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Sodium-cooled Fast Reactor Cores using Uranium-Free Metallic Fuels for Maximizing TRU Support Ratio

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I. Introduction

Sodium-cooled fast reactors[1] have been considered as an effective way to transmute TRU nuclides from LWR spent fuels due to their fast neutron spectra and so lots of works have done on the core design studies using ternary metallic or oxide fuels containing depleted uranium as the fertile nuclides. The depleted uranium plays important roles in the SFR burner cores because it substantially contributes to the inherent safety of the core through the negative Doppler coefficient and large delayed neutron. However, the use of depleted uranium as a diluent nuclide leads to a limited value of TRU support ratio due to the generation of TRUs through the breeding. In this paper, we designed sodium cooled fast reactor (SFR) cores having uranium-free fuels[3,4] for maximization of TRU consumption rate. However, the uranium-free fuelled burner cores can be penalized by unacceptably small values of the Doppler coefficient and small delayed neutron fraction. In this work, metallic fuels of TRU-(W or Ni)-Zr are considered to improve the performances of the uranium-free cores. In fact, these isotopes have absorption resonances. The neutron absorption cross section of ^{238}U, ^{58}Ni, ^{182}W, and ^{90}Zr are shown in Fig. 1 for comparison.

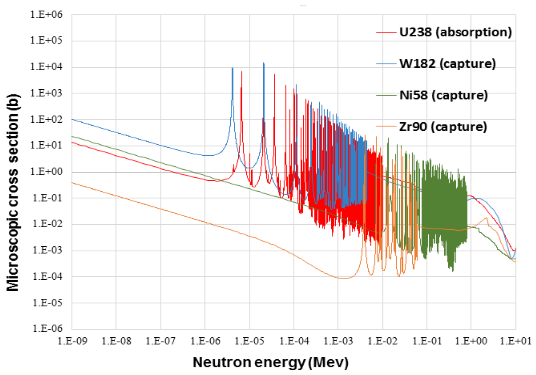

Fig. 1. Absorption or capture cross sections of ^{58}Ni, ^{182}W, ^{90}Zr and ^{238}U

These isotopes are the most abundant isotopes of Ni, W, and Zr. This figure shows that the absorption resonance peaks of ^{238}U and ^{182}W are located in the same energy range, between 1x10^{-6} and 1x10^{-2} MeV. And ^{58}Ni has relatively high energy range of absorption resonance peaks between 1x10^{-2} and 1.00 MeV. Also, it is noted that ^{58}Ni has narrow resonances in the mean energy region of fast neutron spectrum, which can contribute to the reduction of sodium void worth and to high effective delayed neutron fraction. The objective of this work is to consistently compare the neutronic performances of uranium-free sodium cooled fast reactor cores having TRU-Zr metallic fuels added with Ni or W and also to clarify what are the problematic features to be resolved.

II. Computational Methods and Models

The REBUS-3 equilibrium model[5] with a nine group cross section was used to perform the core depletion analysis where the feed TRU contents are searched such that k-eff at EOEC (End of Equilibrium Cycle) is 1.005. The nine group cross section were produced by collapsing the 180 group cross sections with the 150 group core region-wise neutron spectra that were calculated with TWODANT R-Z geometrical model[6]. The 150 group cross section library of ISOTXS format is generated using TRANSX code[7] and a MATXS format which was generated with the NJOY code for master nuclides. The core physics parameters were evaluated with 80 group cross section and DIF3D HEX-Z nodal option. The decay chain spans the range from ^{232}Th to ^{246}Cm. We assumed 99.1% and 5% recovery for actinides and rare earth fission product, respectively, and the other fission products are assumed to be completely removed to waste stream during reprocessing. The composition of external TRU feeding corresponds to the TRU composition of LWR spent fuel having discharge burnup of 50MWd/kg and 10 years cooling.

III. Core Design Study and Performance Analysis

III.A. Reference Configuration Cores

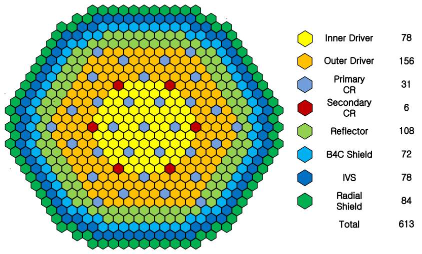

Fig. 2. Reference core configuration

The reference core configuration is shown in Fig. 2. The active core region is divided into two regions composed of the different type assemblies. The outer core region is comprised of the normal hexagonal fuel assemblies which consist of 271 fuel pins (i.e., 10 hexagonal rings of fuel pins) in a duct. On the other hand, a new fuel assembly design devised for achieving power flattening with a single TRU content in charging fuel is used in the inner core region[2].

Table I Main design parameters of the reference core

Design parameter	Specification
Power (MWe/MWt)	400/1015.6
Fuel type(Ternary metal alloy)	
Reference	TRU-U-10Zr
Fertile-Free	TRU-W(or Ni)-10Zr
Number of rods per FA	[a]271 /217
Smear density of fuel	75%
Duct wall thickness(mm)	[a]3.7 / 11.5
Assembly pitch (cm)	16.22
Rod outer diameter(mm)	7.5
Wire wrap diameter(mm)	1.4
Clad thickness(mm)	0.53
Fuel cycle length (EFPD)	332
Number of fuel management batches	4
Average linear power density (W/cm)	177.0
Core active height(cm, cold)	90
Volume fraction(fuel/coolant/structure)	
Inner core	30.6/30.8/38.6
Outer core	38.3/36.9/24.8

[a]Values for the normal and new assemblies, respectively

Table I summarizes main design parameters of the reference core. All cores considered in our work rate 1015.6MWt (400MWe). The outer diameter of fuel rod is 7.5mm and clad thickness is 0.53mm. The duct thickness for the normal and the thick duct assemblies are 3.7 and 11.5mm, respectively. The cycle length is 332 EFPD (Effective Full Power Days) and four fuel management scheme is used both for inner and outer core regions. The active core is 90cm high at cold state. The average linear heat generation rate is 177.0W/cm. For this reference core configuration, the performances of the cores loaded a ternary metallic fuel of TRU-U-10Zr and TRU-W(or Ni)-10Zr are analyzed and the results are given in Table II. In Table II, it is shown that the reference core using TRU-U-10Zr fuel has a high TRU conversion ratio and a low TRU transmutation rate because this reference core has no any way to reduce conversion ratio except for use of thick duct assemblies in inner core region. This reference core has TRU support ratio of 0.73 which corresponds to 69kg TRU consumption per cycle. In comparison with the reference core, the cores using non-uranium fuels have much larger TRU consumption rate of ~350kg/cycle because these cores used uranium-free driver fuels. This TRU consumption rate corresponds to TRU support ratio of ~3.7. However these cores have larger burnup reactivity swing than reference core due to the poor breeding of fissile materials. Of these cores using non-uranium fuels, the core using tungsten-based fuel (i.e., TRU-W-10Zr) has smaller burnup reactivity sowing of 5606pcm due to its larger heavy metal inventories because tungsten isotopes have higher absorption cross section than zirconium isotopes and so larger amount of heavy metal inventories are required for criticality. The small burnup reactivity swing reduces the amount of reactivity control by control rods. In Table III, the contents of major actinides in fuels are analyzed in detail. As shown in Table III, the cores using uranium-free fuels have much higher TRU and MA (Minor Actinide) contents than the reference core. This feature is resulted from much higher discharge burnup and smaller conversion ratio. Also, these uranium-free fuelled cores have smaller fissile contents than the reference core. Figure 3 compares the core neutron spectra of the cores considered. This figure shows that the cores using non-uranium fuels have harder neutron spectra than the reference core except for the core using nickel-based fuel (i.e., TRU-Ni-10Zr).

Table II Comparison of performances of the reference configuration cores

Design parameter	TRU-U-10Zr	TRU-Zr	TRU-Ni-10Zr	TRU-W-10Zr
Burnup reactivity swing (pcm)	1452	7193	6740	5606
Average discharge burnup (MWD/kg)	114	256	240	193
TRU support ratio	0.73	3.70	3.72	3.75
Cycle average TRU conversion ratio	0.85	0.43	0.44	0.40
TRU consumption rate (kg/cycle)	69.0	349.0	351.0	354.0
Fuel inventories (kg, BOEC/EOEC)				
TRU	3783 / 3715	4469 / 4123	4833 / 4485	6162 / 5812
U, Ni, or W	14246 / 13969	-	7124 / 7124	11801 / 11801
Zr	2063 / 2063	5389 / 5389	1402 / 1402	2075 / 2075
Total	20092 / 19747	9858 / 9512	13432 / 13083	20169 / 19817
TRU contents in Fuel (wt%, BOEC/EOEC)	18.8 / 18.8	45.3 / 43.3	36.0 / 34.3	30.6 / 29.3
3D power peaking factor	[a]1.60 / 1.58	1.52 / 1.47	1.56 / 1.51	1.54 / 1.49
Peak linear power density (W/cm)	[a]283 / 280	266 / 258	275 / 265	273 / 261
Fast neutron fluence (n/cm^2)	3.02x10^{23}	3.27x10^{23}	2.97x10^{23}	2.60x10^{23}

[a]Values at BOEC and EOEC

Table III Comparison of the contents of major actinides for the cores

Design parameter	TRU-U-10Zr	TRU-Zr	TRU-Ni-10Zr	TRU-W-10Zr
TRU contents in Fuel (wt%, BOEC/EOEC)				
^{238}Pu	0.6 / 0.6	3.1 / 3.1	2.4 / 2.4	2.1 / 2.1
^{239}Pu	9.4 / 9.4	11.5 / 10.0	9.0 / 7.8	7.9 / 7.1
^{240}Pu	6.0 / 6.1	18.2 / 17.9	14.6 / 14.3	12.2 / 12.0
^{241}Pu	0.8 / 0.8	3.0 / 3.0	2.4 / 2.3	1.7 / 1.7
^{242}Pu	0.6 / 0.6	2.5 / 2.6	2.0 / 2.1	1.5 / 1.6
MA	1.4 / 1.4	7.1 / 6.8	5.6 / 5.3	5.0 / 4.8
TRU (Pu+MA)	18.8 / 18.8	45.3 / 43.3	36.0 / 34.3	30.6 / 29.3

Table IV Comparison of the Reactivity Coefficients of the Cores

Design parameter	TRU-U-10Zr	TRU-Zr	TRU-Ni-10Zr	TRU-W-10Zr
Fuel Doppler coefficient (pcm/K, 900K,BOEC)				
TRU	0.006339	-0.048683	-0.084214	0.003476
U, Ni, W, or Zr	-0.455911	-0.000205	-0.000051	-0.188265
Total fuel	-0.452096	-0.062812	-0.088773	-0.189383
Fuel axial expansion coefficient (pcm/K, BOEC)	-0.377	-0.376	-0.339	-0.368
Radial expansion coefficient (pcm/K, BOEC)	-0.813	-0.941	-0.823	-0.761
Sodium void worth (pcm, BOEC)	1810(5.5$)	1102(4.3$)	1419(5.5$)	2276(9.6$)
Control rod worth (pcm, BOEC)				
Primary	15237(46$)	19208(75$)	16578(63$)	13004(54$)
Secondary	4112(12$)	5100(20$)	4411(16$)	3516(14$)
Effective delayed neutron fraction (BOEC)	0.00332	0.00255	0.00260	0.00237

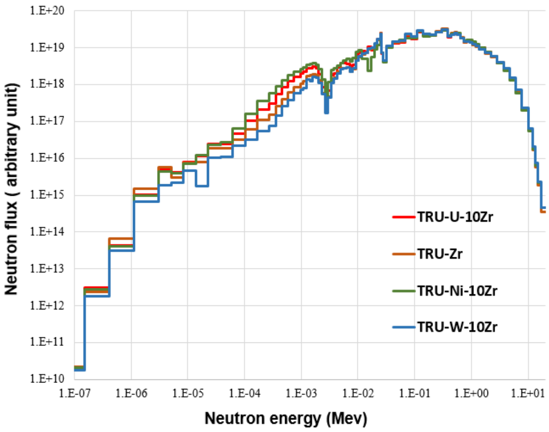

Fig. 3. Comparison of core neutron spectra

Table IV compares the detailed results of the reactivity coefficients. The results show that the use of the uranium-free fuels leads to much less negative fuel Doppler coefficients. However, it is noted that in spite of the absence of ^{238}U, the Doppler coefficients of all the uranium-free cores are still negative. Also, this table shows that the cores fuelled with TRU-Ni-10Zr and TRU-Zr have relatively small value of sodium void worth comparable to that of the reference core. In particular, it should be noted that the core fuelled with TRU-W-10Zr has much larger sodium void worth of 9.6$ than these two core but this core has most negative Doppler coefficient due to high resonance absorption of Tungsten isotopes while this high resonance absorptions of Tungsten isotopes contribute to high sodium m void worth. For the effective delayed neutron fraction, as expected, the uranium-free fuelled cores have much smaller effective delayed neutron fraction due to the absence of ^{238}U. Of the uranium-free fuelled cores, the core fuelled with TRU-Ni-10Zr has the highest effective delayed neutron fraction, which might be resulted from the high energy resonances of Nickel isotopes.

Table V Comparison of the uranium-free core neutron balances (reaction probabilities)

Type	TRU-U-10Zr		TRU-Zr		TRU-Ni-10Zr		TRU-W-10Zr	
	Sodium flooded	Sodium voided	Sodium flooded	Sodium voided	Sodium flooded	Sodium voided	Sodium flooded	Sodium voided
Sodium void worth (pcm)	1810(5.5$)		1102(4.3$)		1419(5.5$)		2276(9.6$)	
Leakage	0.247	0.273([a]0.026)	0.317	0.352 (0.035)	0.263	0.291(0.028)	0.226	0.248(0.022)
Radial	0.109	0.116	0.139	0.148	0.119	0.126	0.102	0.107
Axial	0.138	0.157	0.178	0.204	0.144	0.164	0.124	0.141
Fission	0.347	0.353	0.360	0.364	0.358	0.363	0.353	0.362
Captrure	0.408	0.376([a]-0.032)	0.323	0.285(-0.038)	0.379	0.346(-0.033)	0.422	0.391(-0.030)
(n,2n)	0.0016	0.0017	0.0004	0.0004	0.0003	0.0003	0.0011	0.0012

[a]Voided-Flooded

Table V compares the neutron balances for both the sodium-flooded and sodium-voided cases of all the cores. As shown in Table V, the core using TRU-W-10Zr fuels has the smallest increase of neutron leakage under sodium voiding than the core using TRU-Zr fuels even if this core has the hardest neutron spectrum, which results in the increase of sodium void worth.

IV. Summary and Conclusions

In this paper, a consistent comparative study of 400MWe sodium cooled burner cores having uranium-based fuels and uranium-free fuels was done to analyze the relative core neutronic features. Also, we proposed a uranium-free metallic fuel based on Nickel. From the results, it is found that tungsten-based uranium-free metallic fuel gives large negative Doppler coefficient due to high resonance of tungsten isotopes but this core has large sodium void worth and small effective delayed neutron fraction while the nickel-based uranium-free metallic fuelled core has less negative Doppler coefficient but smaller sodium void worth and larger effective delayed neutron fraction than the tungsten-based one. On the other hand, the core having TRU-Zr has very high burnup reactivity swing which may be problematic in compensating it using control rods and the least negative Doppler coefficient. From the study, it is considered that the cores using uranium-free metallic fuels (specifically using nickel-based uranium-free fuel) can be designed to have reasonable values of the core performances except for the burnup reactivity swing which should be significantly reduced. So, our future study will be focused on how to reduce the burnup reactivity swing of the uranium-free fuelled cores.

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