Modelling Of CANDU® Fuelling Operations With AECL Code Refuel

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Abstract

REFUEL is an AECL code that can simulate successive one-full-power-day RFSP-IST snapshots of a 380-, 480-, 292- and 520-channel CANDU® core using online refuelling. The code can maintain zone fill and zone controller insertion levels near the desired nominal position for any number of zones and zone controller units. REFUEL has been used to model many fuelling schemes, including two-, four- and eight-bundle-shift push-through schemes with 12 or 13 fuel bundles per channel. Other non-conventional fuelling schemes are also possible, such as multiple fuel types per channel and non-push-through fuelling schemes. This paper focuses on new developments in the code design since the publication of a previous paper.

1. Introduction

RFSP-IST [1] is a lattice code that simulates a CANDU® core as an average over time and as a series of instantaneous snapshots, and predicts the burnups and power distribution for each fuel bundle. Modelling of a CANDU core refuelling simulation can be started from any instantaneous snapshot generated by RFSP-IST. This snapshot can be artificially created with a 'patterned'-random fuel burnup distribution, or taken from a core-following simulation of an operating CANDU core. REFUEL [2] is used to pick channels for refuelling during any RFSP-IST-simulated one-day snapshot of the core, subsequent to RFSP-IST-generated instantaneous snapshot data. REFUEL can also start with a fresh core fuel distribution, and take successive snapshots until the core is ready for refuelling, and beyond. A reference power distribution is used as the target distribution when averaged over time.

There are three stages in the automatic selection of channels for refuelling: the elimination stage, ordering of the remaining candidates, and the final selection stage. The process is iterative and the refuelling requirements are automatically adjusted during each iteration, to arrive at a final set of channels to be refuelled, the number of which meets the user-defined range of channel refuellings requested for the next day.

Once the channels to be refuelled have been chosen, the program creates a new RFSP-IST input file with these data, to simulate refuelling(s) during the next full-power-day (FPD). The RFSP-IST module "*SIMULATE" is used to create all snapshots of the core, using the spatial control option. During the input creation stage, relative flux levels of all zones are calculated, for the optional creation of new Φ-nominals. These zone thermal flux targets are compared to the core average, by the reactor regulating system (RRS) when determining whether to raise or lower the zone fill/insertion levels.

Sections 2 to 9 outline the process of channel selection for refuelling. Figure 1 shows the steps that are performed in REFUEL to generate the new RFSP-IST input.

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2. Input and Output Data

The REFUEL code data files have been streamlined as much as possible, to provide all core-specific data in a standard manner. All core-specific data are identified in the input, so that one version of the code is sufficient for all current and proposed CANDU designs. Parameters are made generic enough to be applicable for at least five core designs, many zone controller layouts and their numbering and labelling conventions. The 'fixed' input is read in the main REFUEL routine, as well as in the subsequent READTAV routine. Three of these files can remain fixed for the entire set of snapshot simulations. The READRFSP routine reads the snapshot data from the preceding time step. Subroutines READTAV and READRFSP are identified as steps 2 and 3, respectively, in Figure 1.

Upon completion of the channel selection, the code will create the RFSP-IST input for the *SIMULATE options, and generate an output in a form that REFUEL can read. These steps are performed in the RFSPINP routine (see step 8 in Figure 1).

This output can be used to generate 'RIPPLE' data for regional overpower protection (ROP) or neutron overpower (NOP) analysis. It can also be used for fuel element integrity analysis to generate maximum linear heat generation rates for comparison to stress-corrosion-cracking (SCC) limit data. This part can be generated through a post-processing routine within REFUEL.

3. Elimination Rules

The first stage in the selection of channels for refuelling involves creating a short list of channels for further refuelling consideration. The elimination of over 90% of the channels from further consideration is accomplished through the application of 17 rules, each of which must be met by every candidate channel, to maintain eligibility for refuelling. Twenty channel elimination and selection rules are user-defined in the main input file, to accomplish this part of the job. Each of these rules can be turned on or off in the REFUEL input file, either by setting the logical array variable to true or false, or by making the rule limit non-restrictive.

Rules 1 to 13 are limits on the maximum bundle and channel power of each channel and its neighbours. Rule 1 defines the maximum channel power before refuelling. Rule 3 defines the maximum bundle power before refuelling. Rules 2 and 4 are similar to rules 1 and 3, multiplied by a factor that includes the anticipated reactivity increase for that channel after refuelling, as calculated by RFSP-IST. This factor is intended to be a predictor of the channel or bundle power increase as a function of burnup. The channel power or bundle power should increase more if the reactivity insertion is larger, and rules 2 and 4 strive to capture this logic. Rule 5 tests the power ripple prior to refuelling as a fraction of the time-average channel power.

Rules 6 to 13 check that the neighbouring channel powers and maximum bundle powers are below a user-defined threshold, to ensure that power limits will not be exceeded in the neighbouring channels. Rules 14 to 16 prescribe minimum limits on burnup and time between successive refuellings. Rule 17 is used to eliminate channels retroactively, by repeating a case, if a high-powered channel or bundle exceeds the operating power limit. These limits are shown as the values of the array RLIMIT in Table 1. The actual rule limits are read from a REFUEL input file. Templates for this input file are available for all CANDU cores in operation or in consideration. The order of these rules cannot be adjusted in the input file, but the rule limits, rule increments and their applicability are variables.

The rule increments are values that are added to an array that is in the shape of the core, with numbers at each channel location representing the sum of all increments that were added for failed rules at that location. If the value for a particular location is zero, then that channel is a candidate for further consideration. Otherwise, the failed rule(s) is(are) apparent from the sum of rule increments. The location of high-powered neighbouring channels, as defined in rules 6 to 13, are shown in Figure 2. The locations of freshly fuelled neighbouring channels, as defined in rule 15, are shown in Figure 3.

The remaining three rules, 18 to 20, are applicable to high-power channels near the current zone fill/insertion level. These selection rules are shown in Table 2 and the applicable channels are shown for a particular zone fill/insertion level in Figure 4.

As a first guess, each rule should eliminate at least 90% of the channels on the first pass, because a high-power channel will generally have high-power neighbours, lower burnup, a large ripple and a recent refuelling in the near vicinity. The ideal initial rule base will allow about 1% of available channels to qualify as refuelling candidates on the first pass, because the channels are later put into the order in which they originally qualified. If $IRULE_{ij}$ remains zero after the application of rules 1 through 17, then channel (i,j) becomes a candidate for further selection criteria, where 'i' and 'j' represent the row and column of the channel, respectively. Otherwise, the $IRULE_{ij}$ number is the sum of unique increments, added for each failed rule listed below that prevents the channel from being a candidate.

4. Refining the Elimination Rules

A recursive feature has been built into this selection process, to obtain a certain number of candidate channels. The user defines this number of channel candidates to be within a range that does not exceed 100 candidates. The rules should be initially defined to produce no more than 10% of the candidates that are required for the final selection process, because part of the ordering technique defined in Table 3 depends on how soon a channel qualifies for refuelling under more stringent conditions.

If there are too few candidates, then the minimum required acceptance of all of these rules is relaxed by the increment listed in Table 1, to allow for more candidates to qualify. This procedure is repeated until enough candidate channels, relative to the lower threshold, remain after elimination. It is also possible that there will be more qualifying channels than needed. In this situation, the minimum required acceptance criterion for each rule is made more stringent, to eliminate more channels from further consideration.

The rules listed above are values assigned by the user that are initially intended to eliminate over 99% of the total channels for a typical CANDU core. Cores that require less than two channels to be refuelled per FPD will need about 20 channels to qualify for the next stage of selection. Some prototype cores require an average of up to seven channels to be refuelled per FPD, so they will need over 30 channels to qualify for the next stage of selection. The rules must be gradually relaxed to allow more channels to qualify, because the order of picking provides one of the final selection criteria. The process described in Sections 3 and 4 is performed in the ELIMIN subroutine of REFUEL, defined as step 4 in Figure 1.

5. Balancing the Number of Refuellings in Each Direction

REFUEL automatically balances the number of refuellings in each direction, for each axial pair (or set) of zones. The program reads the refuelling history from the input files that are present in the directory, over a user-defined time frame. The refuellings must be balanced in each direction for each axial zone pair. For CANDU 6 reactors, the number of channels fuelled in each direction is not equal for every axial zone pair. In this case, for every axial zone pair, the program will count the number of channels fuelled from each end of the core. It will then try to match the ratio of refuellings for each end to the ratio of channels fuelled from each end of the zone pair, over the user-defined period.

The number of channels refuelled in each zone, in each direction, is a key selection criterion used in REFUEL. The best method for minimising the axial tilt involves controlling the total number of refuellings in each direction. This control is achieved by ordering the channel candidates preferentially, with the smallest ratio of channels in a zone pair being fuelled first. The balance of refuellings in each direction is determined in the ZONEFIL subroutine of REFUEL, defined as step 5 in Figure 1.

The channel candidates are then ordered, as defined by the criteria of Table 3, in the ELIMORD subroutine of REFUEL, defined as step 6 in Figure 1. Channels in zones with the lowest zone fill/insertion level are placed at the top of the list for first selection. The optimum number of channels to be refuelled in the next FPD is chosen from this ordered list.

6. Selection of Channels to be Refuelled

The selection process is performed in the SELECHAN routine, defined as step 7 in Figure 1. The first step involves reducing the chance that a high-powered channel near a zone controller will exceed power limits. For each channel identified in Figure 3 to be close to current zone fill/insertion levels, its channel power is compared to the respective values defined in rules 18–20. REFUEL's internal record of current zone levels will be reduced by one lattice pitch, for those zones for which there is a high-power channel near the location of the current zone fill/insertion level. This will, in turn, increase the requirements to refuel a channel in that pair of zones, if a candidate exists. The definition of a high-power channel near a zone fill level is given in Table 2 under rules 18–20. These rules help to prevent a drop in some zone fill/insertion -levels when there is a chance that a high-power channel near that zone compartment will exceed channel power limits.

REFUEL determines if a high-power channel or bundle is close to the tip or fill level of the zone controller. REFUEL assumes that a channel close by will experience a significant increase or decrease, depending on whether the zone controller fill/insertion-level decreases or increases. If no channel in this zone is refuelled, then the need for reactivity suppression is diminished and the zone controller fill/insertion level will usually decrease. Channel power limits for rules 18–20 are set by the user to levels that may keep channel or bundle powers below the user-defined limit, if the zone controller is at a level or position that is close to one of these channels. If a high-power channel near a zone fill/insertion level is identified by one of these rules, then the program will set the target fill/insertion for that zone to be higher so that some channel in that zone may be refuelled.

The next step involves determining the zone levels for the given FPD without refuelling, and comparing this to the average zone level. This difference in zone levels is converted to a unitless relative reactivity, which can be compared to the reactivity-increase array within RFSP-IST for this time step. If the anticipated zone level after an FPD without refuelling is still higher than the average zone level, then it will have a positive zone reactivity requirement, signifying that no more refuelling is needed. For every zone that requires refuelling, the zone reactivity requirement will be negative.

Next, the channel candidates can be chosen for all pairs of zones in which the reactivity requirement for both zones are negative. The reactivity increase for both the front and back half of the selected channel is added to the zone reactivity value, to measure the effectiveness in re-establishing the zone levels at their nominal levels. If the zone reactivity of either zone becomes positive, then no more channels in that pair of zones will be refuelled. Once a channel is chosen, all other candidates within $\sqrt{3^2+1^2}$ lattice pitches are eliminated from further consideration. Any other candidates within $\sqrt{5^2+1^2}$ lattice pitches are marked, where a second mark will eliminate them also from further consideration.

7. Refining of Selection Criteria

For different reactors and fuelling schemes, the number of channels to be refuelled on each day of the week can be significantly different. Thus, there is a user-defined option in the REFUEL input file to set the number of channels to be refuelled within certain limits above and/or below the core average value for each day of the week.

Two seven-integer arrays are read in for the upper and lower limits, where the first day represents Sunday, and day 7 represents Saturday. After the program has gone through the entire list of refuelling candidates, it counts the number of selected channels. The feature to restrict fuelling on certain days of the week can be bypassed by setting the maximum for all days of the week to one value of no more than 9, and the minimum for all days of the week to another value of no less than 0 and no more than the maximum value for that day. Weekly fluctuations in refuelling rate are common practice in most existing CANDU power plants.

If less than the minimum number of channels is chosen to be refuelled, then the program will increase the target zone fill/insertion levels by 0.2% and repeat the selection process. This effectively increases fuelling requirements by 12 μk, or by about 1 μk for the zone reactivity requirement of each zone, allowing more channel candidates to be selected for refuelling. If too many channels are to be refuelled, then the program will reduce the target zone fill/insertion levels by 0.3% and then repeat the selection process. This, in turn, produces less negative zone reactivity requirements, allowing less channel candidates to be selected for refuelling.

Note that these increments are very small, which means that the process will be repeated a number of times until an acceptable number of channels are chosen. It helps to allow a variable number of acceptable channels to be refuelled for each day, because the program will use these criteria to 'hunt' for the right number of selected channels. Sometimes several channels qualify at the same criteria levels, so the program tries to find a 'tie-breaker' by using different increment and decrement values. Rules 18–20 are unaffected by the refining process of the final selection. This function is also performed in the SELECHAN routine.

8. Creation of the RFSP-IST Input File

The process described in Sections 8 and 9 is performed in the RFSPINP routine, defined as step 8 in Figure 1. Once the channels to be refuelled have been chosen, the program creates a new RFSP-IST input file with these data, for refuelling during the next FPD. The input file is built line-by-line from an RFSP-IST input template file, which is read one line at a time. A number of variables mentioned below are set by the program and inserted in integer format into the new input file.

A user-specified variable decides how often (in FPDs) the direct-access file is to be created in the REFUEL input file. The RFSP-IST input file must be designed to read the most recent direct-access file and include all previously calculated channels to be refuelled up to and including the new data. A core-specific template is available for each current CANDU core and some proposed core designs.

REFUEL opens the RFSP-IST input of the most recent FPD and reads all the previous refuelling information that is not already captured in a direct-access file. This information is written directly into the new RFSP-IST input file. On those occasions when the direct-access file was created in the previous run, the previous RFSP-IST input is neither required nor opened. REFUEL has successfully created RFSP-IST input files for a wide range of RFSP-IST calculation options.

9. Revision of Zone Flux Targets

During the RFSP-IST input creation stage, the relative thermal neutron flux levels are calculated for each zone and for each group of similar zones within the core, for the previous snapshot. A user option can instruct REFUEL to create new Φ-nominals, which are zone thermal fluxes that are relative to the average thermal flux of the whole core. RRS uses these Φ-nominals to assess whether to raise or lower the zone fill/insertion levels.

The thermal neutron flux in all bundle positions of the core is calculated at every snapshot. These values are averaged over each of the zones and compared to the previously calculated target values. The thermal neutron flux of all zones that are deemed to be symmetrically similar are averaged together also, and this average is used as a guide for achieving core symmetry. The difference of instantaneous zone levels from their average values is incorporated, to account for differences in zone-controller-related flux suppression for any given snapshot.

Zone flux is dependent on zone level, which depends on the Φ-nominal. Because these parameters are so interrelated, a unitless equation had to be designed , by dividing each of the parameters by their average over the core. Several user-defined variables may still need to be included in the REFUEL input, such as differences related to the number of zones axially, and the fuelling scheme.

The flux is calculated in each of these zones by adding the flux for every bundle in the zone and dividing by its total number of bundles. Each zone-average flux is then averaged with three other similar zones throughout the core, except for the central two zones, which are averaged with each other. For zones with three other similar zones, the formula presented below can be interpreted as representing 50% of the zone flux itself and 50% of the average flux of the other three similar zones. For zones that are assumed to be like only one other in the core, the formula works out to 2/3 of the zone flux itself and 1/3 of the similar zone flux.

The zone levels are also taken into account to ensure that the zones will remain in the active optimum range of their design for the next couple days of refuelling. Finally, the new target flux is calculated by adding 30% of this value to 70% of the previous target flux for that zone. Since this is a geometric series, the 70% value is comprised of 30% from the most recent flux redistribution calculation prior to the current snapshot, which means 51% of the proposed Φ-nominals are derived from flux levels of the most recent snapshot and the most recent record in the direct-access file of RFSP-IST. This combination allows the code to maintain some stability while basing the majority of the flux distribution on the most recent performance of the core.

The methodology used a combination of contributing factors and was intended to produce the most constant Φ-nominal flux targets in an equilibrium core. The following formula, which can be reapplied as often as the user wants to create a snapshot record in the mass storage file of RFSP-IST, was determined by trial-and-error as follows:

$$\mathrm{PHINEW}_z = \left[\frac{0.3(\mathrm{PHICUR}_z + 2\,\mathrm{PHISIM}_z)}{3} + \frac{(\mathrm{ZLEVEL}_z - \mathrm{AVZLEV})}{10\,\mathrm{TAZLEV}}\right] + 0.7\mathrm{PHIOLD}_z$$

where

$PHINEW_z$	is the new average relative flux target (Φ_{nom}) for zone z,
$PHICUR_z$	is the previous average relative flux of all bundles in zone z,
$PHISIM_z$	is the previous average relative flux of all similar zones, including zone z,
$PHIOLD_z$	is the Φ-nominal of zone z in the previous snapshot,
$ZLEVEL_z$	is the previous zone controller fill/insertion level in zone z,
AVZLEV	is the average zone controller fill/insertion level for the previous snapshot,

and

TAZLEV	is the intended time-average zone controller fill/insertion level.

The average neutron fluxes for each zone relative to the average for the core ($\Phi_{nominals}$) are calculated for each snapshot, and used to redefine the RFSP-IST target flux distribution every ISTEP FPD. Note that these values are unitless multipliers of the average flux for the whole core. They can be updated as often as every time the direct-access file is written, to track the changing flux distribution as the initial core ages into an equilibrium core. The idea is to maintain all zone controller fill/insertion levels at or near 50% on average, while minimising the effect of anomalous zone flux levels by averaging over a number of snapshots.

The new Φ-nominal is 30% of the calculated target value and 70% of the previous Φ-nominal, as recorded in the previous RFSP-IST input that is used to create a mass storage file. The calculated target value is a combination of the current relative zone flux (Φ_{nom}) and the relative zone levels from the previous FPD snapshot.

The user input IPHI can be set to a positive integer representing the frequency of the proposed Φ-nominal calculation. The frequency of recalculation must be an integer multiple of the frequency of direct-access file creation. To perform this part of the calculation, additional input cards are required in the RFSP-IST input template. Modification of these Φ-nominals is a necessity for initial-core-to-equilibrium transition simulations. For the initial core, the reactor had to undergo a major shift in the flux distribution as the initial fuel types were shuffled through the core. It should be emphasised that the Φ-nominals will be revised only if their change is triggered by setting IPHI to a positive non-zero value.

10. Regulation of Zone Controller Level

The zone controllers work best near their mid-range (i.e.,time-average design value), where they can react better to either positive- or negative-reactivity insertion. They are usually designed to offset the flux/reactivity change caused by a single refuelling with no more than 10% of their total reactivity worth, and to maintain a critical system for up to a week without refuelling. They should be able to maintain the core power shape even if a single device has failed in the core. The nominal zone fill/insertion levels, usually used by RFSP-IST in the *TIMEAVER module, are used as a target by REFUEL.

Zones are arranged in axial pairs, typically called the front zone and back zone when referred to individually within the pair. If both zone levels dip below the target value, then the REFUEL code will try to find a channel within that zone to refuel. The number of channels to be refuelled on any given day of the week can be set to a minimum and maximum value. This allows the user to preclude weekend refuelling.

If the number of zone pairs requiring refuelling is not within this range for a given FPD, then the target zone levels are adjusted within REFUEL. If the target is increased, more zone pairs will be refuelled; if the target is decreased, less zone pairs will be refuelled.

If one of the zones in a pair has a lower flux or a lower zone controller fill/insertion level, then channels with exit-burnup fuel in that end of the core will be chosen preferentially to refuel that zone pair. The primary zone of each channel within a zone pair is defined by the user. Usually, the zone at the exit-burnup end of the channel receives the largest initial benefit of refuelling. The reactivity insertion on refuelling is higher at the exit-burnup end, because reactivity drops off more rapidly towards the end of life than at the beginning of life.

However, the number of channels refuelled in each direction must be kept in balance, because the long-term effect of fuelling a channel is weighted heavily towards the fresher-fuel end. Balance is achieved by counting the number of channels refuelled in each direction during the (multiple FPD) simulation, and by trying to match the ratio of the total number of channels refuelled in each direction per zone pair.

If the core is undergoing a transition from a fresh to equilibrium core or from one fuelling scheme to some other scheme, then it is expected that the flux shape of the core will change as the fuel composition within the core is modified. The thermal neutron flux is calculated within RFSP-IST, and the average flux within each zone can be monitored at each snapshot within REFUEL. If the average zone controller levels are no longer near the target value, then the target fluxes, called 'PHI NOMS' within RFSP-IST, should be modified to new flux targets which would allow zone controller levels to vary within a permissible range about the target (time average) value.

11. Results of Some Refuelling Simulations

A prototype core was developed several years ago, for which a transition-to-equilibrium study was required from an initial core configuration. The zones and zone controllers used for this study are shown in Figure 5. The zone levels for a prototype core in transition from initial fresh fuel loading to an equilibrium fuel burnup distribution are illustrated in Figure 6 for 1200 consecutive one-FPD snapshots. The target zone levels were 50% for this set of snapshots, and the average over time was 45%. The average thermal neutron flux for similar zones in the above core are illustrated in Figure 7, relative to the average core flux distribution for the same transition core over 1200 consecutive one-FPD snapshots. Figure 7 demonstrates that the power distribution migrates to the centre of the core as the initial burnup distribution ages, and is pushed through the channel to the exit-burnup end.

The maximum channel powers per snapshot for this core are shown in Figure 8 as a percentage of the maximum time-average channel power. The maximum bundle powers per snapshot for this core are shown in Figure 9 as a percentage of the maximum time-average bundle power in the core. These figures predict the maximum ripple as a function of the maximum time-average channel power level and power distribution. Figures 8 and 9 demonstrate that an initial core power distribution can be more axially flattened than a time-average distribution, because there is no restriction, such as a push-through fuelling scheme, on the power history of bundles in the core. As the more enriched fuel bundles get pushed to the centre of the core, peak bundle powers and channel powers increase. When the core reaches an equilibrium state, the peak powers as a percentage of the time-average maximum will vary by about 3 %.

The REFUEL code was originally designed for a 480-channel CANDU 9 core with enriched fuel. It has been used with RFSP-IST to simulate a core with 13 bundles per channel, and a core with one coolant 'bundle' + 12 fuel bundles, for 1000 FPDs each. A summary of the output showed that there is more axial peaking and lower exit burnup in the 12-fuel-bundle-per-channel core. A prototype core with two zone controllers per zone was also modelled, and the zone levels defined in RFSP-IST were synchronised within each zone.

CANDU 6 cores have been simulated with 37-element natural uranium fuel bundles, and the average of the channel powers over 600 one-FPD snapshots was within 2% of the time-average value, as shown in Figure 10. Note that, over 600 FPDs, the average burnup of each channel varies by up to 10% compared to that of the reference power shape, because some channels can be fuelled three or four times during this period, while others are refuelled only twice. Fuelling ripples were recorded for each channel over 600 one-FPD snapshots for input into a regional overpower protection code such as ROVER-F [3]. By combining the REFUEL output with the relative power densities generated by WIMS-IST [4] for each burnup, a reliable estimate of linear element ratings and linear power boost can be generated. This will help in the assessment of conformance to stress-corrosion-cracking limits.

This code was developed as a design tool, but it has excellent operations potential. If there is a business incentive, then REFUEL can be further developed to automate the RFSP-IST modelling of any size time-step, relative power level and fuelling operation timing. REFUEL, with RFSP-IST, can currently model any CANDU fuelling operation for a multiple of one-FPD time steps. It is expected that any operations work to be generated using REFUEL would require a number of incremental time steps around each refuelling operation.

12. References

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3 C.J. Jeong, H.B. Choi, “Regional Overpower Protection System Analysis for the Direct use of Spent Pressurized Water Reactor Fuel in CANDU Reactors (DUPIC)”, IEEE Transactions on Nuclear Science Vol. 52 Part 3 p.450-456, 2005 February.

4 D. Irish, S.R. Douglas, “Validation of WIMS-IST”, Proceedings of 23rd Annual Conference of the Canadian Nuclear Society, Toronto, 2002 June 2-5.

Figure 1 REFUEL subroutine call logic

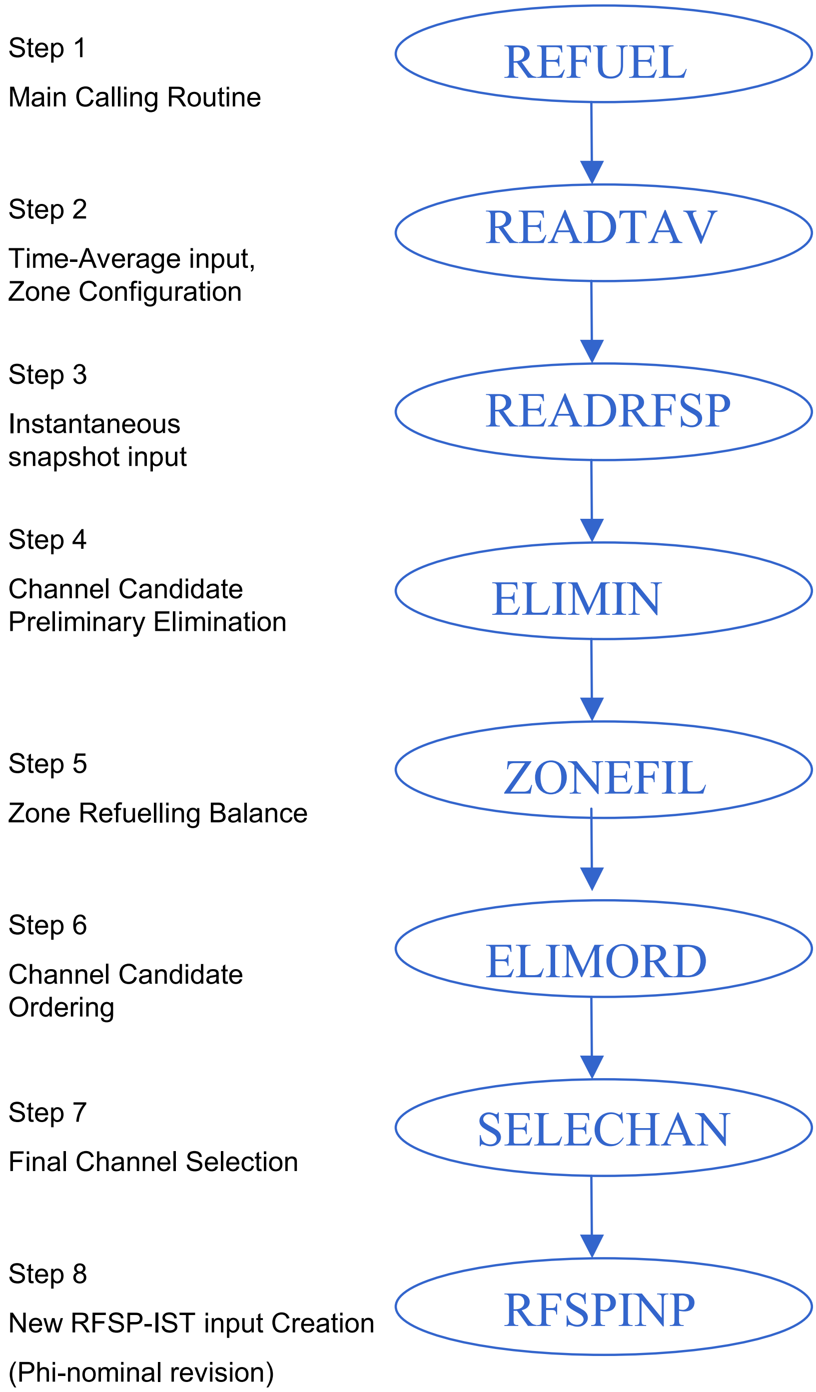

Table 1 Elimination rules (used for the CANDU 6 core)

Rule #	$TEXT_r$ Definition	Increment to $IRULE_{ij}$ if eliminated*	$RLIMIT_r$ (for CANDU 6 core)	$RINC_r$ increment to $RLIMIT_r$ (%)
1	Channel Power Too High (kW)	1	6100	0.15
2	Reactivity-Increase-Factored Channel Power Too High (kW)	2	6700	0.15
3	Bundle Power Too High (kW)	4	750	0.15
4	Reactivity-Increase-Factored Bundle Power Too High (kW)	8	920	0.15
5	Maximum Channel Ripple (% x 10)	16	960	0.15
6	First (4) Neighbours of High–Power Channel (kW)	100	6600	0.15
7	Second (4) Neighbours of High-Power Channel (kW)	200	6650	0.15
8	Third (12) Neighbours of High–Power Channel (kW)	400	6700	0.15
9	Fourth (16) Neighbours of High–Power Channel (kW)	800	6800	0.15
10	First (4) Neighbours of High–Power Bundle (kW)	100	830	0.15
11	Second (4) Neighbours of High–Power Bundle (kW)	200	835	0.15
12	Third (12) Neighbours of High–Power Bundle (kW)	400	840	0.15
13	Fourth (16) Neighbours of High-Power Bundle (kW)	800	845	0.15
14	Burnup (Percentage of Time Average)	32	101	-0.25
15	Last Refuelling (FPD before Current)	1600	120	-1
16	Last Refuelling of Immediate Neighbours (in FPD)	3200	6	-1
17	Candidates Eliminated by Previous Test Run	64	n/a	

* Only channels with non-zero IRULEij entry qualify for further consideration. This increment is intended to be a unique identifier.

Figure 2 Channel neighbours affected by high power rules (#6 - #13)

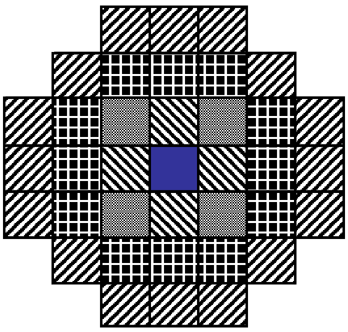

Figure 3 Channels affected by last refuelling rules (#15, #16)

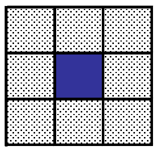

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Table 2 Selection rules (used for the CANDU 6 core)

Rule #	Definition	RLIMIT Value (for CANDU 6 core)	Proximity to Zone Level
18	Channel Powers over current Zone Levels	6650 kW	0.5 Lattice Pitches
19	Channel Powers of First (4) Neighbours of current Zone Levels	6700 kW	1.1 Lattice Pitches
20	Channel Powers of Second (6) Neighbours of current Zone Levels	6750 kW	1.8 Lattice Pitches

Figure 4 Channels affected by zone-level proximity rules (#18, #19, #20)

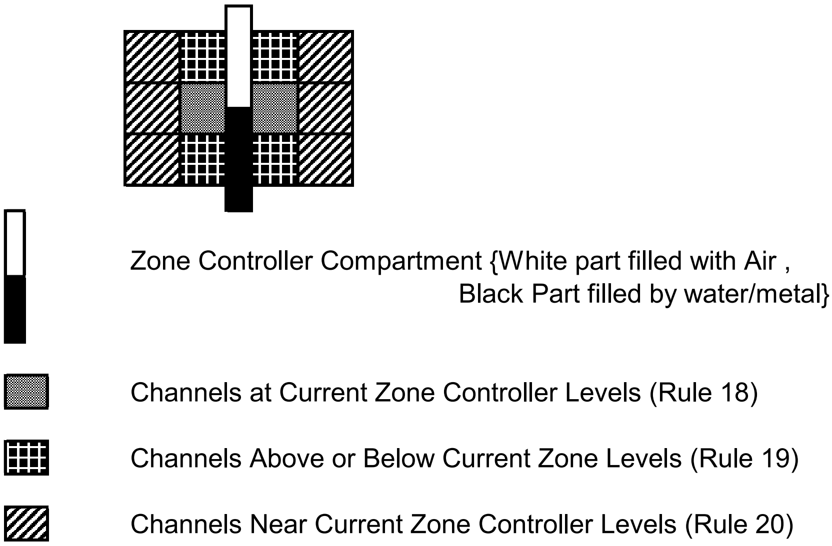

Table 3 Ordering of candidate channels prior to final selection

Burnup-Related Sorting Conditions	Explanation
Channels of zone pairs ordered by increasing zone levels of front and back zones. (The first pick should go to zones that need refuelling the most, as determined by relative zone levels).	Channels in zones with lowest/least inserted zone levels first. (Neighbouring channels of selected channels are eliminated even if in neighbouring zones)
Second ordering condition: Anticipated reactivity-increase following refuelling on a per bundle basis.	Channels with biggest potential reactivity insertion first
Third ordering condition: Channels retain the order in which they qualified during the elimination stage, but those channels that have not been refuelled the longest go first.	Most qualified channel picked first, preferentially replacing those that have been in the core longest.
Channels within zone pairs ordered by # refuellings in each direction (overlooked if the difference is 1 or less).	Choose channels that would reduce the difference in the number of channels fuelled in each direction.
Front-to-back refuelling balance within each pair of zones, as long as the two channels have been picked within ten iterations of each other in the ELIMIN routine.	Choose channels that would reduce the front-to-back zone fill/insertion difference.

Figure 5 Zones and zone controller locations for a 1200-FPD simulation.

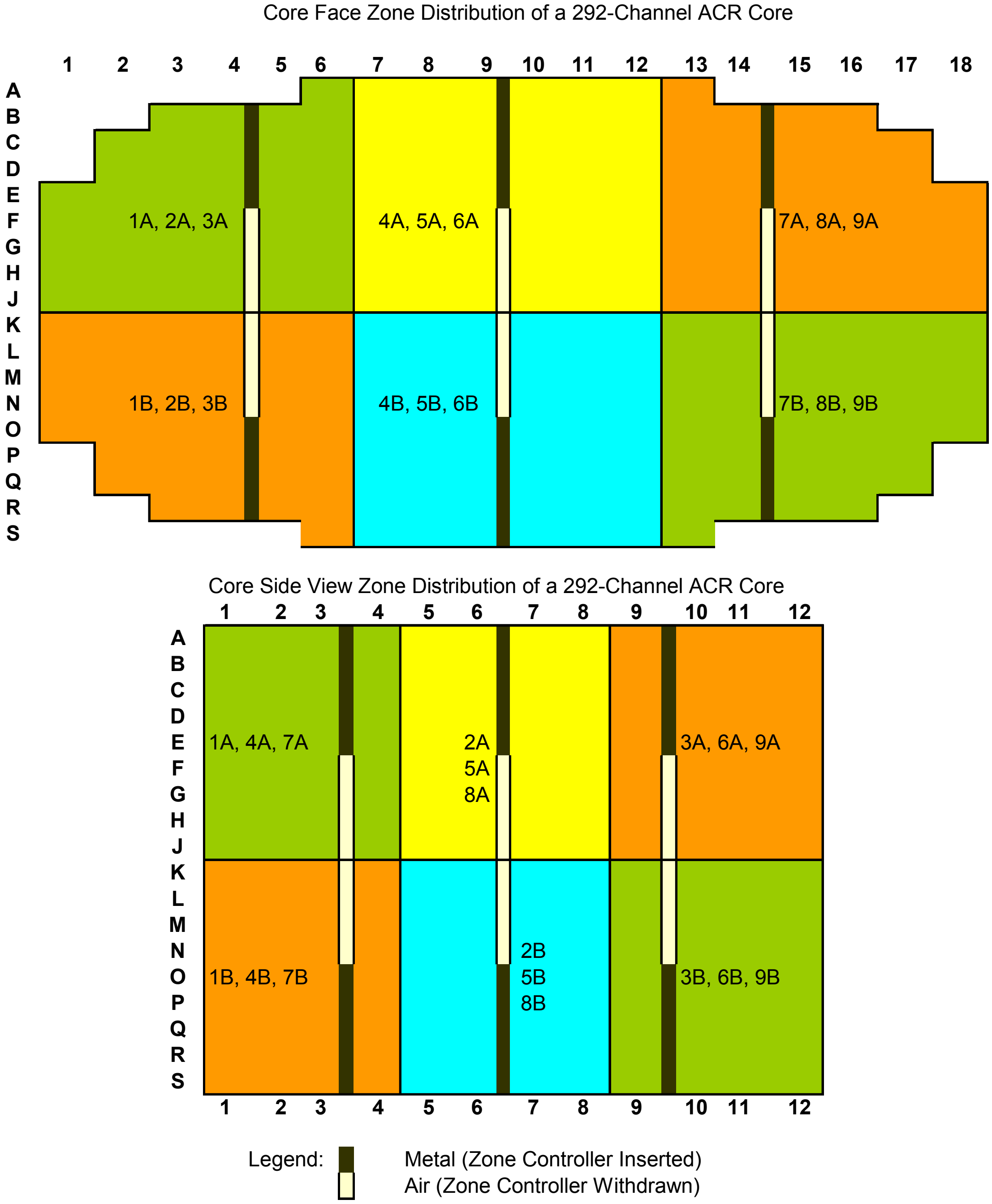

Figure 6 Zone fill/insertion levels over a 1200-FPD transition to an equilibrium core (averaged over similar zones).

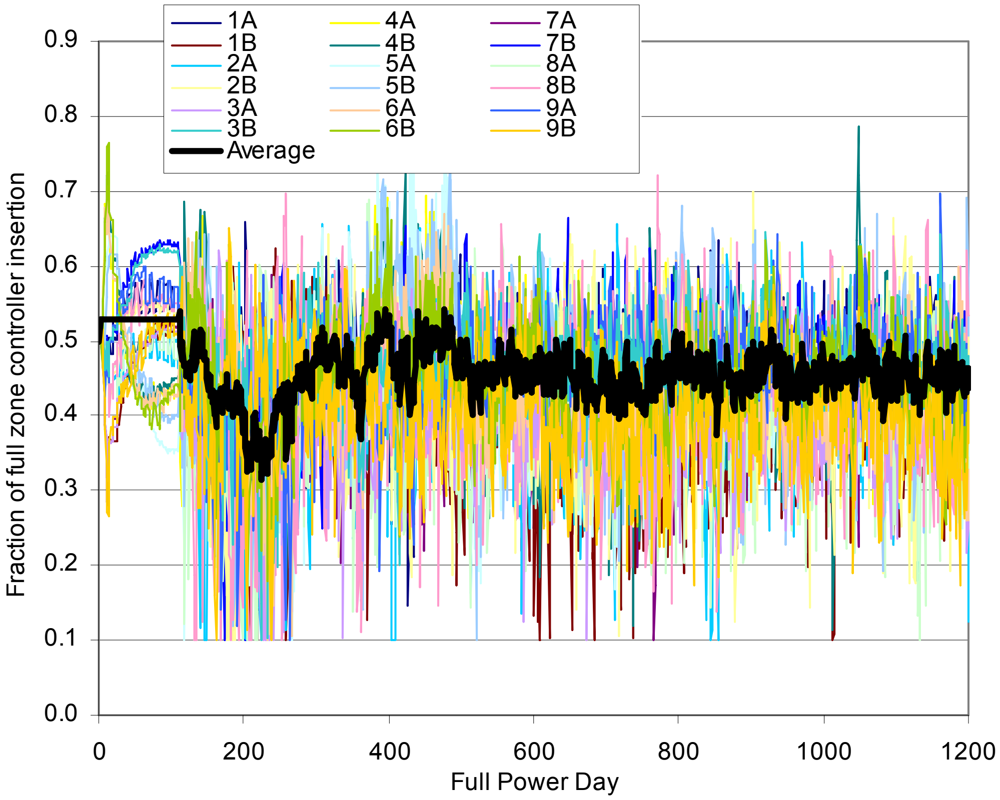

Figure 7 Zone flux relative to core average over 1200 FPD transition-to-equilibrium core (averaged over similar zones)

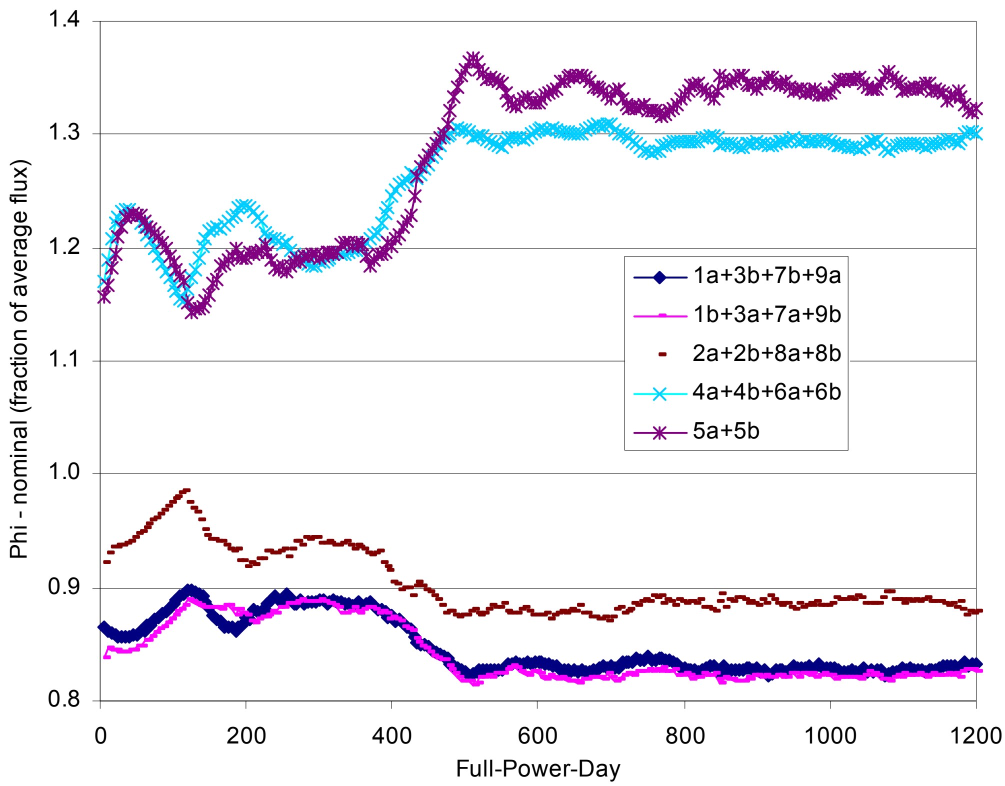

Figure 8 Maximum instantaneous channel power relative to the maximum time-average channel power over the entire core.

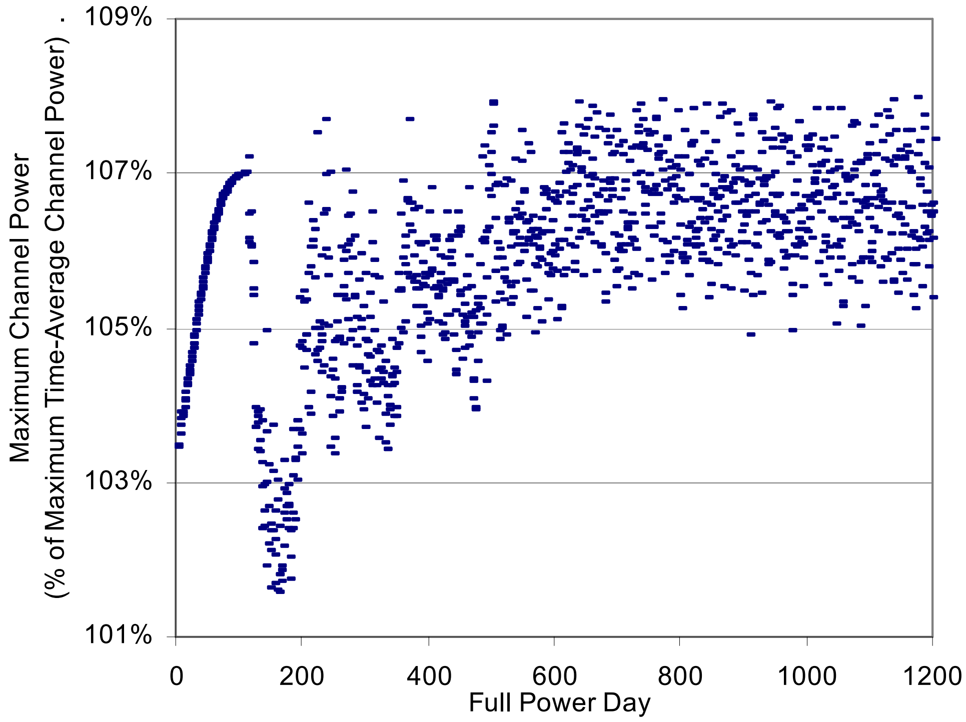

Figure 9 Maximum instantaneous bundle power relative to the maximum time-average bundle power over the entire core.

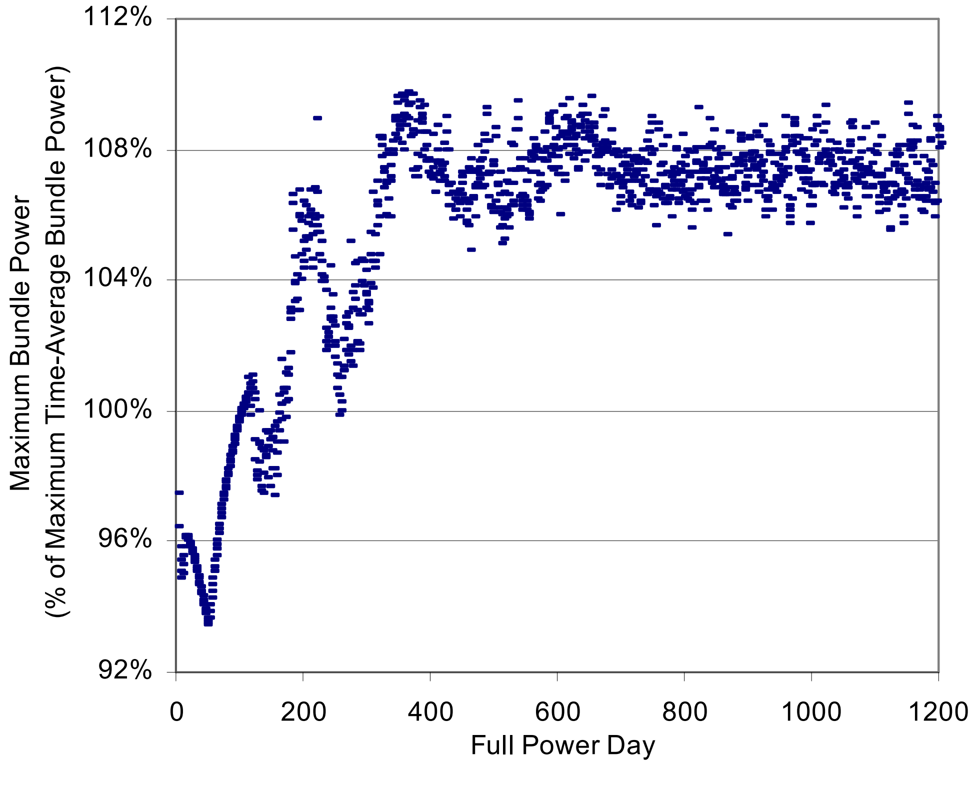

Figure 10 Average channel power over 600 FPD snapshots as a percentage of time-average channel power

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									102	101	101	102	101	102								
B						102	102	102	101	101	101	101	101	101	101	101	102					
C					101	102	102	101	101	100	101	101	100	100	100	101	102	102				
D				101	101	101	100	100	100	100	100	100	99	99	100	100	100	101	101			
E			101	100	101	100	99	99	99	99	99	99	99	99	99	99	100	100	100	101		
F			101	100	100	99	99	99	99	100	100	100	100	99	99	99	99	99	100	101		
G		102	101	100	100	99	100	99	100	100	99	99	100	100	99	100	100	100	100	100	102	
H		101	101	100	100	100	99	99	100	100	99	100	100	99	99	99	99	99	100	100	101	
J	102	101	100	100	99	99	100	99	100	100	100	100	100	100	100	99	99	99	99	101	102	102
K	101	100	100	99	99	99	99	100	100	100	100	100	100	100	99	99	100	99	100	100	101	102
L	101	100	99	99	98	99	98	99	100	100	100	100	101	100	100	99	99	98	99	100	101	101
M	101	100	99	99	98	98	98	100	100	101	101	101	101	100	100	99	98	99	99	100	101	101
N	101	100	100	99	98	99	98	99	100	100	101	100	101	100	100	98	98	98	99	100	101	102
O	101	101	100	99	98	99	99	99	100	101	101	100	100	100	99	98	99	98	99	100	102	102
P		102	101	100	100	99	99	100	99	100	100	100	100	100	99	100	99	100	100	101	101	
Q		102	102	101	100	99	100	100	100	100	100	100	100	100	100	100	100	100	101	101	102	
R			102	102	101	100	100	100	100	100	99	100	100	101	100	100	101	101	101	101		
S			102	102	101	100	100	100	100	100	99	99	99	100	100	100	101	101	102	102		
T				102	101	101	101	100	100	100	100	100	100	100	101	101	102	102	102			
U					101	101	100	101	100	100	101	101	101	101	101	101	102	102				
V						102	102	101	101	101	101	101	101	101	101	102	102					
W									101	100	100	101	100	100								
	1	2	3	4	5	6	7	8	9	10	11	12	1	14	15	16	17	18	19	20	21	22