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An Advanced Option for Sodium Cooled TRU Burner Loaded with Uranium-Free Fuels

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1. Introduction

The effective burning of LWR spent fuel TRU can be achieved by using advanced sodium cooled fast reactor (SFR) coupled with a closed fuel cycle in order to reduce the accumulated LWR spent fuel and its long-term radiotoxicity including heat generation[1,2,3]. The sodium cooled fast reactors of this kind that are called burners are designed to have low conversion ratio by reducing fuel volume fraction or reducing neutron leakage or increasing neutron absorption. However, the typical SFR burners have a limited ability of TRU burning rate due to the fact that they use metallic or oxide fuels containing fertile nuclides such as ^{238}U and ^{232}Th and these fertile nuclides generate fissile nuclides through neutron capture even if they are designed to have low conversion ratio (e.g., 0.6). To further enhance the TRU burning rate, the removal of the fertile nuclides from the initial fuels is required and it will accelerate the reduction of TRUs that are accumulated in storages of LWR spent fuels. However, it has been well-known[4] that the removals of the fertile nuclides from the fuel degrade the inherent safety of the SFR burner cores through the significant decrease of the fuel Doppler effect, the increase of sodium void reactivity worth, and reduction of delayed neutron fraction. So, the maximization of TRU burning rate requires the development of advanced concept which can minimize the degradations of the inherent safety features without loss of high TRU burning capability.

In this paper, an advanced option for this purpose is proposed and the 400MWe SFR burner cores using this option and metallic fertile-free fuels are designed and analyzed in view point of the core physics. The option is to use an axially central absorber region and 6 or 12 moderator rods for each fuel assembly to minimize the degradation of the core physics parameters such as burnup reactivity swing, sodium void reactivity worth, and Doppler coefficient. Also, we considered the depletion of the boron which is contained in the axially central absorber region and analyzed the effects of the boron depletion on the burnup reactivity swing. We expected that the axially central absorber region will reduce the sodium void reactivity worth by increasing the neutron absorption leaking into this absorber region when the sodium coolant is voided and this absorber region increases the initial heavy metal inventory for maintaining criticality, which reduces the burnup reactivity swing without loss of TRU burning rate. The moderator rods are introduced to improve the Doppler effects and to reduce sodium void reactivity worth by softening the core neutron spectrum. This work provides the results of performance analyses for the new cores having different fuels and design options. In addition, the balance of reactivity (BOR) analysis was performed to evaluate the inherent safety features of the cores. In Sec. 2, the computational methods and models are described. Sec. 3 gives the core designs and their performances. Finally, the summary and conclusions are given in Sec. 4.

2. Computational Method 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 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[7]. The decay chain spans the range from ^{232}Th to ^{246}Cm. We assumed 99.9% 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. In this work, we considered the depletion of boron-10 which is contained the axially central absorber region. For this purpose, a simple depletion chain is added into the existing actinide depletion chain by considering the (n,α) reaction of B-10. On the other hand, the depletions of the Tungsten and Nickel were not considered even if they were treated as active isotopes for searching the feed TRU contents in fuel.

3. Core Design and Performance Analysis

3.1 Description of the Core Designs

The cores considered rate 400MWe (1015.6). The configuration is shown in Fig. 1. Actually, this configuration was developed to achieve power flattening with a uniform charge fuel composition through the core in our previous works[8]. This power flattening was achieved by loading the new special fuel assemblies having smaller number of fuel rods and thicker duct in the inner core region than in the outer core region. The normal fuel assemblies comprised of 271 fuel pins within a normal duct of 3.7mm thick are loaded in the outer region. As shown in Fig. 1, the inner and outer core regions consist of 78 and 156 driver fuel assemblies, respectively. The reactivity control system consists of two separate control rod groups (i.e., primary and secondary groups comprised of 31 and 6 control rod assemblies, respectively). A large number of primary control rod assemblies were considered to cope with the large burnup reactivity swing that may be expected in the burner cores. As in the previous study[9], we considered two different fertile-free metallic fuels that use Nickel and Tungsten, respectively, to improve the fuel Doppler effects because the cores loaded with fertile-free fuels typically have very small or nearly zero values of the Doppler coefficients. They are ternary metallic alloys of TRU-Ni-10Zr and TRU-W-10Zr, respectively. Table I summarizes the main design parameters of the cores.

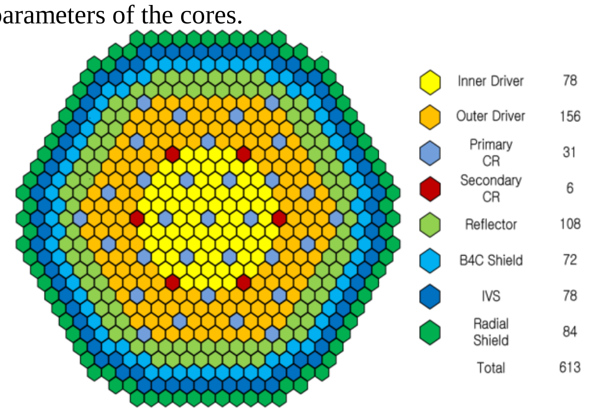

Fig. 1. Radial configuration of the cores

Table I: Main design parameters of the cores

Design parameter	Specification
Power (MWe/MWt)	400/1015.6
Fuel type(Ternary metal alloy)	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)	[b]175.0/218
Core active height(cm, cold)	90
Absorber region height (cm, cold)	18
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
[b]Values for the cores having no absorber region and having absorber region, respectively

As mentioned previously, Nickel and Tungsten are considered as the diluent material to improve the Doppler coefficient by using the resonance capture characteristics. The height of the axially central absorber region is selected to be 18cm. Fig. 2 shows the axial configuration including the axial absorber region. The active core height is 90cm for the reference core having the axially central absorber region which was designed in the previous work. The absorber material is boron carbide whose B-10 content is 20.0wt%. The average linear heat generation rate of the reference core having no absorber region is 175.0 W/cm and it is increased to 218 W/cm for the cores having the absorber region. All the cores considered in this work use the same four batch refueling scheme and the same cycle length of 332 EFPDs.

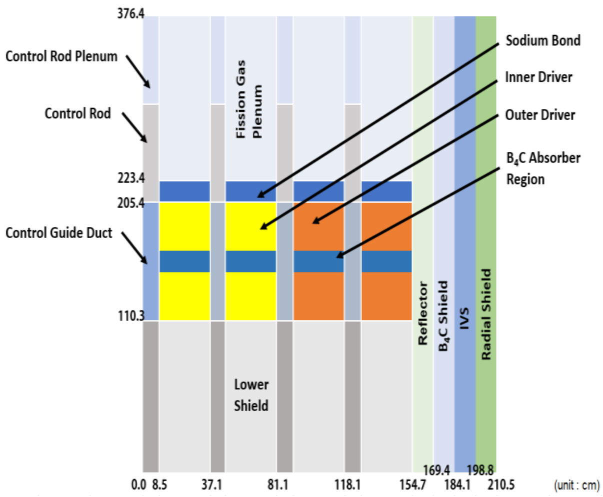

Fig. 2. Axial configuration of the cores having absorber region

3.2 Core Performance Analysis

First, we designed and analyzed the cores having 18cm thick axially central absorber region for each of the fertile-free metallic fuels described in Sec. 3.1. The performances of these two cores are compared with those of the reference cores having no the absorber region. Table II summarizes the performances of these four cores. In Table II, the reference cores loaded with TRU-Ni-10Zr and TRU-W-10Zr are denoted as Case A-1 and Case B-1, respectively while the corresponding cores having the axially central absorber are denoted as Case A-2 and Case B-2, respectively. As shown in Table II, all the cores have large burnup reactivity swings due to small breeding through the neutron capture by fertile nuclides. The use of the axially central absorber leads to the significant reductions of the burnup reactivity swing by 2265 pcm (i.e., 33.6%) and 1466 pcm (26.2%) for the nickel-based and tungsten-based fuelled cores, respectively. These significant reductions of the burnup reactivity swing are resulted from the reductions of the discharge burnup which is due to the increases of the initial heavy metal loading to keep the criticality and from the depletion of B-10 in the absorber region. The comparison with the burnup reactivity swings for the cores having absorber region without the depletion of B-10 showed that the significant reduction of burnup reactivity swing comes mostly from the effect of the discharge burnup reduction and the contribution from the B-10 depletion is small (about several hundred in pcm). The average discharge burnups are reduced by 23.3% and 35.5% for the nickel-based and tungsten-based fuelled cores, respectively. On the other hand, it is noted that all the cores have very high TRU support ratio larger than 3.7 and their differences in TRU support ratios are very small because they used fertile-free fuels. This fact means that these cores can consume the amount of TRUs discharged from ~4 PWRs of the same thermal power and cycle length. Also, it is shown in Table II that they have the similar TRU burning rates higher than 340 kg/cycle. The cores have peak linear power densities less than 450 W/cm and the cores having axially central absorber have very high TRU contents in fuels. However, the performances of the fertile-free metallic fuels for high burnup and high TRU contents should be verified through the irradiation tests but we implicitly assumed their feasibilities because these material issues are out of the scope of this work.

Table II shows that all the cores have negative Doppler coefficients and the use of the axially central absorber leads to the significant reduction of the Doppler coefficients due to the reduction of the diluent resonant nuclides. Also, the decomposition of the Doppler coefficient shows that the negative Doppler coefficient is mainly contributed from tungsten for the tungsten-based fuelled cores while it is mainly from the actinides for the nickel-based fuelled cores. So, the effectiveness of nickel is much smaller than that of tungsten. Also, it is noted that these cores have large negative reactivity coefficients for radial core expansion and the cores having axially central absorber show very large negative reactivity coefficients for radial core expansion due to large axial neutron leakage.

Table II: Comparison of the performances of the cores loaded with fertile-free fuels

Design parameter	Case A-1	Case A-2	Case B-1	Case B-2
Fuel driver type	TRU-Ni-10Zr		TRU-W-10Zr	
B4C absorber thickness (cm, cold)	N/A	18	N/A	18
Average linear power (W/cm)	175	218	175	218
Burnup reactivity swing (pcm)	6740	4475	5606	4140
Average discharge burnup (MWD/kg)	240	184	256	165
TRU support ratio	3.72	3.73	3.70	3.75
Cycle average TRU conversion ratio	0.44	0.36	0.43	0.36
TRU consumption rate (kg/cycle)	351	351	354	354
Fuel inventories (kg, BOEC/EOEC)				
TRU	4833/4485	6591/6240	6162/5812	7436/7084
Ni, or W	7124/7124	2928/2928	11801/11801	6931/6931
TRU contents in Fuel (wt%, BOEC/EOEC)	36.0/34.3	69.0/68.2	30.6/29.3	51.8/50.5
Peak linear power density (W/cm)	275	428	273	440
Fast neutron fluence (n/cm^2)	2.97×10^{23}	2.46×10^{23}	2.60×10^{23}	2.32×10^{23}
Fuel Doppler coefficient (pcm/K, 900K, BOEC)				
Total fuel	-0.0887	-0.0249	-0.1894	-0.0738
TRU	-0.0842	-0.0237	0.00348	-0.00226
Non TRU(Ni, or W)	-0.000051	-0.000226	-0.1883	-0.0689
Radial expansion coefficient (pcm/K, BOEC)	-0.823	-1.07	-0.761	-1.01
Fuel axial expansion coefficient (pcm/K, BOEC)				
Fuel only	-0.339	-0.39	-0.368	-0.37
Sodium void worth (pcm, BOEC)	1419 (5.5$)	1033 (4.5$)	2276 (9.6$)	1230 (5.6$)
Control rod worth (pcm, BOEC)				
Primary	16578	8918	13004	7771
Secondary	4411	2492	3516	2186
Effective delayed neutron fraction (BOEC)	0.00260	0.00228	0.00237	0.00221

The nicked-based fuelled cores have smaller sodium void reactivity worth than the tungsten-based fuelled cores because they have smaller TRU inventories. For these cores, the uses of the axially central absorber lead to the reductions of sodium void reactivity worth by 1$ and 4$ for the nickel and tungsten-based fuels, respectively. From these results, it is considered that the new cores having axially central absorber have reasonable levels of sodium void reactivity worth for the sodium voiding through the active core plus upper fission gas plenum. However, these new concept cores have much smaller control rod reactivity worth than the reference cores having no the axially central absorber. This fact is caused from the large capture of neutrons in the absorber region. Also, these new cores have the reduced delayed neutron fractions which make the reactivity control more difficult. At present, we did not optimize the control rod assembly designs and their locations. The current design of the control rods uses natural boron and so it is considered to make it possible to further increase the control rod reactivity worth.

Next, we analyzed the neutron spectra of the cores given in Table II. Fig. 3 compares the neutron spectra of the cores. As shown in Fig. 3, the tungsten-based fuelled reference core (i.e., Case A-1) has much harder spectrum than the nickel-based fuelled core (i.e., Case B-1) due to higher absorption cross section of tungsten for low energy neutrons than that of nickel. Also, this figure shows that the uses of the axially central absorber region lead to the significant spectrum hardening due to further capture of the low energy neutrons by the absorber and this spectrum hardening is larger in the nickel-based fuelled cores than the tungsten based fuelled cores. The consideration of the moderator rods comes from the expectations of the further reduction of sodium void reactivity worth and the improvement of the Doppler coefficient resulted from the spectrum softening. Table III summarizes the performances of the cores having the moderator rods and they are compared with those of the cores having no moderator rods. Next, we considered 6 or 12 $ZrH_{1.8}$ moderator rods for each fuel assemblies in the cores having the axially central absorber region. Table III shows that the uses of 12 $ZrH_{1.8}$ moderator rods per one fuel assembly lead to the reductions of burnup reactivity swings by 241 pcm and 213 pcm for the nicked-based and tungsten-based fuelled cores, respectively. But the moderator rods do not affect the TRU burning rate because the TRU burning rate for the fertile-free core is mostly determined by the thermal power of the core (i.e., the consumption rate of TRUs is proportional to the core total fission rate).

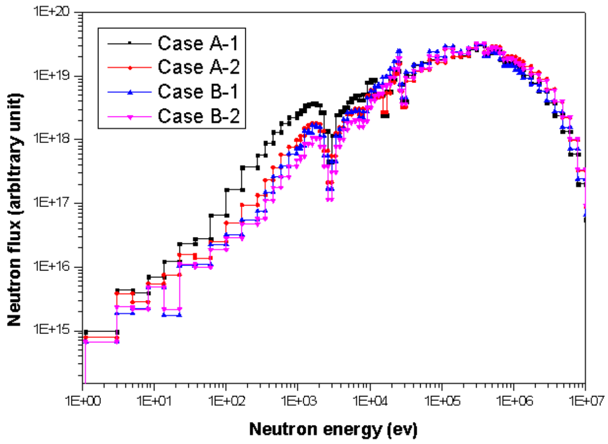

Fig. 3. Comparison of the core neutron spectra

Table III: Comparison of the performances of the cores having moderator rods

Design parameter Fuel driver type	Case A-2	Case A-2-(a) TRU-Ni-10Zr	Case A-2-(b)	Case B-2	Case B-2-(a) TRU-W-10Zr	Case B-2-(b)
B4C absorber thickness (cm, cold)		18			18	
Number of moderator rods	N/A	6	12	N/A	6	12
Average linear power (W/cm)	218	224	230	218	224	230
Burnup reactivity swing (pcm)	4475	4355	4234	4140	4034	3927
Average discharge burnup (MWD/kg)	184	182	181	165	162	160
TRU support ratio	3.73	3.73	3.73	3.75	3.75	3.75
Cycle average TRU conversion ratio	0.36	0.39	0.42	0.36	0.38	0.41
TRU consumption rate (kg/cycle)	352.0	352	352	354.0	353	353
Fuel inventories (kg, BOEC/EOEC)						
TRU	6591/6240	6670/6320	6722/6371	7436/7084	7589/7237	7705/7354
Ni, or W	2928/2928	2609/2609	2319/2319	6931/6931	6424/6424	5954/5954
TRU contents in Fuel (wt%, BOEC/EOEC)	69.0/68.2	71.8/70.7	74.4/73.3	51.8/50.5	54.2/53.0	56.4/55.3
Peak linear power density (W/cm)	428	442	456	440	455	470
Fast neutron fluence (n/cm^2)	$2.46x10^{23}$	$2.27x10^{23}$	$2.11x10^{23}$	$2.32x10^{23}$	$2.14x10^{23}$	$2.00x10^{23}$
Fuel Doppler coefficient(pcm/K,900K, BOEC)						
Total fuel	-0.0249	-0.0583	-0.1029	-0.0738	-0.1305	-0.1801
TRU	-0.0237	-0.0579	-0.1026	-0.00226	-0.0159	-0.0330
Non TRU(Ni, or W)	-0.0002	-0.000	0.000	-0.0689	-0.1134	-0.1465
Radial expansion coefficient (pcm/K, BOEC)	-1.07	-1.03	-0.990	-1.01	-0.964	-0.927
Fuel axial expansion coefficient (pcm/K, BOEC)						
Fuel only	-0.390	-0.372	-0.358	-0.372	-0.370	-0.368
Sodium void worth (pcm, BOEC)	1033(4.5$)	811(3.5$)	646(2.8$)	1230(5.6$)	1054(4.7$)	912(4.0$)
Control rod worth (pcm, BOEC)						
Primary	8918	8429	8014	7771	7245	6821
Secondary	2492	2340	2212	2186	2026	1898
Effective delayed neutron fraction (BOEC)	0.00228	0.00231	0.00233	0.00221	0.00224	0.00226

The uses of the moderator rods lead to the slight reduction of the fuel discharge burnup due to the increase of initial TRU inventory resulted from the higher neutron absorption through spectrum softening. The nickel-based and tungsten-based fuelled cores with 12 moderator rods per fuel assembly have their average discharge burnups of 181MWD/kg and 160 MWD/kg, respectively. Actually, the fractional destruction rates of

TRUs are roughly proportional to the average fuel discharge burnup. As expected, the use of moderator rods substantially improves the Doppler coefficients. For example, the use of 12 moderator rods per fuel assembly for the nickel-based fuel increases the Doppler coefficient by factor of ~5.0. Also, the sodium void reactivity worths were considerably reduced with the use of moderator rods but the control rod worths were reduced. The nickel-based and tungsten-based fuelled cores with 12 moderator rods per fuel assembly have 2.8$ and 4.0$ sodium void reactivity worth, respectively. Fig. 4 compares the neutron spectra of the cores having axially central absorber region and 12 moderator rods per fuel assembly. As shown in this figure, the nickel-based fuelled core has softer neutron spectra than the tungsten-based fuelled core while it is observed from Fig. 4 and Fig. 3 that the difference in neutron spectra is reduced with the moderator rods.

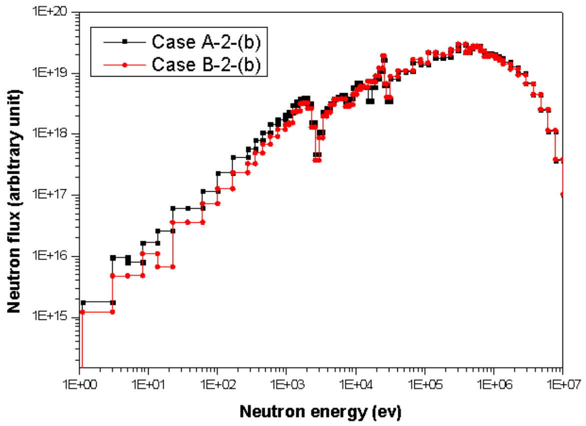

Fig. 4 Comparison of the neutron spectra for the cores having 12 moderator rods

Finally, we performed the BOR[10] (Balance of Reactivity) analysis to understand the safety features of the new cores prosed in this work. This BOR methodology for sodium cooled fast reactor was first derived by Wade and Hill to check if the core has passive self-controllability under ATWS (anticipated transients without scram) like unprotected loss-of-flow transient (ULOF), unprotected loss-of-heat-sink (ULOHS), and unprotected transient overpower (UTOP). This self-controllability can be used as a measure of the inherent safety features of the cores. To meet this self-controllability, the Doppler coefficient, fuel expansion coefficient, radial expansion coefficients, and control rod driveline expansion coefficient should be negative, and the coolant expansion reactivity should be negative or only slightly positive. From Wade and Hill, it was shown that the self-controllability for a sodium cooled fast reactor is satisfied if the following three criterions are met :

$$\begin{aligned} &A/B \le 1, \\ &1 \le C\Delta T_c / B \le 2, \\ &\Delta\rho_{TOP}/B \le 1, \end{aligned} \qquad (1)$$

In this equation, the quantities A, B, and C are related to the temperature reactivity coefficients mentioned above. The exact expressions for them are given in Ref. 8. For self-controllability, the quantities A, B, and C should be all negative. In Eq.(1) ΔT_c is the full-power, steady-state coolant temperature rise which was assumed to be 150^oC in this work. $\Delta\rho_{TOP}$ represents the reactivity vested in a single control rod. Table IV compares three criterions given in Eq.(1) for the six cores described above. As shown in Table IV, the most cores satisfy all the criterions for the self-controllability except for the last criterion associated with UTOP. But it is noted that the reference tungsten-based fuelled core having no axially central absorber region (i.e., Case B-1) does not satisfy the second criterion associated with ULOHS, which is due to the large sodium void worth of this core. With the axially central absorber region, all the cores satisfy all the criterions except for the last one. However, it should be noted these cores having the axially central absorber region can be changed to satisfy the last criterion by slightly reducing the cycle by ~10% with the assumption of linearity between the burnup reactivity swing and $\Delta\rho_{TOP}$. With the additional use of 12 moderator rods, the cores still do not satisfy the last criterion but the gaps are very small. In this work, these quantities are conservatively calculated without consideration of the control rod driveline expansion. So, it is expected that the cores having axially central absorber would satisfy all the criterions for the self-controllability.

Table IV: Comparison of the results of BOR analyses

Design parameter	Case A-1	Case A-2	Case A-2-(a)	Case A-2-(b)	Case B-1	Case B-2	Case B-2-(a)	Case B-2-(b)
Fuel driver type		TRU-Ni-10Zr				TRU-W-10Zr		
B4C absorber thickness (cm)	N/A		18		N/A		18	
Number of moderator rods	N/A	N/A	6	12	N/A	N/A	6	12
A (pcm)	-62.2	-62.1	-64.5	-69.1	-83.6	-66.3	-75.0	-82.2
B (pcm)	-131.2	-180.0	-180.1	-179.7	-107.0	-165.8	-167.4	-168.6
C (pcm/°C)	-0.869	-1.254	-1.294	-1.329	-0.62	-1.129	-1.196	-1.249
A/B	0.474	0.345	0.358337	0.384	0.781	0.399	0.448	0.487
$C\Delta T_C/B$	1.0277	1.079	1.113722	1.146	0.897	1.056	1.107	1.148
$\Delta\rho_{TOP}/\lvert B\rvert$	2.286	1.106	1.076233	1.048	2.331	1.111	1.072	1.036

4. Summary and Conclusions

In this work, new option for the sodium cooled fast TRU burner cores loaded with fertile-free metallic fuels was proposed and the new cores were designed by using the suggested option. The cores were designed to enhance the inherent safety characteristics by using axially central absorber region and 6 or 12 $ZrH_{1.8}$ moderator rods per fuel assembly. For each option, we considered two different types of fertile-free ternary metallic fuel (i.e., TRU-W-10Zr and TRU-Ni-10Zr). Also, we performed the BOR (Balance of Reactivity) analyses to show the self-controllability under ATWS as a measure of inherent safety.

The core performance analysis showed that the new cores using axially central absorber region substantially improve the core performance parameters such as burnup reactivity swing and sodium void reactivity worth. In particular, this option reduces the burnup reactivity swing by increasing initial heavy metal loading and through the depletion of B-10 in the absorber region. The additional introduction of 6 or 12 ZrH1.8 moderator rods per fuel assembly further reduces burnup reactivity swing and sodium void reactivity worth, and improves the Doppler coefficient due to the neutron spectrum softening. Also, the BOR analysis showed that the new cores having axially central absorber region satisfy all the criterions for self-controllability except for the one associated with UTOP but this criterion can be easily satisfied with small change of cycle length or fuel rod design. The final cores with moderator rods almost satisfied all the criterions for self-controllability.

From these results, it is concluded that the new SFR TRU burner cores have high TRU support ratio of ~3.7 and the good inherent safety characteristics which can copy the unprotected transients.

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