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Analysis of Fuelling Sequence and Fatigue Life for 4-Bundle Shift Refuelling Scheme in CANDU6 NPP

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Abstract

A 4-bundle shift refuelling method of CANDU6 F/H (Fuel Handling) System is analyzed to assess the operational flexibility and capacity of F/H system. The current 8-bundle shift refuelling scheme requires to refuel eight fuel bundles from a single fuel channel, and to refuel 14 fuel channels in a week on average assuming that the reactor is in a steady state. The analysis showed that the 4-bundle shift refuelling method increases F/M (Fuelling Machine) duty cycle and operator load. However, the fuelling method change from the 8- to 4-bundle shift refuelling will not require additional team of operators. A marginal increase in the maintenance cost may be resulted in by the change of fuelling method and the increase of fatigue usage factors requires some components to be replaced during the F/M lifetime.

Key Words : core disruptive accident, liquid metal reactor, energy release

1. Introduction

This paper reviewed and analyzed the CANDU6 F/H System operational capacity, especially the 4-bundle shift refuelling scheme. The current fuelling method for CANDU6 NPP is 8-bundle shift refuelling scheme which was chosen to reduce the F/M usage and plant management overhead. However an accurate assessment and estimation of operational capacity of CANDU6 F/H system was never been done. In a recent study [1], a conservative estimate of F/H system 4-bundle shift refuelling scheme was analyzed without considering fatigue aspect. This paper presents more accurate analysis of F/H system operational time in addition to fatigue related aspect due to increased fuelling demand. Unlike other nuclear equipment, F/H system consists of moving equipment such as F/M head, carriage, bridge etc. Hence accurate analysis of the sequence of motion of these equipment is important for the calculation of more accurate refuelling time.

The need for more frequent fuelling arises when fuels fabricated from enriched uranium are to be used. For example, DUPIC (Direct Use of PWR spent fuel In CANDU) fuel cycle requires fuelling demand to be increased by 2 times as much as the current 8-bundle shift refuelling scheme [2]. A 4-

Table 1. 8-bundle Shift Refuelling Time for a Channel (unit : min.)

Operation	Fuelling a single channel	Fuelling 2 channels with same flow direction	Fuelling 2 channels with opposite flow direction
System start up	30	30	30
New fuel transfer operation	41	41	82
Reactor face fuelling operation	69	138	138
Spent fuel discharge operation	53	106	106
System shutdown	30	30	30
Total	223	345	386

Table 2. Fuelling Operation Time at NFP (New Fuel Port)

Step	Operation	Time(min)
0	Traverse from reactor face to the NFP	5.75
1	Raise NFP drain port, depressurize F/M head, lower magazine D2O level, remove snout plug.	6.28
2	Transfer guide sleeve from magazine to snout	2.67
3	Receive eight fuel bundles in magazine.	13.42
4	Transfer guide sleeve from snout to magazine	2.53
5	Install snout plug in snout, raise D2O level, unclamp and retract Z-motion.	10.28
Total	40.93	

bundle shift refuelling scheme reduces the amount of new fuel bundle introduction to a channel at a time, therefore it can be regarded as more benign to core than 8-bundle shift refuelling scheme. The study does not touch safety aspect of 4-bundle shift refuelling method, but focuses on the analysis of fuel handling system operational capacity and the cost increase due to switch from 8- to 4-bundle shift refuelling scheme. The study includes the F/M control sequence, refuelling time, the current operator management scheme, and F/M fatigue usage factors etc., based on the whole core 4-bundle shift refuelling scheme. A partial implementation of 4-bundle shift refuelling, i.e. combination of the 8- and the 4-bundle shift refuelling scheme, is not considered in the study.

2. 8-bundle Shift Refuelling Scheme

Current refuelling operation of a CANDU reactor is 8-bundle shift refuelling scheme carried out by two F/Ms. The upstream F/M loads 8 new fuel bundles into the core while downstream F/M discharges 8 spent fuel bundles. Table 1 shows average fuelling time for a channel. Fuelling time can vary depending on the location of channel and refuelling mode weather FAF (Flow Assisted Fuelling) mode or FARE (Flow Assist Ram Extension) mode, [3]. A FARE mode fuelling takes about 10-15 minutes longer than FAF mode fuelling.

Table 2 shows single channel, 2 channel with same flow direction and 2 channel with opposite

Table 3. Fuelling Operation Time for Channel O-11 with FAF Refuelling Mode

Step	Operation		Up-stream machine	Down-stream machine
	Upstream	Downstream		
1	Traverse	Traverse	5.38	5.32
2	Fine home, clamp on, snout leak test, remove snout plug and store in magazine.	Fine home, clamp on, snout leak test, remove snout plug and store in magazine.	11.05	9.00
3	Remove closure plug and store	Remove closure plug and store	2.48	2.68
4	Install guide sleeve in snout	Install guide sleeve in snout	2.57	2.70
5	Remove Shield plug and store in magazine	Channel leak test, disengage shield plug, wait	4.73	2.60
6	Pickup ram adapter		0.53	Wait
7	6 bundles load to core		3.62	Wait
8		Retract Bram to position B0 holding fuel string and wait	Wait	1.63
9	2 bundles load to core		1.53	Wait
10		Store Shield Plug	Wait	3.38
11		Pick up ram adapter	Wait	0.62
12		Store 4 bundles to magazine and side stop inserted	Wait	4.58
13	Store ram adapter	Store 4 bundles to magazine	1.27	5.07
14	Reinstall shield plug	Store ram adapter	3.87	1.30
15	Wait	Replace Shield Plug	Wait	6.83
16	Channel leak test, remove guide sleeve from snout to magazine.	Channel leak test, remove guide sleeve from snout to magazine.	3.13	3.28
17	Reinstall closure plug from magazine to end-fitting.	Reinstall closure plug from magazine to end-fitting.	2.58	2.75
18	Place snout plug in snout, leak test, unclamp, retract Z-motion, center Y-correction.	Place snout plug in snout, leak test, unclamp, retract Z-motion, center Y-correction.	9.02	8.50
	Total time (min.)*	Replace Shield Plug	68.82	65.93

*Total time for each machine takes account the waiting period.

flow direction fuelling time. For 2 channel fuelling with same flow direction, flow direction of the 2nd channel is the same as that of the 1st channel, while for 2 channel fuelling with opposite flow direction, flow direction of the 2nd channel is the opposite of the 1st channel. This makes control sequence different for both cases and resulted in different fuelling time.

Table 4. Fuelling Operation Time at SFP (Spent Fuel Port)

Step	Operation	Time(min)
1	Traverse from reactor face to the SFP.	6.13
3	Fine home, clamp on, remove snout plug and store in magazine.	5.27
4	Install guide sleeve from magazine to snout.	2.48
5	Pick up ram adapter from magazine.	0.65
6	Raise spent fuel drain port, lower magazine D2O level.	2.32
7	Fuel Transfer Canal Containment Gate close and Leak test, Ball Valve open	1.82
9	Index magazine and Lower C-Ram force to 4	0.17
10	Advance F/M C-ram to load two bundles onto ladle	1.02
11	Retract F/M C-ram to clear and retract fuel stop	0.17
12	Lower ladle	1.65
13	Index rack	0.12
14	Raise ladle and advance fuel stop	1.42
15	Repeat steps 9 to 15, three times	13.60
16	Close port valves, Open FTC C/G	1.42
17	Deposit ram adapter in magazine.	1.30
18	Remove guide sleeve from snout to magazine.	2.73
19	Install snout plug in snout, raise D2O level, unclamp and retract Z-motion.	10.40
	Total	53.05

Table 2 shows detailed steps of F/M control sequence at NFP (New Fuel Port). The F/M receives two new fuel bundles and store in its magazine tube at a time. Therefore, in 8-bundle shift scheme, four magazine tubes are used to store new fuel bundles. It is important to note that the steps shown in Table 2 consists of many sequences and each sequences are break down again further to smaller control steps.

Table 3 shows detailed F/M control sequences at reactor face. The upstream F/M loads new fuel bundles while downstream F/M discharges spent fuel bundles. The upstream F/M loads 6 new fuel bundles while downstream machine opens channel and removes Channel Closure and Shield Plug. The two F/Ms communicate each other to check the status of the other before proceeding to the next sequence. After inserting 6 new fuel bundles, downstream F/M starts to unload 2 spent fuel bundles while the upstream F/M loads the last 2 new fuel bundles. With new fuel bundles in the End Fitting zone, upstream F/M pushes the whole fuel bundle string downward until 8 spent fuel bundles are removed from the core.

Table 4 shows detailed steps of spent fuel discharge operation at SFP (Spent Fuel Port). Once F/M clamped on to SFP, it began to open the port and start to discharge 2 spent fuel bundles at a time. For 8-bundle refuelling scheme, it requires 4 times of spent fuel discharge operation. After discharging all spent fuel bundles from F/M magazine, it closes the port by closing port ball valves.

A typical organization for the operation and maintenance of F/H system for two CANDU6 NPP consists of four teams of operators. Of which two teams are dedicated to regular refuelling operation and one team of mechanical engineers and another team of electrical engineers are dedicated to repair and maintenance. The Mechanical and Electrical Groups are responsible for maintenance of the F/H system. Mechanical and Electrical Group consist of 6 engineers each with external support personnel ranging from 5 to 10 engineers.

For routine maintenance and checking of Fuel Handling System, usually a day in a week is set aside. This will leave refuelling operation for the rest of week-days. If Wednesday is set aside for maintenance of Fuel Handling System, then to meet the fuelling requirement, 3 channel refuelling jobs are carried out on Monday, Tuesday, Thursday, Friday, and 2 channel refuelling jobs on Saturday.

3. Analysis of 4-Bundle Shift Refuelling Scheme

Based on the 8-bundle shift refuelling operation time presented in the previous Chapter, the 4-bundle shift refuelling operation time can be estimated. In order to meet the required amount of fuels to handle, fuelling should take place at least four channels a day on average or 16 fuel bundle replacement a day. Fuelling time depends on the number of channels to fuel and direction of channel flow for the given fuelling job.

The F/M is designed to store up to 10 fuel bundles for FAF refuelling and 8 fuel bundles for FARE refuelling, hence a 2-channel refuelling job is possible. Therefore it is possible that a F/M carries a full capacity of new fuel bundles and loads the 1st channel with new fuel then receives spent fuel from the 2nd channel. This is like storing both new and spent fuel bundles in the same F/M magazine. Although it is possible to manage this kind of fuelling sequence with careful programming, it is best to avoid such scenario in order to prevent accidental loading and discharging of wrong fuel bundles. A way to prevent such event from happening is by assigning the same role to the F/M whether to be an upstream or downstream machine throughout the refuelling operation. There are various fuelling job combinations for a 4-bundle shift refuelling method depending on the number of fuel channels to visit at a time.

Table 5 enumerates various fuelling jobs depending on different number of channels and channel flow direction. As described in Section 2, for normal refuelling operation of 8-bundle shift scheme, a 3-channel refuelling job or 2-channel refuelling job a day is required. For 4-bundle shift refuelling scheme, to maintain the same amount of fuelling demand, a maximum of 6-channel visit a day would be required. Table 5 shows some of possible fuelling jobs excluding jobs that requires to store new and spent fuel in the same F/M magazine. There are 3 schemes available for 2 channel refuelling job. The first case is for 2-channel refuelling that has the same flow direction. The upstream F/M receives 8 new fuel bundles from NFP and inserts 4 bundles to the first channel and moves to the second channel and inserts 4 new fuel bundles. The downstream F/M removes 4 spent fuel bundles from each channel and discharges at SFP. The second case is when the two channel flows are the same and each channel is treated separately. So the upstream machine receives only 4 bundles from NFP and insert 4 fuel bundles to the first channel, and goes back to NFP and receive 4 new fuel bundles and move back to channel, and insert 4 new fuel bundles. The downstream machine discharges 4

Table 5. Refuelling Job Combinations for 4-bundle Shift Refuelling Scheme

Job Scheme	Work Flow (for upstream machine)	Job No. (Ch. Flow Dir.)
1 ch. refuelling	NFP ⇒ F/C ⇒ Home	1(⇒)
2 ch. refuelling	NFP⇒F/C⇒F/C⇒Home NFP⇒F/C⇒Home, NFP⇒F/C⇒Home NFP⇒F/C⇒S/W to Downstream⇒F/C⇒SFP	1(⇒ ⇒) 1(⇒), 2(⇒) 1(⇒), 2(⇒)
3 ch. refuelling	NFP⇒F/C⇒Home, NFP⇒F/C⇒Home,NFP⇒F/C(Home) NFP⇒F/C⇒F/C⇒Home, NFP⇒F/C⇒Home NFP⇒F/C⇒Home, NFP⇒F/C⇒F/C⇒Home NFP⇒F/C⇒Home, S/W to Downstream⇒F/C⇒ SFP, NFP⇒F/C⇒Home	1(⇒), 2(⇒), 3(⇒) 1(⇒ ⇒), 2(⇒) 1(⇒), 2(⇒ ⇒) 1(⇒), 2(⇒), 3(⇒)
4 ch. refuelling	NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home	1(⇒), 2(⇒), 3(⇒), 4(⇒)
	Combination of 2 ch. + 2 ch. refuelling	
5 ch. refuelling	NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home	1(⇒), 2(⇒), 3(⇒), 4(⇒), 5(⇒)
	Combination of 2 ch. + 2 ch. + 1 ch. refuelling	
6 ch. refuelling	NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home, NFP⇒F/C⇒Home	1(⇒), 2(⇒), 3(⇒), 4(⇒), 5(⇒), 6(⇒)
	Combination of 2 ch. + 2 ch. + 2 ch. refuelling	

spent fuel bundles to the SFP each time. The third case is when the two channel flows are different and treat both separately. So the upstream machine receives 4 new fuel bundles from NFP, and moves to reactor face and inserts 4 new fuel bundles. The downstream machine discharges 4 spent fuel bundles at SFP each time.

For channels involving more than 3 channels, it will be a combination of single channel and 2 channel refuelling job. There will be many cases depending on the channel flow direction and order of channel combination of 2-channel visit and 1 channel visit. In case of 3 channel fuelling job, 4 cases arise; 1) all separate 1 channel fuelling, 2) 2 channel combined fuelling followed by 1 channel fuelling, 3) 1 channel fuelling followed by 2 channel combined fuelling, and 4) all separate 1 channel fuelling with alternating channel flow direction. However in all cases, mixing of new fuel bundle and spent fuel bundle should be excluded.

Table 6 shows fuelling job time for cases presented in Table 5. For each fuelling job, a pre-operational 30 min. check up is included. After finishing the fuelling job, another 30 min. of check up is done before shutting down the system. A single channel fuelling job will consist of following sequences.

1) Get new fuel bundles by upstream F/M (35 min.).
2) Move both F/Ms to the designated channel and refuel on reactor(61 min).

Table 6. 4-bundle Shift Refuelling Time unit: min

Refuelling job scheme	At NFT	On Reactor	At SFP	Elapsed Time*
Single ch. [1(⇒)]	35	61	44	200
2 ch. combined [1(⇒ ⇒)]	41	112	53	266
2 ch. separate [1(⇒), 2(⇒)]	35	122	88	305
2 ch. separate [1(⇒), 2(⇒)]	70	122	88	340
3 ch. separate [1(⇒), 2(⇒), 3(⇒)]	35	183	132	410
3 ch. refuelling. [1(⇒ ⇒), 2(⇒)]	41	173	132	406
3 ch. refuelling [1(⇒), 2(⇒ ⇒)]	35	173	132	400
4 ch. refuelling [1(⇒), 2(⇒), 3(⇒), 4(⇒)], Max. time comb.	140	244	176	620
4 ch. [1(⇒ ⇒), 2(⇒⇒)], Min. time comb.	41	224	106	501
5 ch. refuelling [1(⇒), 2(⇒), 3(⇒), 4(⇒), 5(⇒)], Max. time comb.	175	305	220	760
5 ch. refuelling [1(⇒⇒), 2(⇒⇒), 3(⇒)], Min. time comb.	41	285	150	536
6 ch. refuelling [1(⇒), 2(⇒), 3(⇒), 4(⇒), 5(⇒), 6(⇒)], Max. time comb.	210	366	264	900
6 ch. refuelling [1(⇒⇒), 2(⇒⇒), 3(⇒⇒)], Min. time comb.	41	336	159	596

* Elapsed Time include pre-operation checkup (30min.) and post-operation checkup (30 min.).

3) Discharge spent fuel bundles by downstream machine (44 min.).

A 2 channel refuelling job where both channel flow directions are the same is as follows:

1) Receive new fuel bundles by upstream F/M (35 min.)
2) Move both F/Ms to the first designated channel and refuel on reactor (61 min.),
3) Discharge spent fuel bundles by downstream F/M at the same time receive new fuel bundles by upstream F/M (44 min),
4) Move both F/M back to the second designated fuel channel,
5) Refuel on reactor (61 min),
6) Discharge spent fuel by downstream F/M (44 min).

A 2 channel refuelling job where both channel flow directions are opposite will consists of following sequences.

1) Receive new fuel bundles by upstream F/M (35 min.)
2) Move both F/Ms to the first designated channel, refuel on reactor (61 min.)
3) Discharge spent fuel bundles by downstream F/M (44 min.)
4) Switch downstream F/M as upstream F/M, move upstream F/M to NFP, receive new fuel bundles by upstream F/M (35 min)
5) Move both F/M back to the second designated fuel channel, refuelling on reactor (61 min)
6) Discharge spent fuel bundles by downstream F/M (44 min)

The logic of above refuelling sequences are applied to other type of refuelling job as well, see

Table 5.

To carry out similar fuelling demand of current 8-bundle shift refuelling method, six channel refuelling operations are required on several days (Mon., Tue., Thu., Fri.), and on these days F/Ms have to operate for around 12 hours and 40 minutes. On Saturday, four channel refuelling operations are required which takes around 9 hours and 10 minutes. Therefore total refuelling operation time in a week is 59 hour 50minutes (3590 min.) based on tables 2 and 3. To get the most conservative result, refuelling operation by a single channel job only will requires 24 separate channel fuelling operations in a week and it will take around 80 hours. Hence total refuelling time will be in between these two figures. It is also noted that the refuelling time is on average, it doesn' t take into account the parameters such as FARE mode refuelling and channel locations.

Switching from 8- to 4-bundle shift refuelling scheme requires longer refuelling time as estimated above. In order to meet the current refuelling scheme, at least 6 channel refuelling operation is required on Mon., Tue., Thu., and Fri. The actual fuelling time will fall between the upper bound and the lower bound of fuelling time shown in Table 6.

The current operator management scheme with 2 team of operators can support up to 16 hours on weekdays and 8 hours on Saturday. Considering the current refuelling demand, a 6 channel 4-bundle shift refuelling job will take the maximum of 15 hours by treating each channel as a separate job. This refuelling time is based on Table 6 and assumes fuelling is carried out by auto-mode; therefore, the current manpower can cover for 4-bundle shift refuelling scheme. However, refuelling time can be reduced by appropriate combination of channels to refuel. For example, a 6 channel 4-bundle shift refuelling job will take the minimum of 10 hours by combining 2 channels for each reactor visit. Hence 2 team of operator can manage 4-bundle shift refuelling scheme.

4. Fuel Handling System Fatigue Life Re-evaluation

The 4-bundle shift refuelling scheme will double the F/H System operation cycle compare to 8-bundle shift refuelling scheme. Consequently, it increases the fatigue usage factor and reduces component replacement interval. Table 7 shows pressure boundary components of F/M Head fatigue usage factors. Note that the 4-bundle shift refuelling fatigue usage factor is calculated based on that of 8-bundle shift refuelling scheme [4]. Due to the increase of usage, Magazine Housing and Ram Housing are now included as replacement items. However, these are the major components of F/M Head, the cost of replacing them may be the same as replacing F/M Head itself. As a result, a refined fatigue analysis of affected F/M Head pressure boundary components are required to reduce fatigue usage factors by removing analysis margins included in the current fatigue analysis. If it is still desirable to replace F/M major components, an installation of new F/M Head shall be necessary.

Some of component that does not meet the life of F/M Head should be replaced as indicated in Table 7. Other components that are not listed in Table 7 such as F/M Carriage, F/M Bridge, F/M Ram Assembly and Catenary will require careful check up during regular overhaul period. As the usage of moving component increases, the function and performance of the parts will degrade.

When existing station changes its fuelling method from 8-bundle shift to 4-bundle shift, it will affect the fatigue life indicated in Table 7. In such a case, the fatigue life has to be assessed by the total refuelling cycles during the life time of plant.

Table 7. F/M Pressure Boundary Components Fatigue Usage Factors

Component		8-b. shift scheme		4-b. shift scheme	
		Fatigue Usage Factor	Repl. Int. (year)	Repl. Usage Factor	Fatigue Int. (year)
Snout Assembly	Center Support	0.99	N/A	1.98	15
	Center Support Seal Holder Ring	10.0	3	20.0	1.5
	Lock Ring	0.1	N/A	0.2	N/A
	Screw Gear	0.09	N/A	0.18	N/A
	Clamping Barrel	0.6	N/A	1.2	25
	Wedge Segment	0.3	N/A	0.6	N/A
	Center Support Bolt	0.6	N/A	1.2	25
Snout Emer. Lock Assembly	Emergency Lock-Cover	0.06	N/A	0.12	N/A
	Capscrews Holding the Emer. Lock-Cover	0.4	N/A	0.8	N/A
	Lock Assembly Mounting Capscrews	0.4	N/A	0.8	N/A
Magazine	Main Housing	0.9	N/A	1.8	17
	End Cover Flange	0.1	N/A	0.2	N/A
	Ram End	0.3	N/A	0.6	N/A
	Brackets	0.15	N/A	0.3	N/A
	Techlok Clamp	0.4	N/A	0.8	N/A
	Gearbox Housing	0.00	N/A	0.00	N/A
	End Cover	0.86	N/A	1.72	17
Separator Assembly	Clamp Stud	0.84	N/A	1.68	18
	Cylinder Block	0.06	N/A	0.12	N/A
	Cylinder Head	0.06	N/A	0.12	N/A
	Cap Screw	0.21	N/A	0.42	N/A
	Pistons	0.06	N/A	0.12	N/A
Gland Plate	Gland Plate	0.021	N/A	0.042	N/A
	Gland Plate Bolts	0.4	N/A	0.8	N/A
Coolant Connector	Flange & Hub	0.37	N/A	0.74	N/A
	Bolts	0.87	N/A	1.74	17
Ram Housing Assembly	Magazine Housing Extension	0.5	N/A	1.0	N/A
	Ram Housing	0.7	N/A	1.4	21
	Rear Forging	0.05	N/A	0.1	N/A
	10" Techlok Clamp	0.3	N/A	0.6	N/A
	10" Techlok Clamp Stud	0.2	N/A	0.4	N/A
Ball Screw Seal Assembly	Housing	0.5	N/A	1.0	N/A
	Assembly Bolts	0.7	N/A	1.4	21
	Retainer	0.7	N/A	1.4	21
	Seal Sleeve	2.3	13	4.6	6.5
	Retaining Nut	0.04	N/A	0.08	N/A
Gearbox, Main Shaft and Tape Dr.	Gearbox and Tape Drive	0.14	N/A	0.28	N/A
	Main Shaft	0.06	N/A	0.12	N/A
	Bolts	0.7	N/A	1.4	21
	Snout Assembly Cavity Outlet Fitting	0.34	N/A	0.68	N/A

5. Conclusions

Fuelling method change from the 8- to 4-bundle shift refuelling scheme increases the number of refuelling operations. With the 8-bundle shift refuelling scheme 14 channel refuelling a week is required on average, while with the 4-bundle shift refuelling scheme 28 channel refuelling a week is required. For the same fuelling demand, the fuelling time for 8-bundle shift scheme is around 470~550 (min.) and that for 4-bundle shift scheme is around 600~900 (min.). The analysis showed that the 4-bundle shift refuelling scheme is still within the range of current operator management limit. Note that the analysis assumed a full automatic and no interruption during refuelling operation.

The significant increase in refuelling activity causes hardware fatigue usage factor to increase by two-fold, and resulting in some of major components to be replaced within the plant lifetime. Consequently, a refined fatigue analysis or replacement of F/M components is recommended. This will be the main cost associated with 4-bundle shift refuelling scheme compared to 8-bundle shift refuelling scheme.

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