15.9 Boiling Water Reactor Stability

15.9.1 Introduction

General Design Criterion (GDC) 10 states that:

> The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

GDC 12 states that:

> The reactor core and associated coolant, control, and protection systems shall be designed to assure that power oscillations which can result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed.

Coupled neutronic-thermal-hydraulic instabilities, also known as density-wave instabilities, are safety concerns for boiling water reactors (BWRs). Three recognized modes of density-wave instability are (1) global (when the power and flow of all the core channels oscillate in phase), (2) regional (when the power and flow of half the core channels oscillate out-of-phase with the other half), and (3) single-channel flow instability (when the flow in a single channel oscillates accompanied by small power oscillations).

Early design and testing in operating BWRs led to a detect-and-suppress stability solution, based on high APRM flux scram as the safety protection for the fuel. After observed instability events at several operating BWRs, the most well-known of which was the LaSalle event in March, 1988, it was recognized that the protection systems in place at the time might not be sufficient to insure meeting GDC 10 and 12. As a result of these events at operating BWRs, the BWR Owner's Group developed several options for BWRs to meet GDC 10 and 12 (References 15.9-1 through 15.9-3).

15.9.2 ABWR Stability Mitigation Features

The ABWR design assures that stability performance in the normal operating region is more stable than current operating BWRs by incorporating the following design features:

(1) Smaller inlet orifices, which increase the inlet single-phase pressure drop, and, consequently, improve the core and channel stability

(2) Wider control rod pitch, which increases flow area, and, reduces the void reactivity coefficient and improves both core and channel stability

(3) More steam separators, which reduce the two-phase pressure drop, and improve stability

In addition, the ABWR has adopted a multi-layered defense in depth strategy for protecting its fuel, based primarily on the Owner's Group Options I-A and III. Option I is based on having an operating exclusion region, outside of which instabilities are very unlikely to occur. In Option I-A, immediate automatic protective action, either by scram or select rod insert, is taken if the plant enters the exclusion region. ABWR has chosen the Selected Control Rod Run-In (SCRRI) option.

Option III is LPRM-based detect and suppress that looks at local power variations via various algorithms that are designed to detect increasing periodic oscillations typical of limit-cycle instability behavior, and provides scram protective action before the Safety Limit Minimum Critical Power Ratio (SLMCPR) can be reached. ABWR has adopted an Oscillation Power Range Monitor (OPRM) system.

In summary, there are five types of protective measures that limit the likelihood of stability events in the ABWR and to suppress them should they occur:

- A 9-Reactor Internal Pump (RIP) minimum speed line, which administratively prevents intentional operation in a region where core instabilities are a possibility;
- A SCRRI system, which automatically inserts selected control rods if an event puts the plant unintentionally into a region on the power / flow map where core instabilities are a possibility;
- A control rod block to prevent automatic control rod withdrawal under prescribed conditions during power ascension;
- An OPRM system, which automatically detects oscillations and initiates reactor scram if setpoints of any of three detection algorithms are exceeded while operating in the OPRM armed region; and
- Backup Stability Protection (BSP) exclusion zones, which administratively require the operator to exit the region or to scram the reactor if an event puts the plant unintentionally into a region on the power / flow map where core instabilities are a possibility.

Figure 15.9-1 summarizes the automatic logics, and Figure 15.9-2 shows the applicable power and flow ranges for the automatic features. The flow setpoint of 36% is higher than the expected flow with 8 RIPs, but less than the expected flow with 9 RIPs. Therefore operation with 8 RIPs or less during power ascension above 25% power or at minimum pump speed with power above 30% is precluded by the rod block or SCRRI functions. [The OPRM system is armed whenever the core flow is less than 60% and the reactor power is greater than 25%.]

15.9.3 Stability Analysis

Decay ratios for the three density wave instabilities were obtained at several power/flow combinations in or near operating Region III of the reference power/flow maps shown in

Figures 4.4-1 and 4.4-2. The equilibrium core loading of Figure 4.3-1 was used for the evaluations. Nominal plant heat balances under part power conditions were used to determine the off-rated feedwater temperature and system pressure corresponding to a given power level. In addition, analyses were performed to determine the limiting cycle exposure point (Reference 15.9-4).

15.9.3.1 Global Stability

Figure 15.9-3 shows the results of the global stability analysis. At a given flow, the results were interpolated to indicate the power level for decay ratio of 0.65 and at 1-2σ as input to the BSP analysis in section 15.9.3.4

15.9.3.2 Regional Stability

The purpose of this analysis is to determine if the global mode is conservative for establishing the BSP exclusion zones. The analysis is performed at the global mode threshold statepoints or at higher power levels in order to determine if diverging regional mode oscillations will occur. If diverging regional mode oscillations occur, these results are used to find the regional mode stability threshold. The more limiting stability mode is determined by comparing the regional and global mode stability threshold statepoints. It was determined that the regional mode is bounded by the global mode. See Reference 15.9-4.

15.9.3.3 Channel Stability

The purpose of this analysis is to determine if the global mode is conservative for establishing the BSP exclusion zones. The analysis is performed at the global mode threshold statepoints or at higher power levels in order to determine if diverging channel mode oscillations will occur. If diverging channel mode oscillations occur, these results are used to find the channel mode stability threshold. The more limiting stability mode is determined by comparing the channel and global mode stability threshold statepoints. It was determined that the channel mode is bounded by the global mode. See Reference 15.9-4.

15.9.3.4 Backup Stability Protection

As discussed in the previous sections, the global stability mode was determined to be the most limiting.

The BSP region boundaries are described by functions that bound the statepoints for the limiting mode. The bounding function is described by a statepoint along the 102% flow control line [PA, WA] and the natural circulation line [PB, WB] as follows:

$$P = P_B \times \left[\frac{P_A}{P_B}\right]^{\frac{W-W_B}{W_A-W_B}}$$

where:

P = Maximum percent rated power for a given core flow

P_A = percent rated power at point A on the 102% power rod line

P_B = percent rated power at point B on the natural circulation line

W = percent rated core flow

W_A = percent rated core flow at point A

W_B = percent rated core flow at point B

These results are shown in Figure 15.9-4 for the exit and scram lines to be used by the plant operator if the plant inadvertently has less flow or more power than allowed by these lines.

15.9.4 OPRM Setpoints

The OPRM system is described in section 7.6.1.1.2. There are three algorithms used to determine an OPRM channel trip - Amplitude Based Algorithm (ABA), Growth Rate Algorithm (GRA) and Period Based Detection Algorithm (PBDA).

15.9.4.1 Amplitude Based and Growth Rate Algorithms

The ABA initiates a reactor trip signal when the relative signal amplitude exceeds a specified value. The relative OPRM signal value is compared continuously to a threshold setpoint to determine if the signal is greater than the expected noise level. If the amplitude threshold is exceeded, the algorithm begins to look for oscillatory behavior that is within the range of expected frequencies. If the range of frequencies is satisfied and the signal exceeds the amplitude setpoint, an ABA trip is generated.

The GRA initiates a reactor trip signal when the amplitude growth rate exceeds a specified value. The growth rate portion of the detection algorithm follows the same logic as the amplitude based portion, except that a trip is initiated if the calculated growth rate between successive peaks exceeds the algorithm setpoint.

The ABA and GRA are considered defense in depth and are not credited in the analysis performed for the PBDA. Therefore the generic algorithm constants shown in Table 7.6-2 are used.

15.9.4.2 Period Based Detection Algorithm

The PBDA is based on the observation that thermal-hydraulic instabilities result in neutron flux oscillations that have a known frequency range. The PBDA makes use of the number of successive oscillation cycles within that frequency range and the oscillation amplitude to determine if a reactor trip signal should be generated. The oscillation amplitude is selected to protect the Safety Limit Minimum Critical Power Ratio (SLMCPR). The trip logic of the PBDA is presented in Figure 7.6-14.

Since the PBDA is intended to protect the SLMCPR, a relationship must be derived between the oscillating signals from the OPRM cells and the resulting change in MCPR of the limiting fuel channels. This relationship is comprised of two parts. The first part is developed from an analysis of the reactor core to determine the relationship between channel power variations and the resulting variations in Minimum Critical Power Ratio (MCPR), also known as Delta CPR Over Initial MCPR Versus Oscillation Magnitude (DIVOM). The second part is the relationship between the amplitude of the Hot Channel power Oscillation Magnitude [HCOM] and the amplitude of the OPRM cell oscillations [S].

The first part of the analysis simulates a trip of three RIPs while at the operating limit MCPR at the maximum rodline with nine RIPs operating at minimum speed. There will be a change in MCPR following the trip of the RIPs as the power and flow decrease to a new statepoint corresponding to operating with six RIPs at minimum speed on the maximum rodline. The MCPR at the end of this initial transient is the initial MCPR prior to the onset of the instability. An asymmetric perturbation is introduced at the new statepoint to initiate diverging regional oscillations. These perturbations will result in time varying power, flow and MCPR for each channel. The data from twenty of the hottest channels are selected to produce pairs of delta-MCPR and corresponding delta-channel power. These data are used to develop the DIVOM curve, which provides a relationship between delta-MCPR over initial MCPR versus HCOM. This curve can be extrapolated to find the HCOM corresponding to an oscillation that reaches the safety limit MCPR. This analysis is performed each cycle to confirm that the OPRM setpoint is bounding.

The second part of the analysis develops a relationship between the OPRM cell amplitude and the HCOM necessary to initiate a reactor trip in time to prevent an oscillation from reaching the safety limit. This relationship is determined using transient 3D simulations of diverging regional mode oscillations. The OPRM signals are created from the LPRM detector signals in the same way as they are by the OPRM hardware in the plant. The HCOM is calculated for each channel from the predicted channel power. The OPRM system generates an RPS trip when two out of four channels in an OPRM cell have generated trip signals. Absent any delays, the OPRM system reflects the point in time when the maximum allowed HCOM is reached. The maximum HCOM in the core is calculated from the oscillating channel power for all channels in the core. The treatment of delays due to OPRM cell processing, trip overshoot, trip delay, etc. is described in Reference 15.9-4.

The result of this response analysis confirms that the standard values of the PBDA amplitude trip setpoint, Sp = 1.1 and the confirmation count setpoint, Np = 10 will keep the fuel above the SLMCPR should an instability event occur that requires OPRM mitigation.

15.9.5 COL License Information

The COL applicant shall evaluate plant data for steam dome pressure and feedwater temperature for low power and flow conditions and, using that information, together with the fuel design, establish BSP curves based on the core loading pattern.

The COL applicant shall perform a DIVOM analysis based on the core loading pattern to confirm the OPRM setpoints.

15.9.6 References

15.9-1 NEDO-31960-A, "BWR Owners' Group Long Term Stability Solutions Licensing Methodology," June 1991.

15.9-2 NEDO-31960-A Supplement 1, "BWR Owners' Group Long-Term Stability Solutions Licensing Methodology Supplement 1," March 1992.

15.9-3 NEDO-32465-A, "BWR Owners' Group Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology for Reload Applications," August 1996.

15.9-4 WCAP-17137-P, Rev 0, "Westinghouse Stability Methodology for the ABWR," October 2010.

Table 15.9-1 Option III Backup Stability Protection (BSP) Regions

Power / Flow Point	% Flow	% Power	Comments
A1	36.0	56.3	BSP scram region – nominal feedwater temperature
B1	19.0	25.0	
A2	40.0	61.5	BSP exit region – nominal feedwater temperature
B2	19.0	25.0	

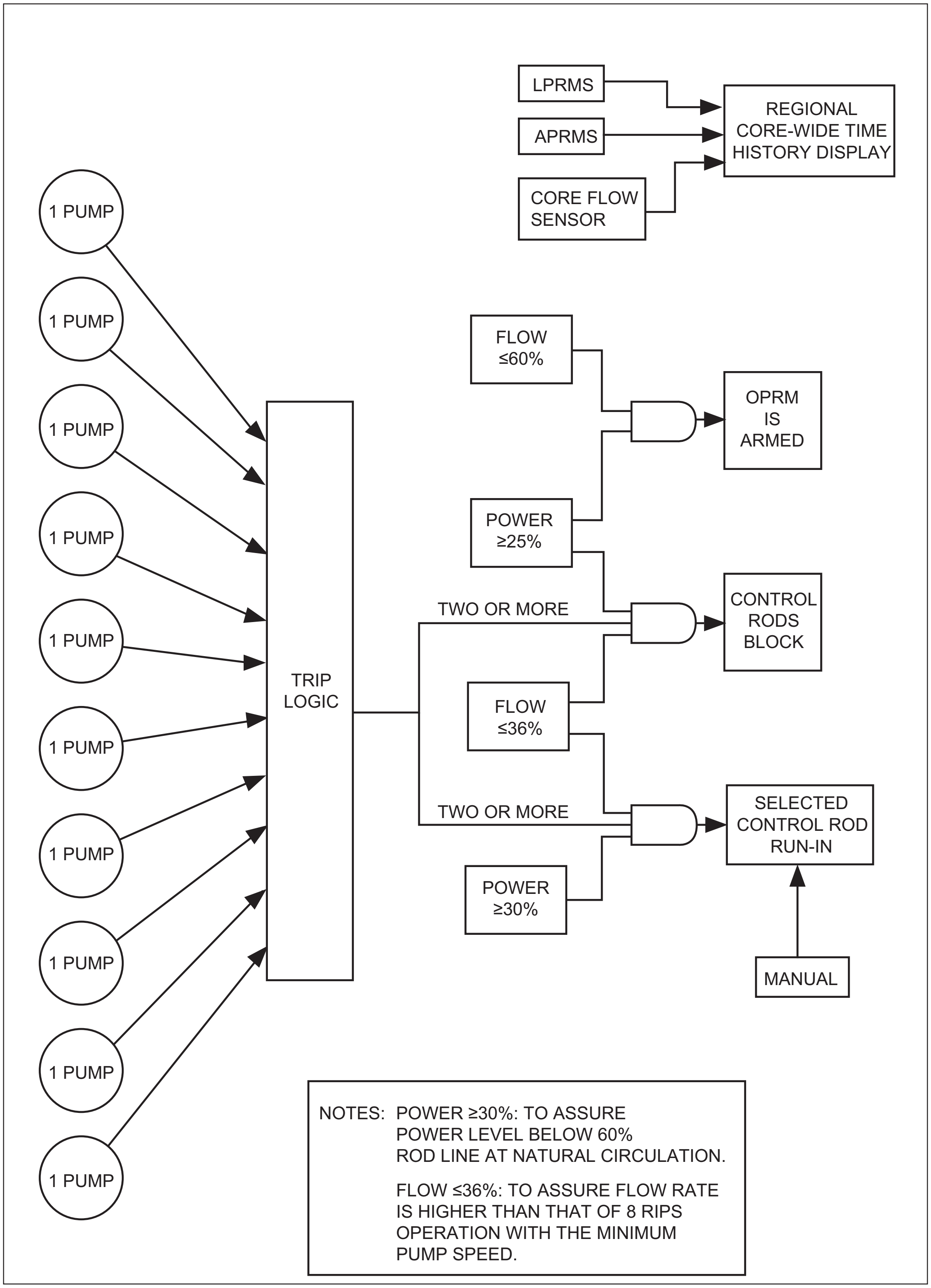

Figure 15.9-1 Stability Controls and Protection Logic

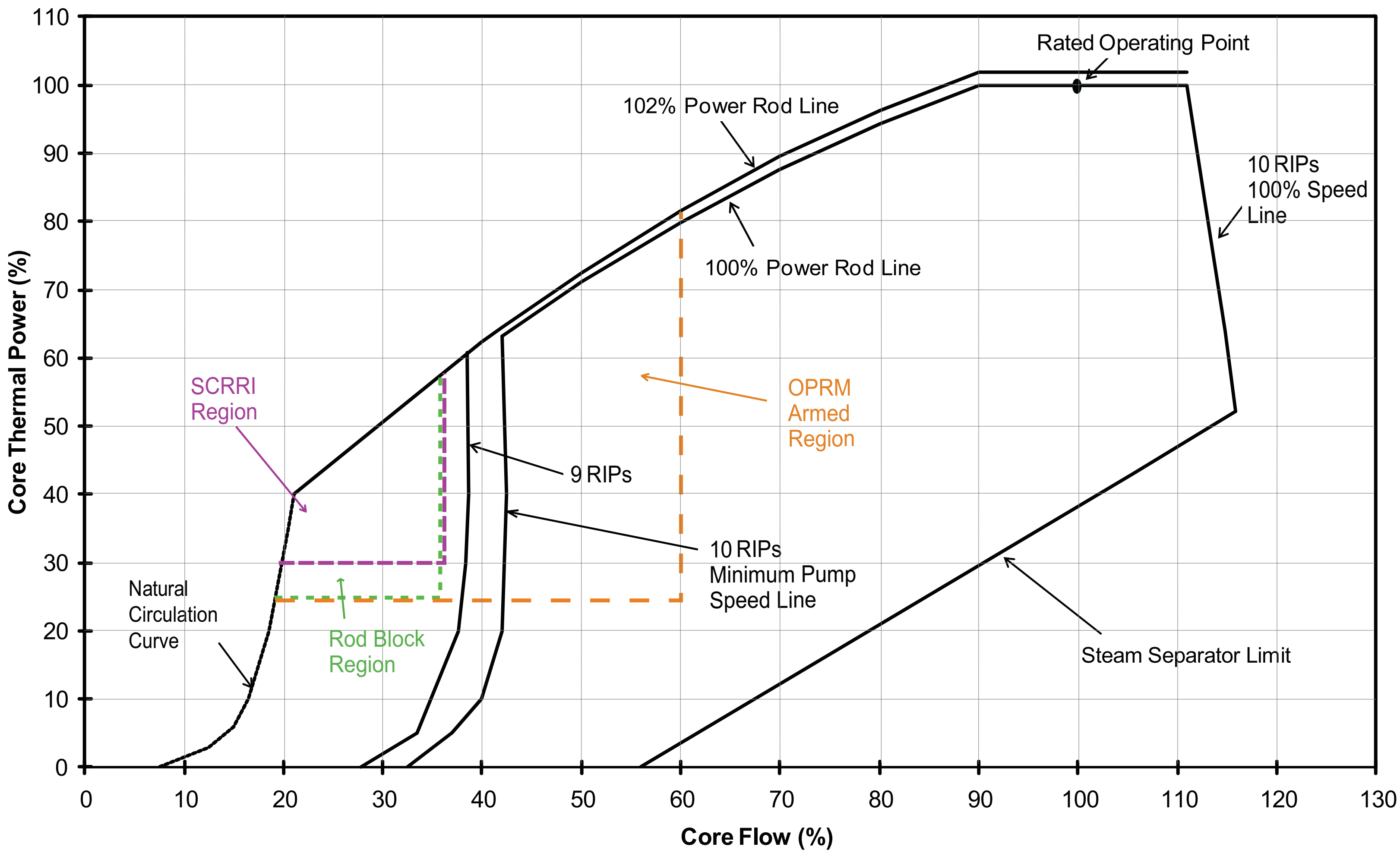

Figure 15.9-2 ABWR Power/Flow Map With Stability Protection Zones

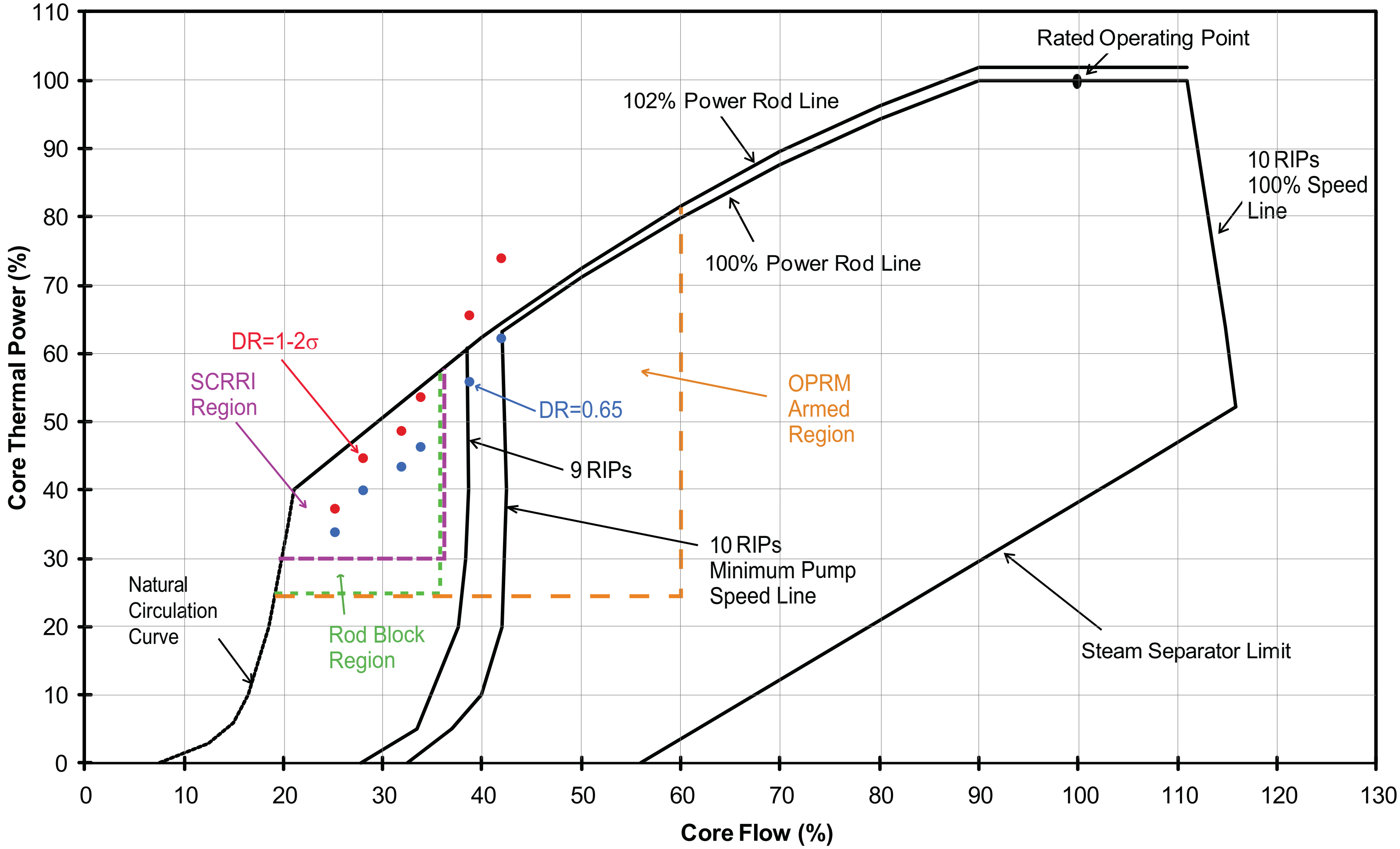

Figure 15.9-3 Global Mode Stability Results

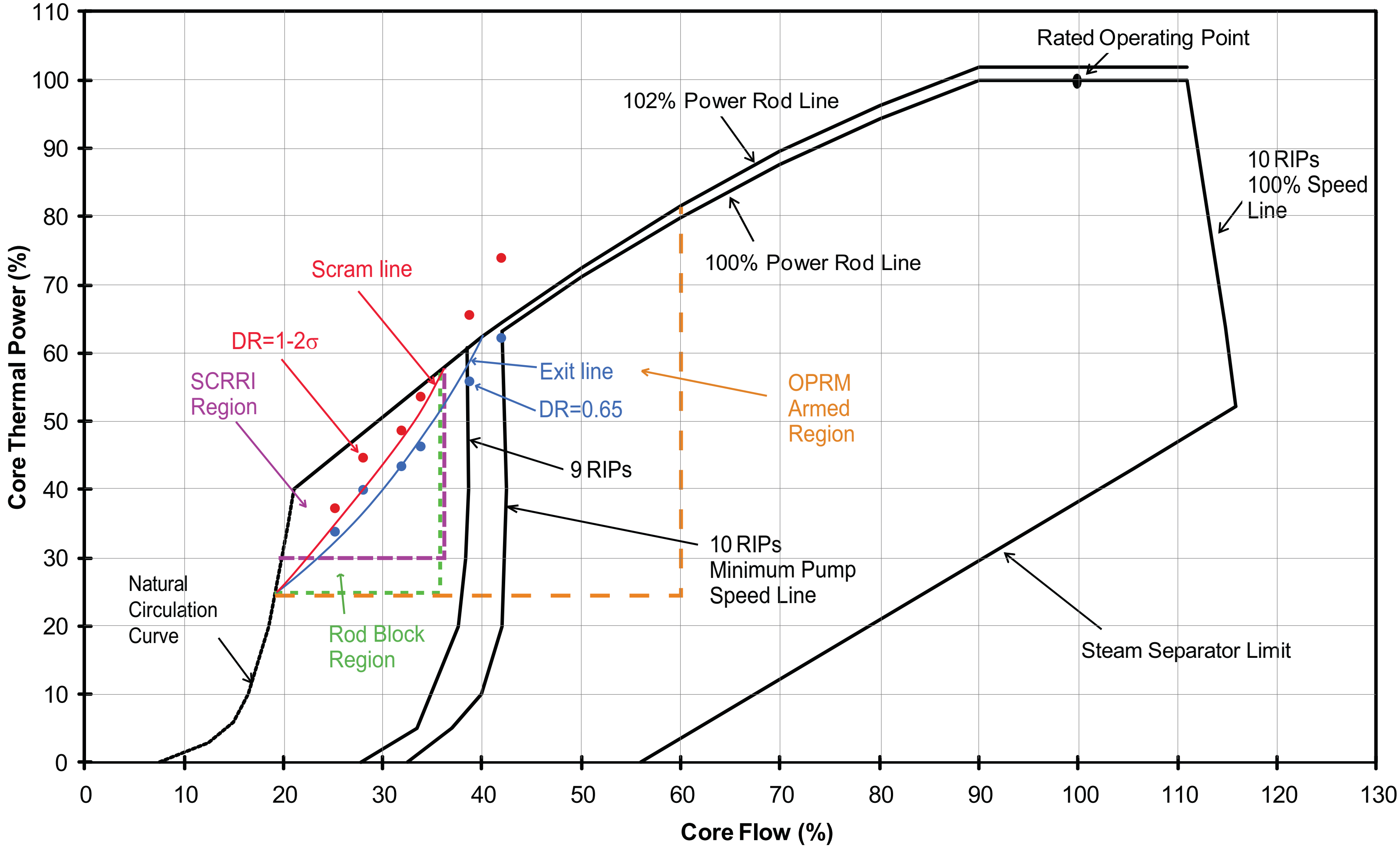

Figure 15.9-4 BSP Exclusion Zones