SIMULATION OF LONG-TERM FUELLING OPERATIONS FOR THE ACR-1000™

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Abstract

The Advanced CANDU Reactor™[1] (ACR-1000™) features on-power refuelling, retaining a characteristic design feature from the traditional CANDU®[2] reactor. To confirm or predict important design parameters it is necessary to perform simulations of fuelling representative of station operation. Long-term fuelling simulations have traditionally been called 'core-follow' simulations and are used to predict or confirm parameters such as channel power, bundle power, channel power peaking factor (CPPF) and burnup. To perform a core-follow simulation for a reactor fuelled during operation (on-power) a sustainable fuelling strategy must first be developed. To this end, the methodology used to perform the core-follow simulations, the methodology used to develop channel fuelling selection criteria, and some supporting results are detailed in this paper.

1. Introduction

The target discharge fuel burnup in the ACR-1000 is 20 MWd/kgU, nearly three times the burnup in the current CANDU reactors using natural uranium (NU) fuel. To arrive at a core-configuration with the target burnup the ACR will operate in three consecutive configurations.

1. Initial Core
2. Transition
3. Equilibrium

These three distinct cores necessitate two distinct fuelling regimes (three if the initial core loading is counted as a fuelling regime). For each fuelling regime, the challenge is to develop a sustainable fuelling strategy demonstrating adherence to safety criteria, operability and economic utilization of fuel. Furthermore, during the design process, a fuelling strategy must be developed for each design-iteration accommodating changing design criteria and changing relative importance of those design criteria with only a modest investiture of engineering-effort. The logical extension of this requirement is the development of a software-tool capable of applying general channel selection criteria to produce a core-follow for a given core-configuration.

This paper presents the methodology used to perform the core-follow simulations of the ACR equilibrium core and the initial to equilibrium transition, effective selection criteria, and some supporting results.

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2. Fuelling

In the ACR, as in the Natural Uranium (NU) CANDU reactor, once a channel is fuelled, ^{235}U is depleted as it fissions, simultaneously neutron absorbing fission products accumulate. At some point the fuel becomes a net absorber of neutrons. Consequently, channels must be periodically refuelled to ensure the reactor remains critical.

Unlike the NU CANDU, the fuel is evenly doped with a burnable neutron absorber. As a result, the channel power of a recently fuelled channel increases after fuelling, peaks after several days, then slowly decreases until it is fuelled again. The channels neighbouring a fuelled channel are also affected, their powers responding to the change in local neutron flux. In the long term this differential fuelling shapes the global power distribution of the reactor.

The distribution of channel powers averaged over time is known as the 'time-average' [1] or 'reference' power distribution. At any given instant a channel's power will be different from its time-average power. The ratio of a given channel's instantaneous power to its time-average power is referred to as the channel's ripple. It is the ripple, channel power, bundle power and burnup that comprise the salient outputs of the core-follow. Other information such as fuel residency statistics gleaned from the core-follow provide important interdisciplinary input as well.

The process of fuelling the reactor online is accomplished by means of two fuelling machines. In the reference equilibrium core, two bundles from the first fuelling machine are added to the fuel string in the direction of coolant flow. Meanwhile, downstream, the fuelling ram removes the majority of the channel's fuel string from the core so that the second fuelling machine can accept the two spent bundles. The entirety of the fuel string, less the two spent bundles, is then driven back into the core. To keep the average zone control rod (ZCR) insertion constant this process is repeated *on average* five times a day.

3. Methodology

RFSP-IST is a 2-group 3-dimensional diffusion code used to perform fuel-management calculations [2]. The industry standard tool was used to perform the necessary reactor fuelling simulations in the ACR design core-follows. The reactor regulating system (RRS) algorithm is included in the full core model allowing for the use of reactivity device insertions as outputs from the core-follow. The use of RFSP as part of the methodology to generate equilibrium[3] core-follows can be seen in Figure 2.

While RFSP is used to simulate the core and fuelling operations a series of scripts perform the other processes in Figure 2 such as channel selection, preparation of the RFSP input file, parsing and archiving the pertinent information from the RFSP outputs, updating the channel selection criteria and general control of the algorithm. Overall the algorithm is a microcosm of the progression used fuel channels at a CANDU station. Capturing the process as series scripts allows the user to exploit

[3] However only the RFSP INSTANTAN starting point defines this methodology as the 'equilibrium core-follow methodology' and not the more generic 'core-follow methodology'.

any parallelism afforded by their computing resources used in addition to the previously mentioned benefit engineering-effort economy.

A similar method, REFUEL, has already proved successful for modelling fuelling of the CANDU 6 reactor [3]. There are two significant high level differences between REFUEL and the algorithm presented in this paper. First, the miss-selection of channels according to user input acceptance criteria results in a re-selection. Second, this process of miss-selection changes the selection criteria. In this way, a fuelling strategy can also be considered an output of the algorithm.

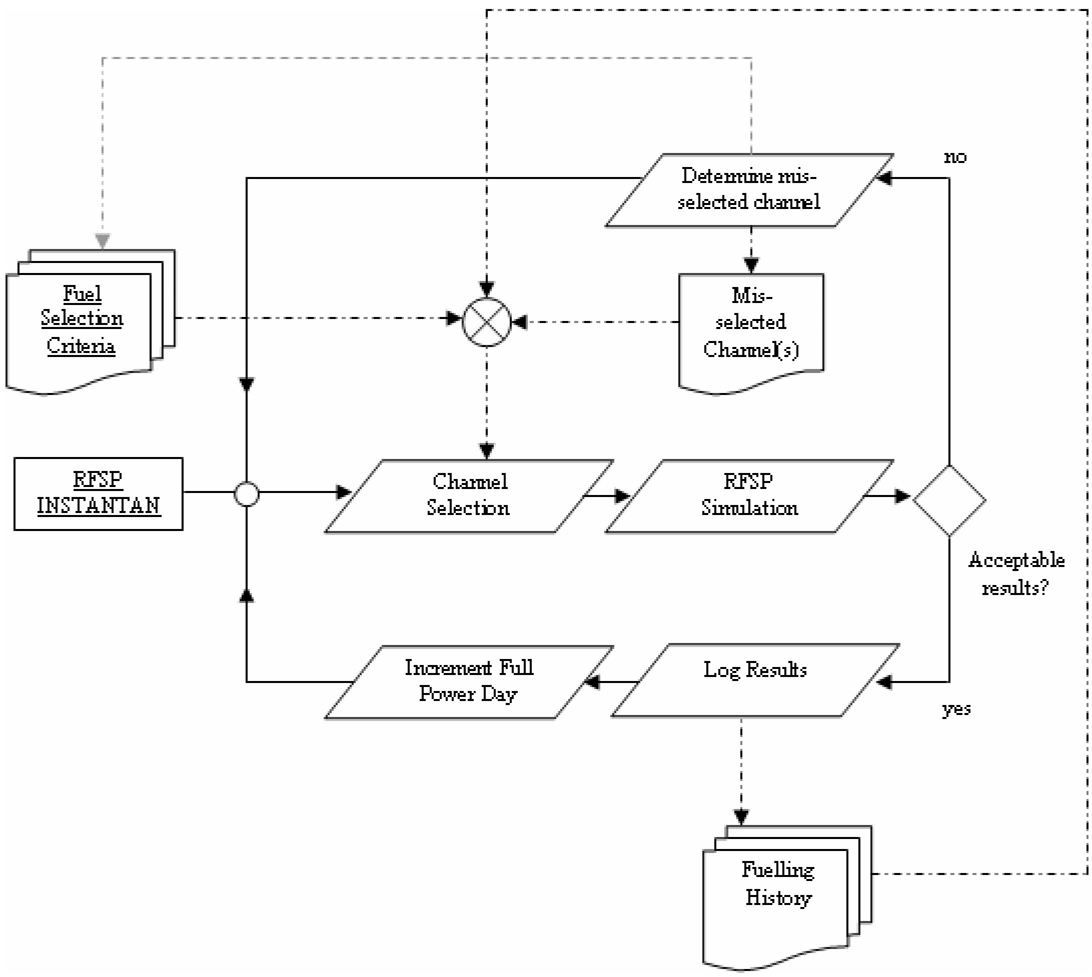

Figure 2: Methodology used to perform core-follow simulations using RFSP.

3.1 Starting point

The ideal starting point for an equilibrium core-follow would be some model of the equilibrium core itself. It is the need for this model, however, that necessitates the core-follow simulation. As there is no direct model of the equilibrium core antecedent to its simulation, a suitable surrogate must be used. In practice an equilibrium-core-follow simulation could use any core model to initiate the simulation. For instance, some distribution inspired by the time-average model could be used as a starting point; however the first several hundred FPDs of steps would have to be discarded. Effectively, the initial discounted RFSP simulations would represent the time needed to transition from the starting point to some configuration approaching the equilibrium core being modelled.

The closer the starting point is to the equilibrium configuration the shorter the transition period, and hence, the number of simulation results that have to be discarded is fewer. The average (over time) properties of an equilibrium core-follow should be insensitive to the starting point.

The starting point for the ACR equilibrium core-follows is a patterned random distribution (patterned RANDIS) modelled using the INSTANTAN module of RFSP. A program (RANDIS) creates an age pattern, Figure 3, intended to mimic the age pattern that would be arrived at by reactor operation. Maximum channel powers and bundle powers are *typically* within five percent of those determined via core-follow simulation. The INSTANTAN starting point is an approximation of the equilibrium core, but not a completely faithful model. Consequently, the first several FPDs must still be discounted; they are not indicative of core-follow results as a whole. The requirement for insensitivity to starting point provides an indication as to the appropriate number of simulated FPDs to discount when evaluating fuelling studies.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
A											0.16	0.06	0.32	0.36	0.94	0.44										
B								0.44	0.22	0.76	0.54	0.96	0.66	0.58	0.04	0.22	0.88	0.30	0.12							
C							0.84	0.10	0.88	0.02	0.24	0.50	0.28	0.68	0.38	0.76	0.02	0.60	0.18	0.80						
D						0.34	0.26	0.52	0.30	0.60	0.70	0.08	0.82	0.90	0.16	0.54	0.24	0.70	0.92	0.34	0.26					
E				0.08	0.14	0.56	0.72	0.98	0.12	0.18	0.92	0.14	0.40	0.48	0.06	0.96	0.50	0.08	0.14	0.56	0.72	0.98	0.12			
F				0.82	0.40	0.86	0.42	0.64	0.46	0.80	0.34	0.56	0.86	0.78	0.32	0.66	0.28	0.82	0.40	0.86	0.42	0.64	0.46			
G			0.68	0.90	0.48	0.78	0.74	0.20	0.62	0.84	0.26	0.72	0.42	0.74	0.36	0.58	0.68	0.90	0.48	0.78	0.74	0.20	0.62	0.84		
H		0.04	0.38	0.16	0.06	0.32	0.36	0.94	0.44	0.10	0.52	0.98	0.64	0.20	0.94	0.04	0.38	0.16	0.06	0.32	0.36	0.94	0.44	0.10	0.52	
J		0.22	0.76	0.54	0.96	0.66	0.58	0.04	0.22	0.88	0.30	0.12	0.46	0.62	0.44	0.22	0.76	0.54	0.96	0.66	0.58	0.04	0.22	0.88	0.30	
K		0.88	0.02	0.24	0.50	0.28	0.68	0.38	0.76	0.02	0.60	0.18	0.80	0.84	0.10	0.88	0.02	0.24	0.50	0.28	0.68	0.38	0.76	0.02	0.60	
L	0.52	0.30	0.60	0.70	0.08	0.82	0.90	0.16	0.54	0.24	0.70	0.92	0.34	0.26	0.52	0.30	0.60	0.70	0.08	0.82	0.90	0.16	0.54	0.24	0.70	0.92
M	0.98	0.12	0.18	0.92	0.14	0.40	0.48	0.06	0.96	0.50	0.08	0.14	0.56	0.72	0.98	0.12	0.18	0.92	0.14	0.40	0.48	0.06	0.96	0.50	0.08	0.14
N	0.64	0.46	0.80	0.34	0.56	0.86	0.78	0.32	0.66	0.28	0.82	0.40	0.86	0.42	0.64	0.46	0.80	0.34	0.56	0.86	0.78	0.32	0.66	0.28	0.82	0.40
O	0.20	0.62	0.84	0.26	0.72	0.42	0.74	0.36	0.58	0.68	0.90	0.48	0.78	0.74	0.20	0.62	0.84	0.26	0.72	0.42	0.74	0.36	0.58	0.68	0.90	0.48
P	0.94	0.44	0.10	0.52	0.98	0.64	0.20	0.94	0.04	0.38	0.16	0.06	0.32	0.36	0.94	0.44	0.10	0.52	0.98	0.64	0.20	0.94	0.04	0.38	0.16	0.06
Q	0.04	0.22	0.88	0.30	0.12	0.46	0.62	0.44	0.22	0.76	0.54	0.96	0.66	0.58	0.04	0.22	0.88	0.30	0.12	0.46	0.62	0.44	0.22	0.76	0.54	0.96
R		0.76	0.02	0.60	0.18	0.80	0.84	0.10	0.88	0.02	0.24	0.50	0.28	0.68	0.38	0.76	0.02	0.60	0.18	0.80	0.84	0.10	0.88	0.02	0.24	
S		0.54	0.24	0.70	0.92	0.34	0.26	0.52	0.30	0.60	0.70	0.08	0.82	0.90	0.16	0.54	0.24	0.70	0.92	0.34	0.26	0.52	0.30	0.60	0.70	
T		0.96	0.50	0.08	0.14	0.56	0.72	0.98	0.12	0.18	0.92	0.14	0.40	0.48	0.06	0.96	0.50	0.08	0.14	0.56	0.72	0.98	0.12	0.18	0.92	
U			0.28	0.82	0.40	0.86	0.42	0.64	0.46	0.80	0.34	0.56	0.86	0.78	0.32	0.66	0.28	0.82	0.40	0.86	0.42	0.64	0.46	0.80		
V				0.90	0.48	0.78	0.74	0.20	0.62	0.84	0.26	0.72	0.42	0.74	0.36	0.58	0.68	0.90	0.48	0.78	0.74	0.20	0.62			
W				0.16	0.06	0.32	0.36	0.94	0.44	0.10	0.52	0.98	0.64	0.20	0.94	0.04	0.38	0.16	0.06	0.32	0.36	0.94	0.44			
X						0.66	0.58	0.04	0.22	0.88	0.30	0.12	0.46	0.62	0.44	0.22	0.76	0.54	0.96	0.66	0.58					
Y							0.68	0.38	0.76	0.02	0.60	0.18	0.80	0.84	0.10	0.88	0.02	0.24	0.50	0.28						
Z								0.16	0.54	0.24	0.70	0.92	0.34	0.26	0.52	0.30	0.60	0.70	0.08							
ZZ											0.08	0.14	0.56	0.72	0.98	0.12										

Figure 3: Potential channel age map.

For non-equilibrium core-follows the issue of starting point is in general more straightforward. For example, the initial core is designed using RFSP, the transition from this initial core to the relevant equilibrium core would simply start from the RFSP simulations of the initial core. Schematically this would simply be represented by changing 'RFSP INSTANTAN' to 'RFSP Direct Access File' in Figure 2.

3.2 Channel selection

Once a starting point has been determined and given RFSP determined core characteristics, candidates for fuelling must be selected from amongst the channels. This is accomplished by weighting all channels according some channel selection criteria. These channel selection criteria simultaneously encompass operational constraints and channel weighting algorithms likely to arise in simulation results meeting the imposed acceptance criteria.

3.2.1 Number of channels to be selected

Falling somewhat outside the purview of channel selection is the number of channels to be fuelled on a given FPD. Two considerations contribute this number. The first being average zone control rod insertion, relating to the appropriate amount of reactivity to be introduced via fuelling. The second being any operational constraints considered in the model, such as fuelling machine availability, planned maintenance, and staffing schedules etc. In either case the number of channels fuelled *on average* follows from the predictions from the time-average model.

In this way the process differs from fuelling at some existing CANDU stations where the number of bundles to be fuelled in each 'run' is constant. Thus it is the fuelling schedule that is used to keep the zone levels within the desired range.

3.2.2 Excluding channels

Having determined the appropriate number for of channels to fuel the task turns to selecting these channels from the 520 that constitute the ACR. This is accomplished by weighting each channel and selecting from among the candidates the channel with the highest weighting. Each channel is then re-weighted to account for the fuelling of the previous channels in the fuelling run. The process is repeated until the desired number of channels has been selected.

The first considerations applied are the operational constraints - being the most rigid. Typically the weighting process for these constraints consists of assigning a channel a weight of negative infinity thereby excluding it from further consideration. An example of such a constraint routinely encoded in the channel selection algorithm is the requirement that only channels of a like flow direction be selected in a run – in doing so removing half the channels as candidates for fuelling on each full power day that the constraint is imposed.

Also excluded from consideration by means of a negative infinity weighting are channels whose powers are too high for their spatial location, channels containing a bundle whose power exceeds a maximum, channels whose ripple is in excess of unity, channels in the vicinity of channels of excessive power, channels in the vicinity of channels with excessive ripple, channels adjacent a given number of lattice pitches from a channel refuelled a given number of FPDs ago and channels which have been refuelled less than a given time ago all as prescribed by the user defined channel selection criteria. Table 1 provides some sample exclusion conditions for a core follow.

Table 1: Sample exclusion criteria.

Parameter	Exclusion criteria (channel *i,j*)	Variables
Flow direction (alternating each full power day)	(*i*+*j*) modulo 2 = *FPD* modulo 2	*i* – channel row. *j* – channel column. *FPD* – full power day.
Channel power	channel *i,j* power > P_{max} *i,j*	P_{max} *i,j* – user defined channel power limit for a candidate channel
Local channel power	channel *i′,j′* power > *f*(*d,Psub*)	*d* – Cartesian distance in lattice pitches between *i,j* and *i′,j′*. *Psub* – user defined parameter governing the importance of avoiding channel power 'hotspots' .
Channel ripple	channel *i,j* ripple > *Rmax*	*Rmax* – user defined ripple limit for a candidate channel.
Local channel ripple	channel *i′,j′* power > *f*(*d,RIPsub*)	*RIPsub* – user defined parameter governing the importance of avoiding ripple 'hotspots' .
Channel history	channel fuelled in the last *H* days	*H* – user defined parameter governing the minimum channel dwell time.
Proximity to fuelled channel	*f*(*d_min* ,*t_min*)	*d_min* – user defined minimum allowable distance to a candidate channel fuelled *t_min* FPD ago.

3.2.3 Weighting channels

Once channels have been excluded each has a weighting of either zero or negative infinity. Positive or negative weightings are then added to non-excluded channels on the basis of the remaining selection criteria. Positive weightings are awarded based on low ripple, high channel age[4], zones with low relative zone control rod insertions. Negative weightings, on the other hand, are awarded to channel locations near channels refuelled some number of days ago, channels in zones whose local zone control rod insertions is high, channel locations with low channel age and channels near channels in zones already selected in the run. Similar to Table 1 above Table 2 provides some (by no means exhaustive) sample weighting criteria.

The channels are iteratively weighted and selected to arrive at a fuelling run. In the event that the number of non-excluded channels is not sufficient to make up the run the restrictions governing channel selection are gradually relaxed until there are sufficient non-excluded channels.

If an RFSP simulation results in parameters that exceed acceptance criteria the channel nearest to the location of the overage is identified as the likely offender. In addition to excluding this potentially mis-selected channel during the next iteration the channel selection criteria are also

[4] In core-follow generation channel age is taken to be the ratio of a channels exit irradiation to its RFSP determined time-average exit irradiation.

changed. In some core-follows of novel core-configurations for whom the optimum channel selection criteria has not been determined these mis-selected channels provide important feedback that can be used in the improvement of channel selection criteria. When a channel is mis-selected in the core-follow of a novel core-configuration the channel power and ripple candidacy limit for that spatial location and its 3 two fold symmetric equivalents are slightly altered. In this way successive mis-fuelling *tends* to improve the channel selection criteria for subsequent channel selection iterations.

Table 2: Sample channel weighting increments.

Parameter	Weighting (channel *i,j*)	Variables
Zone level	$f(ZC\text{-}ZL) = W_{ZL} \times (ZC\text{-}ZL)$	*i* – channel row. *j* – channel column. ZL – zone level of the zone associated with channel *i,j* *ZC* – user defined target average relative ZCR insertion. W_{ZL}– user defined relative importance of adhering locally to the target ZCR insertion.
Irradiation	$f(maxIR(i,j)\text{-}ExIR(i,j))$ $= W_{IR} \times (maxIR(i,j)\text{-}ExIR(i,j))^{IR}$	*maxIR(i,j)* – channel *i,j* maximum bundle irradiation. *ExIR(i,j)* – channel *i,j* exit irradiation as predicted by the time-average model. W_{IR}, *IR*– user defined relative importance of fuel utilization.
Ripple	Channel ripple: [0.95,1.0) $\rightarrow$ $+2 \times W_{RP}$ [0.90,0.95) $\rightarrow$ $+3 \times W_{RP}$ [0.85,0.90) $\rightarrow$ $+4 \times W_{RP}$ $(-\infty, 0.85)$ $\rightarrow$ $+7 \times W_{RP}$	W_{RP} – user defined relative importance of fuelling low ripple channels.
Proximity to recently fuelled channels	$f(d,t) =$ $-5 \times W_F$ if $t<6$ AND $d<2.5$ $-2 \times W_F$ if $t<2$ AND $d<4$ $-1 \times W_F$ if $t<1$AND $d<6$	*d* – Cartesian distance in lattice pitches between *i,j* and *i′,j′*. *d* – full power days since channel *i′,j′* was fuelled. W_F– user defined relative importance of avoiding recently fuelled channels.

Because the only properties distinguishing core-follows are the starting point, and rules and weightings imposed to make up the selection criteria it is reasonable to arrive at different core follows using the algorithm pictured in Figure 2 all that needs to be done is to change the channel selection criteria or starting point as necessary. In fact the traditional channel selection criteria can be removed entirely and replaced by user input. In this way the algorithm becomes a 'front-end' to facilitate manual core-follows relying on the engineering judgement of experienced designers as opposed to the formal application of rules.

3.3 RFSP fuelling simulation

Once the channels for the FPD have been selected according to the selection rules, the RFSP input file is prepared. As very few parts of the RFSP input change between time steps, it is a simple matter to automate their generation[5]. When the input files are run and pertinent information stripped from the RFSP output file this information is compared to the design acceptance criteria for channel powers, bundle powers, ripple etc. In the event the RFSP output meets the acceptance criteria then the output and information is logged and RFSP output archived for verification. Conversely, if the RFSP output does not meet one or more of the acceptance criteria, the channel likely responsible for the violation identified so that the channel selection criteria can be amended and another set of channels selected, the RFSP input and output of the previous run deleted and the reselected channels captured in an RFSP input file which is then rerun. In this way, as core-follows are done for a given core-configuration, the selection criteria is updated and the likelihood of selecting a set of channels that meets the acceptance criteria increases.

3.4 Core-follow output

The output of a core-follow is the sum of information gleaned from the successive RFSP output files, the channels selected found in the successive RFSP inputs and the modifications made to selection criteria during the core-follow. The amalgam of this information summarizes the operation of the reactor over the length of the core-follow.

Of note is that all core-follows merely meeting acceptance criteria are not equal. What distinguish these core-follows are the 'rules' and their corresponding weightings used in their generation. For example, at some point in the design process it may be desirable to keep all the average zone control rod insertions close to some nominal value. In this case the impetus would be to weight heavily on rules dictating what zone a channel is fuelled in. Or else it may be preferable to, at all times, stay close to the time-average distribution, in which case the impetus would be to weight heavily the rules associated with ripple and channel age. In practice, a core-follow is a compromise between several, at times conflicting, design criteria. The fitness of any core-follow can be determined so long as the relative importance of each of the design criteria can be expressed quantitatively. This fitness then would allow for a comparison of different fuelling strategies arising from different channel selection criteria.

[5] The preparation of the input file is effectively a series of 'find and replace' operations on a template file

4. Results

Normalized results summarizing an equilibrium core-follow appear in Figure 4. In the presented core-follow the relative ZCR insertion was the sole criteria used to determine the number of channels to fuel. The targeted nominal ZCR insertion was taken to be 0.50 for the simulation. Only channels of like flow direction were fuelled on any given FPD. In the selection criteria particular impetus was given to keeping all 16 local within a limited range. The core-follow achieved a burnup of 20.5 MWd/kgU fuelling an average of 5.00 channels each full power day.

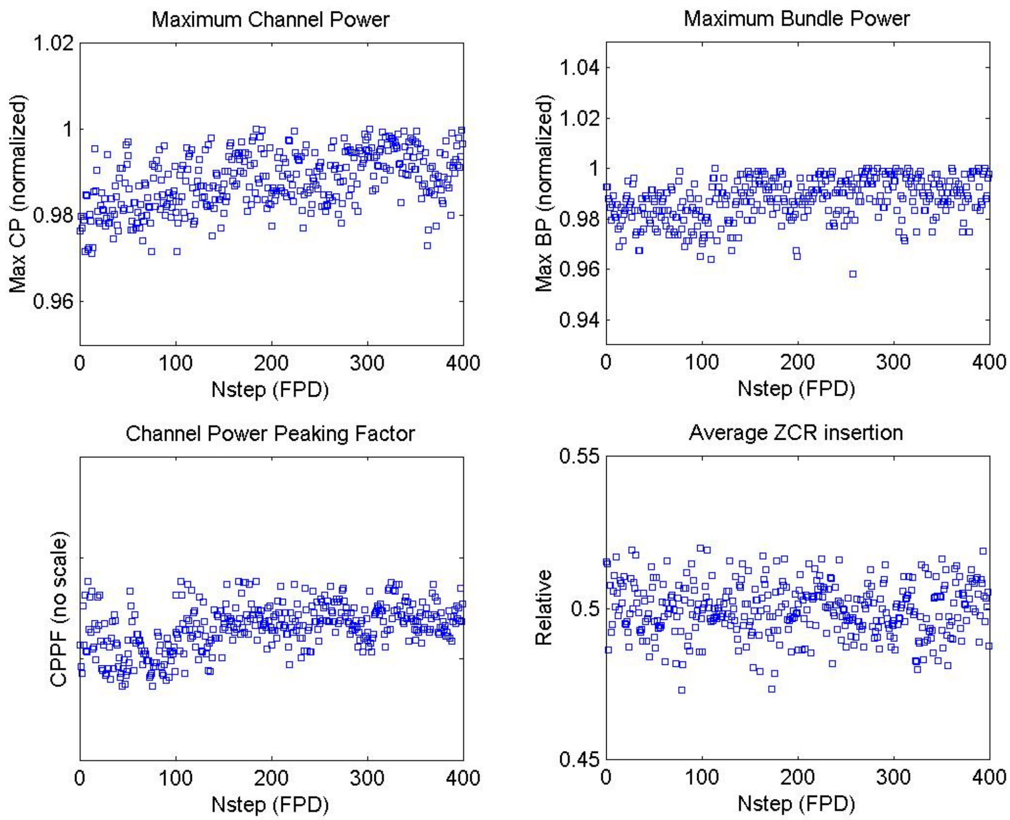

Figure 4: Results of an equilibrium core-follow.

Typically, run times on the AECL Linux cluster are approximately 8 minutes for the RFSP simulation. The ancillary computing associated with each full power day of simulation is on the order of the run time for the RFSP calculation.

5. Conclusion

Presented in this paper is the algorithm used to perform long-term fuelling simulation during the design of the ACR-1000. Its implementation as a software design-tool has allowed for the evaluation of multiple fuelling strategies of multiple core-configurations. It has made possible the use simulation results to make design decision in situations that previously relied on engineering judgement alone.

That said, the purpose of the tool is *not* to replace/exceed manual selection of channels for fuelling. The purpose is to demonstrate a design's viability from a fuelling standpoint in a way that is efficient in terms of engineering-effort. As such, the results of the core-follow simulation provide a lower bound on what is achievable with the judicious application of a fuelling engineer's experience.

The algorithm is ACR specific only in terms of channel selection. Indeed, the algorithms application to a diverse set of core-configurations both equilibrium and transition is suggestive of a wider range of applicability. The use of the algorithm on reactors other than the ACR would only depend on the feasibility of encoding channel selection criteria for, and the suitability of RFSP to simulate, said reactor.

6. References

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