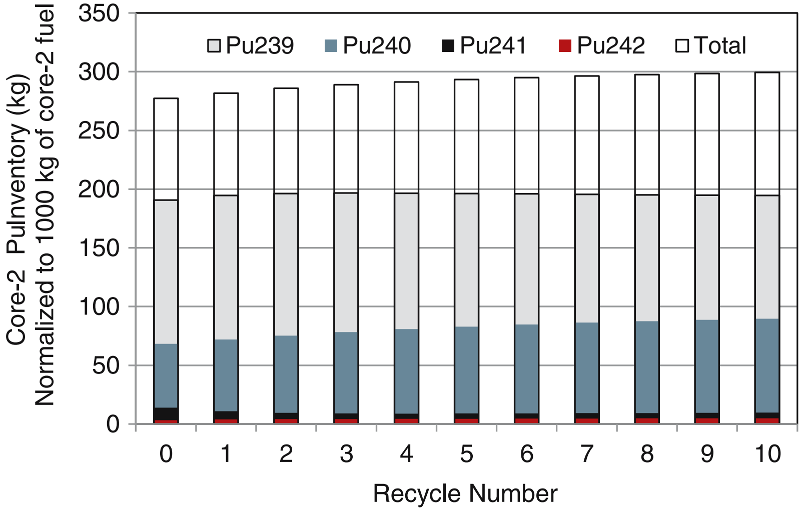


Figure 4. Core-2 Pu inventory over consecutive cycles.

Table 6. Effect of multiple recycling of PFBR fuel with PHWR external feed on core parameters.

Parameters	0	*	1	2	3	4	5	6	7	8	9	10
k_{eff}	1.0878	Δk (pcm)	−153	−197	−216	−198	−180	−125	−100	−83	−32	−57
β_{eff} (pcm)	351	$\Delta\beta_{\mathrm{eff}}$ (pcm)	−4.01	−6.36	−7.19	−7.37	−7.27	−7.12	−6.74	−6.51	−6.12	−6.16
Fuel worth (ρ_{f}) (pcm)	346	$\Delta\rho_{\mathrm{f}}/\rho_{\mathrm{f}}$ (%)	0.30	0.50	0.57	0.63	0.64	0.62	0.60	0.60	0.82	0.59
Fuel Doppler worth (ρ_{D}) (pcm)	773.5	$\Delta\rho_{\mathrm{D}}/\rho_{\mathrm{D}}$%)	−1.04	−2.22	−1.69	−3.53	−3.96	−4.45	−4.48	−4.65	−5.32	−5.07
Prompt neutron life-time (l_{p}) (μs)	0.41244	$\Delta l_{\mathrm{p}}/l_{\mathrm{p}}$ (%)	1.58	0.75	0.22	−0.22	−0.56	−0.92	−1.02	−1.19	−1.79	−1.45

* Values indicate difference from cycle-0 for k_{eff} and β_{eff}; l_{p}: fuel worth for 1% fuel addition.

(d) There was a slight decrease in fissile fraction (i.e., sum of U^{235}, Pu^{239} and Pu^{241} fractions) of about 0.5% over ten recycles.

However, the changes mentioned above show a tendency of saturation after a few cycles. The saturation tendency is apparent from figures 3 and 4, wherein the relative increase in Pu between the beginnings of consecutive cycles is graphically indicated for core-1 and -2. For example, while core-1 Pu increases by 3.5% from the beginning of the 1st cycle to that of the cycle-0, the Pu increase from the beginning of the 9th cycle to that of the 10th was only 0.35%. The corresponding changes for the core-2 Pu are 4 and 0.7%, respectively. The saturation tendency was also observed in the external PHWR Pu requirement. It was observed that the core-1 (core-2) PHWR Pu requirements were about 7 kg (35 kg) for the first recycle, and then the requirement reduced and saturated to about 5 kg (31 kg) beyond the 6th recycle.

3.1 *Effect of recycling on core parameters*

The reference physics calculations of PFBR were done with the compositions corresponding to BOL. Criticality (k_{eff}) calculations have been carried out using a two-dimensional (R–Z) multigroup diffusion code ALCI-ALMI [7]. A 26-group XSET-93 multigroup cross-sections were considered for the calculations. The code system with the cross-section set has been validated and the estimated uncertainty in the k_{eff} value is about 1%, i.e., 1000 pcm [6]. Reactivity worth estimations viz., fuel and fuel Doppler were performed using the first-order perturbation theory code NEWPERT [8]. The fuel worths were estimated by perturbing the system with 1% increase in fuel number density. The fuel Doppler worths were estimated by perturbing the system with an increase in temperature from 473 to 1173 K in core regions.

Change in plutonium vector and enrichment during fuel recycling could have unfavourable impact on the core and safety parameters. Hence neutronic calculations (k_{eff} and perturbation) have been performed for the 10 recycles. Table 6 gives the values of

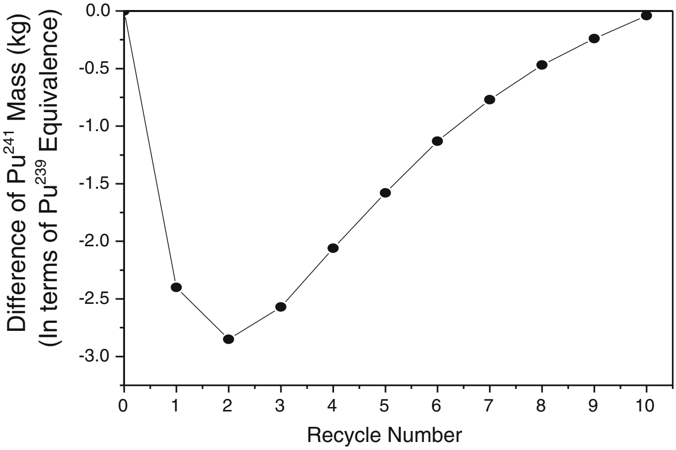


Figure 5. Variation of differences observed in Pu^{241} masses for 10 recycles from cycle-0.

Table 7. BOC fuel composition for core-1 per 1000 kg of fuel: PFBR radial blanket external Pu feed.

	Inventory (kg) against cycle number										
Nuclide	0	1	2	3	4	5	6	7	8	9	10
Pu^{238}	0.21	0.41	0.42	0.42	0.43	0.43	0.44	0.45	0.46	0.46	0.47
Pu^{239}	142.45	144.65	145.01	144.55	143.84	143.21	142.62	142.14	141.74	141.42	141.18
Pu^{240}	50.94	56.13	60.51	64.04	66.84	69.05	70.82	72.18	73.23	74.06	74.73
Pu^{241}	10.35	8.38	7.88	7.94	8.18	8.47	8.73	8.95	9.13	9.28	9.39
Pu^{242}	2.48	3.04	3.37	3.63	3.87	4.10	4.32	4.53	4.73	4.92	5.08
Am^{241}	0.62	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.15	0.15
Total	207.07	212.74	217.30	220.72	223.29	225.41	227.07	228.41	229.42	230.28	231.00
Pu^{239} eq.	163.14	163.17	163.21	163.21	163.17	163.21	163.19	163.19	163.19	163.16	163.19
U^{232}	0.00	1.9E-06	2.7E-06	5.4E-06	5.4E-06	5.4E-06	5.4E-06	5.4E-06	5.4E-06	5.4E-06	5.4E-06
U^{235}	1.98	1.30	0.91	0.69	0.57	0.50	0.46	0.44	0.42	0.42	0.41
U^{236}	0.55	0.73	0.82	0.86	0.89	0.90	0.90	0.90	0.90	0.90	0.90
U^{238}	790.42	785.06	780.99	777.78	775.16	773.23	771.62	770.28	769.21	768.41	767.60
U-total	793.09	787.21	782.86	779.38	776.77	774.56	772.96	771.62	770.55	769.75	768.94
Total	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00
Pu%	20.7	21.28	21.73	22.07	22.33	22.54	22.7	22.84	22.94	23.03	23.1
Fissile%	15.48	15.44	15.38	15.32	15.26	15.22	15.18	15.15	15.13	15.11	15.1
Pu^{239} eq.%	78.79	76.7	75.11	73.95	73.08	72.41	71.87	71.45	71.12	70.86	70.64

Table 8. BOC fuel composition for core-2 per 1000 kg of fuel: PFBR radial blanket external Pu feed.

	Inventory (kg) against cycle number										
Nuclide	0	1	2	3	4	5	6	7	8	9	10
Pu^{238}	0.28	0.47	0.48	0.47	0.47	0.46	0.46	0.46	0.46	0.46	0.46
Pu^{239}	190.72	194.53	196.21	196.65	196.60	196.30	195.93	195.53	195.19	194.82	194.58
Pu^{240}	68.20	71.92	75.32	78.26	80.79	82.95	84.79	86.33	87.60	88.68	89.60
Pu^{241}	13.86	10.88	9.54	9.01	8.88	8.93	9.06	9.22	9.37	9.51	9.63
Pu^{242}	3.33	3.81	4.07	4.23	4.36	4.46	4.56	4.66	4.76	4.85	4.95
Am^{241}	0.83	0.17	0.15	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15
Total	277.27	281.69	285.88	288.84	291.16	293.26	294.88	296.28	297.44	298.54	299.30
Pu^{239} eq.	218.42	218.42	218.45	218.40	218.42	218.42	218.42	218.42	218.42	218.37	218.42
U^{232}	0.00	1.4E-06	2.3E-06	4.7E-06	4.7E-06	4.7E-06	4.7E-06	4.7E-06	4.7E-06	4.7E-06	4.7E-06
U^{235}	1.81	1.33	1.00	0.79	0.65	0.56	0.50	0.46	0.43	0.42	0.40
U^{236}	0.51	0.64	0.72	0.78	0.82	0.85	0.87	0.88	0.90	0.90	0.91
U^{238}	720.40	716.21	712.49	709.53	707.21	705.35	703.72	702.33	701.16	700.07	699.30
U-total	722.73	718.31	714.35	711.16	708.84	706.74	705.12	703.72	702.56	701.46	700.70
Total	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00
Pu%	27.72	28.18	28.58	28.88	29.12	29.32	29.49	29.63	29.75	29.85	29.94
Fissile%	20.64	20.67	20.67	20.65	20.61	20.58	20.55	20.52	20.5	20.47	20.46
Pu^{239} eq.%	78.79	77.52	76.44	75.63	74.99	74.48	74.05	73.7	73.41	73.16	72.96

k_{eff}, β_{eff}, fuel worth, fuel Doppler worth and prompt-neutron lifetime corresponding to BOL and the differences observed in the parameters for 10 recycles, from cycle-0 values. These results correspond to the case of external Pu feed from PHWR. Calculated breeding ratio was observed to increase with recycles, from 1.05 at BOL to 1.1 at 10th recycle. This is due to the increase in mass fraction of Pu^{240} in the core and its capture cross-section being higher than that of U^{238}.

From table 6, it can be seen that k_{eff} values are practically constant, magnitude of deviation is well within 220 pcm. However, the small systematic variation in k_{eff} values are noticed in table 6. As shown in figure 5, the mass of Pu^{241} has the same variation as

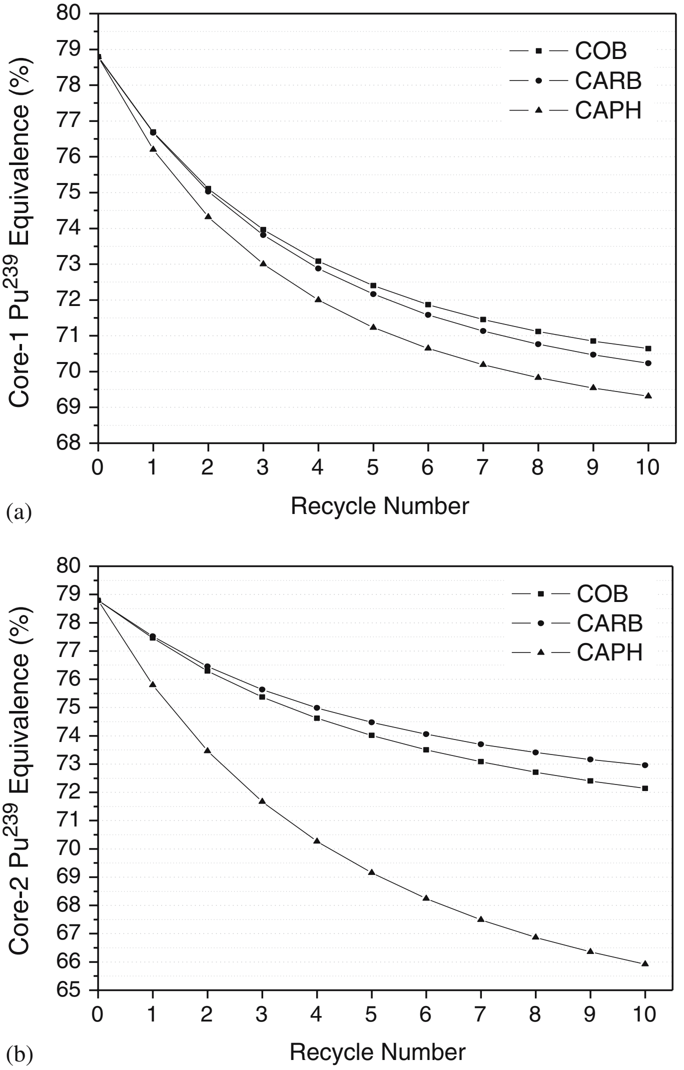
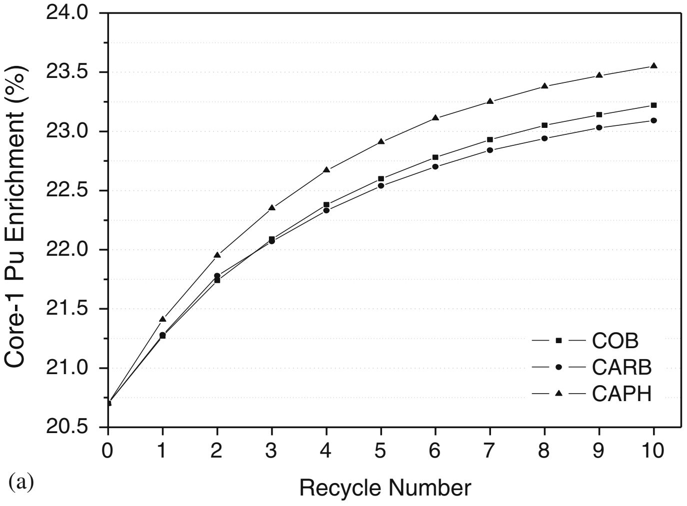


Figure 6. Variation of (**a**) core-1 and (**b**) core-2 Pu^{239} equivalence (%) with recycling for COB, CARB and CAPH.

that observed for k_{eff}. Pu^{239} equivalence of Pu^{241}, computed for BOL, is used to arrive at the required plutonium fractions for the recycle studies. A small systematic error in the Pu^{239} equivalence value will explain the observed variation in k_{eff}. The β_{eff}, fuel worth and fuel Doppler worths are nearly constant. The changes in β_{eff} values lie within 8 pcm, fuel worth within 3 pcm and fuel Doppler worth within 40 pcm with respect to the cycle-0 fuel worth. The variation of prompt neutron life-time is also negligible. Though the total Pu reactivity worth remains the same, the plutonium composition is different in each recycle and hence responsible for the nominal differences noticed in the core



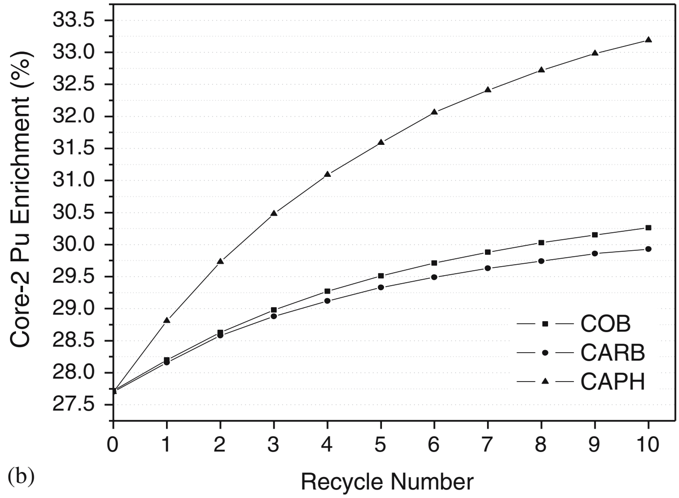


Figure 7. Variation of (**a**) core-1 and (**b**) core-2 Pu enrichments with recycling for the three cases.

and the safety parameters. As practically there is no significant variations in the physics parameters, multiple recycling of fuel in PFBR with external Pu feed from PHWR is feasible from the reactor physics considerations.

3.2 *Fuel recycling with external Pu from radial blanket*

The study on multiple recycling of fuel with external feed from PFBR blanket plutonium, carried out earlier [1,2], is repeated with the changes considered in this study, i.e., recovery of core Pu including Pu bred in axial blankets, and the modifications in the in-core cooling and reprocessing periods. The estimated BOC inventories for all the 10 cycles are presented in tables 7 and 8 for core-1 and -2, respectively. Each of these results was normalized to a total BOC inventory of 1000 kg. As the compositions of plutonium bred in axial and radial blankets are similar, the results showed negligible variations over the observations reported in the earlier studies.

3.3 *Comparison of different external Pu options*

Considering the multiple recycling of PFBR fuel with external plutonium feed from (i) PHWR, (ii) PFBR radial blanket and (iii) PFBR axial and radial blankets as different options, the variations in the most important parameters viz., Pu^{239} equivalences, Pu enrichments of core-1 and -2, increase in the Pu^{240} mass with recycling are compared in figures 6, 7 and 8. Table 9 gives the different cases considered with identifications for each case given in column 4.

Significant increase in Pu^{240} mass is noticed in all the cases. The relative increase in Pu^{240} masses at the 10th recycle with respect to cycle-0 are 51, 47 and 56%, respectively for COB, CARB and CAPH. In core-1, the Pu^{239} equivalences (%) at 10th recycling, for COB, CARB and CAPH, were 70.64, 70.23 and 69.31, respectively, showing a reduction of 8.56, 8.15 and 9.48 from cycle-0. Similarly, the Pu^{239} equivalences (%) for core-2 are 72.14, 72.96 and 65.92, respectively and the reductions are 6.65, 5.83 and 12.87 from cycle-0. So the reactivity worth of refabricated fuel tends to decrease with respect to

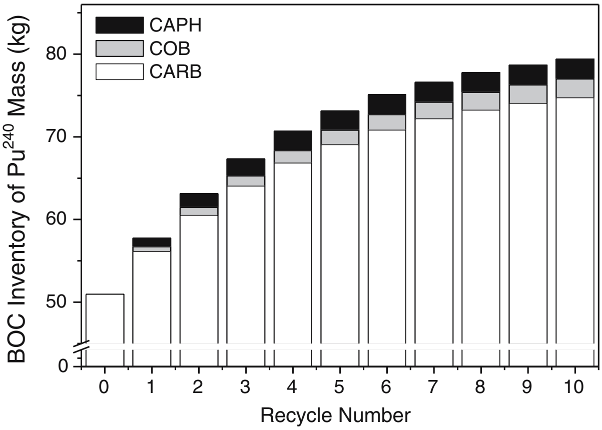
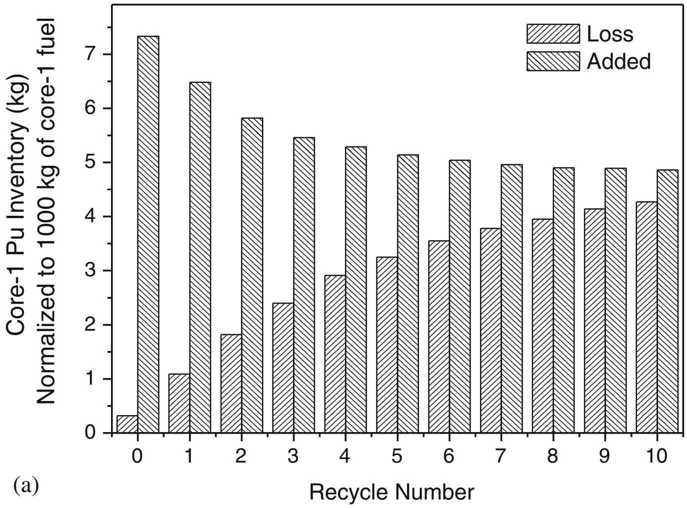


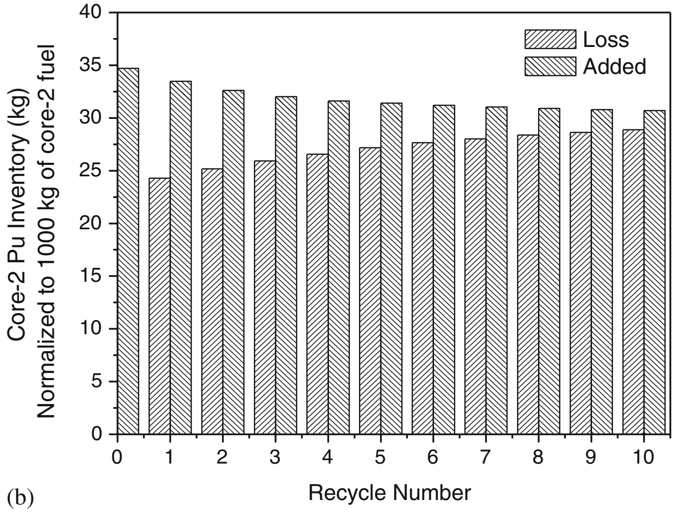
Figure 8. Comparison of BOC Pu^{240} mass (kg) in CAPH, COB and CARB.

Table 9. Different cases considered in this study with identifications for each case.

Cases	Pu Extraction	External Pu options	
1	Core alone	PFBR blankets (axial and radial)	COB
2	Core and axial blanket bred	PHWR	CAPH
3	Core and axial blanket bred	PFBR radial blanket	CARB



(a)



(b)

Figure 9. Amount of Pu lost and external PHWR Pu added in (**a**) core-1 and (**b**) core-2 (loss include Pu burnt in the core, bred in axial blanket and the Pu lost in reprocessing).

recycling. However, to maintain the fuel worth as at BOL, the enrichment requirements in core-1 and -2 are increased.

The core-1 enrichment requirement increased from 20.7% at cycle-0 to about 23.5% at 10th recycle, an increase of about 3% from cycle-0 value for all the three cases. The enrichment requirement in core-2 is slightly different from that of core-1 for the three cases. For COB and CARB cases, the core-2 enrichment requirement increased from 27.7% at cycle-0 to about 30% at 10th recycle, an increase of only about 2.5% from cycle-0 value. As mentioned in §3.2, similarity in the qualities of plutonium bred in axial and radial blankets makes the plutonium burning and the Pu^{239} equivalence (%) almost the same for the two cases. But in CAPH case, due to the large reduction ($\sim$13%) in Pu^{239} equivalence (%), the core-2 enrichment requirement increased from 27.7% at cycle-0 to about 33% at the 10th recycle, an increase of about 5% from cycle-0 value. This difference is due to the compositions (qualities) of plutonium bred in blankets and that produced in PHWR.

The evolution of Pu^{239} equivalences (%) of core-1 and -2, with recycling, showed a considerable difference in CAPH case. As mentioned earlier, the reductions in Pu^{239} equivalences (%) between cycle-0 and 10th recycle in core-1 and -2 are about 9.5 and 13%, respectively. Large reduction in core-2 is due to (a) low internal breeding in core-2, (b) more fissile plutonium burning during burnup and (c) lower plutonium breeding in the axial blanket of core-2 region compared to that of core-1. Figure 9 gives the amount of plutonium loss and the amount of external PHWR plutonium required, in core-1 and -2, respectively, for CAPH case. In this figure ‘Loss’ indicates the Pu burnt in the core + Pu bred in axial blankets + Pu lost during reprocessing. It can be noticed that the total loss of Pu in core-2 is considerably high compared to that lost in core-1. Due to these reasons, replenishment of core-2 demands more external PHWR plutonium (which contains about 25% of Pu^{240}) and thus results in increased Pu^{240}.

4. Conclusions

It was found that the multiple recycling of PFBR fuel with external plutonium feed from PHWR was feasible with appropriate increments in plutonium enrichments to compensate for the reduction in the worth of spent fuel, with respect to recycles. It was found that, for recycling PFBR discharge fuel, core-1 (core-2) required about 7 kg (35 kg) of PHWR Pu for the first recycle, and then the requirement decreased and reached saturation value of about 5 kg (31 kg) beyond the 6th recycle.

Impact of multiple recycling on PFBR core parameters due to the modifications in the fuel composition has been studied using neutronic calculations. The calculated k_{eff}, β_{eff}, fuel worth, fuel Doppler worth and prompt neutron lifetime were practically constant and hence multiple recycling was possible in PFBR. The recyclability of PFBR fuel has been judged purely based on the reactor physics considerations of criticality and excess reactivity requirements. However, for practical implementation, further analyses such as limit on maximum allowable Pu content in fuel based on chemistry/metallurgical considerations need to be addressed. A comparison of the fuel composition evolution and enrichment required with different external plutonium options viz., PHWR and PFBR radial blanket has been made and the results are brought out.

Further refinements in the study, with Pu^{239} equivalence calculated at each recycle, consideration of batch fuelling, evolution of reactivity feedback coefficients and flux peaking effects will be done in future experiments.

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