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Option Study for SFR Transmutation Reactor Core

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1. Introduction

Nuclear power contributed to the welfare of mankind as well as industrial development. Safety is now a major concern after Fukushima accident and an option of liquid metal cooled fast reactor is focused because of its feature of long term cooling without offsite power. Another feature of fast reactor is the capability of waste burning. Transuranic isotopes (TRU) can be destroyed with high efficiency in the fast spectrum core. Many kinds of transmutation fast reactors were designed for the practical choice of future power plants.

The prototype sodium-cooled fast reactor (SFR) named KALIMER has been investigated by KAERI in the Rep. of Korea. Rated power of reference design is 600MWe and the bigger size is the better for material testing as prototype reactors. However, from the point of view in transmutation performance the smaller core is the more effective. In this paper, the size effect on TRU transmutation was studied for the future reference.

As a separate independent study, an option of small experimental SFR was proposed by Kyung Hee University in the name of Multipurpose Experimental Sodium-cooled Fast Reactor (MESOF). At previous study, preliminary MESOF reactor was proposed [1][2]. It was designed for irradiation experiments for various fuels and materials with different coolant.

Now an impact by loading various types of driver fuel was evaluated. Driver fuel is changed to both U-TRU-Zr and UO_2 fuel respectively. Because of characteristics of TRU, the feature of safety is focused on the U-TRU-Zr fuel. Lower physical density of UO_2 fuel may make to change some fuel pin parameters. These are main study point in this paper.

The main calculation tools are TRANSX-DANTSYS-REBUS3 code system. Effective cross section is generated with TRANSX and DANTSYS (with TWODANT module using 2-D transport calculation), and nuclear design and evaluation are done in REBUS. The MCNPX is partially used for validation and evaluation of parameters, such as effective delayed neutron fraction. Code validation for the application for a small core SFR was done at the previous study [1][2].

2. MESOF cores with various fuels

In a previous study on MESOF, core was loaded with U-Zr and designed to have many irradiation experimental tubes for testing of various fuels. In this study, driver fuels are replaced with different fuels for a feasibility study.

It is desired to transform the U-Zr core to full U-TRU-Zr core for transmutation research. As a feature of experimental reactor, a core with conventional UO_2 fuel may be tested for extreme case. In this paper, two extreme cases were tested for a core design and core performance was checked and compared with each other. UO_2 fuel is standard for LWR and was tested at JOYO SFR in Japan. Because of low physical density, there is a limitation in fissile loading even with higher enrichment. However, TRU core may not have any limitation in design except some concerns on safety parameters.

2.1. Referenced core loaded with U-Zr fuel

MESOF is an experimental reactor with 300MW thermal power. Preliminary proposed MESOF reactor was loaded 66 U-Zr fuel assemblies as a driver fuel. 6 fuel test assemblies, 3 material test assemblies and 3 fuel test loops are designated for experimental application. 207 reflector assemblies are wrapping the core reducing the neutron leakage effectively. There are 7 primary control assemblies and 3 secondary control assemblies.

The driver fuel is composed of U-10%Zr which U^{235} is enriched 19.5%. U-16.5%TRU-10%Zr is in fuel test assemblies which TRU composition is from LWR spent fuel. The material loaded in material test assemblies is HT9.

The design specification of reactor and fuel assembly is described in below table I. Reactor layout is drawn below figure 1.

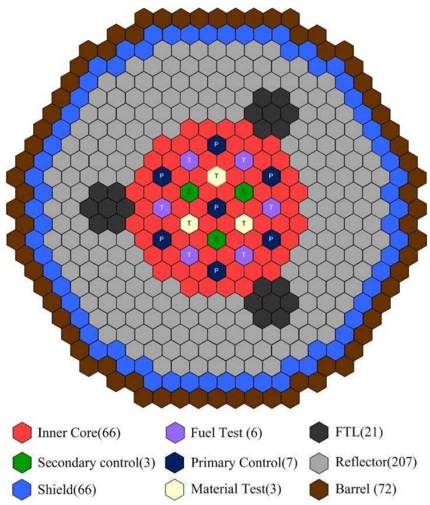

Fig. 1. Radial core layout of MESOF

Table I. Design specification of fuel assembly of MESOF

Parameter	Design value
General	
Overall length of duct, cm	335.0
Assembly pitch, cm	16.142
Duct outer flat-to-flat distance, cm	15.71
Duct wall thickness, cm	0.394
Duct inside flat-to-flat distance, cm	14.922
Fuel assembly	
Number of pins	271
Fuel pin pitch, cm	0.8876
Fuel pin diameter, cm	0.737
Thickness of clad, cm	0.041
Outer radius of clad, cm	0.3685
Inner radius of clad, cm	0.3275
Fuel slug radius, cm	0.2837
Active core height fuel, cm	87
Gas plenum height, cm	120
Clad outer radius with wire-wrap, cm	0.3770
Lower reflector height, cm	60
Length of displaced sodium bond, cm	19

Table II. Performance characteristics & kinetic parameters of MESOF

Reactor power, MW_{th}	300
Cycle length, days	120
Number of driver assemblies	72
Fuel form	U-10%Zr
U enrichment, %	19.5
k-effective value [BOC/EOC]	1.00385 / 0.99482
Peaking factor [BOC/EOC)	1.87359 / 1.93403
Power density of active core, kW/cm^3 [inner core/FTA/FTL]	220.3 / 122.7 / 0
Peak linear power, kW/m	34.4
Active core average flux, $10^{15} n/cm^2$-sec	1.72
MTA average flux, $10^{15} n/cm^2$-sec	2.54
Fuel test loop average flux, $10^{15} n/cm^2$-sec	0.69

2.2. Fuel options for the alternative core

U-TRU-Zr fuel is one of the options of alternative fuel as a driver fuel. Because of many restrictions, U-TRU-Zr fuel core may not be used for the first core of SFR in Korea. For a future option, a feasibility of transition from U-Zr core was studied MESOF.

The composition of U-TRU-Zr fuel is adopted from ABTR designed by Argonne National Laboratory [3]. Depleted uranium with 0.16% enrichment of U^{235} and negligible amount of U^{234} and U^{236} is used the alloy. TRU composition comes from spent fuel of conventional LWR composed of 59% fissile plutonium. When TRU weight fraction in the fuel alloy is 27.0%, the reactor will be operated up to the cycle length. 10% natural zirconium is mixed in the alloy and about 1.2% natural molybdenum, represented as a fission product, is also mixed.

Table III. Comparison of the design specification of fuel assemblies between alternative cores

	U-TRU-Zr core	UO_2 core
Number of fuel pins	271	547
Fuel pin pitch, cm	0.8876	0.6311
Outer diameter of clad,cm	0.737	0.55
Inner diameter of clad, cm	0.655	0.48
Clad thickness, cm	0.041	0.035
Fuel slug diameter, cm	0.5674	0.463
P/D ratio	1.204	1.1475
Wire-wrap diameter, cm	0.1585	0.0811
Smear density, %	75	87
Fuel volume fraction	0.3036	0.4081
Bond volume fraction	0.1010	0.0305
Coolant volume fraction	0.3713	0.3189
Structure volume fraction	0.2241	0.2425

The other fuel option for alternative core is a conventional UO_2 fuel. As UO_2 is the most familiar fuel for conventional LWRs and some SFRs such as JOYO and MONJU in Japan.

To change the U-Zr fuel to UO_2, fuel volume fraction should be increased because of lower physical density compared with metallic fuel. Therefore design specification of fuel assemblies for UO_2 core is changed and it is described in table III. The design specification of fuel pin is adopted from JOYO reactor [4]. The thickness of wire-wrap is thinned and P/D ratio is reduced to increase the fissile inventory.

2.3. Core performance characteristics

Core performance characteristics and burnup calculation are done with DIF3D module in REBUS which is nodal diffusion theory code. For effective cross section generation, TRANSX and TWODANT module in DANTSYS are used. Details are in table IV.

U-TRU-Zr core has advantages for experimental irradiation and safety because of higher flux level and lower peaking factor compared with other cores. But the reactivity swing is about 4 times higher than others despite same cycle length. Therefore it should be checked whether the reactor has enough reactivity margin or not.

The characteristics of UO_2 core are similar with U-Zr core except fast neutron flux and power density. The peak fast fluence of UO_2 core is 10% lower than other cores because of softened flux spectrum. The peak linear power density of UO_2 core is reduce to half due to twice the number of fuel pins in each assembly.

Table IV. Comparison of the core performance characteristics among various cores

	U-Zr core	U-TRU-Zr core	UO_2 core
k-eff [BOC/EOC]	1.00385 / 0.99482	1.01764 / 0.99961	1.00438 / 0.99394
Peaking factor [BOC/EOC]	1.87359 / 1.93403	1.71761 / 1.75223	1.88306 / 1.90157
Conversion ratio	0.4265	0.5045	0.4517
Peak power density of active core, W/cm^3	412.89	372.76	407.45
Peak fast fluence, n/cm^2	2.17E+22	2.67E+22	1.88E+22
Peak LPD, kW/m	34.4	31.0	16.8
MTA avg. flux, 10^{15}n/cm^2-sec	2.39	3.03	2.34
Active core avg. flux, 10^{15}n/cm^2-sec	1.72	2.19	1.64
FTL avg. flux, 10^{15}n/cm^2-sec	0.643	0.871	0.562

2.4. Safety parameters of U-TRU-Zr core

2.4.1. Reactivity coefficient

The reactivity coefficients are among the parameters which evaluate inherent safety of reactor. The effective delayed neutron fraction is calculated with MCNPX using TOTNU option [5]. Calculation of Doppler coefficient is done with MCNPX by power fitting at various fuel temperatures, other feedback coefficients are obtained by direct comparing the reactivity change with DIF3D.

The most important parameter in safety features is sodium void worth. The sodium void worth for U-Zr, and U-TRU-Zr core are -2.7$ and -1.4$ respectively. Doppler coefficients of U-TRU-Zr and U-Zr core are drawn in figure 2 and it can be recognized that Doppler coefficient of U-TRU-Zr core is less than U-Zr core. Axial and radial expansion coefficients of U-TRU-Zr core are larger than U-Zr core whereas the sodium density coefficient is larger for U-Zr core. Detailed safety analysis for UO_2 core is not performed because it is unnecessary in current study.

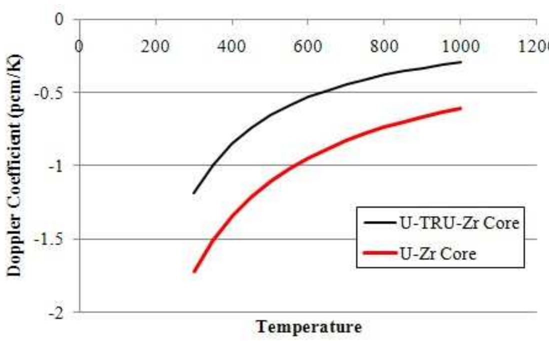

Fig. 2. Comparison of the Doppler coefficient between U-Zr and U-TRU-Zr core

Table V. Comparison of the reactivity coefficients between U-Zr and U-TRU-Zr core

Reactivity coefficient	Fuel type	
	U-Zr	U-TRU-Zr
Effective beta	0.006957	0.003230
Doppler coefficient, (pcm/K)	$-227.0xT^{-0.856}$	$-840.9xT^{-1.151}$
Expansion coefficient, (pcm/K)		
- Axial	-0.35	-0.998
- Radial	-0.78	-0.945
Sodium density coefficient, (pcm/K)	-1.280	-0.5435
Sodium void worth	-2.714$ (-1,888pcm)	-1.393$ (-450pcm)

2.4.2. Reactivity requirement

The primary control system should be able to compensate reactivity losses; stuck of the largest rod worth, 115% overpower condition and reactivity fault. And primary control system should be able to control excess reactivity and uncertainty also.

The secondary control system should be able to shut down from 115% to hot standby condition with unfavorable condition which the strongest control rod is stuck. But excess reactivity and uncertainty are not considered because secondary control system will be only working when primary control system failed.

In the table VI, the necessary assumptions are employed for uncertainty calculation. The uncertainty of temperature defect is same as 20% of the temperature defect, the uncertainty of burnup reactivity is same as 50% of reactivity swing and the uncertainty of criticality precision and fissile loading are each 1$.

Table VI. Reactivity requirement of the primary and secondary control system of U-TRU-Zr core (unit: $)

	Primary	Secondary
Temperature defect	**2.401**	**0.851**
- Full power to hot standby	0.851	0.851
- Hot standby to refueling	1.550	
Overpower (15%)	**0.128**	**0.128**
Fuel cycle excess reactivity	**5.487**	
Uncertainties (RMS)	**5.224**	
- Temperature defect (20%)	0.480	
- Burnup reactivity (50%)	2.744	
- Criticality prediction	1	
- Fissile loading	1	
Reactivity fault	**1.358**	**1.358**
Total	**14.598**	**2.337**

2.4.3. Shutdown margin

The shutdown margin is evaluated by subtracting the reactivity requirement from reactivity worth available. The reactivity worth available means the (n-1) rod worth and the primary and secondary control system have 16.6$ and 10.2$ respectively. The shutdown margin of primary and secondary control system are 2.0$ and 7.9$ for U-TRU-Zr core, these are enough to control reactivity.

Table VII. Shutdown margin of the primary and secondary control system of U-TRU-Zr core

	Primary	Secondary
Number of assembly	7	3
Reactivity worth available, $	16.63	10.22
Maximum reactivity requirement, $	14.60	2.34
Shutdown margin, $	**2.03**	**7.88**

3. Parametric study on TRU transmutation for KALIMER-600

The reactor characteristics will be changed with reactor size. The relationship between reactor size and performance characteristics is known widely. But it is still valuable to study whether reactor can be operated or not for small-sized reactor and whether large-sized reactor can be worked as a burner reactor or not. In this chapter, it is described that parametric study on the reactor power level with various design specifications focused on TRU transmutation.

The KALIMER-600 reactor designed by Korea Atomic Energy Research Institute (KAERI) is used for referenced core. In this study, a size effect is focused on to transmute TRU. Therefore set the KALIMER-600 as a referenced core, change reactor size decreasing and increasing to maintain same power density. But diameter to height ratio is not changed. And then, evaluate TRU transmutation and safety parameters for various cases.

3.1. Referenced core

The KALIMER reactor is used as referenced core in this study. It is a 600MWe SFR. It is consisted of 126 inner driver fuel, 198 outer driver fuel, 25 control, 72 reflector, 78 B_4C shield and 84 radial shield assemblies. In-vessel storage (IVS) assemblies are not designed because these are not impact on the reactor. The core layout is shown in figure 3 and detail reactor characteristics are described in table VIII.

Driver fuel consists of SFR self-recycled fuel and external feed. All of the spent fuel of SFR is recycled to reuse as SFR fuel. Some fraction of SFR spent fuel is lost during recycling process. It is assumed that the recovery factor of TRU is 99.9% and rare earth is 5%. Burnt fissile TRU is compensated from TRU of PWR spent fuel and depleted uranium in external feed. The composition of external feed is adopted from PWR spent fuel with cooling time of 10 years.

Main code is REBUS code with equilibrium cycle. The composition of external feed and recovery factor are described above. Other options of recycling scenario are assumed below. Spent fuel of SFR is cooled one year. Total recycling time is 240days and precooling time before reactor loading is 60days.

Table VIII. Performance characteristics of referenced KALIMER-600

Electrical reactor power, MWe	600
Thermal reactor power, MWth	1500
Active core height, cm	89.07
Number of pins per fuel assembly	271
Number of fuel assemblies [inner / outer]	126 / 198
Reactor core I/O temperature, ℃	390 / 545
Number of batches I/O cores	5 / 5
Cycle length, days	332

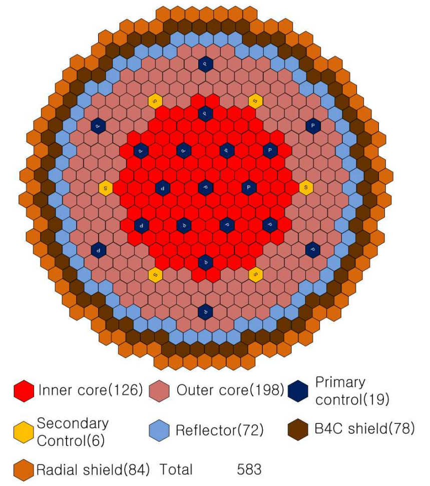

Fig. 3. Radial core layout of KALIMER-600

3.2. 300MWe small- and 1,200MWe large-sized cores

For same power density, equivalent diameter and height of 300MWe small-sized core should be decreased about 0.8 times. And these of 1,200MWe large-sized reactor should be increased about 1.25 times. Reactor size and power are changed for both reactors. Other parameters such as cycle length and recycling scenario are constant. Layouts of both reactors are shown in figure 4 and 5.

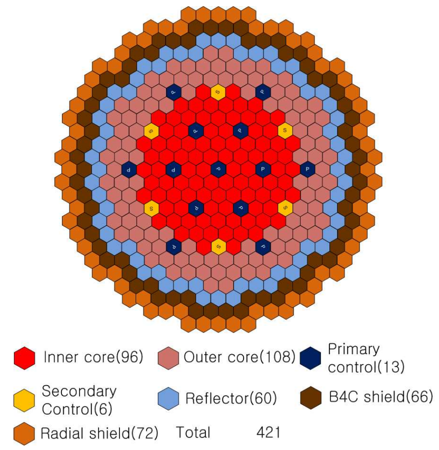

Fig. 4. Radial core layout of small-sized KALIMER-300

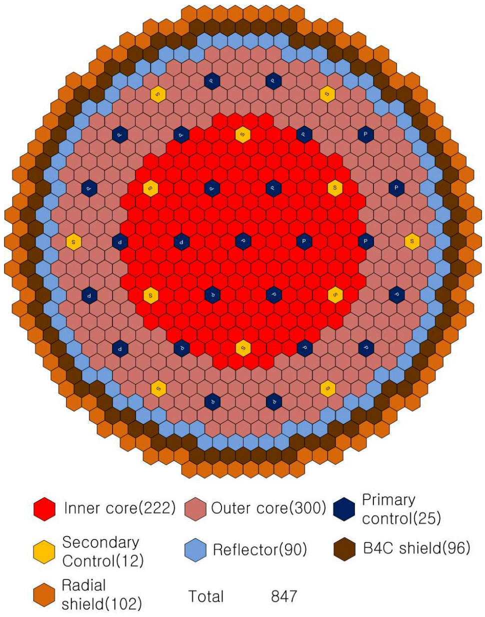

Fig. 5. Radial core layout of large-sized KALIMER-1200

3.3. TRU transmutation and safety parameters comparison by power changing

Five design parameters are considered to evaluate the TRU transmutation and safety. TRU transmutation ratio and TRU support ratio are used for checking TRU transmutation and TRU enrichment, fast fluence and sodium void worth are used for checking safety. TRU transmutation ratio is defined as ratio of TRU transmuted mass to initial charged TRU mass. Goal of TRU transmutation ratio is higher than 20% for active TRU burning. TRU support ratio is defined as mass of spent fuel, from 1,000MWe PWR, used as external feed. The amount of average annual spent fuel from one unit of PWR is about 19tons in Korea and TRU fraction in PWR spent fuel is about 1.4%. So the amount of TRU in average annual spent fuel from one unit of PWR is about 266kg. If the amount of TRU in external feed is 266kg, then TRU support ratio is evaluated 1.0. If it is increased, then TRU support ratio is also increased proportionally. TRU enrichment means the TRU fraction of initial charged U-TRU-Zr fuel. It is limited 30% because of its structural integrity problem. The fast fluence limitation expected in future is $5.0x10^{23}n/cm^2$ for structure material. So the fast fluence during total 5 batches should be lower than limited value. Sodium void worth is the most important safety factor for SFR. It should be lower than 7$.

Eight cases are calculated for each core. These cases are categorized according to fuel and structure volume fraction in REBUS code. There are 4 types of fuel volume fraction which are 25%, 30%, 35% and 40%. In case of 25% of fuel volume fraction, TRU enrichment is large. In contrast, if fuel volume fraction is 40%, TRU enrichment is less. But in both situation, TRU mass may be similar. Large fuel volume fraction condition has large amount of uranium fraction. And there are 2 types of structure volume fraction for extreme cases, 20% and 30%. These are minimum and maximum value for general SFR (fuel pins are not stood extremely densely or thinly). In below graphs, the 25%, 30%, 35% and 40% fuel volume fractions are drawn as the blue, red, green and purple colored lines respectively. And the case of 20% structure volume fraction is drawn as a full line and the case of 30% structure fraction is drawn as a dotted line.

Trend of TRU enrichment as increasing reactor power and fuel volume fraction is drawn in figure 6. The smaller reactor demands the higher TRU enrichment. It is because of higher leakage rate as compared to large-sized reactor. It makes to require larger fission rate therefore small-sized reactor needs more fissile material.

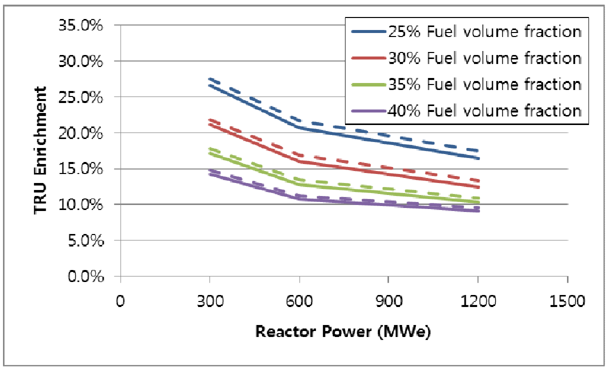

Fig. 6. TRU enrichment variation by power change

TRU transmutation ratio and TRU support ratio are shown in figure 7 and 8. Negative value means that the amount of TRU is increased by breeding during reactor operation. TRU transmutation ratio and TRU support ratio are large for smaller reactor as compared to larger reactor. And TRU transmutation ratio and TRU support ratio in the case of 25% fuel volume fraction are larger as compared to the 40%. The reason is large TRU enrichment. It means that small amount of fertile uranium is loaded and so on breeding also smaller. Therefore reactor makes more TRU burning.

One of the goals is 20% TRU transmutation ratio, but it can be achieved only the reactor case of 25% fuel volume fraction in 300MWe small-sized reactor. Lower than 25% fuel volume fraction is expected to burn more TRU to achieve the goal regardless mid- or large-sized reactor. In addition, TRU enrichment is less than 30% in every case. Therefore fuel volume fraction can be decreased for more TRU burning.

Large-sized reactor has higher flux level generally. It is observed in figure 9 also. But the limitation of fast fluence is satisfied in every case. And difference among them is not too much.

Sodium void worth is related on reactor size strongly. Limitation of sodium void worth is 7$, but it is over in every case for 1,200MWe large-sized reactor. In contrast, sodium void worth of 300MWe small-sized reactor is very small. Furthermore it is evaluated to negative value in some cases. If large-sized reactor is designed, it should make large amount of leakage or absorption rate.

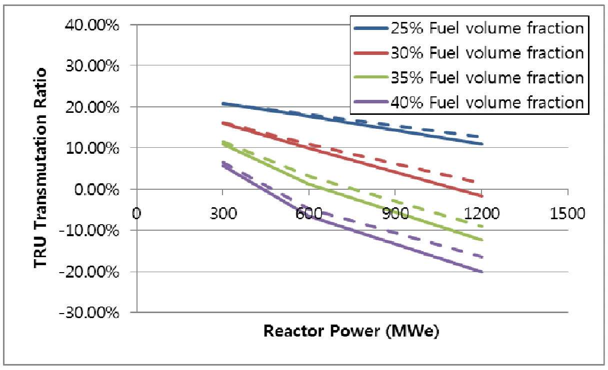

Fig. 7. TRU transmutation ratio variation by power change

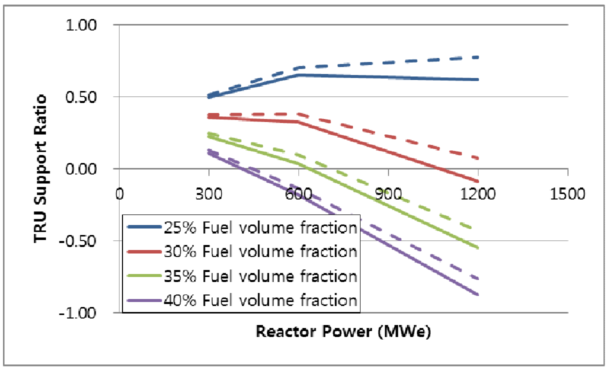

Fig. 8. TRU support ratio variation by power change

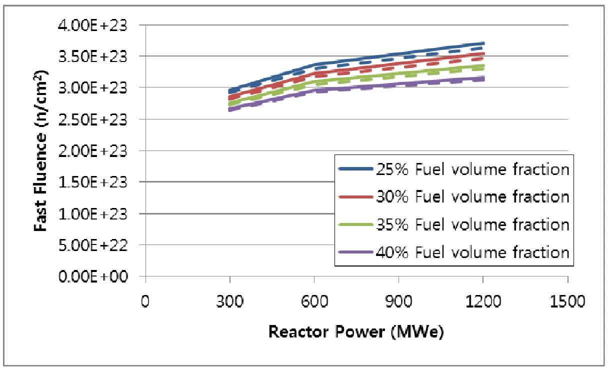

Fig. 9. Fast fluence variation by power change

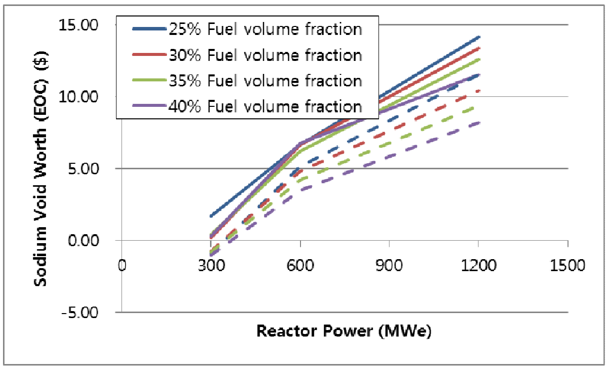

Fig. 10. Sodium void worth variation by power change

5. Conclusion

The impact of new driver fuels; U-TRU-Zr and UO_2 in experimental MESOF reactor was tested in this paper. U-TRU-Zr driver fuel makes higher reactivity swing, but it was not need to be worried because of enough shutdown margin. The core characteristics loaded UO_2 fuel was similar with U-Zr fuel. But fuel pin specification should be more compact because of lower physical density. It caused smaller P/D ratio and thinner wire-wrap. Therefore there would be problem about the probability of thermodynamics problems or mechanical strength.

The parametric study of power rate change was carried out for TRU transmutation and safety of SFR as a TRU burner. Only the case of 25% fuel volume fraction for 300MWe small-sized reactor was able to achieve 20% of TRU transmutation ratio, but other cased of larger fuel volume fraction or larger-sized reactor were not. But if reduce fuel volume fraction, TRU transmutation ratio would be better. Sodium void worth of 300MWe small-sized reactor was too low, so it did not need to worry about it. But sodium void worth of 1,200MWe large-sized reactor could not be able to achieve limitation value.

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