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Bruce “B” Core Conversion.

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The CANDU reactor is one of the few commercial power reactors with a small positive void coefficient. Supplementary, a postulated large break loss of coolant accident (LLOCA) in the primary heat transport system will cause the relocation of fuel towards the inlet end of channels. With the current Bruce “B” Fuelling-against-Flow configuration, this will result in a moving of fuel bundles of low burnup to regions of greater neutron flux, introducing positive reactivity and increasing the power pulse. In order to improve LLOCA consequences and hence increase safety margins, Bruce “B” units are being converted to a Fuelling-with-Flow scheme. This will result in reversal of the fuel burnup profile relative to the coolant flow direction, eliminating the positive fuel string relocation reactivity.

This paper discusses the safety and implementation aspects of the core conversion that have been considered.

KEYWORDS: CANDU, LLOCA, on-power reorder, Reactor Regulating System (RRS), Neutron Overpower Protection (NOP).

1. Introduction

The reactors at Bruce “B” are of a CANDU design. It is a heavy water moderated, natural uranium on-power fuelled reactor with pressure tubes. The core consists of 480 horizontal, 6.3-meter long pressure tubes, containing the fuel and coolant. There are 13 natural uranium fuel bundles in each pressure tube. Each fuel bundle is about 49.5 centimeters long and weighs 22.5 kg. The pressure tubes are located inside six meters in diameter, horizontally mounted cylindrical vessel (the calandria) that also contains the heavy water moderator and reflector. A typical overall arrangement is shown in Figure 1.

Pressurized heavy water coolant is pumped through the pressure tubes, cooling the fuel and carrying heat from the fuel to the outlet header and to the steam generators. This arrangement brings several unique safety features described below.

- Each pressure tube is isolated and insulated from the heavy water moderator by a concentric calandria tube. This configuration separates the moderator system from the high temperature, high-pressure coolant in the pressure tubes.
- Due to this physical separation from the coolant, the moderator operates at the relatively cool temperature of about 62°C. This cool moderator can act as a heat sink under certain accident conditions.

- In the CANDU design, all reactivity devices for control and shutdown are introduced into guide tubes positioned in the low-pressure moderator.
- Pressure tube leaks can be readily detected by monitoring the moisture content and pressure in the annular, gas filled space between the pressure tube and calandria tube.

More details on CANDU reactors and technology can be found on the CANDU Owners Group (GOG) web-site. [1]

2. Core Conversion Process

Beginning in the early 1990s, three significant phenomena affecting fuel and fuel channel integrity were identified at Bruce "B". These phenomena were:

- Pressure tube fretting caused by Flow Induced Vibration (FIV) of the inlet fuel bundle in Position 13 in the region where fuel was supported abnormally and at the bundle mid-plane.
- Acoustic pressure pulsation in certain "acoustically active" channels resulting in enhanced pressure tube fretting.
- Fuel string relocation reactivity that increases the magnitude of the power pulse in the event of a large upstream pipe break in the Heat Transport System (HTS). This has been immediately addressed by a combination of operating and design changes that increased the shutdown system effectiveness and reduced the magnitude of the positive reactivity insertion.

To provide a fundamental solution, Bruce Power has undertaken to convert the fuelling direction to Fuelling-with-Flow (FWF) and reduce the fuel string complement from 13 to 12 bundles. This will eliminate the positive fuel string relocation reactivity associated with a Fuelling-against-Flow (FAF) fuelled core, and allow the removal of the 13th fuel bundle from each fuel channel, which ensures that pressure tube fretting will not occur.

Two different methods will be used for on-power reorder (OPR) at Bruce "B": a cascade reorder scheme and a so-called "Bowles" method. These two methods are shown graphically in Figure 2. A 14-bundle cascade scheme of reordering that involves Travelling Depleted Bundle (TDB) allows for operation at high power. The cascade reorder and "Bowles" methods will be used on channels in the 4- and 8-bundle fuelling regions, respectively. These two fuelling regions are presented in Figure 3.

2.1 14-Bundle Cascade Reorder Scheme

Cascade reorder will be used on channels in the 4-bundle fuelling region. It involves shuffling entire fuel strings between channels with opposite flow directions (shown graphically in Figure 2). This is the approach that was used for OPR at Bruce "A". For Bruce "B", the basic cascade approach has been improved by utilizing the TDB with 0.4% wt U-235 as the first bundle inserted between the low burnup bundles of successive cascade channels. It will reduce flux peaking during fuel string movements. The 14-bundle reorder scheme would be carried out as follows:

- Step 1: A 14-bundle FAF push on an initial seed channel would be carried out using a TDB and 13 fresh bundles. The 13 fresh bundles could be a combination of 0.7% and 0.4% wt

U-235 bundles, depending on the specific channel. This 14-bundle push displaces the leading TDB and the bundles from positions 1 through 13 that were in the seed channel into the receiving Fuelling Machine (FM) head.

- Step 2: The 14 displaced bundles will then be fuelled against the flow into a predetermined channel. It will displace the lead TDB and the bundles in positions 1 through 13 into the receiving FM head and leave the bundles from the previous channel, such that the previous channel position 13 is now at the latch end. This will effectively reverse (i.e. reorder) the channel burn-up profile.
- Step 3: The Step 2 of the process is repeated in a cascading operation until a batch of channels is reordered. The 13 bundles from the last reordered channel and the TDB could be either sent to the Irradiated Fuel Bay, or recycled into the original seed channel for that batch.

The burn-up profile of the reordered channel will be the reverse image of the donor channel, with the high burn-up bundle now at the flow outlet end. The resulting bundle power profile of the reordered channel will also be approximately the reverse image of the donor channel.

2.2 “Bowles” Method

The “Bowles” method will be used on the 100 fuel channels in the 8-bundle fuelling region and is shown graphically in Figure 2. It is a new method that will significantly simplify reordering of channels in the 8-bundle fuelling region. It involves fuelling four high burnup bundles into the outlet end of a channel in the 8-bundle push region. This adequately changes the channel burn-up profile to allow subsequent refueling (FWF) with 8-bundles. The “Bowles” method can be worked into normal fuelling operations and will be carried out as follows:

- Step 1: Fuelling an inner zone channel with fresh bundles. This 4-bundle push displaces the discharged bundles from positions 10 through 13 into the receiving fuelling machine.
- Step 2: The four discharged bundles will then be fuelled against the flow into a predetermined 8-bundle push channel in the outer zone, displacing the bundles from positions 10 through 13 into the receiving fuelling machine head. The highest burn-up bundles will be inserted last, which will essentially reorder the channel.

2.3 Removal of 13th Bundle

An important aspect of the Core Conversion project involves the removal of the 13th fuel bundle from each fuel channel, thereby converting the core to a 12-bundle fuel string design. Removal of the 13th bundle removes the potential for pressure tube fretting in the vicinity of the rolled joint, and eliminates the possibility of fuel string constrained axial expansion in the event of a large break LOCA, obviating the need for gap management.

Removal of the 13th bundle will be performed as part of the first FWF operation on a reordered channel. When the inlet fuelling machine is loaded up with fresh fuel at the new fuel port, one carrier will be loaded with only one bundle instead of two (only one bundle will be inserted as two are removed).

3. Bundle and Channel Power Management

During normal operation, compliance with license limits is achieved using the computer code SORO (Simulation of Reactor Operation). Fuelling operations and reactivity device status are monitored and used to provide input for SORO simulations; the SORO simulations calculate the power in every bundle and channel in the reactor. To ensure compliance with the license limits for bundle/channel power, it is necessary to allow for possible errors in the SORO simulations. Therefore, the SORO simulation results are compared to reporting limits, which are lower than the license limits and presented in Table 1. For bundle power and for outer zone channel power, the compliance limit is 95% of the license limit. For inner zone channel power, the compliance limit is 97% of the license limit.

3.1 Effect of On-Power Reorder (OPR) on Bundle and Channel Power Error Allowances

During normal fuelling operations, 4 or 8 non-irradiated fuel bundles are introduced into channels with low power and high burnup. Because of the fuelling batch size and low initial starting power, refueled channels are not normally limiting in terms of maximum bundle/channel power. Given these circumstances, it is acceptable to use a steady state simulation tool (SORO) to predict these important parameters. As discussed above, suitable allowances are made for SORO error.

For cascade OPR, an entire channel of irradiated fuel is moved from one channel to another. As a result, this fuel experiences a xenon transient on discharge; this xenon transient produces an effect on reactivity during and after refueling. To assess the impact of xenon transient during the Bruce “B” single-channel reorder operation, detailed local-parameter history-based simulations were performed. [2]

When fuel is recycled from one channel to another, the fuel being inserted into the reactor is experiencing significant variation in the concentration of neutron-absorbing xenon. This effect is ignored in SORO, which assumes equilibrium xenon. Therefore, SORO will tend to over-predict power during the initial stages of a recycled fuel push. However, this changes after the reorder fuel push is completed. As shown in the analysis, transient xenon effects can cause real power to exceed SORO predicted power several hours after completion of fuelling. The power peaking factor is applied to address this effect.

3.2 Process for Bundle and Channel Power Management during OPR

As discussed in the previous section, bundle/channel power management for OPR must address power overshoot due to transient xenon effects. The required bundle/channel power peaking factors were calculated as a function of the time that recycled bundles are out-of-core. As a general rule, longer time out-of-core produces more severe xenon transients requiring larger peaking factor. These power peaking factors as a function of time spent out-of-core are presented in Table 2. This process can be summarized as follows:

- Transient xenon error allowances will be applied assuming that recycled fuel spends no longer than 10 hours out-of-core.
- To address transient xenon effects, bundle/channel power reporting limits for all channels will be reduced by 3% across the board during OPR activities.
- This power peaking factor can be removed 12 hours after completion of OPR fuelling.

This approach is very conservative. For recycled fuel residing out-of-core for up to 10 hours, the analysis shows that a 3% allowance is needed only for channels immediately adjacent to a cascade channel, and that the required allowance decreases with distance from the channel undergoing OPR.

4. Reactor Regulating System (RRS)

The long-term control of reactivity and power distribution in Bruce B, as in other CANDU reactors, is achieved by on-power refueling. Short-term control is provided by light water zone control system. This system is designed to perform two main functions:

- To provide short-term reactivity control to maintain reactor power at the demanded level during normal operation (i.e. operating control of reactivity).
- To control spatial power distribution by suppressing regional power transients associated with space dependent reactivity perturbations.

For the purpose of spatial control, the reactor is divided into 14 zones, as shown in Figure 4. Spatial control is obtained by means of a column of H_2O and an associated thermal neutron detector in each zone. There are six vertical zircaloy tubes traversing the core; four contain two H_2O compartments, and two contain three compartments. Bulk reactivity control is achieved by varying the H_2O level in all compartments by the same proportion. Spatial flux control is achieved by differential adjustment of the H_2O level in individual compartments.

4.1 RRS Detector Responses

During OPR as the TDB moves nearby RRS detectors, changes in the signal may cause changes in the H_2O level of Zone Control Units. Results for the RRS detector response indicate that the signal variation ranges from –5 to +5%, as the depleted bundle moves near the detector locations. These predicted signal variations of RRS detectors are similar to the corresponding values for regular fuelling. [3]

5. Neutron Overpower Protection (NOP) System

A set of 102 detectors is employed by two independent Shutdown Systems to provide Neutron Overpower Protection (NOP) in order to maintain fuel and fuel channel integrity for a variety of accidents.

The NOP systems for Shutdown Systems One and Two provide timely trips for events leading to an increase in the bulk or spatial power in the core.

Safety Analysis of the NOP trip setpoint is performed using a set of 556 flux shapes referred to as the Neutron Overpower Protection design basis set. These flux shapes are intended to be representative of normal operating conditions, as well as certain abnormal reactivity device configurations which can occur as a result of control system failures. The normal NOP trip setpoint is calculated such that all flux shapes in the design set are protected.

In addition to the design bases flux shapes, supplementary analysis was performed for a set of 455 additional flux shapes commonly referred to as the “non-design basis set”. The non-design-basis-set consists of flux shapes, which are representatives of various highly unusual reactivity device configurations resulting from control system failures. These flux shapes were used to establish the trip setpoint for the Abnormal Flux Shape position of the NOP trip setpoint hand-switches.

The OPR process uses TDB between the donor and the receptor channel fuel bundles. As the TDB moves through the receptor channel, the NOP and RRS detectors that are located nearby will respond with a reduced or increased signal.

5.1 NOP Detector Responses

Results for NOP detectors indicate that the maximum signal increase can be as high as 6-7%, as the depleted bundle moves near the detector locations. In general, detectors those drift high by more than 3% may reduce the NOP margin to trip. A reactor power de-rating may be required in order to maintain adequate operating margin and prevent spurious reactor trips. [3]

5.2 NOP Trip Coverage

The cascade reorder process temporarily creates clusters of uni-directionally fuelled channels in a core that is normally fuelled bi-directionally. Figure 3 shows the core with clusters of 11 channels. NOP trip coverage is affected during core conversion due to concentration of fresher bundles axially in the cluster. This leads to localized power increases, which could mean earlier onset of dryout in a Loss of Regulation event. NOP analysis was performed to establish the effect on NOP trip coverage and consequent required trip setpoint calibration factor, as a function of a cluster size.

Based on the analysis results, use of a single “worst case” calibration factor would result in significant de-rating. To avoid this, NOP trip setpoint factors will be based on actual core conditions during OPR. The NOP calibration factor will be increased by a factor of 1.026 for cluster sizes of up to 11 channels and by a factor of 1.050 for cluster sizes ranging from 12 to 17. Clusters containing more than 17 channels will not be permitted. These calibration factors will be applied until cascade reordering is completed. After cascade reordering is completed, the NOP calibration factor can be reduced to 1.008. This will remain in place until the 13th bundle is removed from all 380 channels in the 4-bundle fuelled region. [4]

6. Conclusions

Based on the analysis results, it was found:

- Use of the TDB could avoid de-rating of the reactor power as required to meet safety criteria;
- Additional MCP/MBP correction factors are needed to account for Xenon transient due to OPR process;
- During the reorder, signal variations of RRS detectors may change Liquid Zone Controller levels slightly higher than in a regular fuelling;
- Higher NOP detector calibration factors are required to account for clustering of uni-directionally fuelled channels;
- The output of NOP detectors may drift high by more than 3% and, as a result, reduce the NOP margin to trip. Therefore, a reactor power de-rating may be required to maintain adequate NOP margin;
- In order to properly monitor the MBP/MCP compliance, additional SORO pre-simulations of the reorder sequence will be required as part of the fuelling routine; and

- No adverse impact on fuelling the reordered core and operation with 12-bundle channels was discovered.

References

1) Reference library on CANDU technology, http://canteach.candu.org .
2) J. V. Donnelly and I. Martchouk, “Transient Xenon Effects during Inner Zone Core Re-order”, Nuclear Safety Solutions, B0015/AR/007 (2003).
3) E. Braverman, “On-Power Reorder Physics Analysis”, Bruce Power, NK29-REP-35050-00014 (2003).
4) M. J. S. Levine, “Bruce B NOP Analysis to Support Continued Operation During On-Power Core Conversion”, Nuclear Safety Solutions, B0015/AR/007 (2003).

Table 1 Operating Limits

	License Limit, kW	Reporting Limit, kW
Maximum Channel Power, Inner Zone	6480	6286
Maximum Channel Power, Outer Zone	6030	5728
Maximum Bundle Power	810	769.5

Table 2 Xenon Transient Power Peaking Factors

Time Spent Out-Of-Core	Required Power Peaking Factor
4 hours	1.5%
6 hours	2.0%
8 hours	2.5%
10 hours	3.0%

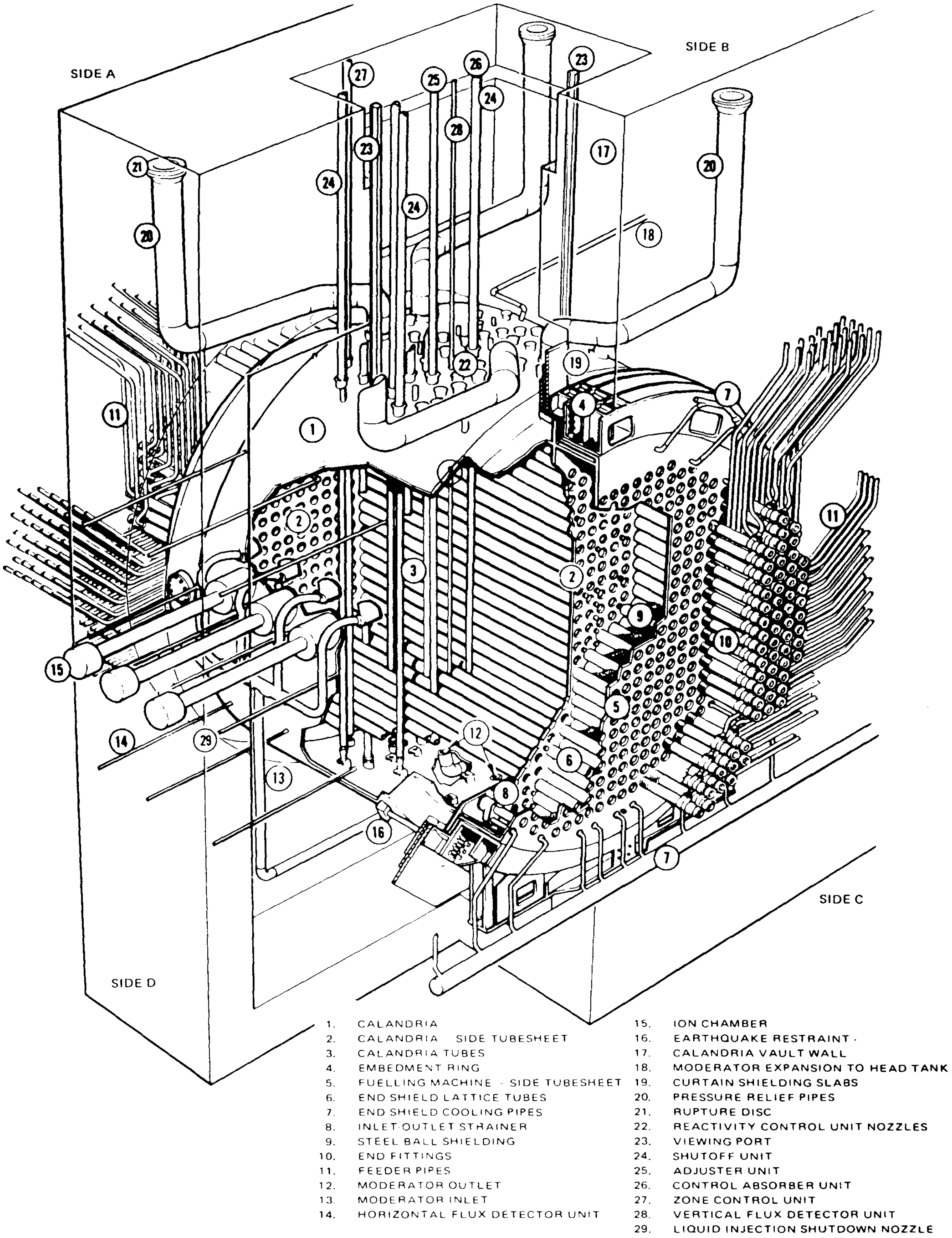
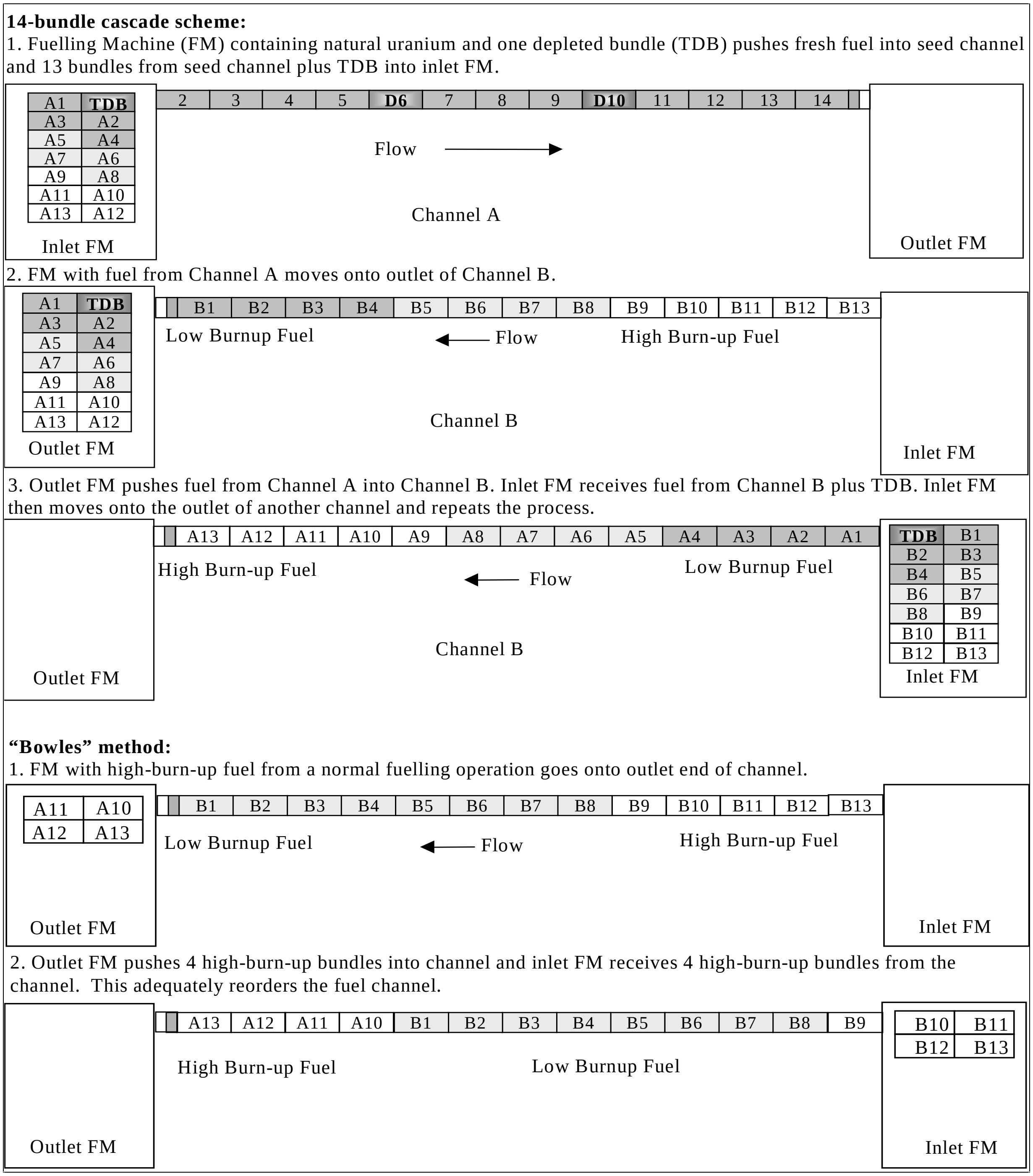


Fig. 1 Bruce “B” reactor assembly.



14-bundle cascade scheme:

1. Fuelling Machine (FM) containing natural uranium and one depleted bundle (TDB) pushes fresh fuel into seed channel and 13 bundles from seed channel plus TDB into inlet FM.

2. FM with fuel from Channel A moves onto outlet of Channel B.

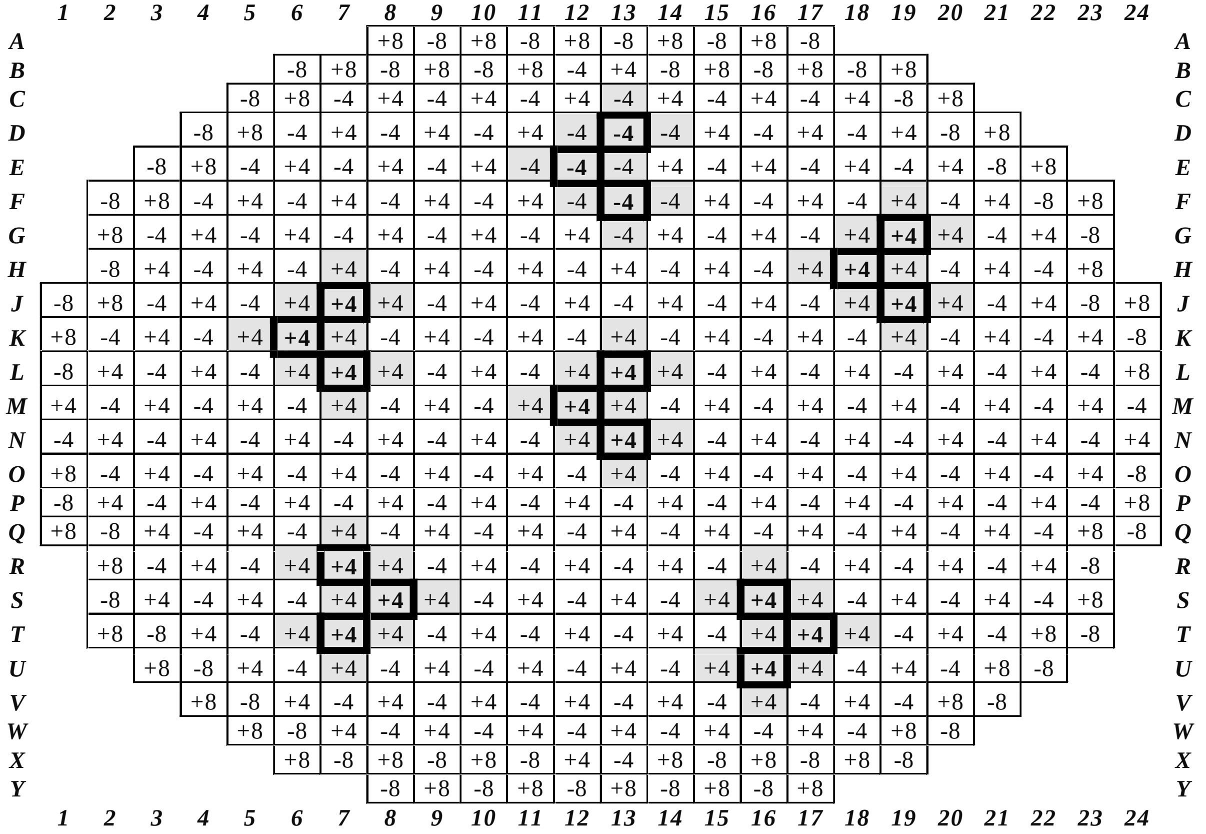
3. Outlet FM pushes fuel from Channel A into Channel B. Inlet FM receives fuel from Channel B plus TDB. Inlet FM then moves onto the outlet of another channel and repeats the process.

"Bowles" method:

1. FM with high-burn-up fuel from a normal fuelling operation goes onto outlet end of channel.

2. Outlet FM pushes 4 high-burn-up bundles into channel and inlet FM receives 4 high-burn-up bundles from the channel. This adequately reorders the fuel channel.

Fig. 2 Bruce "B" on-power reoder schemes**.**



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
A								+8	-8	+8	-8	+8	-8	+8	-8	+8	-8								**A**
B						-8	+8	-8	+8	-8	+8	-4	+4	-8	+8	-8	+8	-8	+8						**B**
C					-8	+8	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-8	+8					**C**
D				-8	+8	-4	+4	-4	+4	-4	+4	-4	**-4**	-4	+4	-4	+4	-4	+4	-8	+8				**D**
E			-8	+8	-4	+4	-4	+4	-4	+4	-4	**-4**	-4	+4	-4	+4	-4	+4	-4	+4	-8	+8			**E**
F		-8	+8	-4	+4	-4	+4	-4	+4	-4	+4	-4	**-4**	-4	+4	-4	+4	-4	+4	-4	+4	-8	+8		**F**
G		+8	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-8		**G**
H		-8	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+8		**H**
J	-8	+8	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-8	+8	**J**
K	+8	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-8	**K**
L	-8	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+8	**L**
M	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	**M**
N	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	**N**
O	+8	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-8	**O**
P	-8	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+8	**P**
Q	+8	-8	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+8	-8	**Q**
R		+8	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-8		**R**
S		-8	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+8		**S**
T		+8	-8	+4	-4	+4	**+4**	+4	-4	+4	-4	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+8	-8		**T**
U			+8	-8	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	**+4**	+4	-4	+4	-4	+8	-8			**U**
V				+8	-8	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+8	-8				**V**
W					+8	-8	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+4	-4	+8	-8					**W**
X						+8	-8	+8	-8	+8	-8	+4	-4	+8	-8	+8	-8	+8	-8						**X**
Y								-8	+8	-8	+8	-8	+8	-8	+8	-8	+8								**Y**
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	

Note:

+/-4 Delineate reordered channels

Channel "+8" designates 8-bundle push from west-to-east, vice versa for "-8"

Channel "+4" designates 4-bundle push from west-to-east, vice versa for "-4"

Fig. 3 Bruce “B” fuelling map with clusters of 11 uni-directionally fuelled channels**.**

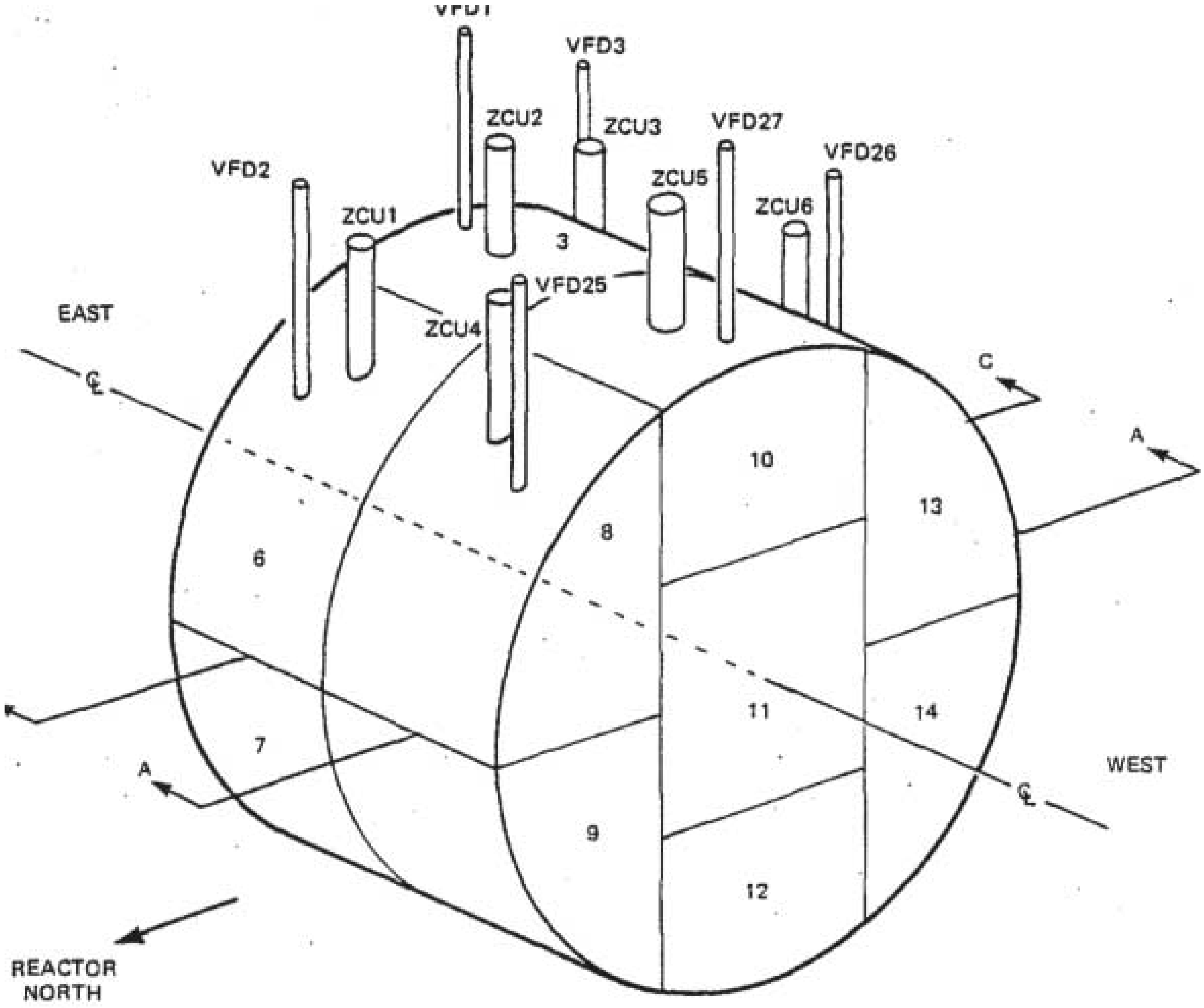


Fig. 4 Reactor Regulating System: Zone Control Units (ZCU) and Detector Assemblies (VFD).