Applicability of Various Fuel Forms with TRU for Small SFR

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1. Introduction

The metallic fuel has been used commonly in sodium cooled fast reactor (SFR). It is known as a well-suited fuel form for SFR because of high theoretical density, high thermal conductivity and harder neutron spectrum. These advantages make metal fuel be used for EBR-II from the early R&D ages even though its own limits including reprocessing problems. On the other hand the oxide fuel developed for LWRs has benefits of huge operational experiences and database. Besides the MOX fuel, many kinds of oxide fuel have been used in SFR in Japan, France and others. The nitride fuel has better characteristics than oxide in many aspects including much higher swelling resistance. It is a promising option for SFR.

The core performance and safety features of small sized reactor are different with larger sized reactor because of larger neutron leakage. Especially, it is expected to reduce positive sodium void effect or make negative due to larger effect of neutron leakage than spectral hardening effect. However, the importance of each control rod is very high because of a few control rods. Detail calculation for rod worth should be cared for the safety against rod withdrawal accidents.

The prototype SFR which is named PGSFR has been planned to be constructed in the Rep. of Korea. Rated power of reference design is 150MWe and this is a small-sized SFR. [1] In this paper, many fuel options to be used for future will be examined for comparison in order to check design limitation and safety features in advance.

The main calculation tools are TRANSX-DANTSYS-REBUS code system for fast reactor. The effective cross sections, weighted region-wise flux, are made by TRANSX and DANTSYS (with TWODANT module) and burnup calculation of core is done by REBUS (with DIF3D module). MCNPX code is partially used such as calculation of effective delayed neutron fraction. The code validation for small SFR with TRANSX-DANTSYS-REBUS code system was done at the previous studies. [2, 3]

2. Reactor Model

The MESOF reactor is selected for an evaluated model. MESOF (Multipurpose Experimental SOdium-cooled Fast reactor) is a conceptual small sized research SFR design by Kyung Hee University. [2, 3] The preliminary proposed MESOF was designed to be operated with full uranium core with U-Zr and designed to be used for experimental irradiation of various fuels at the fuel test loops. In this study, it is evaluated that the impact by loading metallic, oxide and nitride fuel as a driver fuel.

2.1. Referenced MESOF Reactor

MESOF is a small 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 irradiation experiment. 207 reflector assemblies are wrapping the core reducing the neutron leakage effectively. 7 primary control assemblies control excess reactivity and 3 secondary control assemblies make the reactor trip in emergency condition.

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

The design specifications of reactor and fuel assembly are described in below table I and II. The reactor layout is drawn below figure 1. [2, 3]

In previous study, diffusion model in DIF3D showed differences in k-effective by about 0.7% underestimated consistently compared with MCNPX. [2] It means that the k-effective at EOC in table II is underestimated therefore the k-effective at EOC less than 1.0 is not surprising.

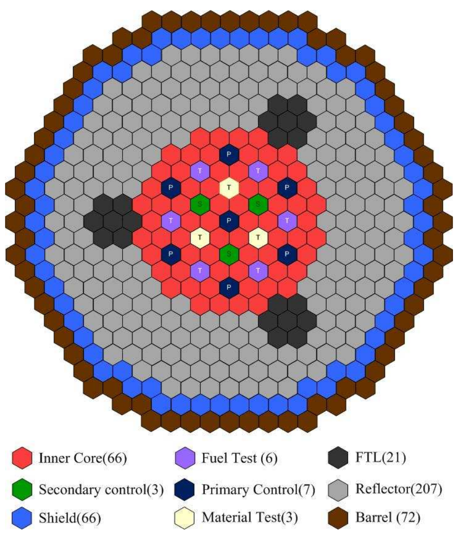

Fig. 1. Radial core layout of MESOF

Table I. Design specification of fuel assembly of referenced 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 referenced MESOF

Reactor power, MWth	300
Cycle length, days	120
Number of driver assemblies	66
Fuel form	U-10%Zr
U^{235} 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, watt/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

The U-Zr fuel was chosen as a driver fuel for the referenced MESOF design. In this paper, it is changed to metallic, oxide and nitride fuel with TRU as a driver fuel and it is evaluated the applicability for three types of fuels by carrying out the core performance characteristics and safety analysis. The specification of fuel options are in table III.

The composition of uranium and TRU are adopted from ABTR designed by Argonne National Laboratory [4]. Depleted uranium with 0.16% enrichment of U^{235} and negligible amount of U^{234} and U^{236} are used the composition of uranium. TRU composition comes from spent fuel of conventional LWR composed of 59% fissile plutonium.

The metallic fuel has been estimated the most suitable fuel type for SFR and the satisfactory experience gained with real reactor such as EBR-II. Its high theoretical density provides better neutron economy and high thermal conductivity makes lower fuel temperature. It does not contain moderating isotopes therefore it makes harder neutron spectrum. It means that the metallic fuel is good for TRU transmutation. Its downside is only relatively large swelling therefore the smear density should be lower. In this study, the ternary alloy which is composed 63% depleted uranium, 27% TRU and 10% zirconium is selected for the metallic fuel.

The benefits of oxide fuel come from large experience gained from LWR and fully developed manufacturing process. But its lower theoretical density causes reducing neutron economy and its lower thermal conductivity enhances fuel temperature and hinders safety features. The mixture of 66.7% UO_2 and 33.3% TRU-O_2 is used for the oxide fuel in this study.

The nitride fuel is a promising option for SFR because it has the advantages of metallic fuel, such as high theoretical density and high thermal conductivity, besides low swelling rate also. Its demerit is that it needs to enrich N^{15} because of production of C^{14} from (n, p) reaction of N^{14}. Therefore, in this study, it is assumed that N^{15} enrichment is 95%. The uranium-plutonium mixed mononitride ((U, TRU) N) is used as a nitride fuel and TRU weight fraction in uranium and TRU is selected 26.3%.

Table III. Specifications of various fuel options

	Metallic	Oxide	Nitride
Fuel form	U-TRU-Zr	Mixture of UO_2 - TRU-O_2	(U, TRU) N
TRU contents in heavy metal	30.0 wt.%	34.4 wt.%	26.3 wt.%
Theoretical density	15.50 g/cm^3	11.15 g/cm^3	14.3 g/cm^3
Smear density	70%	85%	85%

3. Results

3.1. 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.

The uranium and TRU density in metallic fuel is larger than in oxide fuel but smaller than in nitride fuel due to their theoretical and smear density. It makes the reactivity swing larger for the oxide fuel and smaller for the nitride fuel than for the metallic fuel. It is also related to conversion ratio. On the other hands, the level of power peaking and flux among them are similar each other. Details are in table IV.

Table IV. Comparison of the core performance characteristics among various fuel options

	Metallic	Oxide	Nitride	U-Zr Reference
Reactivity swing, pcm	1803	2018	1449	903
Peaking factor [BOC/EOC]	1.71761 / 1.75223	1.78209 / 1.77638	1.77997 / 1.78147	1.87359 / 1.93403
Conversion ratio	0.5045	0.4810	0.6195	0.4265
Peak power density of active core, W/cm^3	372.76	386.25	387.39	412.90
Peak fast fluence, n/cm^2	2.67E+22	2.72E+22	2.39E+22	2.17E+22
Peak LPD, kW/m	31.0	32.2	32.3	34.4
MTA avg. flux, 10^{15}n/cm^2-sec	3.03	3.00	2.86	2.54
Active core avg. flux, 10^{15}n/cm^2-sec	2.19	2.14	2.04	1.72
FTL avg. flux, 10^{15}n/cm^2-sec	0.871	0.798	0.759	0.69

3.2. Safety Analysis

3.2.1. 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] All of the feedback coefficients are obtained by direct comparing the reactivity change with DIF3D.

One of the most important parameter in safety feature is the sodium void worth. The sodium void worth for the metallic, oxide and nitride fuel are negative value, -1.4$, -1.5$ and -0.03$ respectively. Negative reactivity by the leakage effect is inserted effectively along sodium void because reactor size is quite small. Sodium density coefficients for all fuel options are negative value in the same manner. All of the other reactivity coefficients are negative for all fuel options normally. Details are in the table V.

Table V. Comparison of the reactivity coefficients among various fuel options

Reactivity coefficient	Metallic	Oxide	Nitride	U-Zr Reference
Effective beta	0.003230	0.003303	0.003265	0.006391
Isothermal temperature coefficient, (pcm/K)	-0.69	-0.79	-0.83	-0.12
Expansion coefficient, (pcm/K)				
- Fuel axial	-0.998	-0.226	-0.185	-0.075
- Core radial	-0.827	-0.874	0.840	-0.23
Sodium density coefficient, (pcm/K)	-0.1089	-0.1682	-0.0128	-0.13
Sodium void worth	-1.393$ (-450pcm)	-1.465$ (-484pcm)	-0.031$ (-10pcm)	-1.54$ (-984pcm)

3.2.2. Shutdown margin

The primary control system should be able to compensate reactivity losses; stuck of the largest worth rod, 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. These cause many blanks in table VII.

In the table VI and VII, 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$.

The reactivity requirements of both the primary and secondary control systems for the metallic and oxide fuel are similar. But the reactivity requirement for the nitride fuel is smaller; about 0.8 and 0.7 times than others for the primary control system and secondary respectively.

Table VI. Reactivity requirement of the primary control system of various fuel options (unit: $)

	Metallic	Oxide	Nitride	U-Zr Reference
Temperature defect	**2.088**	**1.448**	**1.330**	**1.553**
- Full power to hot standby	0.747	0.482	0.443	0.687
- Hot standby to refueling	1.341	0.966	0.887	0.866
Overpower (15%)	**0.112**	**0.072**	**0.066**	**0.10**
Fuel cycle excess reactivity	**5.487**	**5.986**	**4.381**	**1.41**
Uncertainties (RMS)	**5.162**	**5.283**	**4.457**	**3.0**
- Temperature defect (20%)	0.418	0.290	0.266	0.3
- Burnup reactivity (50%)	2.744	2.993	2.191	0.7
- Criticality prediction	1	1	1	1
- Fissile loading	1	1	1	1
Reactivity fault	**1.358**	**1.605**	**1.055**	**0.5**
Total	**14.207**	**14.394**	**11.289**	**6.563**

Table VII. Reactivity requirement of the secondary control system of various fuel options (unit: $)

	Metallic	Oxide	Nitride	U-Zr Reference
Temperature defect	**0.747**	**0.482**	**0.443**	**0.687**
- Full power to hot standby	0.747	0.482	0.443	0.687
- Hot standby to refueling	-	-	-	-
Overpower (15%)	**0.112**	**0.072**	**0.066**	**0.1**
Fuel cycle excess reactivity	**-**	**-**	**-**	**-**
Uncertainties (RMS)	**-**	**-**	**-**	**-**
- Temperature defect (20%)	-	-	-	-
- Burnup reactivity (50%)	-	-	-	-
- Criticality prediction	-	-	-	-
- Fissile loading	-	-	-	-
Reactivity fault	**1.358**	**1.605**	**1.055**	**0.5**
Total	**2.217**	**2.159**	**1.564**	**1.287**

The shutdown margin is evaluated by subtracting the reactivity requirement from reactivity worth available. The reactivity worth available means the (n-1) rod worth.

The shutdown margin with various fuel options for the primary control system and secondary are indicated in the table VIII and IX respectively. The shutdown margins of the primary control system for all of the fuel types are enough, larger than 2$ and smaller than 5$. On the other hands, the reactivity requirements for the secondary control system are quite smaller than for the primary control system; only less than 0.2 times. But the reactivity worth available for the secondary control system are about 0.6 times than for the primary control system. Thus the shutdown margins of the secondary system for all of the fuel options are very big therefore these are not considerable safety features.

Table VIII. Shutdown margin of the primary control system of various fuel options

	Metallic	Oxide	Nitride	U-Zr Reference
Number of assembly	7	7	7	7
Reactivity worth available, $	16.63	17.70	15.86	8.23
Maximum reactivity requirement, $	14.21	14.39	11.29	6.563
Shutdown margin, $	**2.42**	**3.31**	**4.57**	**1.667**

Table IX. Shutdown margin of the secondary control system of various fuel options

	Metallic	Oxide	Nitride	U-Zr Reference
Number of assembly	3	3	3	3
Reactivity worth available, $	10.22	10.83	9.76	5.05
Maximum reactivity requirement, $	2.22	2.16	1.56	1.287
Shutdown margin, $	**8.00**	**8.67**	**8.20**	**3.763**

3.2.3. Quasi-static Analysis

The codes for analysis of SFR accident according to time have been developed. Meanwhile, simple preliminary assessment method of safety potential for severe accidents of fast reactor is here, the quasi-static analysis. It is the way to define the parameters A, B and C and it can be evaluated the safety potential for the unprotected loss of flow (ULOF), unprotected loss of heat sink (ULOHS) and unprotected transient over-power (UTOP) accidents by the relations of A, B and C.

A represents the reactivity variation due to increase of the fuel temperature from average coolant temperature to average fuel temperature. B represents the reactivity variation coming from temperature increasing of fuel and coolant from core inlet temperature to average coolant temperature. C is the reactivity feedback coefficient associated to the core inlet temperature. [6] These A, B and C parameters for each fuel options are indicated in table X. The restriction for safety at severe accident and the quasi-static reactivity balance for each fuel options are in table XI. [2]

The metallic and nitride fuel options are proven the safety potential for ULOF and ULOHS accident. But for the ULOF accident of oxide fuel, the quasi-static reactivity balance is exceeded the restriction. It means, as is well known, oxide fuel is exposed to the danger for ULOF accident even if reactor size is small. Meanwhile, the quasi-static reactivity balances for UTOP accident are larger than restriction for all of the fuel options. It means relatively large reactivity is inserted at the strongest control rod withdrawn condition. In other words, each control rod worth is relatively larger. There are two reasons. The first, fissile fuel is TRU whose main fissile isotope is Pu^{239} therefore the effective delayed neutron fraction is dropped. The second reason is the small number of control rods. It increases the importance of each control rods. The reactivity worth should be reduced to promise the safety at UTOP accident condition. The simplest solution is to deplete the B^{10} enrichment of B_4C in control rod. It provides smaller rod worth and then safety potential will be secured at UTOP accident. However, the reduced B^{10} enrichment causes reduced shutdown margin. Therefore it should be selected proper amount of B^{10} enrichment.

Table X. The value of A, B and C parameters of various fuel options

	Metallic	Oxide	Nitride	U-Zr Reference
A, (cent)	-12.91	-72.17	-15.34	-7.2
B, (cent)	-82.83	-68.78	-64.26	-51.3
C, (cent/K)	-0.813	-0.623	-0.572	-0.57

Table XI. Quasi-static reactivity balance of various fuel options

Accident	Restriction	Metal	Oxide	Nitride	U-Zr
ULOF	A/B < 1.0 and A & B both are negative	0.16	1.05	0.24	0.14
ULOHS	$1.0 < (C\Delta T_c/B) < 2.0$ and C should be negative	1.52	1.40	1.38	1.73
UTOP	$\Delta\rho^{TOP} / \lvert B\rvert < 1.0$	1.64	2.33	1.64	0.80

4. Conclusions

The core performance characteristics and safety analysis for small sized SFR with metallic, oxide and nitride fuel with TRU are performed by calculation of reactivity coefficient, shutdown margin and quasi-static analysis. The theoretical density of oxide fuel is relatively low therefore its TRU fraction in heavy metal is relatively higher than others. For nitride fuel, the TRU fraction in heavy metal is relatively lower than others due to higher theoretical density and higher smear density. In the aspect of core performance, all of the fuel options are shown similar power peaking and flux level. The results of reactivity coefficient and shutdown margin are indicated enough safety but the result of quasi-static analysis is indicated lack of safety potential at UTOP accident condition for all of the fuel forms. It comes from the reactor size and main fissile isotope, not fuel form. The number of control rod for small sized reactor is small and it makes higher importance of each control rod. And Pu^{239} in TRU which is main fissile isotope is another reason of lack of safety potential at UTOP accident. Pu^{239} makes to drop the effective delayed neutron fraction in the core. This risk at UTOP accident is expected to be solved to deplete the B^{10} of B_4C in control rod. However it makes to reduce the shutdown margin. The compatibility of the safety potential at UTOP with enough shutdown margin is the last homework for applicability of metallic, oxide and nitride fuel in small sized SFR. Meanwhile, for the oxide fuel, the ULOF accident also does not assure safety potential from the result of quasi-static reactivity balance.

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