Application of FeCrAl Alloy Fuel Cladding for a YGN3 Reactor Neutronics Design

HyunWook Kang [a], Hyun chul Lee [a*]
[a] *Nuclear Engineering Division, School of Mechanical Engineering, Pusan National University,*
2, Busandaehak-ro 63beon-gil, geumjeong-gu, Busan 46241, Korea
[*] *Corresponding author: hyunchul.lee@pusan.ac.kr*

1. Introduction

In the Fukushima nuclear accident, it was recognized that hydrogen explosion could seriously affect the accident. In high-temperature steam environments, the oxidation rate of current Zr-based alloys increases rapidly, resulting in hydrogen generation and explosion. Therefore, fuel claddings must maintain inherent performance during normal operation as well as accident conditions in order to improve the reliability and safety of nuclear power plants. FeCrAl alloys, one of Accident-Tolerant Fuels (ATF), have a slower oxidation rate than Zr and are advantages for hydrogen brittlement. Because of these characteristics, the development of ATF is currently a major concern for LWR research [1]. This study aims to find the average fuel enrichment of the core using FeCrAl cladding that meets the design requirements of Yonggwang Unit 3 (YGN3) with Zr based cladding.

2. Pin-cell problem with FeCrAl alloy and Zr-4

The substitution of Zr-4, a conventional cladding material, with FeCrAl alloys causes loss of reactivity. Thus, to compensate for the loss of reactivity, changes in fuel concentration are essential. In this section, sensitivity tests for reactivity and U^{235} enrichment changes using a single pin-cell model are performed. The code used for the calculation is STREAM/RAST-K(ST/R2) code developed by UNIST, and ST/R2 code are two-step code used to solve whole core problems. The composition of using FeCrAl is Fe-13Cr-6Al which is representative of FeCrAl. It is composed of 13wt% chromium and 6wt% aluminium in iron base. Design parameter of pin-cell are shown in Table I.

Table I: Design parameter of fuel pin-cell [2]

Parameter	Values
Pellet OD [mm]	8.1915
Clad Thickness [μm]	571.5
Clad OD [mm]	9.4966
U Enrichment [wt%]	4.9

Fig. 1 shows the results of reactivity for FeCrAl alloy and Zr-4 cladding at U^{235} enrichment of 4.9wt%. Considering the 3-batch, the average of the reactivity of each batch is shown in Fig. 2. When FeCrAl alloys are used for the cladding, the overall reactivity tends to be lower than when using Zr-4. This reactivity loss can be compensated for by increasing the fuel enrichment by 1.2wt%, as shown in Fig. 2.

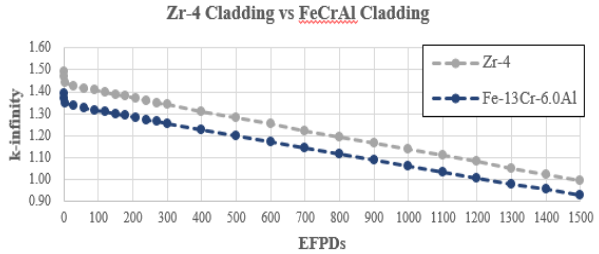

Fig. 1. Comparison of reactivity when using the FeCrAl alloy and Zr-4 cladding under the same conditions.

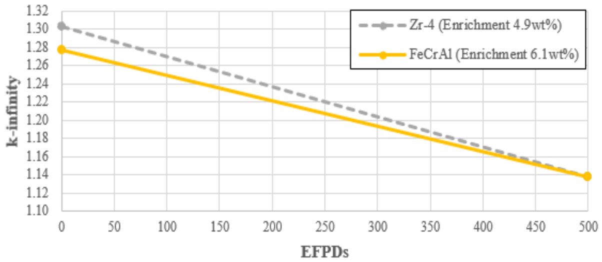

Fig.2. Comparison of cycle lengths of FeCrAl alloy cladding and Zr-4 cladding with changes in concentration.

3. Whole-core problem with FeCrAl alloy and Zr-4

The nuclear design target was set prior to whole core calculation with FeCrAl cladding, and the design target referred to the Nuclear Design Report (NDR) of YGN3 cycle 1 and cycle 2. The codes used for calculate the NDR and core using FeCrAl cladding are the DIT/ROCS and ST/R2 codes, respectively. Table II shows nuclear design target.

Table II: Nuclear Design Target [3-4]

Parameter	Values
Cycle Length [day]	≥370 (Cycle 1) ≥276 (Cycle 2)
Fuel Assembly (FA) Max Power	≤1.380
Pin Peaking Factor	≤1.530
Axial Max Power	≤1.335
Moderator Temperature Coefficients (MTC) [pcm/K]	≤0 (Negative)
Fuel Temperature Coefficients (FTC) [pcm/K]	≤0 (Negative)
Isothermal Temperature Coefficients (ITC) [pcm/K]	≤0 (Negative)

Table III: Compare Assembly specifications on YGN3 Cycles 1~2 with FeCrAl Cladding[3-4].

	YGN3 NDR in Cycle 1-2		FeCrAl Cladding in Cycle 1-2	
Assembly Type	Fuel Enrichment (wt%)	Gd_2O_3 wt% in Fuel	Fuel Enrichment (wt%)	Gd_2O_3 wt% in Fuel
A0	1.30	-	2.17	-
B0	2.37	-	3.17	-
B1	2.36 / 1.30	4.0	3.36 / 2.30	1.0
B2	2.37	4.0	3.47	1.0
C0	2.87 / 2.35	-	3.82 / 3.30	-
C1	2.87 / 2.36	4.0	4.17 / 3.66	2.0
D0	3.35 / 2.87	-	4.40 / 3.92	-
D1	3.36 / 2.85	4.0	4.71 / 4.20	1.0
D2	3.35 / 2.87	4.0	4.55 / 4.07	3.0
E0	4.08 / 3.61	-	5.08 / 4.61	-
E1	4.08 / 3.61	6.0	5.08 / 4.61	2.0
E2	3.60 / 3.11	6.0	4.55 / 4.06	3.0
Average Fuel Enrichment	2.39 (Cycle 1) 3.02 (Cycle 2)	-	3.43 (Cycle 1) 4.09 (Cycle 2)	-

The type of assembly and loading pattern in whole core were based on YGN3 cycle 1 and cycle 2. To satisfy design target, the uranium concentration, loading pattern, gadolinium fraction, and gadolinium pin position were changed. Fig. 3 shows the geometry of the assembly type using cycle1 and cycle 2. Table III shows the specifications of the assembly into the core using FeCrAl cladding.

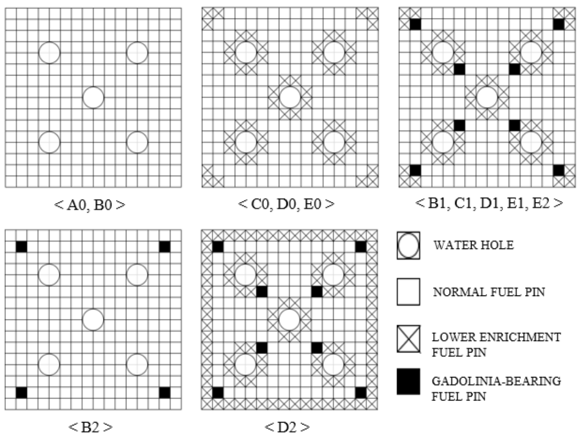

Fig. 3. Assembly Type of the Core using FeCrAl Cladding [3-4].

Fig. 4 shows the loading pattern in cycle 1, and Fig. 5-7 show the power distribution in Beginning Of Cycle (BOC), Middle Of Cycle (MOC) and End Of Cycle (EOC) in cycle 1. Table IV shows the comparison between the calculated core result and the design target.

The Fuel Assembly (FA) max power is 1.257, 1.250 and 1.221 in BOC, MOC and EOC, respectively, and it is below the design target of 1.380. The cycle length is 370.3 days and it satisfies design target of 370 days or more. Pin peaking and axial max power are 1.527 and 1.321 respectively, all of which meet the design target. Fuel Temperature Coefficient (FTC), Moderator Temperature Coefficient (MTC) and Isotope Temperature Coefficient (ITC) are all negative and these indicate that the design target was satisfied. The maximum value of negative MTC in the BOC, which has a 600ppm boron concentration with moderator temperature of 296.1℃, is -10.97. The result of YGN3 cycle 1 in NDR is -10.52, which is similar to the core using FeCrAl cladding. Average U^{235} enrichment is shown to increase 1.04wt% in Table III compared to NDR in cycle 1. Table IV shows a comparison of the calculation results of the core using FeCrAl cladding with the YGN3 NDR data in cycle 1.

A0 A0	B1 B1	B2 B2	A0 A0	B2 B2	B1 B1	C1 C1	D0 D0
B1 B1	B0 C1	A0 A0	D2 D2	A0 A0	B2 B2	C1 C1	C0 C0
B2 B2	A0 A0	C1 C1	A0 A0	C1 C1	A0 A0	D2 D2	B0 B0
A0 A0	D2 D2	A0 A0	C1 C1	A0 A0	D2 D2	D0 D0	
B2 B2	A0 A0	C1 C1	A0 A0	C1 B0	D1 D1	B0 B0	
B1 B1	B2 B2	A0 A0	D2 D2	D1 D1	C0 C0		
C1 C1	C1 C1	D2 D2	D0 D0	B0 B0		NDR Design Core	
D0 D0	C0 C0	B0 B0					

Fig. 4. Loading Pattern Comparison between NDR and Core using FeCrAl Cladding in Cycle 1.

0.775 0.890 14.89	0.973 1.041 6.93	1.142 1.182 3.44	0.815 0.936 14.93	1.172 1.207 2.99	1.053 1.117 6.12	1.242 1.210 -2.57	1.043 0.867 -16.91
0.973 1.041 6.93	1.172 1.199 2.33	0.815 0.927 13.87	1.222 1.257 2.84	0.824 0.941 14.08	1.212 1.210 -0.14	1.202 1.154 -3.96	0.884 0.739 -16.45
1.142 1.182 3.44	0.815 0.927 13.87	1.113 1.209 8.65	0.785 0.919 17.15	1.142 1.204 5.43	0.854 0.908 6.32	1.162 1.036 -10.88	0.586 0.488 -16.73
0.815 0.936 14.93	1.222 1.257 2.84	0.785 0.919 17.15	1.113 1.196 7.46	0.824 0.916 11.14	1.271 1.176 -7.55	1.043 0.878 -15.80	
1.172 1.207 2.99	0.824 0.941 14.08	1.142 1.204 5.43	0.815 0.916 12.50	1.162 1.114 -4.16	1.132 1.064 -6.04	0.596 0.506 -15.14	
1.053 1.117 6.12	1.212 1.210 -0.14	0.854 0.908 6.32	1.271 1.176 -7.55	1.122 1.064 -5.21	0.705 0.627 -11.05		
1.242 1.210 -2.57	1.202 1.154 -3.96	1.152 1.036 -10.11	1.043 0.878 -15.80	0.596 0.506 -15.14		NDR(A) Design Core(B) Diff.(%)[(B-A)/A]	
1.043 0.867 -16.91	0.884 0.739 -16.45	0.586 0.488 -16.73					

Fig. 5. Power Distribution Comparison between NDR and Core using FeCrAl Cladding in cycle 1 at BOC.

0.864 0.961 11.19	1.043 1.109 6.34	1.102 1.154 4.69	0.884 0.949 7.34	1.132 1.148 1.38	1.122 1.127 0.41	1.212 1.201 -0.89	0.864 0.824 -4.67
1.043 1.109 6.34	1.102 1.237 12.21	0.884 0.963 8.90	1.251 1.250 -0.14	0.904 0.951 5.27	1.162 1.162 -0.03	1.162 1.155 -0.62	0.755 0.720 -4.62
1.102 1.154 4.69	0.884 0.963 8.90	1.182 1.223 3.53	0.904 0.956 5.75	1.192 1.205 1.12	0.904 0.927 2.63	1.102 1.046 -5.15	0.526 0.498 -5.30
0.884 0.949 7.34	1.251 1.250 -0.14	0.904 0.956 5.75	1.202 1.202 0.04	0.924 0.932 0.95	1.251 1.168 -6.67	0.924 0.855 -7.46	
1.132 1.148 1.38	0.904 0.951 5.27	1.192 1.205 1.12	0.924 0.932 0.95	1.222 1.055 -13.65	1.132 1.045 -7.69	0.546 0.508 -6.92	
1.122 1.127 0.41	1.162 1.162 -0.03	0.904 0.927 2.63	1.251 1.168 -6.67	1.132 1.045 -7.69	0.675 0.619 -8.31		
1.212 1.201 -0.89	1.162 1.155 -0.62	1.102 1.046 -5.15	0.914 0.855 -6.45	0.546 0.508 -6.92		NDR(A) Design Core(B) Diff.(%)[(B-A)/A]	
0.864 0.824 -4.67	0.755 0.720 -4.62	0.526 0.498 -5.30					

Fig. 6. Power Distribution Comparison between NDR and Core using FeCrAl Cladding in cycle 1 at MOC.

0.943 0.952 0.95	1.082 1.079 -0.26	1.132 1.125 -0.63	0.943 0.953 1.04	1.122 1.124 0.17	1.092 1.098 0.56	1.142 1.165 2.05	0.834 0.840 0.74
1.082 1.079 -0.26	1.142 1.193 4.52	0.953 0.961 0.86	1.261 1.221 -3.18	0.943 0.957 1.46	1.122 1.136 1.23	1.112 1.135 2.08	0.745 0.749 0.62
1.132 1.125 -0.63	0.953 0.961 0.86	1.201 1.193 -0.66	0.953 0.964 1.11	1.181 1.188 0.54	0.923 0.945 2.41	1.072 1.061 -1.00	0.536 0.544 1.47
0.943 0.953 1.04	1.261 1.221 -3.18	0.953 0.964 1.11	1.191 1.187 -0.38	0.953 0.952 -0.06	1.201 1.171 -2.53	0.893 0.889 -0.51	
1.122 1.124 0.17	0.943 0.957 1.46	1.181 1.188 0.54	0.953 0.952 -0.06	1.171 1.063 -9.25	1.092 1.063 -2.69	0.556 0.555 -0.23	
1.092 1.098 0.56	1.122 1.136 1.23	0.923 0.945 2.41	1.201 1.171 -2.53	1.082 1.063 -1.79	0.675 0.664 -1.70		
1.142 1.165 2.05	1.112 1.135 2.08	1.072 1.061 -1.00	0.893 0.889 -0.51	0.556 0.555 -0.23		NDR(A) Design Core(B) Diff.(%)[(B-A)/A]	
0.834 0.840 0.74	0.745 0.749 0.62	0.536 0.544 1.47					

Fig. 7. Power Distribution Comparison between NDR and Core using FeCrAl Cladding in cycle 1 at EOC.

Table IV: Comparison of Design Parameters for Cycle 1 of YGN3 Reactor [3-4].

Design Parameter	Zr Cladding (NDR)	FeCrAl Cladding
FA Max Power at BOC	1.280	1.257
FA Max Power at MOC	1.260	1.250
FA Max Power at EOC	1.260	1.221
Cycle Length	370.0	370.3
Pin Peaking Factor	1.530	1.527
Axial Max Power	1.350	1.321
MTC at BOC [pcm/K]	-10.52	-10.97
MTC at MOC [pcm/K]	-18.78	-20.46
MTC at EOC [pcm/K]	-47.61	-56.74
FTC at BOC [pcm/K]	-2.82	-2.59
FTC at MOC [pcm/K]	-2.76	-2.63
FTC at EOC [pcm/K]	-2.90	-2.56
ITC at BOC[pcm/K]	-14.20	-13.60
ITC at MOC[pcm/K]	-23.81	-23.12
ITC at EOC[pcm/K]	-51.62	-59.57

Fig. 8 shows the loading patterns in cycle 2, and the power distribution in cycle 2 in BOC, MOC and EOC are shown in Fig. 9-11. Table V shows the comparison between the calculated core result and the design target. The maximum FA power of 1.328 in the MOC satisfied the design target of 1.380 or less in cycle 2. The cycle length is 277.2 days, which is 1.2 days longer than design target of 276 days. The pin peaking factor is 1.528 and the axial max power is 1.137, which is lower than the design targets of 1.530 and 1.335, respectively. In addition, FTC, MTC and ITC are all negative and satisfed the design target. In condition of 600ppm boron concentration with moderator temperature of 296.1℃, the maximum value of negative MTC in the BOC is -19.73 and the result of YGN3 cycle 2 in NDR is -18.98. Average U^{235} enrichment is shown to increase 1.07wt% in Table III compared to NDR in cycle 2. Table V shows the results of calculation of the core using FeCrAl cladding in cycle 2 and the data of YGN3 cycle 2 NDR.

B1 B1	C1 C1	E2 E2	B1 B1	D0 D0	B0 B0	E2 E2	D2 D2
C1 C1	C0 C0	B2 B2	C0 C0	C1 C1	B0 B0	D2 D2	E0 E0
E2 E2	B2 B2	E2 E2	B2 B2	E2 E2	C1 C1	E2 E2	B0 B0
B1 B1	C0 C0	B2 B2	D2 D2	C1 C1	D1 D1	E0 E0	
D0 D0	C1 C1	E2 E2	C1 C1	E1 E1	D2 D2	D0 D0	
B0 B0	B0 B0	C1 C1	D1 D1	D2 D2	C1 C1		
E2 E2	D2 D2	E2 E2	E0 E0	D0 D0		NDR Design Core	
D2 D2	E0 E0	B0 B0					

Fig. 8. Loading Pattern Comparison between NDR and Core using FeCrAl Cladding in Cycle 2.

0.883 0.941 6.51	1.032 1.109 7.42	1.330 1.307 -1.71	0.963 0.973 1.06	1.211 1.160 -4.20	0.993 0.969 -2.42	1.241 1.137 -8.34	0.685 0.648 -5.38
1.032 1.111 7.63	1.141 1.163 1.89	0.993 1.058 6.57	1.132 1.138 0.55	1.082 1.113 2.87	1.102 1.047 -4.94	1.072 1.025 -4.38	0.933 0.808 -13.36
1.330 1.311 -1.47	0.993 1.060 6.81	1.310 1.322 0.88	0.973 1.064 9.37	1.320 1.319 -0.12	1.032 1.067 3.34	1.151 1.055 -8.36	0.516 0.468 -9.31
0.963 0.968 0.56	1.132 1.137 0.48	0.973 1.065 9.49	1.042 1.123 7.75	0.993 1.088 9.60	1.032 1.073 3.99	1.032 0.946 -8.36	
1.211 1.163 -3.94	1.082 1.116 3.16	1.320 1.323 0.21	0.983 1.094 11.38	1.211 1.247 2.98	0.754 0.806 6.83	0.457 0.472 3.41	
0.993 0.980 -1.25	1.102 1.055 -4.27	1.032 1.071 3.80	1.032 1.078 4.40	0.754 0.807 7.04	0.377 0.422 11.92		
1.241 1.145 -7.74	1.072 1.031 -3.83	1.151 1.060 -7.94	1.022 0.949 -7.14	0.457 0.473 3.69		NDR(A) Design Core(B) Diff.(%)[(B-A)/A]	
0.685 0.652 -4.84	0.933 0.813 -12.90	0.516 0.470 -8.87					

Fig. 9. Power Distribution Comparison between NDR and Core using FeCrAl Cladding in cycle 2 at BOC.

0.865	1.004	1.371	0.944	1.113	0.954	1.272	0.700
0.893	1.041	1.286	0.940	1.101	0.963	1.210	0.701
3.25	3.69	-6.21	-0.41	-1.04	0.90	-4.89	0.17
1.004	1.103	1.004	1.103	1.033	1.063	1.043	0.924
1.042	1.093	1.018	1.085	1.069	1.038	1.050	0.858
3.82	-0.95	1.46	-1.61	3.48	-2.40	0.63	-7.14
1.371	0.994	1.371	0.994	1.371	1.024	1.192	0.537
1.288	1.020	1.311	1.037	1.327	1.067	1.126	0.521
-6.08	2.63	-4.39	4.38	-3.25	4.27	-5.53	-2.97
0.944	1.103	0.994	1.053	1.014	1.024	1.004	
0.936	1.084	1.038	1.100	1.081	1.073	0.968	
-0.85	-1.74	4.41	4.41	6.67	4.81	-3.52	
1.113	1.033	1.371	1.014	1.282	0.785	0.487	
1.102	1.070	1.328	1.086	1.287	0.840	0.510	
-1.00	3.52	-3.14	7.14	0.37	7.05	4.83	
0.964	1.063	1.024	1.024	0.785	0.417		
0.968	1.040	1.068	1.074	0.841	0.470		
0.43	-2.15	4.39	4.94	7.13	12.55		
1.282	1.043	1.192	1.004	0.477		NDR(A)	
1.212	1.051	1.127	0.969	0.511		Design Core(B)	
-5.49	0.74	-5.47	-3.46	7.08		Diff.(%)[(B-A)/A]	
0.696	0.924	0.537					
0.702	0.859	0.521					
0.89	-7.08	-2.91					

Fig. 10. Power Distribution Comparison between NDR and Core using FeCrAl Cladding in cycle 2 at MOC.

0.856	0.985	1.333	0.935	1.104	0.955	1.284	0.706
0.895	1.031	1.261	0.938	1.098	0.967	1.212	0.724
4.56	4.64	-5.42	0.30	-0.58	1.26	-5.59	2.54
0.985	1.085	0.985	1.075	1.015	1.055	1.045	0.935
1.032	1.080	1.006	1.074	1.061	1.039	1.056	0.883
4.74	-0.45	2.15	-0.04	4.55	-1.49	1.11	-5.65
1.333	0.985	1.343	0.985	1.353	1.025	1.204	0.567
1.262	1.008	1.281	1.023	1.300	1.063	1.134	0.546
-5.33	2.29	-4.67	3.90	-3.96	3.76	-5.84	-3.75
0.935	1.085	0.985	1.055	1.015	1.035	1.015	
0.934	1.073	1.024	1.087	1.071	1.074	0.983	
-0.12	-1.10	3.91	3.01	5.54	3.81	-3.15	
1.104	1.015	1.353	1.015	1.323	0.816	0.507	
1.098	1.061	1.300	1.075	1.274	0.857	0.536	
-0.58	4.56	-3.91	5.95	-3.74	5.01	5.69	
0.965	1.055	1.025	1.025	0.816	0.448		
0.972	1.041	1.064	1.075	0.857	0.495		
0.66	-1.32	3.82	4.90	5.05	10.66		
1.284	1.055	1.204	1.015	0.507		NDR(A)	
1.213	1.057	1.134	0.983	0.536		Design Core(B)	
-5.53	0.19	-5.84	-3.14	5.70		Diff.(%)[(B-A)/A]	
0.706	0.935	0.567					
0.724	0.882	0.546					
2.55	-5.66	-3.76					

Fig. 11. Power Distribution Comparison between NDR and Core using FeCrAl Cladding in cycle 2 at EOC.

Table V: Comparison of Design Parameters for Cycle 2 of YGN3 Reactor [3-4].

Design Parameter	Zr Cladding (NDR)	FeCrAl Cladding
FA Max Power at BOC	1.340	1.323
FA Max Power at MOC	1.380	1.328
FA Max Power at EOC	1.260	1.300
Cycle Length	276.0	277.2
Pin Peaking Factor	1.530	1.528
Axial Max Power	1.140	1.137
MTC at BOC [pcm/K]	-18.98	-19.73
MTC at MOC [pcm/K]	-27.55	-32.00
MTC at EOC [pcm/K]	-40.97	-53.05
FTC at BOC [pcm/K]	-2.75	-2.70
FTC at MOC [pcm/K]	-2.83	-2.80
FTC at MOC [pcm/K]	-2.83	-2.80
ITC at BOC [pcm/K]	-22.56	-22.47
ITC at MOC [pcm/K]	-31.18	-34.85
ITC at EOC [pcm/K]	-44.65	-56.01

4. Conclusions

As shown in Fig. 1, FeCrAl cladding has a higher reactivity loss than Zr based cladding. Thus, when fuel cladding is replaced with FeCrAl cladding, the fuel enrichment must be increased to compensate for this reactivity loss. This study aims to find the average fuel enrichment of the core using FeCrAl cladding that meets the design requirements of YGN3 with Zr based cladding. In the core using FeCrAl cladding, the loading pattern of the core, the fuel enrichment, the gadolinium fraction and the location of the burnable poison rod were changed to satisfy the design conditions of YGN3. The average fuel enrichment of the core using FeCrAl cladding that met the design conditions was increased by about 1.04wt% in cycle 1 and about 1.07wt% in cycle 2 than the average fuel enrichment of YGN3. In the future, cycle 3 and equilibrium core cycle using FeCrAl cladding that satisfies the design conditions will be compared with the fuel enrichment of YGN 3, and the economic effects of cladding change will be analyzed.

REFERENCES

[1] Hyun-Gil Kim, Jae-Ho Yang, Weon-Ju Kim, Yang-Hyun Koo, Development Status of Accident-tolerant Fuel for Light Water Reactors in Korea, Nuclear Engineering and Technology, 48, 2016, p1-15.

[2] N. M. George, K. A. Terrani, J. J. powers, Neutronic analysis of candidate accident-tolerant iron alloy cladding concepts, ORNL, TM-2013, 121.

[3] Nuclear Design Report for Yonggwang Unit 3 Cycle 1, KAERI, TR-542, 1995.

[4] Nuclear Design Report for Yonggwang Unit 3 Cycle 2, KAERI, TR-605, 1996.