

BWRSC: An On-Line Stability Exclusion Region Calculator For BWRs

B.J. Gitnick	M. Karasulu	G.S. Grochowski	J.L. Thompson	J.S. Miller
SCIENTECH, Inc.	New York Power Authority	New York Power Authority	Gulf States Utilities	Gulf States Utilities

ABSTRACT

The computer program BWRSC was developed to calculate and graphically present the stability exclusion region on a BWR power/flow map. BWRSC is an acronym for Boiling Water Reactor Stability Calculator. Unlike existing stability monitors which can only measure the decay ratios at the current plant operating state, this new code projects what the decay ratios would be after a change in operating conditions. This capability makes possible the on-line calculation of the stability exclusion region consistent with current reactor parameters obtained directly from the plant process computer. In the on-line mode, BWRSC can provide reactor operators and technical support staff with an extremely important prediction of the reactor stability during proposed operational maneuvers. The BWRSC code can also be used off-line for engineering evaluations of new fuel designs and reload strategies.

Introduction

BWRs have experienced power oscillations during high power/low flow operating conditions. These oscillations are the result of coupled hydrodynamic/neutronic feedbacks. The hydrodynamic instabilities, referred to as "density wave oscillations", are caused by the time lag between a perturbation in the inlet flow and the resulting change in the two-phase pressure drop. Because the coolant is also the moderator, the density wave oscillations are augmented by the gain of the neutronics. Oscillations can be sustained in a core-wide mode, where the fluxes and bundle flows are in-phase across the core; or in an out-of-phase (regional) mode, where the fluxes and channel flows can have a 180 degree phase shift between different regions of the core. Out-of-phase oscillations tend to occur in large BWRs with low eigenvalue separation, where, typically, halves of the core will oscillate about a diagonal of symmetry.

Sustained power oscillations violate the NRC's General Design Criteria (GDC-12) and large oscillations can exceed thermal limits, leading to fuel damage. Oscillations can be avoided by restricting operation so that unstable operating conditions are not encountered. Typically, an exclusion region is specified as a constraint on the power/flow operating domain. However, in addition to power and flow, other operational parameters such as feedwater temperature and axial power shape can have a significant impact on stability. The strong sensitivity to variations in input

parameters is such that plant and cycle specific stability analysis will be required. BWRSC automates the continuous on-line calculation of the stability exclusion region, including the effects of flow reduction and loss of feedwater heating transients. Use of BWRSC allows the stability calculation to be consistent with measured plant conditions, obtained directly from data transferred from the plant process computer. If the exclusion region is precalculated generically, a sizable allowance must be included for uncertainties in the assumed conditions and input parameters. The result of these conservatisms is an overly large exclusion region which may severely restrict operational flexibility.

The stability calculations performed by BWRSC are presented graphically as an exclusion region overlaid on the power/flow map in a format useful for plant operators (Figure 1).

Overview of the BWRSC Code

BWRSC is a system of codes linked together to automate BWR stability calculations: the REBAL¹ heat balance and pressure balance code, the FIBWR² core flow and pressure drop code, the LAPUR³ frequency domain stability code, and the SIMULATE⁴ core neutronics simulator code. Two additional modules have been developed specifically for BWRSC: RESURF and EDITR. The REBAL module of BWRSC is used to initialize adjustable parameters in the heat balance and feedwater performance models. The LAPUR frequency domain stability code has been selected for inclusion in BWRSC. LAPUR has been extensively benchmarked⁵ for both in-phase and out-of-phase power oscillation events. FIBWR and SIMULATE are widely used and well known. These codes are used by BWRSC to generate thermal-hydraulic and neutronic inputs to LAPUR. RESURF generates the exclusion region contour based on the LAPUR calculated decay ratio results. The methodology used by REBAL, LAPUR, and RESURF is described in this paper. EDITR is a housekeeping module that facilitates file and database maintenance from within the BWRSC code system.

Stability analyses are typically performed using either frequency or time domain codes. Frequency domain methods evaluate the open loop transfer function for the coupled neutronics-fuel pin heat conduction-channel flow interactions, derived from a small perturbation (linearized) form of the reactor kinetics and thermal-hydraulic equations. The alternate approach, time domain methods, are complex and resource-consuming. Frequency domain analysis methods have several distinct advantages over time domain methods:

- Elimination of numerical dispersion
- Simplicity
- Speed

Frequency domain methods calculate the growth/damping rate of an assumed small initial disturbance. Frequency domain methods are theoretically correct only for systems with small oscillations, because these methods linearize the thermal-hydraulic and nuclear responses (which are generally non-linear) to determine the feedback functions. These methods cannot be used to accurately predict oscillation behavior for large disturbances, i.e., after the oscillation amplitude becomes large enough for the non-linear effects to be important. However, it is appropriate for BWRSC to use frequency domain methods to map the boundaries of the stability exclusion region.

Decay ratio is the parameter that quantifies the tendency of the core to oscillate. The decay ratio is defined as the ratio of the power peak of two successive oscillations. If the decay ratio is greater than 1, the oscillation will continue to grow. Separate decay ratios are calculated for the in-phase core oscillation mode, and for each out-of-phase mode analyzed.

A number of core and fuel parameters, power distributions and operational strategies have been found to have an impact on BWR stability. These parameters may vary from plant to plant and cycle to cycle, and in fact, may vary significantly as the exposure and operating conditions of the plant change. The in-phase decay ratio has been found to be very sensitive to the following parameters⁶:

- Two-phase to single-phase pressure drop ratio
- Feedwater temperature
- Void reactivity coefficient
- Fuel time constant
- Axial and radial power shape

In addition, the tendency towards regional oscillations (out-of-phase) mode is sensitive to the higher order harmonic modes of the neutronics. The half core oscillations, for example, excite the first azimuthal harmonic mode⁶.

Generic calculations of the exclusion region have the difficulty that the input values selected must be both appropriate and conservative for a wide range of changing conditions. It is obvious that if the exclusion region is calculated generically, a sizable allowance must be included to account for uncertainties in the assumed conditions and input parameters.

BWRSC was designed to run in an on-line mode, obtaining reactor state parameters from a data file generated by the plant process computer. The code may also be run in an off-line mode where the power/flow reactor state data are user-specified. As BWR stability is most limiting at high power/low flow conditions which may result from a flow reduction transient or loss of feedwater heater event, the REBAL module is used to compute reactor conditions which would result from a shift in power/flow from the current operating state. The LAPUR module then evaluates the relative stability at these conditions. These calculations are repeated parametrically; the RESURF module then maps out the stability exclusion region. BWRSC updates its decay ratio database and exclusion region periodically. Figure 2 presents an overview of the calculation process.

Parametric Points

It would be convenient if the latest measured power/flow thermal-hydraulic state data could be used to initialize the required LAPUR calculations directly. However, the region of potential instability generally occurs at a low flow/high power condition, whereas the reactor will generally be operating at high flows, or at a low power if at a low flow. Low flow/high power conditions would only be entered inadvertently during startup, or after some transient experienced while at low power, or from high flow as a result of a flow reduction transient.

A fixed set of (typically nine) additional power/flow state points is therefore evaluated using REBAL and LAPUR. These power/flow points form a matrix, which straddles the low flow/high power region. As shown in Figure 2, BWRSC first reads an updated set of power/flow state parameters (from the plant process computer), and runs the REBAL module, which performs mass, energy and pressure balance calculations. REBAL uses the measured plant data (power, steam flow, pressure and feedwater enthalpy) to recalibrate several parameters used internally to calculate feedwater enthalpy, reactor pressure, and steam flow at different power/flow conditions. REBAL then calculates a consistent set of thermal-hydraulic state parameters (pressure, steam flow, feedwater enthalpy) for input to the LAPUR frequency domain decay ratio calculation at the power/flow points specified for the parametric calculations.

In addition to the thermal-hydraulic parameters, the reactivity coefficients, eigenvalue separation and axial power shapes are read by LAPUR from a data file for each of the parametric power/flow state points. These values are generated by the SIMULATE⁴ code. SIMULATE updates the information in these data files periodically, typically once a day, but more frequently during startup and power maneuvers.

The in-phase and out-of-phase decay ratio results of the parametric LAPUR calculations are passed to the RESURF module to calculate and display the stability exclusion region contour. This is the appropriate exclusion region for low flow operation, either as a result of a planned operational maneuver or of a flow reduction transient.

General Electric, in a topical report prepared for the BWR Owners' Group⁷, has identified the Loss of Feedwater Heater (LOFH) as the most severe of the low power transients in terms of the potential impact on stability. BWRSC will optionally calculate a second exclusion region, consistent with conditions following a loss of feedwater heater transient. The REBAL/LAPUR sequence is rerun for each of the parametric power/flow data points, this time with REBAL calculating the degraded feedwater temperature and resulting steam flow. Additional SIMULATE runs are performed to generate LAPUR neutronics data for the LOFH condition. The LOFH region is separately calculated using RESURF. RESURF can then display either the LOFH or the low flow exclusion region, or a combined exclusion region.

As the reactor conditions change, the decay ratio database must be periodically updated. To reflect the latest available information, the REBAL calculation for the current reactor state precedes the REBAL/LAPUR calculation for each of the parametric power/flow points. Every time a decay ratio for a parametric point is recalculated, the RESURF exclusion region contour is recalculated as well. In this way, the exclusion region boundary responds smoothly and rapidly to changes in reactor conditions.

REBAL

The REBAL module determines the thermal-hydraulic conditions of a BWR at any power/flow state, including: primary system pressures, enthalpies, flows, feedwater temperature, and recirculation loop resistance (pump speed or valve position). Separator/dryer, core and jet pump flow/pressure drop

relationships are determined using an iterative procedure to solve for lower plenum pressure and core inlet subcooling. REBAL performs a detailed heat balance (including pump heat changes), and determines steam flow and feedwater temperature compatible with a user-supplied balance-of-plant performance curve. This curve can be adjusted to model a drop in feedwater temperature by a feedwater train efficiency (enthalpy rise degradation) factor:

$$\eta = \frac{h(T_{fw\ degraded}) - h(T_{condenser})}{h(T_{fw\ rated}) - h(T_{condenser})}$$

Reactor steam dome pressure is obtained from a steady-state form of the BWR pressure controller equations:

$$P_{dome} = P_{turbine\ set} + \Delta P_{control\ valve} (W_{stm} / W_{stm, rated}) + \Delta P_{steam\ line} (W_{stm} / W_{stm, rated})^2$$

During the REBAL initialization step, the feedwater train efficiency and turbine set pressure parameters are adjusted to yield the measured feedwater enthalpy and dome pressure at the actual power and steam flow. BWRSC uses the REBAL calculated thermal-hydraulic state parameters (pressure, steam flow, feedwater enthalpy) for input to the LAPUR frequency domain decay ratio calculation at the power/flow points specified for the parametric calculations. The feedwater enthalpy and reactor pressure of these subsequent REBAL calculations are therefore consistent with measured plant conditions.

LAPUR

The LAPUR5 code, developed by Oak Ridge National Laboratory is used to perform frequency domain stability analysis in BWRSC. LAPUR has been widely benchmarked⁵ against a spectrum of in-phase and out-of-phase stability events. LAPUR consists of two autonomous modules, LAPURX and LAPURW.

LAPURX solves the steady-state, two-phase coolant flow and fuel-pin heat transfer equations. LAPURX calculates linearized flow and heat transfer response coefficients for input to the frequency domain module LAPURW. The LAPURX module uses simple models for the flow and pressure drop solution; for example, LAPURX does not consider bypass or water tube flow in the flow distribution calculation. For this reason, the FIBWR code has been included in BWRSC. FIBWR results are used to calculate equivalent loss coefficients and model parameters for LAPURX, as well as the leakage/water tube flows needed for LAPUR inputs. Axial power data for LAPURX and FIBWR are generated by SIMULATE.

LAPURW, the frequency domain stability solution module of the LAPUR code, is considered

state of the art. LAPURW requires either two-group cross-sections or void/doppler reactivity coefficients. Given the eigenvalue separation for the higher harmonic eigenvalues, LAPURW has the capability to calculate the decay ratios for out-of-phase oscillations. Neutronic information for LAPURW is also produced by SIMULATE.

RESURF

The RESURF module calculates the contours of the stability exclusion region on the power/flow map. The decay ratio limits are supplied to RESURF in a file containing user specified in-phase and out-of-phase stability criteria. Decay ratio limits are typically set below 1.0 to include an allowance for uncertainties in the measurement of plant data and the calculational method. Benchmark studies will be performed to determine appropriate values for the decay ratio limits. The map of the decay ratio limits can be displayed by BWRSC, such as that presented in Figure 3.

RESURF begins by fitting two response surfaces, one for the in-phase decay ratios and one for the out-of-phase decay ratios calculated by LAPUR at the parametric power/flow points:

$$DR_{I-P} = f_{I-P}(Power, Flow) \quad DR_{O-P} = f_{O-P}(Power, Flow)$$

Our experience has shown that the response surfaces can be accurately represented by second order polynomials.

A specific power is selected and, for any given flow, both of the corresponding decay ratios can be calculated, corresponding to a single point on the decay ratio limit map. A search is made for a flow that makes the corresponding point land on the decay ratio limit line. This (power, flow) pair is then plotted as one of the points which define the exclusion region boundary curve on the power/flow map. This scheme is illustrated in Figure 4. By repeating this process for a range of power values, the boundary of the exclusion region can be traced on the power/flow map.

Conclusion

The BWRSC code system has been developed as an on-line BWR stability calculator. BWRSC computes and displays the stability exclusion region consistent with current plant conditions, thus minimizing the uncertainty associated with selecting inputs that conservatively bound a number of potential plant conditions.

BWRSC is currently being tested at two utilities. It is anticipated that BWRSC will be used both as an operator informational aid and to support engineering evaluations of new fuel designs and operational modes. In the future, many BWRs will have an auto-scrum requirement to guard against instabilities. With the use of BWRSC, the risk of scrams from inadvertent maneuvering into unstable power/flow regions can be minimized. Some plants will not need an auto-scrum function because of their small core size and tight inlet orificing. These plants will benefit from the increased flexibility provided by the plant and cycle specific results of the BWRSC stability calculator.

Acknowledgments

This work was partially supported by the New York Power Authority and Gulf States Utilities.

References

1. B. J. GITNICK, "Consistent Initialization of Pressure and Flow Parameters for BWR Transient Analysis at Off-Rated Power and Flow Conditions," Nuclear Technology, pp 92-104 (Jan. 1991).
2. B. J. GITNICK, A. F. ANSARI and R. R. GAY, "FIBWR: A Steady-State Core Flow Distribution Code For Boiling Water Reactors," EPRI-NP-1924-CCM (July 1981).
3. P. J. OTADUY and J. MARCH-LEUBA, "LAPUR User's Guide," NUREG/CR-5421, ORNL/TM-11285 (June 1989).
4. D. M. VER PLANCK, et. al., "SIMULATE-E: A Nodal Core Analysis Program for Light Water Reactors: Computer Code User's Manual," EPRI-NP-2792-CCM (1983).
5. J. MARCH-LEUBA, "LAPUR Benchmark Against In-Phase and Out-Of-Phase Stability Tests," NUREG/CR-5605, ORNL/TM-11621 (Oct. 1990).
6. B. S. SHIRALKAR, "Trends in BWR Transient Analysis," Paper Presented at the Seventh International RETRAN Meeting, New Orleans, Louisiana (Sept. 1991).
7. "BWR Owners' Group Long Term Stability Solutions Licensing Methodology," NEDO-31960, General Electric Co. (June 1991).

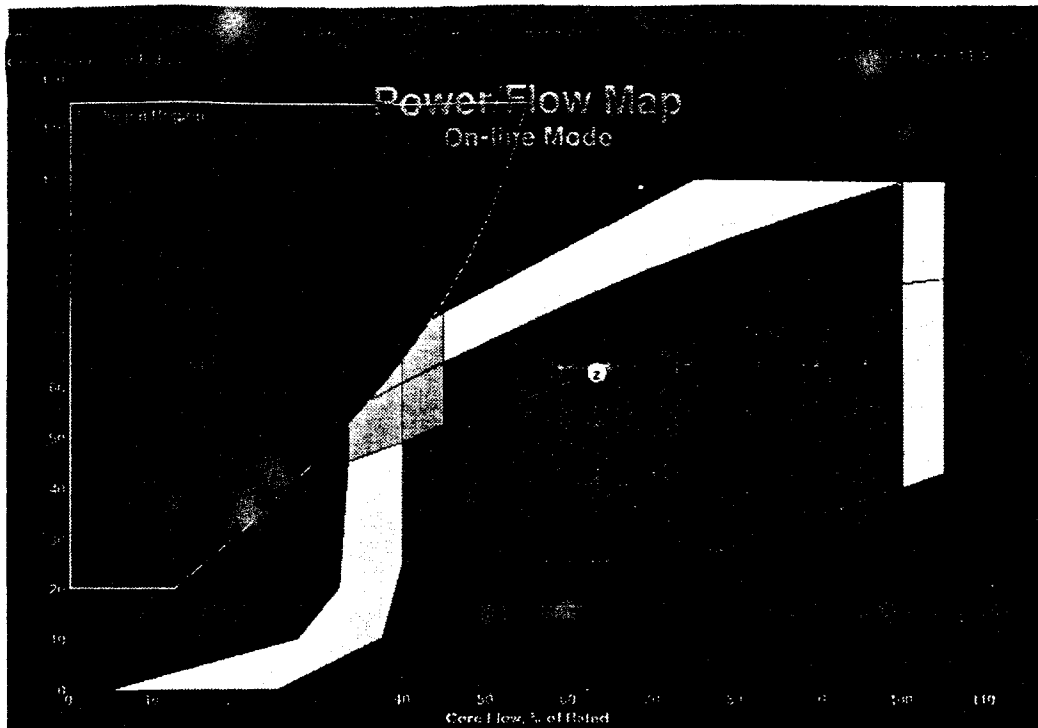


FIGURE 1. BWRSC Power/Flow Map Showing Stability Exclusion Region

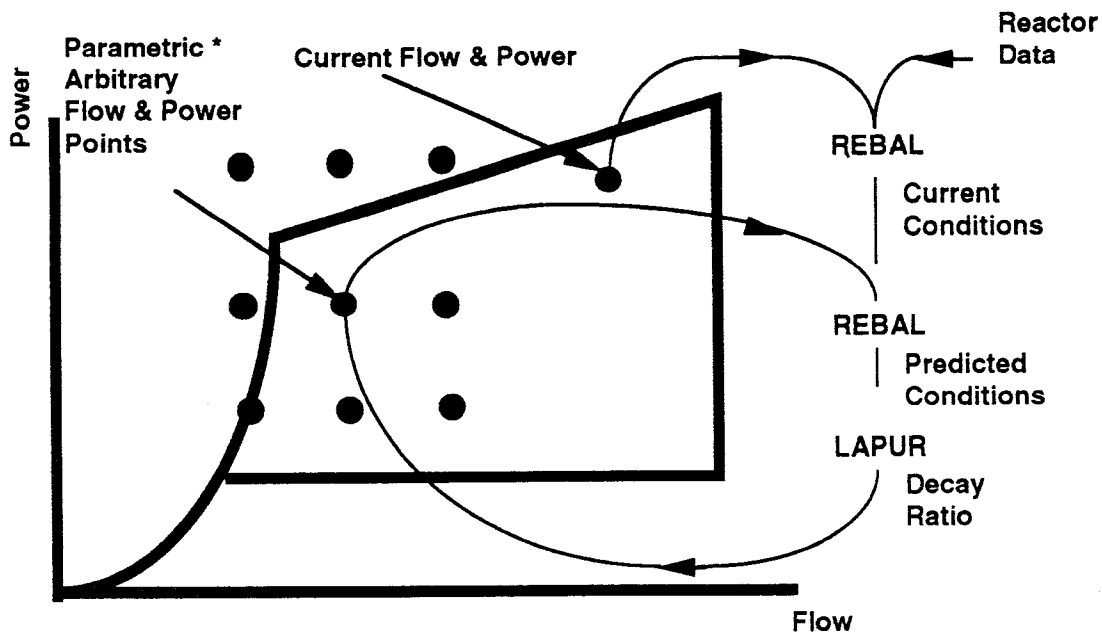


FIGURE 2. Flow of Information

*Neutronic and thermal-hydraulic input data for LAPUR at these points are regenerated periodically by SIMULATE and FIBWR.

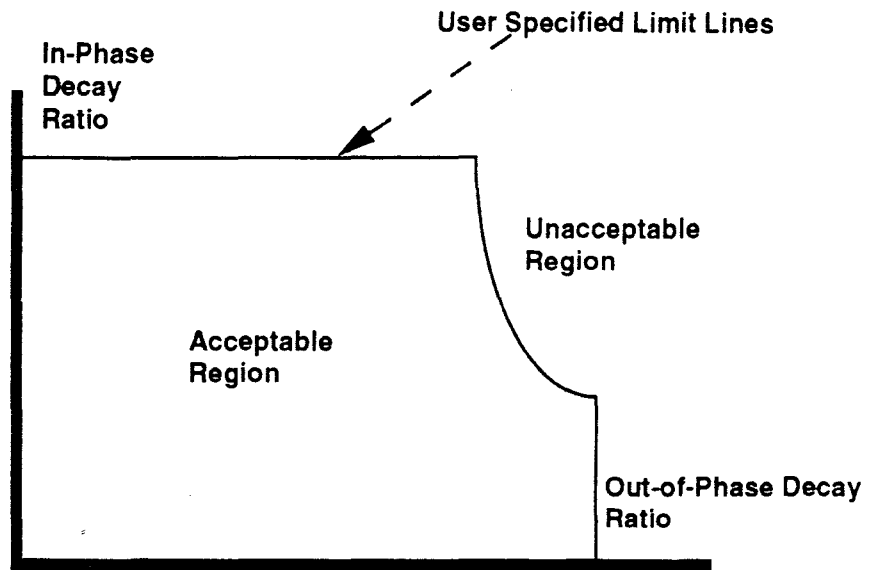


FIGURE 3. Typical Decay Ratio Limits Map

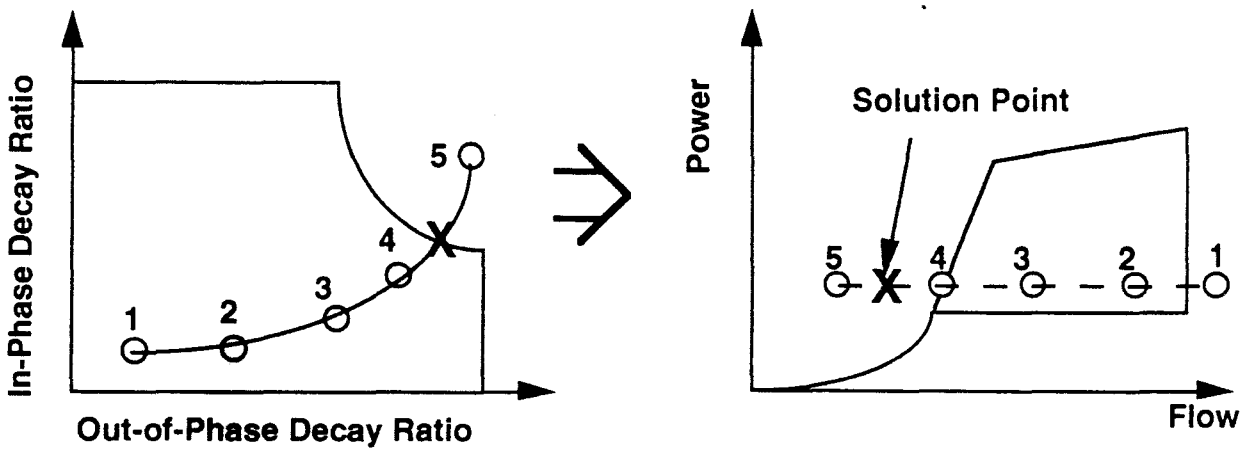


FIGURE 4. RESURF Solution Method