CONTROL BLADE PATTERN OPTIMIZATION USING EVOLUTIONARY ALGORITHM FOR THE CANADIAN SCWR

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Summary

The Canadian SCWR has been simulated with the diffusion code PARCS, including proposed reactivity control devices. Transport calculations of the lattice cell have been performed with SCALE/TRITON to determine the few-group neutronic parameters as functions of burnup for input in PARCS. 89 cruciform control blades have been implemented in the model to remove part of the excess reactivity and to balance radial core power. The goal of this study is to minimize the channel power ripple by adjusting the control blades throughout the cycle. This was achieved by coupling PARCS to an optimization software (DAKOTA). An automated process has been developed to find a control blade sequence that holds each channel power as close to constant as possible while keeping the core reactivity around the desired value throughout the cycle, while also maintaining acceptable maximum nodal powers.

1. Introduction

In the current Canadian SCWR design [1] static orifices at each channel inlet will regulate the flow through the channel to be proportional to its reference power to ensure a uniform channel outlet temperature of 625 °C. Without reactivity control devices channel powers change significantly during a cycle and it is not possible to match the flow due to these transients. As a consequence each channel power has to remain constant and matched to the flow rate or the outlet temperature will drift. As of this writing no system has been proposed to keep each channel power constant throughout the cycle. A set of BWR-like cruciform control blades has thus been proposed in this work to address this challenge in addition to holding down the initial excess reactivity. The blades are then analyzed and the optimal positions through the fuelling cycle are determined such as to minimize the channel power changes anticipated with burnup.

The design of the control blades and the lattice calculations with the SCALE/TRITON code are first described [2]. Using the homogenized and condensed cross sections from SCALE/TRITON, a full-core SCWR model has been created with the PARCS code [3]. Finally, the DAKOTA optimization software [4], using a genetic algorithm, has been coupled to PARCS to find the control blade insertion levels throughout the cycle that maintains the channel powers as constant as possible while satisfying the desired constraints.

2. Control blade design

The 2D infinite lattice cell with a control blade was modelled in SCALE/TRITON as shown in Figure 1. The transport equation is solved for different stages of fuel burnup and thus generates a set of few-group homogenized cross sections indexed by burnup. Moreover, as the coolant density considerably changes axially (roughly by a factor 10), the core has been divided into twenty slices to account for the density change's impact on the lattice physics. Therefore, the above sets of condensed and averaged cross sections have been simulated in SCALE/TRITON for those twenty positions using appropriate local averaged temperatures and densities.

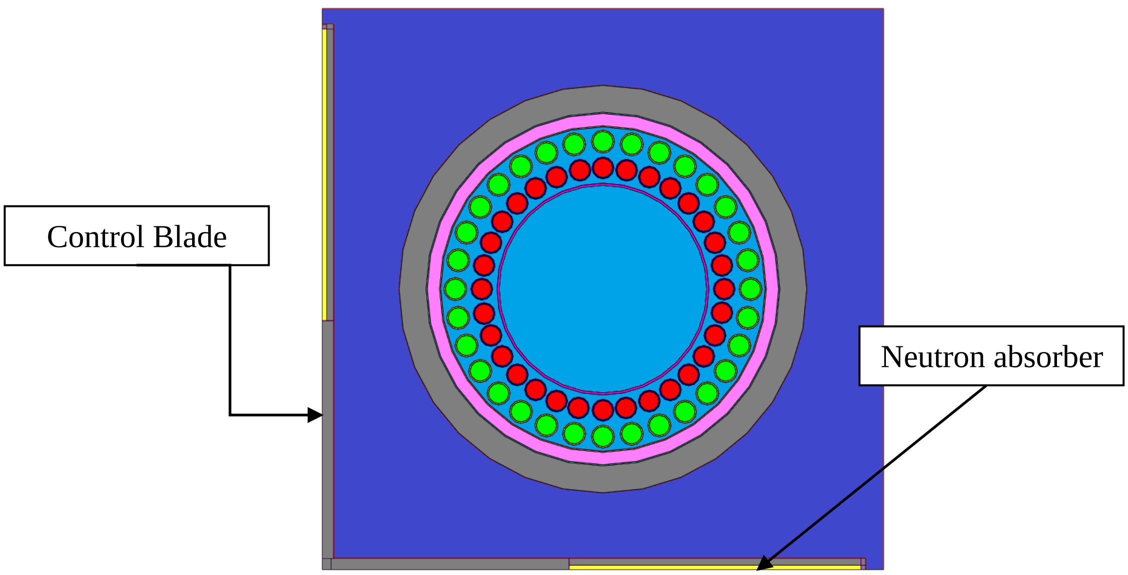

Figure 1 Canadian SCWR 64-element lattice cell

The specifications of the control blade are given in Table 1 below. As can be seen in Figure 2, the neutron absorbing material is located near the tip of the blades because it tends to reduce the flux (power) tilt in the fuel pins.

Table 1 - Control blade specifications

Half span	24.2 cm
Thickness	1 cm
CB material (wt%)	Sn:3.5; Mo:0.8; Nb:0.8; Zr:94.9
Length of absorber	13 cm
Thickness of absorber	0.4 cm
Absorber material	Stainless Steel 304
Density	7.94 g·cm^{-3}

3. Full-core model: PARCS

The Canadian SCWR core is quarter symmetric; therefore only 84 out of the 336 channels have been simulated in PARCS. Each assembly has been divided into 20 axial positions with the 20 lattice physics properties calculated beforehand. Heavy water radial and axial reflectors have also been included into the model and are 100 cm and 75 cm thick, respectively. Locations of the control blades are shown in Figure 2.

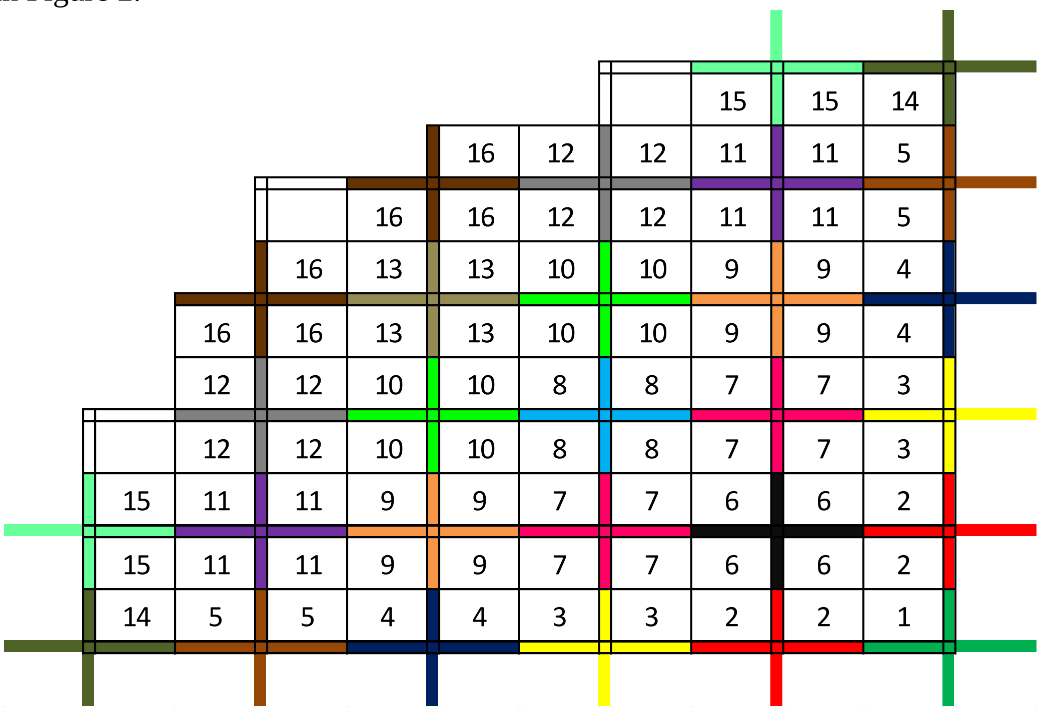

Figure 2 - Control blade locations and bank numbers (same color = same bank)

4. Control blade pattern optimization

4.1 Evolutionary algorithm

First an initial population is generated (here a population represents 50 individuals). For each individual in this population, a random position is attributed to each control blade within the predefined range. PARCS is then run for each individual in the population and the outputs are collected by DAKOTA. Afterwards, the individuals are classified in terms of their fitness. From this organized population, crossovers and mutations are applied at a fixed probability chosen by the user.

Like in genetics, two individuals can give birth to an offspring by each bringing part of their genetic information. This action tends to choose two relatively good individuals in order to (ideally) find a better solution. Mutations are then applied to the newly generated individuals. This action allows the method to look for other solutions in the larger phase space.

The fitness of all the individuals generated from crossovers and mutations are now evaluated and added to the initial population. The ones with the lowest fitness are deleted and a new initial population has thus been created. This last process can be seen as evolution since the most fit individuals are more likely to survive. With the new population, crossover and mutations are applied again and the whole process is repeated until convergence criteria are satisfied or iteration limits are reached.

4.2 Coupling goal

Since the current design of the Canadian SCWR includes static inlet orifices for each assembly, the power of each assembly should remain as constant as possible over the cycle in order to ensure uniform coolant outlet temperatures of 625°C in each channel. A control blade sequence (positioning of the control blades with time) has to be found in order to fit as closely as possible a predefined channel power distribution at any time during the cycle. Thus, the goal of this study was to minimize the standard deviation of the 84 channel powers, relative to their desired power.

However, there are constraints to be respected: the initial excess reactivity is around 110 mk and has to be compensated at day 0 by the insertion of neutron absorbers (a combination of burnable poison, control blades and a soluble poison). As only control blades are used in this study, the total initial excess reactivity was not fully compensated but about 35% has been removed.

In the simulation, there are 84 channels, each with 20 axial positions, which gives a total of 1680 nodes. Each node has a certain power and linear element rating (LER) associated to it. The average LER of the Canadian SCWR can be evaluated using the following equation:

$$LER = P_{tot}/N_{ch}L_{ch}N_{pins}$$

where P_{tot} is the core total power (2540 MW), N_{ch} is the total number of fuel channels (336), L_{ch} is the length of a fuel channel (5 m), and N_{pins} is the number of pins per channel (64). Therefore, the average LER is equal to 23.6 kW·m^{-1}. A maximum of 40 kW·m^{-1} has been suggested in early studies and has been included as a constraint, thus the power in a given node should not exceed a normalized nodal power of 1.7 [5].

In order to find an acceptable solution while respecting the above constraints, a total of 16 banks of control blades can be inserted into the core with discrete steps of 25 cm. As the core is 5 meters high, 21 positions can be occupied by each blade. Therefore, the space to be searched contains $21^{16} \approx 1.43\text{x}10^{21}$ possibilities.

The coupling process won't be described in details but the main features are listed below:

- Core depleted by steps of 5 FPD
- Optimization of the control blades position every 20 FPD
- Only the closest positions from the previous optimization are allowed
- At the BOC, only the closest positions from the previous BOC control blades positions are allowed (except for the first optimization where the entire space is searched)

The results obtained from the optimization process are shown and discussed in the next section.

5. Results and discussion

On Figures 3 and 4, the targeted channel powers (in MW) are given in the grey boxes while the standard deviation (in MW) throughout the cycle, with respect to those channel powers is given below. By looking at the two figures, the overall standard deviation is significantly lower for the core with the control blades.

Targeted channel power (MW)

Standard deviation over the cycle (MW)

						7.20	5.88	7.61	6.74
						0.38	0.27	0.37	0.32
				7.29	7.21	6.64	8.26	7.32	6.54
				0.39	0.32	0.24	0.31	0.25	0.20
		4.78	6.41	6.39	7.82	8.71	6.56	6.52	8.54
		0.32	0.37	0.26	0.24	0.21	0.09	0.07	0.12
		6.22	7.98	7.47	8.84	6.90	7.87	8.89	6.60
		0.35	0.37	0.22	0.16	0.03	0.04	0.05	0.08
	7.25	6.36	7.45	6.67	7.66	7.90	9.13	8.02	8.01
	0.40	0.26	0.22	0.09	0.04	0.09	0.16	0.20	0.22
	7.20	7.81	8.84	7.66	6.74	8.92	6.82	6.92	9.33
	0.33	0.24	0.16	0.04	0.10	0.19	0.25	0.30	0.39
7.19	6.64	8.71	6.90	7.90	8.92	6.88	8.00	9.32	7.05
0.38	0.24	0.21	0.03	0.09	0.19	0.27	0.36	0.45	0.40
5.89	8.26	6.56	7.88	9.13	6.82	8.00	9.46	8.20	9.27
0.27	0.31	0.09	0.03	0.16	0.25	0.36	0.48	0.45	0.49
7.61	7.32	6.52	8.89	8.02	6.92	9.32	8.20	6.72	7.38
0.37	0.25	0.07	0.05	0.20	0.30	0.45	0.45	0.37	0.36
6.74	6.54	8.54	6.60	8.01	9.33	7.06	9.27	7.38	5.79
0.32	0.20	0.12	0.08	0.22	0.39	0.40	0.49	0.36	0.25

Figure 3 - Channel powers (MW) and their standard deviation (MW) over the cycle (no control blades)

						7.65	6.16	7.80	7.08
						0.16	0.08	0.08	0.08
				7.22	7.53	6.87	8.07	7.17	6.64
				0.11	0.16	0.18	0.06	0.07	0.05
		4.78	6.54	6.50	8.08	8.78	6.47	6.44	8.59
		0.11	0.05	0.05	0.12	0.08	0.03	0.03	0.10
		6.36	8.27	7.81	8.81	6.81	7.74	8.84	6.99
		0.09	0.08	0.13	0.07	0.03	0.08	0.11	0.06
	7.20	6.47	7.81	6.96	7.78	7.88	8.88	7.95	8.10
	0.12	0.04	0.13	0.11	0.06	0.05	0.14	0.07	0.05
	7.52	8.08	8.80	7.78	6.83	8.92	6.64	6.62	8.71
	0.15	0.11	0.08	0.06	0.06	0.04	0.08	0.08	0.11
7.65	6.87	8.77	6.81	7.88	8.92	6.88	7.68	8.65	6.86
0.15	0.18	0.08	0.03	0.05	0.04	0.09	0.10	0.15	0.05
6.16	8.07	6.47	7.74	8.88	6.64	7.68	8.96	8.06	9.32
0.08	0.06	0.03	0.08	0.14	0.08	0.10	0.21	0.13	0.06
7.80	7.17	6.44	8.84	7.95	6.62	8.65	8.06	6.72	7.41
0.08	0.07	0.03	0.11	0.07	0.08	0.15	0.13	0.05	0.03
7.08	6.64	8.60	7.00	8.10	8.71	6.86	9.32	7.41	5.77
0.08	0.04	0.10	0.06	0.05	0.11	0.05	0.06	0.03	0.07

Figure 4 - Channel powers (MW) and their standard deviation (MW) over the cycle (control blades)

To observe the deviation of the channel powers from their target values during the cycle, the standard deviation of the 84 channels has been plotted every 5 Full Power Days (FPD) during the cycle in Figure 5. The graph explicitly shows that the control blades managed to keep the channel powers closer to their reference values. However, the deviation is higher at BOC and EOC. The discrepancy at EOC could be reduced by a better refueling scheme that flattens the power distribution and avoids a channel burning too quickly or slowly. Moreover, all the blades have not been fully removed at EOC because the nodal peak power would become too large; this issue could also be avoided by using a better refueling scheme. As for the BOC, the use of burnable absorbers in fresh fuel could help in reducing the discrepancy from the onset by flattening the power distribution in the core.

Figure 5. Standard deviation of the 84 channel powers throughout the cycle, with respect to their individual power target

6. Conclusion and future wok

In this study the use of cruciform control blades inserted from the bottom of the core has been investigated for the Canadian SCWR. A coupling process between the diffusion code PARCS and the optimization software DAKOTA has been developed to minimize the power ripple in each channel over the length of the cycle while contraining k_{eff} and the maximum nodal power. The results obtained have been compared to the case without any control devices and the use of control blades has considerably improved the power ripple. The reference fueling scheme provided by AECL is no longer optimal for cases with control blades and hence it is recommended to redo the fueling scheme as part of a larger core optimization process.

The work performed for this paper was a preliminary study. As the limiting factor for the Canadian SCWR is the sheath temperature, the reactor physics code PARCS will be coupled to the thermal-hydraulic code RELAP5 in the future in order to predict the local sheath temperature and the outlet coolant temperature.

Finally, the largest power deviations are mostly at the BOC or EOC for each channel. Therefore, an optimized refueling scheme should be found to improve the power deviations at EOC. The implementation of burnable absorber in fresh fuel might also improve the ripple at BOC while reducing the initial excess reactivity. Ultimately soluble boron in the moderator could also be used to bring the excess reactivity to zero during the first FPD.

7. References

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