Impact of Spatial Kinetics in Severe Accident Analysis for a Large HWR

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ABSTRACT

The impact of spatial kinetics on the analysis of severe accidents initiated by the unprotected withdrawal of one or more control rods is investigated for a large heavy water reactor. Large inter- and intra-assembly power shifts are observed, and the importance of detailed geometrical modeling of fuel assemblies is demonstrated. Neglect of space-time effects is shown to lead to erroneous estimates of safety margins, and of accident consequences in the event safety margins are exceeded. The results and conclusions are typical of what would be expected for any large, loosely coupled core.

I. INTRODUCTION

The impact of spatial kinetics on the analysis of unprotected control rod withdrawal accidents which lead to fuel melting and relocation is investigated for a large heavy-water-moderated reactor. The analysis utilizes a computer code which directly couples the spatial kinetics computer code, DIF3D-K,1,2 to a single- and two-phase thermal-hydraulics model,3 and the MARTINS fuel relocation model.4 Two-group cross sections were evaluated using the MACOEF macroscopic cross section correlation methodology.5 The study considers reactivity insertion rates ranging from approximately 0.03 to 0.05 S/s, and neglects the fuel after it moves beyond the boundaries of the active core.

The heavy water reactor is characterized by radial and axial dimensions that are large compared with the square root of the neutron migration area. Localized perturbations in the core configuration can cause large changes in power in regions close to the disturbance and relatively small changes farther away. Since similar behavior can be expected in any large, loosely coupled core, the implications for accident analysis identified in the results which follow are believed to be generic for reactors with core dimensions large compared with the neutron migration length.

II. REACTOR DESCRIPTION

The reactor core has one-sixth symmetry, so long as the control rods in each one-sixth sector are positioned in the same way. A core map for a one-sixth sector is shown in Fig. 1. The core is somewhat more than 5 m in diameter and nearly 4 m in height. Each fuel assembly consists of five cylindrical tubes with a sleeve outside the outermost tube. All the tubes, the cylindrical sleeve, and the hexagonal cell share a common axis. The innermost and outermost tubes contain strong absorbing material and are used for isotope production. The three middle tubes contain enriched uranium. The space between the tubes and sleeve and between the assemblies is filled with heavy water, which serves as both coolant and moderator. Each control assembly contains one half-length and three full-length control rods. The blanket assemblies contain

Fig. 1. One-sixth core sector showing fuel (F), control (C), blanket (B), and vacant (V) assemblies.
absorbing material and heavy water, and function as radial shields. The vacant assemblies contain sleeves and heavy water. The unlabeled assemblies were included in the neutronic model of the core and were assumed to be identical to the vacant assemblies.

Some neutronic features of the reactor which may be helpful in interpreting results to be presented later are as follows: 1) A uniform, core-wide increase in the temperature inside the fuel assemblies causes a reactivity change of -8 pcm/K ($\beta = 650$ pcm). 2) Removal of heavy water from the coolant channel between the outer fuel tube and the outer absorber tube in all fuel assemblies causes a reactivity change of 1800 pcm. 3) Removal of heavy water from all coolant channels between the inner and outer absorber tubes in all fuel assemblies causes the reactivity to change by -2100 pcm.

The portions of the fuel assemblies which extend past the upper and lower core boundaries are assumed to be surrounded with strong absorbers which effectively shield these regions from the moderator neutron flux. Thus, when fuel melts and relocates beyond the core boundary, the reactivity effect is as if the fuel were completely removed from the reactor.

III. COMPUTER MODEL

For cases in which a rod is withdrawn simultaneously from the same control assembly in each one-sixth sector of the core, the DIF3D-K model treats each assembly in the sector explicitly, and uses periodic boundary conditions at the boundaries between sectors. In those cases in which only two or three rods are withdrawn from a localized region of the core, the DIF3D-K model treats each assembly in the reactor explicitly. Within each fuel assembly, the MACOEF implementation correlated the two-group macroscopic cross sections to the temperature, heavy water density, fuel density, and absorber (material from the inner and outer absorbing tubes) density in each of 13 regions; coolant, fuel, and absorber densities averaged over the 13 regions; and two variables indicating the presence or absence of control rods in the control assembly next to the fuel assembly. The 13 regions are coolant and metal for each of the six tubes in the fuel assembly and the moderator space outside the sleeve. In the control assemblies, the MACOEF implementation correlates the two-group cross sections to a separate variable for each of the four control rods.

The thermal-hydraulic and fuel-relocation models provide reactivity feedback for the DIF3D-K model. In the problems with one-sixth core symmetry, detailed thermal-hydraulic and fuel relocation (where necessary) calculations are performed for each of 12 distinct fuel assemblies, one assembly representing the group of six fuel assemblies surrounding each of the 11 control assemblies (note that only five fuel assemblies are adjacent to control assembly 17 in Fig. 1) and a 12-th assembly representing the remaining fuel assemblies that are not adjacent to any control assembly. For the cases without one-sixth symmetry, a pseudo half-core symmetry is assumed in which all fuel assemblies above a diagonal line extending across the full diameter of the core and passing through the bottom row of five control assemblies in Fig. 1 are assumed to be thermal-hydraulically identical to the corresponding assemblies below the line. In these cases, 38 distinct fuel assemblies, one for each group of six fuel assemblies surrounding a control assembly (except for assemblies corresponding to control assembly 17) on or above the pseudo-symmetry line, and three additional assemblies to represent the fuel assemblies in each one-sixth sector not adjacent to any control assembly, are modeled.

IV. COMPUTATIONAL RESULTS

Calculations are shown below for symmetric six-rod withdrawal transients and asymmetric two- and three-rod withdrawal transients. The coolant pumps continue to operate in all cases. In the symmetric transients, a full-length control rod was withdrawn simultaneously in each one-sixth sector from the control assemblies corresponding to assembly 21 in Fig. 1. In the asymmetric two-rod transients, a full-length rod was withdrawn simultaneously from control assemblies 20 and 21 in the one-sixth sector shown in Fig. 1, but the rod configuration in the remaining five one-sixth sectors was left unchanged. In the asymmetric three-rod transients, a full length rod was withdrawn simultaneously from control assemblies 21 and 16 in Fig. 1. In the one-sixth sector shown, the full-length rod from the assembly labeled 16 closest to assembly 21 was withdrawn, and in the one-sixth sector just below the sector shown, the rod was withdrawn from the control position corresponding to the assembly labeled 16 and farthest away from assembly 21. The configuration of the remaining four one-sixth sectors was unchanged.

In all calculations, the rods moved upward through the core with a speed of 0.46 m/s when the ends of the rods were in the regions just above or just below the core and a speed of 0.25 m/s when the ends of the rods were in the core. The rods were fully withdrawn in 17 s. With these speeds, the average reactivity insertion rate was about 0.054 $$/s in the case of the six-rod and three-rod transients, and 0.029 $$/s in the two-rod transient.

The calculation of reactivity feedback using the MARTINS fuel relocation model makes use of the option which assumes that gases in the fuel cause the disrupted
the upper core boundary by the pressure-drop in the voided coolant channels. The fuel is then pushed toward the upper core boundary by the pressure-drop in the coolant channel.

A. Six-Rod Transients

The reactor power and the net reactivity for the nominal six-rod withdrawal transient are shown as solid curves in Fig. 2. At about 8.7 s, when more than half of the total rod motion reactivity has been inserted, coolant voiding begins in fuel assemblies next to the control assemblies where the control rods are moving. The power has increased to about twice nominal by this time. The initial voiding is between the outer fuel and absorber tubes, and the resulting positive reactivity feedback accelerates the rate of power increase. For almost two seconds prior to voiding initiation, the reactivity feedback caused by the general heat-up of the core offsets the positive reactivity caused by the rod motion and the net reactivity levels off just below 0.3 $. Between 8.7 and 10.1 s, voiding initiates between the outer fuel and absorber tubes in several more fuel assemblies. Just after 10.1 s, voiding begins to take place between the middle and the outer fuel tubes, but the resulting negative reactivity feedback is not sufficient to offset the positive feedback caused by voiding between the outer fuel and absorber tubes. It is not until after the initiation of voiding between the inner and middle fuel tubes that the voiding reactivity feedback becomes negative. The outer fuel tubes disrupt and begin to relocate in the fuel assemblies adjacent to the moving rods just after 12.6 s. The initial effect of the fuel disruption is to cause the reactivity feedback rate to increase, but within about 0.2 s, fuel begins to move beyond the upper core boundary and the feedback rate becomes negative. Except for minor reversals, the feedback rate remains negative until just before 13.3 s when the outer fuel tubes disrupt in several more fuel assemblies. The feedback rate becomes positive until fuel from these assemblies begins to relocate beyond the upper core boundary. Enough fuel is removed to make the reactor subcritical, and the transient is terminated. More fuel tube disruptions can be expected, but these additional events are unlikely to cause the reactor to reach critical again.

If fuel motion reactivity feedback were suppressed, the net reactivity would reach a peak value just under 0.5 $ and then begin to decrease on the strength of negative voiding and temperature reactivity feedbacks. The reactor power would reach a peak of about 4.5 times nominal just after 13 s.

Fig. 2. Six-rod transient with initial voiding outside (solid) and inside (dashed) the outer fuel tube.

Fig. 3. Axial power normalized to a peak of unity at the initial time.

There are two aspects to the space-time effects that occur during the transient. First, the power in the lead fuel assemblies is about 30% higher than in an average assembly at the time when voiding initiates. The difference diminishes to about 20% when fuel disruption begins and to about 10% when the peak reactor power is reached. Second, substantial shifts in the axial power shape within a fuel assembly occur, particularly near the moving control rods. Figure 3 illustrates the shifting for the lower right (Fig. 1) fuel assembly adjacent to the...
Fig. 4. Assemblies where voiding (shaded) and fuel relocation (darkly shaded) are in progress for initial voiding outside (top) and inside (bottom) the outer fuel tube.

moving control rod. The shape of the axial power at time zero is determined by the fact that full-length rods are fully inserted and the half-length rod is placed symmetrically about the core midplane. The power is somewhat higher near the bottom of the core because temperatures are lower in this region. As the control rod moves upward through the core, the power rises sharply near the bottom of the assembly, and the rise follows the rod upward through the core. Additional structure develops in the power shape when fuel begins to move toward the top of the core.

Much of the power increase in the foregoing transient is caused by the fact that initial voiding takes place in a part of the fuel assembly where the voiding reactivity feedback is positive. A second case considers the same rod withdrawal sequence but with the flow between the outer fuel and absorber tubes increased by 5%, an amount sufficient to cause initial voiding to occur between the middle and outer fuel tubes where the voiding reactivity feedback is negative. Flow between the middle and outer fuel tubes was reduced enough to maintain constant assembly flow. The dashed curves in Fig. 2 show the power and net reactivity for this case. Voiding begins only slightly later than in the original transient, but does not begin between the outer fuel and absorber tubes until almost 12.4 s. The negative voiding feedback causes the net reactivity to decrease fast enough to prevent the power from rising very much above the level it had reached when voiding began. Fuel disruption in the outer fuel tubes occurs just before 15.5 s in the fuel assemblies adjacent to the moving rods. As in the first case, the fuel motion initially contributes positive feedback, but then as fuel is removed from the core, the reactor becomes subcritical. Figure 4 shows the core states at the end of the two transients.

B. Two-Rod Transient

The reactor power and the net reactivity for this transient are shown as the solid curves in Fig. 5. Coolant voiding between the outer fuel and absorber tubes initiates
just before 10.2 s when the reactor power has reached just over 1.5 times nominal. Voiding reactivity feedback remains positive throughout the transient. Within a couple of seconds of void initiation, the net reactivity, which had leveled off, begins to increase and drives the reactor power to nearly twice nominal. The outer fuel tubes disrupt in the six fuel assemblies surrounding the outer moving control rod at about 14.7 s. Fuel disrupts in the outer fuel tubes of the six assemblies surrounding the inner moving control rod between 15.1 and 15.2 s. The reactivity feedback rate remains positive and increases just after fuel motion begins, but as the fuel begins to relocate past the upper core boundary, reactivity feedback becomes negative. The transient is terminated when the net reactivity reaches zero and is still going down. The lightly shaded areas in Fig. 6 show assemblies where coolant voiding is in progress and the darkly shaded areas show assemblies where voiding and fuel relocation have begun.

Axial power shifting in this transient is similar to that observed in the six-rod transient. It is very pronounced in the fuel assemblies adjacent to the moving control rods, and can be observed even in assembly positions diametrically opposite the moving rods. The shifting is much less pronounced in these latter assemblies.

Severe inter-assembly power shifting occurs. This is illustrated by the sequence of three-dimensional plots shown in Fig. 7. These plots show that the percent change in power increases everywhere in the reactor, but that the increase is very modest in assembly positions far removed from the moving control rods and is very dramatic in assemblies near the moving rods. For example, at 12 s into the transient, the power change in a

Fig. 6. Voiding (shaded) and fuel relocation (darkly shaded) patterns for two-rod transient.

Fig. 7. Inter-assembly power shifting in the two-rod transient.
fuel assembly adjacent to the outer moving control rod is 2.8 times the change in an average fuel assembly. By contrast, in a fuel assembly the same distance from the center, but on the opposite side of the core, the change is a factor of 1.7 smaller than the change in an average assembly. By the time when peak power is achieved, the change in the assembly next to the moving rod has dropped to 2.6 times the change in an average assembly, and the change in the assembly on the opposite side of the core is a factor of 1.8 smaller than in an average assembly.

To further illustrate the importance of accounting for space-time effects, the two-rod transient was recomputed using the point-kinetics option of DIF3D-K. Because the point-kinetics calculation fails to account for the inter-assembly power shifting, the normal feedback calculation underestimates the reactivity effect of the moving control rods. To compensate, the reactivity effect of the moving rods was simulated by an input table providing a linear reactivity insertion with a maximum insertion after 17 s equal to the calculated worth of the fully withdrawn rods. The remaining reactivity feedbacks were calculated by the DIF3D-K coupling with the thermal-hydraulic and fuel relocation models. The dashed curves in Fig. 5 show the power and net reactivity from the point-kinetics calculation. The point-kinetics calculation indicates that neither voiding nor fuel disruption and relocation occur during the transient, in complete disagreement with the space-time result. Between 20 and 25 s into the transient, the peak coolant temperature increased to within about 10 K of the temperature required to initiate voiding. The difference between the peak coolant temperature and the temperature required to initiate voiding began a gradual increase after 25 s.

C. Three-Rod Transient

The solid curves in Fig. 8 show the power and net reactivity for this transient. The overall progression of this calculation is similar to that for the two-rod transient. The power and reactivity increase for about 7 s. Then the reactivity feedback rate from the core heat-up catches up with and over compensates for the feedback caused by the rod motion, and the power and reactivity begin to decrease until reactivity feedback due to coolant voiding, which initiates just before 7 s, begins to drive the power and reactivity upward again. Fuel disruption begins in outer fuel tubes of the six assemblies surrounding the middle of the three moving rods at about 10 s, and following a brief period when the fuel motion reactivity feedback is positive, both the power and the net reactivity begin to decline. The decline in reactivity is interrupted at about 10.6 s when fuel disruption initiates in outer fuel tubes of the 12 assemblies surrounding the two outer moving rods, and again at about 11.5 s when fuel disruption begins in the outer fuel tubes of 12 assemblies surrounding two control assemblies in the next outer row of control assemblies. The reactor was more than 0.15 $ subcritical and the reactivity was going down when the calculation terminated.

Significant inter- and intra-assembly power shifting occurs in this transient just as in the two-rod transient. Figure 9 compares the average fuel assembly power with the average power in the six assemblies next to the middle of the three moving control rods and the average power in the six assemblies surrounding the control assembly diametrically opposite the assembly containing the moving rod. At about 7.5 s, the change in power in the assemblies next to the moving rod is about 2.7 times the change in the average assembly and the change in the average assembly is about 1.8 times the change in the assemblies in the diametrically opposite location. By the time peak reactor power is reached, these ratios have changed to about 2.6 and 2 respectively. Shifts in the axial power shape within individual assemblies are similar to those observed for the two-rod case.
much larger, failure to account for such effects lead to underestimation of the power level in assemblies near the moving rods by as much as 30%.

The thermal-hydraulic and fuel relocation models used in the calculations are characterized by the ability to model individual fuel assemblies in considerable detail. Thus, coolant temperatures in each flow path and temperature distributions in each fuel or absorber tube are calculated at several axial locations within each of several fuel assemblies. This permitted full advantage to be taken of the macroscopic group constant correlations which include density and temperature variables for each of 13 radial regions within the fuel assembly. The utility of this modeling detail is illustrated by the six-rod transient where the reactivity consequences of adjusting the flows

The three-rod transient was recomputed using the point-kinetics option of DIF3D-K. The rod motion was simulated using an input table giving the reactivity insertion as a linear function of time. Other feedbacks were computed by using the DIF3D-K coupling to the thermal-hydraulic and fuel relocation models. The dashed curves in Fig. 8 show the point-kinetics prediction of the power and net reactivity. Between 11.8 and 12.5 s, voiding initiates in all fuel assemblies. The outer fuel tubes disrupt and fuel relocation begins in 330 fuel assemblies between 14.9 and 15.7 s. Figure 10 shows the voiding and disruption patterns at the end of the spatial-kinetics and point-kinetics calculations. The point-kinetics calculation greatly exaggerates the accidents consequences in this case.

V. CONCLUSIONS

The heavy water reactor considered in this study is characterized by radial and axial dimensions that are large compared with the square root of the neutron migration area. This leads to the possibility of localized perturbations in the core configuration causing large changes in power in regions close to the disturbed region and relatively small changes in regions substantially removed from the disturbance. Such changes can be expected in any large, loosely coupled core. Thus, the implications for safety analysis identified in this study are generic to reactors with dimensions large compared to the square root of the neutron migration area. The calculations for the six-, two-, and three-rod withdrawal transients show the importance of accounting for space-time effects in accounting for the consequences of such localized perturbations. Space-time effects are particularly dramatic in the two- and three-rod transients, but even in the six-rod problem, where the degree of symmetry is

![Fig. 9. Comparison of average assembly power (solid) with power in assembly adjacent (dashed) and diametrically opposite (dashed) the moving control rods.](image)

![Fig. 10. Voiding (shaded) and fuel relocation (darkly shaded) patterns for spatial kinetics (top) and point kinetics (bottom) calculations of the three-rod transient.](image)
on the inside and outside of the outer fuel tube was examined.

The point-kinetics approximation is shown to be an unreliable predictor of accident consequences. In the two-rod transient, for the same total reactivity insertion, the point-kinetics approximation erred on the side of optimism by predicting there would be no coolant voiding and no fuel disruption whereas the spatial-kinetics calculation predicted a significant amount of coolant voiding and some fuel disruption and relocation. In the three-rod transient, the point-kinetics approximation erred on the side of pessimism by predicting coolant voiding in every fuel assembly, and extensive fuel disruption and relocation while the spatial-kinetics calculation predicted coolant voiding in a limited portion of the core and a relatively small amount of fuel disruption and relocation.

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REFERENCES


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