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Optimal Core Design P/D ratios and HM Recycling Fraction of ENHS Core

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1. Introduction

The ENHS (Encapsulated Nuclear Heat Source)[1] is a small liquid metal lead-bismuth or lead cooled fast-spectrum “battery type” innovative Gen-IV reactor. It has been conceptually designed to have the following special features: over 20 effective full power years of operation without refueling and fuel shuffling and with nearly zero burnup reactivity swing; module fabricated, fueled and weld sealed in the factory; 100% natural circulation; nearly constant power shape throughout life; autonomous operation and superb safety.

The fuel fed into the reference ENHS core comes from fuel discharged from light water reactors (LWR) to which depleted uranium is added. However, on the long run it is envisioned that ENHS reactors will operate on a fuel-self-sustaining (FSS) closed cycle[2] – the fuel remaining in the ENHS core that reached its End Of Life (EOL) will be reprocessed to remove all or part of the fission products, mix the heavy metal (HM) with makeup fuel, re-fabricate fuel elements and load them into the core of a new ENHS module.

A recent study[3] found that the pitch-to-diameter (P/D) ratio of the ENHS cores that use ENHS recycled TRU keeps increasing with the number of fuel recycles. This increase is advantageous since complementary thermal-hydraulic study[4] recently showed that it is possible to significantly increase the power level of the ENHS core by increasing the core P/D ratio. An increase in the power level using practically the same Heavy Metal (HM) inventory is expected to improve the economic viability of the reactor.

The objective of this paper is to identify the design parameters for the optimal equilibrium ENHS core. After reaching equilibrium, the initial fuel composition and inventory is identical to that of the next core.

2. Model and Method

The reactor model used for this study is basically the same as used for the reference ENHS design[1]. The fuel is TRU-U(10Zr) metal fuel that is 1.56 cm in diameter, has a smear density of 75% and clad with 0.13 cm thick HT-9. The axial dimensions are the same while the radial dimensions vary with the P/D ratio. The radial thickness of all the regions outside of the core is the same for all considered cores.

The fuel recycling period assumed for the equilibrium cycle is a total of 5 years consisting of 3 years cooling, 1 year reprocessing and 1 year fuel re-fabrication and loading into the core of a new ENHS module. It is assumed that all fission products (FP) are removed from the discharged fuel during reprocessing.

The design variables of this study are the core pitch-to-diameter (P/D) ratio and the fraction of the discharged TRU that is recycled. For a given P/D ratio and a given core power level, the optimization searches for that combination of TRU concentration and the fraction of the discharged TRU that is recycled and that gives a Beginning Of Equilibrium Cycle (BOEC) of k_{eff} of ~ $(1+\beta)$ ~ 1.005 along with minimum reactivity swing during the core life. This search is repeated for a number of P/D ratios so as to find the specific ratio that gives the lowest burnup reactivity swing. Sensitivity of the optimal core design to the design power level is searched in the power range from 125 MWt to 250 MWt. The reference average discharged burnup of 5.38 atom % is preserved for all cases regardless of the power level.

All the neutronic calculations are done with the K-CORE system using R-Z geometry like as the reference core design. For depletion analysis the core is divided into three radial and three axial equal-volume zones.

3. Results

Figures 2, 3 and 4 show the sensitivity of the equilibrium cycle k_{eff} evolution to the P/D ratio when the core power level is, respectively, 125, 170 and 250 MWt. The P/D=1.61 case in Fig. 2, the P/D=1.62 case in Fig. 3 and the P/D=1.63 case in Fig. 4 corresponds to k_{eff} evolutions of equilibrium cycle when 99.9 w/o of the discharged HM is recycled from one core to next one; we are referring to this scenario as “full recycling” as it is assumed that 0.1 w/o of the HM is lost during reprocessing and refabrication. It is found that in the full recycling scenario the burnup reactivity swing is larger than desirable – more than 2 times of the delayed neutrons fraction (β) and the End Of Equilibrium Cycle (EOEC) k_{eff} falls down below 1.000. It is concluded that in the full recycling mode of operation the equilibrium cycle core design does not satisfy the design goals of the ENHS reactor.

It is possible to flatten the k_{eff} evolution with burnup by reducing the P/D ratio and increasing the conversion ratio by reducing the parasitic neutron capture in the coolant and hardening the neutron spectrum. However, reducing P/D ratio while using full recycling will result in too high a BOEC k_{eff}. This led us to introduce additional design variable – the “recycling fraction”. By reducing the recycling fraction below 99.9% and correspondingly increasing the depleted uranium makeup it is possible to attain both the desirable conversion ratio and desirable BOEC (and EOEC) k_{eff}.

The upper three plots in Figures 2, 3 and 4 show the k_{eff} evolution with burnup for different P/D ratios and recycling fractions. Table I summarizes these optimal

P/D ratios and the corresponding recycling fractions giving the minimum burnup reactivity swing for the three different core powers. Table I shows that the P/D ratio of optimal equilibrium cycle tends to increase slightly with the core power: P/D =1.54 for 125 MWt, P/D=1.55 for 170 MWt and P/D=1.57 for 250 MWt.

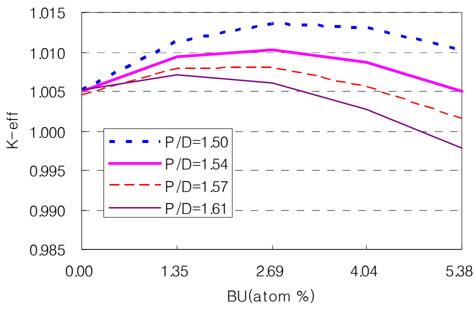

Fig. 2. k_{eff} evolution with 125 MWt core power

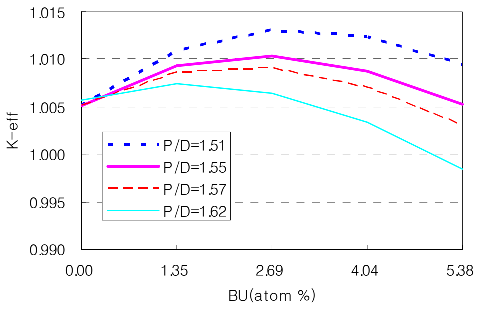

Fig. 3. k_{eff} evolution with 170 MWt core power

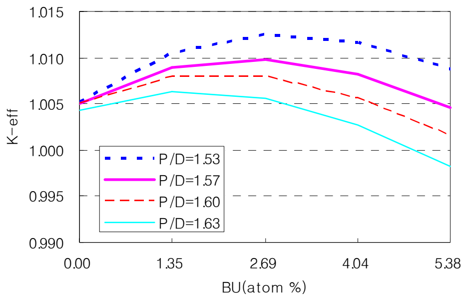

Fig. 4. k_{eff} evolution with 250 MWt core power

TABLE I
Optimal Core Design P/D ratios and HM Recycling Fraction

Core Power (MWt)	Optimal eq. cycle P/D ratio	Optimal recycling fraction	Max. burnup reactivity swing (%$\delta\rho$)
125	1.54	0.987	0.538
170	1.55	0.988	0.527
250	1.57	0.990	0.528

Figure 5 shows the ENHS equilibrium cycle HM recycling fraction dependence on the P/D ratio and core power. As the P/D ratio increases, the coolant volume fraction increases and the conversion ratio becomes smaller due to softening of the neutron spectrum and increasing of parasitic neutron capture. Consequently, the fraction of the TRU (and accompanying U) to be recycled need to be increased.

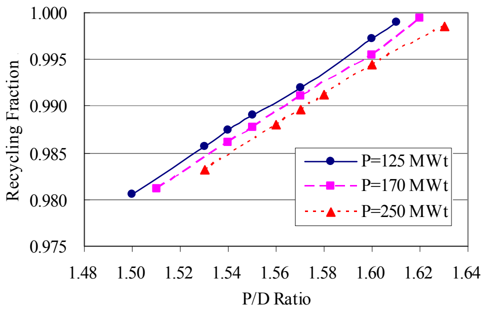

Fig. 5. HM recycling fraction of ENHS equilibrium cycle versus P/D ratio

4. Conclusion

The P/D ratio of the optimal equilibrium core is significantly larger than that of the reference first-cycle core. The optimal P/D ratio and the recycling fraction giving the minimum burnup reactivity swing tend to increase with the core power level for a given discharge burnup: P/D =1.54 for 125 MWt, P/D=1.55 for 170 MWt and P/D=1.57 for 250 MWt. For comparison, the P/D ratio of the reference core that is loaded with Pu discharged from LWR is 1.36. The larger P/D ratio cores can operate at a higher power level when using natural circulation cooling.

5. Acknowledgement

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