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Analysis of Channel Flow Low During Fuelling Operation of Selected Fuel Channels at Wolsong NPP

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Abstract

Wolsong NPP are CANDU6 type reactors and there are 4 CANDU6 type reactors in commercial operation. CANDU type reactors require on-power refuelling by two remote controlled F/Ms (Fuelling Machines). Most of channels, fuel bundles are float by channel coolant flow and move toward downstream, however in about 30 % of channels the coolant flow are not sufficient enough to carry fuel bundles to downstream. For those channels a special device, FARE (Flow Assist Ram Extension) device, is used to create additional force to push fuel bundles. It has been showing that during fuelling operation of some channels the channel coolant flow rate is reduced below specified limit (80% of normal), and consequently trip alarm signal turns on. This phenomenon occurs on selected channels that are instrumented for the channel flow and required to use the FARE device for refuelling. Hence it is believed that the FARE device causes the problem. It is also suspected that other channels that do not use the FARE device for refuelling might also go into channel flow low state. The analysis revealed that the channel flow low occurs as the FARE device is introduced into the core and disappears as the FARE device is removed from the core. This paper presented the FARE device behavior, detailed fuelling operation sequence with the FARE device and effect on channel flow low phenomena. The FARE device components design changes are also suggested, such as increasing the number of flow holes in the tube and flow slots in the ring orifice.

Key Words : CANDU6, Fuel Channel Flow, CANDU Fuelling Operation, Remote Controlled Fuelling Machine, Variable Geometry Orifice

1. Introduction

At Wolsong NPP, fuelling operation is carried out routinely on a daily basis by two F/Ms. The two F/Ms are clamped to the designated channels, in which the upstream F/M inserts new fuel bundles while downstream F/M removes spent fuel bundles. For CANDU reactors channel flow distribution is not uniform, i.e. there are more flows in the center channels than channels located in the perimeter of reactor. During fuelling operation, fuel bundles in the center channels float along with channel flow, however the fuel bundles in the outside channels do not develop sufficient drag forces that can be used for fuelling. For fuelling of channels with low coolant flow, F/M ram can be used to push fuel string so that downstream F/M can remove spent fuel bundles. However using F/M ram is not advisable because of the activation of the ram and the radiation dose increase to F/M maintenance personnel. The FARE device concept was introduced at Pickering NPP to assist fuelling operation. The FARE device is a portable fluidic device that can be stored in F/M magazine and inserted into channel. It consists of three major parts, i.e. fuel support part, orifice part, and F/M interface part. The Pickering type FARE device has fixed geometry ring orifice, while CANDU6 type FARE device has movable ring orifice. Pickering type FARE device is used for relatively narrow range of channel flow distribution (15.1~21.5 kg/s), and adopted fixed ring orifice design. CANDU6 type FARE device is used for wide range of channel flow distribution (9.5~21.5 kg/s), and adopted movable ring orifice design to cover whole range of flow variation with one FARE device, references 1.

At Wolsong NPP, all units show some anomalies during fuelling operation of selected fuel channels. These channels show that coolant flow rate drops below specified level. This phenomenon occurs only on a channel that is instrumented for the channel flow rate and required the FARE device for fuelling operation. Because there are only 12 measured channels, it is suspected that other channels that use the FARE device for fuelling might exprience channel flow low phenomenon. In CANDU reactors, reactor header flow blockage is determined by 2-channel flow blockage out of 3 instrumented channels that belong to the same header. If there are 2 channel flows are blocked, where the channels are belong to the same header, a reactor trip is occurred to prevent reactor integrity compromise. If only 1 channel flow is below specified limit, an alarm signal goes on in MCR. Hence whenever fuelling operation occurs on an instrumented channel that required the FARE device, operators are on alert to prepare for emergency maneuver. Therefor, it is necessary to investigate the symptoms of channel flow low to reduce the chance of reactor shut down.

In the development of the FARE device, only the steady state behavior was considered, reference 1. The test consisted of measuring pressure, temperature and flow rate. The hydraulic drag force of the FARE device was calculated from the pressure drop between before and after the FARE device test section. The tested flow range was 6 to 23 (kg/s) that enveloped the actual cannel flow range where the FARE device is to be used. However, the test did not include the transient phase of fuelling operation. As F/M pushes the FARE device into the core flow region, it passes stagnant end fitting flow region and the end fitting liner hole region, then submerges into active core flow region. It is suspected that channel coolant flow low occurs during this transient period. In fact, the channel flow rate changes as the FARE device moves toward downstream due to reduction of hydraulic impedance caused by removal of spent fuel bundles.

In order to investigate the transient behavior of the FARE device, a detailed analysis of fuelling operation at reactor face is necessary. In CANDU reactors, for symmetric neutron flux shape the coolant flow direction of neighboring channel is opposite, hence F/M can be an upstream or a downstream machine depending on which channel it clamps to. After clamping on to a channel, each F/Ms operate independently until both machines remove snout plug, channel closure and shield plug. At which time they communicate to check each other before inserting new fuel bundle or removing spent fuel bundle. Once all new fuel bundles are inserted into core flow region, the upstream F/M can proceed to reinstall shield plug, channel closure and snout plug. In case of fuelling operation using FARE device, the upstream F/M needs to do extra steps to insert the FARE device into the core flow region and recover the FARE device from the channel. Hence refuelling takes longer for channels with the FARE device.

The channel flow low occurs as soon as the FARE device is inserted into channel and disappears when the FARE device is deep into the core, then reappears as it moves back into upstream end fitting. This channel flow low phenomenon depends on the channel flow rate. In order to reduce flow resistance of the FARE device, number of design change options are discussed in this paper. Full test of provisional design of the FARE device is planned as next stage of the FARE device improvement project.

2. Channel Flow Range Analysis

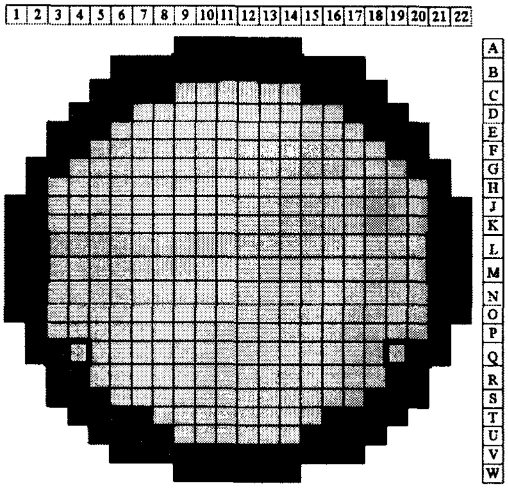

Fig. 1. FARE Channel Layout and Instrumented Channels

Figure 1 shows channel map in which channels shaded in green color is the ones that require the use of the FARE device for refuelling. The center channels are shaded in yellow and do not require the FARE device for fuelling. The instrumented channels for coolant flows are indicated by thick lined box. The coolant flows of instrumented channels are monitored in real time continuously. The channel coolant flow is measured by orifice type flow meter installed in the horizontal section of inlet feeder and the readings are transmitted to MCR as percent to the reference value for the channel. The channel flow low alarm goes off if channel flow drops below 80% of nominal flow for the corresponding channel at full power with 4 PHT (Primary Heat Transport) pumps. If only 2 PHT pumps are running, then the set point is adjusted to 70%.

In the past, it has been noted that the channel coolant flow reading drops during the refuelling of instrumented channels when the FARE device is inserted into the core. It was indicated by means of alarm signal on in MCR. Although a single channel flow low event would not initiate reactor trip, another low flow from an instrumented channel that belongs to the same reactor header will trigger a reactor emergency shut down.

Table 1 shows the instrumented channel design

Table 1. Instrumented Channel - Design and Measured Flow Rate

	Channel	W2-Measured Flow Rate (kg/sec)	W2-Design Flow Rate (kg/sec)	W1-Design Flow Rate (kg/sec)	
Inlet Header #2	B13	19.2	17.06	17.3	FARE channel
	M21	21.7	19.32	19.2	FARE channel
	Q19	23.6	22.23	20.8	Center Channel
Inlet Header #4	B14	18.5	17.34	17.5	FARE channel
	L21	21.6	19.53	19.4	FARE channel
	Q20	23.4	18.12	17.5	FARE channel
Inlet Header #6	B9	19.3	17.34	17.5	FARE channel
	L2	21.5	19.55	19.4	FARE channel
	Q3	19.8	18.11	17.5	FARE channel
Inlet Header #8	B10	19.4	17.05	17.3	FARE channel
	M2	21.8	19.37	19.2	FARE channel
	Q4	22.8	22.20	20.8	Center Channel

Table 2. FARE Channel Minimum and Maximum Flow

	Wolsong unit-1	Wolsong unit-2
FARE channel minimum flow	11.1 (kg/s)	11.53 (kg/s)
FARE channel maximum flow	20.4 (kg/s)	20.54 (kg/s)

and measured flow rates arranged for each header. There are 4 inlet headers and 4 PHT pumps in CANDU6 reactor, in which 3 instrumented channels belong to each header as shown in Table 1. The measured channel flow and design channel flow is different and measured channel flow should envelop the design channel flow as shown in Table 1. The minimum and maximum channel flow of all the FARE channels is given in Table 2. From Table 2, it can be concluded that the minimum value of FARE device hydraulic test flow range should be greater than 11.0 (kg/s) and the maximum should be less than 20.54 (kg/s). Note that the current FARE device was tested for the range of 6~23(kg/s), which envelops the FARE channel flow range with some margin. Also note that the Table 2 was compiled from the complete channel flow map.

The channel flow distribution will change slightly when F/M head is connected to a channel and inflow of coolant from F/M occurs. Because fuel channels are parallel flow network system, change of flow impedance in a channel will cause change in channel flow distribution. However, the effect on the channel flow distribution is negligible due to the fact that the inflow from a F/M is small (1.89 kg/s). The F/M D2O flow is designed to prevent leakage of primary coolant from the main loop and contamination of the F/M head components. The contamination of F/M components will

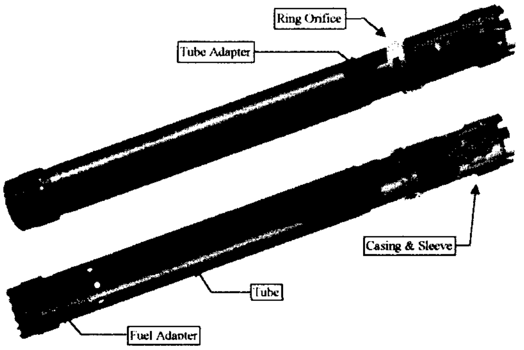

Fig. 2. 3D Model of FARE Device Assembly and Components

prevent routine maintenance of F/M. Note that for the same reason, F/M D2O is supplied from the D2O storage system and the F/M D2O supply system has filtration circuit.

3. FARE Device Structure and Hydraulic Characteristics

The FARE device consists of 3 main parts as shown in Figure 2. The upper figure of Figure 2 is appearance and the lower figure is cutaway view of the FARE device. The FARE device is approximately 2-fuel bundle length to be compatible with F/M operation. The FARE device shown in Figure 2 is a 3D CAD model in which components are shaded in different color to distinguish each other.

The geometry of fuel adapter contact face to fuel bundle is similar to fuel bundle end plate so that it can support fuel bundle string properly. The casing and sleeve is the parts that interface with F/M rams, and the same mechanism is used in other F/M components such as shield plug, channel closure and snout plug etc, see reference 7. The tube adapter and ring orifice is the parts that control flow resistance. The ring orifice has grooves in the perimeter to give more consistent bypass flow stream pattern. Finally the tube is designed to make the FARE device length approximately 2-fuel bundle length.

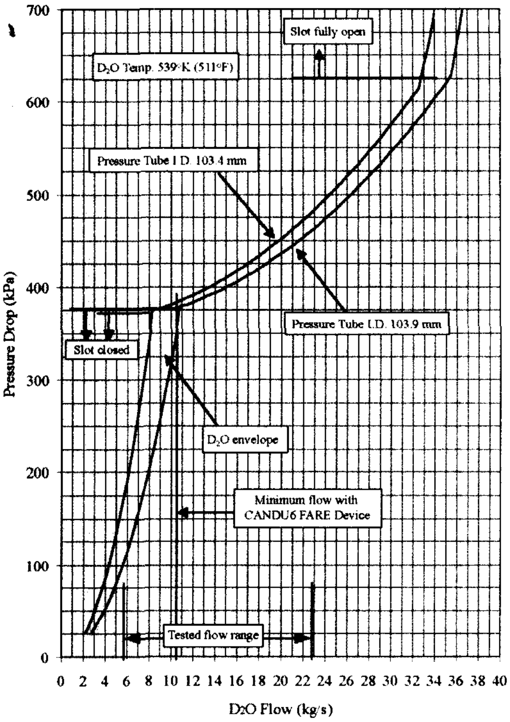

Fig. 3. FARE Device Hydraulic Characteristics

Although springs are not shown in the figure, there are two different springs are used, one is installed inside of tube adapter and the other is installed inside of casing assembly, see reference 6. The spring installed inside of tube adapter, controls orifice-opening force, and determines the FARE device hydraulic characteristics. The spring material should be selected carefully, because it is used in elevated temperature of around 300℃ and in high radiation environment, the creep of spring should not degrade spring performance over time. The current FARE device spring material is Inconel X750 and does not show any sign of degradation. Hence it will be used for the new FARE device design.

Figure 3 shows the steady state FARE device hydraulic characteristics. The test was done for the flow range of 5.8~22.8 (kg/s). At flows below 9.5 (kg/s), the FARE device ring orifice is closed and the flow resistance is proportional to the square of flow velocity. As the flow increases, the ring orifice starts to open at 8.3 (kg/s). Once the ring orifice is open, some of the flow can go into the orifice slot and tube adapter bore and flows bore of tube and fuel adapter. This creates more flow area and reduces flow resistance. In Figure 3, the pressure drop across the FARE device shows rather flat response above 9.5 (kg/s). Above this flow range, the ring orifice spring contracts as flow increases, therefore, the flow into the tube adapter increases and the pressure drop across the FARE device reduces.

When using the FARE device in channel, an accident condition has to be considered too. One such scenario is inserting the FARE device in the center channel where the FARE is not necessary for fuelling operation. Because channel flow maximum is around 28.4(kg/s), reference 8, the tested flow upper limit covers this range. It showed that the ring orifice is not open completely and still has some margin for more flow. Therefore flow resistance will not drastically increase by the channel flow increase.

Another scenario is that the FARE device is left in the core even after the fuelling operation is finished due to fuelling operation sequence mix up. This incident cannot happen, due to the fact that the upstream F/M has to recover the FARE device after all spent fuel is discharged. The FARE device can be picked up by F/M C-ram, however, a fuel bundle cannot be picked up by F/M C-ram. Hence the operator can notice fuelling operation sequence mix up when the upstream F/M C-ram cannot pick up the FARE device.

4. FARE Device Behavior During Fuelling Operation at Reactor Fuel Channel

4.1. Fuelling Operation with FARE Device

At Wolsong NPP, fuelling operation occurs routinely on a daily basis. Fuelling of 2 channels per day is required on average if 8-bundle shift refuelling scheme is implemented as in Wolsong NPP, see reference 2. This on-power refuelling requires remote controlled fuel-handling system because of high radiation field in reactor and spent fuel discharge area. The overall flow of fuel is shown in Figure 4 below.

New fuel bundle is stored in a storage facility on site and transferred in to the new fuel storage area in the containment building. For fuelling operation, new fuel bundles are manually loaded in the new fuel loading equipment. From there, new fuel bundle is loaded into remote controlled F/M by new fuel loading equipment. The F/M inserts new fuel bundles in the specified channel at the upstream end and another F/M removes spent fuel from the downstream end of that channel. The spent fuel is then discharged to spent fuel discharge bay. Spent fuel is then transferred to reception bay by underwater transfer system. All of these activities are done automatically and remotely. Spent fuel is then transferred to storage

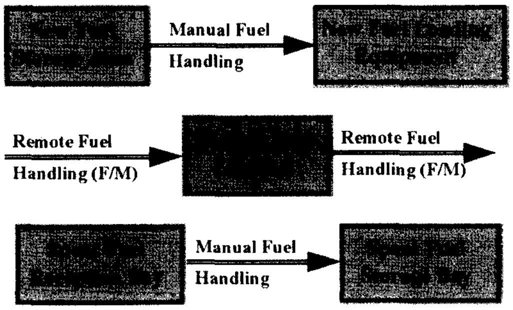

Fig. 4. Fuel Flow in Wolsong NPP

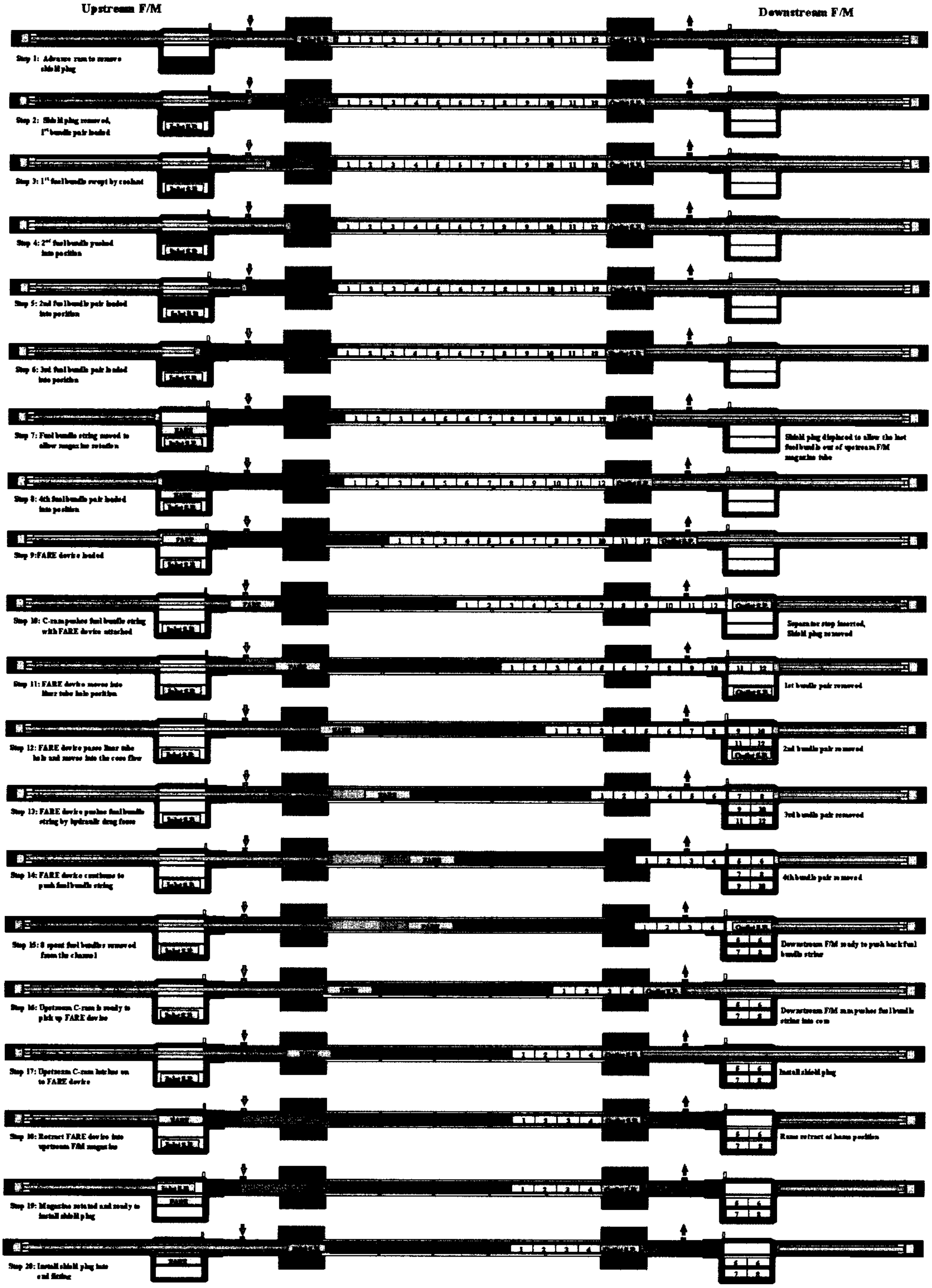

Fig. 5. Fuelling Operation using FARE Device

bay for long term storage.

The upstream F/M receives new fuel at the new fuel port and transverse to the designated fuel channel, and the downstream F/M moves to the designated fuel channel. Both F/Ms clamp on to the designated fuel channel and check for leakage. If the seal is incomplete, clamping operation need to be done again. Upon success of the test, snout plug and channel closure are removed and stored in F/M magazine. The snout cavity leak detection is done by applying high pressure then closing the supply valve and checking for the pressure change. If pressure drop of snout cavity is more than preset value, a leakage occurs and clamping operation needs to be done again.

Because the bore of F/M snout and part of end fitting where channel closure is installed is larger than that of channel, it is required to install guide sleeve in the F/M snout. So that fuel bundles can move in and out of F/M snout. When both F/Ms installed guide sleeve in the snout, they are now ready to remove shield plug and insert new fuel bundles into and remove spent fuel bundles from the channel. From this step on both machines communicates to check the status of other machine before proceeding further. Figure 5 shown detailed steps of fuelling operation at reactor face. Each step is explained as follows.

Step 1 : Both F/Ms are ready to remove shield plug.

Step 2 : The upstream shield plug is removed and stored in F/M magazine, and the 1st new fuel bundle pair is inserted into end fitting.

Step 3 : The front fuel bundle of is swept by coolant flow.

Step 4 : 1st new fuel bundle pair is in complete contact with fuel string in the core.

Step 5 : A 2nd new fuel bundle pair is inserted into the fuel string.

Step 6 : A 3rd new fuel bundle pair is loaded in to position, however, the second fuel bundle is still in the upstream F/M magazine. Hence it is required to retract downstream shield plug to make room for the fuel string.

Step 7 : Downstream shield plug is moved just enough to make the upstream end of fuel bundle out of the way for separator.

Step 8 : The magazine tube containing 4th fuel bundle pair is swung into position ready to load the fuel bundle pair.

Step 9 : The downstream shield plug is further removed to make room for FARE device insertion and FARE device is loaded into channel.

Step 10 : All fuel string, the FARE device and downstream shield plug is moved toward downstream F/M magazine, and shield plug is stored in F/M magazine.

Step 11 : The 1st pair of spent fuel bundles is moved in downstream F/M magazine. At this stage, the FARE device is in the end shield region of liner tube and the flow holes of liner tube are directly overlap with the FARE device.

Step 12 : The 2nd pair of spent fuel bundle is stored in downstream F/M and the FARE device is now fully in the core flow region. The upstream F/M ram stops extending into core flow region.

Step 13 : The 3rd pair of spent fuel bundle is removed and stored in the downstream F/M magazine.

Step 14 : The 4th pair of spent fuel bundle is removed and stored in the downstream F/M magazine.

Step 15 : The FARE device and 12 fuel bundle string is held by downstream F/M separator. The downstream shield plug is rotated in position to be installed in

Table 3. Channel B14 Fuelling Operation History

time	flow rate (%)	F/M command
9:40	100	Before Closure Plug removed
9:49	97	Closure Plug removed
9:57	97	Upstream Shield Plug removed
9:59	97	1st fuel pair inserted
10:01	97	2nd fuel pair inserted
10:02	96	3rd fuel pair inserted
10:04	95	Downstream F/M B-ram retract
10:10	95	Downstream F/M store Shield Plug in Magazine
10:14:07	75	Trip time : 10:14:09
10:15	75	Reset time : 10:15:56
10:19	82	Downstream F/M receives 4th spent fuel pair
10:24	78	Trip time : 10:24:43
10:24:30	75	Reset time : 10:25:24
10:25:51	95	FARE tool removed from core.

channel.

Step 16 : The downstream F/M pushes shield plug back into core.

Step 17 : The downstream shield plug installed in the end fitting. The FARE device is out of core flow region. The upstream F/M picks up the FARE device.

Step 18 : The FARE device is stored in the F/M magazine tube.

Step 19 : The upstream shield plug is rotated in position to be installed in channel.

Step 20 : The upstream shield plug is installed in channel.

The steps 11~17 are related to insertion and recovery of the FARE device into core flow region. After finishing above steps, both F/Ms are ready to remove guide sleeve and install channel closure and snout plug. Before disengaging the F/M from end fitting, it is again required to check leakage of channel closure and snout plug.

When the upstream F/M inserts the FARE device into the core, it uses C-ram to push the FARE device without locking into the device. As the FARE device is pushed into core flow region, the upstream F/M C-ram stops extending into the reactor core. Once the FARE device is moved to the active core flow region, the drag force of the device starts to push fuel bundle string. The downstream F/M can now be able to receive 12 spent fuel bundle pairs. After all spent fuel is removed from the channel, the downstream F/M reinstalls shield plug with fuel bundle string and the FARE device in front of it. The down stream F/M can then proceed to remove guide sleeve, install channel closure, install snout plug and unclamp from channel end fitting. In the mean time, the upstream F/M C-ram locks onto the FARE device that has been moved out of core by the downstream F/M and recovers the FARE device from channel and stores it in the magazine. The upstream F/M can now reinstall shield plug, remove guide sleeve, reinstall channel closure and snout plug and test for leakage before unclamping from the channel.

4.2 Fuelling Operation of Channel B14

Table 3 shown Wolsong unit 1 channel B14 fuelling operation data. This channel requires the FARE device for fuelling operation, see Figure 1. The channel flow is 100% before opening channel closure, however, the channel flow drops somewhat after opening the channel. It is due to the increase in impedance of core flow region caused by the inflow from the upstream and downstream F/M. The coolant flow measured at the upstream inlet feeder decreases, however actual flow in the core region should not decrease as much. The flow rate maintains at around 95% during the removal of channel closure, shield plug and the insertion of new fuel bundles.

The flow rate drops below 80% when the FARE device enters into the liner tube flow-hole region and it is step 11 of Figure 5. The movement of fuel bundle string stops for a moments while downstream F/M stores 1st pair of spent fuel in the magazine tube and rotates empty magazine tube in position to receive another pair of spent fuel bundle pair. It is also note that when the FARE device is in the liner tube hole region, the flow resistance is the greatest. As the FARE device pushes fuel string toward downstream, flow resistance decreases. Hence flow rate recovers to around 80%, a marginal value for channel flow low. After removing 4 pair of spent fuel bundles, the coolant flow resistance increases again as the FARE device and fuel bundles are moved back into empty core region. Hence the flow rate goes below 80% again. This is channel B14 fuelling operation and typical of the FARE channel fuelling operation.

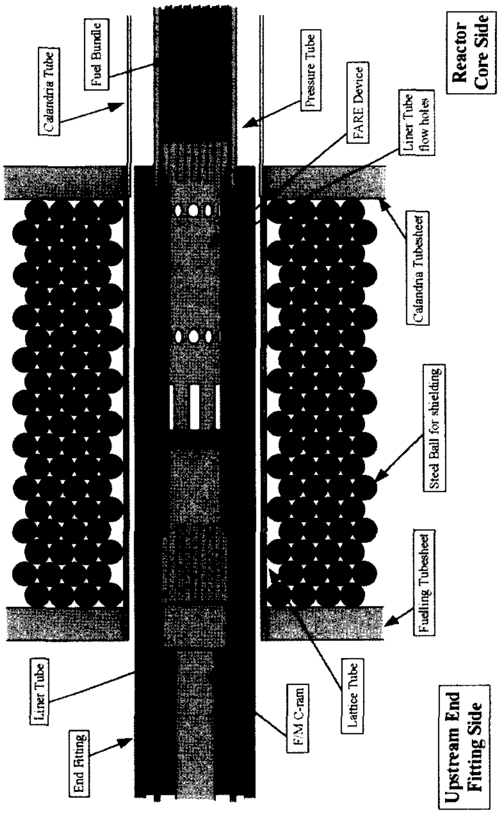

Fig. 6. FARE Device in Liner Tube Flow-hole Region

Figure 6 shows the instance when the FARE device is in the liner tube flow-hole region. Because the FARE device is not yet inserted into the active core flow region, the ring orifice is still closed. And the coolant flows from liner tube flow-hole and through the gap between liner tube and the FARE device O.D. then goes into core. Some of the coolant can flow into the FARE device bore through the flow-hole in the tube.

When the FARE device is fully inserted into active core flow, the coolant flows into the gap between the casing of the FARE device and pressure tube I.D. Because there is no opening in the casing, see Figure 2, the coolant flows outside of the casing, and toward ring orifice. The ring orifice opens according to the flow rate. Some of the coolant flows through the gap between pressure tube and ring orifice O.D. and remaining coolant flows into the FARE device bore through the orifice slots then flows toward fuel adapter flow-hole. The FARE device in other channel may behave differently depending on the flow rate for that channel. Because the flow rate recovery is quite small after the FARE device is fully moved into the active core flow, around 5~7%, it may be possible that the channel flow low trip signal may go on as long as the FARE device is inserted into the active core flow.

5. FARE Device Ring Orifice Spring Pre-load Force

5.1. Current FARE Device Ring Orifice Spring Pre-load Force

The FARE device orifice spring pre-load determines at which flow rate the ring orifice starts to open, and is the most important factor for defining the FARE device hydraulic characteristics. The spring pre-load for the current FARE device ring orifice can be calculated from Figure 3.

At flow rate of 8.5~10.5(kg/s) the ring orifice starts to open, and the pressure drop is 375(kPa). The pressure drop acting on ring orifice balances with spring load. Therefore, at the instance of the ring orifice opening, the spring pre-load equals the FARE device drag force.

Spring pre-load force:

$$F_s = \Delta P \cdot A_o = \Delta P \pi/4\,(D_o^2 - D_i^2)$$
$$= 375{,}000/9.8 \cdot \pi/4 \cdot (0.1^2 - 0.084^2)$$
$$= 99\ (\text{kg}) = 219(\text{lb})$$

FARE device drag force:

$$F_d = \Delta P \cdot A_f = \Delta P \cdot \pi/4 \cdot D_o^2$$
$$= 375{,}000/9.8 \cdot \pi/4 \cdot 0.1^2 = 300\ (\text{kg})$$
$$= 665(\text{lb})$$

where ΔP is pressure drop, Ao is the orifice area where pressure is applied, and A_f is total FARE device sectional area where pressure is applied.

At flow rate of 21.5(kg/s) the upper limit of flow rate for which the FARE device is to be used, the pressure drop is 450 (kPa). The spring force and the FARE device drag force is

Spring pre-load force:

$$Fs = \Delta P \cdot A_o = \Delta P \cdot \pi/4(D_o^2 - D_i^2)$$
$$= 450{,}000/9.8 \cdot \pi/4 \cdot (0.1^2 - 0.084^2)$$
$$= 106\ (\text{kg}) = 235(\text{lb})$$

FARE device drag force:

$$F_d = \Delta P \cdot A_f = \Delta P \cdot \pi/4 \cdot D_o^2$$
$$= 450{,}000/9.8 \cdot \pi/4 \cdot 0.1^2$$
$$= 360\ (\text{kg}) = 800\ (\text{lb})$$

It can be concluded that the current FARE device exerts at least 300 (kg) of drag force to the fuel bundle string when it is fully inserted in the active core. The maximum drag force it exerts on fuel bundles is at most less than 360(kg) for the FARE channel upper limit of 21.5 (kg/s). This drag force should overcome the friction force by the fuel bundles.

5.2. Required FARE Device Drag Force and Spring Pre-load Force

Previous section calculated the FARE device drag force range. In order to assess the required FARE device drag force, the calculation of fuel bundle drag force and friction force is required. Assuming flow rate of 10.5 (kg/s) as conservative lower limit where the FARE device ring orifice opens (table 2 shows that the minimum channel flow is around 11(kg/s)), the drag forces of the

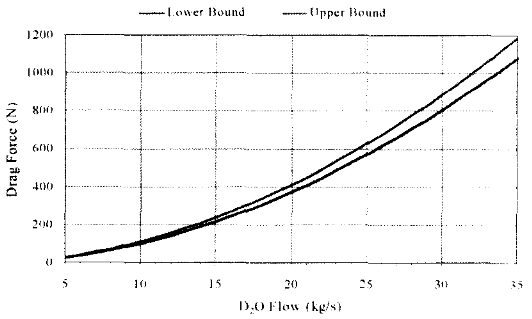

Fig. 7. Single Fuel Bundle Drag Force

FARE device and fuel bundles can be calculated. The combined drag force of the FARE device and fuel bundle should be greater than the friction forces of fuel bundle and the FARE device in order to be able to move fuel string toward downstream F/M magazine. Because smaller channel flow rate produces smaller fuel bundle drag force, it consequently requires larger FARE device drag force and higher flow resistance by the FARE device. Hence too much conservatism will results in a FARE device design that cannot eliminate channel flow low phenomena.

The maximum number of fuel bundles that the FARE device to push during fuelling operation is 18 bundles, see Figure 5 step 12. This is the instance when the maximum fuel bundle friction and the minimum channel flows occurs. The static and dynamic friction coefficient of a fuel bundle is found to be 0.6 and 0.69 respectively, reference 3.

The fuel bundle drag force for flow rate at 10.5 (kg/s) is approximately 10(kg), see Figure 7 for the fuel bundle drag force. The 2-bundle hydraulic test and 12-bundle hydraulic test shows different drag force when converted to single fuel bundle drag force see reference 3. Figure 7 showed it as upper bound and lower bound. It is note that during fuelling operation multiple fuel bundles are in the channel, and how the bundles align with neighboring fuel bundle affect the total fuel string drag force. Here the calculation is carried out based on lower bound for conservative estimation.

A fuel bundle weight is around 23.7(kg) and the FARE device weight is around 20 (kg). In the calculation the FARE device weight is treated as the same as fuel bundle weight. Because spent fuel bundle removal consist of sporadic movement of stop and go, static friction is considered in the calculation.

The required minimum FARE device drag force is the difference between fuel string drag force and total friction force.

Total fuel bundle string drag force
$= 18 \times 10 = 180$ (kg)
Total static friction force ($\mu = 0.68$)
$= 19 \times 23.7 \times 0.68 = 306$ (kg)
Required FARE device drag force
$= 306 - 180 = 126$ (kg)

The FARE device drag force should be at least 126 (kg). The current FARE device drag force calculated previous section at flow rate of 10.5 (kg/s) is 300(kg). Hence it is more than enough to overcome the friction force and be able to push fuel bundle string. On the other hand too much drag by the FARE device causes flow reduction more than necessary and resulted in channel low flow phenomenon.

In order to increase channel flow, reduction of the FARE device drag force is necessary. Because it was assumed that at flow rate of 10.5 (kg/s) the FARE device ring orifice opens, the FARE device drag force should at least balance with orifice spring pre-load force. Assuming 10~20% reduction in the FARE device drag force, the corresponding orifice spring force can be obtained as follows.

FARE drag force (10% reduction),
$F_d = 300 \times 0.9 = 270$ (kg)

FARE drag force (20% reduction),

$$F_d = 300 \times 0.8 = 240 \text{ (kg)}$$

Spring pre-load force,

$$F_s = \Delta P \cdot A_o = F_d \cdot A_o/A_f$$
$$= F_d \cdot (D_o^2 - D_i^2)/ D_o^2$$

For F_d = 270 (kg), the spring pre-load F_s $= 270 \times (0.1^2 - 0.084^2) / 0.1^2 =$ 79.5 (kg)

For F_d = 240 (kg), the spring pre-load Fs $= 240 \times (0.12 - 0.0842) / 0.12 = 70.5$ (kg)

where, D_0 Indicates ring orifice outside diamerter,

D_i indicates ring orifice inside diameter.

This result showed that in order to increase flow rate about 10 %, orifice spring pre-load should be reduce to around 70~80 (kg). A similar calculation can be done for the upper limit of channel flow at 21.5 (kg/s) where the FARE device to be used, the corresponding spring force would be around 90(kg).

6. FARE Device Design Change

As analyzed in the above sections, the FARE device needs improvement. The current FARE device causes too much coolant flow restriction and resulted in trip alarm signal on during the fuelling operation. In order to reduce flow resistance by the FARE device, number of the FARE device component needs to be changed. Some components that do not need to be changed are casing and sleeve assembly. It interfaces with F/M ram and does not directly related to the hydraulic characteristics of the FARE device. Fuel adapter may not need to be changed because it is already designed to be compatible with fuel bundle end plate. Hence the remaining components that need to be redesigned are tube body, ring orifice assembly and ring orifice spring.

In order to reduce flow resistance, more flow holes in the tube body and more orifice slots in the tube adapter is required. Figure 8 shows current design and Figure 9 shows a provisional improved design. Design optimization on how many flow holes in the tube body and tube adapter needs further experiment. A tentative design change of the improved tube body has holes through the

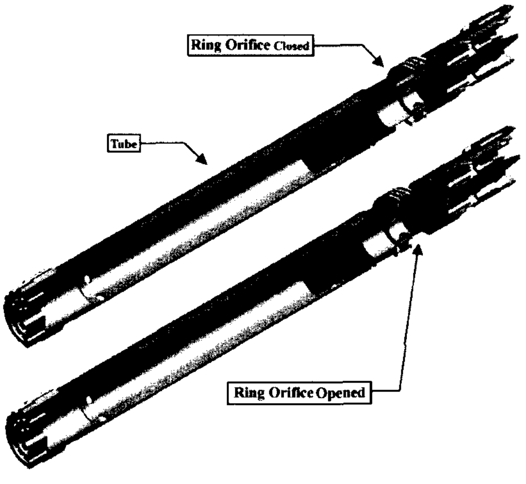

Fig. 8. 3D Sectional View of Current FARE Device

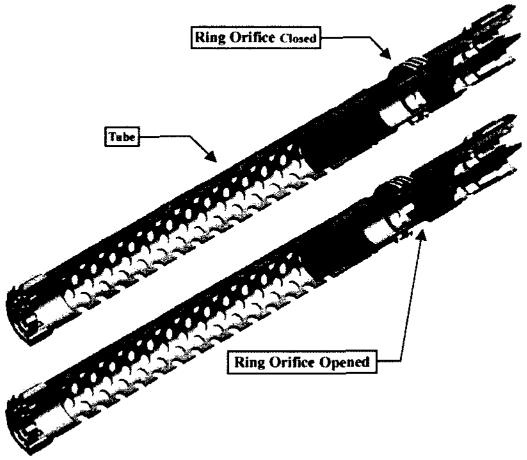

Fig. 9. 3D Sectional View of FARE Device Provisional Design Cange

body and tube adapter has 8 orifice slots as shown in Figure 8. By increasing ring orifice slot number, the upper limit of flow where ring orifice is completely open is higher than current design.

The orifice spring pre-load force needs to be adjusted to allow more flow through orifice slot. It was calculated that around 80(kg) of pre-load would be adequate value without jeopardizing the FARE device' s ability to push fuel bundle string. Because the main objective of the FARE device is to create enough drag force that can be used to overcome fuel bundle string friction force, excessive reduction of the FARE device flow resistance must be avoided. Especially if channel flow is low, total drag force of the FARE device and fuel bundle string may drop below the total friction force of the FARE device and fuel bundle string.

The outermost channels, see Figure 1, are especially critical in this regard, because their flow rate is lower than inside channels. This is the main reason that the calculation shown in the previous section considered the low flow channel. The calculation showed that the low flow channel has some margin that can be used to reduce flow resistance. The lowest channel flow is around 11 (kg/s), see section 2, and the calculation given in section 5 is more conservative because it assumed channel flow of 10.5 (kg/s). If channel flow is lower than this value, it might not be possible to reduce FARE device flow resistance as much. In such cases two different FARE devices may need to be used. Using 2 different kind of FARE devices is not acceptable for the operational point of view. There is other way to reduce flow resistance of the FARE device such as reducing the diameter of tube body and ring orifice diameter other than making more flow-holes in the tube and orifice slots. These design changes also have to be considered in the optimization of the FARE device design. The fabrication cost and the easy of assembly of components have to be considered too.

7. Conclusions and Discussions

The current FARE device operational characteristics were analyzed to find the cause of channel flow low phenomenon. It was concluded that more than excessive flow restriction by the FARE device was the reason for the channel flow low during fuelling operation. Because flow reduction is around 25 %, see Table 3, as soon as the FARE device was inserted into active core flow region, about 10 % increase of channel flow is recommended to be able to prevent channel flow low alarm.

Suggested design changes included redesign of tube having more flow holes and ring orifice having more flow slots as well as orifice spring having less pre-load compression. The ring orifice spring pre-load compression is recommended to to be around 80 (kg). This change of orifice spring pre-load will open orifice slot at lower channel flow rate and will result in reduction of flow resistance.

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