RECYCLING OF HIGH BURNUP SPENT PWR FUEL IN CANDU REACTORS

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ABSTRACT

Multiple recycling schemes for reusing the spent DUPIC fuel into the CANDU reactor after mixing with some fresh enriched UO_2 fuel has been studied. The spent PWR fuel is from 5 wt% enriched fuel with 60000 MWD/T burnup. HELIOS code was used for PWR and CANDU, in which all of the available fission products were considered. The decay of 10 years was also provided for reuse of the spent fuel. For mixing of the fresh fuel different U^{235} enrichments have been considered. By increasing the enrichment the fissile contents at discharge stage became increased and also the saving of uranium reserves would decrease. There would be an increase of reduction in waste. As for as mixing material enrichment is concerned 5 wt% enrichment provides more good results for uranium saving and disposal reduction as well. For this mixing of fuel the required mixing is about 20%. The reduction in waste disposal is about 96% in first recycling step compared with the once through DUPIC model 67%. The uranium saving for recycling is 7%, during first recycling step compared with the once through DUPIC model 22%. In multiple recycling models we can reduce the waste disposal, which is the ultimate goal of DUPIC fuel also.

1. INTRODUCTION

The fissile contents of the spent fuel from Pressurized Water Reactor (PWR) ~1.5 wt% which is higher than that of the fuel of Canada deuterium uranium (CANDU) reactor. In order to use the amount of fissile contents available in spent PWR fuel into CANDU reactors, the concept of the DUPIC (Direct Use of spent PWR fuel in CANDU reactors) fuel cycle has been detailed studied in last decade [1,2]. The reactor physics and thermal hydraulic calculations show that the spent PWR fuel can be used into CANDU reactor after the oxidation and reduction of oxide fuel (OREOX) process without involving any reprocessing [1-3]. Economic analysis for DUPIC fuel handling, fabrication, cycle and disposal has also proved it to be feasible. With DUPIC fuel cycle, it has been found that it could save uranium resources up to 20% and also reduce the spent fuel arising ~65% [4 - 7].

In this study, a possibility of multiple recycling of high burnup spent PWR fuel in CANDU reactor has been investigated. The spent DUPIC fuel has fissile contents as 0.32 wt% of U^{235}, 0.35 wt% of Pu^{239} and 0.085 wt% of Pu^{241}, resulting in a total fissile content about 0.758 wt%. This amount of fissile contents is near to the fissile contents of natural uranium. In the DUPIC spent fuel, fission products are also present so to compensate the negative reactivity some fresh UO_2 was mixed with the spent fuel to make it possible to get the desired burnup. Also different U^{235} wt% enrichment was used

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for mixing. The referenced spent fuel is of 5.0 wt% initial enrichment with 60000 MWd/T burnup in PWR. HELIOS code was used for calculations of PWR and CANDU. The available fission products in HELIOS code were used in the calculations for recycling. The decay of 10 years was also provided for reuse of the spent fuel. In these calculations, full core was not modeled and only lattice calculations were performed.

2. REACTOR CALCULATIONAL MODELING

2.1 PWR LATTICE MODEL

The reference PWR fuel assembly for spent fuel employed in this study is a typical 17 x17 fuel assembly of 950 MW (electric) PWR of Yonggwang power plant [8]. The design parameters are given in Table I. To obtain the spent fuel composition pin cell calculations were performed. The geometry is illustrated in Fig. 1. The cell pitch was adjusted according to the fuel to moderator ratio. The gap between fuel and clad was treated separately. The specular reflective boundary condition was used to all the external surfaces of the cell. The normal operating temperature for fuel, clad and coolant/moderator were taken as 1000, 585, and 580 ^{o}K, respectively. No burnable poison was considered throughout PWR pin cell calculations. The composition of spent fuel from low and high discharge burnup cases was calculated using HELIOS computer code and for decay of 10 years was also calculated.

Table I. Design parameters of a typical PWR.

Parameters	Value
Rated Power ($MW_{thermal}$)	2775
Number of assemblies/channels	157
Active core height (cm)	365.76
Type	17 X 17
Cladding material	Zr-4
Fuel temperature (^{o}K)	1000
Clad temperature (^{o}K)	585
Moderator/coolant temperature (^{o}K)	580
Pin radius (cm)	0.4025
Clad inner radius (cm)	0.411
Clad outer radius (cm)	0.475
Lattice pitch (cm)	1.26
Power density (W/g)	41.73
H_2O / U molecular ratio, Lattice	2.8

2.2 CANDU LATTICE MODEL

To study the spent PWR fuel in a CANDU reactor, typical 43 fuel rod cluster geometry was used as a reference having central rod and second ring rods larger diameter as compared to others. For the lattice calculations, the fuel gap is smeared into the clad material and endcap is not considered. One half symmetry of the core model was designed two dimensionally, and the specular reflective boundary condition was used to all the external surfaces of the cell. Normal operating conditions for fuel, clad, coolant and moderator were 960.16, 561.16, 561.16, and 342.16 ^{o}K, respectively. The central rod of the fuel bundle contains 4.3 wt% natural dysprosium. The CANDU half-cell is shown in Fig. 2.

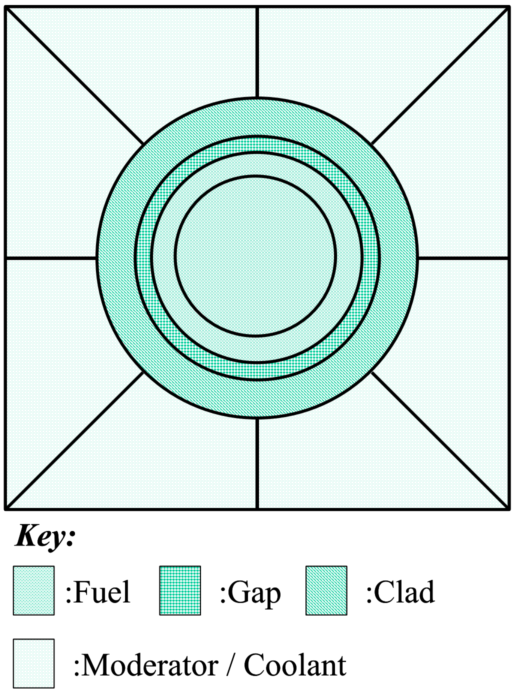

Figure 1. PWR pin cell geometry used in HELIOS calculations (Not on scale).

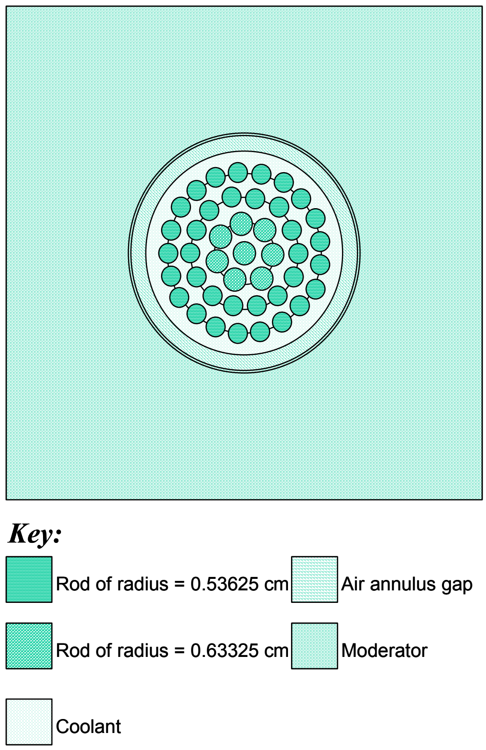

Figure 2. 43-fuel bundle CANDU geometry employed in HELIOS calculations.

For an on-line refueling reactor like CANDU the discharge burnup is achieved at the point where the area above the line K_{inf} in the K_{inf}-versus-burnup plot equals the area below that line [9]. The reference K_{inf} is typically 1.054 and 1.045 for the natural uranium and DUPIC fuel, respectively.

3. ANALYSIS

PWR spent fuel was direct utilized into CANDU reactor after OREOX processing. This spent fuel was not able to give us 15000 MWd/T discharge burnup. A 10% of fuel was replaced with 5 wt% enriched fresh fuel. In the central rod 4.3 wt% dysprosium was also introduce to compensate the void reactivity in both cases. The important physics parameters such as Doppler coefficient of reactivity and void reactivity coefficient were calculated at fresh condition. The spent fuel was then recycled to reuse into the CANDU reactor after some mixing of fresh UO_2 fuel. The initial enrichment of mixing fuel was changed from 5 wt% to 19.99 wt%. The mixing scheme was also investigated.

3.1 MULTIPLE RECYCLING

For multiple recycling different enrichments for mixing of fresh fuel were taken from 5 wt% to 19.99 wt%. It was also found that in CANDU bundle, the outer fuel rod ring burned more during irradiation due to the power distribution. Typical power sharing of the rod rings at fresh, equilibrium and discharge stages is tabulated in Table II. Also the central rod contains dysprosium for the compensation of void reactivity. During recycling scheme one central rod and some outer ring rods were replaced to maintain the fuel balance. In this study, a 4.3 wt% of dysprosium was mixed for all cases.

Table II. Relative Pin Power for DUPIC Fuel

Burnup (MWd/T)	Ring 1	Ring 2	Ring 3	Ring 4
0	0.11669	0.19957	0.27201	0.41173
7000	0.15486	0.22255	0.27315	0.34944
14000	0.19303	0.23373	0.26336	0.30988

For 5 wt% fresh fuel loading the discharge burnup of recycled fuel after mixing with different number of rods of outer ring was studied and it was found that replacing nine fuel rods and one central rod with fresh 5 wt% fuel can provide desired burnup. The mixed fuel was used in CANDU reactor again and studied the physics parameters. The replacement became 20.35%. For mixing of 10 wt% fuel the same strategy as for 5 wt% fuel. To get the burnup more than 15000 MWD/T four rods of outer ring were replaced including the central fuel rod. This is about 11.7% mixing with fresh fuel. In 15.0 wt% fresh fuel mixing, two rods from outer ring were replaced including the central fuel rod. This presents as 7.35 % of the replacement of the spent fuel. Employing the same strategy for 19.99 wt% fresh fuel mixing, we replaced two rods from outer ring including central rod also. This mixing for low burned fuel shows about 5.2 % replacement of spent fuel with fresh fuel. The weight of important heavy elements and fissile contents at fresh and discharge stage with 5.0 wt% fresh fuel loading are shown in Table III.

3.2 PHYSICS PARAMETERS CALCULATIONS

The important physics parameters such as void reactivity coefficient and Doppler coefficient of reactivity were calculated at fresh condition. For different enrichment cases three recycling steps were considered. To calculate the Doppler coefficient of reactivity the temperature was changed from 283.16 ^oK to 1474.16 ^oK. The Doppler coefficient of reactivity for temperature increase and temperature decrease from normal operating temperature was calculated separately as:

$$\alpha_T (pcm/^oK) = \frac{k_1 - k_2}{T_1 - T_2} \times 10^5. \quad (1)$$

where; k_1, k_2 are k_{inf} for normal and perturbed, respectively.
T_1, T_2 are temperature (^oK) for normal and perturbed, respectively

Table III. Important heavy metals loading during recycling and fissile contents with 5.0 wt% of fresh fuel mixing.

Actinide	DUPIC Fuel		1-recycling		2-recycling		3-recycling
	Fresh	Discharge	Fresh	Discharge	Fresh	Discharge	Fresh
U^{235}	1.23501	0.42290	1.53785	0.45426	1.57176	0.40057	1.53496
U^{236}	0.66107	0.77688	0.58631	0.74397	0.55972	0.72916	0.54818
U^{238}	96.8208	97.5728	96.9485	97.7149	97.0546	97.8456	97.1528
Np^{237}	0.08247	0.07649	0.05899	0.05914	0.04537	0.05008	0.03828
Pu^{238}	0.03972	0.05691	0.05039	0.04923	0.04169	0.03878	0.03245
Pu^{239}	0.57319	0.37881	0.29886	0.33515	0.26080	0.32355	0.25136
Pu^{240}	0.27487	0.35887	0.27538	0.31158	0.23819	0.28980	0.22064
Pu^{241}	0.10909	0.09853	0.04585	0.08323	0.03841	0.07701	0.03542
Pu^{242}	0.09351	0.15202	0.11142	0.15364	0.11313	0.15298	0.11263
Am^{241}	0.07283	0.02245	0.04663	0.01245	0.03379	0.00823	0.02849
Am^{243}	0.02706	0.03859	0.02856	0.04032	0.02985	0.04145	0.03067
Fissile Contents	1.91729	0.90024	1.88256	0.87264	1.87097	0.80113	1.82174

The Doppler coefficients of reactivity after mixing with 5.0 wt% fresh fuel are depicted in Fig. 3. For the coolant void reactivity, the coolant density was changed from 0.807859 to 0.0001 g / cm^3. It was assumed that the coolant is homogenized in the coolant channels. The change in the void reactivity coefficient was calculated as:

$$\alpha(mk) = 1000 \times \left[\frac{1}{k_{normal}} - \frac{1}{k_{perturb}} \right]. \qquad (2)$$

After mixing with 5.0 wt% fresh fuel, the changes in void reactivity coefficient are shown in Figs. 4. The results of physics parameters for different enrichment loading are listed in Table IV. The system K_{inf} versus burnup at different recycling steps are shown in Figs. 5.

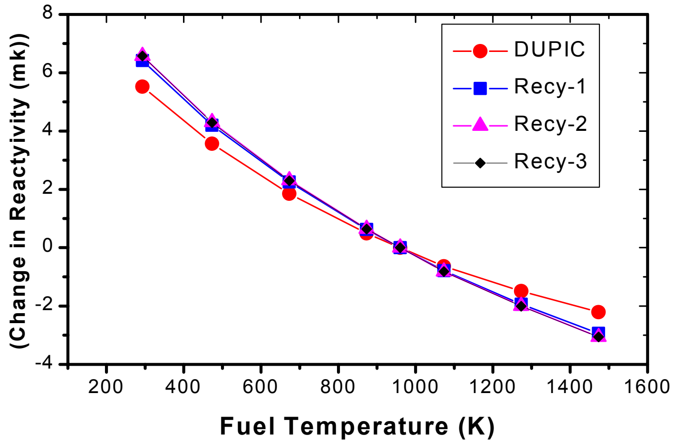

Figure 3. Change in system reactivity versus fuel temperature for different recycling steps with 5.0 wt% enrichment.

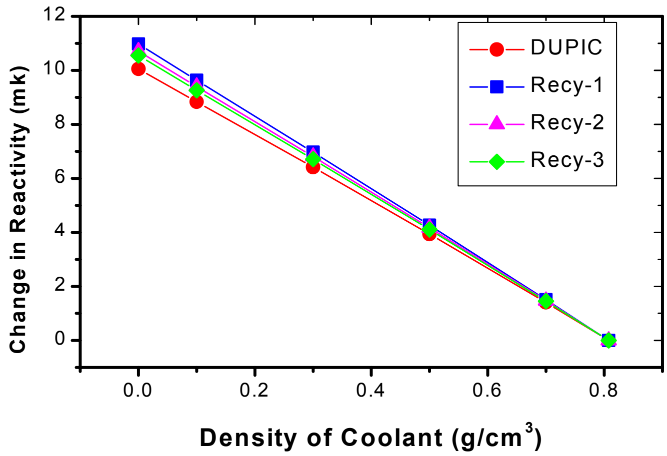

Figure 4. Change in void coefficient of reactivity versus coolant density for different recycling steps with 5.0 wt% enrichment.

Table IV. Discharge burnup, Change in void reactivity coefficient and Doppler coefficient for high burned PWR fuel with mixing of fresh UO_2 having different uranium enrichment.

Parameter	wt%	DUPIC Fuel (Mixed with 5.0 wt%)	One-recycling	Two-recycling	Three-recycling
Discharge Burnup (MWD/T)	5	17000 (0.92023)	17600 (0.92647)	18900 (0.91464)	18700 (0.91103)*
	10		16000 (0.95073)	20800 (0.90858)	18000 (0.92466)
	15		15800 (0.94272)	18300 (0.91231)	15800 (0.94340)
	20		19500 (0.92052)	20100 (0.91664)	19900 (0.91827)
Change in Void (mk)	5	10.053	10.981	10.709	10.550
	10		10.780	10.528	10.507
	15		10.897	10.897	10.826
	20		10.780	10.684	10.586
Doppler Coefficient ($\times 10^{-2}$ mk/°K)	5	1.136 (0.587)	1.304 (0.768)	1.370 (0.821)	1.375 (0.823)**
	10		1.352 (0.758)	1.452 (0.854)	1.400 (0.801)
	15		1.301 (0.717)	1.301 (0.717)	1.342 (0.576)
	20		1.367 (0.780)	1.408 (0.817)	1.396 (0.809)

* - Multiplication factor at discharge stage.

** - Doppler coefficient of reactivity for temperature increase from nominal value.

3.3 MASS FLOW CALCULATIONS

To calculate the mass flow during the recycling steps, typical PWR with power 950 MWe, 34.23% efficiency and 0.8 capacity factor was used. The discharge burnup for PWR was considered as 60000 MWd/T. For CANDU it was assumed a reactor of power 713 MWe with capacity factor of 90% and an efficiency of 33%. The discharge burnup for DUPIC fuel was taken as 14500 MWd/T [7]. To establish the DUPIC fuel cycle, the PWR-to-CANDU reactor ratio was also calculated about 3. For material flow calculations, the tail assay in the enrichment facility is 0.25 wt%. To calculate the uranium requirement for different uranium enrichment following relation was used;

$$M_f = M_p \frac{(e_p - e_t)}{(e_f - e_t)} \tag{3}$$

where, e_p = Fresh feed material enrichment.
e_f = Feed material enrichment for enrichment (0.711 wt%).
e_t = Tail enrichment (0.25 wt%).
M_p = Mass of uranium to be charged in the DUPIC facility.
M_f = Mass of uranium feed in enrichment plant.

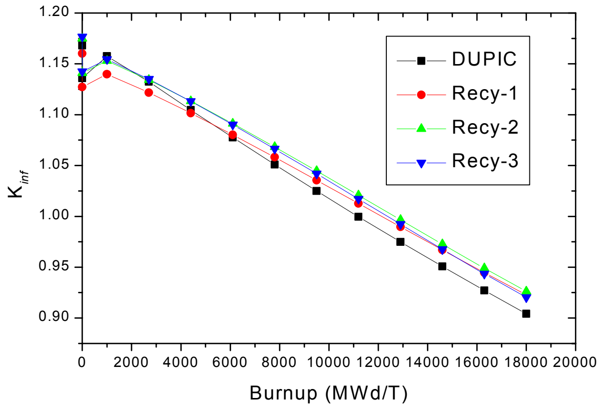

Figure 5. System reactivity versus discharge burnup for different recycling steps with 5.0 wt% enrichment.

The calculations were performed to get the loading of uranium per year in PWR and then the requirement for CANDU reactor. The spent fuel as waste was also calculated for once through cycle and multiple cycles. The flow of the feed material (5 wt% case) and spent fuel for once through and multiple recycle models is shown in Fig. 6. The loading of uranium and disposal for feed material of different enrichments are tabulated in Table V. The uranium saving for different enrichments is shown in Figs. 7. The reduction in disposal of spent fuel was also calculated and is shown in Fig. 8, for different fresh fuel enrichments.

SUMMARY AND CONCLUSION

Multiple recycling schemes for reusing the spent DUPIC fuel into the CANDU reactor after mixing with some fresh UO_2 fuel has been studied. In the DUPIC spent fuel fission products are also present, therefore it is necessary to mixing with fresh UO_2 fuel for compensating negative reactivity. The high burnup PWR fuel are mixed with various kinds of fresh fuel enrichment.
The Doppler coefficient of reactivity during multiple recycling is not much affected and shows even good behavior. Doppler coefficient of reactivity is $1.136\text{x}10^{-2}$ mk/^{o}K for once through cycle while for recycling this value changes from 1.301 to $1.452\text{x}10^{-2}$ mk/^{o}K. The increase in this parameter is good for the reactor safety. As for as void reactivity coefficient is concerned its value increased. Void reactivity coefficient is 10.053 mk for once through cycle while for mutiple recycle this value changes from 10.528 to 10.981 mk. It is due to the presence of Pu and also same mixing of dysprosium wt% in our analysis. Increasing the dysprosium loading in the central rod can reduce the increase in void

reactivity coefficient. In our study the discharge burnup for multiple recycling is more than the once through cycle so we can increase the dysprosium loading.
The fissile contents at the end of second recycling would be 1.01923 with 19.99 wt% fresh fuel mixing. Although waste decreases, but the uranium saving would be decreased.

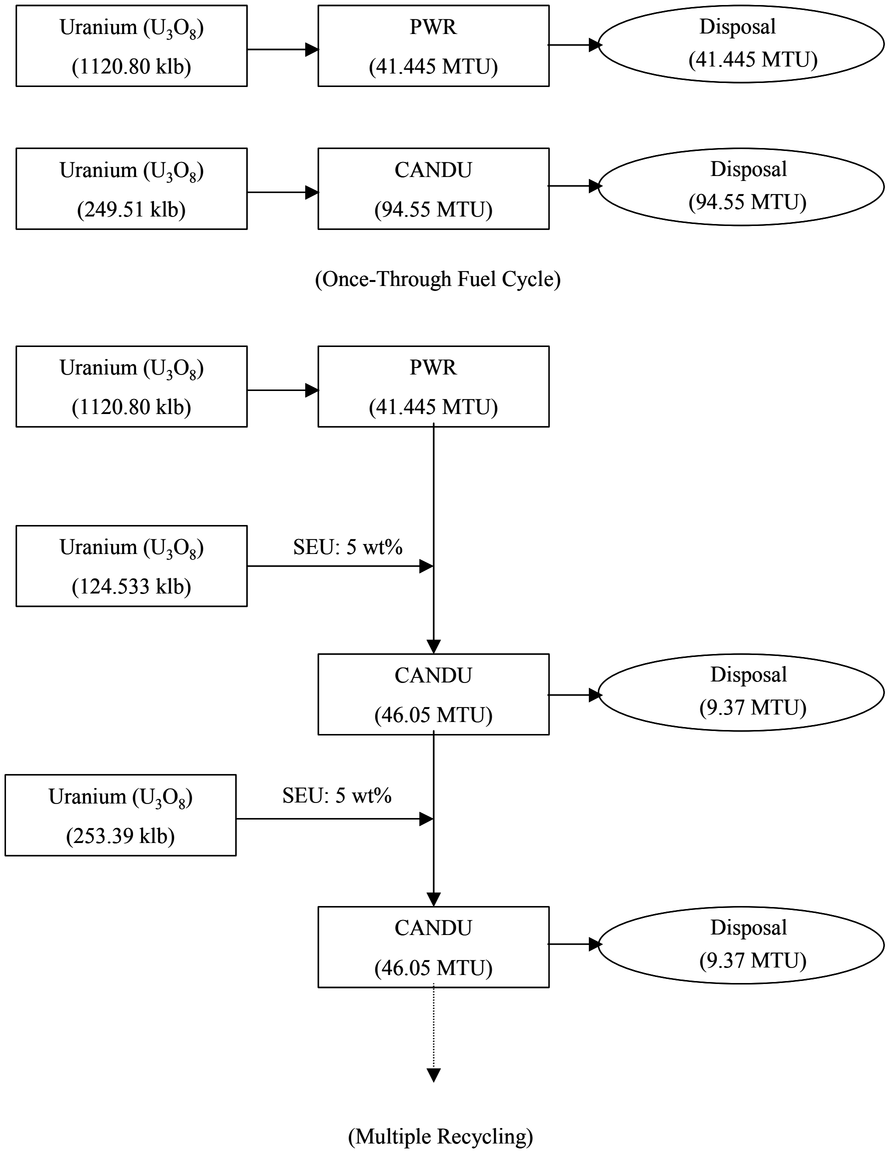

Figure 6. Recycling scheme and mass flow with 5 wt% uranium mixing.

Table V. Uranium loading and waste disposal during multiple recycling for different uranium enrichments.

Enrichment	5 wt%	10 wt%	15 wt%	19.99 wt%
Loading (klb U_3O_8)	253.39	299.19	284.68	324.96
Disposal (THM)	9.37	5.39	3.39	2.89

Low - PWR spent fuel from low burnup
High - PWR spent fuel from high burnup
THM - Tons of Heavy metal

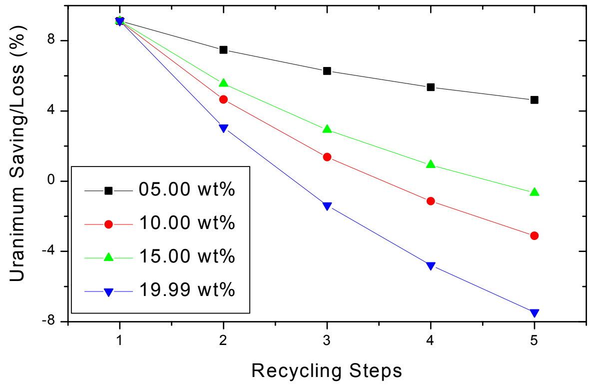

Figure 7. Uranium saving /loss due to multiple recycling with different fresh fuel enrichment.

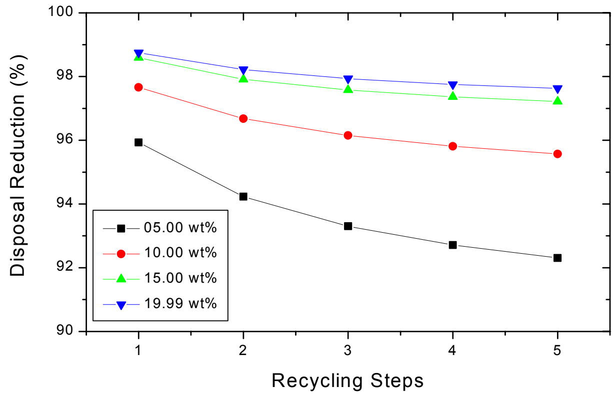

Figure 8. Disposal reduction due to multiple recycling with different fresh fuel enrichment.

From this study this could be inferred that multiple recycling is possible with spent DUPIC fuel. As for as mixing material enrichment is concerned 5 wt% enrichment provides better results in uranium saving and disposal reduction as well. By increasing the mixing material enrichment the uranium saving would be no more. For mixing of 5 wt% enriched fuel the required mixing is about 20%. The waste disposal reduction in once through DUPIC fuel cycle is about 67%. With multiple recycling this value became 96% for first recycling case. In this way waste disposal can be reduced more. The uranium saving for once through DUPIC fuel is 22% and for recycling this vale is 7% during first recycling step. The uranium saving is less in multiple recycling as compared to the once through DUPIC fuel cycle. Although in multiple recycling enrichment is required. Due to decrease in waste the cost of waste disposal would decrease. As the amount of spent fuel for OREOX process is decreased so the cost for this process would also be decrease. So cost for enrichment, waste disposal, and OREOX process can provide the economic balance. For this cost economics analysis is also required.

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