BRUCE "B" CORE CONVERSION

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ABSTRACT

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 cause fuel bundles of low burnup to move to regions of greater neutron flux, introducing positive reactivity and increasing the power pulse. In order to improve LLOCA consequences and hence increase safety margin, Bruce Power is converting 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 some safety and implementation aspects of the core conversion that have been considered.

1. INTRODUCTION

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 rolled joint burnish mark 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, primarily at the inlet bundle position, and fuel bundle end plate cracking, primarily at the outlet bundle position due to inadequate end plate support at the latch.
- 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).

The method chosen to address burnish mark fretting and fuel string relocation reactivity was to use long fuel bundles to shorten the length of the fuel channel gap and to position the outboard bearing pad of the 13th bundle on the spacer sleeve (i.e., the Gap Management Program). This was supplemented by use of Flow Straightening Inlet Shield Plugs (FSISPs) in the Inner Zone (IZ) channels to reduce FIV of the inlet bundle and to further reduce the length of the fuel channel gap. The original Bruce "B" fuelling map showing Inner and Outer Zones and 8- and 4-bundle fuelling regions is presented in Figure 1.

While these design changes have managed the problems associated with burnish mark fretting and LLOCA power pulse, they have not eliminated them and are not considered to be the optimum solution. To provide a more 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. Conversion to FWF scheme eliminates the positive fuel string relocation reactivity associated with a Fuelling-Against-Flow (FAF) fuelled core, thereby allowing the removal of the 13^{th} fuel bundle from each fuel channel. Removal of the 13^{th} fuel bundle ensures that fuel string constrained expansion will not occur under LLOCA conditions and also eliminates the fuel bundle from the flow inlet region of the fuel channel. This ensures that pressure tube fretting will not occur in the region of the pressure tube that is most susceptible to fretting damage.

1.1 Bruce "A" On-Power Reorder (OPR) of Units 3 and 4.

At Bruce "A", conversion to FWF was also chosen as the design option for dealing with the LLOCA power pulse issue. In 1997, OPR was performed on IZ channels in Bruce "A" Units 3 and 4. The 12-bundle cascade that was used for the Bruce "A" OPR is shown graphically in Figure 2. For this 12-bundle cascade scheme, the reordered channel became the limiting channel in the midst of the push, while two low burnup ends of successive cascade channels are in the centre. For OPR cascade, the Bruce "A" campaign assumed large (and conservative) default peaking factors. This led to a significant de-rating being applied for the duration of the OPR cascade operations.

2. BRUCE "B" CORE CONVERSION PROCESS

Two different methods will be used for OPR at Bruce "B": a cascade reorder scheme and a so-called "Bowles" method. A new 14-bundle cascade scheme of reordering that involves Travelling Depleted Bundle (TDB) significantly improves the process allowing for operation at high power. The cascade reorder and "Bowles" methods will be used on channels in the 4-bundle and 8-bundle fuelling regions, respectively (Figure 1).

For Unit 6, the 280 inner zone channels were reordered during the 2002 Spacer Location and Repositioning (SLAR) outage. To briefly summarise, core reorder during SLAR outages involves removing the fuel bundles from the channel being SLARed and returning them to the same channel in a pair-wise reversed order after the SLAR operation is complete

2.1 14-Bundle Cascade Reorder Scheme.

Cascade reorder will be used on channels in the 4-bundle fuelling region. For Unit 6, where the 280 inner zone channels have already been reordered, this represents a further 100 4-bundle push channels. The cascade reorder is shown graphically in Figure 3. It involves shuffling entire fuel strings between channels with opposite flow directions. This is the approach that was used for OPR at Bruce "A".

For Bruce "B", the basic cascade approach has been improved by utilising 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 as shown in Figure 3. 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 latch 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 4. 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 refuelling (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 as shown in Figure 5. 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. This is done by comparing the SORO simulation results to reporting limits (i.e. license compliance limits) which are lower than the license limits. These limits are 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 OPR on Bundle/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, refuelled 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. The irradiated donor fuel experiences a xenon transient on defuelling; this xenon transient produces an effect on reactivity during and after refuelling. To assess the impact of xenon transient during the Bruce "B" single-channel reorder operation, a detailed local-parameter history-based simulations were performed.

When fuel is recycled from one channel to another, the fuel being inserted into the reactor is experiencing significant increase 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/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 summarised 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. NEUTRON OVERPOWER (NOP) TRIP COVERAGE

The cascade reorder process temporarily creates clusters of uni-directionally fuelled channels in a core of fuel that is normally fuelled bidirectionally. Figure 6 shows the core with clusters of 11 channels. In the analysis of Bruce "A" OPR, it was established that NOP trip coverage is affected during core conversion. This is because the concentration of fresher bundles axially in the uni-directionally fuelled cluster tends to lead to localised power increases, which could mean earlier onset of dryout in the event of a postulated 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 uni-directional cluster size.

Based on the analysis results, use of a single "worst case" calibration factor would result in significant derating. To avoid unnecessary deratings, NOP trip setpoint factors for OPR will be based on actual core conditions, not a worst case presumption. The NOP calibration factor will be increased by a factor of 1.026 for cluster sizes 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, cluster size will no longer matter, and the NOP calibration factor can be reduced to 1.008. This factor will remain in place until the 13th bundle is removed from all 380 channels in the 4-bundle push region. After all that, all OPR NOP trip setpoint calibration factors can be removed.

5. CONCLUSIONS

Core conversion significantly increases margins to fuel channel failure in the event of a large break LOCA, and provides a viable means of effectively eliminating or mitigating the effects of pressure tube fretting and end plate cracking under normal operating conditions.

The analysis described in the article provides a technical confidence that core conversion can be safely implemented.

Table 1: Operating Limits.

	Licence 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%

	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:

Delineate Inner and Outer Zones

Delineate 8- and 4-bundle fuelling regions.

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"

Figure 1: Original Bruce "B" Fuelling Map.

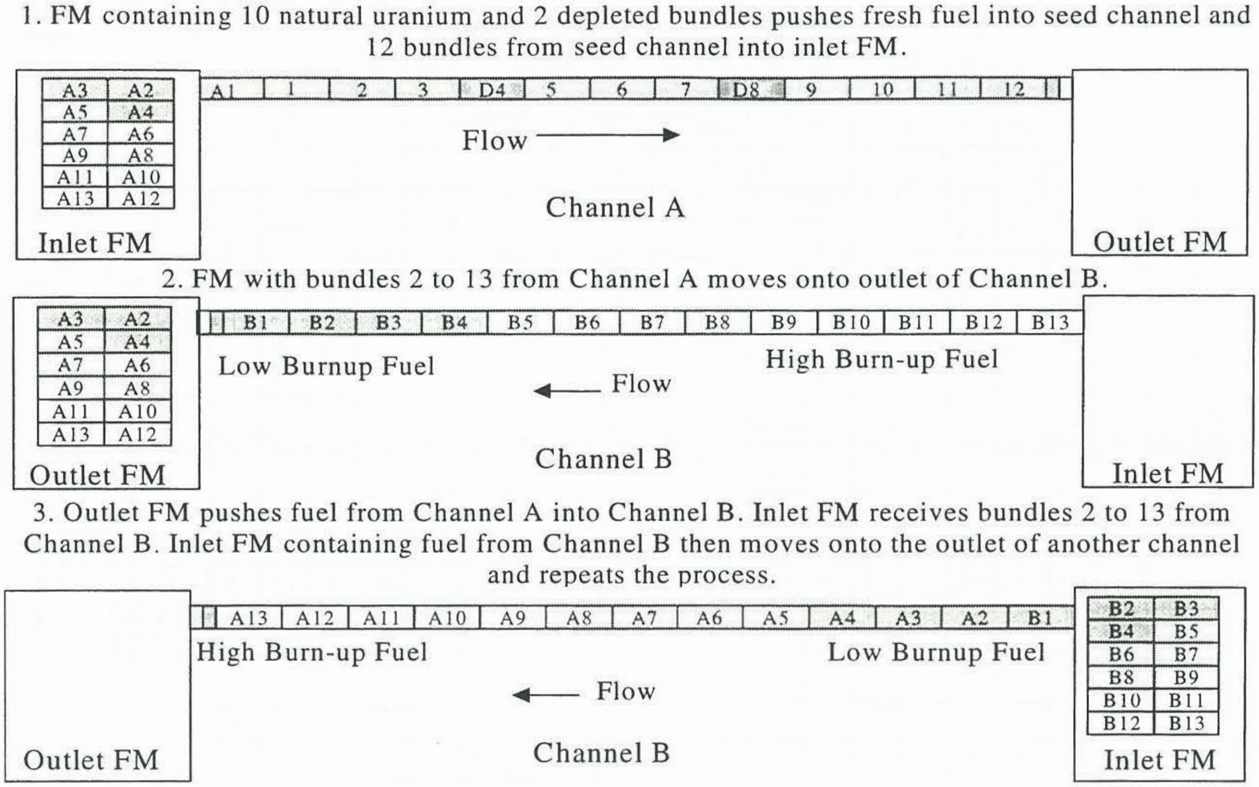


Figure 2: 12-Bundle Cascade Reorder Scheme for Bruce “A” OPR.

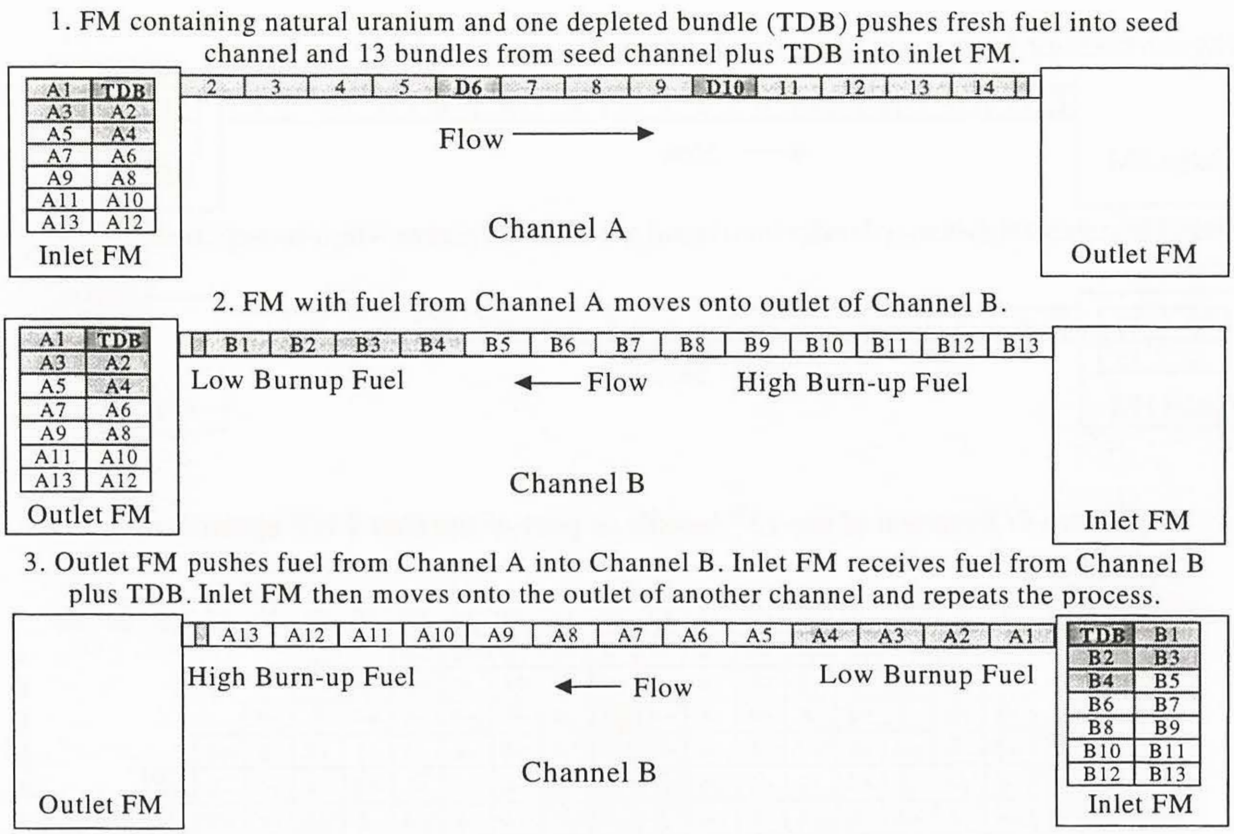


Figure 3: 14-Bundle Cascade Reorder Scheme for Bruce "B" OPR.

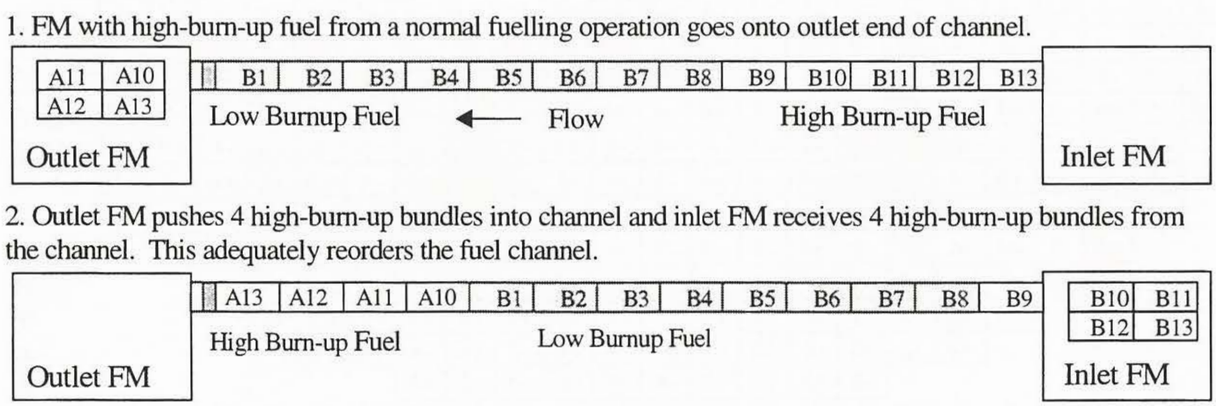
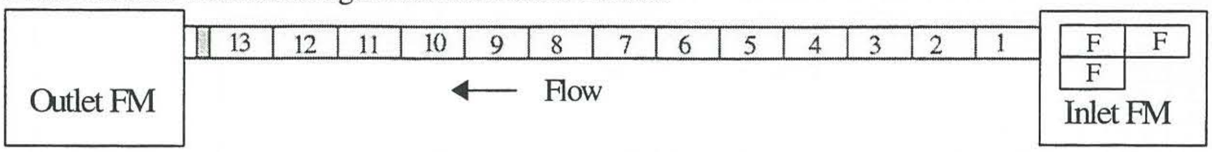


Figure 4: "Bowles" Method.

1. FM with three fresh bundles goes onto inlet end of channel.



2. Outlet FM pushes 4 high-burn-up bundles into channel and outlet FM receives 4 high-burn-up bundles from the channel.

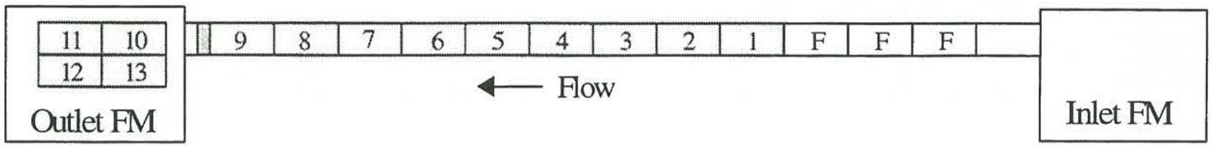


Figure 5: Removal of the 13th bundle as part of the first FWF operation.

	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 channels reordered

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"

Figure 6: Clusters of 11 Unidirectionally Fuelled Channels.