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PIUS SCRAM REACTIVITY ANALYSIS*

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ABSTRACT

A detailed evaluation of the scram reactivity for the PIUS reactor design has been carried out. The scram reactivity resulting from the injection of highly borated pool water was calculated for a series of time-dependent linear ramp and square-wave pool flows. The three-dimensional core distribution of the pool water was modeled and the spatial reactivity effects of the distributed boron were determined. For pool flows that increase as a linear ramp, the spatial reactivity effects of the distributed boron were very small. In this case, a constant core-average boron reactivity coefficient can be used to model the PIUS scram reactivity.

I. INTRODUCTION

An analysis has been performed to evaluate the scram reactivity for the PIUS reactor.¹ The analysis includes a series of parametric calculations which determine the reactivity effects associated with the use of the flow of soluble boron through a set of density locks for reactor control/scram. The analysis employed the NODE-P2 three-dimensional nodal code² to calculate the effect of selected input boron flow distributions on the core reactivity. The study considered the reactivity effects of the time-dependent spatial boron distributions resulting from several assumed variations in the mass flow rates from the boron pool. The effect of the reduced pool water temperature on the reactivity coefficient was determined and found to be relatively small. Both beginning and end of cycle conditions were analyzed. The study concluded that pool flow injections which increase as a linear ramp can be described using a core-wide constant boron coefficient allowing a point kinetics representation of the scram. For pool flows which increase more rapidly than a linear ramp, spatial neutronics calculations will be required to provide an accurate determination of the scram reactivity in PIUS transient analyses.

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II. CALCULATIONAL METHODOLOGY

A. REACTIVITY ANALYSIS

The basic calculational methodology employed the NODE-P2 three-dimensional nodal code to calculate the core reactivity and power distribution, and perform the required depletion analyses. A series of parametric calculations were performed to determine the core reactivity for a set of assumed time-dependent input boron flows. The high-concentration boron coolant enters the core when the density locks open in response to a reactor upset. The boron pool water contains 2200 ppm soluble boron and is maintained at 122°F, while the reactor coolant contains less than 400 ppm soluble boron and is maintained at an inlet temperature of 500°F. The boron pool flow is assumed to mix uniformly with the reactor coolant system flow before entering the bottom of the core. In this study, several boron distributions were determined by representing the time-dependent mass flow from the boron pool as a linear ramp or a square-wave pulse. The reactivity was evaluated as the boron flows up through the core by performing a series of steady-state analyses for the sequential instantaneous three-dimensional boron distributions. In this study the boron distributions were assumed to be uniform in the horizontal plane and varied only axially.

B. DETERMINATION OF THE CORE BORON DISTRIBUTION

The boron flow through the core was determined by assuming the coolant velocity was the same in all fuel assemblies and independent of the neutronic feedback. The effect of the colder pool water on the scram reactivity was included by varying the inlet subcooling. The calculations were performed in two steps: (1) the inlet subcooling was held constant at the value corresponding to the initial reactor coolant system temperature, and (2) the inlet subcooling varied with the mass flow rate from the boron pool, resulting in a decreasing inlet coolant temperature. It is important to note that the reactivity effects determined in this study are parametrized in terms of the calculated boron distributions. Consequently, the assumptions made in calculating the boron distributions only affect the range of distributions considered, and not the relationship between the scram reactivity and the boron distribution.

C. BORON REACTIVITY COEFFICIENT

In the PIUS design, an upset in the core operating conditions is expected to result in the opening of the lower density locks and the flow of the highly borated pool water into the core. The increase in coolant boron concentration provides the required negative control/scram reactivity. The instantaneous boron reactivity coefficient $\alpha_B(t)$ is defined

$$\alpha_B(t) = \Delta\rho(t) / \Delta B(t), \quad (1)$$

where the change in core reactivity $\Delta\rho(t)$ is

$$\Delta\rho(t) = [k_{eff}(t) - k_{eff}(o)] / k_{eff}(o), \quad (2)$$

and $k_{eff}(t)$ is the instantaneous core multiplication. The core-average boron concentration is defined as an average of the local boron concentration over the core volume V

$$B(t) = \frac{1}{V} \int B(\underline{x}, t) d\underline{x}. \quad (3)$$

In the analysis of situations involving nonlinear flow it will be convenient to define the boron reactivity coefficient in terms of the spatially weighted boron concentration

$$B_w(t) = \int P(\underline{x}, t) B(\underline{x}, t) d\underline{x}, \quad (4)$$

where $P(\underline{x}, t)$ is the normalized core power distribution. This importance weighting of the local boron concentration accounts for the reduced (increased) effectiveness of the boron poison in the regions of low (high) neutron flux. If the boron concentration is uniform then $B_w = B$, and the core-average spatially weighted boron concentration is independent of the power distribution.

It is important to note that the modeling of the scram reactivity simplifies greatly when the core-wide reactivity coefficient α_B is not a function of the reactor statepoint so that $\alpha_B(t) = \text{constant}$.

III. ANALYSIS RESULTS AND DISCUSSION

A series of three-dimensional neutronic core analyses has been performed to determine the reduction in core reactivity as a result of the injection of highly borated 2000-ppm pool water during a reactor scram.^a Calculations were performed for both a linear ramp injection and a square-wave pulse injection of pool water. In the linear ramp injection, the borated pool flow is taken to be a time-dependent fraction αt of the reactor coolant flow. Ramp rates of $\alpha = 0.05, 0.10$, and 0.15 , corresponding to 5, 10, and 15% pool flow per second, were considered. In the square-wave pulse scram injection, the fraction of reactor coolant flow from the borated pool increases instantaneously from zero to β for a period of 1.2 seconds (approximately two-thirds of the core transit time). Pulse heights of $\beta = 0.10$, and 0.15 were considered.

In Figure 1, the scram reactivity ρ is plotted versus core-average boron concentration for the $\alpha = 0.10$ case in which the pool fraction of the coolant flow increases as $\alpha t = 0.10 t$. The scram reactivity exhibits a linear dependence on the core-average boron concentration B with the time-independent boron reactivity coefficient α_B given by the slope of the $\rho(B)$ curve. The boron reactivity coefficient determined by fitting the data of Figure 1 is $\alpha_B = -1.31 \times 10^{-2} (\% \Delta k/k)/\text{ppm}$ (see column-4 of the Table).

In Figure 2, the scram reactivity ρ is presented for the three $\alpha = 0.05, 0.10$, and 0.15 linear ramp pool flow cases. Again, the core reactivity resulting from the boron injection is a linear function of the core-average boron concentration B and is characterized by a constant boron coefficient α_B . The boron coefficients for these cases are given in the Table and are seen to increase from -1.36 to $-1.26 \times 10^{-2} (\% \Delta k/k)/\text{ppm}$ as the ramp rate increases from $\alpha = 0.05$ to $\alpha = 0.15$. This decrease in the magnitude of the boron coefficient for the higher ramp rates is due to the fact that in these cases the boron distribution is peaked more toward the bottom of the core and away from the high-importance regions near the core midplane.

The borated pool water is at a reduced temperature of 122°F relative to the 500°F core inlet temperature. Consequently, the reduced temperature of the pool provides a positive reactivity

^a The slightly larger 2200-ppm boron concentration of the PIUS pool water is believed to have a negligible effect on the conclusions of the present study.

contribution to the scram reactivity. In order to estimate this effect, a calculation was performed in which the core inlet temperature was reduced based on the instantaneous pool flow and an assumed pool temperature of 250°F. Since NODE-P2 calculations were performed in the steady-state mode, the coolant temperatures at all axial locations are based on the instantaneous inlet temperature and are, therefore, lower than the physical situation in which the higher elevation temperatures are based on earlier and warmer inlet temperatures. This approximation results in an overprediction of the effect of the cooler pool temperature. In Figure 3, the scram reactivity ρ is presented as a function of boron concentration for an $\alpha = 0.15$ linear ramp for both a constant 500°F inlet temperature and a reduced pool inlet temperature of 250°F^b. Based on these results it is concluded that the cooler 122°F pool inlet temperature will result in a relatively small decrease in the scram reactivity.

The reactivity worth of the boron injection increases with core life due to the depletion of the gadolinium, which results in a reduction in gadolinium thermal absorption and a more thermal spectrum. Both of these effects tend to increase the reactivity effect of the boron poison. The scram reactivity versus boron concentration is presented in Figure 4 for the $\alpha = 0.10$ pool flow case for both beginning-of-cycle (BOC) and end-of-cycle (EOC) conditions and indicates the linear behavior observed in the earlier ramp flow calculations. In the Table the boron reactivity coefficient is seen to decrease from -1.31 to -1.45×10^{-2} (% $\Delta k/k$)/ppm from BOC to EOC conditions. The BOC and EOC reduced-inlet-temperature cases are also presented in Figure 4 and indicate a more positive pool-water-temperature reactivity effect for EOC conditions. This is a result of the more negative EOC temperature coefficient due to the reduced gadolinium absorption and a more thermal spectrum.

The axial distributions of the coolant boron concentration are relatively smooth for the linear ramp pool flow injection. For the $\alpha = 0.15$ linear ramp injection, the local boron concentration increases linearly by ~ 400 ppm over the height of the core. In order to evaluate the effects of the strong spatial variations in the core boron concentration several square-wave pulse cases were calculated. In the $\beta = 0.15$ pool flow pulse, the boron concentration increases from 400 to 640 ppm across the front of the square-wave pulse.

The scram reactivity ρ for the $\beta = 0.15$ pulse is presented in Figure 5. The values of scram reactivity ρ when the center of the pulse is in the bottom of the core ($z_p < 0.5H$) and in the top of the core ($z_p > 0.5H$) are indicated separately. The boron worth is reduced when the pulse is in the bottom of the core due to the reduced neutron flux and importance of this region relative to the axial locations close to the core midplane. Additionally, as the boron pulse moves from the bottom of the core to the core midplane the axial flux distribution shifts away from the poison and towards the top of the core. This axial redistribution of the flux further reduces the differential boron scram reactivity. In Figure 5, it is seen that as the pulse approaches the core midplane the flux redistribution is complete and the pulse begins to enter the high-flux region increasing the differential scram worth. (This is analogous to the effect produced by control rod insertion which results in the typical scram S curve). Relative to the uniform case, the differential poison worth is reduced by more than a factor of two at the bottom of the

^b The slight initial increase in reactivity in the case of the reduced inlet temperature (curve with the solid triangles) is a result of the (approximate) use of the instantaneous cooler inlet temperatures for all axial elevations in the steady-state calculation. As a result, the average core coolant temperature is always slightly cooler than in the actual situation where the temperature of the coolant at the top of the core is determined by an earlier and warmer inlet temperature.

core and is increased by $\sim 15\%$ at the core midplane.^c From Figure 5 it is also seen that the scram reactivity is essentially symmetric about the core midplane, with a slightly larger reactivity insertion when the pulse is in the bottom of the core. This is due to the reduced coolant temperature which results in increased axial peaking and a more thermal spectrum.

In order to quantify the effect of the spatial boron distribution further, the core-average spatially weighted boron concentration B_w was determined. As defined in Equation 4, B_w is determined by weighting the local boron concentration with the instantaneous power distribution. In Figure 6, the boron scram reactivity is plotted versus the power-weighted boron concentration B_w for the pool flow $\alpha = 0.10$ linear ramp and the $\beta = 0.10$ and $\beta = 0.15$ pulse boron injections. It is evident that when the boron scram reactivity is determined using the power-weighted boron concentration via $\rho(B_w)$, a constant core-wide boron coefficient α_B is obtained. In the Table the boron coefficients for these cases are presented and range from -1.34 to -1.50×10^{-2} ($\% \Delta k/k$)/ppm.

It is noteworthy that the boron coefficient for the $\alpha = 0.10$ ramp flow injection only changes by $\sim 3\%$ when defined in terms of the power-weighted boron concentration B_w . This approximate equivalence of the $\rho(B_w)$ and $\rho(B)$ curves for the linear ramp injection implies that $B_w = B$. This, in fact, follows from the resulting linear dependence of the local boron concentration

$$B(z) = B + B_1(z - z_m), \quad (5)$$

where B is the core-average concentration and z_m is the elevation of the core midplane.^d Since $P(z)$ is (to a good approximation) even about the core midplane and $B(z)$ is odd, the Equation 4 integral of the linear term in Equation 5 vanishes, and the weighted-boron $B_w = B$ and is independent of the power distribution. Consequently, for pool flows $W_p(t)$ that increase linearly ($W_p = \alpha t$) over the core coolant transit time $\Delta\tau$ (i.e., $\Delta\tau^{(n-1)} W_p^{(n)} \ll W_p^{(1)}$), the local boron concentration varies linearly over the height of the core and the scram reactivity may be described with a constant core-wide boron reactivity coefficient α_B . In this case, a point-kinetics modelling of the boron scram may be used in PIUS transient analyses.

IV. SUMMARY AND CONCLUSION

A parametric analysis has been performed to characterize the scram reactivity for the PIUS design. Three-dimensional NODE-P2 calculations of the core multiplication k_{eff} have been performed to determine the scram reactivity resulting from the flow of the highly borated pool water into the core. Both linear ramp and square-wave pulse boron pool flows have been considered. The boron distributions considered were uniform in the horizontal plane.

For the linear ramp pool flows considered, the boron distributions increase linearly with core height and the spatially weighted boron concentration is independent of the core power distribution, allowing the scram reactivity to be characterized by a constant core-wide boron reactivity coefficient. For the square-wave pulse pool flows, the boron distributions include strong spatial variability and the

^c It is noteworthy that a similar variation in differential boron worth may also be expected for corresponding radial variations in the boron poison concentration.

^d This linear dependence of $B(z)$ assumes that the core flow velocity is constant during the scram. If the flow velocity varies significantly some error will be introduced into the inferred α_B .

scram reactivity can not be described using a unique boron reactivity coefficient. When the local boron concentration is weighted with the instantaneous power distribution, the scram reactivity can be described in terms of a single constant boron reactivity coefficient.

The boron reactivity coefficient was $\sim 10\%$ larger at the end-of-cycle than at the beginning-of-cycle, and the positive reactivity effect of the lower-temperature pool water was found to be relatively small.

These results suggest that for pool flows which increase linearly, the inserted reactivity is independent of the power distribution and the scram reactivity can be described by a constant core-wide reactivity coefficient α_B allowing a point-kinetics description of the scram. However, in cases where the pool flow increases more rapidly than a linear ramp, the inserted reactivity depends on the instantaneous power distribution and spatial neutronics calculations will be required to provide an accurate determination of the time-dependent coupling between the boron and power distributions and ensure an accurate scram reactivity calculation.

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TABLE
BORON REACTIVITY COEFFICIENTS⁺

Type of Pool Flow	Fuel Burnup	Spatially Weighted Boron	Boron Reactivity Coefficient α_B^* ($\times 10^{-2}(\% \Delta k/k)/\text{ppm}$)
Ramp, $\alpha = 0.05$	BOC	no	-1.36
Ramp, $\alpha = 0.10$	BOC	no	-1.31
Ramp, $\alpha = 0.15$	BOC	no	-1.26
Ramp, $\alpha = 0.10$	EOC	no	-1.45
Ramp, $\alpha = 0.10$	BOC	yes	-1.34
Ramp, $\alpha = 0.10$	EOC	yes	-1.50
Pulse, $\beta = 0.10$	BOC	yes	-1.48
Pulse, $\beta = 0.15$	BOC	yes	-1.50

⁺ In all of these calculations the inlet temperature was held constant.

* Because of the unavailability of detailed PIUS core design data at the time of this study, assumptions were required in the modeling and loading of the Gd fuel and these specific values of α_B depend to a certain extent on these assumptions.

REFERENCES

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2. "ARMP-02 Documentation," EPRI NP-4574-CCM, Part II, Chapter-11, October 1988.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

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