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Sodium versus Lead-Bismuth Coolants for the ENHS (Encapsulated Nuclear Heat Source) Reactor

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Abstract *– The neutronic feasibility of designing cores for the ENHS (Encapsulated Nuclear Heat Source) reactor using sodium rather than lead-bismuth coolants is investigated. The cores considered are to be of uniform composition and to have no blanket elements and solid reflectors. They are to operate up to the fuel radiation damage limit without refueling, without fuel shuffling and with bunrup reactivity swings that is lower than 0.2%. It was found possible to design once-for-life cores for the ENHS reactor that will feature nearly zero burnup reactivity swing using either Pb-Bi (Pb is essentially the same) or sodium coolants. Relative to Pb-Bi cooled cores, sodium cooled cores feature tighter lattice and therefore more compact cores, spikier power distribution and more positive coolant temperature coefficient of reactivity. Due to their larger peak-to-average power distribution, the average discharge burnup of all-sodium cooled cores is smaller by ~5% than that of Pb-Bi cooled cores. Of the sodium-cooled cores considered, the one using lead-bismuth for the secondary coolant offers flatter power distribution and significantly larger reactivity worth of the peripheral absorber.*

I. INTRODUCTION

The Encapsulated Nuclear Heat Source (ENHS) is a Pb or Pb-Bi cooled innovative 125 MW_{th} reactor intended primarily for countries with small and medium electricity grid [1-6]. Unique features of the ENHS that affect the core design include 20 years of operation without refueling, no fuel shuffling, 100% natural circulation and autonomous operation. In order to achieve these features it was decided to design the core so as to maintain a nearly zero burnup reactivity swing and to have a significantly negative temperature reactivity feedback. Previous studies [7, 8] found that it is possible to achieve the above stated design goals when Pb or Pb-Bi are used for the primary and secondary coolants. The primary purpose of this work is to assess the feasibility of designing ENHS cores using sodium for the coolant. Another purpose of this work is to compare the neutronic characteristics of Na versus Pb-Bi cooled cores.

Three ENHS reactors having different coolants for the primary and secondary cooling systems are considered. The first reactor (DESIGN-I) uses lead-bismuth for both primary and secondary coolants; this design was reported upon in references [7, 8]. The second reactor (DESIGN-II) uses sodium for the primary and secondary coolants. The third reactor (DESIGN-III) uses sodium for the primary coolant and lead-bismuth for the secondary coolant.

Following a general description of the ENHS core model and computational system used for this study (Section II), we describe the three different cores designed (Section III) and compare their properties (Section III). The core design variables are, in addition to the coolant, the pitch-to-diameter (p/d) ratio and the initial plutonium weight percent. Only neutronic design issues are addressed.

II. REACTOR DESCRIPTION AND COMPUTATIONAL METHODS

Figure 1 and Table I describe the geometry, dimensions and compositions used for modeling the ENHS reactor (DESIGN-I) where the primary and secondary systems use lead-bismuth as the coolant. The axial dimensions of the figure are the same for other two considered cores while the radial dimensions are different from each other. The radial dimensions are determined from the pitch-to-diameter ratios giving the minimum burnup reactivity swing. The core is a bundle of fuel rods positioned at the bottom on grid plate pedestals. There are no blanket rods and no reflector rods. The unit cell is triangular. For the neutronics calculation the core is homogenized into a single annular cylindrical region. The reference core has 125cm long fuel and is designed to generate $125MW_{th}$ thermal power with an average linear heat generation rate of 101.4W/cm. The number of total fuel rods needed is 9862. The fuel in all the rods is of a uniform composition (U-Pu-10Zr) and the fuel smear density is assumed to be 75% of the nominal density. The uranium is depleted to $0.2^{w}/_{o}$ U-235 and the plutonium initial composition is assumed to be: $67.2\ ^{w}/_{o}\ ^{239}$Pu, $21.7\ ^{w}/_{o}\ ^{240}$Pu, $6.4\ ^{w}/_{o}\ ^{241}$Pu, and $4.7\ ^{w}/_{o}\ ^{242}$Pu. The cladding inner radius and cladding thickness are 0.65cm and 0.13cm, respectively.

Lead is used in this study instead of Pb-Bi as the neutronic characteristics of Pb and Pb-Bi are nearly the same. For DESIGN III lead-bismuth is used only in the down comer region whereas sodium is used for the coolant in all other regions. The structural material is HT-9. However, stainless steel having 64.8w/o Fe, 17w/o Cr, 14w/o Ni, 2.8w/o Mo, and 1.5w/o Mn is used in this study. This leads to a conservative design as replacing the SS with HT-9 increases BOL k_{eff} by 0.75%.

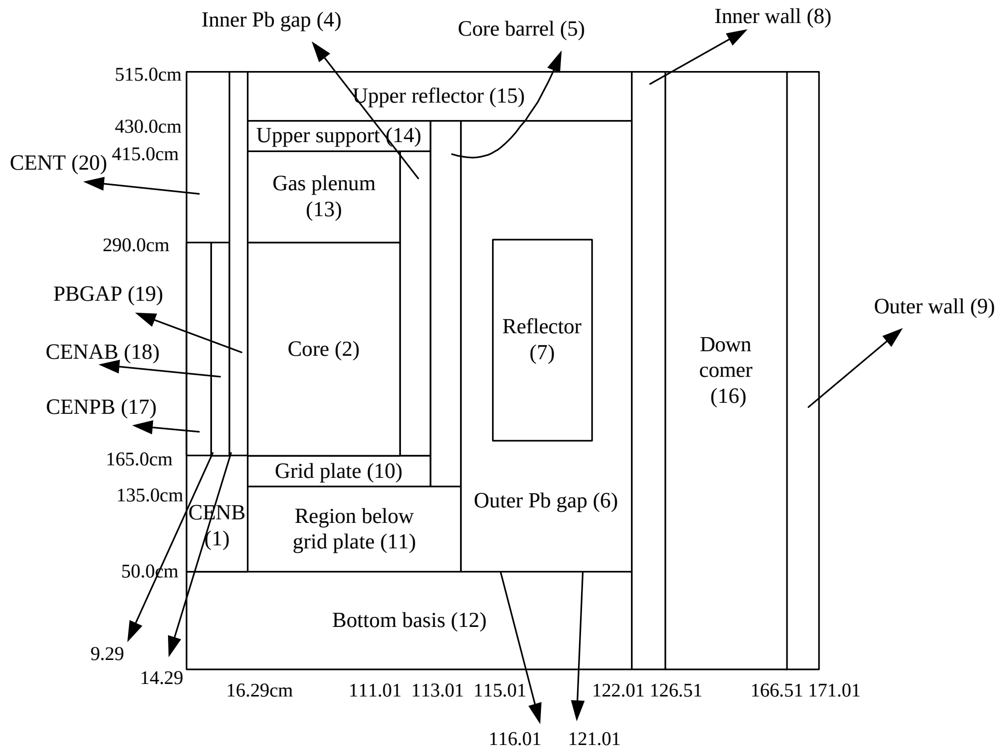


Figure 1. Configuration of the reference ENHS reactor (DESIGN I)

Table I. Material Compositions for the Reference ENHS Reactor (DESIGN I)

Region No.	Region name	Material volume fractions	Temp (K)
1	Bottom of absorber	99%Pb-Bi + 1%SS	698
2	Core region	50.24%Pb-Bi + 34.56% fuel + 15.20%SS	698
4	Inner Pb-Bi[a] gap	100%Pb-Bi	698
5	Core barrel	100%SS	698
6	Outer Pb-Bi gap	100%Pb-Bi	623
7	Space for peripheral absorber	100%Pb-Bi	623
8	Inner structural wall	100%SS	623
9	Outer structural wall	100%SS	623
10	Lower grid plate	50%Pb-Bi + 50%SS	623
11	Below grid plate	80%Pb-Bi + 20%SS	623
12	Bottom base	100%SS	623
13	Fission gas plenum	50.24%Pb-Bi + 15.20%SS	773
14	Upper grid plate	50%Pb-Bi + 50%SS	773
15	Upper reflector	100%Pb-Bi	773
16	Down comer	100%Pb-Bi	624
17	Pb-Bi region of absorber	100%Pb-Bi	698
18	Space for central absorber	100%Pb-Bi	698
19	Gap of absorber	100%Pb-Bi	698
20	Top of absorber	20%SS	698

The DIF3D code [9] is used with the R-Z cylindrical model to solve the neutron diffusion equation. The depletion calculation is performed with the REBUS-3 code [10] using the neutron flux obtained from the 80 group DIF3D calculation. For space dependent isotopic depletion, the core is divided into nine equal volume zones (three radial/three axial zones). The atomic densities in each zone are assumed to be constant. The multigroup cross sections for the neutronics calculations are generated from the ENDF/B-VI based 150 group cross section library [11] for master nuclides and from the ENDF/B-VI based 80 group cross section library [12] for fission products. The cross section sets (ISOTXS format) used in DIF3D are generated from these libraries using TRANSX [13] that accounts for self-shielding and temperature effects. 17 lumped fission products and one dummy isotope are used to model 172 fission products for each of the fissionable isotopes ranging from U-234 to Cm-246. All physics parameters at BOL are calculated using the 150 group cross section set while those at EOL are calculated using the 80 group cross section set because the 150 group cross section library is not available for fission products. This computational method has been benchmarked against MOCUP [14, 15].

III. CORES DESIGN AND PERFORMANCE

III.1 Optimal Core Designs

The search for the optimal cores involves a parametric search of a combination of lattice pitch-to-diameter (p/d) ratio and initial plutonium weight percent that gives a BOL k_{eff} of 1.0042 and as flat as possible k_{eff} over 20 years of full power operation. The above target k_{eff} value is slightly larger than unity so as to accommodate uncertainties in data and computations. Figure 2 shows the k_{eff} evolution with burnup for the three designs. Table II shows the corresponding optimal p/d ratios, initial plutonium concentration and the burnup reactivity swing.

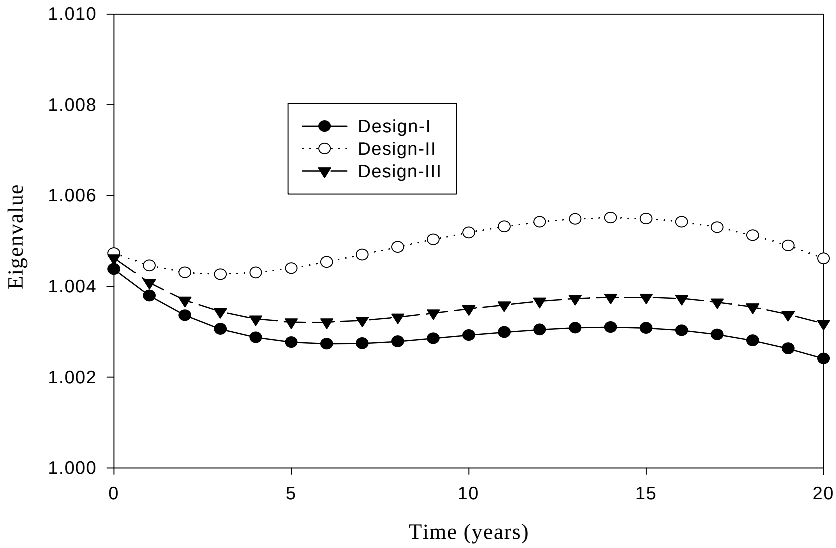


Figure 2. Comparison of the k_{eff} eigenvalue evolution of the optimal cores

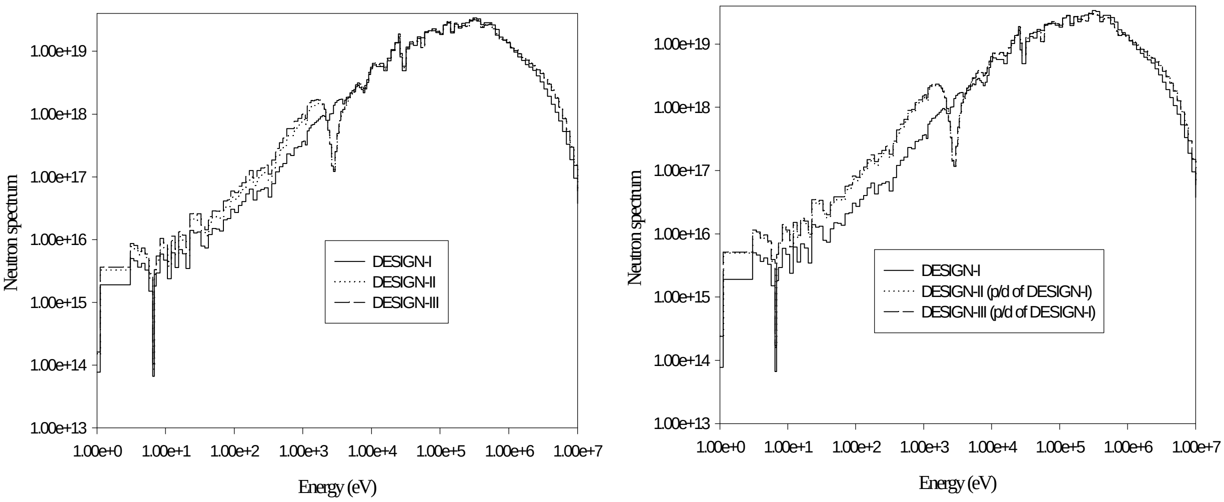
Table II. P/D Ratio, Initial Pu Enrichment, and Burnup Reactivity Swing

Characteristic	Design-I	Design-II	Design-III
P/D	1.35	1.16	1.20
Initial Pu enrichment (wt%)	11.344	11.012	11.145
Burnup reactivity swing (dk,%)	0.197	0.125	0.144

The different slopes of the k_{eff} evolution of three cores is not inherent characteristic of the different cores; the slope can be modified by fine tuning the p/d ratio and corresponding plutonium weight percent. The same applies to the resulting burnup reactivity swing; the maximum burnup reactivity swing over 20 years is less than 0.2% -- this is less than 0.5$. It is concluded that uniform composition cores that have no blankets or solid reflectors can be designed for the ENHS using sodium for the primary coolant with either sodium or Pb-Bi secondary coolant. The optimal p/d ratio with all sodium cooling is smaller than with all Pb-Bi cooling by 14%. The initial plutonium inventory needed for all sodium cooling is lower than for all Pb-Bi cooling by 3%.

III.2 Neutron Balance and Spectra

Figure 3a compares the neutron spectra of DESIGN-I, DESIGN-II and DESIGN-III while Figure 3b compares the neutron spectra of DESIGN I, DESIGN-II with the p/d ratio of DESIGN-I and DESIGN-III with the p/d ratio of DESIGN-I. It is seen (Fig. 3a) that DESIGN-I has the hardest neutron spectrum. Of the sodium-cooled cores, DESIGN-III has a slightly softer spectrum than DESIGN-II. This is probably due to the somewhat larger p/d of DESIGN-III. The pitch of DESIGN-III is larger than that of DESIGN-II because the leakage probability from DESIGN-III is smaller (Table IIIa) due to the superior reflection properties of Pb-Bi. Although the sodium-cooled cores are more leaky (Table IIIa), the fraction of neutrons absorbed in sodium is smaller. The combined neutron loss via leakage and absorption in the coolant varies only slightly from design to design. Had the pitch of all the cores was to be that of DESIGN-I, the neutron loss rate in the sodium-cooled cores would have been significantly larger (Table IIIb) and the spectrum of these cores would have been significantly softer (Figure 3b).



(a) DESIGN-I, II, III (b) DESIGN-I, II, III using DESIGN-I p/d

Figure 3. Comparison of the neutron spectra

Table IIIa. Neutron Balance in the Reference Designs

Fraction of neutron lost in core (%)	DESIGN-I	DESIGN-II	DESIGN-III
Via leakage)	17.2	19.5	18.47
Via absorption in coolant	1.53	0.122	0.149
Combined	18.7	19.62	18.61

Table IIIb. Neutron Balance in Equal p/d Designs

Fraction of neutron lost in core (%)	DESIGN-I	DESIGN-II p/d of DESIGN-I)	DESIGN-III (p/d of DESIGN-I)
Via leakage)	17.2	22.2	20.5
Via absorption in coolant	1.53	0.26	0.26
Combined	18.7	22.5	20.8

III.3 Reactivity Coefficients

Tables IV and V compare selected characteristics of the three reference cores at BOL and EOL, respectively. Most of the reactivity coefficients at EOL are more positive than those at BOL. The temperature coefficients of reactivity are found all negative except for that of the coolant expansion. However, the negative reactivity coefficient associated with the radial expansion of the core structure can compensate for the coolant thermal expansion effect. Sodium cooled cores have significantly more positive reactivity coefficients of coolant expansion than do lead-bismuth cooled cores. This is probably due to the fact that the thermal expansion coefficient of sodium is more than twice that of Pb-Bi. The void coefficients for 100% voiding of the inner and middle zones of the cores are positive. The void coefficient for the all-sodium reactor is the smallest as sodium does not make as good a reflector as does Pb-Bi. However, creation of voiding in the Pb-Bi cooled ENHS core is practically impossible since the boiling temperature of Pb-Bi is 1943K; that is 1000K higher than the operating temperature and even higher than the melting temperature of the metallic fuel and clad. This is not the case in sodium-cooled cores because the sodium boiling temperature is 1165K.

Table IV. ENHS Reference Cores Physics Data at BOL

Performance Parameter	Design-I	Design-II	Design-III
Peak-to-average power density	1.767	1.979	1.838
Peak linear heat rate (W/cm)	177.8	198.4	184.1
Peak-to-average channel power	1.425	1.609	1.518
Peak-to-average power density in hot channel	1.241	1.222	1.205
Peak fast (E>0.1MeV) neutron flux (n/cm^2-s)	5.681E+14	6.016E+14	5.381E+14
Doppler effect (dk/kk' -^{o}C)	-5.78547E-06	-7.74013E-06	-8.78411E-06
Axial fuel expansion (dk/kk' -^{o}C)	-4.42189E-06	-4.67289E-06	-4.58022E-06
Coolant expansion (dk/kk' -^{o}C)	+5.17092E-07	+2.55179E-06	+4.90317E-06
Grid-plate radial expansion (dk/kk' -^{o}C)	-8.97388E-06	-9.74617E-06	-9.78798E-06
Cold (350^{o}C) to hot (480^{o}C; fuel: 700^{o}C) ρ swing (dk)			
Doppler effect	-2.03373E-03	-2.58298E-03	-2.72680E-03
Axial fuel expansion	-0.56615E-03	-0.64540E-03	-0.64323E-03
Coolant expansion	+0.04453E-03	+0.50108E-03	+0.57576E-03
Grid-plate expansion	-1.15292E-03	-1.29691E-03	-1.27101E-03
Total	-3.70827E-03	-4.02421E-03	-4.06500E-03
Void reactivity effect (dk)			
Voiding inner 1/3 core	+2.54917E-02	+1.93969E-02	+2.15242E-02
Voiding middle 1/3 core	+0.88586E-02	+0.73246E-02	+0.97206E-02
Voiding outer 1/3 core	-0.31642E-02	-0.04298E-02	-0.12343E-02
Voiding whole core	+3.11058E-02	+2.65124E-02	+3.31608E-02
Peripheral absorber reactivity worth (dk)	0.01130	0.01306	0.02343
Central absorber reactivity worth (dk)	0.042	0.03692	0.03456
Peripheral absorber+central absorber worth(d k)	0.0609	0.05343	0.06404

Table V. ENHS Reference Cores Physics Data at EOL

Performance Parameter	Design-I	Design-II	Design-III
Peak-to-average power density	1.778	2.000	1.859
Peak linear heat rate (W/cm)	178.7	200.5	186.2
Peak-to-average channel power	1.435	1.626	1.526
Peak-to-average power density in hot channel	1.235	1.227	1.213
Peak fast (E>0.1MeV) neutron flux (n/cm^2-s)	5.895E+14	6.104E+14	5.469E+14
Peak burnup after 20 EFPY (GWD/tHM)	95.2	107.1	99.22
Average burnup after 20 EFPY (GWD/tHM)	50.7	50.7	50.5
Peak fast fluence (E>0.1MeV) (n/cm^2)	3.646E+23	3.847E+23	3.476E+23
Doppler effect (dk/kk' -^{o}C)	-4.55582E-06	-6.00346E-06	-6.85144E-06
Axial fuel expansion (dk/kk' -^{o}C)	-4.39633E-06	-4.74674E-06	-4.67921E-06
Coolant expansion (dk/kk' -^{o}C)	+9.68071E-07	+4.27626E-06	+6.73033E-06
Grid-plate radial expansion (dk/kk' -^{o}C)	-6.80369E-06	-7.16587E-06	-6.95412E-06
Cold (350^{o}C) to hot (480^{o}C; fuel: 700^{o}C) ρ swing (dk)			
Doppler effect	-1.65620E-03	-2.22095E-03	-2.53791E-03
Axial fuel expansion	-0.57690E-03	-0.60673E-03	-0.61615E-03
Coolant expansion	+0.14029E-03	+0.58601E-03	+0.87160E-03
Grid-plate expansion	-0.89738E-03	-0.92329E-03	-0.91712E-03
Total	-2.99013E-03	-3.16495E-03	-3.19958E-03
Void reactivity effect (dk)			
Voiding inner 1/3 core	+2.65734E-02	+2.21336E-02	+2.4492E-02
Voiding middle 1/3 core	+0.94506E-02	+0.83456E-02	+1.09435E-02
Voiding outer 1/3 core	-0.29761E-02	-0.01066E-02	-0.16255E-02
Voiding whole core	+3.28106E-02	+3.06038E-02	+3.77504E-02
Peripheral absorber reactivity worth (dk)	0.01047	0.01163	0.02109
Central absorber reactivity worth (dk)	0.042	0.03599	0.03359
Peripheral absorber+central absorber worth(d k)	0.0609	0.50972	0.60132

III.4 Absorbers Reactivity Worth

The peripheral absorber is designed to have reactivity worth that is sufficient to compensate for the reactivity variations associated with changes in the reactor state from the startup temperature of 350C through BOL at full power to EOL at full power. The total reactivity deficiency that needs to be compensated is ~1.07%. The peripheral absorber of DESIGN-I referred to in Table IV and V is made of $80^v/_o$ tungsten at 75% nominal density and of $20^v/_o$ SS. Tungsten is chosen for the absorber as its density is higher than that of Pb-Bi so that the peripheral absorber can be scrammed by gravity. On the other hand, the peripheral absorbers of DESIGN-II and III are made of $40^v/_o$ tungsten (75% nominal density), $40^v/_o$ B_4C (75% nominal density), and $20^v/_o$ SS because the reactivity worth of DESIGN-I like peripheral absorber is too small for the sodium cooled cores (DESIGN-II, III). The boron is enriched to 92% ^{10}B. The thickness of the peripheral absorbers for the three reactors is 5.0cm. The reactivity worth of the peripheral absorber of DESIGN-III is almost twice that of DRESIGN-II (Table IV and V). This is due to the combined effect of the leakiness of a sodium-cooled core and the good reflection propertied of Pb-Bi. If desirable, the reactivity worth of the peripheral absorber can be increased by increasing its thickness.

The central absorber is designed to have sufficient reactivity worth to be able to shut down the core. In addition, the combined insertion of the central and peripheral absorbers is to bring k_{eff} to below 0.95. The central absorber of DESIGN-I is made of $50^v/_o$ tungsten (75% nominal density), $30^v/_o$ B_4C (75% nominal density), and $20^v/_o$ SS while those of DESIGN-II and III are made of $40^v/_o$ tungsten (75% nominal density), $40^v/_o$ B_4C (75% nominal density), and $20^v/_o$ SS. In all three designs the central absorber is in the form of an annular cylinder that is 5cm thick; its radii are 9.29cm and 14.29cm (Figure 1). If desirable, the reactivity worth of the central absorber can be increased by increasing its thickness.

III.5 Power Distribution

Of the three reference designs, DESIGN-II has largest power peaking factor of 1.979 whereas DESIGN-I has the smallest power peaking factor of 1.767. Figure 4 shows the BOL axial power distribution in the hottest channel and the radial power distribution for the three reference cores. Figure 4b shows that lead reflectors flattens the radial power distribution relative to sodium reflector. The figure also shows that with sodium coolant there is a noticeable power spiking at the inner boundary; it is due to the enhanced slowing down of neutrons at the central cavity when filled with Na.

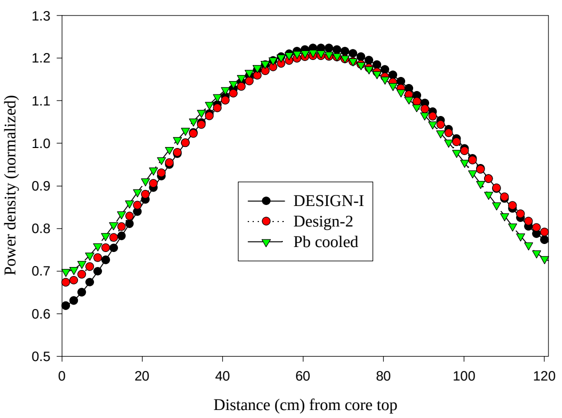


Figure 4a. Axial power distributions in the hottest channel at BOL

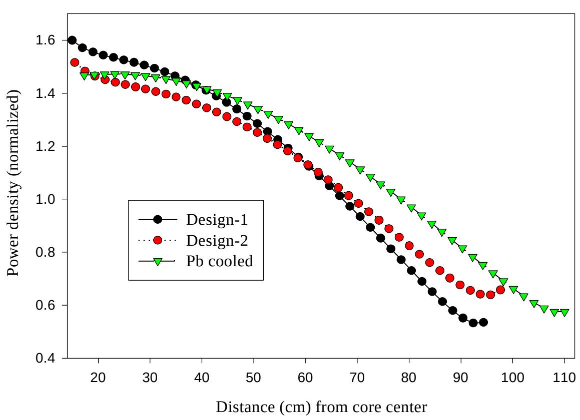
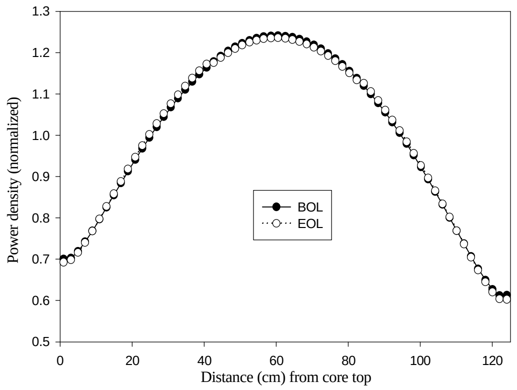


Figure 4b. Radial power distributions at BOL

Figure 5 shows that the power distribution is nearly constant through the core life. Figure 5(a) and 5(b) show the axial power distributions of DESIGN-I at BOL and EOL in the hottest channel and the radial power distributions at BOL and EOL, respectively.



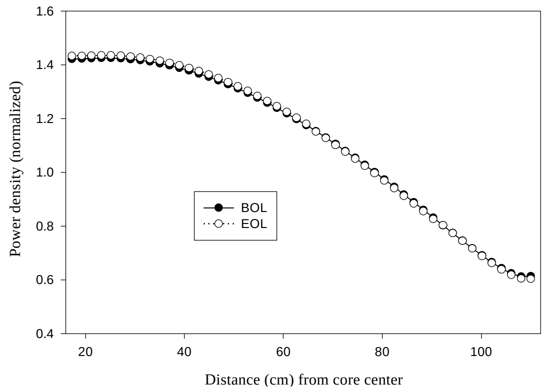
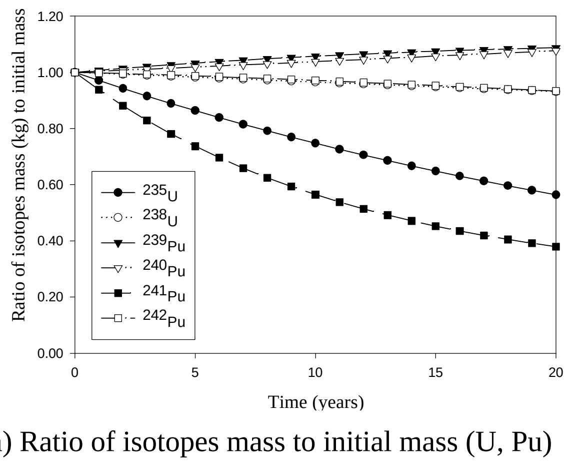


Figure 5a. Axial power distribution at BOL and EOL (normalized)

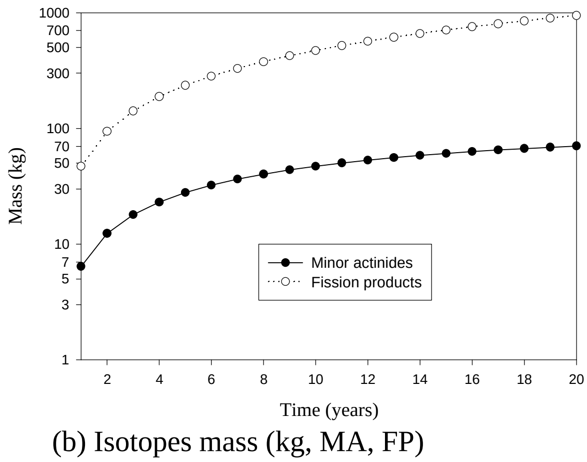
Figure 5b. Radial power distribution at BOL and EOL (normalized)

III.6 Fuel Composition Evolution

Figure 6 shows the evolution with burnup of the fuel isotope inventory in DESIGN-I. The other designs show similar trends. The total plutonium inventory increases in 20 years of full power operation by 3.6~4.4%. The inventory of Pu-239 and Pu-240 increases by 116kg (8.7%) and 33kg (7.7%), respectively while the inventory of Pu-241 and Pu-242 decreases by 78.92kg (62%) and 6.26kg (7%), respectively. The particularly large decrease in the Pu-241 inventory is due to the fact that the average power density of the ENHS cores is significantly lower than that of a high power density fast reactor the plutonium feed is assumed taken from. The few percent increase in the plutonium as well as of the total transuranics inventory is needed to compensate for the negative reactivity effect of the fission products; their inventory keeps increasing with time. Fortunately, the few percents increase in the transuranics inventory enable to bring the k_∞ of the discharged fuel back to the BOL k_∞ after removal of just fission products and addition of depleted uranium makeup fuel.



(a) Ratio of isotopes mass to initial mass (U, Pu)



(b) Isotopes mass (kg, MA, FP)

Figure 6. Evolution of fuel isotopes inventory

IV. CONCLUSIONS

Neutronically, it is possible to design the once-for-life uniform composition and blanket free cores for the Encapsulated Nuclear Heat Source that will feature nearly zero burnup reactivity swing using either Pb-Bi (Pb is essentially the same) or sodium coolants. Relative to Pb-Bi cooled cores, sodium cooled cores feature tighter lattice and therefore more compact cores, spikier power distribution and more positive coolant temperature coefficient of reactivity. Due to their larger peak-to-average power distribution, the average discharge burnup of all-sodium cooled cores will be smaller by ~5% than that of Pb-Bi cooled cores. Of the sodium-cooled cores considered, the one using lead-bismuth for the secondary coolant offers flatter power distribution and significantly larger reactivity worth of the peripheral absorber.

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