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José March-Leuba

E. D. Blakeman

Oak Ridge National Laboratory
Instrumentation and Controls Division
Oak Ridge, Tennessee 37831-6010

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A STUDY OF OUT-OF-PHASE POWER INSTABILITIES IN BOILING WATER REACTORS*

José March-Leuba and E. D. Blakeman

Oak Ridge National Laboratory
Instrumentation and Controls Division
Oak Ridge, Tennessee 37831-6010, U.S.A.

ABSTRACT

This paper presents a study of the stability of subcritical neutronic modes in boiling water reactors that can result in out-of-phase power oscillations. A mechanism has been identified for this type of oscillation, and the LAPUR code has been modified to account for it. Numerical results show that there is a region in the power-flow operating map where an out-of-phase instability mode is likely even if the core-wide mode is stable.

INTRODUCTION

This paper presents a study of the stability of subcritical neutronic modes in boiling water reactors (BWRs) that can result in out-of-phase power oscillations of the type observed in a BWR during special dynamic tests.[1] In those tests, the reactor power established a self-sustained oscillation (i.e., a limit cycle) of large amplitude in such a manner that half the core increased power while the other half underwent a decrease in power. The resulting average power, though, remained essentially constant during these oscillations.

The study of out-of-phase BWR instabilities is of relevance because of their safety implications. In particular, the automatic safety systems in BWRs rely on average power measurements to scram the reactor; therefore, large-amplitude out-of-phase power oscillations could be established in the core without resulting in an automatic scram. Indeed, in the tests described in ref. 1, local oscillations of amplitude as large as 70% were measured while the average reactor power oscillated only by approximately 12%.

Using a simple phenomenological model, it was shown in ref. 2 that subcritical modes can become unstable under certain conditions even when

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the fundamental mode is stable. In those cases, the unstable subcritical mode dominates the reactor response, thus providing an explanation for the observed out-of-phase oscillations. In this paper, we document the results of more accurate numerical calculations of this phenomenon. To this end, we have modified the frequency-domain BWR stability code LAPUR (ref. 3) to model subcritical neutronic dynamics and their associated thermohydraulic reactivity feedback. The results of the present simulation have confirmed the conclusions presented in ref. 2, in the sense that subcritical mode instabilities are possible in BWRs.

BACKGROUND

It is well known that, under normal steady state reactor operation, all modes but the fundamental have negative eigenvalues so they decay with time and do not significantly affect the reactor dynamics; however, this situation might not be the case under special conditions. It has been established experimentally[4] that momentum dynamics and the recirculation-loop flow path play an important role in defining reactor stability because, for the fundamental mode of oscillation, any change in power is accompanied by a change in inlet flow. The amount of this change is determined by momentum dynamics in the core and recirculation-loop characteristics. However, an out-of-phase mode of oscillation in parallel channels, such as the one observed in ref. 1, does not require changes in total inlet flow because the two oscillating core regions adjust their flows to maintain equal pressure drops across the core. That is, if the flow increases in channel 1, the flow of channel 2 decreases by the same amount (at least within the linear operating region) and the total flow remains unchanged. This mechanism allows for large flow oscillations within each channel, and it has the effect of increasing the gain of the thermohydraulic component in the BWR dynamics feedback, thus decreasing the reactor stability.

The mechanism described above is represented schematically in Figs. 1 and 2. In these figures, the arrows represent the flow intensity through the representative channels during an oscillation of period T. The case represented in Fig. 1 corresponds to the fundamental (core-wide) mode of oscillation for which the whole core behaves as a unit. In the out-of-phase mode of oscillation, which is represented in Fig. 2, a constant inlet flow is maintained by readjusting individual channel flows.

In essence, there are two competing effects in the out-of-phase mode: on one hand, the neutronics component is subcritical and tends to damp out oscillations; on the other hand, the thermohydraulic component in the out-of-phase mode has more gain than in the fundamental mode and tends to destabilize it. The relative importance of the two above effects depends on the degree of subcriticality of the out-of-phase mode. Thus, it seems plausible that there is a threshold subcritical reactivity at which the out-of-phase mode can become unstable, even if the fundamental mode is stable.

THE NEUTRONIC MODEL

The general solution of the time-dependent one-group diffusion theory for homogeneous systems can be shown to be a summation over all modes of the product of the time-dependent part of each mode times its spatial shape. That is,

$$\Phi(t, r, z, \theta) = \sum_{m=0}^{\infty} n_m(t)\ \phi_m(r, z, \theta) \quad . \tag{1}$$

Assuming a cylindrical reactor of radius R and height H, it can be shown that the space-dependent part of the fundamental and first subcritical modes can be described respectively as

$$\phi_0(r, z, \theta) = J_1(2.40\ r/R)\ \sin(\pi\ z/H) \quad , \tag{2}$$

and

$$\phi_1(r, z, \theta) = J_1(3.83\ r/R)\ \sin(\pi\ z/H)\ \sin(\theta) \quad . \tag{3}$$

Graphically, Fig. 3 shows a comparison between these two modes.

The time-dependent part of the solution satisfies the following modal point kinetics equations:

$$\frac{dn_m}{dt} = \frac{\alpha_m + \rho_m - \beta}{\Lambda_m} + \lambda\ c_m \quad , \tag{4}$$

$$\frac{dc_m}{dt} = \beta\ n_m - \lambda\ c_m \quad , \tag{5}$$

where only one group of delayed neutrons precursors (c_m), with constant λ_m and fraction β, is considered for the mth mode. Each mode has its own generation time, Λ_m, and subcritical reactivity, ρ_m, given by the expression

$$\rho_m = D\ \Delta B^2/\nu\Sigma_f \quad , \tag{6}$$

where D is the diffusion coefficient, $\nu\Sigma_f$ is the fission cross section, and ΔB^2 is the difference between the geometric bucklings of the fundamental ($m = 0$) and the mth mode (note that, since the reactor is critical, $\rho_0 = 0$). The parameter α_m represents the feedback reactivity for mode m, which is determined by the thermohydraulics.

For typical BWR parameters ($\Delta B^2 = 3.5E\text{-}4 - 1.8E\text{-}4 = 1.7E\text{-}4\ \text{cm}^{-2}$, $D = 1$ cm, and $\nu\Sigma_f = 0.02\ \text{cm}^{-1}$), the first mode subcritical reactivity is approximately $\rho_1 = -1.2$ dollars. This reactivity is inversely proportional to the fission cross section [see Eq. (6)], and thus it increases with burnup. As a rule of thumb, a reactor with more burnable poison and more inserted control rods will have a lower subcritical reactivity than a reactor at the end of a cycle with all control rods out. For instance, at an exposure of 10*E*4 MWD/*T*, the above reactor will have a first-mode subcritical reactivity of −1.6 dollars.

Under normal conditions, only the fundamental mode dominates the reactor response, but under certain conditions the first subcritical mode can become unstable and oscillate on its own. In this case we will observe a flux distribution tilting from one side to other of the core, as represented graphically in Fig. 4. This figure has been obtained by adding both components of Fig. 3 at different times during the oscillation.

THE THERMOHYDRAULIC MODEL

A thermohydraulic model of a BWR must include fuel, core coolant, and recirculation-loop dynamics. The dynamic processes involved can be summarized as follows: An energy balance in the fuel region yields the heat transferred to the core coolant. The energy and continuity balance equations are solved in the coolant region to obtain the core enthalpy (i.e., void fraction) distribution. Neglecting second-order effects, the momentum equation can integrate this distribution to yield the core pressure drop. The recirculation-loop momentum equation yields the core inlet flow from the pressure drop across the jet pumps that must equal the pressure drop across the core. The thermohydraulic loop is closed when the inlet flow is coupled to the coolant energy and continuity equations. Finally, the thermohydraulic and neutronic models are coupled via the fuel temperature and void reactivity feedbacks, which yields the α_m term in Eq. (4).

There are two general approaches to dynamic modeling when partial differential equations are involved: one is nodal and the other is modal. In a nodal approach, the space dependence is integrated over finite nodes, resulting in a set of ordinary differential equations (ODEs) in time for the amplitudes of node average values. In a modal approach, the space dependence is integrated over the whole reactor volume, but it is weighted by modal shape factors. The modal approach results in a set of ODEs for the modal amplitudes. Given the nature of the problem addressed in this paper, a mixed nodal-modal approach has been used. For the axial dependence, the nodal approach described in ref. 3 and implemented in the LAPUR code has been used to model in detail the density wave propagation. For the radial dependence, though, we used a modal approach to account for the observed core-wide (fundamental mode) or out-of-phase (subcritical mode) instabilities.

It can be shown that the core region equations for the out-of-phase mode are the same as for the core-wide (fundamental) mode. The only difference between the two modes arises on the core boundary conditions (i.e., inlet flow and pressure drop). For the core-wide mode, the boundary conditions are determined by the recirculation-loop dynamics. For the out-of-phase mode, however, the boundary conditions are fixed, and they determine the necessary inlet flow to maintain a constant pressure drop across the core. This boundary condition can be implemented either by rearranging the individual open loop transfer functions as they are combined to form the closed loop or by setting the gain of the recirculation-loop pressure-to-flow transfer function to an arbitrarily large number and using an existing core-wide stability code. Both methods yield the same result because both minimize pressure drop variations.

RESULTS

The particular application of this model has been implemented by performing slight modifications of the LAPUR code that now performs a two-step calculation. First, LAPUR estimates the core-wide stability in the usual manner. Then the out-of-phase stability is determined by coupling a subcritical neutron dynamics model with the open loop transfer functions calculated in step one rearranged to satisfy the zero-pressure-drop change boundary condition. The stability of the out-of-phase mode is then determined as a function of subcritical reactivity values.

Figure 4 shows the LAPUR calculated closed loop transfer function for a case in which the out-of-phase mode is more unstable than the core-wide mode. The slightly different structure observed in the subcritical mode is due to its increased flow feedback that makes it more unstable. Nevertheless, the dynamic structures of two modes look fairly similar, and the frequency of oscillation is of the same order of magnitude (about 0.4 Hz).

The main results of this work are condensed in Fig. 5, which shows the stability boundaries for the core-wide and out-of-phase modes in a power/flow map. Note that the two boundaries cross each other so that four regions are defined: Region A, where both modes are stable; Region B, where only the core-wide mode is unstable; Region C, where both modes are unstable; and Region D, where the core-wide mode is stable but the out-of-phase mode is unstable.

Regions C and D of Fig. 5 are of relevance to BWR safe operation. In particular, the present results indicate the existence of a Region D of instability where conventional codes would predict stable behavior of the core-wide mode. The existence of Region C could have implications on the calculation of limit cycle amplitudes should a reactor become unstable and fail to scram. In Region C, regional (out-of-phase) oscillations would be superimposed to a probably large-amplitude limit cycle oscillation core wide. This superimposition could lead to even larger oscillation amplitudes.

The stability boundary of the out-of-phase mode depends on the subcritical reactivity value of the corresponding neutronic mode [Eq. (6)], as can be observed in Fig. 6. The lower (more negative) the subcritical reactivity, the farther away the stability boundary is from the normal operating regime. The subcritical reactivity is inversely proportional to the fission cross section and directly proportional to the geometric buckling. Therefore, out-of-phase instabilities will be favored over core-wide instabilities under the following conditions: (a) at the beginning of a cycle, (b) when many control rods are inserted, (c) when there are large amounts of burnable poison, and (d) in large cores that decrease the buckling. Observation of Fig. 5 also indicates that out-of-phase instabilities will be more likely at higher flows (Region D).

SUMMARY

The present work describes a mechanism that explains the out-of-phase instabilities observed in BWRs. This mechanism has been modeled by upgrading the LAPUR BWR stability code. Numerical simulations have shown that there is a region in the operating power-flow map where out-of-phase instabilities are possible even if the core-wide dynamic mode is stable. The stability boundary depends on the subcritical reactivity of the out-of-phase mode. For any operating condition, there is a threshold reactivity value above which the cut-of-phase mode is more unstable than the core-wide mode.

ACKNOWLEDGMENTS

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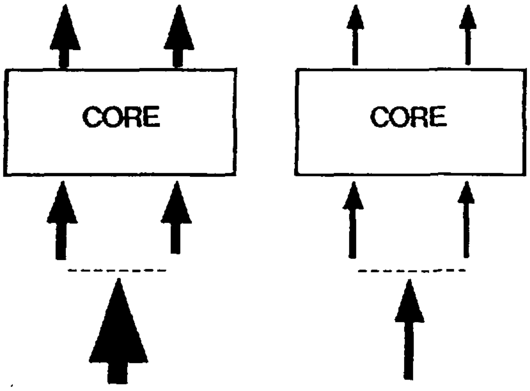

Fig. 1. Flow patterns for a core-wide oscillation of period T. Arrow thickness represents flow intensity.

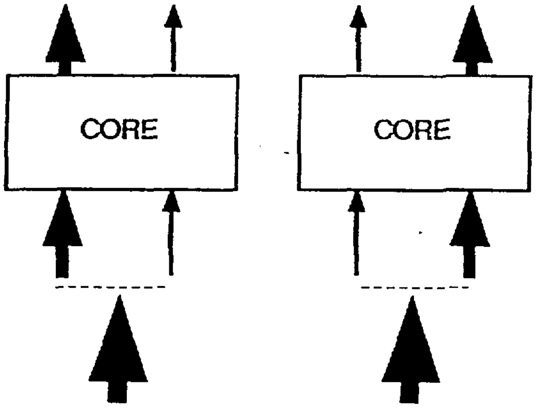

Fig. 2. Flow patterns for an out-of-phase oscillation of period T. Arrow thickness represents flow intensity.

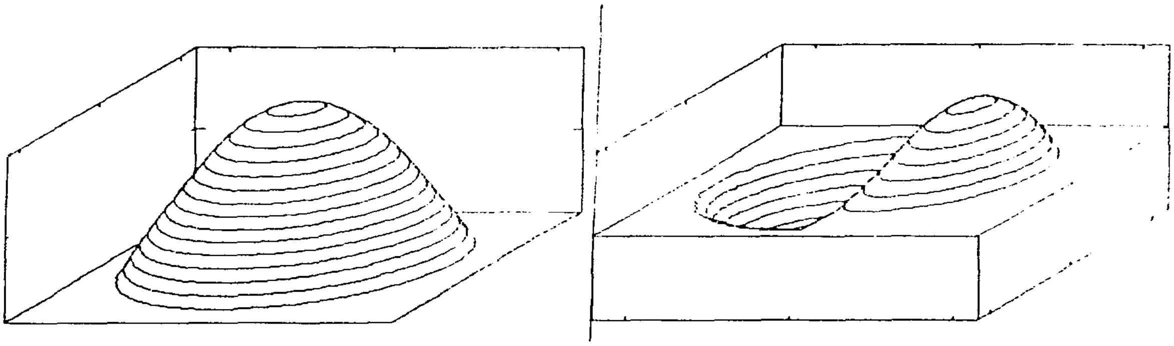

Fig. 3. Space dependence of neutronic modes: (a) fundamental (core-wide) mode, (b) subcritical (out-of-phase) mode.

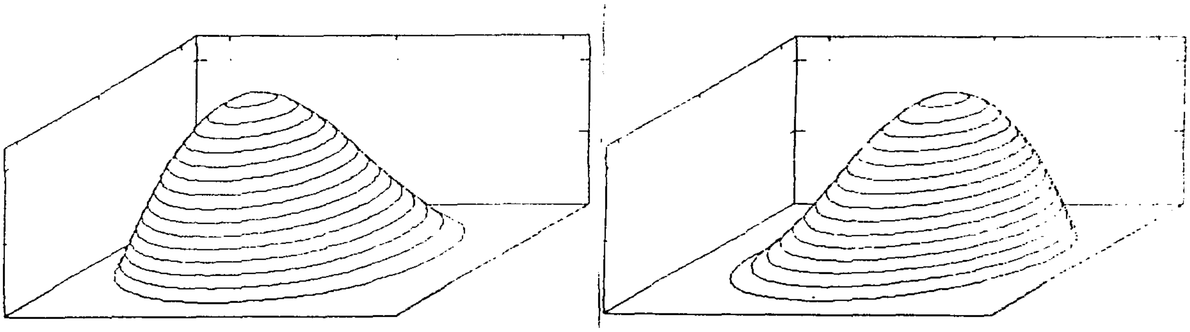

Fig. 4. Space dependence of the total neutron flux during an out-of-phase oscillation of period T.

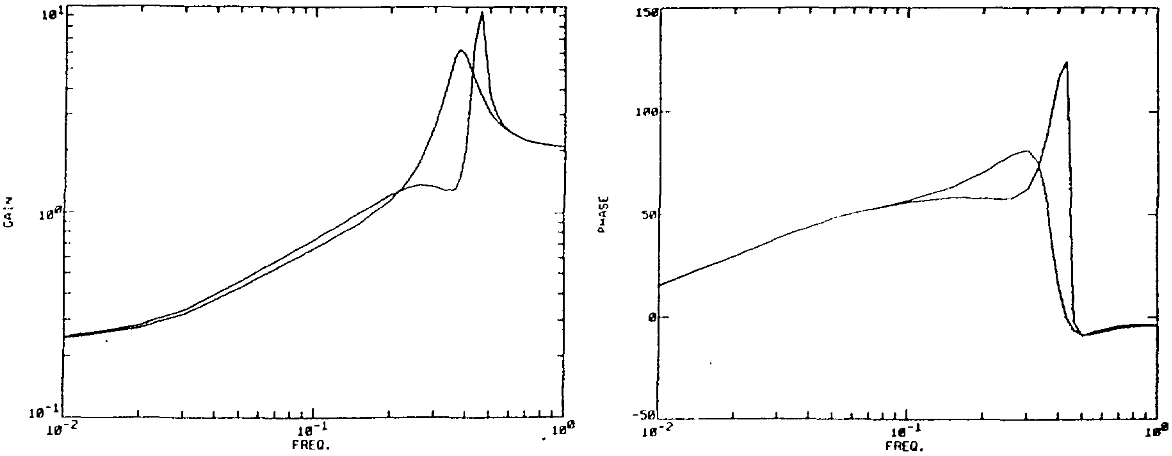

Fig. 5. Comparison between reactivity-to-power closed loop transfer functions of the core-wide and out-of-phase modes in a typical BWR.

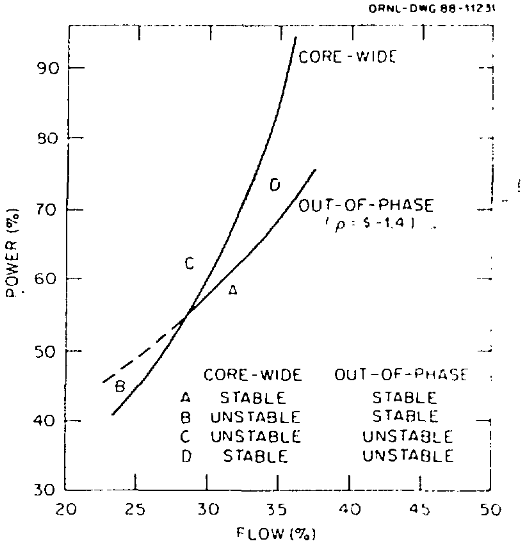

Fig. 6. Stability boundaries for the core-wide and out-of-phase instability modes. Subcritical reactivity of out-of-phase mode is −1.4 dollars.

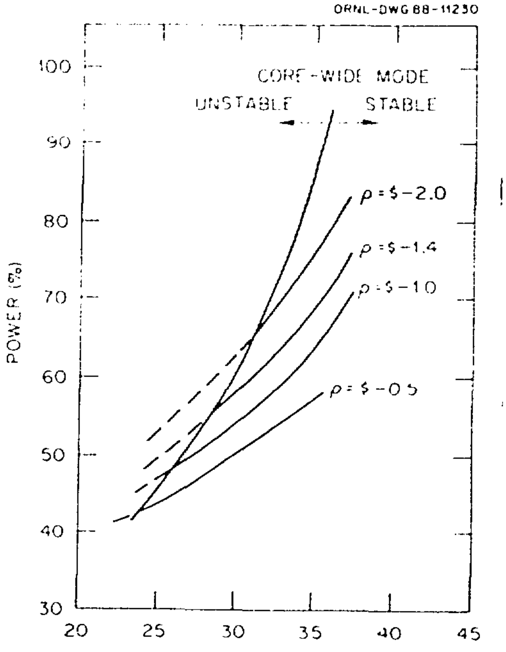

Fig. 7. Stability boundaries of the out-of-phase mode as a function of subcritical reactivity.