ACCELERATING ROP DETECTOR LAYOUT OPTIMIZATION

Doddy Kastanya and Barbu Fodor

Candu Energy Inc.
2285 Speakman Drive, Mississauga, ON, Canada L5B 1K1

Abstract

The ADORE (**A**lternating **D**etector layout **O**ptimization for **RE**gional overpower protection system) algorithm for performing the optimization of regional overpower protection (ROP) system for CANDU®[1] reactors have been recently developed. The simulated annealing (SA) stochastic optimization technique is utilized to come up with a quasi optimized detector layout for the ROP systems. Within each simulated annealing history, the objective function is calculated as a function of the trip set point (TSP) corresponding to the detector layout for that particular history. The evaluation of the TSP is done probabilistically using the ROVER-F code. Since during each optimization execution thousands of candidate detector layouts are evaluated, the overall optimization process is time consuming. Since for each ROVER-F evaluation the number of fuelling ripples controls the execution time, reducing the number of fuelling ripples used during the calculation of TSP will reduce the overall optimization execution time. This approach has been investigated and the results are presented in this paper. The challenge is to construct a set of representative fuelling ripples which will significantly speedup the optimization process while guaranteeing that the resulting detector layout has similar quality to the ones produced when the complete set of fuelling ripples is employed. Results presented in this paper indicate that a speedup of up to around 40 times is attainable when this approach is utilized.

1. Introduction

The regional overpower protection (ROP) systems in the CANada Deuterium Uranium (CANDU®) reactor protect the reactor against overpower in the fuel which could originate from either a bulk power increase during a slow-loss-of-regulation (SLOR) event or from a more localized power peaking within the core (for example, due to certain reactivity device configurations). The overpower could lead to fuel sheath dryout which is a condition where the fuel is operating at temperatures higher than the desired temperature. During a dryout event the coolant around the fuel sheath surface produces many small bubbles that could eventually coalesce into a vapour film enveloping the fuel element. This reduces the heat transfer from fuel to the coolant and in turn further elevates the fuel temperature. If uncontrolled or undetected, this event could lead to fuel failures.

To protect the core from this fuel failure event, in the CANDU 600 MW (CANDU 6) design, there are two ROP systems where each system consists of three independent safety channels and

[1] CANDU is a registered trade-mark of Atomic Energy of Canada Limited, used under exclusive license by Candu Energy Inc.

is connected to a fast-acting shutdown system. These two systems use different mechanisms to shutdown the reactor and are physically separated (see Figure 1). More detailed descriptions of the ROP systems can be found in [1].

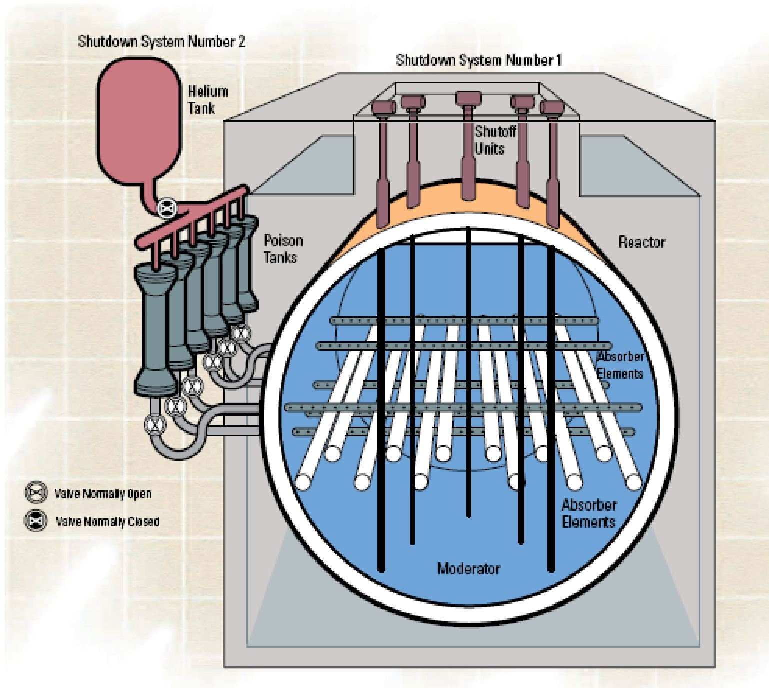

Figure 1. CANDU 6 Shutdown System.

The placement of the ROP detectors in the core is a challenging discrete optimization problem. The design for the current CANDU 6 plants were determined using a method called the detector layout optimization (DLO) [2]. Unfortunately, when the design process involves thousands of potential detectors and hundreds of flux shapes[2], the DLO methodology does not perform well. To circumvent this issue, in recent years the DETPLASA [1] and ADORE [3] algorithms have been developed. It has been shown that both algorithms can produce a solution for a design problem where more than 500 flux shapes and more than 2000 candidate detectors are involved.

Both of these new algorithms employs the simulated annealing (SA) stochastic optimization technique [4] to come up with an optimized detector layout for the ROP system. For each history in the SA iteration where the performance of a given detector layout is evaluated, the goodness of this detector layout is measured in terms of its trip set point (TSP) value which is obtained by performing a probabilistic TSP calculation using the ROVER-F code [5]. Since for each ROVER-F evaluation the execution time is a strong function of the number of fuelling ripples used in the analysis, reducing the number of fuelling ripples will reduce the overall

[2] "Flux shapes" are various flux and power distributions caused by changes to device configuration (including zone-controller fills) or xenon distribution from the nominal distribution (where the term "nominal" refers to normal operating core configuration where the average zone controller level is around 50%, the adjusters are fully inserted, and the mechanical control absorber rods as well as the shutoff rods are fully withdrawn).

execution time. This approach has been investigated and the results are presented in this paper. The challenge is to construct a set of representative fuelling ripples which will significantly speedup the optimization process while guaranteeing that the resulting detector layout has similar quality to the ones produced when the corresponding original complete set of fuelling ripples is utilized.

2. Methodology

2.1. ROP TSP Calculations

The current safety requirement of an ROP system is that it must actuate a reactor trip before the onset of intermittent dryout (OID) in any fuel channel. Realistically, it is physically prohibitive to detect the dryout of a fuel bundle among 4560 fuel bundles in a 380-channel CANDU 6 reactor. Instead of monitoring the OID directly, the ROP analyses are performed by monitoring two quantities called the margin-to-trip (MTT) and the margin-to-dryout (MTD). The MTT is defined as the ratio between the reactor power at which the ROP system will actuate the shutdown system and the actual reactor power. The MTD is defined as the ratio between the channel power at which dryout will first occur (the corresponding channel power level is called the critical channel power or CCP) and the actual channel power. The relation between these two quantities is the basic equation in the ROP analysis.

Mathematically, the basic ROP safety requirement can be described by the following inequality:

$$MTT \leq MTD \tag{1}$$

or

$$\frac{TSP}{\phi} \leq \frac{CCP}{CP} \tag{2}$$

where TSP is the trip set point, ϕ is the detector reading (appropriately normalized to 100% full power), CCP is the critical channel power and CP is the channel power.

2.1.1. Basic Equation (deterministic)

In the design and operation of the ROP systems, changes in the neutron flux distribution (and the corresponding power distribution) from the nominal condition can be categorized into two types:

a. *Flux Shapes*. The flux shapes are various flux and power distributions caused by changes to device configuration (*e.g.*, changes in liquid zone controller fill, shutoff rod position, mechanical control absorber position, or adjuster position) or xenon distribution from the nominal distribution.

b. *Fuelling Ripples*. Fuelling ripples are the variations in the core power distribution that are due to fuelling. This is an important aspect in CANDU fuel management since it employs an "on-power" refueling philosophy where, to maintain a critical reactor, the core is being fuelled few times a week while still operating at full power (or at the maximum licensed operating power). The fuelling ripples used in the ROP analyses come from either plant operating data or core-follow simulations. More detailed discussion on fuelling ripples is provided in Section 2.2.

Starting with these two definitions, the basic ROP safety requirement (as shown in Eq. (2)) can be further expanded. The requirement is that for any flux shape k and ripple q, each safety channel must trip before the power in any fuel channel reaches the corresponding CCP for that fuel channel. This means that the detector locations, detector channelizations in the safety channels, and the trip set point (TSP) must be determined carefully such that for each flux shape considered, there is at least one detector $j_{p,i}$ in each safety channel i which satisfies the following expression:

$$TSP(j_{p,i}) \leq \phi(j,k) \times r_{CPRL}(k,q) \, , \tag{3}$$

where $TSP\left(j_{p,i}\right)$ is the installed trip set point for protecting detector j (the subscript p is used to emphasize that it is a protecting detector), in logic channel i; and, $\phi(j,k)$ is the normalized detector reading at detector j for flux shape k (and may include various calibration terms depending on plant operation). The detector reading for each flux shape is normalized to the detector reading for the nominal flux shape and thus is invariant to fuelling ripple; and $r_{CPRL}(k,q)$ is the minimum critical power ratio (*i.e.*, the MTD) for flux shape k and fuelling ripple q. Symbolically it can be written as

$$r_{CPRL}(k,q) = \min_{m}\left\{\frac{CCP(m,k)}{CP(m,k) \times RIP(m,q)}\right\} \tag{4}$$

where m is the fuel channel index and $RIP(m,q)$ is the ripple value for channel m for q fuelling ripple set.

In practice, there are some modifications to be made to Eq. (4) to account for the followings:

1. *Allowance for uncertainties*. The final trip set point for a given ROP design is determined by a trip probability calculation for each of the design-basis flux shapes. These are flux shapes that may occur during normal reactor operation. In this calculation, the TSPs are, in effect, adjusted until they meet the target trip probability for the pre-determined set of flux shapes.

2. *Fuelling Ripple*. The *RIP* term in Eq. (4) refers to the channel ripple which is defined as the ratio of observed (*i.e.*, snapshot from the plant operation) channel power to the nominal flux shape channel power.

3. *Calibration and channel power peaking factor (CPPF)*. Ripples and, hence, the corresponding CPPF (which is the maximum value of channel ripples for a particular snapshot) are tracked during operation and relevant factors are applied to the detector readings. It should be noted that the detector calibration factor is plant specific.

To account for these modifications, the protection equation may be written in the final form,

$$TSP(j_{p,i}) \leq \phi(j,k)_{prot} \times \left\{\frac{CCP(m,k)}{CP(m,k) \times RIP(m,q)}\right\}_{Lim} \times D_C \tag{5}$$

where the subscript "prot" denotes the detectors that protect flux shape k. For each flux shape, there must be at least one protecting detector in each safety channel for each shutdown system. The factor "D_C", the detector calibration factor, represents a number of correction factors for CCPs and detector readings.

To determine the appropriate TSP value which will satisfy the target trip probability, a probabilistic TSP calculation is performed using the ROVER-F code. The details concerning steps for calculating the TSP can be found in [5].

2.2. Fuelling Ripples

One of characteristic features of the CANDU reactors is its ability to perform on-power refueling. Considering the fact that the CANDU reactor is fuelled by natural uranium fuels, the on-power refueling is needed to maintain the reactor at a critical condition. Responding to fuelling, the power in a channel just refueled increases immediately then decreases over time until this channel is fuel again. The neighboring channel powers are also affected due to the changes in the neutron flux distribution in the area adjacent to the channel being fuelled. This process, when performed on all fuel channels over a long period of time, will eventually produces average channel power distribution over this time period which is comparable to the time-average results. The variation in the channel power distribution between a snapshot after refueling a channel and the corresponding time-average channel power distribution is called the fuelling ripple. The fuelling ripple for each fuel channel is defined as the ratio of the current channel power to the nominal channel power.

For the purpose of calculating the ROP trip set point, the fuelling ripples can come from either the actual fuelling history from an operating CANDU reactor or from core-follow studies using the *SIMULATE module of RFSP (Reactor Fuelling Simulation Program) code [6]. The fuelling ripples which come from the operating reactor will depend on the experience of the station fuelling engineer in selecting the channels to be fuelled on any specific day. The selection of channels to be fuelled will be based on various selection criteria such as absolute channel power, channel power of the neighboring fuel channels, the distance between the channel of interest and the recently fuelled channel(s), and maximum bundle irradiation for the channel of interest and its neighbor. When performing core-follow studies, all of these criteria can be programmed so that the core-follow simulation, which usually simulates several hundred effective full power days (EFPD) of operation, can be automated.

2.3. Sets of Reduced Fuelling Ripples

For the present study, the complete set of fuelling ripples simulates 399 EFPD of operation (*i.e.*, the data come from a core-follow study). The optimization run using this complete set of fuelling ripples is time consuming. On average, for this size of fuelling ripples, a single

ROVER-F execution can be completed in around 230 seconds to 260 seconds[3], depending upon the size of the ROP system (*i.e.*, the number of detectors per safety channel). This execution time will translate into around 160 hours to 180 hours for a single optimization run where around 2500 configurations or histories are evaluated. Needless to say, the execution time will increase proportionally as more configurations are evaluated in each optimization.

In order to reduce the execution time, four sets of reduced fuelling ripples have been considered:

1. Collapsed Ripple – Maximum. For each fuel channel m, the fuelling ripples (with a total of Q ripples) are collapsed into a single ripple value which is determined based on the following formula

$$RIP_m^{MAX} = \max_{q=1,\cdots,Q} RIP(m,q) \tag{6}$$

2. Collapsed Ripple – Average. For each fuel channel m, the fuelling ripples (with a total of Q ripples) are collapsed into a single ripple value which is determined based on the following formula

$$RIP_m^{AVG} = \frac{1}{Q}\sum_{q=1}^{Q} RIP(m,q) \tag{7}$$

3. Representative CPPF Average. First of all, the average CPPF value is determined. Then the fuelling ripple whose CPPF is within $\pm$0.0010 from the average CPPF is included in the fuelling ripple set. Please keep in mind that the width of the band for fuelling ripple inclusion is a user defined parameter. For this analysis, the value 0.0010 is chosen so that the size of the reduced fuelling ripple is 25 ripples.

4. No Ripple. The fuelling ripple for all fuel channels is set to 1.0.

It is obvious that these approaches will reduce the execution time and the advantage will become more significant as the number of fuelling ripple, Q, increases. Figure 2 illustrates the implementation of the first two approaches. Four fuel channels (L-15, L-16, M-15, and M-16) are considered in this example and the number of fuelling ripples is 25. The fuel channel map at the bottom of this figure shows the locations of these four channels in the core. This figure illustrates the variations in the fuelling ripples from channel-to-channel. The first approach, "Collapsed Ripple – Maximum", is chosen since it provides an enveloping ripple value for each fuel channel. It might be too conservative since the worst overpower will be considered for each channel. The second approach, "Collapsed Ripple – Average", represents an average behavior for each fuel channel over a long period of time (depending on how many ripples are in the set).

All of these approaches seem reasonable; however, it is important to demonstrate that results obtained from optimization runs using these reduced ripple sets have similar qualities to the ones obtained from optimization run using the complete set of fuelling ripples.

[3] On Xeon 5140 processor.

2.4. Assessing the Effect of Fuelling Ripple Set on the Quality of Detector Layout Configuration

To quantify the effect of collapsing the fuelling ripples using four approaches discussed in the previous sub-section, multiple optimization runs have been executed. Five sets of fuelling ripples are considered: (i) Complete Ripple Set (RIP 1); (ii) Collapsed Ripple – Maximum (RIP 2); (iii) Collapsed Ripple – Average (RIP 3); (iv) Representative Average CPPF (RIP 4); and, (v) No Ripple (RIP 5).

The optimization runs are executed for an ROP system which consists of 56 detectors. These 56 detectors are placed into four safety channels, each of which has 14 detectors. For each set of ripples, 20 optimization runs are executed in order to observe the average behavior from these runs.

Two criteria are used to judge the goodness of results from utilizing the reduced set of fuelling ripples:

a. Trip Set Point. Multiple optimization runs are usually executed in trying to find the best possible solution. The TSP values corresponding to the results from these optimization runs are expected to vary within a certain range. This observation is true regardless of the size of fuelling ripples used in the analysis. To quantify that results from the optimization runs using the reduced set of fuelling ripples have similar qualities to the ones from optimization runs using the complete set of fuelling ripples, one can plot the distribution of TSP values from various optimization runs (*i.e.*, 20 optimization runs for each set of fuelling ripples) and observe whether or not the results cover similar range of TSP values.
b. Limiting Flux Shapes. The TSP for a detector layout configuration has a corresponding limiting flux shape. During each execution of ROVER-F code, the user can specify the number of limiting flux shapes to be printed out in the output file. In this study, three most limiting flux shapes (*i.e.*, three flux shapes with the lowest TSP values) from each optimization run are recorded. The limiting flux shapes from 20 optimization runs using either RIP 2, RIP 3, RIP 4 or RIP 4 are compared against the limiting flux shapes from 20 optimization runs using RIP 1. It is desired to have a lot of common flux shapes among these sets of limiting flux shapes since it indicates that the ADORE algorithm used during this optimization is sufficiently robust to arrive at various solutions which still cover similar limiting flux shapes and is relatively independent of the set of fuelling ripples.

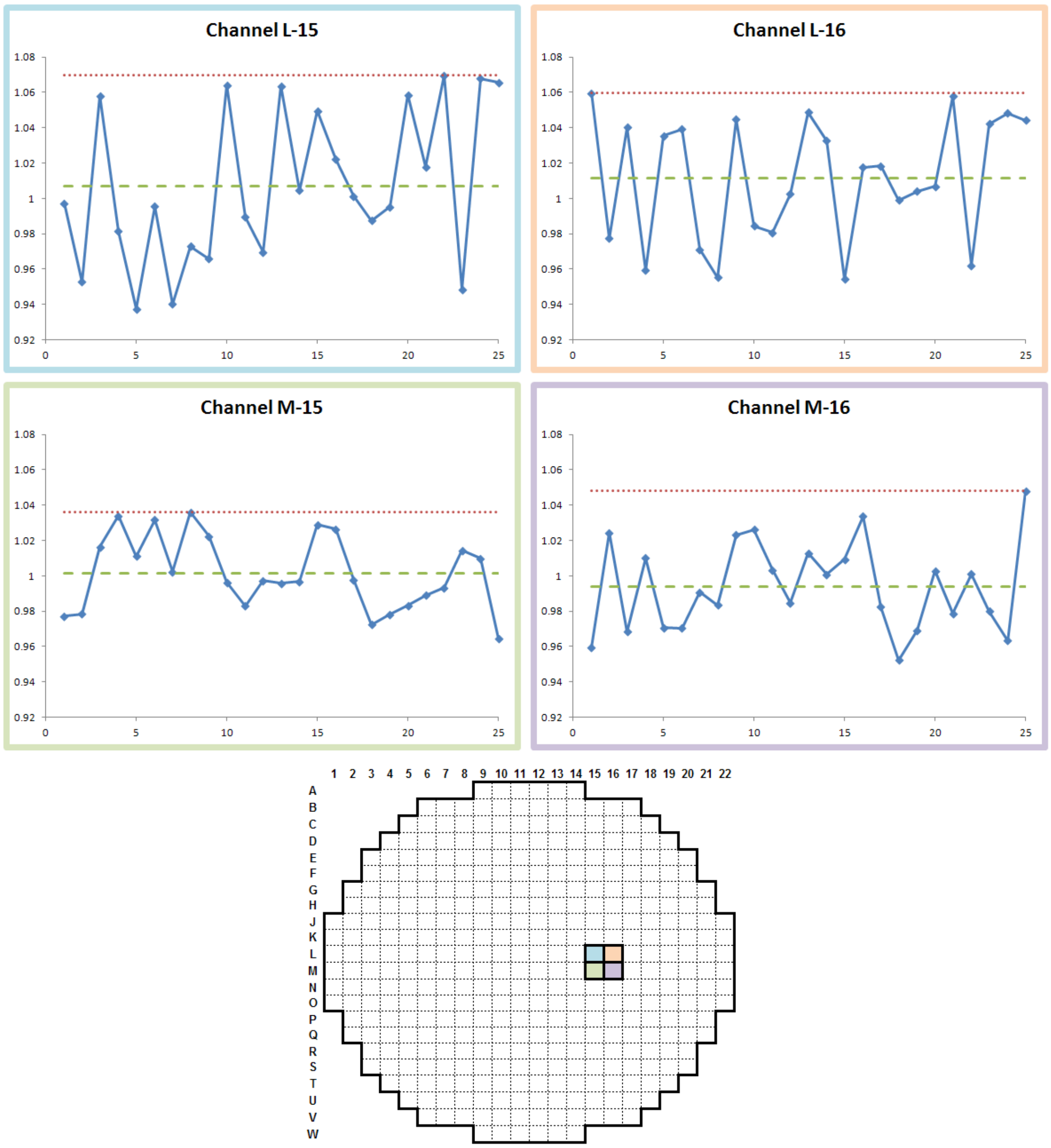

Figure 2. An Example of Fuelling Ripples.

3. Numerical Results

The ROP system evaluated in this study is a 56-detector configuration. For each set of fuelling ripples, there are 20 optimization runs executed. The simulated annealing parameters for these 20 runs are kept constant except for the multiplier used for reducing the temperature within the simulated annealing algorithm. The values of these multipliers for various optimization cases are summarized in Table 1.

Table 1 Simulated Annealing Temperature Reduction Multiplier.

Optimization Case	Multiplier	Optimization Case	Multiplier
1	0.95	11	0.85
2	0.94	12	0.84
3	0.93	13	0.83
4	0.92	14	0.82
5	0.91	15	0.81
6	0.90	16	0.80
7	0.89	17	0.79
8	0.88	18	0.78
9	0.87	19	0.77
10	0.86	20	0.76

The main objective of having a reduced set of fuelling ripples for calculating the ROP TSP value is to reduce the execution time during the optimization. Therefore, the first item to evaluate is the reduction of execution time. Table 2 summarizes typical execution times for various set of fuelling ripples. From this table, one can see that the speedup obtained by utilizing a reduced set of fuelling ripple can be as high as 42 times. Observing the results in Table 2, one might ask why the average execution time for RIP 5 is significantly different from RIP 2 and RIP 3, while all of these three approaches utilize a single set of fuelling ripple. It should be noted that the TSP calculation in ROVER-F is an iterative process which begins with a guess value of TSP. The closer the guess to the final converged value, the faster the iteration will be. Since the same TSP guess value is used for all cases (*i.e.*, 1.2200), the required number of iterations will be different depending upon how far the converged TSP values are from the guess value. As it will be shortly shown in Section 3.1, the TSP values for many of RIP 5 cases are significantly further away from the 1.2200 value compared to RIP 2 and RIP 3 cases.

Table 2 Summary of Typical Execution Times for 56-Detector Configuration.

	Average Execution Time per History (sec)	Speedup
RIP 1	235.07	N/A
RIP 2	5.47	42.97
RIP 3	6.43	36.56
RIP 4	24.62	9.55
RIP 5	15.51	15.16

Based on the results shown in Table 2, it is clearly desirable to adopt a reduced set of fuelling ripples during the optimization. What remains to be shown is the goodness of the results. In the previous section, two criteria were established to evaluate the goodness of the results. The outcomes of these evaluations are discussed in the next two sub-sections.

3.1. Evaluation of Trip Set Point

The results of this evaluation are summarized in Figure 3. For this analysis, the TSP values are binned into seven bins, each of which has a width of 0.025 (or 2.5%FP[4]). The x-axis represents the bin-centre and the y-axis represents the frequency (or population) for each bin. It should also be noted that the TSP values are obtained based on a full set of fuelling ripples; in other words, the resulting detector layouts obtained from either RIP 2, RIP 3, RIP 4 or RIP 5 optimization (where a reduced set of fuelling ripples is utilized) are re-evaluated using the complete set of fuelling ripples (*i.e.*, RIP 1) since this is the basis of the ROP calculation methodology. From this figure, one can draw a general conclusion that the five approaches (*i.e.*, RIP 1, RIP 2, RIP 3, RIP 4, and RIP 5) produce similar TSP values. However, looking closer at the plot, one can see that the "Collapsed Ripple – Maximum" (RIP 2) and "Representative Average CPPF" approaches produce more consistent results to the RIP 1 approach.

Table 3 summarizes the root-mean-square (RMS) difference between the results obtained by using RIP 2, RIP 3, RIP 4 or RIP 5 and those obtained by using RIP 1. For each set of fuelling ripples (*i.e.*, RIP 2, RIP 3, RIP 4 or RIP 5), the RMS value is calculated by using the following formula:

$$RMS^{\gamma} = \sqrt{\frac{\sum_{i=1}^{20}\left\{TSP_i^{\gamma} - TSP_i^{RIP1}\right\}^2}{20}} \tag{8}$$

where i is the case number and γ is the fuelling ripple set (RIP 2, RIP 3, RIP 4, or RIP 5). This table demonstrates numerically that on average the RIP 4 approach produces the closest TSP values to the RIP 1 approach.

Table 3 Summary of RMS Differences in TSP Values.

	RMS
RIP 2	0.0095
RIP 3	0.0171
RIP 4	0.0076
RIP 5	0.1252

[4] FP – Full Power

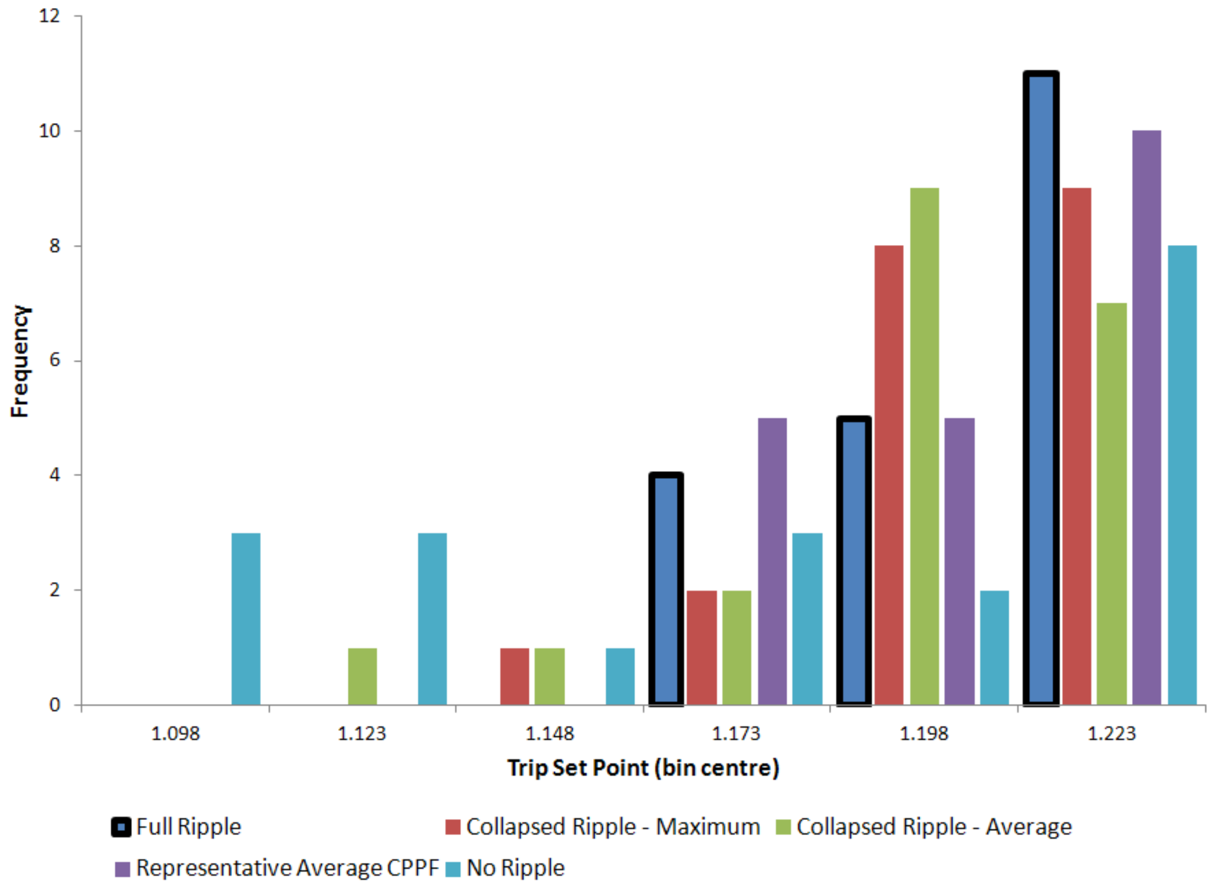

Figure 3 Trip Set Point Comparison.

3.2. Evaluation of Limiting Flux Shapes

When executing the ROVER-F code for determining the TSP for a particular detector layout configuration, the user can request the code to print out a list of limiting flux shapes (*i.e.*, the flux shapes with the lowest TSP values). In this study, three most limiting flux shapes are recorded. Table 4 summarizes the three limiting flux shapes for the three fuelling ripple options for the 56-detector ROP system. From this table, one can see that there are many limiting flux shapes which are in common in RIP 1, RIP 2, RIP 3, RIP 4, and RIP 5.

These results are succinctly summarized in a graphical form in Figure 4. The x-axis represents the binning of the flux shapes (in a group of 25 flux shapes) and the y-axis represents the frequency for each bin. From this figure, one can see that there are groups of limiting flux shapes which are common for all five different sets of fuelling ripples. This indicates that the results of the optimization converge to similar solutions (*i.e.*, protecting the core from similar limiting flux shapes). This figure also shows that the "Collapsed Ripple – Maximum" (RIP 2) and "Representative Average CPPF" (RIP 4) produce closer results to the optimization using the full set of fuelling ripples. This plot, as well as Figure 3, also shows that RIP 5 gives the least favorable agreement with the results from RIP1.

Table 4 Three Most Limiting Flux Shapes for Various Optimization Runs.

Optimization Case	Fuelling Ripple Set				
	Complete Ripple Set (RIP 1)	Collapsed Ripple – Maximum (RIP 2)	Collapsed Ripple – Average (RIP 3)	Representative Average CPPF (RIP 4)	No Ripple (RIP 5)
1	211, 207, 313	207, 313, 211	313, 212, 209	313, 314, 207	206, 314, 209
2	212, 211, 228	314, 244, 212	211, 206, 203	212, 211, 203	313, 207, 206
3	213, 207, 211	209, 314, 193	213, 207, 211	212, 213, 207	227, 314, 210
4	208, 314, 313	211, 203, 210	210, 212, 37	206, 211, 203	210, 314, 313
5	212, 313, 206	211, 314, 210	227, 212, 211	213, 206, 229	314, 36, 313
6	313, 213, 36	314, 206, 36	207, 211, 225	313, 43, 42	227, 209, 208
7	36, 314, 37	314, 211, 36	314, 36, 313	36, 43, 206	206, 190, 198
8	212, 196, 42	210, 314, 37	313, 314, 228	212, 314, 313	211, 213, 313
9	36, 42, 190	314, 211, 210	313, 212, 196	210, 42, 36	314, 225, 212
10	225, 208, 313	43, 36, 208	313, 213, 212	313, 314, 36	314, 313, 207
11	43, 314, 207	36, 210, 202	314, 253, 195	314, 37, 36	229, 314, 42
12	42, 36, 48	43, 37, 229	313, 206, 314	314, 37, 243	36, 42, 243
13	212, 37, 42	210, 37, 211	313, 314, 43	313, 43, 314	314, 43, 36
14	207, 36, 196	43, 37, 36	314, 36, 42	212, 196, 36	36, 42, 43
15	42, 212, 48	369, 43, 42	313, 37, 36	212, 314, 313	314, 36, 313
16	37, 43, 314	43, 36, 314	314, 313, 43	211, 37, 228	464, 465, 463
17	42, 36, 193	43, 37, 42	314, 313, 212	211, 192, 36	195, 203, 206
18	37, 43, 36	43, 369, 37	314, 255, 253	213, 314, 45	227, 313, 36
19	36, 219, 42	43, 37, 36	314, 313, 37	42, 192, 36	36, 42, 43
20	196, 36, 37	43, 37, 314	313, 314, 213	210, 313, 43	36, 43, 314

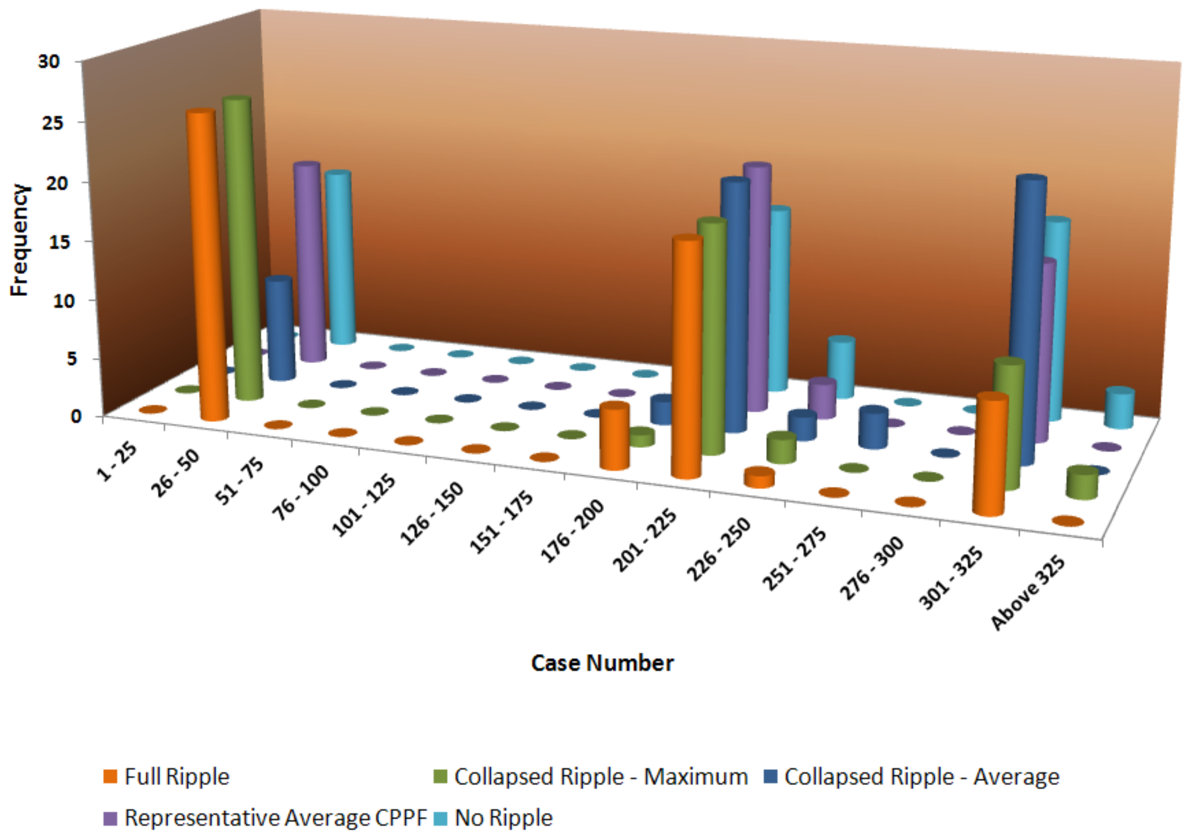

Figure 4 Comparison of Limiting Flux Shapes.

4. Conclusion

The optimization process for finding an optimized detector layout for the ROP system in the CANDU reactor using the ADORE algorithm is time consuming. One option to reduce the execution time is to utilize a smaller set of fuelling ripples. Four approaches have been evaluated in which the total number of fuelling ripples is significantly reduced. These four approaches are called “Collapsed Ripple – Maximum”, “Collapsed Ripple – Average”, “Representative Average CPPF”, and “No Ripple”. Numerical results show that all approaches produce comparable results to the optimization utilizing the complete set of fuelling ripples and a significant reduction in the average execution can be attained. However, the “Collapsed Ripple – Maximum” approach is the most preferable one since it provides a higher speed-up and produces more consistent results to the optimizations where no simplification is introduced.

5. References

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