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Sensitivity of Energy Deposition to Reactor Parameters in Rod Ejection Accident

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ABSTRACT

This study quantifies the sensitivity of energy deposition to the delayed neutron fraction, reactivity insertion, and fuel specific heat for rod ejection accident simulated by PARCS code which is a 3-dimensional core kinetics code. The results show that the sensitivity of fuel energy deposition to delayed neutron fraction and reactivity insertion strongly depends on the reactivity of the ejected control rod. At high rod worth or small delayed neutron fraction, its sensitivity is low, but as the reactivity insertion decreases to the point where the excursion is just prompt critical, the sensitivity becomes very large. The sensitivity to specific heat is independent of the ejected rod worth.

INTRODUCTION

As longer fuel cycles are used, the discharge burnup and uranium enrichment have gradually increased. In recent years, several experiments have been performed to examine the behavior of high-burnup fuel subjected to a power pulse which represents rod ejection accident (REA), and they show that a few of the fuel rods have failed at energy depositions that are low relative to the current acceptance criteria for fuel integrity during REA [1,2]. Other recent studies of high-burnup fuel also show that property changes at the surface of the pellet and in the clad due to irradiation can make the fuel more vulnerable to power pulses. These activities have called into question the current acceptance criteria based on experiments of new and low burnup fuel, and thus new studies to address this issue have been undertaken by the light water reactor community throughout the world [3]. With the possibility that for high-burnup fuel the acceptance criteria may become more stringent, and with new, more rigorous, calculation methods available, it is expected that best-estimate methods be used in the future.

In the accident analysis, in particular, for best-estimate calculations, it is important to understand the uncertainties for core parameters. D.J. Diamond and L. Neymotin [4] assessed the sensitivity of BWR rod drop accident (RDA) due to the uncertainties of the most important parameters controlling the power excursion during a RDA: the reactivity worth of the control rod, the delayed neutron fraction, the fuel reactivity feedback, etc. The dependence of fuel behavior on some parameters is not still quantified yet. For example, it has been recently discussed in a high-burnup issue meeting that the stored energy during REA may be strongly sensitive to the change in the delayed neutron fraction. Hence, this study provides the sensitivity analysis of the energy deposited in the fuel during REA leading to superprompt critical for the reactor parameters such as the delayed neutron fraction, reactivity insertion and specific heat. For the sensitivity analysis, PARCS code [5], which is a 3-dimensional core kinetics code, is used. The PARCS uses NEM/ANM methods to solve the nodal equations.

ENERGY DEPOSITION BASED ON POINT KINETICS

The energy deposition at time t during power excursion is defined as

$$Q(t) = \int_0^t P(t')dt' \tag{1}$$

where P denotes the total power of the core. The total energy release for an initial power pulse is given by

$$Q_m = 2Q(t_m) = 2\int_0^{t_m} P(t)dt \tag{2}$$

where t_m is the time at a peak power. At $t= t_m$, the derivative in power transient becomes equal to zero.

Assuming the prompt-kinetics approximations and the adiabatic boundary condition of thermodynamics at the fuel cladding, Equation (2) is approximately given by [6]

$$Q_m = -2(\beta-\rho_o)/\gamma \tag{3}$$

where ρ_0 is a reactivity worth of the ejected control rod, γ the conversion factor given by specific heat, c_p, and density of the fuel. β is the total delayed neutron fraction.

Then, S_β, the sensitivity of Q_m to β, is analytically obtained as

$$S_\beta = (\delta Q_m/Q_m)/(\delta\beta/\beta) = -\beta/(\rho_0-\beta) \tag{4}$$

Similarly, S_ρ, the sensitivity to ρ_0, is

$$S_\rho = (\delta Q_m/Q_m)/(\delta\rho/\rho) = \rho_0/(\rho_0-\beta) \tag{5}$$

Also, S_{cp} is

$$S_{cp} = (\delta Q_m/Q_m)/(\delta c_p/c_p) = 1 \tag{6}$$

RESULTS

For the usage of the PARCS code, two group nodal cross section data with four partial cross section should be assigned to each fuel assembly. These cross section data are usually calculated from neutronics codes. A PWR MSLB benchmark core [7] provided by the US NRC and OECD/NEA was used for data availability in the 3-dimensional core analysis of REA. This benchmark provides the cross section data of each assembly.

Of interest is a large power pulse subjected to REA, which is possible when the ejected control rod worth is larger than the total delayed neutron fraction. It, however, was known from the steady-state calculations that the reactivity worth of each rod in regulating banks at full power is less far than the prompt critical reactivity. Hence, the core configurations corresponding to a zero power condition were chosen, and, furthermore, the rod worth was artificially increased by doubling the absorption cross section of that control rod, so that the excursion is superprompt critical.

The energy depositions for 3 sets of β ($0.9\beta_0$, β_0 and $1.1\beta_0$) were calculated for $1.15\$<\rho_0<1.36\$$ ($\beta_0=0.005211$). It is shown in Figure 1 that the sensitivity of fuel energy deposition to the delayed neutron fraction strongly depends on the ejected rod worth; the sensitivity becomes large as ρ_0 decreases. Figure 2 shows that the sensitivity to reactivity insertion becomes large as the delayed neutron fraction increases. From the above results, it is demonstrated that the sensitivity to the delayed neutron fraction and reactivity insertion depends on the value of the reactivity dollar of the ejected control rod (ρ_0/β); i.e., at high rod worth or low delayed neutron fraction, the sensitivity is low, but as the rod worth decreases to the point where the excursion is just prompt critical, the sensitivity becomes very large. The sensitivity of energy deposition to specific heat is given in Figure 3. The sensitivity to specific heat is nearly constant as reactivity insertion.

Figures 1 and 2 also show that, in predicting the sensitivity to the delayed neutron fraction and reactivity insertion, the point-kinetics can be a good model, but the point-kinetics approximation generally tends to overestimate the sensitivity as the reactivity insertion in dollar decreases.

CONCLUSIONS

REAs leading to superprompt criticality were analyzed for various core conditions by using PARCS code, and the sensitivity of energy deposition due to the variations of the delayed neutron fraction, the reactivity insertion and specific heat was quantified. The sensitivity from the 3-dimensional calculations generally follows what would be expected based on simple point-kinetics. For example, the sensitivity of energy deposition to delayed neutron fraction was strongly dependent on the ejected control rod worth. It is finally concluded that as the reactivity insertion in dollar decreases, the sensitivity to delayed neutron fraction and reactivity insertion becomes large; e.g., more than 50% change in energy deposition for 10% uncertainty in delayed neutron fraction during a REA leading to nearly prompt critical. On the other hand, the sensitivity to specific heat was independent of the ejected rod worth. It should be noted that although the sensitivity increases, the magnitude of the energy deposition decreases as the ejected rod worth decreases.

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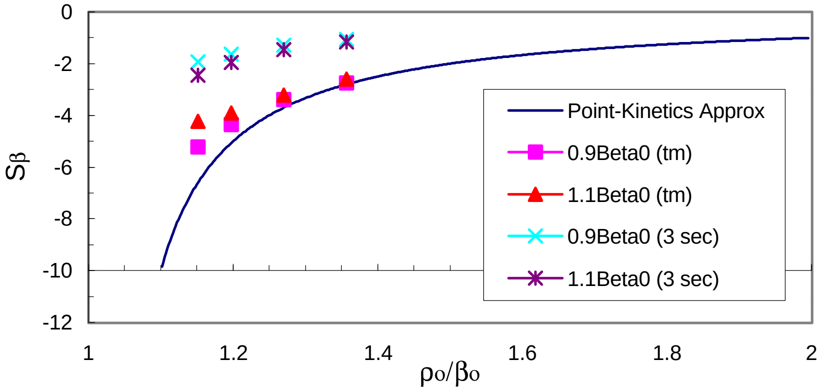


Figure 1 Sensitivity of Energy Deposition to Delayed Neutron Fraction

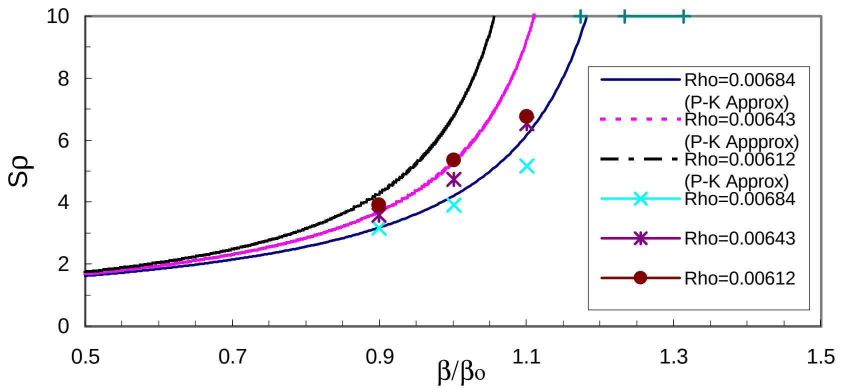


Figure 2 Sensitivity of Energy Deposition
to Reactivity Insertion

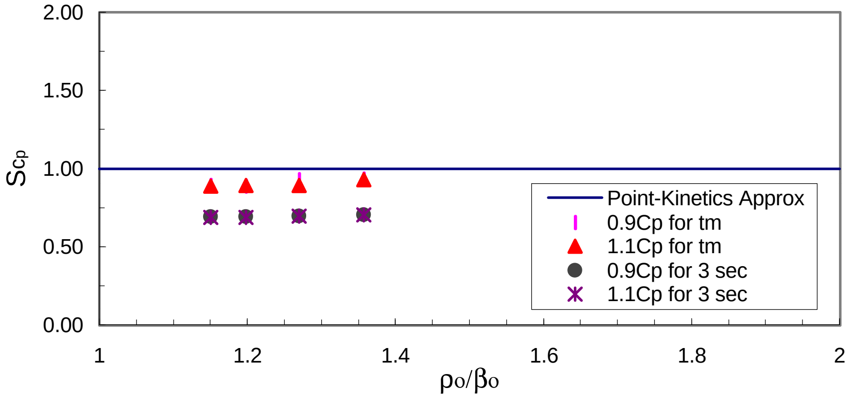
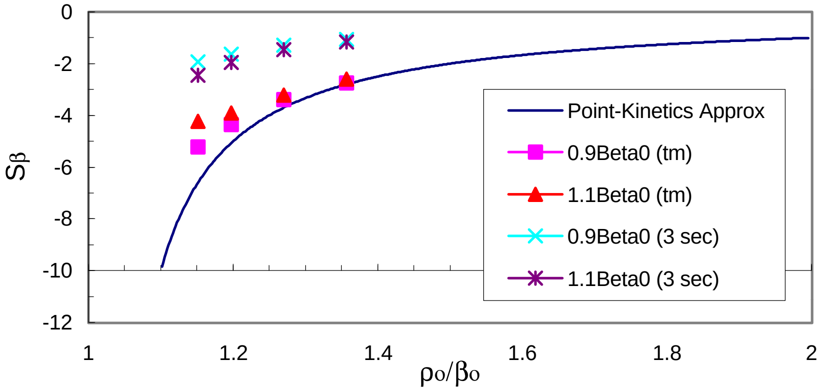


Figure 3 Sensitivity of Energy Deposition
to Heat Capacity



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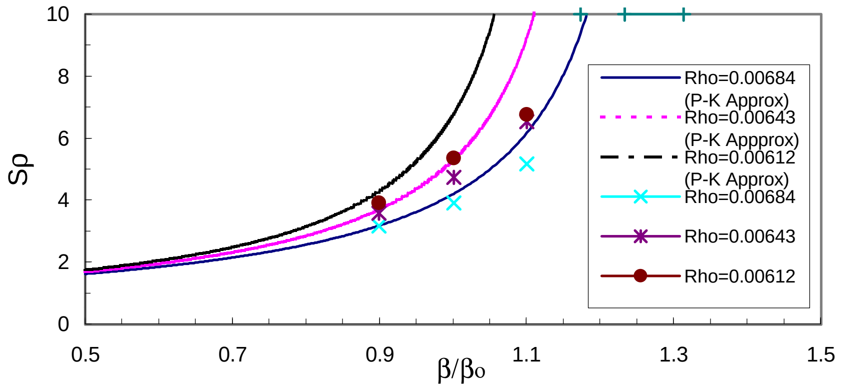

Figure 2 Sensitivity of Energy Deposition
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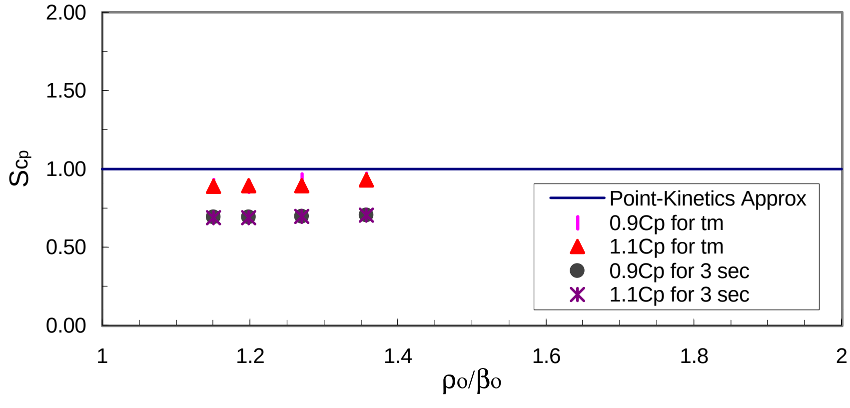

Figure 3 Sensitivity of Energy Deposition to Heat Capacity