Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Application of FeCrAl Alloy Fuel Cladding to a YGN3 Reactor Neutronics Design for cycle 3 and equilibrium cycle

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1. Introduction

The most significant requirement of the nuclear industry is to operate nuclear power plants safely, reliably, and economically over a long period. Since the Fukushima nuclear accident in March 2011, it has become an important issue to improve the accident tolerance of light-water reactors. In the Fukushima accident, the cladding formed of Zircaloy-4 (Zr-4) was damaged, which caused hydrogen explosions. To reduce such damages, the safety of fuel under accident conditions must be improved, this has resulted in increased interest in accident-tolerant fuel (ATF) [1].

This study compared the differences in the core fuel enrichments and core characteristics when using Zr-4 and ATFs as cladding materials. The core nuclear design was performed by referring to the currently operational Yeonggwang 3 (YGN3) reactor. The results of enrichment comparisons in cycle 1~2 were previously successfully performed [2]. In this paper, enrichment comparisons were performed in cycle 3 and equilibrium cycle.

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

For an understand the neutron economy, the reactivities of the fuel rods used in nuclear design were compared. The fuel rod used in cycles 1-3 was GUARDIAN type and the fuel rod used in equilibrium cycle was PLUS7 type. Table I lists the parameters of the pin-cell used in the calculation. Fig. 1 presents a comparison of the reactivities of Zr-4 and FeCrAl alloy claddings used for the GUARDIAN and PLUS7 type using uranium enrichment of 4.9 wt. Fig. 1 show that the FeCrAl alloy cladding tends to be generally less reactive than the Zr-4 cladding. This corresponds to a loss on the neutron side. Fig. 2 displays the k-infinity for each cladding considering 3-batches in each fuel rod type. The uranium enrichment should be increased by 1.2 wt% for the GUARDIAN type and 1.0 wt% for the PLUS7 type.

Table I: Design parameter of GUARDIAN and PLUS7 type.

Parameter	GUARDIAN Type	PLUS7 Type
Fuel Radius [cm]	4.130	4.095
Gap Radius [cm]	4.215	4.180
Cladding Radius [cm]	4.850	4.750
U Enrichment [wt%]	4.900	4.900

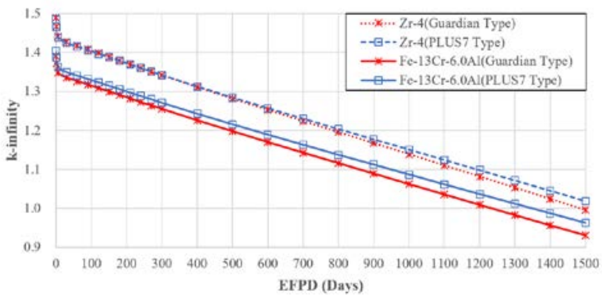

Fig. 1. K-infinity between FeCrAl and Zr-4 cladding using the same enrichment in GUARDIAN and PLUS7 type.

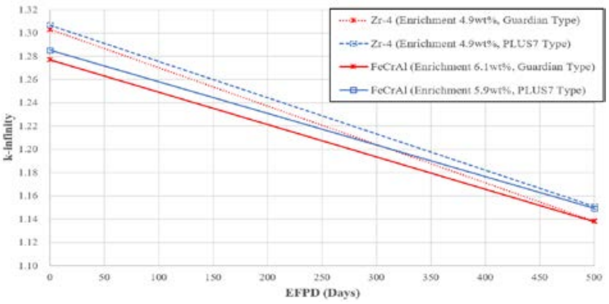

Fig. 2. Comparison of cycle lengths of FeCrAl and Zr-4 cladding with 3-batch by enrichment changes in GUARDIAN and PLUS7 type.

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

According to the change in core average enrichment in cycle 1~2 that was previously performed, 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 [2].

3.1 Cycle 3

The assembly used for the reactor core was a total of 177 assemblies, including the assembly used in cycles 1~2 and the F type assembly added in cycle 3. Each assembly also consisted of a 16x16 array of 236 fuel rods and 5 guide tubes. The specifications of the core are the same as those of the cycle 1-2 that were previously performed [2]. Table II shows the nuclear design target value set in cycle3.

Table II: Nuclear design target parameter in cycle 3

Parameter	Value
Cycle Length [Day]	≥360
Fuel Assembly (FA) Max Power	≤1.380
Pin Peaking Factor	≤1.530
Axial Max Power	≤1.360
Moderator Temperature Coefficients (MTC) [pcm/K]	≤0 (Nagative)
Fuel Temperature Coefficients (FTC) [pcm/K]	≤0 (Nagative)
Isothermal Temperature Coefficients (ITC) [pcm/K]	≤0 (Nagative)

The loading pattern used in cycle3 is shown in Fig. 3. The design according to the type of assembly entering the core is shown in Fig. 4. The assembly used in cycle 3 consists of assembly B ~ E type used in cycle 1 ~ 2 and F type added in cycle 3. Table III shows the specifications of the assembly that enters the core using Zr-4 cladding and FeCrAl cladding. The Gd fraction when Zr-4 is used as the cladding is the value used in YGN3 cycle3, and the Gd fraction when FeCrAl alloy is used as the cladding satisfies the set nuclear design target value. The average fuel enrichment was 3.51wt% with Zr-4 cladding and the average fuel enrichment was 4.61wt% with FeCrAl cladding, which increased by 1.10wt%.

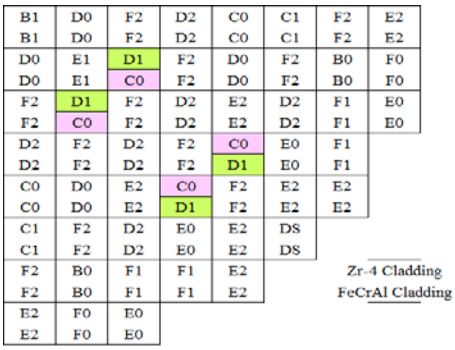

Fig. 3. Comparison of loading pattern using Zr-4 and FeCrAl cladding in cycle 3.

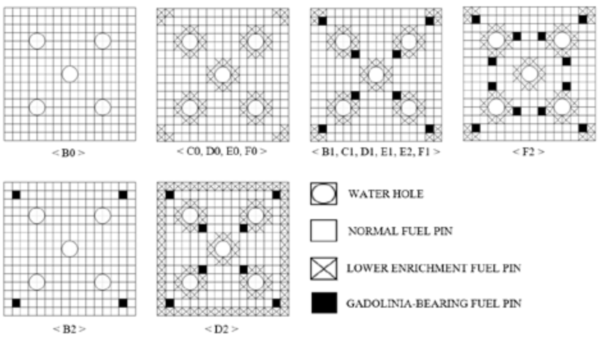

Fig. 4. Comparison of loading pattern using Zr-4 and FeCrAl cladding in cycle 3.

Table III: Description of assembly in core using Zr-4 and FeCrAl cladding in cycle 3

	Zr-4 Cladding		FeCrAl Cladding	
Assembly Type	Fuel Enrichment (wt%)	Gd_2O_3 wt% in Fuel	Fuel Enrichment (wt%)	Gd_2O_3 wt% in Fuel
B0	2.37	-	3.17	-
B1	2.36 / 1.30	4.0	3.36 / 2.30	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
F0	4.11 / 3.59	-	5.36 / 4.84	-
F1	4.11 / 3.59	6.0	5.36 / 4.84	1.0
F2	4.11 / 3.59	6.0	5.36 / 4.84	5.5
Average Fuel Enrichment	3.51	-	4.61	-

The power distribution in cycle 3 in BOC, MOC and EOC are shown in Fig. 5-7. Table IV shows the comparison between the calculated core result and the design target. The maximum FA power of 1.354 in the MOC satisfied the design target of 1.380. The cycle length is 360 days. The pin peaking factor is 1.521 and the axial max power is 1.177, which is lower than the design targets of 1.530 and 1.360, respectively. In addition, FTC, MTC and ITC are all negative and satisfed the design target.

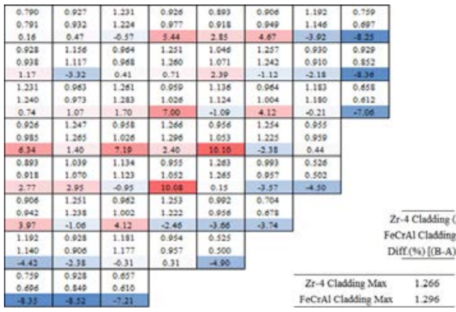

Fig. 5. Comparison of assemblywise power using Zr-4 and FeCrAl cladding in cycle 3 at BOC (ARO, HFP, Eq. Xenon, 0 MWD/MTU)

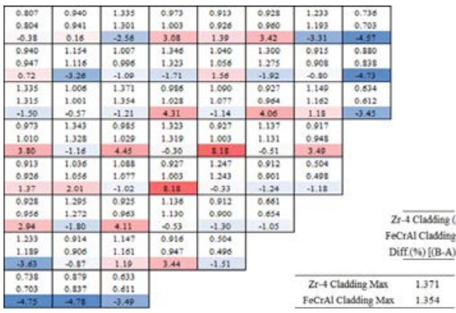

Fig. 6. Comparison of assemblywise power using Zr-4 and FeCrAl cladding in cycle 3 at MOC (ARO, HFP, Eq. Xenon, 7000 MWD/MTU)

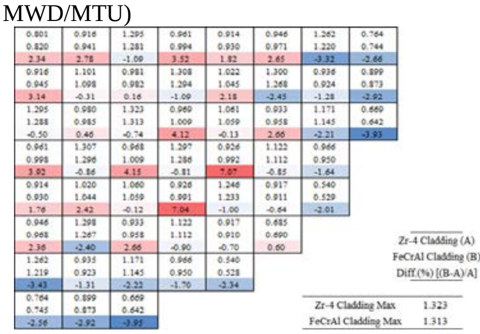

Fig. 7. Comparison of assemblywise power using Zr-4 and FeCrAl cladding in cycle 3 at EOC (ARO, HFP, Eq. Xenon, 13290 MWD/MTU)

Table IV. Calculation results of each cladding in cycle 3

Design Parameter	Zr Cladding	FeCrAl Cladding
FA Max Power at BOC	1.266	1.296
FA Max Power at MOC	1.371	1.354
FA Max Power at EOC	1.323	1.313
Cycle Length[day]	360.0	360.0
Pin Peaking Factor	1.513	1.521
Axial Max Power	1.169	1.177
MTC at BOC [pcm/K]	-31.53	-25.61
MTC at MOC [pcm/K]	-48.53	-43.44
MTC at EOC [pcm/K]	-71.37	-65.70
FTC at BOC [pcm/K]	-2.81	-2.68
FTC at MOC [pcm/K]	-2.84	-2.76
FTC at EOC [pcm/K]	-2.97	-2.92
ITC at BOC [pcm/K]	-34.38	-28.33
ITC at MOC [pcm/K]	-51.41	-46.24
ITC at EOC [pcm/K]	-74.39	-68.67

3.2 Equilibrium Cycle

The reactor core consisted of 177 fuel assemblies and U type assemblies were used. Each assembly consisted of 16 x 16 arrays with 236 fuel rods and 5 guide tubes. The fuel rod type is PLUS7 type and this fuel rod was actually used in YGN3 cycle17. The fuel rod of PLUS7 type has different pellet radius and cladding thickness from the GUARDIAN fuel rod used in cycle 1 ~ 3. In the Equilibrium cycle, the cycle length is 497.5 day, which is the length of the cycle when Zr-4 and FeCrAl Cladding are used for PLUS7 type fuel rod. The other design targets are the same as the design targets previously set in cycle 3.

Fig. 8 shows loading pattern when using Zr-4 and FeCrAl cladding in equilibrium cycle. The design of assembly using in core is shown in Fig. 9. The assembly type used in the equilibrium cycle is U type. The assembly of the once burned is labeled T type, and the assembly of the twice burned is labeled S Type. The materials used for cladding are Zircaloy-4 and FeCrAl alloys. Table V shows the enrichment and Gd fraction that meet the nuclear design target values for each cladding.

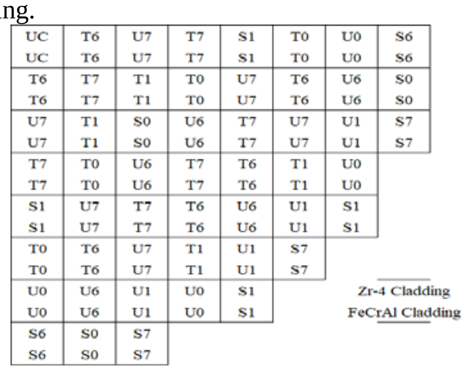

Fig. 8. Comparison of loading pattern using Zr-4 and FeCrAl cladding in equilibrium cycle.

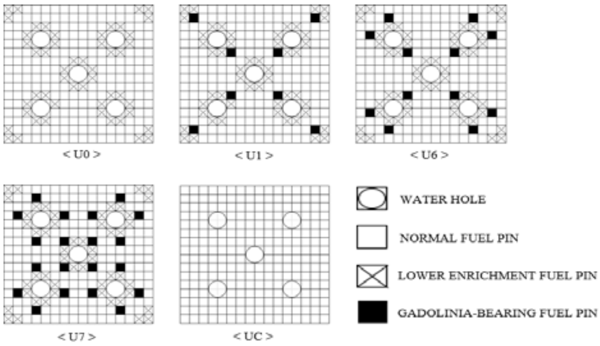

Fig. 9. Enrichment zoning pattern and burnable poison arrangement in equilibrium cycle

Table V: Description of assembly in core using Zr-4 and FeCrAl cladding in equilibrium cycle

Assembly Type	Zr-4 Cladding		FeCrAl Cladding	
	Fuel Enrichment (wt%)	Gd_2O_3 wt% in Fuel	Fuel Enrichment (wt%)	Gd_2O_3 wt% in Fuel
U0	4.65/4.11	-	5.35/4.81	-
U1	4.65/4.11	6	5.35/4.81	1
U6	4.65/4.11	8	5.35/4.81	8
U7	4.65/4.11	8	5.35/4.81	5
UC	2.22	-	2.92	-
Average Fuel Enrichment	4.51	-	5.21	-

Fig. 10-12 show the results of comparing the radial power distribution according to Zr-4 and FeCrAl cladding in Equilibrium cycle BOC, MOC, and EOC. Table VI shows the comparison between the calculated core result and the design target. The maximum FA power of 1.366 in the BOC satisfied the design target of 1.380. The cycle length is 497.5 days. The pin peaking factor is 1.524 and the axial max power is 1.188, which is lower than the design targets of 1.530 and 1.360, respectively. In addition, FTC, MTC and ITC are all negative and satisfed the design target.

Fig. 10. Comparison of assemblywise power using Zr-4 and FeCrAl cladding in equilibrium cycle at BOC (ARO, HFP, Eq. Xenon, 0 MWD/MTU)

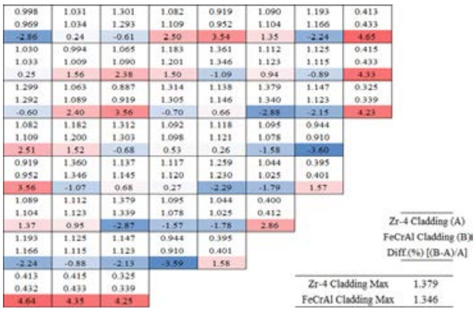

Fig. 11. Comparison of assemblywise power using Zr-4 and FeCrAl cladding in equilibrium cycle at MOC (ARO, HFP, Eq. Xenon, 8990 MWD/MTU)

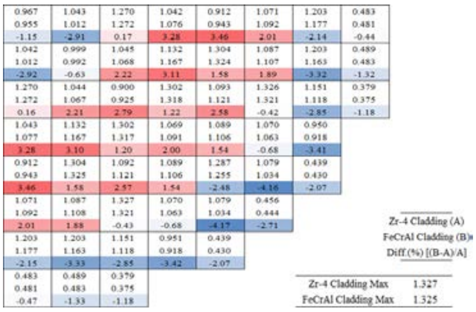

Fig. 12. Comparison of assemblywise power using Zr-4 and FeCrAl cladding in equilibrium cycle at EOC (ARO, HFP, Eq. Xenon, 18435 MWD/MTU)

Table VI: Calculation results of each cladding in equilibrium cycle

Design Parameter	Zr Cladding	FeCrAl Cladding
FA Max Power at BOC	1.357	1.366
FA Max Power at MOC	1.379	1.346
FA Max Power at EOC	1.327	1.325
Cycle Length	497.5	497.5
Pin Peaking Factor	1.523	1.524
Axial Max Power	1.217	1.188
MTC at BOC [pcm/K]	-19.16	-17.98
MTC at MOC [pcm/K]	-42.36	-44.96
MTC at EOC [pcm/K]	-73.57	-68.05
FTC at BOC [pcm/K]	-2.69	-2.59
FTC at MOC [pcm/K]	-2.82	-2.75
FTC at EOC [pcm/K]	-3.03	-2.91
ITC at BOC [pcm/K]	-21.89	-20.62
ITC at MOC [pcm/K]	-45.21	-47.75
ITC at EOC [pcm/K]	-76.65	-71.00

4. Conclusions

This study investigated the differences in the core fuel enrichment and core characteristics on using Zircaloy and FeCrAl materials as cladding materials in cycle 3 and equilibrium cycle.

When using the FeCrAl cladding instead of the Zr-4 cladding, the cycle 3 depletion result from the entire core also satisfied the set design target values. The assembly max power is 1.377 using Zr-4 cladding, which is less than the design target value 1.380, and the cycle length is the same as the design target value 360 days. The maximum axial power was 1.177 using FeCrAl cladding and the design target value was below 1.360, and the maximum pin peaking factor was 1.521, which satisfied the design target value below 1.530. FTC, MTC and ITC are also negative and meet the design target negative value. The cycle 3 average enrichment of the core using FeCrAl Cladding meeting these design targets was increased by 1.10wt% from 3.51wt% to 4.61wt%.

In the euilibrium cycle, the loading pattern, fuel enrichment, and Gd fraction of the core satisfying the design target were found. The assembly max power is 1.379 using Zr-4 cladding, which is less than the design target value 1.380, and the cycle length is the same as the design target value 497.5 days. The maximum axial power was 1.217 using Zr-4 cladding and the design target value was below 1.360, and the maximum pin peaking factor was 1.524, which satisfied the design target value below 1.530. FTC, MTC and ITC are also negative and meet the design target negative value. The euilibrium cycle average enrichment of the core using FeCrAl Cladding meeting these design targets was increased by 0.70wt% from 4.51wt% to 5.21wt%.

REFERENCES

[1] Hyung-Kyu Kim, et al. “On the Minimum Thickness of FeCrAl Cladding for Accident-Tolerant Fuel” Nuclear Technology Vol 198, 342-346, American Nuclear Society (2017).

[2] HyunWook Kang, et al. “Application of FeCrAl Alloy Fuel Cladding for a YGN3 Reactor Neutronics Design”