A PARAMETRIC ANALYSIS OF DECAY RATIO
CALCULATIONS IN A BOILING WATER REACTOR MODEL*

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ABSTRACT

The results of an investigation of the effects of several parameters on the reactivity instability of a Boiling Water Reactor (BWR) calculational model are summarized. Calculations were performed for a typical BWR operated at low flow conditions, where reactivity instabilities are more likely to occur. The parameters investigated include the axial power shape (characterized by two separate parameters), the core pressure, and operating flow. All calculations were performed using the LAPUR code which was developed at the Oak Ridge National Laboratory for the dynamic modeling of large BWR's.

BACKGROUND

It is generally recognized that BWRs are susceptible to three types of instabilities:

(a) Control system instability. These are due to out-of-tune controllers. This instability corresponds to a malfunction of the reactor hardware and is easily corrected by adjusting the controller gains.

(b) Channel thermohydraulic instability. A heated channel in a two-phase-flow regime can oscillate on its own, without the need of neutronic feedback. These oscillations are usually attributed to the so called "density wave" effect that can be summarized as follows: Given an inlet flow perturbation, a "wave" of voids travels upwards through the channel producing a pressure drop that is delayed with respect to the original perturbation. This delay causes a positive feedback (180 degree phase) in the inlet flow at a particular frequency. If the two-phase friction losses are large enough, a self sustained oscillation can be established due to this type of instability.

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Coupled neutronic-thermohydraulic instability. This type of instability is also called reactivity instability because it involves the effect on the neutronics of a density wave through the reactivity effect of the voids.

The difference between the channel (type b) and reactivity (type c) instabilities is that in the reactivity instability there is a power feedback in addition to the flow feedback. The flow feedback for the channel instability, though, is stronger due to the different pressure boundary conditions. In general, channel instabilities are not likely in BWRs because reactivity instabilities dominate the reactor response due to the additional neutronic feedback.

The type of instability most relevant for safe BWR operation is the reactivity instability. Control system instabilities are easily corrected once detected by adjusting the controller gains, and channel instabilities are only of concern under very special situations, such as partial blockage of a single channel. Two types of reactivity instabilities have been observed in commercial BWRs:

(a) Core-wide reactivity instabilities. In this type of instability, the whole core behaves as one, and the oscillations are in-phase across the core.

(b) Out-of-phase reactivity instabilities. In this type of instability, half of core behaves out of phase from the other half. That is, when the power rises on one half of the core, it is reduced on the other one by approximately the same amount, so that the average power remains essentially constant.

There are several computer codes used to model the dynamic behavior of BWRs and to estimate the decay ratio, that is a measure of the reactor stability. Decay ratios greater than 1.0 indicate instability. The smaller the decay ratio, the more stable the reactor is. One of these codes is LAPUR that was developed at the Oak Ridge National Laboratory in 1979 and has been used by the Nuclear Regulatory Commission for auditing stability calculations submitted by vendors and utilities. The more recent version, LAPUR-5, has been modified to model, in an approximate manner, out-of-phase instabilities.

AXIAL POWER SHAPE PARAMETER MODEL

For the present study, the LAPUR code has been modified to incorporate a two-parameter equation to simulate arbitrary core power shapes. The power shape equation is

\[ \Psi(z) = \sin(\pi (z/H)^{N_1} )^{N_2} \]  

The parameter N1 controls the core height, H, at which the power peak occurs and N2 controls the slope of the power shape curve and the peak-to-average power ratio.

Figures 1, 2, and 3 show the results of this equation for various combinations of values of the parameters N1 and N2. Figure 1 shows results for N2 = 1 as N1 is varied from 1 to 4. When N1 is equal to 1 the power shape is a cosine distribution approximating a beginning-of-cycle (BOC) condition. As N1 is increased the power maximum is skewed toward the bottom of the core, thereby simulating an end-of-cycle (EOC) condition. Conversely, Fig. 2
Fig. 1. Axial power shape as a function of peak location parameter $N_1$.

Fig. 2. Axial power shape as a function of peaking factor parameter $N_2$ for an axially symmetric shape ($N_1 = 1$).

Fig. 3. Axial power shape as a function of peaking factor parameter $N_2$ for a bottom peaked shape ($N_1 = 3$).
shows the results for $N_1 = 1$ and $N_2$ varied from 1 to 0.2. The effect of the decreasing values of $N_2$ is to flatten the power shape. Figure 3 is similar to Fig. 2 except that $N_1 = 3$ as evidenced by the skewed power shape. Thus, it can be seen that by varying these two parameters any reasonable desired power shape can be simulated.

CALCULATIONAL RESULTS

For the present calculations, a typical reactor model was set up for simulation with the LAPUR code. This model consisted of a single thermohydraulic channel with 1.9 MW of power, 4.25 Kg/s of flow, and 18°C of inlet subcooling, with the geometric characteristics of the channel corresponding to a typical 8 x 8 fuel element. For this study, the axial power shape was generated as a function of two parameters, $N_1$ and $N_2$, according to Eq (1). The reactor operating pressure was also varied between 850 and 1000 psi to study its influence on reactor stability.

Sensitivity to Axial Power Shape Peak Location

Using Eq. (1) to generate axial power shapes, the sensitivity of the reactor stability to axial peak location can be studied by varying the value of the $N_1$ parameter. Figure 4 shows the core-wide decay ratio of a typical reactor vs. the power peak location parameter, $N_1$, at different pressures. It is observed that all the curves have a maximum decay ratio for some value of $N_1$ greater than 1. Thus, these calculations show that as the power is skewed toward the bottom of the core, the reactor reaches a condition of least stability (maximum decay ratio) and then becomes more stable as the power is further shifted toward the bottom.

This finding is contrary to the common belief that bottom-peaked power shapes always result in more unstable operating conditions. Indeed, these results suggest that EOC conditions are not the most unstable point in the cycle lifetime as previously thought, but that the most unstable point occurs sometime in the middle of the cycle, when the axial power shape is optimal. Also, Fig. 4 shows that as the pressure decreases, the peaks of the related curves become progressively greater and occur when the power shape more closely resembles a cosine distribution ($N_1 = 1$). Thus, the point in the cycle at which the most unstable operating conditions occur is also strongly correlated to the operating pressure.

The above result can be explained by the difference in adjoint fluxes between axially symmetric and extremely bottom peaked axial power shapes. Bottom peaked power shapes result in higher average void fractions, which in turn result in higher two-phase pressure drops, producing a destabilizing effect. However, bottom peaked shapes also result in low adjoint flux values in the upper part of the core where most of the void neutronic feedback occurs, and thus it reduces the effective void feedback. In essence, there are two competing effects when the power shape is shifted towards the bottom of the core: on the one hand the thermohydraulics become more unstable, but on the other hand the neutronic feedback has smaller gain. The result is a trade-off between the two effects and an optimal value for peak location exists.
Fig. 4. LAPUR calculated decay ratios as a function of the axial peak location parameter, N1, and operating pressure. Note that the "optimal" peak location depends on operating pressure. Channel power 1.9 MW, flow = 4.25 Kg/s
Sensitivity to Axial Power Shape Peaking Factor

The parameter N2 of Eq. (1) controls the axial peaking factor without altering the peak location. That is, as N2 decreases the power is concentrated around the peak location resulting in higher peak-to-average power ratios. Figures 5 and 6 show the sensitivity of the core-wide decay ratio as N2 is varied along the abscissa keeping N1 (i.e., the peak location) constant. In Fig. 5, a cosine shaped power distribution (N1 = 1) is considered and in Fig. 6 the power shape is heavily skewed toward the bottom of the core (N1 = 3). Both figures show that the decay ratio is inversely related to the parameter N2; thus, for constant axial location of the power shape peak (constant N1), the reactor becomes less stable as the axial peaking factor is reduced. That is, for a given peak location, lower peaking factors result in more unstable conditions. This effect can also be explained in terms of the reduction of the adjoint weighing of the void feedback in the upper part of the core.

Results from the simultaneous variations of the shape factor parameters N1 and N2 are given in Fig. 7. This figure indicates that at a given core pressure, if the power shape is made flatter, the reactor becomes less stable but the overall shape of the curve relating the decay ratio to the power peak location parameter N1 is unchanged. Thus, for a given operating pressure, the occurrence of the most unstable operating point in the cycle depends on the location of the power peak and is nearly independent of the "flatness" of the power distribution curve.

Sensitivity to Operating Pressure

It can be observed in Figs 5 and 6 that the effect of the pressure is dependent on whether the power shape is cosine shaped (N1 = 1) or bottom peaked (N1 = 3). For a cosine shaped distribution, a decrease in pressure decreases the reactor stability, whereas the opposite is true for a bottom peaked distribution. This effect is also shown in Fig 4 where it is observed that the pressure has opposite effects on the decay ratio at the extreme left and right sides of the plots (i.e, for cosine or extreme bottom peaked axial shapes).

The effect of reducing operating pressure on stability was always thought to be negative. However, the above results show that this effect depends largely on the axial power shape characteristics. For a symmetric axial power shape, the effect of reducing pressure is destabilizing; whereas, for a bottom peaked axial power shape, reducing the operating pressure increases the stability. For all the pressures studied, there is an optimal (i.e., most unstable) axial peak location for which the decay ratio is maximum. The optimal peak location, though, depends on the actual operating pressure. This effect results in the observed change in sign for the sensitivity of decay ratio to pressure, as seen in Fig. 4.

Sensitivity to Core Flow

Figure 8 shows results of decay ratio vs. the power peak location parameter N1 for 25% and 40% core flow (25% is nominal value used in previous calculations) at 1000 psi. As anticipated, the higher flow results in a more stable configuration. The decay ratio versus N1-dependent curve is also somewhat flatter for the higher flow rate but exhibits a
Fig. 5. LAPUR calculated decay ratios as a function of the axial peaking factor parameter, \( N_2 \), and operating pressure for an axially symmetric power shape (\( N_1 = 1 \)). Channel power 1.9 MW, flow = 4.25 Kg/s

Fig. 6. LAPUR calculated decay ratios as a function of the axial peaking factor parameter, \( N_2 \), and operating pressure for a bottom peaked power shape (\( N_1 = 3 \)). Channel power 1.9 MW, flow = 4.25 Kg/s
Fig. 7. LAPUR calculated decay ratios as function of axial power shape.

Fig. 8. LAPUR calculated decay ratios as a function of the axial peak location parameter, N1, and operating flow. Note that the "optimal" peak location does not depend on flow. Channel power = 1.9 MW.
maximum value at approximately the same value of N1. Thus, the optimal (i.e., most unstable) axial peak location does not depend on flow rate.

CONCLUSIONS

Two main conclusions relating to low flow conditions in a typical BWR can be derived from the calculational results presented in this paper: First, there is an optimal axial power shape that results in a maximum decay ratio value (i.e., lower stability margin). The least stable power shape configuration is intermediate between a cosine distribution and a distribution heavily skewed toward the bottom of the core. Therefore, the least stable operating condition does not occur at EOC as commonly thought, but at some time between BOC and EOC.

A second conclusion is that the effect of reducing operating pressure is highly dependent on the axial power shape characteristics. For a symmetric axial power shape, a reduction in operating pressure increases the decay ratio and is therefore, destabilizing, as previously expected; however, for extremely bottom peaked shapes, a similar reduction in pressure decreases the decay ratio and is, therefore, stabilizing.

REFERENCES


