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CALCULATION OF LIMIT CYCLE AMPLITUDES IN COMMERCIAL BOILING WATER REACTORS*

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Recent stability tests[1,2] have shown that boiling water reactors can be linearly unstable when operated at low flow and high power. It was observed that under these conditions the amplitude of the resulting power oscillations was limited to about ±10% of the operating power by the appearance of a limit cycle caused by reactor nonlinearities.[3] The existence of a limit cycle corresponds to an oscillation of fixed amplitude and period.

This paper describes an investigation of the dynamic behavior of a boiling water reactor (BWR) in the nonlinear region corresponding to linearly unstable conditions. For this purpose, a nonlinear model of a typical BWR was developed. The equations underlying this model represent: (a) a one-dimensional void reactivity feedback (described by a 12-node axial expansion of the energy, continuity, and momentum equations for the average channel), (b) point kinetics with a single delayed neutron group, (c) fuel behavior (obtained by using a two-node representation of pellet and cladding behavior), and (d) recirculation loop dynamics (described by a single-node integral momentum equation). Note that the nonlinear terms appear in the point kinetics and momentum equations.

The parameters of the model were obtained by constraining the model to match the Vermont Yankee tests.[2] In particular, the void reactivity feedback was adjusted so that the inception of the limit cycle corresponded approximately to the conditions of test 7 in ref. 2. Figure 1 shows a typical response of the reactor to a one-cent reactivity step. Although initially the oscillations appear to diverge, they eventually reach a limit cycle. Even if this limit cycle may not cause an automatic scram on high power, it could impose some strain on the mechanical integrity of the fuel.

Customarily, the decay ratio[1,2] is used to quantify stability; however, for any operating conditions in the nonlinear region the decay ratio is by definition equal to 1.0 due to the appearance of limit cycles. An alternative parameter is therefore needed to describe the dynamic behavior of the reactor in this nonlinear region. Our research indicates that the parameter best suited for this purpose is the amplitude of the oscillations.

Figure 2 shows the contours of constant decay ratio in the stable linear region and contours of constant oscillation amplitude in the nonlinear region. This figure indicates that the stability is more sensitive to flow changes than to power changes, and that the sensitivity of the amplitude to variations in operating condition is very large. Figure 3 highlights the fact that the oscillation amplitude increases rapidly as a function of power along the natural circulation line. Note, however, that the calculated limit cycles were stable, and that the reactor displayed a periodic[3] behavior pattern over the range of power and flows studied in this work.

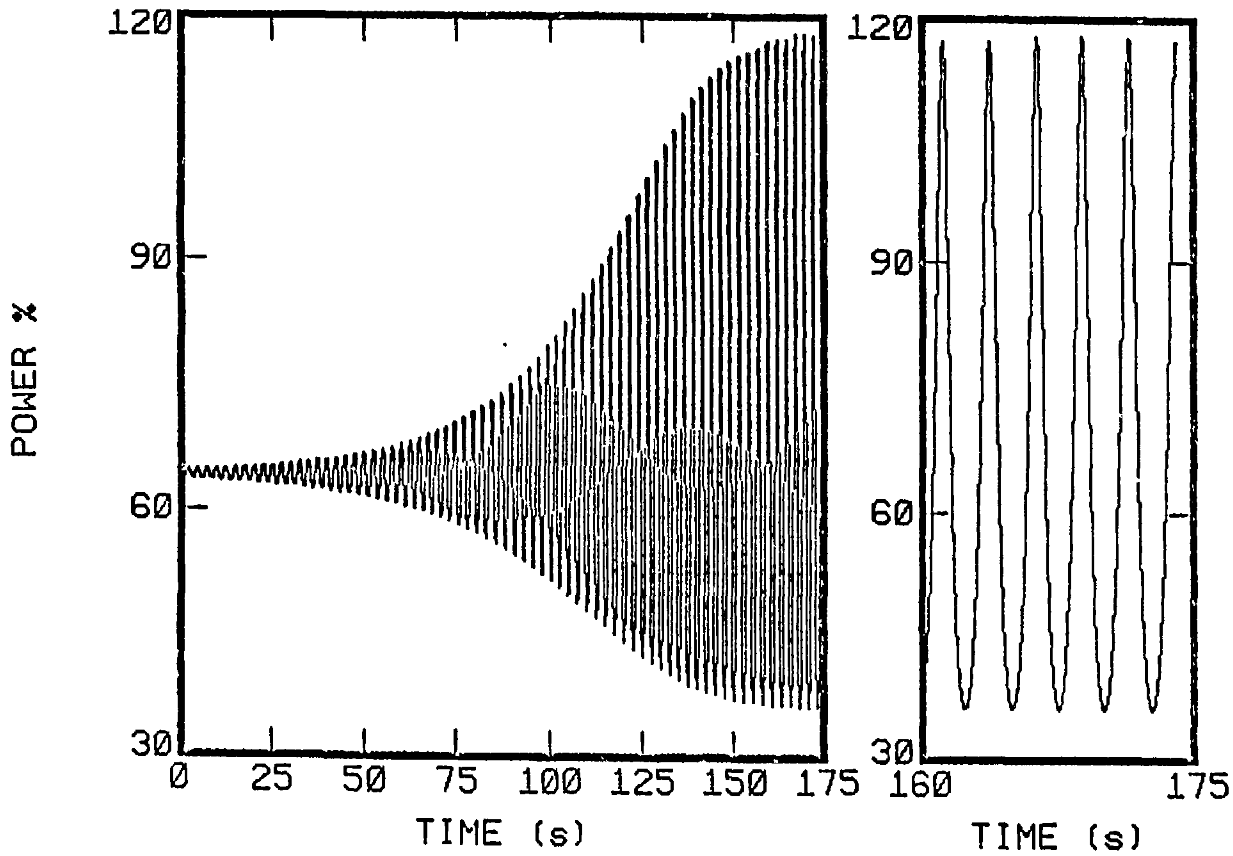
Important conclusions of the research described in this work are that (a) the nonlinear model developed successfully predicts the appearance of the experimentally observed limit cycles, (b) the amplitude of the power oscillations in the nonlinear region is very sensitive to changes in the operating conditions, and (c) limit cycles of large amplitude, but not so large as to cause an automatic scram, are a possible scenario for BWR plant operation.

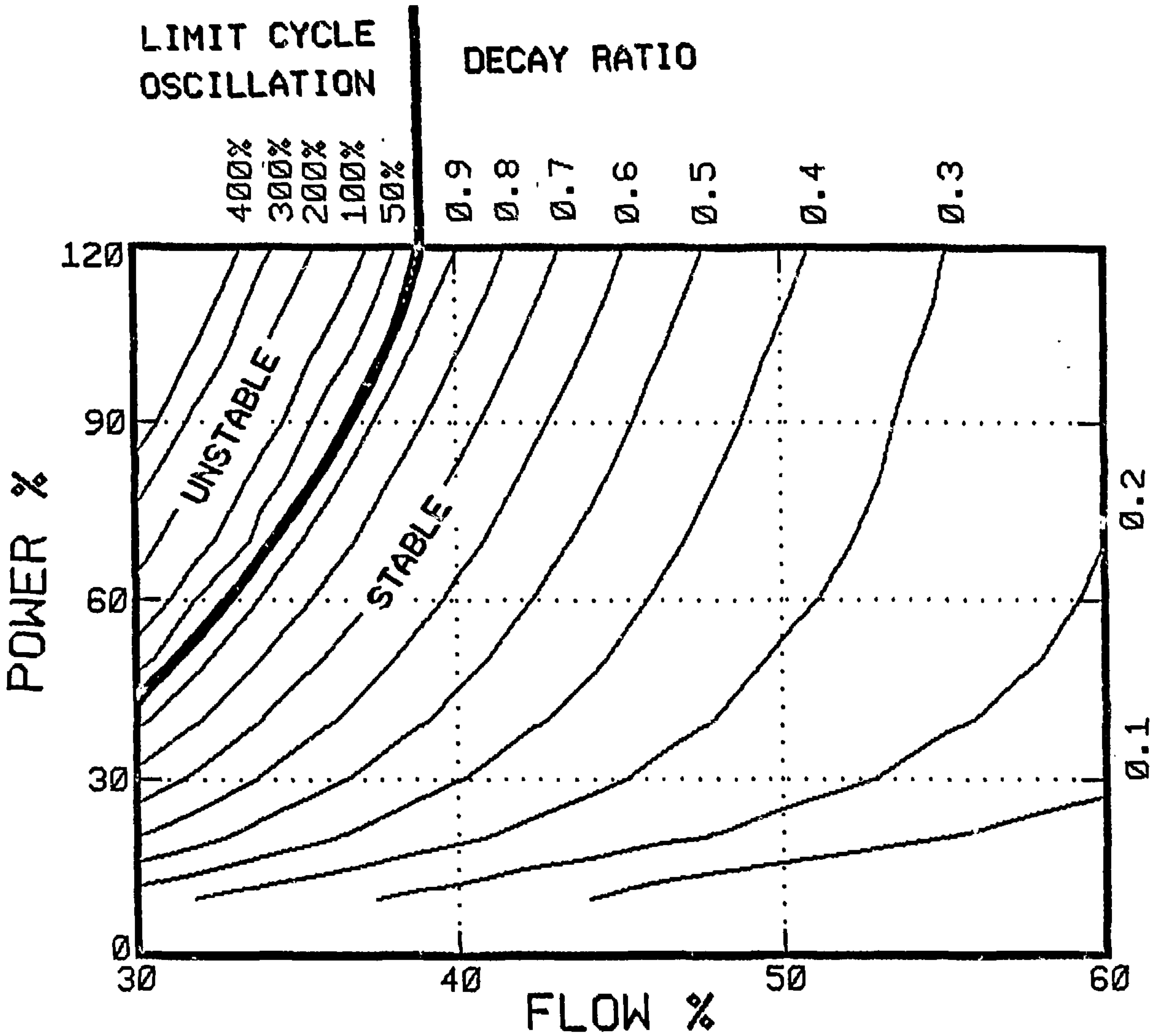
Figure Captions

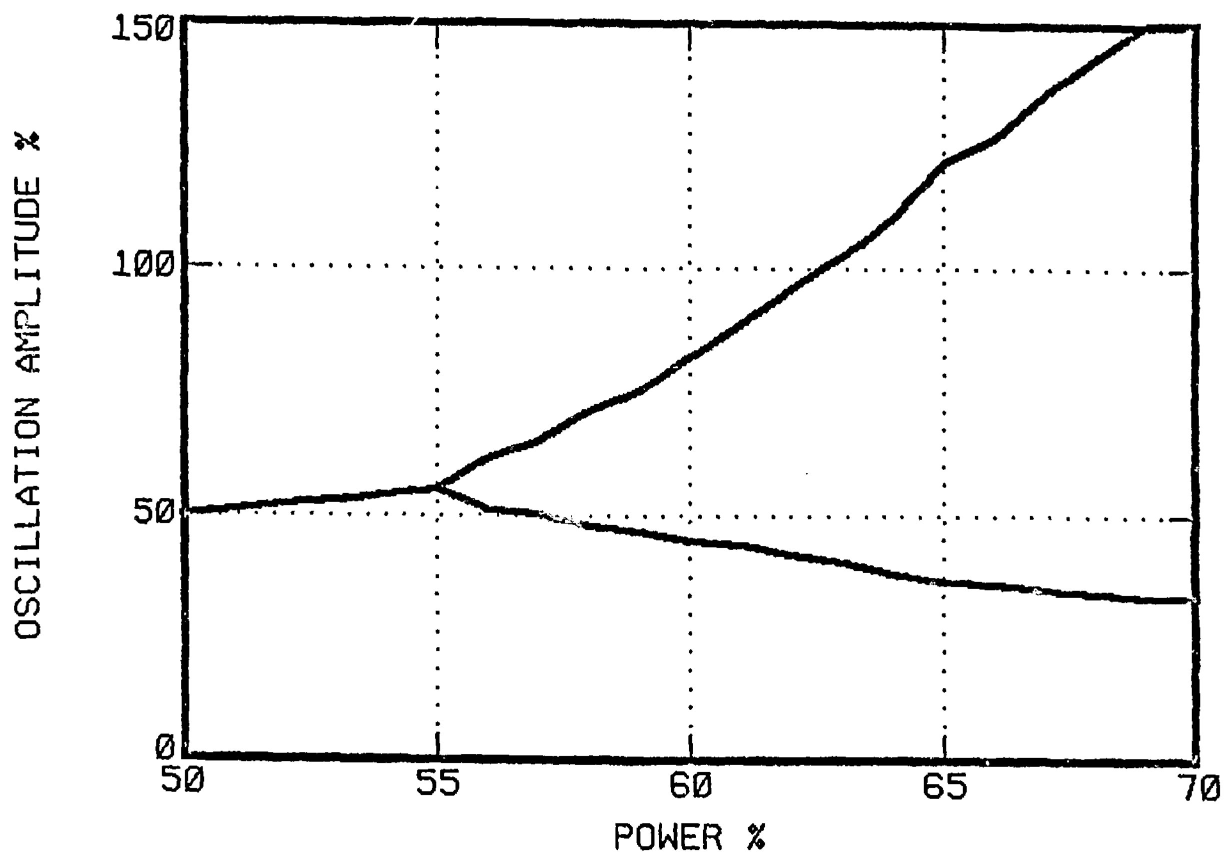
Fig. 1. Reactor response to a one-cent step in reactivity, showing the development of a large amplitude limit cycle. Initial conditions are 64% power and 32% flow. (The patterns within the oscillation are produced by round-off error in the plotter.)

Fig. 2. Lines of constant decay ratio (in the stable region) and constant limit cycle magnitude (in the unstable region).

Fig. 3. Amplitude of the limit cycle (maxima and minima) as a function of power along the natural circulation line. Note the large sensitivity of the amplitude to changes in operating conditions.


POWER %
120
90
60
30
0
25
50
75
100
125
150
175
TIME (s)
120
90
60
30
160
175
TIME (s)


LIMIT CYCLE
OSCILLATION
DECAY RATIO
400%
300%
200%
100%
50%
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
UNSTABLE
STABLE
POWER %
120
90
60
30
0
FLOW %
30
40
50
60


OSCILLATION AMPLITUDE %
0
50
100
150
50
55
60
65
70
POWER %

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