# NEW SELECTION CRITERIA FOR CHANNEL REFUELING OF A CANDU-6 REACTOR: INTRODUCTION TO FLOPPY RULES

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**Abstract-** A revised set of rules is in use at Gentilly-2 NGS for the selection of channels for refuelling. Traditional hard channel rejection rules (of go/no-go type) have been replaced by a more efficient set of soft evaluation rules based on concepts borrowed to the Fuzzy Logic. New evaluation rules, labelled as "Floppy Rules", enable to assess and rate the channel suitability for refuelling by using a smooth and natural continuum of values qualifying excellent, good, fair and poor choices. Global channel suitability for refuelling is measured by combining separate ratings obtained from individual evaluation rules. Each evaluation rule is based on a specific control parameter related to local or lumped core properties. Two new software codes (NEWRULES and REFUEL) designed around the concept of Floppy Rules enable to perform a very efficient selection of optimized channel refuelling sequences either in manual and automatic mode.

## 1. INTRODUCTION

The selection of channels for refuelling is a challenging task for the fuelling engineer at a CANDU station. This activity is fairly time consuming and requires a considerable amount of experience, coupled to good judgement and intuition. Due to numerous and unpredictable real-time constraints, optimized channel selection schemes using fixed geometric or theoretical patterns (as illustrated in figure 2) cannot be sustained for long. Moreover, operating experience shows that it is very difficult to fully translate human decision processes into algorithms for a complete automation of the selection process. Human judgement and intuition have proved to be incommensurably more effective than software for adapting to new or changing situations. Recognizing this fact, an interactive computer program (the SELECT code) has been developed and used at Gentilly-2 NGS during the last fifteen (15) years to assist the fuelling engineer, to reduce the human time devoted to this task and to minimize the risk of errors. Computer power is used to process, screen and display a large amount of core data, while the intuitive and highly adaptive human power takes advantage of interactive software to efficiently choose the best refuelling sequences.

Primary targets of the channel selection process are not immutable. At a new CANDU station, where larger operating margins are available, optimization of the discharged burnup is the prevailing objective of the channel selection process. In the context of reduced operational margins due to plant ageing (mainly from trip margins for Regional Overpower Protection Trip (ROPT)), the optimization of the reactor power distribution clearly becomes the primary objective of the selection of channels for refuelling, showing direct benefits largely offsetting the economic impact of optimized discharged burnup. For the last three (3) years, the power output of Gentilly-2 NGS has been mostly limited by the available margin to trip on the ROPT system, and hence directly by the reactor power distribution. In order to optimize actual as well as future reactor power distributions, the fuelling engineer must take great care while choosing channels. He must use a rigorous approach and display a sense of continuity in the implementation of selection rules. The time spent for selecting channels for refuelling has dramatically increased over the years at Gentilly-2 NGS.

A computer program (SELECT code) has been designed to help the fuelling engineer. The SELECT code provides the user with a screened list of valid choices for refuelling. Channels deemed unsuitable for refuelling are automatically rejected by the application of a number of hard rejection rules (of go/no-go type). These rules are somewhat flexible as the operator may readily change the cut-off threshold. At this point, the selection process is not further automated and still highly relies on human decision to find the best refuelling sequences. With narrower operating margins due to plant ageing, the channel selection process got increasingly complicated and time consuming. Despite the success obtained with this methodology, the need to optimize the reactor power distribution and to increase the efficiency of the selection process to a higher degree have been a strong incentive to thoroughly review our refuelling strategy and our tools.

A review of different problem solving techniques based on the Fuzzy Logic highlighted the great potential of this methodology for improving our own process of channel selection for refuelling. Concepts borrowed to the Fuzzy Logic are the cornerstone of the new evaluation rules (as opposed to old rejection rules), labelled as "Floppy Rules". Like many other decision processes, the suitability of a channel for refuelling may best be quantified by a smooth and natural continuum of values for choices that me be qualified as excellent, good, fair or poor. Channel suitability for refuelling is now assessed and rated by combining the output of a number of separate evaluation functions applied to specific control variables, mostly based on properties of channels and their immediate neighbourhood. This paper reviews the basis for defining better channel selection rules, control variables, adequate weighting of evaluation functions, and also the implementation of this methodology at Gentilly-2 NGS.

## 2. NEW EVALUATION RULES FOR CHANNEL SELECTION

Evaluation rules for channel selection are based on many different core properties: some are related to individual channels (exit burnup, reactivity increase, ...), others to the immediate environment of channels (max. channel overpower, min. channel power margin, predicted burnup spacing, ...), and finally to some core properties averaged over a group of channels (average exit burnup, ratio of actual power to reference power, ...). Besides providing reactivity to the core in a timely manner, the other primary goal of on-line refuelling of a CANDU reactor is to optimize the power distribution by shaping the highly heterogeneous core (as displayed by variations in local properties from channel to channel) to fit the much smoother target flux shape provided by a time-average calculation. The discrete nature of on-line refuelling of CANDU reactors, coupled with narrow operating margins on maximum channel power and overpower, and from time to time with unpredictable real-time constraints, provides all the ingredients for a challenging task to the fuelling engineer.

Channel selection for refuelling should ideally meet simultaneously the following requirements:

- Provide sufficient positive reactivity to enable the operation of the reactor at high power during periods of time where fuel handling systems are not in operation;
- Maintain Liquid Zone Controllers (LZC) levels within their normal control range at any time during a refuelling sequence;
- Maintain LZC levels as close as possible to the Average Zone Level (AZL) at the end of a refuelling sequence (normally at the end of a refuelling day);
- Maintain the reactor power distribution (regionally, axially and locally) as close as possible to the reference power distribution;
- Maximize the operating margin on the ROPT system, by maintaining channel overpowers and Channel Power Peaking Factor (CPPF) at a low value;
- Maximize the operating margin on maximum channel and bundle powers;
- Maximize the burnup of discharged bundles by refuelling channels with an exit burnup close to 100%TA and maintain globally the burnup distribution as close as possible to the reference distribution (i.e. target obtained from the time-average calculation);
- Remove and prevent channel clustering that may result in localized power peaking;
- Ensure the perennial availability of a sufficient number of refuelling candidates and adequate distribution of these channels in the reactor core to balance LZC levels;

In principle, it is possible to meet simultaneously all of these requirements by ensuring that refuelling sites are evenly and adequately distributed in space and time. Real-time constraints may however impose an additional burden on idealized refuelling patterns and may result with an undesirable legacy: channel clustering. The refuelling of multiple channels closely grouped in space and time (known as clustering) generally results with localized power peaking. Clustering generally yields high channel overpowers and low margins to maximum channel and bundle power. Whenever present, clustering is difficult to undo and is prone to replicate itself, as most channels within the group will naturally become available for refuelling within a short span of time in the future.

Hence, selection rules and control parameters have been revised to better meet the above requirements. Two fundamental families of parameters have been identified: one based on properties of individual channels and the other on properties of their neighbours. A cluster of channels is defined as a central channel surrounded by close neighbours within one (1) or two (2) lattice pitches: immediate neighbours for clusters of type 1 (figure 1a) and close neighbours for clusters of type 2 (figure 1b). Due to the discrete nature of channel refuelling at a CANDU station, the dynamic variation of channel properties from one channel to the other (known as ripple) is inevitable. However, average properties of clusters should ideally be maintained nearly uniform from one cluster to the other across the core. Hence, properties of clusters of channels along with properties of the centre channel are used to evaluate the suitability for refuelling. Evaluation rules used for channel selection should be designed to enhance and preserve the homogeneity in the properties of adjacent clusters of channels.

Moreover, different fuelling engineers may perform channel selection in time. Hence the fulfilment of long-term objectives requires a continuous and rigorous application of selection rules in time. The intent of the new evaluation rules is also to act as a driving force to impose an effective refuelling strategy to homogenize core properties of clusters. This strategy should prevent and correct effects of any previous non-optimal refuelling pattern.

## 3. INDIVIDUAL EVALUATION RULES

Old rejection rules, applied to a relevant control parameter, display a sharp transition between channels deemed suitable and not suitable for refuelling (figure 3). The intrinsic difficulty arising from the use of hard rejection rules is that a channel showing a property value just below the cut-off point is not really a bad choice and one that is just above the cut-off point is neither a very good choice. By contrast, new evaluation rules show a much smoother and more natural transition of values for rating channels in a range of very good to bad choices (figure 4). Soft evaluation rules use simple and intuitive functions for rating channels, based on properties of individual channels and their neighbourhood. Both old and new rules may be softened or hardened by displacing the cut-off point. Moreover, the new evaluation rules may be further softened or hardened to a larger extent by scaling up or down the rating (figure 5).

The absolute weighting of evaluation rules is somewhat arbitrary: only the relative weight of one rule compared to the others is of importance. The weighting of individual rules has initially been determined from intuitive considerations. A rating of minus six (–6) is assigned for parameter values at the cut-off point used in the old rejection rules. A rating of zero (0) is assigned for parameter values at (or better than) a target value (perfect score). The operating experience gained over half a year using the new set of floppy rules shows that the initial weighting values intuitively proposed for the evaluation functions are very close to the final and optimized values.

For programming considerations, the evaluation of the best candidates for refuelling and the search for optimized refuelling sequences are separated in two distinct processes. Using the NEWRULES code, a global rating is obtained for each channel in the reactor by combining the ratings of individual evaluation rules. The REFUEL code is subsequently used to perform a manual or automatic search of optimized refuelling sequences, by picking channels within the list of best candidates provided by the NEWRULES code. The REFUEL code uses a different set of evaluation rules, primarily based on the expected response of Liquid Zone Controllers (LZC) to channel refuelling.

Channels are globally rated by the NEWRULES code, using the following evaluation rules:

- Rule #N1: In order to optimize the discharged burnup and the channel power distribution, channels should be refuelled when the exit burnup is as close as possible to the target burnup (provided by the time-average (TA) calculation and defined as 100 %TA). Refuelling a channel before the target exit burnup is reached results in non-optimal use of fissile material in the discharged bundles. On the other hand, refuelling a channel way past its target burnup is not optimal in term of neutron utilisation because the incremental build-up of non-saturating fission products represents a detrimental negative reactivity load on the core. The actual exit burnup (% TA) of individual channels is the evaluating parameter (figure 6)

- Rule #N2: In order to avoid localized power peaking in the core and to ensure the perennial availability of an adequate number of channels at (or near) 100 %TA evenly distributed in space and time, every cluster should bear channels with evenly spaced exit burnup (ideally in increments of 8 %TA). This rule simply prevents from refuelling a channel with a predicted resulting burnup (after refuelling) too close to the actual burnup of one or more channels within the same cluster. This rule has the ability to undo any previously formed clustering by somewhat delaying the refuelling of mature channels. The difference (in %TA) between the predicted final burnup of the centre channel and the actual burnup of other channels in the cluster is the evaluating parameter (figure 7).

- Rule #N3: In order to avoid localized power peaking in the core, to maintain low channel overpowers, large operating margins on maximum channel and bundle powers, and to optimize the reactor power distribution, the average burnup of clusters should be fairly uniform across the core. This rule prevents from refuelling within a cluster of low average burnup. The difference (in %TA) between the average exit burnup of a cluster (excluding the centre channel) and the average core exit burnup is the evaluating parameter (figure 8).

- Rule #N4: In order to avoid localized power peaking in the core and to maintain low channel overpowers, this rule prevents from refuelling next to any overly powered channel. Channel overpower is the ratio of the actual channel power over a reference channel power. Moreover, channels overpowers located in low powered clusters are preventively incremented by the correction term evaluated using rule #7, in order to avoid taking undue advantage in the selection process from any incidental, temporary and favourable local power distribution. Channel overpowers in high powered clusters are not corrected and remain somewhat penalized in the selection process. The maximum corrected overpower of channels in the cluster (excluding the centre channel) is the evaluating parameter (figure 9).

- Rule #N5: In order to avoid localized power peaking in the core and to maintain an adequate operating margin to channel power limits, this rule prevents from refuelling next to highly powered channels. Furthermore, channels powers located in low powered clusters are preventively incremented by a correction term evaluated using rule #7, in order to avoid taking undue advantage in the selection process from any incidental, temporary and favourable local power distribution. Channels powers in high-powered clusters are not corrected and remain somewhat penalized in the selection process. The minimum corrected channel power margin (%) of channels in the cluster (excluding the centre channel) is the evaluating parameter (figure 10).

- Rule #N6: In order to avoid large axial tilts in zone powers and liquid zone controller (LZC) levels, this rule prevents from overly refuelling A (north) or C (south) channels in control zones. The differences between the average dwell time (expressed in Equivalent Full Power Days and converted into a channel deficit) of A_side and C_side channels in each of the seven (7) control zone are the evaluating parameters (figure 11).

- Rule #N7: In order to avoid taking undue advantage in the selection process from any incidental, temporary and favourable local power distribution, channels powers and overpowers located in low powered clusters are preventively incremented by a correction term. The ratio of average power over the average reference power of a cluster of channels (excluding the centre channel) is the evaluating parameter (figure 12).

Within the REFUEL code, optimized channel refuelling sequences are manually or automatically sought by using the following evaluation rules:

- Rule #R1: Control of the reactor power distribution is best achieved when all LZC levels are in their normal operating range. Channel refuelling sequences resulting with one or more LZC levels in limitation (level < 10% or level > 80%) should be avoided. This rule evaluates refuelling sequences based on the expected (intermediate and final) LZC level distribution (figure 15).

- Rule #R2: Control of the reactor power distribution is also best achieved when all LZC levels are close to the average LZC level (AZL). This rule evaluates refuelling sequences based on the expected (intermediate and final) LZC level distribution (figure 16).

- Rule #R3: Optimized refuelling sequences should add a significant reactivity amount to the core (normally, 0.200 milli-k per channel on average). This rule ensures that refuelling sequences with higher reactivity worth are favoured (figure 17).

- Rule #R4: Optimized refuelling sequences should involve mostly channels with high exit burnup (near 100%TA). This rule ensures that refuelling sequences with higher average exit burnup are favoured (figure 18).

- Rule #R5: Changing the refuelling side within a daily refuelling sequence results with additional delays because the feeding fuelling machine (F/M) for the next refuelling cannot load new fuel in parallel with the discharge of bundles to the spent fuel bay by the receiving F/M. Optimized refuelling sequences should then minimize the number of side changes within a daily refuelling sequence. This rule ensures that refuelling sequences with a low number of side changes are favoured (figure 19).

- Rule #R6: In order to avoid localized power peaking in the core, refuelling close to a recently refuelled channel or to a channel already selected for refuelling should be avoided. This rule ensures that channels within two (2) lattice pitches of recently refuelled channels (less than ten (10) Equivalent Full Power Days away) or already selected for refuelling will not be available (figures 1C and 1D). Whenever recently refuelled channels have been processed by the reactor simulation code (HQSIMEX), the exclusion zone is automatically reduced to one (1) lattice pitch (figure 20).

## 4. COMBINING EVALUATION RULES

The ratings of individual evaluation rules must be combined in some way to obtain a final and global rating in order to quantify the suitability for refuelling of any particular channel or sequence of channels. Individual channels or sequences of channels may then be manually or automatically picked on the basis of their global rating.

Different methods for combining individual ratings have been investigated (figures 1C and 1D). One particular method, found to yield results in close agreement with the human subjective evaluation, has been adopted: the global rating of a channel or sequence of channels is simply the square root of the quadratic sum of individual ratings (table 1 and figure 13).

## 5. IMPLEMENTATION OF FLOPPY RULES AT GENTILLY-2 NGS

In a first step, a global evaluation of each channel in the core is obtained from a NEWRULES calculation, using input data maps of core properties previously extracted from the latest production run of the HQSIMEX simulation code. The global rating of individual channels, ranging typically from zero (0) to minus ten (-10), is calculated by combining separate ratings from evaluation rules #N1 to #N8 (figures 6 to 13). Only channels with a global rating ranging from zero (0) to a cut-off value (usually –5) are considered as acceptable candidates for refuelling. A list of candidates for refuelling and their global rating is provided for the next step.

In a second step, optimized refuelling sequences are sought interactively by using the REFUEL code in manual or automatic mode. The search of optimized refuelling sequences considers:

- Initial levels of liquid zone controllers (LZC);
- Predicted final configuration of LZC levels after a complete refuelling sequence;
- Predicted interim configuration of LZC levels within a refuelling sequence;
- Average reactivity increase of the refuelling sequence (in milli-k/channel);
- Average exit burnup of the refuelling sequence (in %TA);
- Number of refuelling side changes to complete the refuelling sequence;
- Vicinity of recently refuelled channels and channels already selected for refuelling;

Predicted LZC levels after each channel refuelling are calculated in the REFUEL code using a linear superposition of the initial LZC configuration and the average LZC response to the refuelling (from the historical data base) of individual channels in the sequence considered. A global rating of the refuelling sequence is obtained by combining separate ratings from evaluation rules #R1 to #R6 (figures 15 to 20). In the manual mode, the user normally picks channels, one at a time, from the list of candidates provided by the NEWRULES code and a global rating of the refuelling sequence is automatically displayed.

In the automatic mode, channels are sought collectively in separate groups of channels (from 1 to 8 at a time, as specified by the user) to fill a day's worth of refuelling. Every possible combination of channels (within the list provided by NEWRULES) is examined by the REFUEL code. Usually, more than 50000 combinations of channels are sought for a typical refuelling sequence of four (4) channels (figure 14). In the automatic mode, the REFUEL code displays a list of the ten (10) best sequences of channels. The user can examine each sequence in details and confirms his choice on any one of these ten sequences. Moreover, previously chosen channels may be dropped individually or collectively. Multiple sequences of channel refuelling may be sought within a single execution of REFUEL.

## 6. CONCLUSION

New floppy evaluation rules are in use at Gentilly-2 NGS for the selection of channels for refuelling since the last six months. The evaluation rules implemented in the NEWRULES and REFUEL codes are powerful and efficient tools for rating the suitability of channels for refuelling and for searching the best refuelling sequences.

During the validation phase of this methodology, optimized refuelling sequences obtained from the REFUEL code in the automatic search mode have been challenged by the best choices made by experienced fuelling engineers using the manual mode. Nearly all the times, the automatic search mode emerged as a clear winner, because every combination of channels within the list of candidates is systematically examined by the REFUEL code.

The use of the automatic search mode provided by the REFUEL code has dramatically reduced the time normally spent by the fuelling engineer for channel selection. This methodology has also proved to be highly adaptive to changing real-time constraints. When properly weighted, the separate evaluation rules work synergistically to impose an effective refuelling strategy. A quick review of the refuelling pattern for channels selected using the automatic search option clearly reveals the underlying refuelling strategy imposed by the evaluations rules.

Moreover, this methodology yields individual and global ratings in close agreement with the qualitative evaluation of experienced fuelling engineers and those ratings can readily be validated. The success obtained so far with this simple approach is beyond our initial expectations.

TABLE 1

## Combining evaluation rules for a global rating of channels

| | Channel burnup | Burnup spacing | Burnup of cluster | Channel overpower | Channel power margin | A/C balance in zones | Global rating | |
|---|---|---|---|---|---|---|---|---|
| | Rule # 1 $f_1(u)$ | Rule # 2 $f_2(v)$ | Rule # 3 $f_3(w)$ | Rule # 4 $f_4(x)$ | Rule # 5 $f_5(y)$ | Rule # 6 $f_6(z)$ | SUM ($f_i$( )) | SQRT( SUM ($f_i$( )^2) ) |
| RATING | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **0** Very good |
| | **-6** Poor / bad | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **-6** Poor / bad | **-6** Poor / bad |
| | **-1** Very good / good | **-1** Very good / good | **-1** Very good / good | **-1** Very good / good | **-1** Very good / good | **-1** Very good / good | **-6** Poor / bad | **-2.4** Good / fair |
| | **-4** Fair / poor | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **-4** Fair / poor | **-4** Fair / poor |
| | **-2** Good | **-2** Good | **0** Very good | **0** Very good | **0** Very good | **0** Very good | **-4** Fair / poor | **-2.8** Good / fair |
| | | | | | | | | **Preferred method** |

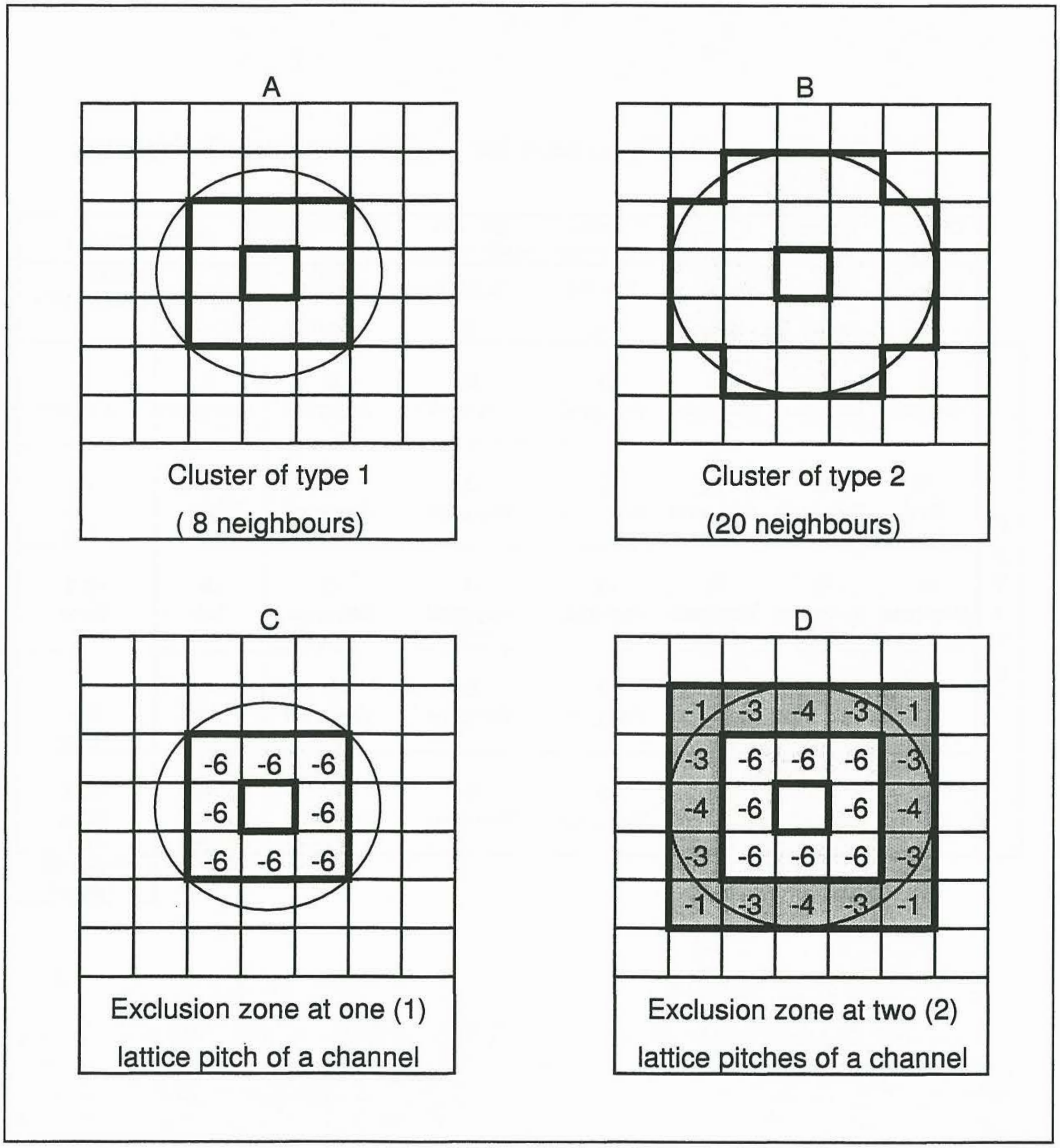
A
Cluster of type 1
( 8 neighbours)
B
Cluster of type 2
(20 neighbours)
C
-6 -6 -6
-6 -6
-6 -6 -6
Exclusion zone at one (1)
lattice pitch of a channel
D
-1 -3 -4 -3 -1
-3 -6 -6 -6 -3
-4 -6 -6 -4
-3 -6 -6 -6 -3
-1 -3 -4 -3 -1
Exclusion zone at two (2)
lattice pitches of a channel

FIGURE 1

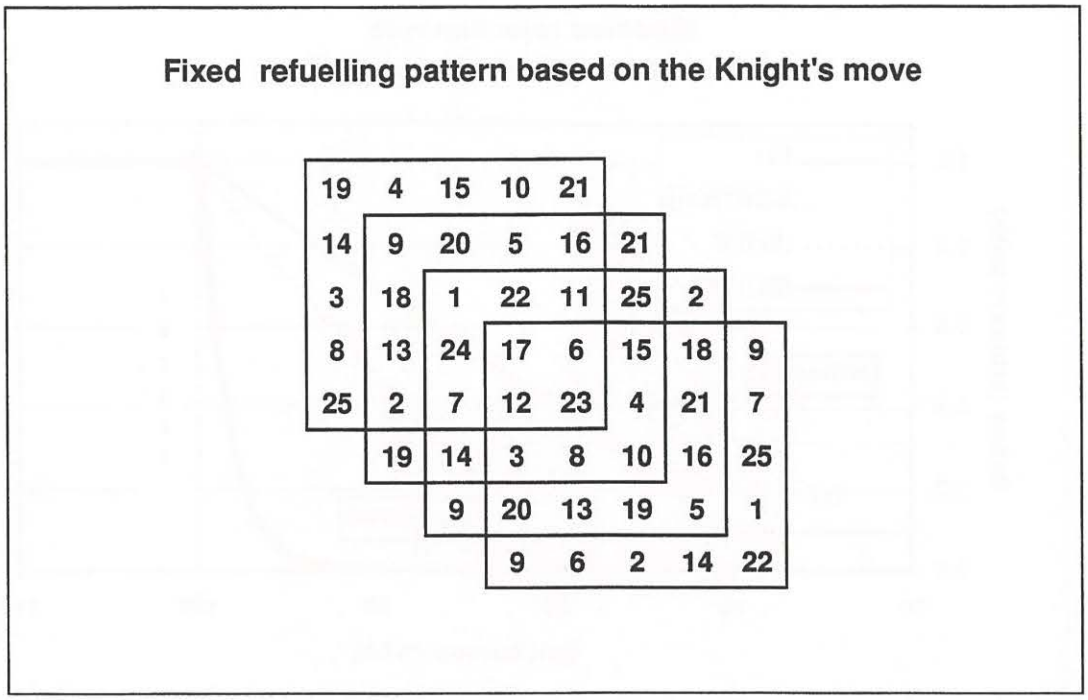


FIGURE 2

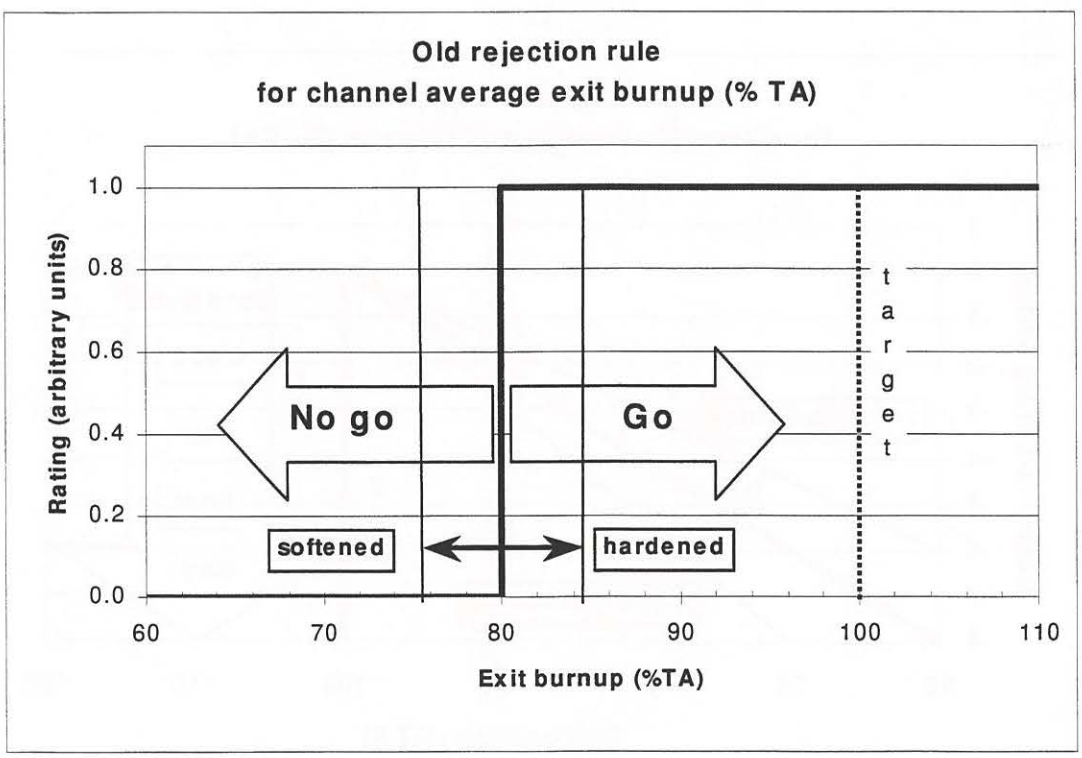


FIGURE 3

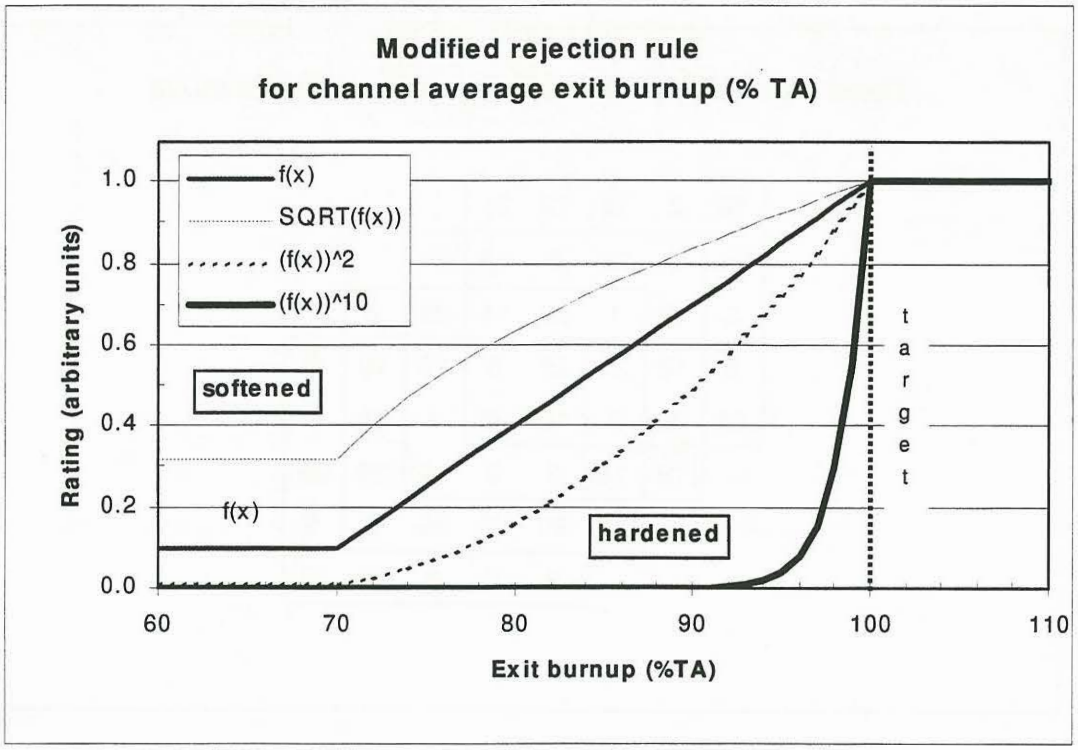


FIGURE 4

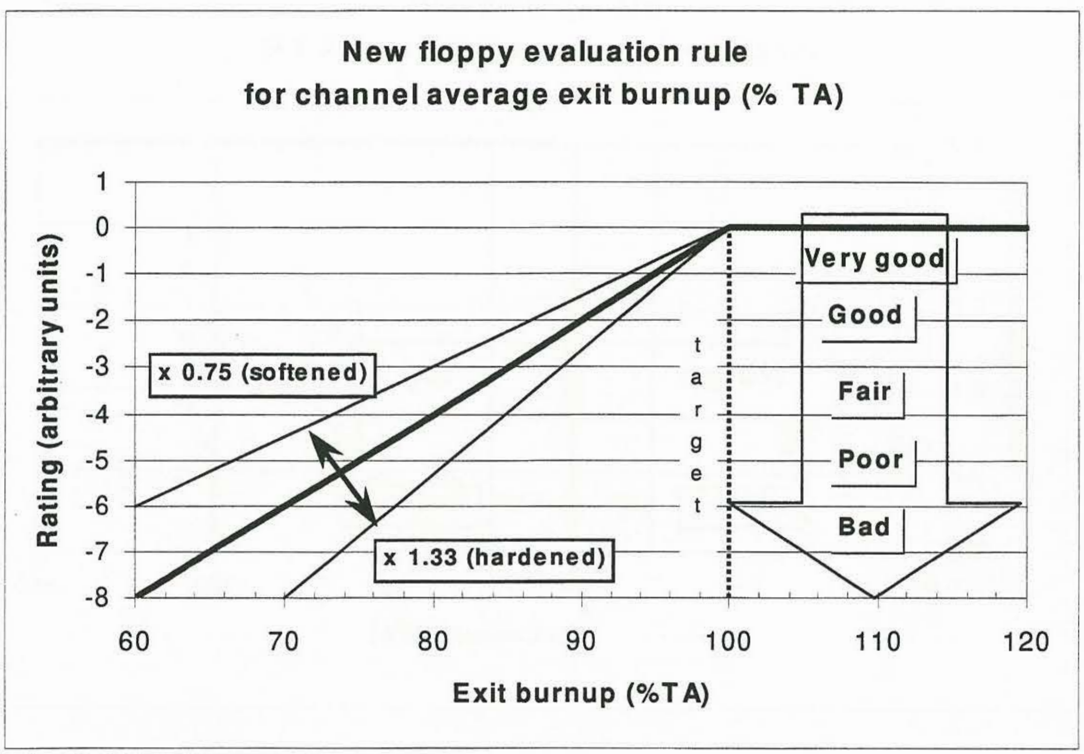


FIGURE 5

## Rule # N1: Average exit burnup of a channel

**Objective:** optimize average fuel exit burnup. Ideally channels should be refuelled at (or near) 100 %TA burnup

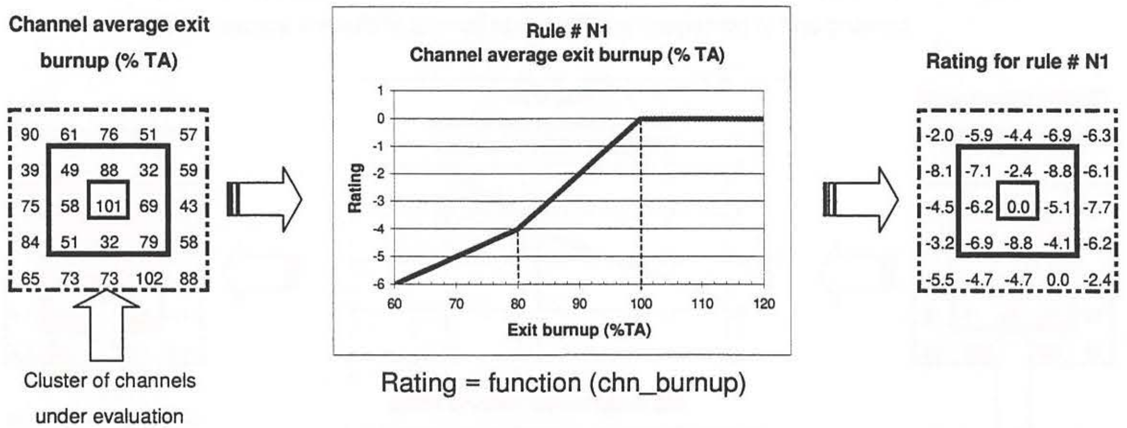


FIGURE 6

## Rule # N2: Burnup spacing of channels in a cluster

**Objective:** spread evenly the exit burnup of channels located inside a cluster (near neighbors) to ensure the perennial availability of a sufficient number channels at (or near) 100 %TA in order to balance LZC levels

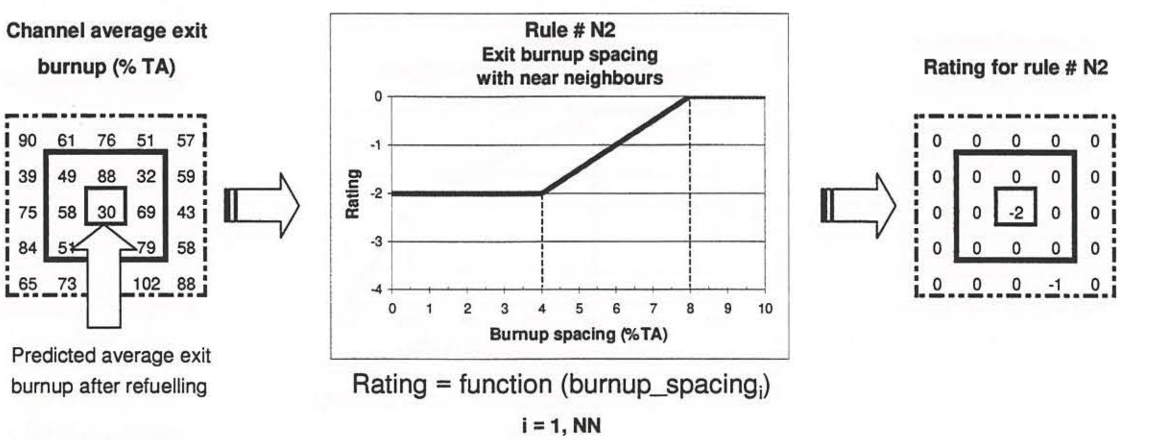


FIGURE 7

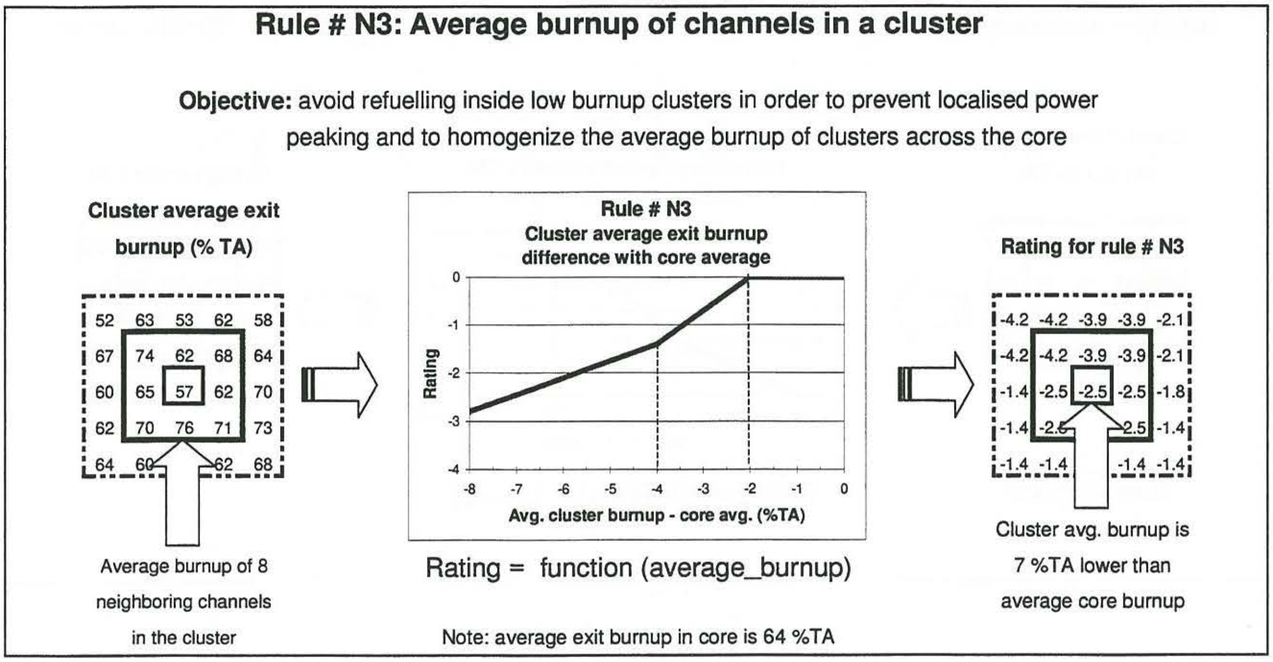


FIGURE 8

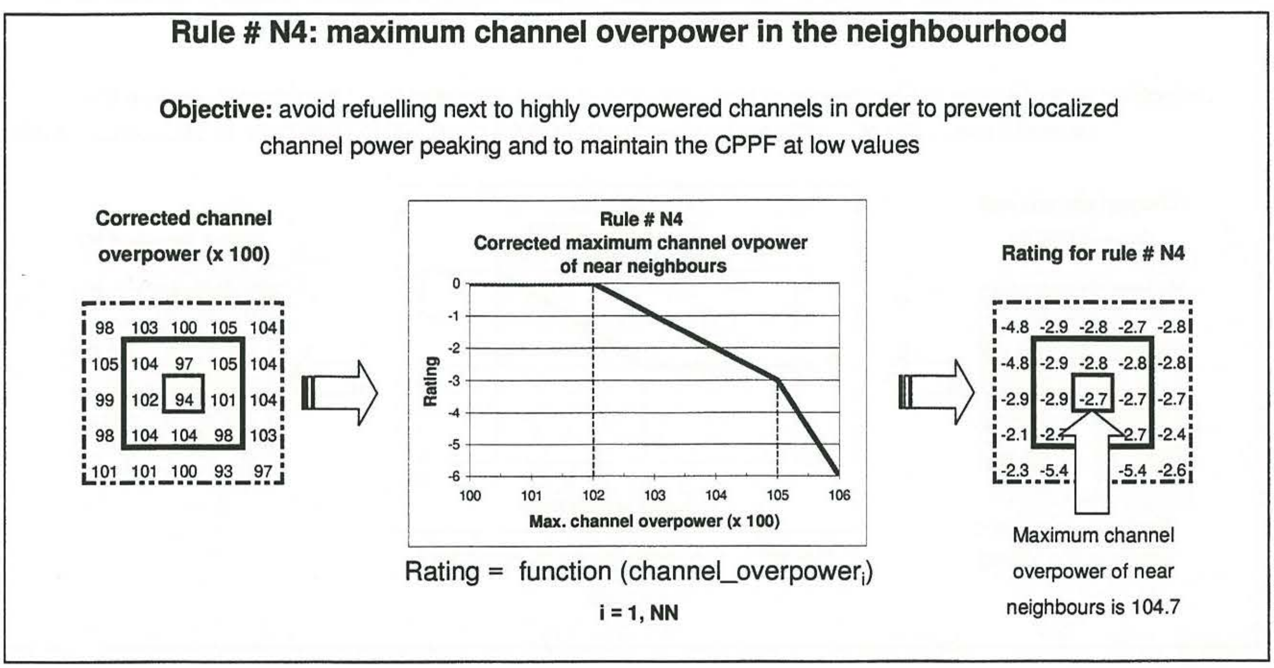


FIGURE 9

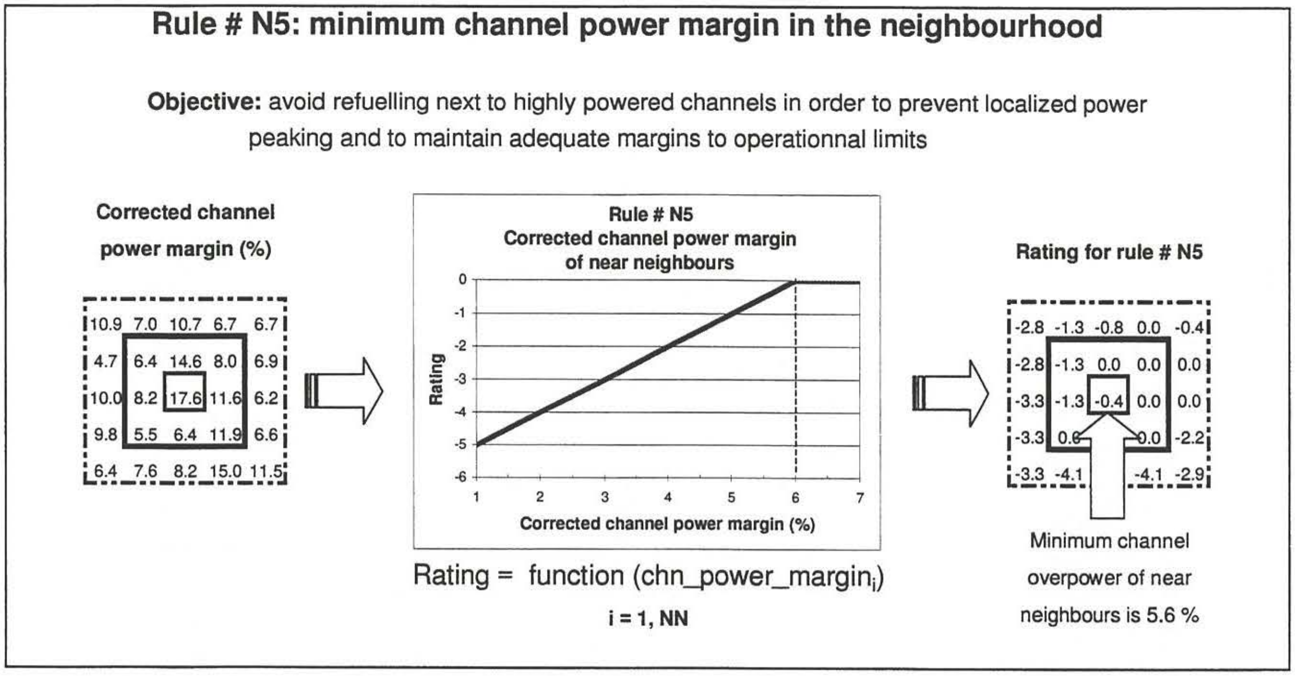


FIGURE 10

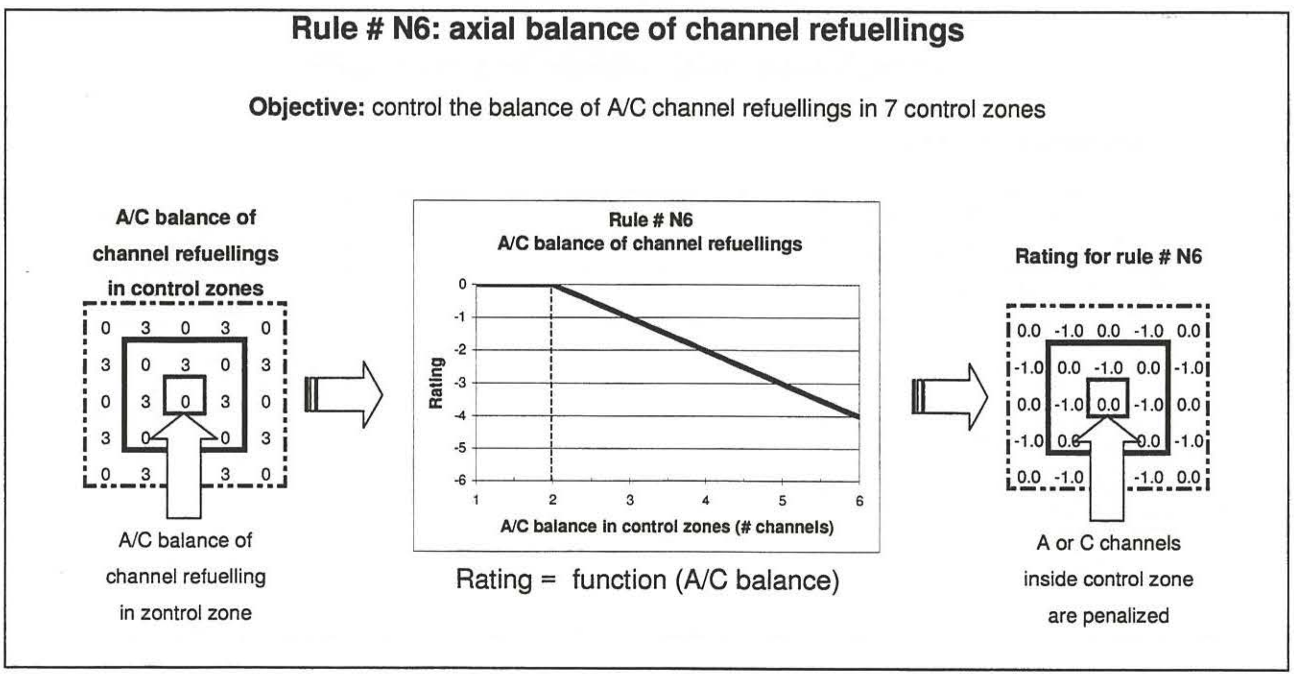


FIGURE 11

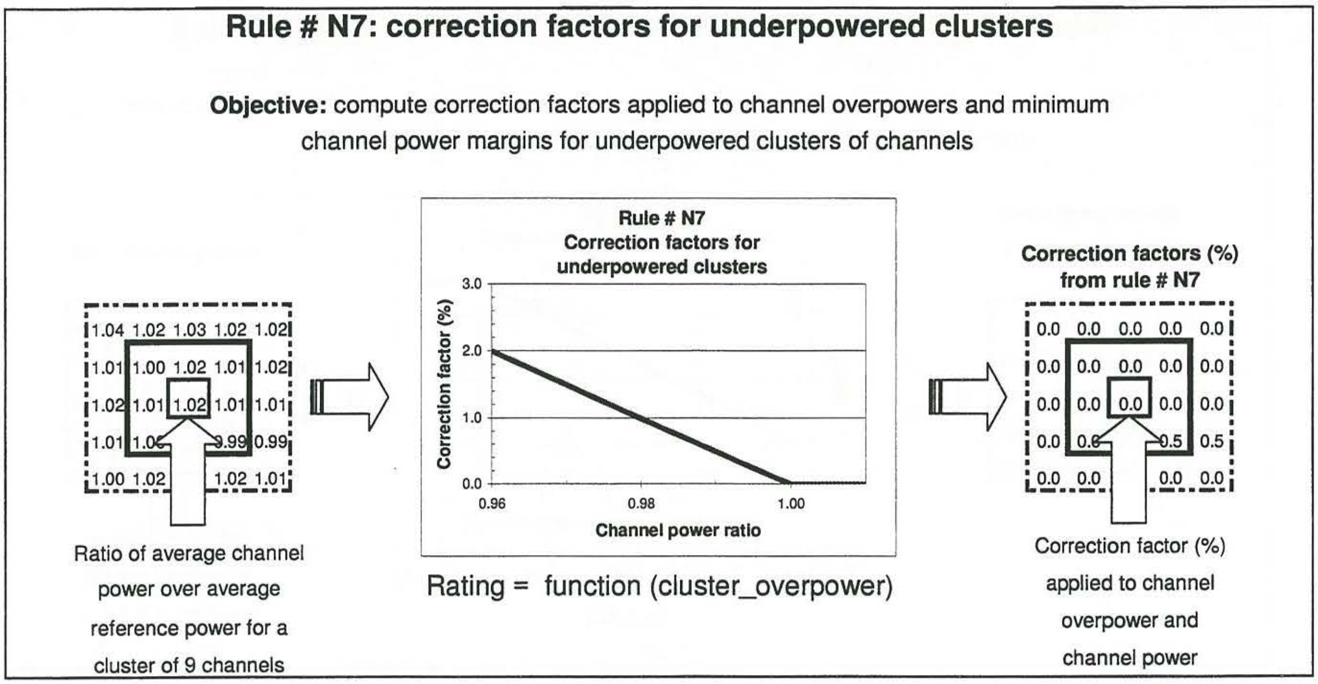


FIGURE 12

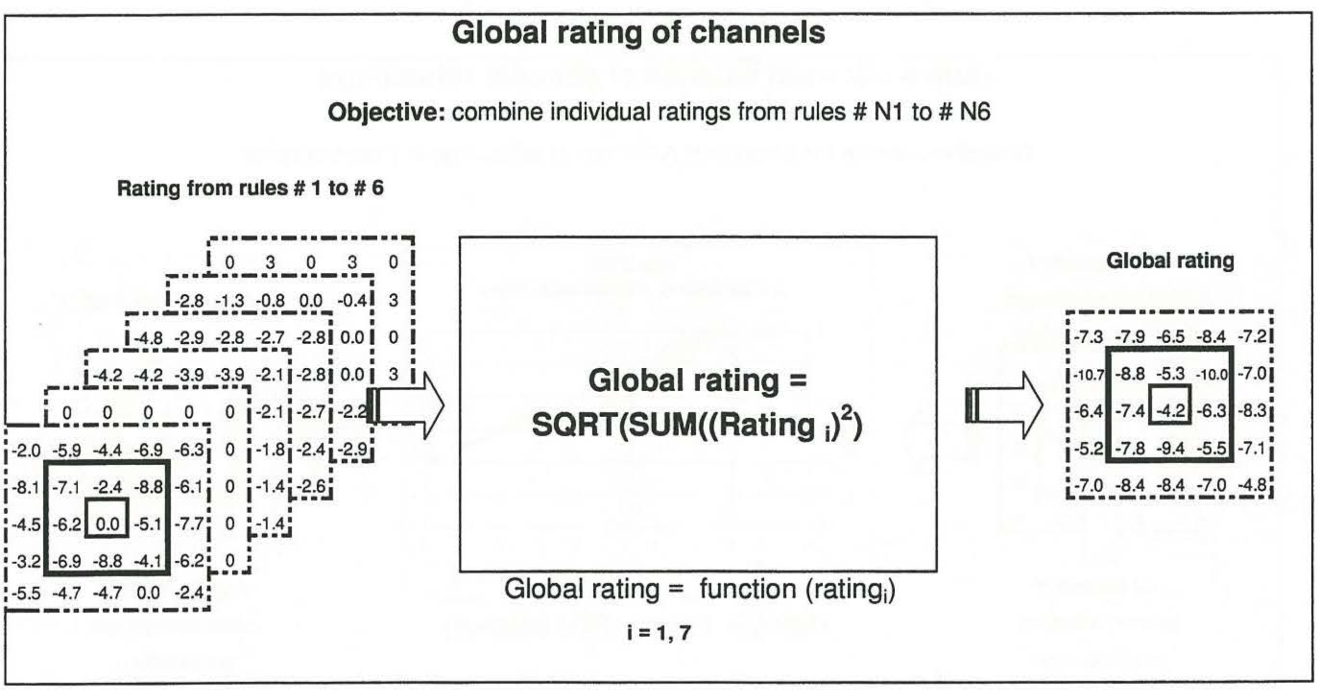


FIGURE 13

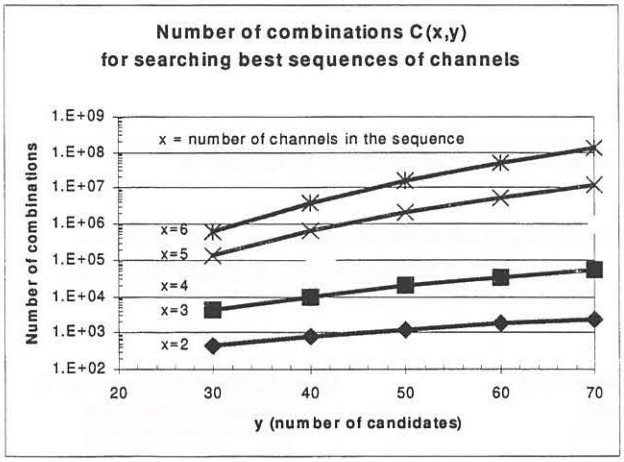


FIGURE 14

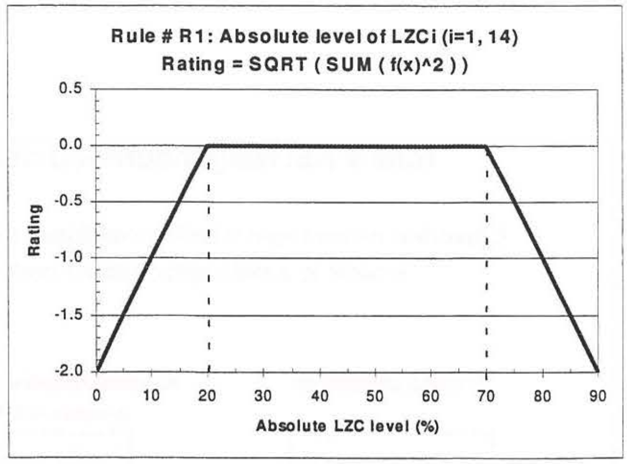


FIGURE 15

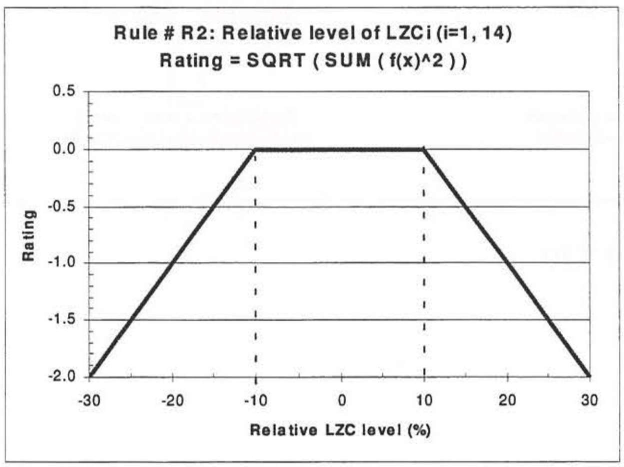


FIGURE 16

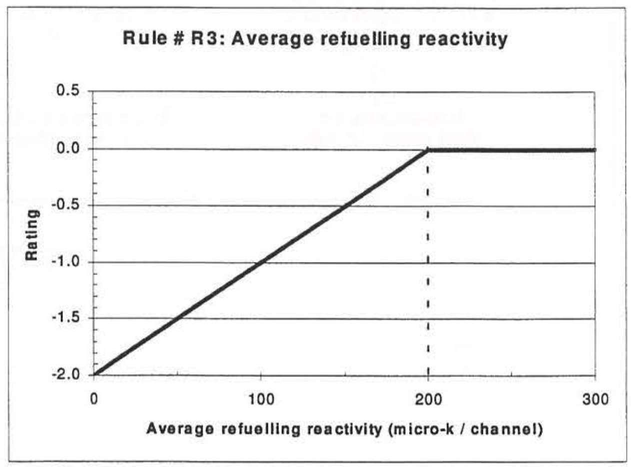


FIGURE 17

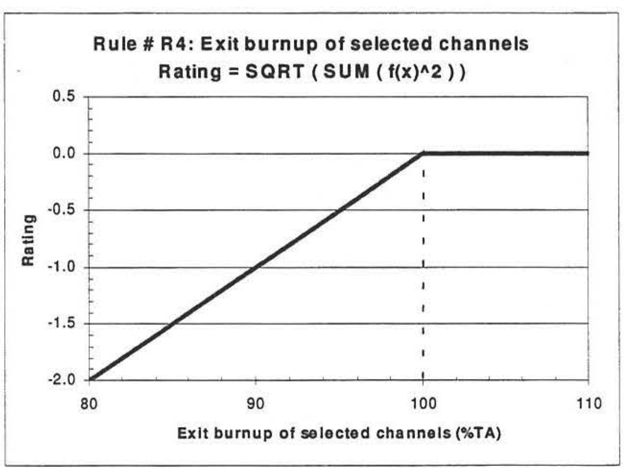


FIGURE 18

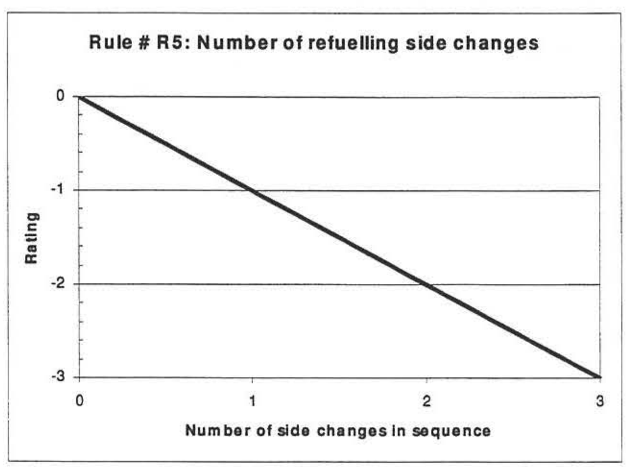


FIGURE 19

## Rule # R6: Neighbourhood of refuelled and selected channels

**Objective:** prevent from refuelling candidates in the viscinity of selected or recently refueled channels in order to avoid localized power peaking and to enhance homogeneization of core properties

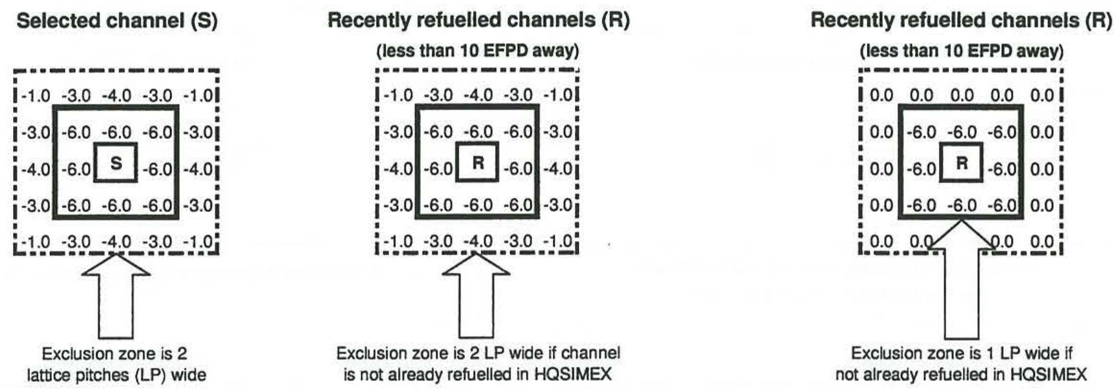


FIGURE 20