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A Parametric Sensitivity Analysis of Nuclear Fuel under RIA with Commercial LWR Conditions

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ABSTRACT*: The fuel rod behaviors in transient state are different from steady state fuel rod behaviors. Currently, KNF is developing a transient fuel rod analysis code. The code is based on 1-D modeling and it can calculate thermal and mechanical behaviors of fuel rod. By using the code, fuel rod thermal performance analysis with several different combinations of initial conditions (power, oxide thickness, gap size, coolant temperature) of APR1400 commercial light water reactor has been performed. The power pulse used for this analysis is obtained from the simulation of RIA by using 3-D point-kinetics code ASTRA. In addition to this, fuel and clad material properties sensitivity analysis under RIA condition has been performed. In this analysis, the factors affecting temperature and clad strain were analyzed. Also, it was found that some parameters behaviors have been significantly affected by burnup level.*

I. INTRODUCTION

Reactivity-Initiated Accident (RIA) is a nuclear reactor accident which is caused by sudden insertion of reactivity worth. Since the fissile isotopes are preferentially build-up at edge of pellet, more reactivity worth is applied at the periphery of the fuel under RIA. Therefore, it causes edge-peaked local power and fuel temperature in the early stage of RIA. These fuel behaviors have been studied through many international experiments. But the analysis for commercial reactor conditions are rarely carried out. In this article, thermal performance analysis of fuel rod of APR 1400 commercial reactor has been performed using the transient fuel rod analysis code. In addition, sensitivity studies about various material properties are also performed.

II. ANALYSIS TOOL

To understand the fuel rod behavior and failure mechanisms during accident condition, many international experiments have been carried out. In addition to this, the simulations using high performance computer have been performed for fuel rod behavior study. The results from experiments and simulations are also used to establish regulatory code and standards. Since the safety regulatory code and standards related to RIA are in the process of being revised by US NRC, it is necessary to develop computer code to evaluate the transient fuel rod performance. As part of this activity, KNF is developing a new transient fuel rod analysis code. The code uses the 1-dimensional modeling approach under the assumption of axisymmetric. (Fig. 1.) It means that the temperature and deformation are calculated by 1-dimensional (radial) equation. The initial conditions are given from the steady state fuel rod performance analysis code, ROPER.

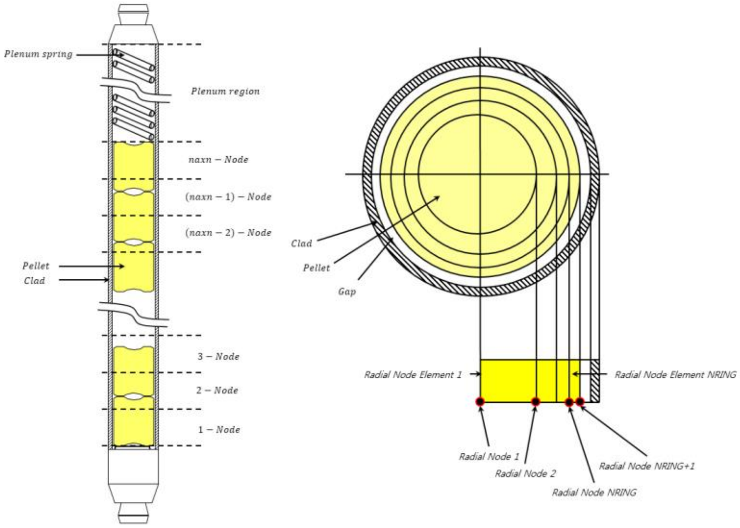

Fig. 1. Fuel Rod Geometry Modeling

For the validation of the code, NSRR and CABRI test series database are used. In validation, measurable quantities such as fuel temperature, fuel and clad elongation, clad permanent hoop strain and fission gas release are compared to calculation results. Among them, fuel temperature is an important factor since it is directly related to fuel failure, fuel deformation and material properties of fuel rod. Therefore, the predictability of fuel temperature should be verified. But, there is no available measurement value of fuel temperature during accident experiments. As an alternative method, code-to-code comparison method has been used using FRAPTRAN code. Left figure of Fig. 2. shows the code and FRAPTRAN results of fuel centerline temperature (FCLT), fuel surface temperature (FST), fuel average temperature (FAT), clad inside temperature (CIT), clad outside temperature (COT). And right figure of Fig. 2. shows radial temperature distribution for NSRR FK-1 test rod. The code results agree well with FRAPTRAN results. Note that vertical lines in right figure are radial positions for fuel surface, clad inner and outer surfaces, respectively.

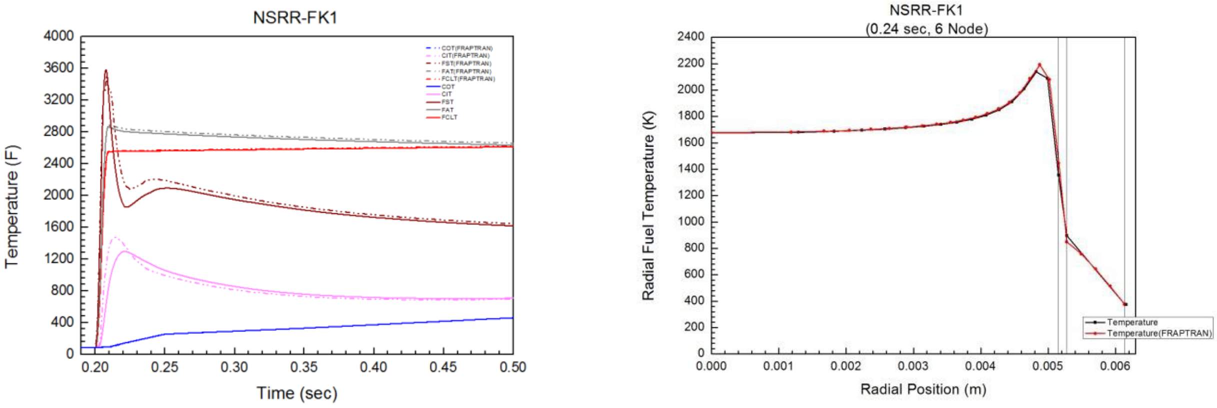

Fig. 2. Temperature Calculation Results of the code and FRAPTRAN (NSRR-FK1 case)

III. THERMAL PERFORMANCE ANALYSIS

For thermal performance analysis, fuel rod geometry of TABLE I was used. By assuming steady state bounding power history of APR1400, fuel initial conditions at burnup levels of 0, 30, and 60 GWd/MTU were calculated. To determine the maximum rod average power of fuel rod during RIA, 3-dimensional core neutron kinetics code ASTRA (Ref. 1) were used. According to ASTRA calculation, maximum core average power occurs at hot zero power. Maximum core average power is about 270% of nominal power and pin peaking factor (Fq) is 14.5. Therefore, about 3915% of core nominal power are used as maximum peak fuel rod average power. Note that the core power and pin peaking factor are the results with conservative assumptions of maximum reactivity worth and conservative thermal hydrodynamic conditions. Also, more conservative higher rod average power of 10000% with narrow pulse case has been analyzed and compared with above cases. Detailed calculation conditions are shown in TABLE II.

TABLE I. Fuel Rod Geometry

Parameter	Unit	Value
Pellet Outside Diameter	inch	0.323
Clad Inside Diameter	inch	0.329
Clad Outside Diameter	inch	0.374

TABLE II. Test Matrix for Thermal Performance Analysis

Burnup (GWd/MTU)	Gap Size (micron)	Oxide Thickness (micron)	Maximum Power (%)	Pulse Width (sec)	Linear Heat Generation Rate (kW/m)	Coolant Temperature (K)	Calculated Fuel Enthalpy (cal/g)
0	50	0	10000	0.08	26.6	590.7	140.7
			4000	0.2			133.5
			4000	0.3			163.4
30[1]	0	10	10000	0.08	25.0	589.0	122.2
			4000	0.2			115.3
			4000	0.3			144.9
		20	10000	0.08	25.0	589.0	123.8
			4000	0.2			117.0
			4000	0.3			147.5
	5	10	10000	0.08	25.0	589.0	123.6
			4000	0.2			116.5
			4000	0.3			146.1
		20	10000	0.08	25.0	589.0	125.1
			4000	0.2			118.4
			4000	0.3			148.6
60	0	100	10000	0.05	16.1	579.4	92.6
			4000	0.2			89.5
			4000	0.3			113.9

[1] Contact usually occurs about 30 GWd/MTU depending on clad creep rate and pellet swelling rate. In the test case, contact and non-contact condition (gap size of 5 micron) are considered with different oxide layer thicknesses.

III.A. Effect of Pulse Width

TABLE III shows the time to reach the maximum temperature regarding to pulse width and burnup level. Calculation results show that the time to reach the maximum fuel temperature is delayed as pulse width increases. The peak fuel average temperature commonly appeared after linear power dropped back to the power level before the accident. However, the time to appear maximum clad temperature and gap conductance have less tendency with power pulse. In some cases, maximum gap conductance appeared before maximum power. Note that maximum power appeared at 6.0 sec.

TABLE III. Calculated Time to Reach the Maximum Temperature

Burnup (GWd/MTU)	Pulse Width (sec)	Time-to-reach the Max. Fuel Temperature (sec)	Time-to-reach the Max. Clad Temperature (sec)	Time-to-reach the Max. Gap Conductance (sec)
0	0.08	6.071	6.067	6.085
	0.2	6.162	6.142	6.185
	0.3	6.235	6.087	6.092
30 (contact condition, oxide 10 micron)	0.08	6.073	6.047	6.007
	0.2	6.171	6.079	6.027
	0.3	6.247	6.102	5.976
30 (contact condition, oxide 20 micron)	0.08	6.074	6.061	6.006
	0.2	6.172	6.106	6.075
	0.3	6.249	6.127	5.974
30 (non-contact condition, oxide 10 micron)	0.08	6.073	6.047	6.006
	0.2	6.170	6.078	6.021
	0.3	6.246	6.101	5.970
30 (non-contact condition, oxide 20 micron)	0.08	6.074	6.061	6.004
	0.2	6.172	6.101	6.020
	0.3	6.249	6.125	5.970
60	0.08	6.076	6.082	5.980
	0.2	6.186	6.153	5.955
	0.3	6.284	6.087	5.891

III.B. Effects of Oxide Thickness and Gap Size

Fig. 3. shows the effects of oxide thickness and gap size on fuel and clad temperature. Fig. 3. (a) shows the effects of oxide thickness on fuel and clad temperature in contact condition at 30 GWd/MTU. It was found that as oxide thickness increase, fuel and clad temperature increase entirely. Fuel Average Temperature, Fuel Surface Temperature and Clad Average Temperature with 20 micron oxide thickness were 29.9K, 53.6K and 86.8K higher than the 10 micron oxide thickness case, respectively. Fig. 3. (b) shows the effect of gap size on fuel and clad temperature at 30 GWd/MTU with 20 micron oxide thickness. It is shown that non-contact condition between pellet and clad results in higher fuel temperatures comparing to contact condition while clad average temperatures are almost the same in different gap sizes. Fuel Average Temperature, Fuel Surface Temperature and Clad Average Temperature with 5 micron gap thickness were 45.1K, 53.6K and 2.9K higher than the 0 micron gap thickness case, respectively. The both higher oxide thickness and higher gap size result in the increase of fuel temperature but oxide thickness is more sensitive factor for Fuel Surface Temperature and Clad Average Temperature than gap size.

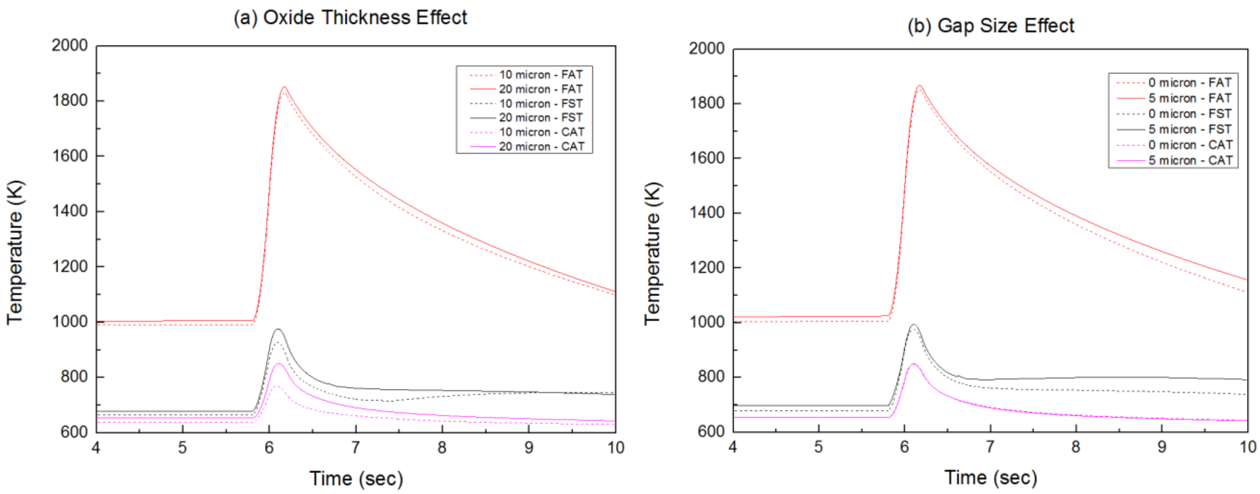

Fig. 3. Effects of Oxide Thickness and Gap Size on Fuel and Clad Temperature

III.C. Effects of Burnup

In reactor, the power of fuel rod varies with burnup. In case of fresh fuel, higher Linear Heat Generation Rate is expected and this leads to higher fuel and clad temperature. In case of high burnup fuel, even though the linear power is relatively low, higher fuel and clad temperatures are expected due to thermal conductivity degradation of pellet and formation of oxide layer in clad. Therefore, the calculation considering these effects is required. Fig. 4. shows the fuel and clad average temperature calculation results with maximum peak fuel rod average power and 0.2 sec pulse width. It is shown that fuel average temperature is higher in low burnup while clad temperature is higher in high burnup. Namely, the maximum Fuel Average Temperatures at 0, 30 and 60 GWd/MTU were 2028.5K, 1851.5K and 1526.8K in Fig. 4. (a). And the maximum Cladding Average Temperatures at 0, 30 and 60 GWd/MTU were 725.2K, 851.1K and 939.0K in Fig. 4. (b).

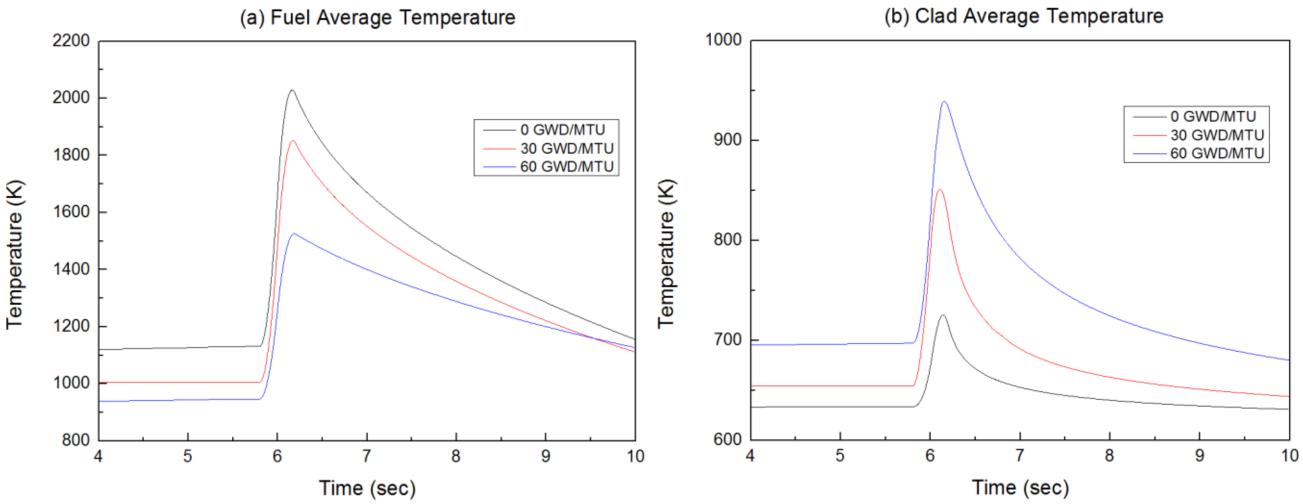

Fig. 4. Effect of Burnup on Fuel and Clad Temperature

IV. SENSITIVITY STUDY

IV.A. Impacts of Material Properties on Fuel Behavior

It is well known that how material properties affect to fuel and clad temperature in steady state. And it is also known that material properties such as the pellet specific heat of fuel and clad have an impact on temperature behavior during LOCA (Ref. 2). As large specific heat lowers the temperature increase of the clad and fuel, accident resistance can be greatly improved by using the materials with high specific heat. In this article, the impacts of fuel and clad material properties on fuel and clad temperature during RIA have been studied. For this, the analysis of fuel behaviors has been performed with material properties listed below. Total 9 thermal and mechanical properties of pellet and clad were selected and each material property value was changed by +10% (upper case) and -10% (lower case).

- Pellet thermal conductivity (PTHCON)
- Pellet heat capacity (PCP)
- Pellet enthalpy (PENTHAL)
- Pellet thermal expansion (PTHEX)
- Clad thermal conductivity (CTHCON)
- Clad heat capacity (CCP)
- Clad thermal expansion (CTHEX)
- Clad young’s modulus (CYOUNG)
- Gap conductance (GAPCON)

TABLE IV shows Best Estimate Case calculation results which use fuel rod data and test conditions of TABLE I and TABLE II. And TABLE V shows that the deviation of fuel parameter from the best estimate results at 30 GWd/MTU, as material property values are changed by ±10%. Among the material properties, pellet enthalpy (PENTHAL), clad thermal conductivity (CTHCON), clad heat capacity (CCP), clad thermal expansion (CTHEX) and gap conductance (GAPCON) showed low impact, that is, less than 10% or 0.07%P of clad total strain or 0.001%P of clad plastic strain on calculation results. However, pellet thermal conductivity (PTHCON), pellet heat capacity (PCP), pellet thermal expansion (PTHEX) and clad young’s modulus (CYOUNG) showed intermediate or high impacts on calculation results.

In the thermal aspect, pellet heat capacity was analyzed as the most impacting factor on pellet and clad temperature. And it was found that clad plastic strain are affected by pellet thermal conductivity, pellet heat capacity, pellet thermal expansion, clad young’s modulus. This clad plastic strain can be explained by the displacement of inside cladding surface or the temperature change which can affect the yield strength of cladding. But as seen in this table, clad average temperature changes are less than 1%, therefore, clad plastic deformations are mostly originated due to pellet deformation. It means that rigid pellet pushes the clad tube from the inner surface and this lead to clad plastic deformation. But it should be emphasized that some factors have the small influence on clad total strain. For example, clad plastic strain are changed by almost more than 0.02%P in clad young’s modulus case. Although plastic deformation shows a relatively large deformation, the amount of contribution to the clad total strain is very small. This because the effect of elasticity and thermal expansions cancels the effect of plasticity change.

TABLE IV. Calculation Results of Best Estimate Case

Fuel Performance Parameter	Unit	Result
Fuel Average Temperature	K	1854.5
Fuel Surface Temperature	K	990.5
Clad Average Temperature	K	847.5
Gap Conductance	W/m^2-K	131882.6
Rod Internal Pressure	psi	1529.9
Clad Total Strain	%	0.677
Clad Plastic Strain	%	0.093

TABLE V. Performance Parameter Variation by Material Properties Change

Fuel Performance Parameter Variation	PTHCON		PCP		PENTHAL	
	+10%	-10%	+10%	-10%	+10%	-10%
Fuel Average Temperature (%)	-1.30	1.58	-3.49	4.09	0.05	-0.05
Fuel Surface Temperature (%)	0.70	-0.72	-1.63	1.87	0.48	-0.51
Clad Average Temperature (%)	0.78	-0.79	-0.83	0.94	-0.15	0.17
Gap Conductance (%)	1.45	-2.61	-0.10	-0.28	-2.28	1.54
Rod Internal Pressure (%)	-1.96	2.42	-5.39	6.49	6.43	-6.42
Clad Total Strain (%P)	0.01	-0.03	0.09	-0.11	0.00	0.00
Clad Plastic Strain (%P)	0.07	-0.03	0.01	-0.02	0.00	0.00

Fuel Performance Parameter Variation	PTHEX		CTHCON		CCP	
	+10%	-10%	+10%	-10%	+10%	-10%
Fuel Average Temperature (%)	-0.01	0.22	-0.20	0.24	-0.03	0.03
Fuel Surface Temperature (%)	-0.04	0.13	-1.04	1.22	-0.20	0.19
Clad Average Temperature (%)	0.01	0.07	-0.58	0.68	-0.19	0.19
Gap Conductance (%)	0.58	0.17	-1.10	1.18	-0.39	0.37
Rod Internal Pressure (%)	-0.65	2.94	-0.36	0.43	-0.05	0.05
Clad Total Strain (%P)	-0.07	0.12	0.00	0.00	0.00	0.00
Clad Plastic Strain (%P)	-0.01	0.09	-0.01	0.01	-0.01	0.01

Fuel Performance Parameter Variation	CTHEX		CYOUNG		GAPCON	
	+10%	-10%	+10%	-10%	+10%	-10%
Fuel Average Temperature (%)	0.00	0.00	0.00	0.01	-0.08	0.10
Fuel Surface Temperature (%)	0.00	0.00	0.00	0.01	-0.46	0.56
Clad Average Temperature (%)	0.00	0.00	0.00	0.00	0.09	-0.12
Gap Conductance (%)	0.00	0.00	0.09	-0.12	-	-
Rod Internal Pressure (%)	0.00	0.00	-0.08	0.11	-0.22	0.26
Clad Total Strain (%P)	0.00	0.00	0.00	0.00	0.00	0.00
Clad Plastic Strain (%P)	0.00	0.00	-0.02	0.02	0.00	0.00

IV.B. Impacts of Burnup on Fuel Behavior

Calculation results in TABLE V have been obtained with the assumption of 30 GWd/MTU. Therefore, it is necessary to confirm if these tendencies are still valid in different burnup levels. Fig. 5. shows sensitivity calculation results regarding to different burnup levels. Material property sensitivities on fuel performance parameters in 0 GWd/MTU shows different tendency from those in 30 and 60 GWd/MTU burnup levels.

In Fig. 5. (a), it is identified that fuel average temperature is influenced by pellet thermal conductivity and pellet heat capacity. And, fuel average temperature is more affected by pellet heat capacity than pellet thermal conductivity. This tendency is not changed as burnup increases. In Fig. 5. (b), we can find that fuel surface temperature is affected by several material properties. For instance, pellet heat capacity has less impact at 0 GWd/MTU compared to 60 GWd/MTU. In Fig. 5. (c) shows that clad average temperature is influenced by several factors but the effects of these factors are less than 2%. It means that clad average temperature is not significantly affected by 9 material properties used in this study. In Fig. 5. (d), it is shown that gap conductance is influenced by pellet thermal conductivity, pellet heat capacity and pellet thermal expansion. Among them, pellet heat capacity and pellet thermal expansion have considerable impact on gap conductance but these tendencies are valid only in 0 GWd/MTU. In Fig. 5. (e), it is shown that rod internal pressure is affected by pellet thermal conductivity, pellet heat capacity, pellet enthalpy rise and thermal expansion. The pellet thermal conductivity and the pellet heat capacity affect the rod internal pressure because fission gas release is dominated by fuel temperature. On the other hand, pellet thermal expansion affects the void volume in fuel rod and consequently rod internal pressure. Finally, Fig. 5. (f), (g) show that clad total strain and clad plastic strain are influenced by several variables. In case of clad total strain, the sensitivity results depending on burnup have been significantly changed. And the clad plastic strain is mainly affected by the pellet thermal expansion and clad young’s modulus but burnup effect is relatively low.

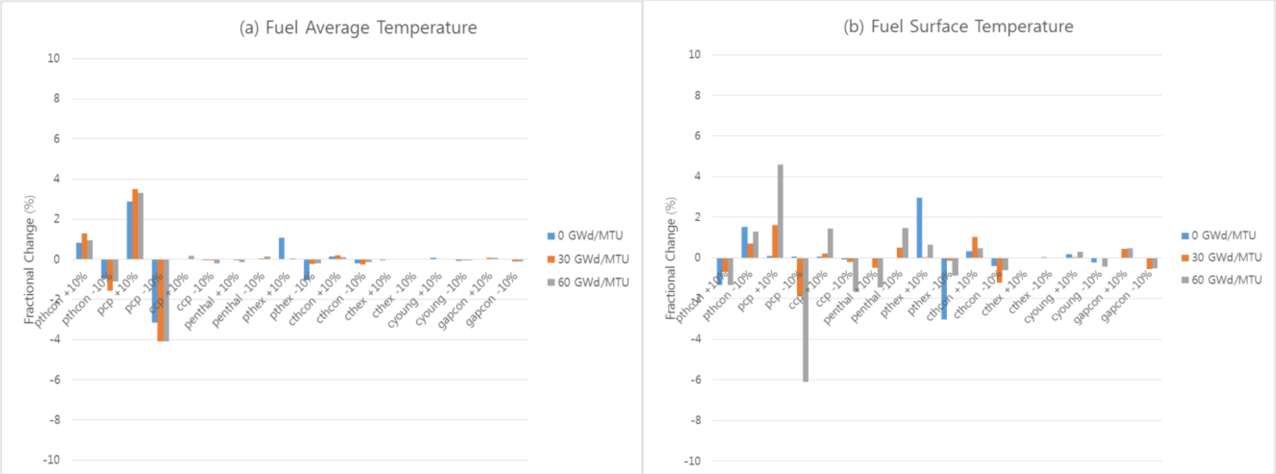

Fig. 5. Sensitivity Analysis Results by Material Properties and Burnup

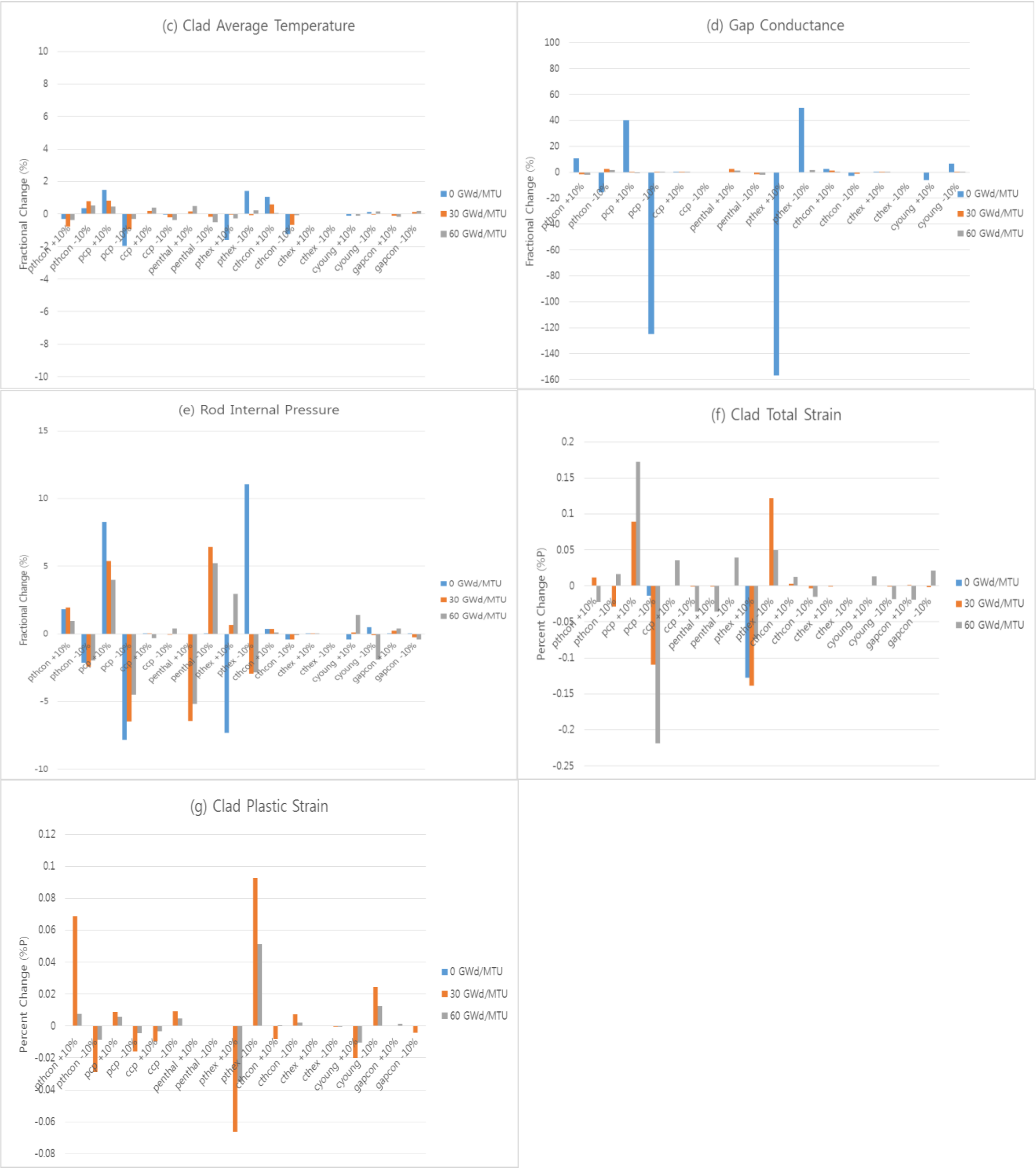

Fig. 5. Sensitivity Analysis Results by Material Properties and Burnup (cont’d)

V. CONCLUSIONS

In this article, thermal performance analysis and sensitivity study of material properties have been performed under RIA condition of APR1400 commercial reactor.

In thermal performance analysis, the effects of initial conditions, such as pulse width, oxide thickness, gap size and burnup, on thermal behavior have been analyzed. From the result, it can be concluded that oxide thickness and gap size are significant factor to fuel temperature behavior in commercial reactor condition. And these two variables have different effects on the temperature distribution inside of the fuel and clad. Also, in case of 0 GWd/MTU fuel average temperature was higher and clad average temperature was lower than 30, 60 GWd/MTU. But the opposite tendency was shown in the high burnup region because of low power and gap close effect.

In the sensitivity study, material sensitivity analysis has been performed for 9 thermal and mechanical properties of pellet and clad. Pellet thermal conductivity, pellet heat capacity, pellet thermal expansion and clad young’s modulus showed intermediate or high impact to fuel behavior. Also, it was identified that sensitivities of material properties are be changed with burnup.

REFERENCES

1. J. I. Yoon, “Verification & Validation of KARMA/ASTRA with Benchmark and Core-Follow Analyses”, ANS-2011, American Nuclear Society (2011)
2. Kurt A. Terrani et al, “The effect of fuel thermal conductivity on the behavior of LWR cores during loss-of-coolant accidents”, Journal of Nuclear Materials 448 (2014)