ROP Optimization Modules in ROVER-F

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Abstract

To maximize reactor operating margin, interest has focused on optimizing the regional overpower protection (ROP) in-core detector systems. Two potential means of accomplishing this task are using fuel-management techniques to increase ROP margins (REFORM), and detector-layout optimization (DLO), which selects assembly and detector locations where they are of maximum benefit. ROVER-F is the design and analysis ROP code that AECL uses to perform probabilistic assessments of the ROP systems. It has recently been expanded to address REFORM and DLO tasks.

1. Introduction

Recently, increased interest has been shown in seeking ways of optimizing the current regional overpower protection (ROP) systems in CANDU® reactors. Several means of enhancing margin to dryout have been proposed. These methods include improvements to the instrumentation (to reduce uncertainties) and to the heat-transport system (to increase critical channel powers, CCPs). Here, we outline some recently developed tools that allow the re-optimization of the ROP system. The ROP system was designed to provide the maximum operational envelope for a set of core conditions. ROP effectiveness is currently analyzed using the code ROVER-F [1]. Over time, variation of core conditions results in departure from an optimized ROP system. The use of REFORM and detector-layout optimization (DLO) methods may help to recover operational margin.

2. The ROP System

The safe operation of CANDU reactors requires the prevention of fuel damage, which may occur if the fuel sheath temperature were to exceed the temperature at which the coolant can efficiently remove heat. The CCP is the power at which this fuel dryout would be expected to occur, and protection against overpowers sufficiently large to cause dryout is provided by two independent regional overpower protection (ROP) systems, one for each of the special reactor shutdown systems. Each of these ROP systems consists of an array of in-core flux detectors, organized into three safety (or logic) channels. Flux detectors associated with SDS-1 (vertical shutoff rods) are arrayed within the vertical detector assemblies. Flux detectors associated with SDS-2 (liquid-poison injection) are arrayed in horizontal detector assemblies. Each ROP system is capable of independently initiating the shutdown of the reactor by actuating the corresponding shutdown system. The ROP safety-system-actuation logic is triplicated: within each of the three safety channels of each ROP system, a single detector reaching its setpoint will actuate ("trip") that safety channel, and the trip of two of the three safety channels in an ROP system will trip the associated shutdown system. Thus the ROP system is designed so that for any potential damaging overpower in the fuel, at least one detector in each safety channel will reach its setpoint.

The probability that each of the ROP systems will generate a signal to actuate a shutdown before dryout occurs in any fuel channel is called the "trip probability". Each ROP system must be designed so as to meet a licensing requirement of a 98% trip probability for each of a "design basis" set of flux shapes. The analysis usually also assumes that the logic channel most likely to trip is unavailable. The design that accomplishes this is a function of several factors:

- the physical layout and channelization of the ROP detectors
- the flux shapes associated with the design basis set of flux shapes
- the uncertainties and biases associated with the channel powers, critical channel powers, and detector responses
- the setpoints determined or selected for each detector

The ratio of the critical channel power to the operating channel power is called the critical power ratio (CPR). This ratio is a measure of the margin (in power) to dryout, and it decreases as the total power increases. A ripple-conservatism factor quantifies the effect of the local power ripple (i.e., the ratio of instantaneous to reference channel power) relative to the allowance made to the detector calibration, based on the maximum ripple in the high-power region of the core (the CPPF region).

ROP uncertainties are divided into three groups:

- Detector-random uncertainties are random errors that vary from detector to detector (e.g., recalibration errors).
- Channel-random uncertainties are random errors that vary from fuel channel to fuel channel (e.g., uncertainty in channel power).
- Common-random uncertainties are random in expected value but affect in a common way all fuel channels or detectors (e.g., uncertainty in the total reactor power).

The detector-random and channel-random uncertainties are applied to all the detectors in the safety channels and the fuel channels, respectively, to produce error densities and distributions for each flux shape. The channel-random and common-random error densities are combined to form a common-mode error density. The detector trip probability distribution is multiplied by the common-mode probability density to arrive at a final value of trip probability for each flux shape.

The flux shapes used for the analysis of the ROP system are of two types:

- flux shapes consisting of the nominal time-average flux shape and perturbations thereon (reactivity device positions, xenon transients, etc.);
- instantaneous flux distributions of the reactor, in the form of channel-power ripples.

The calculation of trip probability is based on all these factors; any change in them will result in a change to the trip probability, and by extension to the trip setpoints required to maintain the 98% trip probability. These calculations are performed at AECL by using the code ROVER-F [1].

3. The ROVER-F code

ROVER-F is a FORTRAN program that calculates, for a given set of flux shapes, the trip probability and the setpoints required to attain the target trip probability. The first incarnation of ROVER-F was obtained by translating modules of the previously existing ROVER/REFORM code from APL to FORTRAN; this initial version was validated by comparison with standardized benchmark cases [1].

A number of additional capabilities, unavailable in ROVER/REFORM, were built into the ROVER-F code. The ability to define the size of the increments used for integration of probability distribution and of convolution has resulted in a greatly increased accuracy in ROP calculations. To simplify the computation of trip probability, the rippled critical power ratios (the CPR obtained from the instantaneous channel powers, as opposed to steady-state channel powers) are binned, or grouped, based on their ratio to the limiting critical power ratio (the minimum of the critical power ratios). ROVER-F permits the specification of the bin size, with the potential for greater accuracy with smaller bin sizes. ROVER-F supports fully variable array dimensioning, permitting it to be used with any detector channelization scheme. ROVER-F is a stand-alone code. Setpoints are calculated automatically, and the code can perform tasks directed by input, such as trip-probability calculations assuming single-detector failure and trip-probability calculations for individual channel-power ripple maps (instantaneous trip probability).

The overall modular design of the ROVER-F code allows the addition of functions that utilize the trip-probability calculations. The ROP design optimization modules (REFORM and DLO) have been added and take advantage of ROVER-F's data structures and probability calculation tools to perform their calculations.

4. REFORM

The application of REFORM factors to the channel power map, for the purpose of increasing the ROP trip margin, 'tunes' the overall power shape of the core to maximize the ROP margin. This power shape may then be used as a target for refuelling.

REFORM adjusts the critical power ratio in each channel in the core so that probabilistic ROP coverage is uniform throughout the core and maximized over all limiting ROP cases.

To accomplish this, some power is diverted from channels for which the limiting ROP case has lower trip probability to channels for which the limiting cases have higher trip probability. Typically, this results in power being redistributed in the high-power region of the core and diverted from the centre of the core to outer channels.

The REFORM module in ROVER-F begins its task by determining the ROP-trip setpoint for each ROP flux shape being optimized. Each channel power is then adjusted, in turn, until the its setpoint for the most limiting flux shape for that channel is reduced to the minimum setpoint. The power for limiting channels is maintained, while the power for other channels is increased to match the limiting CPR. These individual channel powers are then re-normalized (since all channel powers are increased or maintained) to attain the overall reactor power. Typically, in CANDU 6 cores, this normalization results in an increase of the channel powers in the outer core and a decrease of the channel powers in the core interior. The REFORM solution is practically bounded by the channel power map attainable by fuelling. There are limits to the power that may be set as a target for any channel, the variation in power from channel to channel, and the overall shape of the power distribution.

4.1 REFORM Theory

The theory of the REFORM calculation is conceptually simple. It is desirable to increase the power of each fuel channel to reach a CPR such that any further increase in power in that channel would have a negative effect on the trip confidence for the flux shape that is most limiting for that channel. Typically, only a few fuel channels will be limiting to the core as a whole, allowing all other channels to be increased in power, relative to the limiting channels. By normalizing to the overall reactor power, the reference power in these limiting channels is decreased. This decrease, as these cases are limiting, results in an increase in the overall limiting CPR, and thus in the trip confidence and ROP setpoint.

The REFORM factor, the factor by which a fuel channel should be modified, is given by

$$REF = \min_{case}\left[\frac{\Phi}{\alpha\Phi_0^T}\left[\frac{CCP}{CP}\right]\frac{1}{EA}\right]$$

where Φ is the normalized detector reading, CCP is the critical channel power, CP is the channel power, EA is the error allowance, Φ_0^T is the detector trip setpoint, and the change in the detector trip setpoint after the REFORM is α. Thus the process is iterative: as the detector trip setpoint changes, the REFORM factor for each channel also changes. This process converges to a solution. There is a REFORM factor for each channel of the core, and the channel powers are normalized to the reactor power.

4.2 REFORM Validation

The validation of the REFORM module requires, as for the trip-probability calculation, the definition of simple cases that can be analytically solved. Several test cases have been developed, and they all work from a single fundamental state. The CPs, CCPs, detector readings and setpoints, and ripples are all set to uniform values. These values can then be perturbed individually to force a pre-determined analytical solution.

Several tests have been performed, with deviations in CP, CCP, ripple and detector response being tested. These tests are outlined in Table 1, and will be briefly described here.

The simplest of the validation tests is to change the CCP of specified channels. If the CCPs of some channels are decreased, we should see a corresponding decrease in the REFORMED channel powers of those channels (and an increase in the channel powers of the remaining channels). Because the detector responses and setpoints are identical for all cases, only the relationship between the CP and the CCP affects the CPR. The resulting CPR should be identical for all cases. As can be seen from Figures 1 to 3, this is indeed the case. The CCP in ten channels (one in each of 10 flux shapes) was arbitrarily set to 4 MW and in all other channels 5 MW. The resulting REFORMED power map has a limiting CPR of 1.65 for all channels.

We can obtain a similar solution for cases where the channel power has been changed in several channels. In this case, again the limiting CPR of the resulting power shape should be the same for all channels and all cases. The CCP for all channels and cases is the same, and the channel powers of the non-nominal cases remain in their perturbed shapes, but the channel power map of the reference case is changed such that the CPRs are the same for the limiting case for each channel. Note again that only the CPR-limiting, perturbed channels, will have identical CPRs.

To validate against perturbations in detector response and setpoint is more difficult. Because the REFORM factor is based on the individual CPR for a fuel channel, detector parameters will affect the reactor as a whole rather than individual channels. Thus we show the difference for two different setpoints and detector responses.

Perturbations in power ripple are similar to those for detectors in that they affect all cases. Further complicating matters is the ripple-conservatism factor, which corrects for differences between the limiting CPR channel and the limiting rippled CPR channel. Tests were performed to demonstrate that the REFORM factors accounts for this properly, by using the CCP test and applying a ripple to the channels that are perturbed by the CCP change. The limiting CPRs corrected for the ripple conservatism factor should match for all channels.

As can be seen from Table 1, ROVER-F results for all cases are as expected from the analytical considerations.

5. Detector Layout Optimization

Another means by which the ROP margin can be improved is to re-optimize the layout of the assemblies and detectors for ROP coverage. Tools to assist in this process have been developed to determine the minimum deterministic number of detectors for ROP coverage. These are the detector layouts that use the minimum number of detectors to provide ROP coverage for every anticipated shape. This process takes into account the detector response at all analyzed potential detector locations and the flux shapes required for loss-of-regulation analysis, as well as the envelope of flux shapes within which the reactor is expected to operate or manoeuvre. A DLO module has been developed that analyzes all possibilities and determines solutions for the minimum number of detectors and their channelization, for a deterministic solution for ROP coverage. This solution provides trip coverage, but does not account for the ROP uncertainties. Thus, the solutions determined by the DLO may then be used by the ROP analyst to determine a probabilistic solution for ROP coverage, typically by adding further detectors to the solution to eliminate limiting cases.

5.1 The DLO Algorithm

The DLO module works in several stages. The first step is to identify 'economically important' cases (flux shapes) and the operating power levels desired. The trip setpoint is adjusted to the value for which the minimum number of detectors can see each case. For current ROP logic (two-out-of-three-channel trip, with the most effective safety channel assumed unavailable), this means that each case must be seen by at least three detectors, one per safety channel. The result of this process is a matrix of logical values (true or false) indexed by case and detector. A true value indicates that a case is covered by a detector. A false value indicates that it is not covered by that detector.

This matrix is then reduced. This is done in two steps. First, any case that is covered by a set of detectors, for which a subset of detectors can be found that are the tripping detectors for a second case, is considered redundant and that case is removed. This step is taken because any trip that would occur for the case using the smaller number of detectors would also occur for the case using the larger number of detectors.

After reducing the number of cases, the number of detectors is reduced. Any detector that trips for a number of cases that are a subset of the cases that trip for a different detector are considered redundant and that detector is removed. The justification is that the detector covering the larger number of cases makes the other detector redundant. The exception to this rule occurs when the removal of the redundant detector would reduce the number of detectors tripping for any case below the lower limit (three detectors). In this case, it would be impossible to place a detector in each safety channel, so the redundant detector is maintained.

Now all potential solutions for a single safety channel may be determined. This task is performed by generating a logic tree and building individual safety channels on a case-by-case basis. Solutions are generated so that they satisfy every case, by proceeding sequentially through the cases and adding detectors, as necessary. This results in a group of potential solutions that are examined in turn for completeness. Potential solutions are checked to determine whether they are made redundant by the existence of smaller solutions sets. If a detector set with N detectors covers all cases, then any solutions with the same detectors plus others are obviously non-optimal. The single-channel solutions are also cleared of redundant solutions.

The set of single-channel solutions is searched to see if three independent single-channel solutions can be found (three solutions that do not share any individual detectors). This is done for the minimum total number of detectors possible from the single-channel solutions. If no solution is found for a total number M of detectors, then M is incremented, and a search for solutions with M + 1 detectors is initiated until the maximum possible size, based on the size of the single-channel solutions, is reached.

If no solution is found, even at the maximum size, then the setpoint is decreased, to permit more detectors to reach trip and cover cases, and the entire process is repeated, until a solution is found.

The result from this process will be a list of potential solutions using a minimum number of detectors, spread over three safety channels, each covering every case specified. The process can be set to look for solutions of at least a certain size, or below a certain setpoint. The solution set will be complete, unless a very large number of solutions is found, in which case the first 100 solutions will be listed.

5.2 Verification of DLO

To verify that the DLO module works correctly, it is tested on small but non-trivial case sets. These sets can be confirmed analytically to have the same answer as that obtained from the DLO module. Because we confirm that all possible solutions are examined, all that is required is to confirm that the criterion for the solution is correct.

The test chosen has 20 detectors, potentially covering 10 simple cases. The detectors have their readings randomly specified, whereas the setpoints for each detector, and the CPR for each case are set to constant values, for all cases. The setpoint required to obtain a minimum of three detectors for each case is 124.51. The resulting logic table is presented in Table 2. Reduction of the cases in this table eliminates cases 10 and 2. The elimination from consideration of redundant detectors 2, 7, 10, 14, 18, 20, 15 and 11 is due to detector 6, which covers all of the flux shapes covered by these other detectors. Additionally, detectors 13, 9 and 16 could be removed, but these are maintained because their removal would reduce the number of detectors to below three for some cases. Once these detectors are eliminated, the case set can be further reduced, by eliminating cases 1, 6, and 9. Further, 5 detectors cover no cases at the specified setpoint. Thus we have a reduced set in which 5 cases are covered by a total of 7 detectors. The list of covering detectors for each case is seen in Table 3.

Now the DLO process determines whether the cases can be covered by a single detector. The answer is no, and so it increments the number of detectors permissible in each channel. For two detectors per channel four solutions are discovered:

6,17
4, 6
1, 6
1,16

Each of these pairs covers all five cases; however, there is no set of three of these cases that is independent. Thus the solution is incremented to three detectors per channel. There are 10 possible non-redundant solutions identified which use three detectors per channel. However, all but three of these are merely the two detectors-per-channel solutions with a further detector added, and these may be discarded (because they add nothing new, and require an extra detector). Three solutions remain:

9,16,17
9,13,17
4, 9,16

Of these solutions with both two and three per channel, only one combination of three one-channel solutions is found to be completely independent:

1,16
4, 6
9,13,17

Thus the minimum solution for coverage is seven detectors. This solution can easily be verified by hand.

Note that other solutions do exist, using the detectors found to be redundant in the first step. The analyst would be required to examine the detectors that were chosen and eliminated, to determine alternate solutions, using detectors that are found to be redundant. (In this case, detectors 15 and 11 could be switched for detector 9).

6. Conclusions

Both the REFORM and the DLO modules have been incorporated in the ROVER-F ROP analysis and design code. They make use of the ROVER-F trip-probability-calculation module. The REFORM module has been verified by comparison with ROVER/REFORM and has been validated using test cases. The Detector Layout Module has been validated by comparison with test cases that can be solved analytically. Both modules provide tools for use in increasing the ROP margin for CANDU plants.

7. Reference

[1] John Pitre and Frank Laratta, "Validation of the ROVER-F Code for ROP Trip Probability Calculations", in Proceedings of the 18th Annual CNS Conference, Toronto, Ontario, 1997 June 1997.

Table 1: REFORM Benchmark Tests

All tests start with the following parameters:

CCP	= 5 MW in all channels for all flux shapes
CP	= 3 MW in all channels for all flux shapes
Detector Readings	= 1.0 for all detectors for all flux shapes
Detector Setpoints	= 1.25 for all detectors
Ripples	= 1.0 for all channels for all ripples

Test	Means	Results
CCP	Change CCP in10 channels to 4 MW	All channels to equal limiting CPR
CP	Change CP in 9 non-nominal CP to 4 MW	All channels to equal limiting CPR
Detector	Change a single reading in each safety channel for a single case to 0.9.	Trip confidence changes, but no change by REFORM to flux shape.
Setpoint	Change a setpoint in each safety channel for a single case to 1.1	Trip confidence changes, but no change by REFORM to flux shape..
Ripple	As per CCP test and same channel ripples increased to 1.2.	All channels to equal limiting CPR, corrected for ripple.
Ripple	As per CCP test and non-same channel ripples increased to 1.2.	Trip confidence changes, but no change by REFORM to flux shape from the solution for the CCP test above..

Table 2: Table of Covering Detectors for DLO Benchmark Test

ROP Case

Det #	1	2	3	4	5	6	7	8	9	10	Total
1	T	T	F	T	T	F	F	F	T	F	5
2	F	F	F	F	F	F	F	F	T	F	1
3	F	F	F	F	F	F	F	F	F	F	0
4	F	F	F	T	F	F	F	T	F	T	3
5	F	F	F	F	F	F	F	F	F	F	0
6	T	T	T	F	T	T	T	T	T	T	9
7	T	T	F	F	F	F	F	F	F	F	2
8	F	F	F	F	F	F	F	F	F	F	0
9	T	T	F	F	T	T	F	T	F	T	6
10	F	F	F	F	F	F	T	F	F	F	1
11	T	T	F	F	T	F	F	T	F	F	4
12	F	F	F	F	F	F	F	F	F	F	0
13	T	T	F	F	F	F	T	F	T	F	4
14	F	F	F	F	F	F	F	T	F	T	2
15	F	F	F	F	T	F	F	T	F	T	3
16	T	T	T	F	F	T	T	T	T	T	8
17	F	F	T	T	F	T	F	F	F	T	4
18	F	F	T	F	F	F	F	F	F	T	2
19	F	F	F	F	F	F	F	F	F	F	0
20	T	T	F	F	F	F	F	F	F	F	2
	8	8	4	3	5	4	4	7	5	8	

Table 3: Reduced Covering Detector Table for DLO Benchmark

Case

Det #	3	4	5	7	8	Total
1	F	T	T	F	F	2
4	F	T	F	F	T	2
6	T	F	T	T	T	4
9	F	F	T	F	T	2
13	F	F	F	T	F	1
16	T	F	F	T	T	2
17	T	T	F	F	F	2
	3	3	3	3	4	

Figure 1: Initial Reference Channel Powers

								3.00	3.00	3.00	3.00	3.00	3.00								
					3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00					
				3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00				
			3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00			
		3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
		3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
		3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
		3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00		
			3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00			
				3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00				
					3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00					
								3.00	3.00	3.00	3.00	3.00	3.00								

Figure 2: REFORMED Channel Powers

								3.02	3.02	3.02	3.02	3.02	3.02								
					3.02	3.02	3.02	**2.41**	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02					
				3.02	**2.41**	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	**2.41**	3.02	3.02				
			3.02	3.02	3.02	3.02	3.02	3.02	3.02	**2.41**	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02			
		3.02	**2.41**	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	**2.41**	3.02	3.02	3.02	3.02	3.02	3.02		
		3.02	3.02	3.02	**2.41**	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	**2.41**	3.02	3.02	3.02	3.02		
	3.02	3.02	3.02	3.02	3.02	**2.41**	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	**2.41**	3.02	3.02	3.02	3.02	
	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02
	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	
		3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02		
		3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02		
			3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02			
				3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02				
					3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02	3.02					
								3.02	3.02	3.02	3.02	3.02	3.02								

Figure 3: Limiting Critical Power Ratios

								1.66	1.66	1.66	1.66	1.66	1.66								
					1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66					
				1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66				
			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66			
		1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66		
		1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66		
	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	
	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	
1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	
	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	
		1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66		
		1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66		
			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66			
				1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66				
					1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66					
								1.66	1.66	1.66	1.66	1.66	1.66								