Fuel Handling Alternatives to Prepare for Large Scale Fuel Channel Replacement

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Abstract

It is desirable to reduce the duration of defuelling the reactor in preparation for retube, as the cost of replacement power is $750K/day. Three fast defuelling concepts are presented. With the Through Flow Defuelling method, the fuel string is hydraulically pushed into the downstream Fuelling Machine (FM) by flow passing through the fuel channel. The Long Stroke C Ram method replaces the FM C Ram with a longer one capable of pushing all fuel bundles into the receiving FM. Defuelling Hardware uses enhanced design of ram extensions that interconnect mechanically to extend the Ram stroke to push fuel bundles into the receiving FM. This paper will present descriptions of each defuelling concept to prepare for Large Scale Fuel Channel Replacement. Advantages and disadvantages of each concept will be discussed and a recommendation will be made for future implementation.

Introduction

Several CANDU 6 reactors are nearing the end of their operating life and are considering refurbishment projects to further extend the life of the station. Basic station refurbishment includes removal and replacement of fuel channels and feeder pipes as well as the replacement of many other components. In order to replace fuel channels or re-tube, the reactor core must first be defuelled, drained and dried. Substantial time and effort is required to defuel the reactor core with 380 fuel channels each containing 12 fuel bundles. In fact, the defuelling of the reactor is on the critical path and any reduction in the defuelling time will result in a reduction in the refurbishment outage.

1. Through Flow Defuelling (TFD)

During normal on power refuelling operations, fuel bundles are pushed out of the fuel channel and into the FM by coolant flow in the fuel channel as well as by the new fuel bundles that are added. During these operations the FM is maintained at a higher pressure than the fuel channel. This prevents the high temperature reactor coolant from entering the FM to maximize the life of FM components. During shutdown conditions the reactor coolant is at a much lower temperature. By allowing it to be directed through the FM the flow defuelling operation is enhanced. Through Flow Defuelling (TFD) uses one FM to defuel an entire fuel channel during one visit.

1.1 General Description

With the TFD method, the fuel string is pushed through the fuel channel by the Heat Transport System (HTS) flow passing through the FM. During TFD, the reactor is in a "modified" shutdown mode with the HTS maintained at 30-70°C and pressurized at 2-3 MPa with Shutdown Cooling System or HTS pumps running. Normally in shutdown mode the reactor is not pressurized and the HTS pump are not running. Pressure is required to push fluid through the FM and down a new TFD flow return line. The flow is created by opening newly added valves mounted on a modified downstream FM, creating a pressure differential between the HTS pressure and the return line. A flow of 18-50 kg/s is drawn from the HTS through the FM to induce flow through the fuel channels to drag the fuel bundles towards the FM and into the selected FM magazine rotor station. The FMs are temporarily modified with additional plumbing, valves, and catenaries. The flow is then routed back to the HTS via a modified Primary HTS D_2O Storage, Transfer, and Recovery Circuit.

1.2 Fuel Channel Conditions

The HTS must be pressurized and at low temperature. Pressure is required to create the fluid flow needed to push fuel bundles. A low temperature is required in the FM and catenaries to avoid component damage. The final operating condition must be in the acceptable delayed hydride-cracking region for the pressure tube. Conditions at approximately 2 Mpa and below 149°C (FM design temperature) are acceptable, and include a large factor of safety (allowable pressure tube pressures are based on time, temperature and postulated pressure tube flaw size).

To push the entire string, it is calculated that a flow rate of at least 18 kg/s past the string is required. To push the last bundle pair into the FM head, an increased flow rate is needed to give the bundles enough speed to fully move into the FM magazine. This flow rate is dependent on the amount of flow that is diverted at the entrance to the magazine station. To move the last bundle pair, it was calculated that the through flow would have to increase to about 35 kg/s (with 30% of the flow directed along the FM magazine rotor station).

1.3 Implementation of TFD

The TFD configuration is shown in Figure 1. The HTS is maintained partially pressurized by the nitrogen bubble in the pressurizer. Since the HTS pumps are running the Reactor Inlet Header (RIH) pressure is higher than the Reactor Outlet Header (ROH) by approximately 1.5 MPa. All four HTS pumps are run to circulate the coolant through the channels and the Shutdown Cooling System heat exchanger. The FM connects to the ROH side of the channel, i.e. outlet endfitting. The flow over the bundles drags the fuel string towards the FM. At the end of the movement, 6 fuel bundles will remain exposed to the coolant flow and 6 fuel bundles would have moved into the end fitting liner tube outside of the flow area. The separators on the FM will hold the fuel string in place until the magazine is ready to receive the fuel bundles (in pairs). Once the first 6 fuel bundles are removed, the last 6 fuel bundles move into the liner tube and endfitting area and are not subjected to HTS flow. To get these bundles into the FM, the HTS is bled through the FM, intermittently. This flow is referred to as the defuelling flow. The pressure control in the pressurizer will try to make up the bleed flow by transferring water from the Heat Transport D_2O Storage Tank to the HTS.

The defuelling flow is directed to the D_2O recovery tank. During the defuelling process, water accumulates in this tank and the tank level control automatically initiates the recovery pump to pump the water back to the Pressure & Inventory Control (P & IC) system. Since there is a lag in the recovery section, the HTS pressure may not require this flow to be returned to the pressurizer. Therefore this water will be returned back to the Heat Transport D_2O Storage Tank.

The instrumentation, and control functions required to achieve the process described above is already part of the P& IC system, and Primary HTS D_2O Storage, Transfer, and Recovery Circuit.

The D_2O Recovery Tank is continuously vented to the D_2O Vapour Recovery System, therefore, no additional piping is required for this purpose. The connection to the D_2O Recovery Tank from the FM vault sumps is an open connection and would need to be blocked.

1.4 Advantages and Disadvantages

The TFD method can potentially defuel an entire CANDU 6 reactor in the least amount of time in comparison with the other concepts presented in this paper. The current estimated defuelling time would be 21 days.

However, this method requires the highest degree of modification to the station systems, when compared to the other concepts. It is impossible to perform full scale testing of this method and it is difficult to predict, by analysis, the flow distribution in the reactor as the defuelling progresses. TFD also has the most disadvantages, as discussed below.

1.4.1 Debris or "crud" entering the FM

As HTS water enters the FM during TFD there may be a build-up of HTS crud in the FM. This may damage the bearings, seals of the FM and the FM may malfunction during TFD and/or the FM would require a major overhaul after TFD.

1.4.2 TFD flow exit from the FM

Previous TFD flow testing proved the principle that 2 bundles could be "pushed" into the FM using flow. In order to achieve this flow, 5 one inch tubing lines on the test FM were used to achieve the required channel flow of 22 kg/s. However during actual defuelling only 2 one inch lines are available for use on a CANDU 6 FM. Current calculations indicate that in addition to the channel flow, flow from the outlet feeder into the FM could be as high as 28 kg/s, resulting in a total flow into the FM of 50 kg/s. This flow could be impossible to achieve through the available 1 inch lines on the FM.

1.4.3 Pressure drop through the FM

In the tests mentioned above, a pressure drop of 0.8 Mpa was measured. With an actual flow of 50 kg/s and using only 2 one inch lines, the pressure drop during actual defuelling will be much greater. This pressure drop is critical to determine since the channel pressure during TFD has been set to an upper limit of 6 Mpa to avoid damage to the pressure tube.

1.4.4 Flow restrictors

During defuelling, as more channels become emptied of fuel, the flow characteristics through the channels will change since the resistance in the channels is decreasing. This may affect fuel cooling in the remaining channels with fuel. One way to reduce this impact is to place flow restrictors in the channels when they are emptied of fuel. Doing this will increase the cost of TFD (minor impact) and increase the amount of time required for TFD (major impact). Also this would increase the risk of TFD since the spare channel closure station in the FM magazine would need to carry a flow restrictor.

1.4.5 Shutdown cooling pumps versus Heat Transport pumps

The initial concept of TFD assumed that the Shutdown Cooling System (SDC) pumps would be used during TFD. But preliminary calculations indicate that the SDC pumps would not provide sufficient flow and now the HTS pumps will need to be used. This would increase the cost of TFD for the station.

1.4.6 Vibration

As the reactor becomes emptied, flow induced vibration becomes a concern since the HTS pumps will be operating. Analysis of the flow induced vibration of fuel bundles would need to consider the following:

- there is only large flow in the channel, when it is being defuelled;
- the duration is relatively short as compared to normal operating conditions;
- the control valve(s) are only open for each two bundle push;
- the FBs are only exposed to flow for short intermittent periods. This flow is similar, in magnitude, to normal operating conditions when removing FBs.

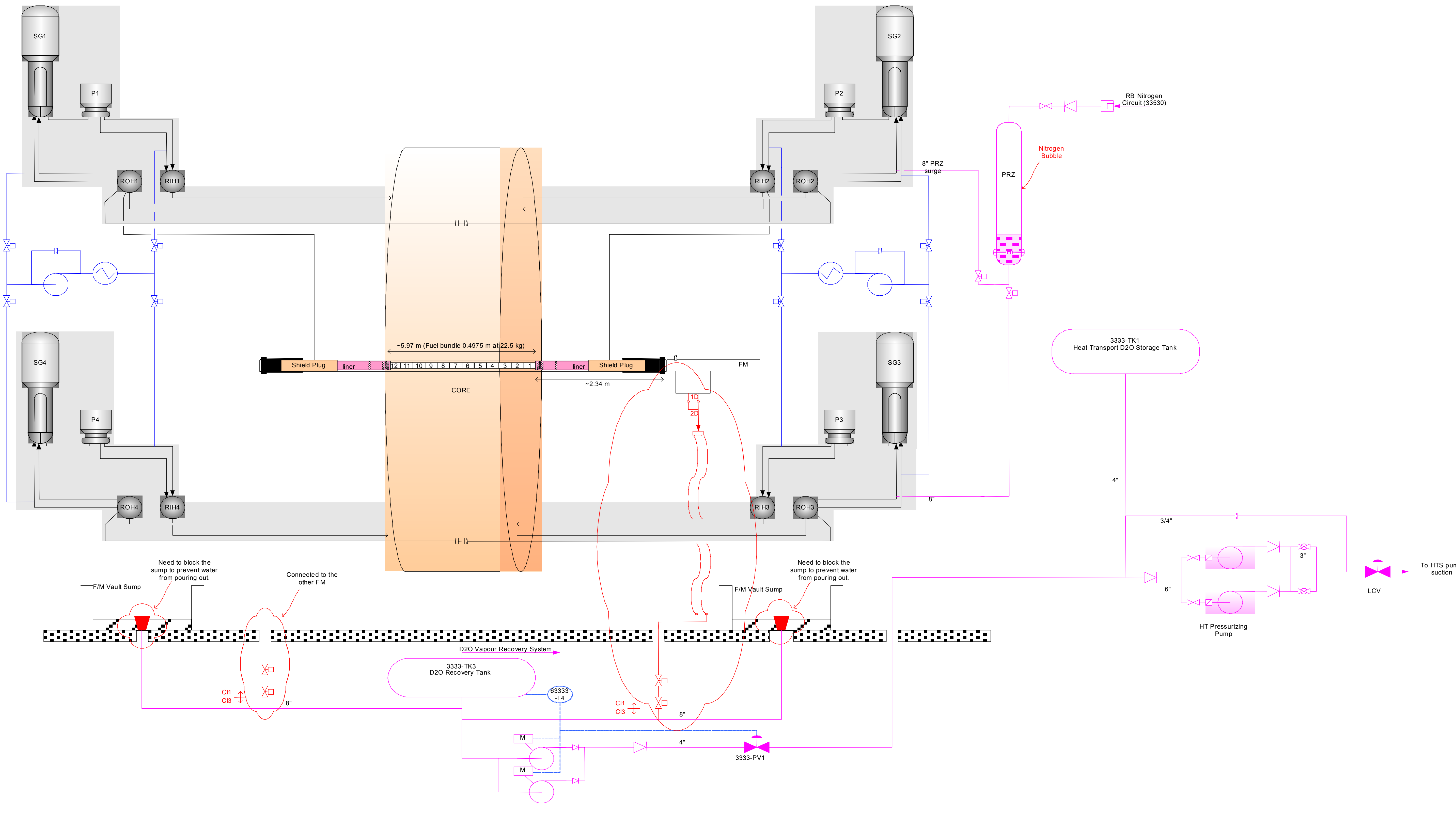

Figure 1: Through Flow Defuelling Proposed Arrangement

2. Long Stroke C Ram (LSCR)

For the LSCR method the actual Fuelling Machine (FM) C Ram is replaced with a much longer ram that is capable of reaching the other FM separators. The LSCR concept has 6 concentric stainless steel tubes with tubes No. 1 and 2 stationary and the other four tubes mobile. The LSCR is advanced hydraulically by D_2O pressure and is retracted using a hydraulic or electric motor via a cable system designed to retract the LSCR to the home position.

2.1 LSCR Mechanical Design

3D CADD models for the LSCR and for a sagged fuel channel were developed to aid in the mechanical design.

LSCR tubes 1 and 2 are the same as the current C ram design. The advantage to this approach is that the supports for mounting in the ram rear forging for 1 and 2 tubes do not need to be modified. LSCR 3 tube has the same inside and outside diameters as the existing C ram 3 tube in order for it to be installed into the existing flanged sleeve and bearing ring in the latch ram trunnion mounting.

The LSCR design must conform to space restrictions in the FM ram. The LSCR C tube wall thickness has been reduced, in comparison to the existing C ram, to accommodate LSCR 4 and 5 tubes. When retracted, all the LSCR components are contained within the space of the existing C ram.

Initially to develop the maximum stroke of the LSCR, the B ram is fully advanced. This also advances the latch ram and LSCR 3, 4, 5 and C tube. Fixed tube 3, moves with the B and latch rams. The LSCR C tube then advances under hydraulic pressure. The advancing C ram tube pulls LSCR 5 and 4 tubes. The resulting total stroke is 520".

The main challenge to the design of the LSCR is the following conflicting requirements:

1. The LSCR must conform to the existing space restrictions in the FM ram.
2. The LSCR must be structurally robust enough to advance and retract inside a sagged fuel channel without any mechanical deformation.

As discussed in section 2.3, current calculations indicate that the initial conceptual design of the LSCR will not meet the second requirement. The next iteration of the LSCR design will consider the use of a more flexible tube joint. Design iterations will continue until stress and force calculations indicate that the LSCR meets requirement 2 above. The next step would be to perform extensive testing to demonstrate that the LSCR can be advanced and retracted on a continuing basis in a sagged channel.

2.2 LSCR Material

The 2 types of materials that were assessed for the construction of the LSCR tubes are:

a) Stainless steels such as 17-4 PH, or Type 410 or Type 302, and

b) Carbon fibre reinforced epoxy composites.

It was determined that the use of carbon fibre composite has the capabilities of being successful, however a high degree of testing is required. It is recommended that the design of the LSCR be based on stainless steel materials as per the current C ram.

2.3 LSCR Stress and Force Calculations

The stress and force requirement calculations, for the LSCR, were performed using rigid-body and solid mechanics based analysis. The principals of axial deformation, uniform elastic bending, thin walled pressure vessels and buckling of columns were all used in determining the principal stresses. Static based calculations were also used in determining the force requirements to drive the LSCR design.

Adding to the complexity of the analysis is the non-linear type of behaviour during retract, and the possibility of pivoting and binding about the tube joints. The C ram assembly consists of multiple tubes that are connected by pistons and stops. A cable retract mechanism will be used to pull the C ram tubes back to the home position. Because the C ram tubes will be bent to conform to the pressure tube geometry, the retract force created by the retract cable mechanism will be offset creating an additional moment about the C ram joints. When combined with the pivoting effect of the tubes it can cause a binding effect, both due to increased friction forces and material deformation. The possibility of pivoting and binding at the tube joints has not been examined, and is dependent on the behaviour of the tubes during cable retracting.

In order to fully assess the behavior of the LSCR during extension and retract within the confinement of the pressure tubes, a non-linear analysis would have to be performed using finite element analysis. This analysis is expected to provide more realistic and more accurate results and will minimize the number of assumptions being made.

2.4 LSCR Retract Drive

The retract cable drive unit will replace the existing C ram tape drive. The drive housing will be designed to mount onto the ram gearbox rear cover. The drive housing and cover are pressure boundary components. The drive housing will contain the cable winding drum and D_2O at LSCR operating pressure. Connected to the winding drum shaft will be an extension shaft that will pass through the pressure boundary via a seal in the drive housing cover. Coupled to the extension shaft will be the gear reducer, drive motor and position monitoring equipment. The drive system could be either electric or hydraulic. Ideally, the drive will be of similar size and weight as the existing C ram tape drive.

2.5 Advantages and Disadvantages

The LSCR method is also advantageous in defuelling in the least amount of time. The current estimated defuelling time would be 36 days.

When compared with TFD, this method requires a lesser degree of modification to the station systems, therefore would be less costly to implement.

The main disadvantage is that because the LSCR has to fit into the space restrictions inside the FM ram, it's structural robustness is reduced during advancement and retraction inside a sagged fuel channel.

3. Defuelling Hardware Method

The defuelling hardware consists of the Fuel Grapple System (FGS) that is designed to enable the fuel channels to be defuelled from either end using one or both fuelling machines (FM). In the case where one FM is disabled the remaining FM will perform the defuelling process with the FGS. When both FMs are operational one of the FMs will operate the FGS while the other will receive the fuel.

The FGS components are manufactured from corrosion resistant materials. These components, which are used in the reactor fuel channel, latch and unlatch from one another by positive mechanical means. Should the components become jammed in the reactor fuel channel, the FGS is designed so that the FM ram head will "break away" from the components without imposing unacceptable loads on the reactor fuel channel and the components themselves. This feature is meant to prevent both FMs from becoming disabled simultaneously on a reactor fuel channel.

The functional requirements associated with the FGS are to be designed to completely defuel any reactor fuel channel using one FM to pull fuel bundles or two fuelling machines working together. They can completely defuel any reactor fuel channel working from the upstream or downstream end with the reactor shutdown.

In the case where one FM is disabled, the remaining FM will defuel the channel by grappling and pulling the fuel bundles from the channel. The components are designed to allow intentional release of the fuel grapple from the fuel bundle by using the FM ram and fuel separator motions.

The FGS allows the fuel grapple assembly to be deposited and stored in a fuelling machine magazine fuel tube with or without a fuel bundle. The fuel grapple extensions, fuel adaptor extension and the ram grapple adaptor are designed to allow each item to be deposited and stored in the FM magazine.

3.1 Fuel Grapple System

The FGS is comprised of extensions and grapples that have the ability to interconnect via mechanical latches. The latches are operated by the FM rams via a ram-grapple adaptor.

The FGS includes the following components:

- Ram grapple adaptor
- Fuel grapple extensions (FGE)
- Fuel adaptor extension (FAE)

3.1.1 Ram Grapple Adaptor

The ram-grapple adaptor is a tool which allows the rams of the FM to operate the latches on the extensions while pulling these components out of the channel. It also provides a means of support for the C ram when it is extended beyond B-ram. It can be stored in magazine station J in place of the normal ram adaptor. The ram-grapple adaptor is designed to be held onto by either B or Cram.

3.1.2 Fuel Grapple Extension

Grapple extensions are used to grapple bundles which are beyond the reach of the rams. At one end of the extension is a set of rocker arms which will lock on contact with either another extension or grapple. At the other end of the extension are two grooves, one internal and one external. The internal groove accommodates the latches of an adjacent extension or the ram-grapple adaptor. The outer groove is used by the separators to hold onto the extension during unlatching operations. Unlatching is accomplished by deflecting the inner extension sleeve by latch ram via the ram-grapple adaptor. This in turn releases the rocker arms.

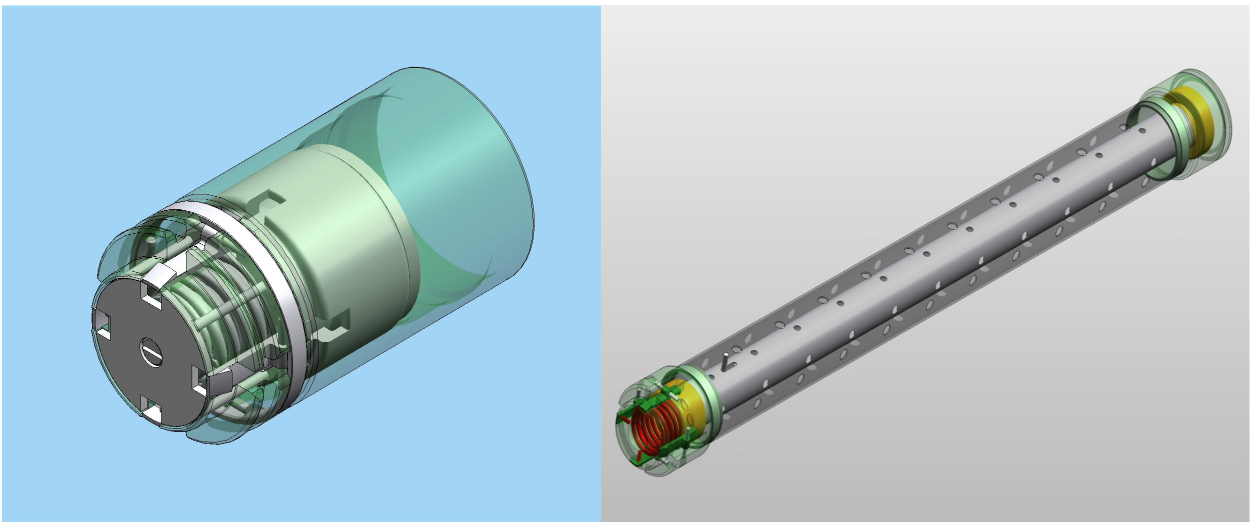

Figure 2: Ram Grapple Adaptor and Fuel Grapple Extension

3.1.3 Fuel Adaptor Extension

Fuel adaptor extension (FAE) is used to push bundles through the fuel channel. At one end of the extension is a flat plate that has holes and a configuration that makes it similar to the front of the ram adaptor. At the other end of the extension are two grooves, one internal and one external. The internal groove accommodates the latches belonging to an adjacent extension or to the ram-grapple adaptor. The outer groove is used by the separators to hold onto the extension during unlatching operations.

3.2 Operations on Reactor (Defuelling Using Both FMs)

To defuel a channel the required sequence of FM operations will vary depending on conditions. Two FM's are required where one handles the FGS components and the other FM will receive the fuel bundles. A normal sequence of operations is listed below:

a) FMs clamp onto the end fittings; remove snout plugs, channel closures, install guide sleeve and remove the shield plugs.

b) Pick up ram grapple adaptor.

c) Index to the FAE station.

d) Push the FAE until the magazine is clear to rotate.

e) Unlatch and retract the ram grapple adaptor.

f) Use feelers to test to make sure the FAE has remained in the channel.

g) Index the magazine to one of the FGE stations.

h) Advance the ram until the magazine is clear to rotate.

i) Use feelers to test to make sure the FGE has remained in the channel.

j) Keep adding FGEs until the required number are present.

k) Advance FAE and FGE grapple to push fuel bundles into the receiving machine.

l) Retract and unlock separate components and store in magazine.

3.3 Design Improvements

For Point Lepreau, improvements have been made to the original design to improve the robustness and functionality of the defuelling hardware. These preliminary concepts and ideas will be reviewed closely during the detail design stage of the project. The component materials were briefly reviewed at this stage and will be fully addressed during the design stage.

The improvements are:

1. Interaction between the various components has been improved by adjusting the tolerances on the dimension of the components.
2. Interaction between the Rocker Arm and the Pivot Pin has been improved by adding a bushing to reduce Pivot Pin wear.
3. Interaction between the Grapple Extension and the Rod – new concept to improve disassembly and assembly of components.
4. Reset Spring – add a spacer for preload.
5. Spring – use a revised spring.
6. Interaction between the Outer Extension Sleeve and the Inner Extension Sleeve – change the profile of the running surface.
7. Interaction between the Outer Extension Sleeve and the Rod – new concept to improve disassembly and assembly of components.
8. Material Coatings/ Material Changes – using new material and material coatings.
9. FM B Ram Head and the Grapple Adaptors Body – improve interface between FM B Ram head and grapple adaptor body.

3.4 Advantages and Disadvantages

The advantage of this method is that it is a proven design that was used at Pickering in 1985 to defuel the entire reactor core. According to Pickering's report the defuelling was done in 65 days. This proves that the method works with some maintenance and inspection limitations. With the improvements proposed, it is expected that the defuelling time will be reduced and also the interval for inspection of the FGS tools will be longer resulting in less radiation exposure to the maintenance personnel. The other advantage is that it is the least costly method to implement.

The main disadvantage is that this method requires the most time to defuel a reactor.

4. Conclusions

The TFD method has a large number of technical challenges and has the highest risk, however also has the highest potential benefit in overall speed of defuelling. This method is the most costly to implement and will not be used on current operating CANDU reactors. This method holds promise when it is included in the design of new CANDU reactors.

The LSCR method has best balance of reducing defuelling time and cost of implementation and is the method that holds the most promise for the defuelling of current operating CANDU reactors. However this method is in the early conceptual stage and cannot be used for the Point Lepreau refurbishment.

New Brunswick Power has selected to use the defuelling hardware method for Large Scale Fuel Channel Replacement at Point Lepreau. This proven method has the least implementation risk of all the concepts presented in this paper. In addition, with the design modifications that AECL has made, there is an improvement in the robustness and functionality of the defuelling hardware.