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A Feasibility Study for Designing U-Pu-Zr Fueled, Lead cooled, Long-Life ENHS Cores having Zero Burnup Reactivity Swing

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Abstract *- The objective of this paper is to design U-Pu-Zr fueled, Long-Life ENHS (Encapsulated Nuclear Heat Source) cores that can maintain zero burnup reactivity swing (~0.5%) up to 15 years without refueling and shuffling. In this study, 125MWth (80W/cm) and 250MWth (120W/cm) cores were selected. The neutronics calculations were performed with the REBUS-3/DIF3D code and nine energy group cross section set. The nine energy group cross section set based on ENDF/B-VI was prepared for each case of this study. The initial plutonium enrichment of all considered cores is determined to have keff=1.0042 for initial, hot state. And the optimal pitch-to-diameter (P/D) ratio was determined such that the reactivity swing is minimized for 15 years. For searched cores, the temperature reactivity coefficients, the lead void reactivity coefficient, reactivity worth of the reflector, mass of heavy isotopes were calculated and analyzed to estimate the feasibility.*

I. Introduction

Recently, a new conceptual design of ENHS (Encapsulated Nuclear Heat Source) reactor in which the core is encapsulated in a reactor vessel and the fission energy is conducted through the vessel wall to a secondary coolant pool has been proposed and studied by several institutes[1,2,3], as part of the Encapsulated Fission Heat Source (ENHS) NERI project. The proposed core model is selected to satisfy the following purposes : (a) Good proliferation resistance, (b) Simplified control, (c) Improved safety, (d) Reduced O&M cost, (e) Improved availability. For these purposes, it is desirable that the core is designed to have small fuel composition change and to be maintained without fuel handling, with small reactivity change up to the radiation damage limit. In this paper, a feasibility study for designing U-Pu-Zr fueled, long life, lead cooled ENHS cores having zero reactivity swing up to 15 years was performed by determining the lattice pitch-to-diameter (P/D) ratio for several cases of core height. In this study, 125MWth (80W/cm) and 250MWth (120W/cm) cores were selected. The neutronics calculations were performed with the REBUS-3/DIF3D code[4,5] and nine energy group cross section set. The nine energy group cross section set based on ENDF/B-VI[6] was prepared by condensing 150 cross section set for each core of this study. The initial plutonium enrichment of all considered cores is determined to have keff=1.0042 for initial, hot state and Pb cavity. And the optimal lattice pitch-to-diameter (P/D) ratio is determined such that the reactivity swing is minimized for 15 years. For searched cores, the temperature reactivity coefficients, the lead void reactivity, reactivity worth of the reflector, mass of heavy isotopes are calculated to estimate the feasibility. From the study, it is concluded that 125MWth (80W/cm) cores can be designed to have burnup reactivity swing of 0.2% while 250MWth (120W/cm) cores have burnup reactivity swing less than 0.8% for 15 years. However, the burnup of 125MWth (80W/cm) cores for 15 years is nearly same the burnup of 250MWth (120W/cm) cores for 10 years. Therefore, it is shown that if the burnup reactivity swing is minimized for 10 years, 250MWth (120W/cm) cores can be designed to have the burnup reactivity swing less than 0.3%.

II. Computational Methodology

II.1 Core Model

The original core model consists of fuel assemblies having 217 rods in a hexagonal array. The central assembly site is reserved for a safety rod assembly. Since this central site is filled with Pb during reactor operation, we calculated for this case. There are no blanket assemblies and no reflector assemblies. The Pb surrounding the core serves the reflector. All fuel rods are of a uniform composition. The fuel is a metallic alloy of U-Pu-10%Zr. Its density is assumed to be 75% of the nominal density. The uranium is 0.2 w/o depleted U-235 and the initial plutonium is from LWR spent fuel : the weight percents of the isotopes Pu-239, 240, 241, and 242 are 67.2, 21.7, 6.4, and 4.7, respectively. The clad is the stainless steel having 64.8w/o Fe, 17w/o Cr, 14w/o Ni, 2.8w/o Mo and 1.5 w/o Mn. The coolant is Pb. The diameter of fuel rod is 1cm and the chad thickness is 0.1cm. The radial reflector assembly includes a voided container (10.0w/o stainless steel) that is 15cm thick and as long as the fuel section in the core. The maximum reactivity is achieved when Pb surrounds the core. Most of our calculations are performed for this lead filled case in the cavity region. The proposed core model is shown in Fig. 1. The core model for neutronics calculation is R-Z homogeneous geometry. In this study, the radii of central control and core region are determined by the core thermal power, average linear heat generation rate, and P/D ratio. The dimensions in Fig. 1 are for 250MWth, 4m core height, P/D=1.15. The density of Pb is determined by 11.368 and (11072-1.2*T)/1000 (g/cm^3) for T=20C and T=673~973K, respectively. The material compositions and temperatures are given Table 1.

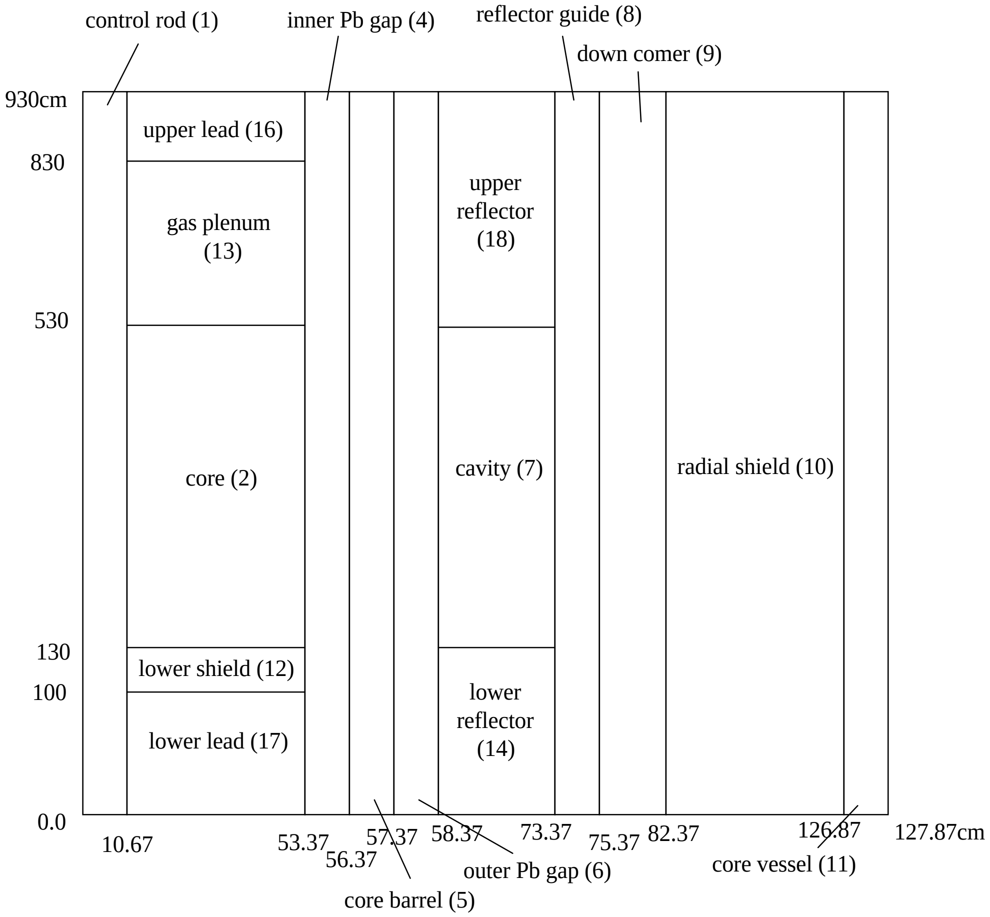

Fig. 1 Core model for neutronics calculation

Table 1 Material compositions, volume fractions, temperatures

Regions (region number)	material, volume fraction	Temperature (K)
Control rod region (1)	99%Pb + 1%SS	753
Core (2)	determined by P/D ratio	753
Inner Pb gap (4)	100%Pb	753
Core barrel (5)	100%SS	753
Outer Pb gap (6)	100%Pb	693
Cavity (7)	100%Pb (or 10%SS[a])	693
Reflector guide (8)	70%Pb+30%SS	693
Down comer (9)	100%Pb	693
Radial shield (10)	100%Pb	693
Core vessel (11)	100%SS	693
Lower shield (12)	100%Pb	693
Gas plenium (13)	determined by P/D ratio	813
Lower reflector (14)	100%Pb	693
Upper Pb (16)	100%Pb	813
Lower Pb (17)	100%Pb	693
Upper reflector (18)	90%Pb+10%SS	693

[a] Lead is not filled.

II.2 The Calculational Model, Methods, and Computer Codes

The nuclear library for master nuclides based on the ENDF/B-VI was processed by the TRNASX code[7] to generate the multi-group cross section set for neutronics calculation. For treatment of fission products, the lumped fission product model, based on isotopic data for 172 fission product isotopes were used to model the fission products from 17 fissionable isotopes (U-235, U-236, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Am-241, Am-242m, Am-243, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246) and one dummy isotope (dump). For neutronics calculation, the REBUS-3 depletion code developed by ANL was used in our calculations. In this code, the neutron diffusion equation using the DIF3D code (with finite difference option) was solved for R-Z geometry having the incoming current zero boundary conditions for outer surfaces of the reactor. In all depletion calculation, the nine group cross section set was used while the basic quantities including temperature reactivity coefficient, void reactivity, reflector worth were calculated by using 150 group cross section set. The nine group cross section sets were generated by using 150 group spectrum for each case. For consideration of space dependent isotopic depletion, the core region was divided into three radial zones and three axial zones (i.e., total nine zones).

III. Calculation Results

The design variables of this study are core thermal power, average heat generation rate, lattice P/D ratio, and core height. In this study, 125MWth (80W/cm) and 250MWth (120W/cm) cores were considered. For 125MWth cores, five core heights of 100cm, 125cm, 150cm, 200cm, 300cm were studied and for 250MWth cores, four core heights of 100cm, 125cm, 200cm, 400cm were studied. For given core thermal power, average linear heat generation rate, core height, lattice P/D ratio, the initial plutonium enrichment (PU/(U+PU)) such that keff of core (hot state, Pb cavity) becomes 1.0042 was determined. And then, the trend of keff for 15 years is estimated by the REBUS-3 code. If keff increases as time, the lattice P/D is increased and the plutonium enrichment is recalculated. However, if keff decreases as time, the lattice P/D ratio is reduced. In this way, the optimal P/D ratio such that the burnup reactivity swing is minimized for 15 years is determined.

III.1 125MWth, 80W/cm Cores

The initial plutonium enrichments for 100cm core height are given Table 2. The results show that the initial plutonium enrichment increases linearly as the lattice P/D ratio increases. Fig. 2 shows the keff versus time for several P/D ratios. From this results, it is shown that the burnup reactivity swing for 15 years can be maintained less than 0.1%.

Table 2 Initial Pu enrichment and keff versus P/D ratio (100cm core height)

P/D ratio	Pu enrichment(%)	Keff
1.245	11.234	1.004248
1.248	11.255	1.004232
1.250	11.269	1.004214
1.255	11.305	1.004204
1.260	11.341	1.004217
1.280	11.486	1.004228

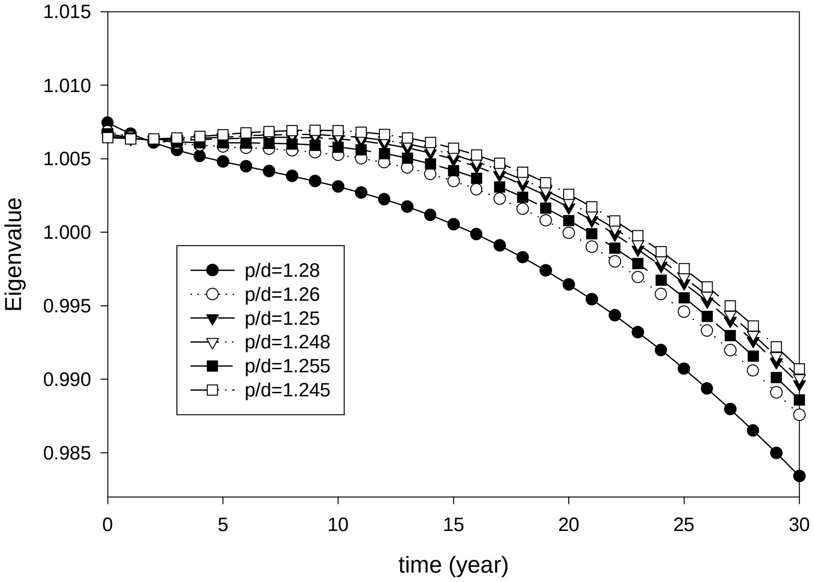

Fig. 2 keff versus time (100cm core height)

This minimum burnup reactivity swing of 0.012% occurs at the P/D ratio of 1.245. It must be noted that keff of the initial core in Fig. 2 is larger than 1.0042. This large value of keff is due to the use of nine group cross section while the initial plutonium enrichment is determined by using 150 group cross section.

Table 3 Optimal P/D ratios and initial Pu enrichments versus core height

Core height(cm)	P/D ratio	Initial Pu enrichment (wt%)	reactivity swing(%)	initial keff
100	1.245	11.234	0.012	1.004248
125	1.300	11.337	0.100	1.004211
150	1.320	11.361	0.100	1.004223
200	1.310	11.360	0.100	1.004262
300	1.180	11.120	0.130	1.004234

In Table 3, the optimal P/D ratios that give the minimum burnup reactivity swing for 15 years are compared. The results show that the P/D ratios for all core heights can be determined such that the burnup reactivity swing for 15 years is less than 0.14%. Table 4 shows core void reactivity (δk) and reflector worth (δk) for considered core heights.

Table 4 Core void reactivity (δk) and reflector worth (δk)

Core height (cm)	core void reactivity	reflector worth
100	+0.01944	0.009468
125	+0.02388	0.012403
150	+0.02645	0.0153
200	+0.02776	0.020671
300	+0.01935	0.029368

The reflector worth must be sufficiently large to compensate or control the reactivity changes due to cold-to-hot temperature change and burnup reactivity swing. For 125MWth (80W/cm) cores, the maximum value of the burnup reactivity change is less than 0.14% and as know later, the cold-to-hot reactivity change is approximately 0.4%. Therefore, the reflector worth must be larger than 0.54%. However, the practical design method is to design such that the core with steel cavity has keff=0.995 at cold state (startup temperature : 350C). Therefore, if the reactor is designed by this method, the reflector worth that can compensate the burnup reactivity swing of 0.14% must be larger than 1.04%. The core void reactivities (100% voided in core region) are all positive. However, in ENHS core, creation of such full voiding is practically impossible since the boiling temperature of Pb is 2022K, significantly higher than the melting temperature of metallic fuel and clad. Next, the neutronic characteristics for 200cm core height are analyzed in detail. Table 5 shows the reactivity coefficients and cold-to-hot reactivity swing.

Table 5 Reactivity coefficients and cold-to-hot reactivity swing (200cm core heigt)

Effects	cold-to-hot		nominal condition	
	difference in keff (δk)	temperature reactivity coefficients (C^{-1})	difference in keff (δk)	temperature reactivity coefficients (C^{-1})
Pb density change	-0.000203	-1.6117E-06	-0.000198	-1.6393E-06
Axial expansion of fuel rod	-0.000623	-4.9479E-06	-0.000528	-4.3672E-06
Radial expansion of core support structure	-0.001036	-8.2346E-06	-0.000976	-8.0774E-06
Doppler effect	-0.001998	-5.9027E-06	-0.001308	-5.9046E-06
Total sum	-0.003860		-0.003010	

As shown in Table 5, the cold-to-hot reactivity swing is -0.39% and all effects are negative. The heavy isotopes mass for this core is given in Table 6. Table 7 shows total plutonium mass, the ratio of fissile plutonium mass to total plutonium mass, breeding ratio, and keff. These results show that total mass of plutonium isotopes increases up to 60kg(4%) after 15 years and the fissile plutonium ratio is nearly constant as 0.73. The reactor breeding ratio is slightly larger than unity. The mass of Pu-239 and Pu-240 increase as time while the mass of Pu-241 and Pu-242 decreases. Fig. 3 shows the change of the heavy isotopes versus time.

Table 6 Heavy isotopes mass changes (kg)

Nuclide	0 yr	5 yr	10 yr	15 yr	20 yr	25 yr	30 yr
U-234	.000E+00	8.133E-03	6.051E-02	1.782E-01	3.635E-01	6.102E-01	9.081E-01
U-235	2.328E+01	1.911E+01	1.575E+01	1.303E+01	1.081E+01	8.990E+00	7.500E+00
U-236	.000E+00	8.212E-01	1.450E+00	1.928E+00	2.289E+00	2.559E+00	2.756E+00
U-238	1.162E+04	1.134E+04	1.107E+04	1.081E+04	1.056E+04	1.031E+04	1.007E+04
PU238	.000E+00	6.495E-01	2.283E+00	4.300E+00	6.375E+00	8.350E+00	1.016E+01
NP237	.000E+00	8.920E-01	1.659E+00	2.315E+00	2.874E+00	3.349E+00	3.750E+00
PU239	1.002E+03	1.044E+03	1.073E+03	1.091E+03	1.101E+03	1.104E+03	1.103E+03
PU240	3.237E+02	3.318E+02	3.402E+02	3.486E+02	3.567E+02	3.643E+02	3.715E+02
PU241	9.546E+01	6.883E+01	5.261E+01	4.275E+01	3.681E+01	3.331E+01	3.132E+01
PU242	7.010E+01	6.884E+01	6.723E+01	6.545E+01	6.364E+01	6.184E+01	6.008E+01
AM241	.000E+00	1.769E+01	2.843E+01	3.498E+01	3.899E+01	4.147E+01	4.302E+01
AM242M	.000E+00	2.093E-01	6.344E-01	1.100E+00	1.530E+00	1.900E+00	2.206E+00
AM243	.000E+00	2.130E+00	3.935E+00	5.461E+00	6.749E+00	7.832E+00	8.741E+00
CM242	.000E+00	1.646E-01	2.800E-01	3.482E-01	3.895E-01	4.158E-01	4.338E-01
CM243	.000E+00	1.423E-03	4.805E-03	8.524E-03	1.190E-02	1.474E-02	1.705E-02
CM244	.000E+00	1.154E-01	3.932E-01	7.566E-01	1.157E+00	1.563E+00	1.956E+00
CM245	.000E+00	2.704E-03	1.785E-02	4.993E-02	9.864E-02	1.615E-01	2.355E-01
CM246	.000E+00	1.956E-05	2.628E-04	1.121E-03	3.001E-03	6.243E-03	1.109E-02

Table 7 Total Pu mass (kg), (Pu-239+Pu-241)/Pu, breeding ratio, keff

time(yr)	Pu	(Pu-239+Pu-241)/Pu	breeding ratio	keff
0	1.49155E+03	.7360	1.15318E+00	1.00577E+00
1	1.49617E+03	.7359	1.14639E+00	1.00569E+00
2	1.50081E+03	.7357	1.13958E+00	1.00569E+00
3	1.50543E+03	.7356	1.13276E+00	1.00577E+00
4	1.51000E+03	.7353	1.12598E+00	1.00589E+00
5	1.51451E+03	.7351	1.11928E+00	1.00603E+00
6	1.51891E+03	.7347	1.11267E+00	1.00617E+00
7	1.52321E+03	.7344	1.10619E+00	1.00629E+00
8	1.52737E+03	.7340	1.09985E+00	1.00637E+00
9	1.53140E+03	.7336	1.09365E+00	1.00642E+00
10	1.53527E+03	.7331	1.08761E+00	1.00641E+00
11	1.53898E+03	.7327	1.08174E+00	1.00634E+00
12	1.54252E+03	.7322	1.07603E+00	1.00620E+00
13	1.54589E+03	.7316	1.07049E+00	1.00599E+00
14	1.54907E+03	.7311	1.06513E+00	1.00571E+00
15	1.55208E+03	.7305	1.05993E+00	1.00534E+00

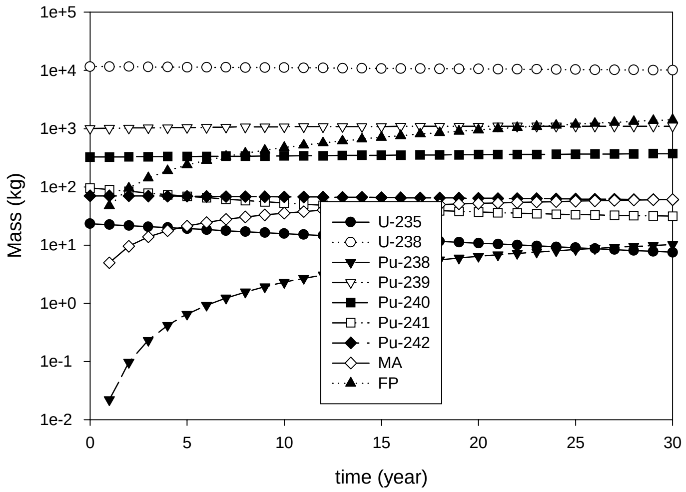

Fig. 3 Heavy isotepes mass changes over time

III.2 250MWth, 120W/cm Cores

The optimal P/D ratios, initial plutonium enrichments, burnup reactivity swings, and initial keffs are given in Table 8. Fig. 4 shows the keff change versus time and P/D ratio for 125cm core height. It is shown that the P/D ratio increased in comparison with that of 125MWth (80W/cm) cores.

Table 8 Optimal P/D ratio and initial Pu enrichment versus core height

Core height(cm)	P/D ratio	Initial Pu enrichment (wt%)	reactivity swing(%)	initial keff
100	1.31(1.34[a])	11.3516(11.5655[a])	0.74(0.28[a])	1.004207(1.004217[a])
125	1.39(1.42)	11.5296(11.7279)	0.74(0.27)	1.004192(1.004220)
200	1.47(1.48)	11.753(11.811)	0.80(0.23)	1.004219(1.004211)
400	1.24(1.26)	11.3002(11.413)	0.78(0.26)	1.004206(1.004274)

[a]Searched values for 10 years

Table 9 Core void reactivity (δk) and reflector worth (δk)

Core height (cm)	core void reactivity	reflector worth
100	+0.027478	0.006617
125	+0.033617	0.008698
200	+0.041940	0.014853
400	+0.027549	0.027756

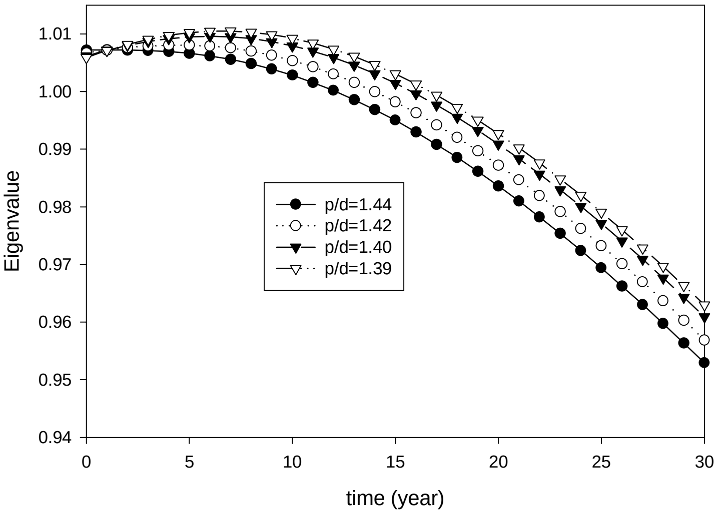

Fig. 4 keff versus time (125cm core height)

As shown in Fig. 4, the reactivity change due to burnup is comparatively larger than the previous case. This is due to the large burnup in comparison with 125MWth (80W/cm) core. The core average burnup of 125MWth (80W/cm) core for 15 years corresponds to that of 250MWth (120W/cm) for 10 years. Therefore, the results show that if the burnup reactivity swing is minimized for 10 years, 250MWth (120W/cm) cores can be designed to have the burnup reactivity swing less than 0.3%. Table 9 shows core void reactivity (δk) and reflector worth (δk) for considered core heights. It is noted that the reflector worth increases as the core height increases. In fact, the reflector worth is insensitive to P/D ratio. The result shows that the core void reactivities are larger than those of 125MWth (80W/cm) cores. This larger values of core void reactivity are due to the hard spectrum resulted from P/D ratio increase. Next, the neutronic characteristics for 125cm core height, P/D=1.42 are analyzed in detail. Table 10 shows the reactivity coefficients and cold-to-hot reactivity swing.

Table 10 Reactivity coefficients and cold-to-hot reactivity swing (125cm core heigt)

Effects	cold-to-hot		nominal condition	
	difference in keff (δk)	reactivity coefficients (C^{-1})	difference in keff (δk)	reactivity coefficients (C^{-1})
Pb density change	+0.00008096	+0.62747E-06	+0.000108	+0.89918E-06
Axial expansion of fuel rod	-0.0004630	-3.59042E-06	-0.0003967	-3.28023E-06
Radial expansion of core support structure	-0.0011913	-9.24454E-06	-0.0011165	-9.23762E-06
Doppler	-0.0019916	-5.74517E-06	-0.0012577	-5.67677E-06
Total sum	-0.0035649		-0.0026629	

As shown in Table 10, the cold-to-hot reactivity swing is -0.36% and all effects are negative except Pb density effect. The heavy isotopes mass for this core is given in Table 11. Table 12 shows total plutonium mass, the ratio of fissile plutonium mass to total plutonium mass, breeding ratio, and keff. These results show that total mass of plutonium isotopes increases up to 98kg(4.8%) for 15 years. However, the change percentage of plutonium mass and the fissile plutonium mass ratio for 10 years are nearly same as those of 125MWth (80W/cm) core.

Table 11 Heavy isotopes mass changes (kg)

Nuclides	0 yr	5 yr	10 yr	15 yr	20 yr	25 yr	30 yr
U-234	.000E+00	1.601E-02	1.129E-01	3.167E-01	6.185E-01	9.972E-01	1.429E+00
U-235	3.091E+01	2.314E+01	1.747E+01	1.328E+01	1.014E+01	7.777E+00	5.991E+00
U-236	.000E+00	1.527E+00	2.548E+00	3.223E+00	3.654E+00	3.912E+00	4.045E+00
U-238	1.542E+04	1.488E+04	1.436E+04	1.387E+04	1.338E+04	1.291E+04	1.245E+04
PU238	.000E+00	1.273E+00	4.226E+00	7.587E+00	1.080E+01	1.368E+01	1.615E+01
NP237	.000E+00	1.518E+00	2.730E+00	3.691E+00	4.446E+00	5.029E+00	5.468E+00
PU239	1.380E+03	1.450E+03	1.486E+03	1.499E+03	1.496E+03	1.481E+03	1.457E+03
PU240	4.455E+02	4.634E+02	4.813E+02	4.982E+02	5.134E+02	5.267E+02	5.380E+02
PU241	1.314E+02	9.166E+01	7.052E+01	5.941E+01	5.381E+01	5.127E+01	5.043E+01
PU242	9.649E+01	9.394E+01	9.067E+01	8.721E+01	8.379E+01	8.053E+01	7.748E+01
AM241	.000E+00	2.305E+01	3.553E+01	4.241E+01	4.626E+01	4.848E+01	4.978E+01
AM242M	.000E+00	3.878E-01	1.080E+00	1.745E+00	2.292E+00	2.712E+00	3.023E+00
AM243	.000E+00	4.221E+00	7.520E+00	1.009E+01	1.208E+01	1.361E+01	1.477E+01
CM242	.000E+00	3.183E-01	5.175E-01	6.262E-01	6.913E-01	7.356E-01	7.700E-01
CM243	.000E+00	4.092E-03	1.279E-02	2.136E-02	2.849E-02	3.414E-02	3.861E-02
CM244	.000E+00	3.420E-01	1.112E+00	2.055E+00	3.028E+00	3.958E+00	4.809E+00
CM245	.000E+00	1.192E-02	7.341E-02	1.931E-01	3.608E-01	5.617E-01	7.816E-01
CM246	.000E+00	1.325E-04	1.668E-03	6.716E-03	1.709E-02	3.396E-02	5.794E-02

Table 12 Total Pu mass (kg), (Pu-239+Pu-241)/Pu, breeding ratio, keff

Time(yr)	Pu	(Pu-239+Pu-241)/Pu	breeding ratio	keff
0	2.05305E+03	.7360	1.13325E+00	1.00669E+00
1	2.06354E+03	.7358	1.12224E+00	1.00720E+00
2	2.07349E+03	.7355	1.11171E+00	1.00759E+00
3	2.08291E+03	.7351	1.10159E+00	1.00789E+00
4	2.09179E+03	.7346	1.09193E+00	1.00805E+00
5	2.10009E+03	.7340	1.08271E+00	1.00805E+00
6	2.10781E+03	.7333	1.07395E+00	1.00788E+00
7	2.11494E+03	.7325	1.06562E+00	1.00753E+00
8	2.12148E+03	.7317	1.05773E+00	1.00699E+00
9	2.12746E+03	.7308	1.05024E+00	1.00626E+00
10	2.13284E+03	.7298	1.04314E+00	1.00536E+00
11	2.13767E+03	.7288	1.03643E+00	1.00427E+00
12	2.14194E+03	.7278	1.03006E+00	1.00300E+00
13	2.14566E+03	.7267	1.02404E+00	1.00156E+00
14	2.14887E+03	.7256	1.01834E+00	9.99955E-01
15	2.15154E+03	.7244	1.01295E+00	9.98191E-01

IV. Summary and Conclusions

In this paper, a feasibility study for designing Pu-U-Zr fueled, long life, lead cooled ENHS cores having zero reactivity swing up to 15 years was performed by determining the lattice pitch-to-diameter ratio for several cases of core height. In this study, 125MWth (80W/cm) and 250MWth (120W/cm) cores was selected. The optimal lattice pitch-to-diameter (P/D) ratio was determined such that the reactivity swing is minimized for 15 years. For searched cores, the temperature reactivity coefficients, the lead void reactivity coefficient, reactivity worth of the reflector, mass of heavy isotopes were calculated and analyzed to estimate the feasibility. From the study, it is concluded that 125MWth (80W/cm) cores can be designed to have burnup reactivity swing of 0.2% while 250MWth (120W/cm) cores have burnup reactivity swing less than 0.8% for 15 years. However, the core average burnup of 125MWth (80W/cm) cores for 15 years is approximately same that of 250MWth (120W/cm) cores for 10 years. Therefore, it is shown that if the burnup reactivity swing is minimized for 10 years, 250MWth (120W/cm) cores can be designed to have the burnup reactivity swing less than 0.3%. The core reactivity changes for full voiding are positive for all cases but the such full voiding is practically impossible in the ENHS cores. The cold-to-hot reactivity swing that was negative was approximately 0.4% for all cases. The core height must be sufficiently large such that the reflector worth can control the reactivity changes due to cold-to-hot reactivity swing and burnup swing.

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