# Power Flattening Options for the ENHS (Encapsulated Nuclear Heat Source) Core

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- Good morning everyone, My topic is on the power flattening options for the ENHS (Encapsulated Nuclear Heat Source) reactor core.

- This work was supproted by the Post-Doctral Fellowship Program of Korea Science and Engineering Foundation (KOSEF) and University of California, Berkeley. user, 2004/10/29

#### □ Introduction

**Reactor Model and Assumptions** 

□ Design Goals, Constraints and variables

□ Core Design Options

**Core Performance** 

**Conclusions** 

#### □ ENHS (Encapsulated Nuclear Heat Source) Design Features

- 125MWt Low power density Pb or LBE cooled core
- A Battery-type Innovative Generation-IV power reactor
- Highly modular, factory manufactured and fueled in large numbers
- No fuel handling in the host country
- At least 20 years autonomous operation without refueling
- Fuel-self-sufficient core (CR~1.0) with a uniform fuel composition/without blanket assemblies: burnup reactivity swing <1\$</li>
- Natural circulation core heat removal : No valves, No pumps
- Very small probability of core damage accidents
- Fully passive removal of decay heat
- Natural safety: Negative reactivity feedback

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u16 - The ENHS reactor is a 125MWt low power density lead or lead-bismuth cooled fast spectrum

The Endits reactor is a r250kWt low power density read of read-bishuth cooled last spectrum battery-type innovative GEN-IV power reactor.
This reactor is highly modular, factory manufactured and fueled and features 20 effective full power years of operation without refueling and fuel shuffling, 100% natural circulation, nearly constant power shape throughout life, autonomous operation and superb safety.
In the original design, the core consists of uniform composition fuel rods and it is designed to have conversion ratio of nearly unity during core life, and nearly zero burnup reactivity swing.

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#### Objective of Present Work

- To assess feasibility of power flattening core options while maintaining flat k<sub>eff</sub> over core life
  - Reduce the peak-to-average power peaking to increase core power
  - Reduce the peak-to-average discharge burnup and fast neutron fluence to increase the fuel utilization and core life
  - Analyze and compares the core performances of the new design options

#### スライド 4

#### u17 - The objective of this work is to assess feasibility of power flattening core design options while maintaining flat keff over core life.

- In this work, the several design options are considered for the reduction of the peak-to-average power peaking that makes it possible to increase core power and to increase the discharge burnup up to fast neutron fluence limit and their core performances are analyzed and compared. user, 2004/10/29



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- This figure shows the geometrical model of the ENHS reactor for neutronic analysis. user, 2004/10/29

# **Reactor Model and Assumptions**

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#### □ Reactor Model, Assumptions, and Computational Methods

- IFR type metallic fuel of Pu-U-10Zr
  - Pu is taken from LWR spent fuel (50GWD/tHM,10years cooling)
  - 75% smear density
- HT-9 for all structural materials including clad
- The lattice pitch of the reference ENHS (2.1216 cm) is kept for all cases.
- The core is homogenized into a cylindrical annulus.
- For depletion analysis, the core is divided into 9 zones (3 radial, 3 axial zones)
  - For the reference ENHS core, the radial and axial divisions are done so as to conserve the volume.
- REBUS-3/DIF3D (80group, R-Z) is used for depletion analysis.
- A multi-group X-section based on ENDF/B-VI is prepared with TRANSX
- All reactivity coefficients are calculated with DIF3D using 80 groups.

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- The IFR type metallic fuel of Pu-U-10Zr is considered here.
  - HT-9 is used for all structures including cladding.

  - In this study, the lattice pitch of the reference ENHS core is kept for all cases.
    The core is homogenized into a cylindrical annulus.
    A multi-group X-section based on ENDF/B-VI is prepared with the TRANSX and an analysis. code.
  - REBUS-3/80group RZ DIF3D was used for depeletion analysis. user, 2004/10/29

# **Design Goals, Constraints and Variables**

#### 🗆 Design Goal

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- The power distribution should be as flat as practical.
- Peak-to-average power should be nearly constant over core life

#### Design Constraints

- Burnup reactivity swing over 20 years should be less than 2\$.
- k<sub>eff</sub> during core life should be larger than unity.
- Total power and core volume are fixed as those of the reference ENHS core.

#### Design Variables

- Fuel rod diameter
- Positions of the interfaces between core regions
- Core region-wise plutonium weight percents (wt%)

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- In this study, we used the following design constraints :

- The burnup reactivity swing over 20years should be less than 2\$ (this is a target value.)
  Keff during core life should be larger than unity.
  The total reactor thermal power and core volume are fixed as those of the reference ENHS core.

- The fuel rod diameter, the positions of the interfaces between core regions, and the core region-wise plutonium weight percents are used as the design variables. user, 2004/10/29

# **Core Design Options**

## □ Reference Core (Reference ENHS core)



A uniform composition (12.20wt% Pu) and single dimension of fuel rod

#### Design-I (BREST-like approach)

- Uniformity of fuel composition is kept but three different fuel rod diameters are used :
  - Inner core : clad inner radius and its thickness are reduced by 5% and 4.5%, respectively.
  - Middle core : same fuel rod diameters as the reference core are used.
  - Outer core : inner clad radius is increased by 12% but the same thickness as the reference ENHS is used.
- The interface between middle and outer cores is moved inwardly by 6.0cm.

## Design-II (Conventional approach)

- A single dimension of fuel rod is kept but three radially different enrichment levels are used (10.52wt%, 12.20wt%, 15.80wt% for inner, middle, and outer cores, respectively)
- This approach is conventional but the question is whether or not it is feasible to maintain nearly flat k<sub>eff</sub> as well as a flat power shape over the core life.
- The interface between middle and outer core regions moved inwardly by 6.0cm.

- u21 The reference ENHS core consists of uniform composition, single dimension fuel rods of 12.20wt%Pu.
  - The first approach Design-I is to use three different fuel rod dimensions but keep the uniformity of fuel composition. This approach is similar to that of Russian BREST reactor.
  - In this design, the clad inner radius and its thickness of the inner core are reduced by 5% and 4.5%, respectively relative to the reference one.
  - In the outer core, the inner clad radius is increased by 12% but the same thickness as the reference is used.
  - In the middle core, the reference fuel rod dimension is used.

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# **Core Design Options**

#### Design-III (Refined approach)

- Similar to Design-II but, in addition, axial enrichment splitting is used:
  - Inner core : 12.1wt%Pu, 9.1wt%Pu, and 12.1wt%Pu for lower, middle, and upper regions, respectively
  - Middle core : 15.1wt%Pu, 11.3wt%Pu, and 15.1wt%Pu for lower, middle, and upper regions, respectively
  - Outer core : 17.3wt%Pu for all three regions
- The radially middle core is expanded inwardly and outwardly by 4.0cm.
- The axially middle core is expanded upward and downward by 10.cm.

# K<sub>eff</sub>, CR, and TRU wt% Evolutions



- New designs have larger burnup reactivity swings than the reference ENHS
- Design-I using uniform fuel composition has smallest burnup swing of ~1\$.
- In Design-II and III, k<sub>eff</sub> increases rapidly after their minimum value.
- The reference ENHS and Design-I have nearly similar CR evolutions.
- CR evolutions of Design-II and III are parallel to each other :
  - CRs are initially much less than unity and then go up to larger than unity and thereafter decrease slightly.
  - This steep variation of CR is correlated with increase of power density in the core center where the Pu wt% is the smallest.

# Core Region-wise k<sub>inf</sub> Changes (BOL k<sub>inf</sub> /change%)

Core designs	Design-I	Design-II	Design-III	Reference	1
Inner core Lower Middle Upper	1.1809/+1.21% 1.1809/+1.44% 1.1809/+1.20%	1.1038/+5.48% 1.1038/+6.18% 1.1038/+5.48%	1.1986/+1.27% 1.0099/+12.1% 1.1986/+1.19%	1.2024/+1.24% 1.2024/+1.09% 1.2024/+1.16%	<mark>u2</mark>
Middle core Lower Middle Upper	1.2010/+0.19% 1.2010/+0.31% 1.2010/+0.11%	1.2043/+0.11% 1.2043/+0.20% 1.2043/+0.06%	1.3602/-4.11% 1.1542/+2.18% 1.3602/-4.15%	1.2024/+0.19% 1.2024/+0.36% 1.2024/+0.16%	
Outer core Lower Middle Upper	1.2534/-0.67% 1.2534/-0.33% 1.2534/-0.66%	1.3930/-4.31% 1.3930/-4.86% 1.3930/-4.32%	1.4624/-4.90% 1.4624/-5.51% 1.4624/-4.92%	1.2024/-0.39% 1.2024/+0.10% 1.2024/-0.32%	

- For the reference ENHS, BOL k<sub>inf</sub> is uniform and its change is very small.
- For Design-I, BOL k<sub>inf</sub> is not uniform but its change is very small.
- For Deisgn-II, k<sub>inf</sub> increases in inner core but decreases in outer core. (k<sub>inf</sub> change in middle core is very small.)
- For Design-III, k<sub>inf</sub> changes for all core regions are large.

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• This table shows the core region-wise infinite multiplication factor and its change percentages between BOL and EOL.

#### **Axial Power Distributions**



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- The axial power distributions of all cores except Design-III are nearly the same and they are nearly constant throughout the core life.
- The axial power distribution of Design-III significantly vary with core life and the central dip is due to the lower plutonium content in the central core region.

#### **Radial Power Distributions**



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□ For the reference ENHS core, the radial power distribution is nearly independent of burnup.

The peak-to-average channel power ratio increases from 1.5 to 1.53 (~1.9%)

For Design-I core, the overall shape of the radial power distribution is also nearly independent of burnup.

The peak-to-average channel power ratio increases from 1.154 to 1.21 (~4.7%)

The radial power distributions of Design-II and III are similar in shape and both vary significantly from BOL to EOL : from 1.217 by 1.9% for Design-II while from 1.148 by 6.8% for Design-III

### **Evolutions of 3-D Power Peaking Factors**



- □ For the reference ENHS and Design-I cores, the 3-D power peaking factors are nearly constant throughout core life.
- Design-II core 3-D power peaking factor varies significantly over life (by ~9.8%)
- Design-III 3-D power peaking factor is nearly constant for 14 years and hereafter increases up to 1.397 by 4.9%.

# **BOL Core Physics Characteristics**

Parameters	Design-I	Design-II	Design-III	Reference ENHS
Average Pu wt% in HM	12.16	13.16	13.59	12.20
Burnp reactivity swing (%dk)	0.365	0.515	0.595	0.221
Peak-to-average channel power	1.154	1.217	1.148	1.500
Peak burnup (GWD/tHM) after 20EFPY	85.6(104.5ª)	74.0 (98.9)	72.3 (105.3)	99.89 (104.4)
Average burnup (GWD/tHM) after 20EFPY	47.2 (57.6)	50.8 (67.9)	51.5 (75.0)	50.80 (53.1)
Peak fast neutron fluence (n/cm <sup>2</sup> )	3.275E+23	2.993E+23	2.746E+23	3.829E+23
Temperature reactivity coefficients				
Doppler effect (dk/kk'C)	-5.4294E-06	-5.4242E-06	-5.6096E-06	-5.2442E-06
Axial fuel expansion (dk/kk'C)	-4.6380E-06	-4.8086E-06	-3.5211E-06	-4.6379E-06
Coolant expansion (dk/kk'C)	+3.1437E-06	+2.9389E-06	+3.2015E-06	+1.6747E-06
Grid plate expansion (dk/kk'C)	-8.3824E-06	-8.7447E-06	-8.4701E-06	-8.0679E-06
Coolant void reactivity effect (%dk)				
Inner core (+gas plenum)	+2.644 (+1.388)	+2.046 (+1.232)	+2.169 (+1.242)	+2.718 (+1.516)
Middle core (+gas plenum)	+1.032 (+0.406)	+2.051 (+1.019)	+2.387 (+1.139)	+0.689 (-0.068)
Outer core (+gas plenum)	-0.271 (-0.756)	-0.642 (-1.079)	-0.592 (-1.126)	-0.694 (-1.045)
Total core (+gas plenum)	+3.519 (+1.404)	+3.551 (+1.536)	+3.971 (+1.690)	+2.555 (+0.424)
Peripheral absorber worth (%dk)	2.760	4.118	4.303	1.990
Central absorber worth (%dk)	3.200	2.130	2.082	4.138
Peripheral + central absorbers worth (%dk)	6.733	7.002	7.138	6.811
Total heavy metal inventory (kg)	18809	17505	17505	17505
Total plutonium inventory (kg)	2287	2303	2379	2135

<sup>a</sup>Peak burnup for fluence of E>0.1MeV neutrons of 4.0x10<sup>23</sup>n/cm<sup>2</sup>

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- □ The average discharge burnup corresponding to a peak fast fluence limit increase by 8.5%, 27.9%, and 41.2% for Design-I, II, and III, respectively.
- □ The burnup reactivity swing for these cores increase from 0.22%dk to 0.37%dk, 0.52%dk, and 0.60%dk for Design-I, II, and III, respectively.
- The reactivity coefficients of the new cores are nearly the same as those of the reference ENHS core except for the coolant expansion – New design cores have slightly less negative coolant expansion reactivity.
- The inner core void reactivity of the new cores is somewhat less positive than the reference ENHS core because of power shift. However, these cores have more negative middle core void reactivity and their total void reactivity is slightly larger than that of the reference ENHS core.
- The new cores have significantly larger peripheral absorber reactivity worth but significantly smaller central absorber worth than the reference ENHS core. The combined reactivity worth of new cores are nearly the same as that of the reference ENHS core.

# **EOL Core Physics Characteristics**

Parameters	Design-I	Design-II	Design-III	Reference ENHS
Average Pu wt% in HM	12.95	13.82	14.17	13.11
Peak-to-average channel power	1.208	1.240	1.226	1.529
Temperature reactivity coefficients				
Doppler effect (dk/kk'C)	-4.4235E-06	-4.4403E-06	-4.5166E-06	-4.2202E-06
Axial fuel expansion (dk/kk'C)	-4.6221E-06	-4.6194E-06	-3.9979E-06	-4.6057E-06
Coolant expansion (dk/kk'C)	+3.3708E-06	+3.1202E-06	+3.3144E-06	+2.5177E-06
Grid plate expansion (dk/kk'C)	-7.9483E-06	-8.2625E-06	-7.9634E-06	-8.0045E-06
Void reactivity effect (%dk)				
Inner core (+gas plenum)	+2.778 (+1.523)	+2.626 (+1.593)	+2.505 (+1.492)	+2.809 (+1.618)
Middle core (+gas plenum)	+1.023 (+0.424)	+1.047 (+0.436)	+1.784 (+0.718)	+0.659 (-0.043)
Outer core (+gas plenum)	-0.247 (-0.694)	-0.550 (-1.149)	-0.604 (-0.966)	-0.668 (-1.009)
Total core (+gas plenum)	+3.628 (+1.563)	+3.254 (+1.246)	+3.613 (+1.470)	+2.644 (+0.572)
Peripheral absorber worth (%dk)	2.452	2.679	2.772	1.817
Central absorber worth (%dk)	3.291	3.130	3.108	4.104
Peripheral + central absorbers worth (%dk)	6.475	6.565	6.653	6.562
Total heavy metal inventory (kg)	17869	16565	16552	16564
Total plutonium inventory (kg)	2314	2289	2345	2171

- The reactivity coefficients at EOL are slightly less negative for all cores than at BOL.
- On the other hand, the total coolant void worth of Design-II and III is less positive at EOL than at BOL; this is because the radial power distribution of these cores at EOL is less outwardly shifted than at BOL.
- The EOL peripheral absorber worth of new cores is reduced while the central absorber worth is increased. The combined absorbers worth at EOL is less than at BOL but is sufficient to reduce k<sub>eff</sub> to below 0.95.

# **Other Options (Going On)**

#### Option-I

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- Extension of the central absorber region
  - Single fuel rod dimension and fuel composition are kept.
  - The central absorber region consists of 5% structure and 95% void.

## Option-II

- Use of the core region-wise lattice P/D ratios
  - Single fuel rod dimension and fuel composition are kept.

Parameters	Reference ENHS	Option-I	Option-II
Plutonium wt%	12.20	12.08	12.35
P/D ratio (IC/MC/OC)	1.36/1.36/1.36	1.28/1.28/1.28	1.44/1.38/1.27
Burnup swing (%dk)	0.221	0.435	0.468
Initial conversion ratio	1.0446	1.0345	1.0236
3-D power peaking factor (BOL)	1.829	1.530	1.459
Channel peak-to-average power (BOL)	1.500	1.316	1.204
Average discharge burnup (GWD/tHM)	50.80	50.8	50.7
Peak discharge burnup (GWD/tHM)	99.89	82.6	93.1
Peak fast neutron fluence (n/cm <sup>2</sup> )	3.829E+23	3.275E+23	3.527E+23

## Option-III

- Use of a small number of absorber rods
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- u23 - At present, we are considering the other three design options for power flattening of the ENHS core.
  - The first option is to extend the central absorber region that is replaced with 5% structure and 95% void.
  - This design keeps the uniformities of fuel rod dimension and composition. But this design has relatively small P/D ratio of 1.28.
  - As shown in this Table, this design is effective in reducing peak-to-average burnup and peak fast neutron fluence.
  - The second option is to use core regionwise different P/D ratios with keeping the uniform composition and dimension of fuel rod.
  - This design option is very effective in reducing the peak-to-average power but not so good in reducing peak-to-average burnup and peak fast neutron fluence.
  - The third option is use to a small number of absorber rods with keeping the uniform composition and dimension of fuel rods. For this design option, we have yet to get the results.

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# **Radial power distribution**



- □ The power distributions are nearly constant throughout core life.
- □ The burnup reactivity swings are slightly larger than 1\$.
- □ In comparison with the reference ENHS, the channel peak-to-average powers of Option-I and –II are reduced from 1.50 to 1.316 and 1.204, respectively.
- □ Option-II is not so effective in the discharge burnup flattening.

- It is possible to design ENHS cores to maintain nearly flat k<sub>eff</sub> over 20 years to have significantly more flattened power density and discharge burnup distributions than the reference ENHS core.
- As the results, it will be possible to design the ENHS reactor to operate at a higher power level and to extract more energy per core loading. This will improve the economics of ENHS reactors.