POWER LEVEL EFFECT IN A PWR ROD EJECTION ACCIDENT

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ABSTRACT

The purpose of this study is to determine the effect of the initial power level during a rod ejection accident (REA) on the ejected rod worth and the resulting energy deposition in the fuel. The model used is for the hot zero power (HZP) conditions at the end of a typical fuel cycle for the Three Mile Island Unit 1 pressurized water reactor. PARCS, a transient, three-dimensional, two-group neutron nodal diffusion code, coupled with its own thermal-hydraulics model, is used to perform both steady-state and transient simulations. The worth of an ejected control rod is affected by both power level, and the positions of control banks. As the power level is increased, the worth of a single central control rod tends to drop due to thermal-hydraulic feedback and control bank removal, both of which flatten the radial neutron flux and power distributions. Although the peak fuel pellet enthalpy rise during an REA will be greater for a given ejected rod worth at elevated initial power levels, it is more likely the HZP condition will cause a greater net energy deposition because an ejected rod will have the highest worth at HZP. Thus, the HZP condition can be considered the most conservative in a safety evaluation.

1. INTRODUCTION

The purpose of this work was to determine the effect of the initial power level on a control rod ejection accident (REA) in a pressurized water reactor (PWR). An REA could cause a power surge, high energy deposition, and unacceptable fuel damage if the pellet (radial-average) enthalpy increase exceeds the damage limit. The limit has been under investigation [1] by the U.S. Nuclear Regulatory Commission and the research in this paper was to provide additional understanding of which reactor initial conditions or parameters affect the result. The initial power level has an effect on both the ejected rod worth and the Doppler feedback, two of the most important parameters that determine the energy deposition. [2] The effect on rod worth is due to the fact that the control rod pattern is changed at different power levels and the power distribution can also shift due to thermal-hydraulic feedback at elevated power levels.

2. METHODOLOGY

To evaluate the dependence of the REA on initial power level, calculations were carried out with a three-dimensional, coupled neutronic/thermal-hydraulic model of Three Mile Island Unit 1 (TMI-1) at end-of-cycle (EOC) [3]. Figure 1 shows the core layout with shutdown control banks 1-4 removed. The core calculations were done with PARCS [4], a two-group nodal diffusion neutron kinetics code with a simplified thermal-hydraulics model applicable to the REA.

In a PWR, the increase in power level from hot zero power (HZP) to hot full power (HFP) is affected by the withdrawal of the regulating control banks (Banks 5, 6, and 7 in Figure 1). Technical specifications for safe operation of a PWR place limits on the amount of insertion for each bank as power is increased. Data for rod position limits in a typical PWR [5] similar to TMI-1 are shown in Figure 2. At HZP (10^{-4}% of full power of 2772 MWt) three control banks remain in the core (Banks 5, 6 , and 7). These banks are removed sequentially to increase power. For example, to operate at 30% power under normal operating conditions, Bank 5 must be fully withdrawn, and Bank 6 must be 65% withdrawn.

Since calculations of the REA events with super prompt-critical rod worths are considered important in safety analysis, adjustment factors were applied to the absorption and fission cross sections of the central assembly containing the control rod assumed to be the ejected rod (Rod 7A) in order to get rod worths greater han $1. This expedient eliminated the need to search for abnormal control rod patterns, or burnup or xenon distributions, which might actually lead to high rod worths. As will be seen, the ejection of a single control rod may not result in a super-prompt critical event.

In order to study the explicit effect on the worth of Rod 7A of going to higher power levels, calculations were done separating the effect of Bank 5 withdrawal from the effect of being at higher power level; thus, the rod position limits specified in Figure 2 were temporarily ignored. For example, calculations for the worth of Rod 7A at 30% power were done with Bank 5 ranging from 0 to 100% withdrawn, and Banks 6 and 7 fully inserted.

Two methods were used for evaluating rod worth: 1) the change in the multiplication factor for two steady state calculations at given conditions with Rod 7A fully inserted or withdrawn, and 2) the peak reactivity during a 3-second transient simulation of an REA with Rod 7A ejected in the first 100 ms. The transient method is a good approximation at low power and rod worths since the changes in the fuel and moderator reactivity components are negligible during the initial portion of the REA.

To test the effect of the initial power on the peak pellet enthalpy rise during an REA, a series of 3-second transient simulations were performed at two power levels with control bank positions fixed (HZP: Bank 5 in, Bank 6 in), (30% power: Bank 5 out, Bank 6 65% out) in accordance with typical operational limits [5]. Adjustments factors applied to the absorption and fission cross sections in the central assembly were modified to give different ejected rod worths. Reactor trip is based on reaching 112% of nominal power.

3. DISCUSSION OF RESULTS

Results for rod worth vs the position of Bank 5 at different power levels are shown in Figure 3. The adjustment factors on the cross sections were set such that the worth of Rod 7A would be ~$1.2 ($\beta$=0.005211) at HZP with all regulating banks inserted. All remaining calculations were done with no other changes to the cross section data set. For the transient calculations, the rod worth was the peak control reactivity ($) during the REA. Initially, the fuel and moderator reactivity feedback components were small; therefore, the control reactivity was approximately the same as the total reactivity. For a given Bank 5 position, and especially with Bank 5 fully inserted, rod worth declines as power increases from HZP to 15% and then to 30%. Although the axial power distributions become flatter, as shown in Figure 4, it is the flattening of the radial power distributions at higher power levels due to thermal-hydraulic feedback as shown in Figures 5 and 6 for a 1/8th symmetric core section, that causes the reduction in the worth of Rod 7A.

This power level effect on the rod worth becomes less noticeable as Bank 5 is withdrawn, as shown in Figure 3. The rod worth declines, and the variation between different power levels is reduced. This occurs because the withdrawal of Bank 5 causes the radial neutron flux and power distributions to shift towards the outer fuel assemblies in the core, as shown in Figure 7 for the 30% power case. Thus, any perturbation caused by the removal of Rod 7A has less of an impact on the flux and power distributions and hence, the effective worth of control rod 7A is reduced significantly. The convergence of the rod worth to ~$0.5 for all power levels with Bank 5 fully withdrawn (Figure 3) demonstrates that this effect becomes even more important than the flattening effect due to thermal-hydraulic feedback at higher power levels.

Figure 3 also shows that the transient calculations of rod worth at elevated power levels, are generally higher than the steady state results, especially for a Bank 5 withdrawal less than 50%. This occurs due to the delayed effect of thermal-hydraulic feedback in the transient case which tends to reduce rod worth due to the radial power flattening effect. It should be noted that the axial power distributions remain relatively unchanged, whether Bank 5 is fully inserted or withdrawn, or whether the calculations are steady state or transient.

The peak fuel pellet enthalpy increase vs. rod worth is shown in Figure 8 for HZP and 30% power using typical control rod insertion limits suggested by Figure 2. If no adjustment factors are used on the cross sections, an REA event at both HZP and 30% will be less than prompt critical ($0.66 and $0.25 respectively). The peak fuel enthalpy rise usually occurs in the low-burnup fuel assembly adjacent to the central assembly containing ejected rod 7A, as indicated by the shading in Figure 1. Figure 8 shows that for a given rod worth the energy deposition will be greater at the higher initial power level with the difference being 5-15 cal/g in most cases considered. This is consistent with results obtained by others. [6]. However, one must recall for example from Figure 3 that a given perturbation in the core composition that would cause a $1.2 REA event at HZP would likely result in a $0.5 REA event at 30% power. While the $1.2 REA at HZP has a peak fuel pellet enthalpy rise of ~17 cal/g, the $0.5 REA at 30% power has a peak fuel pellet enthalpy of ~8 cal/g. Thus, the HZP condition should be considered the most limiting initial condition for the REA.

CONCLUSIONS

Steady-state calculations of the worth of the central control rod with power level demonstrate that thermal-hydraulic feedback at higher power levels lowers the worth of a control rod. Transient calculations of rod worth during an REA at elevated power levels are higher than those computed by a set of steady state calculations due to the delayed effect of thermal-hydraulic feedback. As the regulating bank 5 is withdrawn, the worth of the central control rod drops due to the shift in the neutron flux distribution to the outer fuel assemblies in the core. With bank 5 withdrawn, a perturbation in the flux distribution by control rod 7A in the central fuel assembly will be less significant. Although the peak pellet enthalpy rise during an REA for a given ejected rod worth will be higher at elevated power levels, an ejected rod will not have as high a worth at elevated power levels as at the hot zero power condition. The net result is that an REA at HZP will likely cause a higher net energy deposition than one at greater power levels. Thus, an REA analysis at HZP can be considered the most conservative in a safety evaluation.

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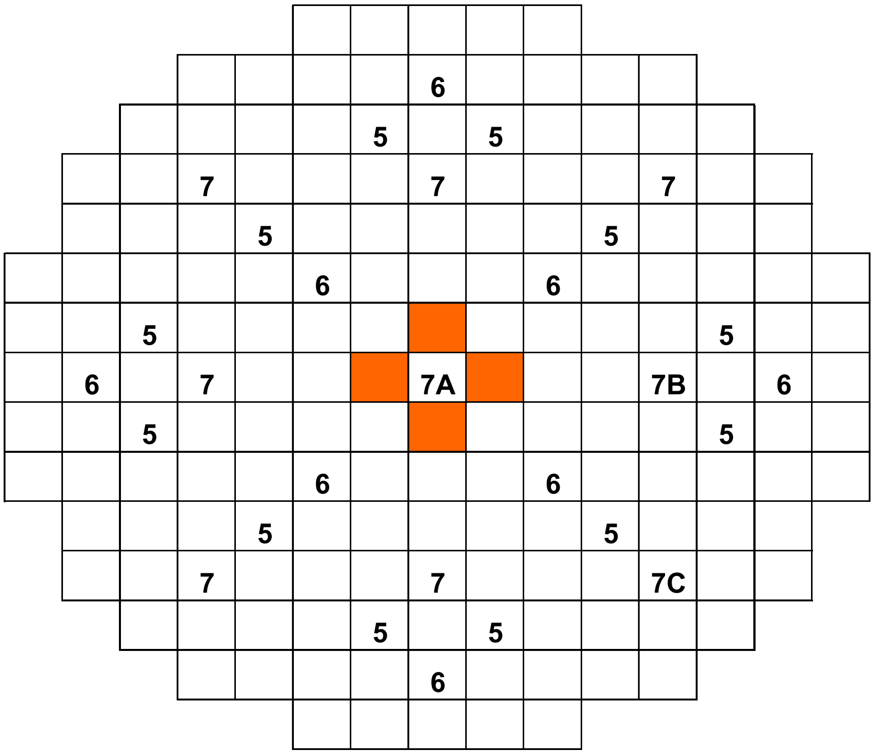

Figure 1. Control Rod Map In TMI-1 Core

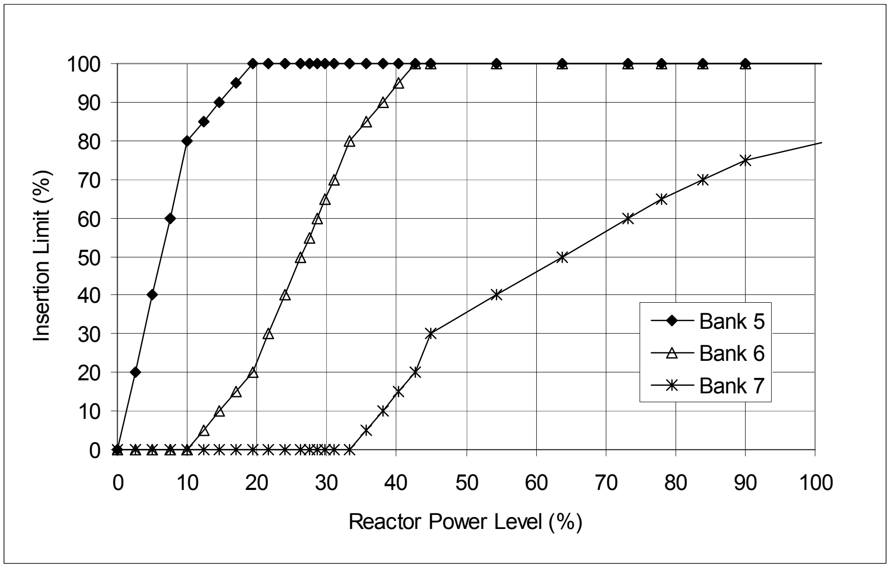

Figure 2. Normal Rod Position Limits for a Sample PWR

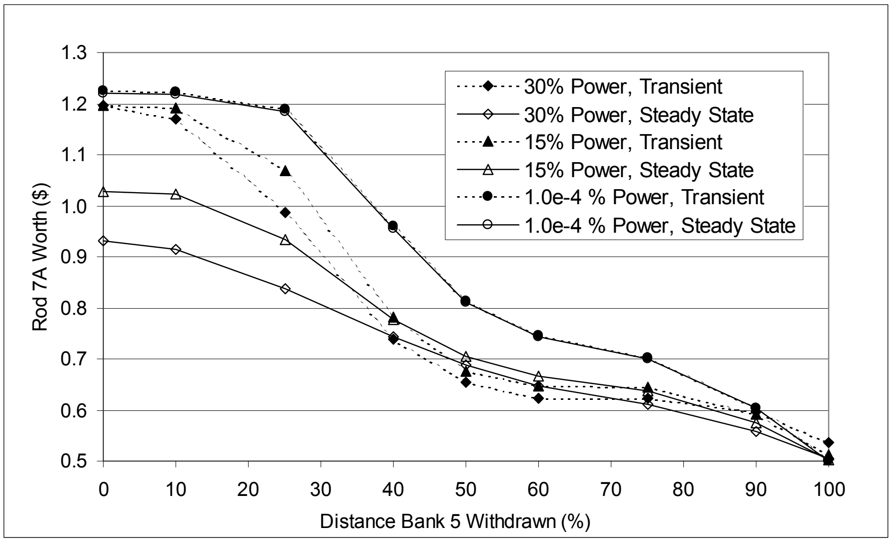

Figure 3. Ejected Rod Worth Dependence on Power Level and Bank Position

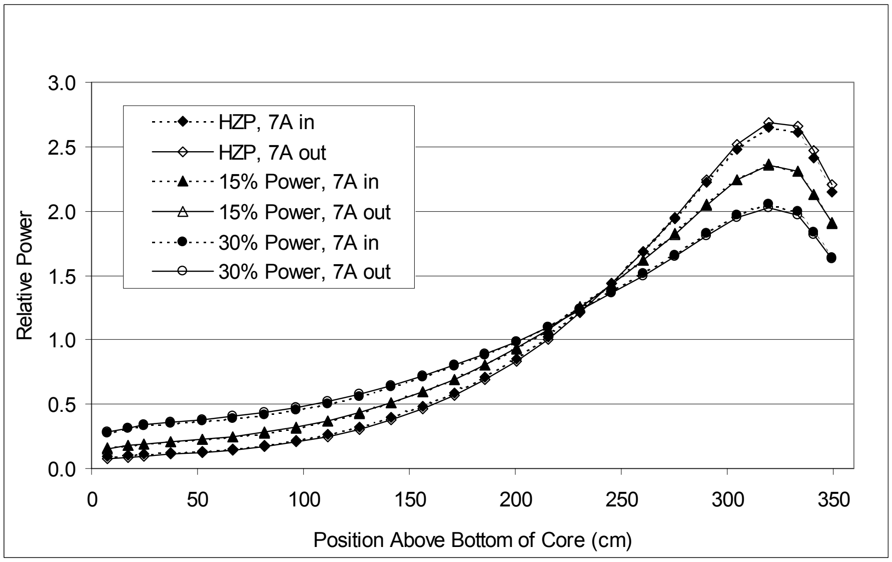

Figure 4. Axial Normalized Steady State Power Distributions at Various Power Levels with Bank 5 Inserted

0.228	1.130	1.241	1.431	0.655	0.903	0.432	0.324	7a in
2.101	***2.676***	***1.905***	***1.744***	***0.666***	***0.782***	***0.340***	***0.244***	***7a out***
	1.053	1.404	1.179	1.259	0.664	1.049	0.441	
	2.004	***2.031***	***1.368***	***1.227***	***0.559***	***0.809***	***0.331***	
		0.727	1.293	1.156	1.457	1.259	0.459	
		0.905	***1.340***	***1.034***	***1.168***	***0.956***	***0.342***	
			0.703	1.362	1.190	0.904		
			0.644	***1.121***	***0.919***	***0.676***		
				0.818	1.312	0.618		
				0.633	***0.978***	***0.454***		
					0.763			
					0.558			

Figure 5. Radial Normalized Steady State Power Distributions at HZP with Bank 5 Inserted

0.229	1.115	1.214	1.405	0.656	0.921	0.447	0.336	7a in
1.768	***2.274***	***1.672***	***1.608***	***0.657***	***0.828***	***0.378***	***0.277***	***7a out***
	1.034	1.379	1.160	1.253	0.673	1.072	0.457	
	1.724	***1.809***	***1.279***	***1.221***	***0.596***	***0.900***	***0.376***	
		0.723	1.282	1.144	1.455	1.272	0.473	
		0.843	***1.306***	***1.055***	***1.253***	***1.060***	***0.388***	
			0.704	1.356	1.187	0.915		
			0.660	***1.187***	***0.999***	***0.755***		
				0.820	1.317	0.629		
				0.692	***1.086***	***0.513***		
					0.773			
					0.630			

Figure 6. Radial Normalized Steady State Power Distributions at 30% Power with Bank 5 Inserted

0.161	0.803	0.930	1.198	0.693	1.228	0.549	0.368	7A in
1.160	***1.524***	***1.200***	***1.307***	***0.683***	***1.146***	***0.501***	***0.332***	***7A out***
	0.761	1.087	1.030	1.341	1.181	1.262	0.485	
	1.180	***1.337***	***1.092***	***1.305***	***1.098***	***1.150***	***0.438***	
		0.640	1.299	1.189	1.560	1.312	0.473	
		0.706	***1.303***	***1.132***	***1.438***	***1.191***	***0.426***	
			1.121	1.401	1.115	0.843		
			1.078	***1.307***	***1.019***	***0.762***		
				0.768	1.140	0.536		
				0.704	***1.031***	***0.482***		
					0.642			
					0.577			

Figure 7. Normalized Steady State Radial Power Distributions at 30% Power With Bank 5 Withdrawn

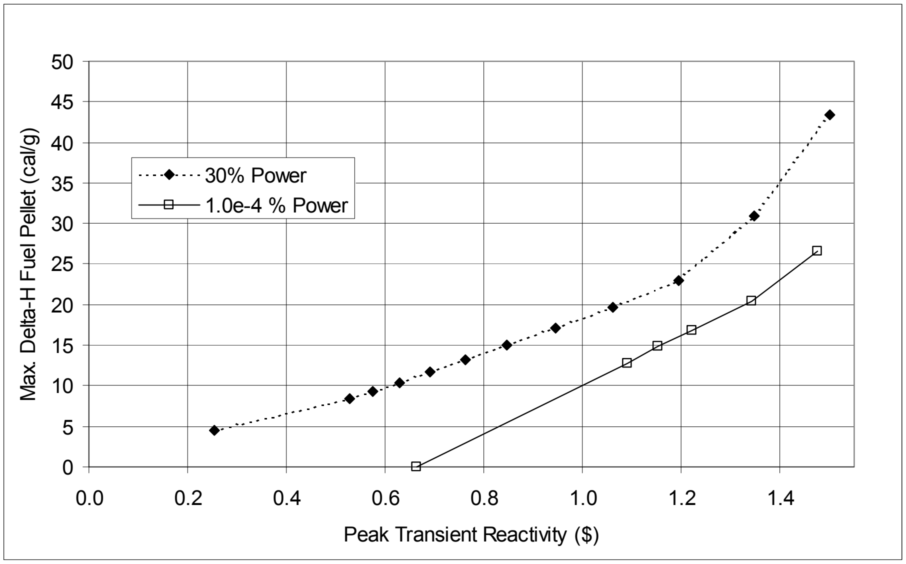

Figure 8. Peak Enthalpy Increase as a Function of Rod Worth