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Sensitivity studies for 3-D rod ejection analyses on axial power shape

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1. Introduction

The power level in a nuclear reactor immediately increases when a single control element assembly is ejected accompanying a rise in reactivity. The Doppler reactivity feedback cut exponentially increasing power back to a lower level and the overpower trip terminates the accident. Even though this happens in a very short period of time, the power excursion can cause significant fuel failures.

The current safety analysis methodology using the point kinetics model combined with numerous conservative assumptions result in unrealistic prediction of the transient behavior wasting huge margin for safety analyses while the safety regulation criteria for the reactivity initiated accident are going strict.

To deal with this, KNF is developing a 3-D rod ejection analysis methodology using the multi-dimensional code coupling system CHASER [1]. The CHASER system couples three-dimensional core neutron kinetics code ASTRA, sub-channel analysis code THALES, and fuel performance analysis code FROST using message passing interface (MPI).

A sensitivity study for 3-D rod ejection analysis on axial power shape (APS) is carried out to survey the tendency of safety parameters by power distributions and to build up a realistic safety analysis methodology while maintaining conservatism.

2. Methods and Results

The CHASER coupling system has been set up using the MPI method. The validation study of the CHASER system to address the NEACRP three-dimensional PWR core transient benchmark problem has already been performed and the result showed reasonable agreement. The safety analysis method to reflect the conservative kinetic parameters to 3D rod ejection calculation is being formulated, and the APS sensitivity study results performed for a APR1400-type nuclear power plant are presented here.

2.1 The CHASER coupling scheme and validation

The coupling scheme including detailed parameter transfer in the CHASER system is presented in Fig. 1. The ASTRA code calculates 3-D full core nuclear power as a control rod is ejected, considering the Doppler and moderator feedback using the fuel temperature, reactor coolant temperature and density transferred from the FROST and THALES codes. The THALES code calculates thermal-hydraulic behaviors of the core. It determines the flow regime, moderator flow, density and temperature using the power and fuel cladding temperatures calculated from the ASTRA and FROST code respectively. The FROST code calculates heat flux and fuel temperature using the power calculated from the ASTRA code, heat transfer coefficient and coolant temperature that are transferred from the THALES code. These calculations are performed iteratively until the heat flux is converged within the specified criteria for each time step.

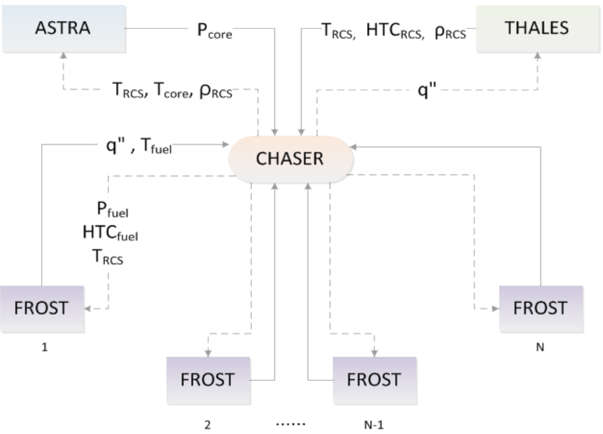


Fig. 1. Coupling scheme of the CHASER system.

A validation study for the CHASER system had been performed for the NEACRP benchmark problem [1], [2]. The transient reactor power and fuel temperature calculation results of benchmark problem with 1.22$ reactivity insertion at hot zero power (HZP) have shown reasonable agreement with previous results using other codes.

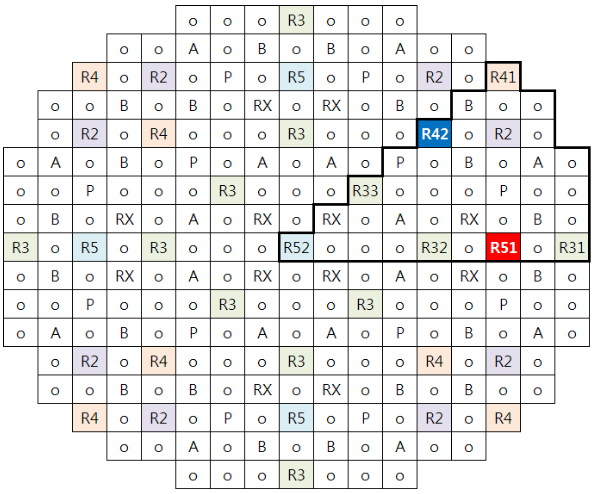
2.2 Ejected rod worth sensitivity analysis on APS

As a preliminary study for the power transient depending on APS, the sensitivity analysis of ejected rod worth, the most important parameter for the power increase, is performed for Shinkori unit 3, cycle 1.

Ejected rod worth values calculated using ASTRA static eigenvalue search are compared. The rod worth is calculated by measurement of the inserted reactivity of the control rod ejection from PDIL position to the top.

The sensitivity analysis is performed for both operating condition of 102% and 1E-7% of nominal power. 8 ejected rod locations, 4 burnup points of beginning of cycle (BOC), intermediate of cycle (IOC), middle of cycle (MOC) and end of cycle (EOC), 3 part strength CEA bank positions from full insertion to fully withdrawn position and 6 APSs for each power level are considered as independent parameters.

The type and location of ejected rod for sensitivity analysis are determined by considering 1/8 core symmetry as in R51, R52, R41, R42, R31, R32 and R33. Fig. 2 shows the control rod configuration of the target core.



					o	o	o	R3	o	o	o					
			o	o	A	o	B	o	B	o	A	o	o			
		R4	o	R2	o	P	o	R5	o	P	o	R2	o	R41		
	o	o	B	o	B	o	RX	o	RX	o	B	o	B	o	o	
	o	R2	o	R4	o	o	o	R3	o	o	o	R42	o	R2	o	
o	A	o	B	o	P	o	A	o	A	o	P	o	B	o	A	o
o	o	P	o	o	o	R3	o	o	o	R33	o	o	o	P	o	o
o	B	o	RX	o	A	o	RX	o	RX	o	A	o	RX	o	B	o
R3	o	R5	o	R3	o	o	o	R52	o	o	o	R32	o	R51	o	R31
o	B	o	RX	o	A	o	RX	o	RX	o	A	o	RX	o	B	o
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	o	R2	o	R4	o	o	o	R3	o	o	o	R4	o	R2	o	
	o	o	B	o	B	o	RX	o	RX	o	B	o	B	o	o	
		R4	o	R2	o	P	o	R5	o	P	o	R2	o	R4		
			o	o	A	o	B	o	B	o	A	o	o			
					o	o	o	R3	o	o	o					

Fig. 2. Control rod configuration and ejected rod location

6 APSs are selected from the APS profile pool generated using the ASTRA xenon oscillation. Axial shape index (ASI) and Fz are considered for APS selection. Selected APSs for HFP and HZP are presented in Fig. 3 and Fig. 4.

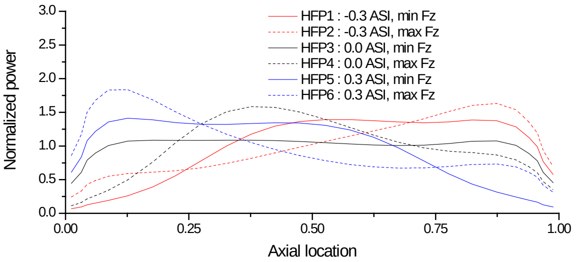

Fig. 3. Selected axial power shapes (HFP)

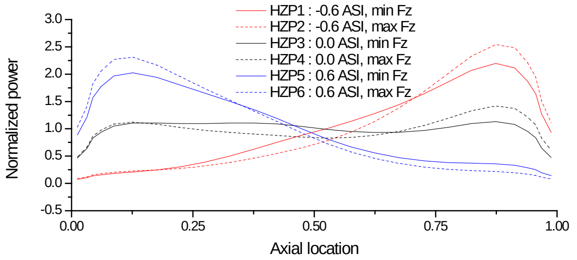

Fig. 4. Selected axial power shapes (HZP)

Table 1 and Table 2 show maximum ejected rod worth cases for each APS. The most limiting ejected rod worth cases for both HFP and HZP are shown to occur for the top skewed APS with maximum Fz.

Table 1. Rod worth sensitivity result (HFP)

APS ID	BU cycle	Ejected rod	Bank P insertion	Ejected rod worth (pcm)
HZP2	EOC	R42	Full	214
HZP1	EOC	R42	Full	212
HZP4	EOC	R42	Half	185
HZP3	EOC	R42	Full	176
HZP5	MOC	R51	No	161
HZP6	MOC	R51	No	160

Table 2. Rod worth sensitivity result (HZP)

APS ID	BU cycle	Ejected rod	Bank P insertion	Ejected rod worth (pcm)
HFP2	EOC	R51	Full	63
HFP1	EOC	R51	Full	43
HFP3	EOC	R51	Full	33
HFP4	EOC	R51	Full	19
HFP6	EOC	R51	No	14
HFP5	MOC	R51	No	5

2.3 Kinetic parameter tuning by cross section modification

The currently developing 3-D rod ejection analysis method can modify cross section for kinetic parameter tuning to utilize the conservative assumptions applied as same as those for previous analysis methods with point kinetics model. This method aims to tune up kinetic parameters including ejected rod worth, scram worth, MTC, FTC, delayed neutron fraction, prompt neutron lifetime.

Using the tuning method, the transient power behaviors as tuning parameters are added are illustrated in Fig. 5. This calculation is performed for HFP, EOC condition of APR1400-type nuclear power plant with a 16x16 assembly. The CHASER calculation model having radial nodes of 964 sub-channels for the full core and 26 axial nodes for each radial node was considered for the analysis.

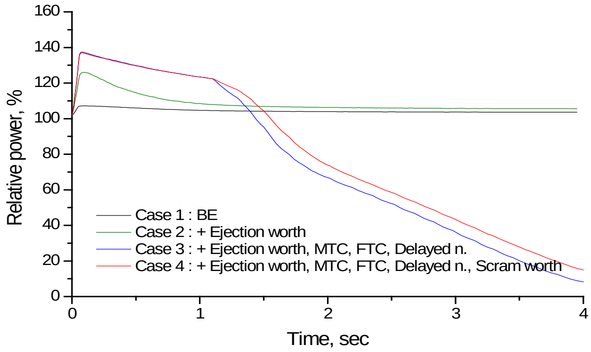

Fig. 5. Power transient trend as tuning parameters are added

Case 1 is a best estimate (BE) calculation for the limiting ejected rod worth condition with nominal APS which corresponds to steady xenon distribution at EOC. For case 2, ejected rod worth is tuned up to a possible maximum ejected rod worth plus uncertainty. Case 3 additionally tuned MTC, FTC, delayed neutron fractions and their decay constants to the most limiting values. In case 4, scram rod worth tuning was added on.. The peak power even did not reach the overpower trip set point of 127.5% of nominal power for Case 1 and Case 2.

The trend shows that the peak power increases as more parameters are tuned. Transient power behavior shows appropriate reflection of kinetic parameter tuning as expected.

2.4 Transient power sensitivity analysis on APS

Even though it is shown that the most limiting ejected rod worth occurs only for the top skewed APS, the combinations of the most limiting ejected rod worth and various APSs are assumed to clarify the APS impact on the transient power behavior. In other words, ejected rod worth values are fixed to the limiting value (0.31$ for HFP and 1.1$ for HZP) while APSs are changed by cases.

APSs are selected considering ASI, Fz for HZP and top quadrant integral (TQI) power for HFP. The limiting ejected rod worth is artificially increased to 1.1$ for HZP to check the power behavior in prompt critical condition. APSs for HFP are presented in Fig. 6 and APSs for HZP are the same as in Fig. 4.

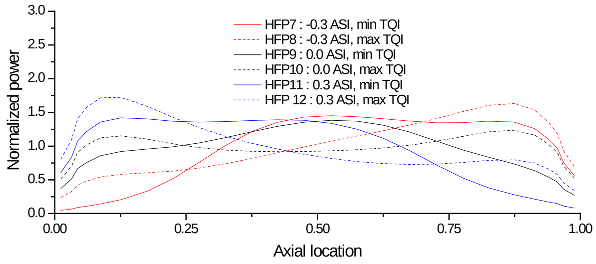

Fig. 6. Selected axial power shapes (HFP)

The transient power sensitiviy analyses results for HFP and HZP are presented in Fig. 7 and Fig 8. Calculation for HZP5 and HZP6 APSs are not performed because tuning the ejected rod worth to 1.1$ was not physically possible using current method for these shapes.

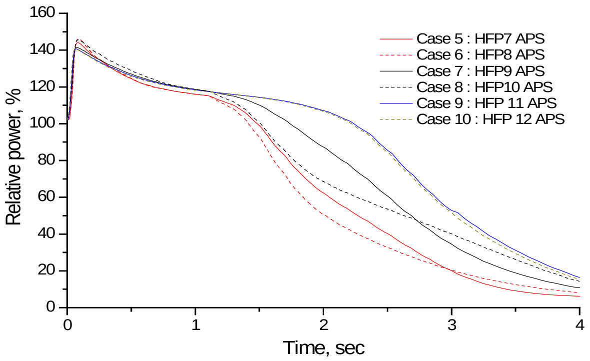

Fig. 7. Power transient behaviors by APSs (HFP)

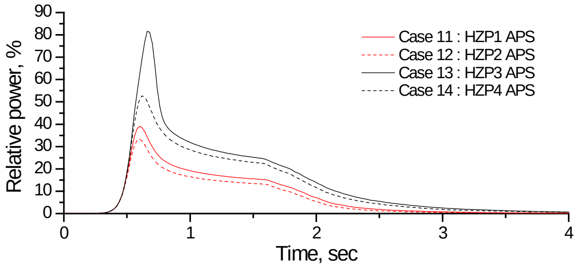

Fig. 8. Power transient behaviors by APSs (HZP)

For HFP case, when the ejected rod worth is same, the peak power values varied within about 5% of deviation mainly by different Doppler reactivity feedback effect for various APSs. However, power integral is more important than peak power for the power transient of HFP cases that directly related to enthalpy rise (stored energy in fuel pellets). Bottom skewed and smaller TQI APSs showed slower scram reactivity insertion so the power decreased slowly.

The Doppler reactivity feedback effect is dominant for HZP case. Sharply increasing power instantly turns back as immediate Doppler feedback reactivity is inserted. The Doppler reactivity feedback was shown to be bigger and the peak power is lower when the power concentration is high (larger Fz). That's because the fuel temperature increases higher for the same ejected rod worth condition.

3. Conclusions

The currently developing 3-D rod ejection analysis methodology using the multi-dimensional core transient analysis code system, CHASER was shown to reasonably reflect the conservative assumptions by tuning up kinetic parameters.

Ejected rod worth and transient power sensitivity analyses on APS are performed using the ASTRA code and the CHASER system. Limiting ejected rod worth appeared with the APSs most skewed to the top for both HFP and HZP conditions.

Power transient sensitivity analysis on APS with fixed ejected rod worth is performed for HFP and HZP. Bottom skewed APS for HFP showed slow scram reactivity insertion so it is expected to be limiting in enthalpy rise aspect. APS having small Fz (flatter shape) showed high peak power for HZP case.

REFERENCES

[1] J. W. Park et al, Code Coupling for Multi-Dimensional Core Transient Analysis, Transaction of the Korean Nuclear Society Spring Meeting, 2015.

[2] H. Finnemann, OCED/NEA/NSC, Results of LWR Core Transient Benchmarks, 1993.