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SFR Breakeven Core Designs with Various Rated Powers

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1. Introduction

The conceptual design of the breakeven core with metallic fuel for a 1,200 MWe SFR is being developed under the framework of the Gen-IV SFR development program [1, 2]. According to the draft road map for a sodium cooled fast reactor (SFR) in Korea, the operation of a demonstrative prototype reactor will be started in 2028. There is still room to decide on the rated power and the type of core, breakeven core or TRU burner, of the commercial SFR in the future for which the prototype plant will be designed. An increased rated power generally enhances the economics of a nuclear power system, and it also changes the neutronic performances of the reactor core. Therefore, the effect of the rated power on the nuclear design has been examined for a SFR breakeven core.

Same design bases were applied to the conceptual design of each core with different rated powers. It was assumed that a metallic fuel of TRU-U-10%Zr was loaded into the core with an enrichment split. All the cores under investigation were divided into three concentric regions; inner, middle, and outer core regions. The neutronic core performance of all these cores has been calculated and compared with each other.

It was observed that a larger core size following the increased rated power improved the fuel economy. The axial height of the core needs to be decreased with a higher rated power in order to meet the sodium void reactivity target. The number of control rods has also to be increased as the core power rises.

2. Design Bases for Conceptual Cores

The core design bases used in this study were as follows: 1) breakeven breeding without blanket (conversion ratio is about 1.0), 2) cycle length of 18 months, 3) sodium void reactivity worth smaller than 8.0 \$, 4) peak fast neutron fluence of less than 5.0×10^{23} n/cm^2, and 5) maximum linear heat generation rate lower than 350W/cm.

The ternary metallic fuel of TRU-U-10%Zr was used for all the cores under investigation. Every core was divided into three concentric regions; inner, middle, and outer core regions. The fuel assemblies loaded into each core region have different TRU enrichments each other. The purpose of dividing the core into three core regions and using an enrichment-split fuel concept is to flatten the power distribution over the core by adjusting the fuel inventory for each core region. The axial B_4C layer used for KALIMER-600 design was not considered in this conceptual design study.

3. Conceptual Cores with Different Power Level

The conceptual cores to meet the design targets have been developed. The total number of fuel assemblies and possible arrangements of the fuel assembly loading were determined by taking account of the desired average linear power and the maximum power density limit, based on the performance parameters for the KALIMER-600 core [3, 4]. All the nuclear core concept design efforts were based on equilibrium cycle mode calculations. The REBUS-3 equilibrium model with a 25 group cross section was used to perform the neutronic analysis for the selected conceptual cores. Four batch reload scheme was assumed as a fuel management strategy for the conceptual cores.

The main design parameters of the conceptual cores are listed in Table I. The core size was increased by loading more fuel assemblies with raised power level in order to keep the power density within the limit. However, the reduced radial leakage followed by the radial enlargement of the core induces a larger positive sodium void reactivity. Therefore, the core height for high rated power needed to be reduced to enhance the neutron leakage for sodium void case. The core height was decreased from 94 cm for 600 MWe to 78 cm for 1,800 MWe core. The reduced core height is effective for achieving a lower sodium void reactivity worth. The fuel outer diameter is 0.85 cm for 600, 900, and 1,200 MWe cores. It was increased for 1,500 and 1,800 MWe cores to maintain a conversion ratio close to 1.0. The fuel rod pitch in 1,500 and 1,800 MWe cores was also increased in order to maintain the gap between fuel rods. The gap between the fuel pins was for sodium coolant to flow and was designed to maintain an acceptable pressure drop along the coolant channel.

Table I. Comparison of the design parameters

Design parameter	600 MWe	900 MWe	1,200 MWe	1,500 MWe	1,800 MWe
Number of fuel assemblies					
- Inner Core	114	156	198	246	300
- Middle Core	96	138	180	234	318
- Outer Core	120	162	246	300	324
- (Total)	(330)	(456)	(624)	(780)	(942)
Core height (cm)	94	90	84	80	78
Fuel rod outer diameter (cm)	0.85	0.85	0.85	0.86	0.87
Fuel pin pitch(cm)	1.01	1.01	1.01	1.02	1.03
Fuel assembly pitch (cm)	18.19	18.19	18.19	18.39	18.56
Pin P/D ratio	1.188	1.188	1.188	1.186	1.184
Clad thickness (mm)	0.595	0.595	0.595	0.595	0.595

4. Neutronic Characteristics of Conceptual Cores with Different Power Level

The neutronic characteristics of the conceptual core are summarized in Table II. The average required TRU enrichment of the fuel is reduced with the power level, from 15.10 wt% for a 600 MWe core to 14.30 wt% for a 1,800 MWe core. It is noted that the variation in TRU enrichment between each region of the core is smaller with larger core. All of the cores were designed to have the conversion ratio close to 1.0. The required fissile plutonium inventory is decreased with the core size, from 6.02 ton/GWe for a 600 MWe core to 4.58 ton/GWe for a 1,800 MWe core. The heavy metal inventory per power is also reduced as the core size increases. The higher discharge burnup, peak fast neutron fluence, and linear heat generation rate of the core with a high rated power were resulted from the reduced specific fuel inventory. Detailed core thermal analysis needs to be performed for the proposed core concepts in order to calculate the inner wall temperature. Comparing the fissile plutonium inventory and discharge burnup, the conceptual core with a high rated power shows more attractive aspect in neutron economy. The sodium void reactivity worths of every core were within the design limit by adjusting the core height.

The variation in the rated power does not strongly effect the reactivity coefficients such as the Doppler, axial expansion, radial expansion, and sodium density coefficients. It should be noted that the control rod worth per control rod is remarkably reduced as the core size increased. Therefore, as many control rods as proportional to the rated power level is required to control the reactivity of the core and to shut down the reactor.

5. Conclusion

A metal-fueled core design concept with various rated powers was examined as a preparation work for the determination of the core type for a SFR system. It was observed that a larger core size following the increased rated power improved the fuel economy. A large core, however, has an increased positive sodium void reactivity. Therefore, the height of the core has to be decreased as the rated power increases in order to meet the sodium void reactivity target in case of not using the additional moderator. The number of control rods has also to be increased as the core power rises.

REFERENCES

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Table II. Neutronic characteristics of the conceptual cores with different rated powers

Design parameter	600 MWe	900 MWe	1,200 MWe	1,500 MWe	1,800 MWe
Feed TRU wt%					
- Inner Core	12.15	12.34	12.92	12.71	12.84
- Middle Core	15.05	14.58	14.19	13.95	13.97
- Outer Core	17.94	17.49	16.72	16.20	15.99
Core average feed TRU wt%	15.10	14.81	14.78	14.43	14.30
Conversion Ratio	0.999	1.001	0.998	1.001	1.005
Fissile Pu inventory (ton/GWe, BOEC)	6.02	5.26	5.02	4.86	4.58
Heavy metal loading (ton/GWe, BOEC)	60.6	53.2	50.9	49.8	50.2
Burnup reactivity swing ($)	0.12	0.15	0.39	0.32	0.28
Cycle length (EFPD)	540	540	540	540	540
Average discharge burnup (MWD/kg)	85.0	96.4	100.6	102.8	102.2
Peak fast neutron fluence (n/cm^2)	3.97×10^{23}	4.56×10^{23}	4.84×10^{23}	4.94×10^{23}	4.96×10^{23}
Average linear heat generation rate (W/cm)	181	205	215	225	230
Peak linear heat generation rate (W/cm)	268	301	303	318	312
Sodium void worth ($, BOC/EOC)	7.24/7.59	7.35/7.74	7.42/7.74	7.48/7.86	7.50/7.83
Control rod worth (pcm/control rod)	442/461	267/273	199/203	150/155	141/142
Reactivity coefficient (pcm/°C, BOC/EOC)					
- Doppler coefficient at 900°K	-0.70/-0.67	-0.70/-0.67	-0.70/-0.66	-0.70/-0.66	-0.70/-0.66
- Axial expansion coefficient	-3.60/-3.52	-3.54/-3.46	-3.52/-3.47	-3.51/-3.45	-3.49/-3.44
- Radial expansion coefficient	-7.48/-7.27	-7.30/-7.10	-7.22/-7.09	-7.19/-7.03	-7.11/-6.99
- Sodium density coefficient	7.76/ 8.22	7.97/ 8.49	8.04/ 8.48	8.08/ 8.58	8.10/ 8.54