A NEW FUEL CHANNEL FOR BRUCE NGS 'A'

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ABSTRACT

This paper describes the design and development of a new Bruce A fuel channel, designed for the Large Scale Fuel Channel Replacement (LSFCR) Program. Fuel channels to this design will be installed in Unit 1 in 1995/96, replacing the original ones installed in the early seventies. The design is suitable for use on Units 2 and 3 as well.

The original fuel channels were not capable of achieving their design life because the effects of radiation on zirconium alloys were imperfectly understood at the time they were designed. The reason for the redesign is to produce a fuel channel that will survive the remaining life of the station, and to eliminate as many of the channel related design problems as practical. In addition, a design that is easy and quick to install is wanted, to reduce radiation exposure to personnel and the duration of the outage.

To achieve these goals, a dedicated design team comprising both fuel channel designers and installation tooling designers was assembled. The fuel channel described in this paper is one of the products of this team.

1. INTRODUCTION

The new Bruce A fuel channels are typical of CANDU reactor fuel channels. Stainless steel end fittings (E/F) are attached to both ends of zirconium alloy pressure tubes (P/T) that pass horizontally through the reactor core. Fuel is installed in the pressure tubes, and heavy water coolant is passed through the fuel channels to remove heat from the fuel. The fuel channels form part of the Primary Heat Transport System (PHTS).

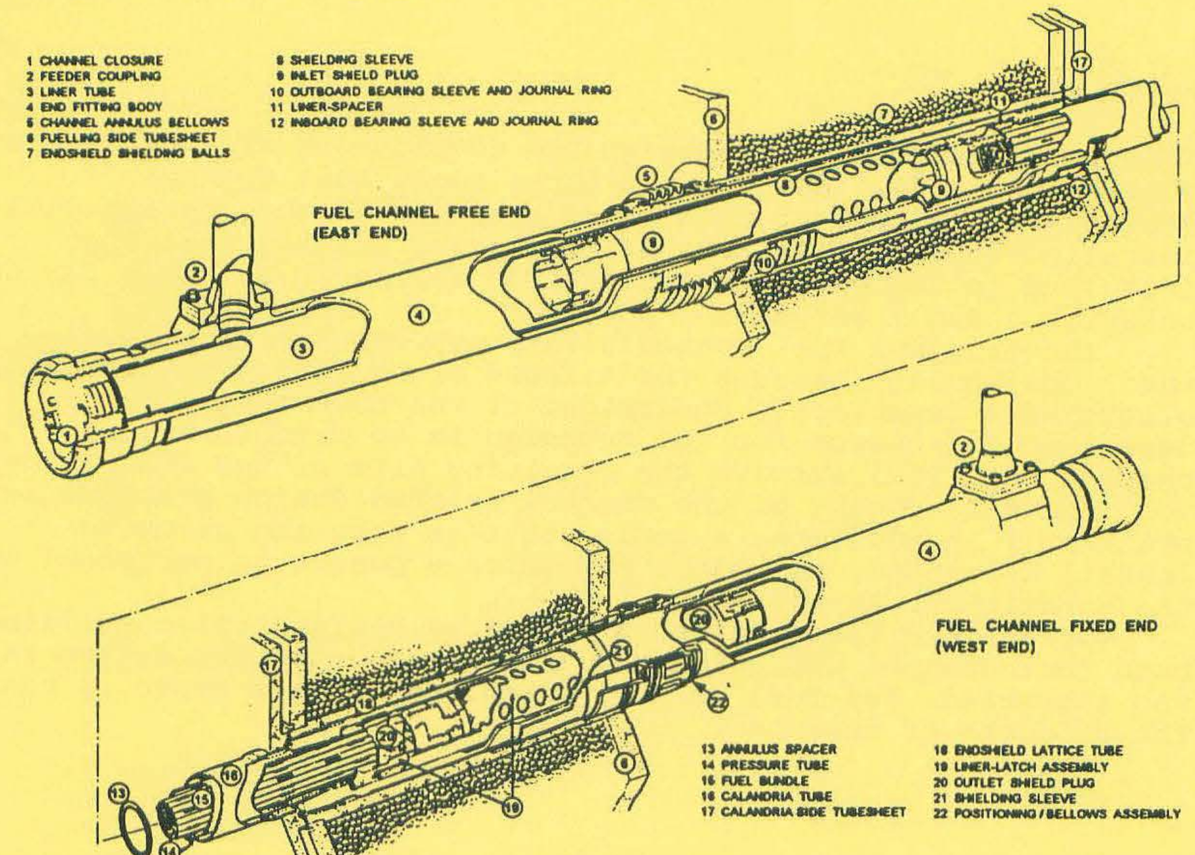

FIGURE 1
THE NEW BRUCE A FUEL CHANNEL

A liner tube is installed in each end fitting, to guide the coolant flow past the shield plug. The liner tube installed in outlet end fittings has a fuel latch attached to its inboard end. The latch holds the fuel in place in the reactor core, resisting the hydraulic force of the coolant flow.

Coolant flows through adjacent fuel channels in opposite directions and consequently end fittings are alternately inlets and outlets. An inlet end fitting has a liner-spacer assembly and an inlet shield plug installed, and an outlet end fitting has a liner-latch assembly and an outlet shield plug. A channel closure is located in the outboard end of each end fitting. The closures and the shield plugs are removed and reinstalled by the fuelling machine during fuel changing operations.

All fuel channels are attached rigidly to the calandria vessel at their west ends with a positioning assembly. At the east end, bellows assemblies allow axial motion of the east end fittings due to thermal expansion of pressure tubes and end fittings, and to radiation induced creep and growth of the pressure tubes. Midway through the reactor life, the positioning assemblies will be unlocked, the fuel channels shifted towards the west to return the east end fittings to their start-of-life positions, and the positioning assemblies relocked.

Feeder pipes are bolted to both inlet and outlet end fittings. A "Grayloc" type seal ring provides a seal between the end fitting body and the feeder hub, which is welded to the feeder pipe. The feeders run across the reactor face between the end fittings, and then to the PHTS headers mounted close to the ceiling of the reactor vault. Coolant flows from an inlet header, through an inlet feeder, into and through the inlet end fitting, through the pressure tube and through the fuel, through the outlet end fitting and outlet feeder to the outlet header.

Four annulus spacers are installed on each pressure tube, to prevent the pressure tube from touching the calandria tube. Thirteen fuel bundles are installed in the fuel channel. Half of each of the two end bundles extend out of the core.

Although this fuel channel is similar to the ones being removed, there are significant differences that are meant to allow the new channel to meet its design requirements. These changes are described in the sections below.

2. PRESSURE TUBE

The pressure tube, except for its slightly thicker end, is a standard zirconium-niobium pressure tube, identical to those used on other CANDU reactors. The initial hydrogen concentration in the finished pressure tube is reduced to as low a level as practical, with the target being 5 ppm maximum.

The pressure tubes are manufactured with one end thicker than the remainder of the tube. The thick end is about 150 mm long, and about 90 mm of this is trimmed off before it is used, leaving the thick portion only in the rolled joint area. The greater wall thickness (about 0.6 mm) is reflected in a smaller inside diameter (before rolling). The outside diameter along the tube is constant.

The thick ended tube makes possible a "flush rolled joint" with the inlet end fitting (See Section 4, below), that reduces the probability of fuel bearing pads fretting on the pressure tube due to abnormal fuel support.

The outside diameter of the pressure tubes, at both ends, will be accurately machined to suit either a zero clearance or a low clearance rolled joint. This is a change from previous practice, where the rolled joint bores in the end fittings were machined to suit measured P/T diameters. On this fuel channel, a single bore diameter will be machined in all end fittings, and the different clearances required provided by the pressure tubes.

This creates a need for two types of pressure tube - one type with a zero clearance rolled joint diameter at the thick walled end, and a low clearance rolled joint diameter at the thin walled end; the other type the reverse.

3. END FITTINGS

End fitting bodies are machined from single piece forgings of type 403 stainless steel, like other AECL designed end fittings.

The outboard end of the end fitting is shaped to accomodate the fuelling machine, which has to latch onto the end fitting, seal to it, remove and reinstall channel closures and shield plugs, and to change fuel.

Inside the end fitting body at the outboard end are the lugs and sealing surface for the channel closure (Section 12). A liner tube assembly (Section 11) is installed into the E/F body, extending from the closure region to the rolled joint.

The feeders are bolted to the side of the E/F body, 16 inches from the outboard end. The E/F feeder sideport is a flat face having four tapped holes for the feeder coupling capscrews, and a flow hole that accepts a "Grayloc" type seal ring.

At the inboard end of the E/F is the rolled joint hub. The hub is a thickened part of the E/F body into which the pressure tube is roll expanded (See section 4).

A carbon steel bellows attachment ring is attached to the outer surface of the E/F body by a heat shrink joint. On the east, the bellows assembly is welded to this ring. On the west, the weld is to the new positioning bellows assembly.

Journal rings (bearings) and shielding sleeves (See sections 7 and 9) are attached to the outside of the E/F body.

Significant changes from the original Bruce A end fittings are:

a) The end fitting was modified to accomodate the new (west end) positioning bellows assembly, but without making it unsuitable for use at the east end where the original bellows is left in place. See sections 5 and 6 below. A small shoulder is provided on the inboard side of the bellows attachment ring (BAR), to increase the resistance of the shrink fit joint to an outwards axial force on the end fitting.

b) The bellows attachment rings have (blind) axial holes through them to allow connection of auxiliary annulus gas system tubing lines. The blind hole has to be drilled about 6 mm deeper to connect to the groove and allow a gas passage.

c) The geometry and dimensioning in the rolled joint region was copied from the Bruce B end fitting design, to provide the necessary accuracy to locate the rolled joint burnish mark between the first groove and the start of taper.

d) Three keyways are provided for liner tube attachment at different rotational positions. This allows a reduction in the number of different end fitting bodies from seven to three.

e) The east and west end fitting bodies are identical. Inlet and outlet end fitting bodies are identical. Three different body designs are still necessary to allow seven feeder port orientations while always holding the closure locking lugs in the same position. Only one rolled joint bore diameter is used.

f) The position of the inboard journal has been moved as close to the calandria side tubesheet as possible, in order to maximize the bearing travel. The position of the feeder port and the E face have been left in the original "start-of-life position, in order to minimize effects on feeders and the fuel handling system. This results in an end fitting body about 40 mm longer than the original ones.

g) Two or three index holes are provided near the outboard end of the end fitting to locate an inclinometer during channel installation, to allow convenient and accurate setting of end fitting rotational position.

h) Some internal E/F diameters have been modified, and an area of chrome plating added, to prevent galling between liner and end fitting body during liner removal and installation.

4. P/T-E/F ROLLED JOINTS

Rolled joints attach the stainless steel end fittings to the zirconium alloy pressure tube. These joints are made by expanding the pressure tube plastically in the hub of the end fitting using a rolled joint expander tool.

The rolled joint on the original fuel channel was designed before knowledge of delayed hydride cracking (DHC) of pressure tubes existed. These joints are "large clearance" joints, with roller extension beyond the parallel region of the end fitting rolled joint bore, and they are characterized by high residual stresses in what became known as "the DHC zone". At Bruce A, to reduce these residual stresses, the pressure tube in the DHC zone (just inboard of the rolled joint) was stress relieved after rolling.

The rolled joints in the replacement channel follow current practice, to keep the residual stresses in the DHC zone of the pressure tube as low as practical. The subassembly joint (west) is a zero clearance rolled joint, made by heating the end fitting before inserting the pressure tube into it. The reactor joint (east) is a low clearance rolled joint, with dimensions controlled to keep residual stresses below the limits specified in CSA N285.2-M89. The end fitting dimensions in the rolled joint region is based on the Bruce B design, in order to provide sufficient space between the first rolled joint groove and the end of the parallel bore for roller positioning, so the end of the rolled region never extends past the end of the parallel bore of the end fitting.

This fuel channel introduces the "flush rolled joint" at the inlet end of the fuel channel, made using a thick ended pressure tube (See Section 2). The additional pressure tube wall thickness is equal to the combined amount of the radial clearance (between P/T and E/F) and the wall reduction that occurs during rolling. The purpose of this is to produce a rolled joint region that has the same inside diameter as the rest of the pressure tube. This eliminates abnormal fuel support, which occurs when axial elongation of the pressure tube causes the end of the inlet fuel bundle to move (relative to the inlet end fitting) off its support on the liner-spacer, into the rolled joint cavity, where the end bearing pad is unsupported. In this situation, flow induced vibration of the fuel bundle can fret the pressure tube.

Development of the flush rolled joint was done at AECL's Chalk River Laboratory, and is the subject of another paper at this conference.

Another change, involving both the end fitting bodies and the liner tubes, makes it possible (for the first time on a Bruce type fuel channel) to make a rolled joint with the liner tube in place. This was done to allow liner tube installation away from the reactor face, to reduce radiation exposure to personnel.

5. POSITIONING BELLOWS ASSEMBLY

At the time the original Bruce A fuel channel was designed, the prediction of the axial elongation of the pressure tube due to radiation induced creep and growth was 18 mm. The fuel channel was designed to accomodate this at the east end, and the west end fitting bellows attachment ring (BAR) was welded to a rigid sleeve. The east end fitting bearings accomodate about 38 mm motion, and this was used up after only 10 years operation. It was then necessary to cut the welds, shift the channels towards the west (to return the east end fittings to their start-of-life positions), and then reweld the end fitting BARs to the sleeves. This was a time consuming and expensive operation.

The replacement fuel channel has a new design bellows assembly at its west end to allow axial repositioning of the fuel channel without the need to cut welds. A positioning assembly provides the axial restraint to hold the channel in place. It will be possible to unlock the positioning assembly to shift the position of the fuel channel, to keep the east end fitting bearings within their engagement allowance. A standard positioning assembly using a stud screwed into the calandria endshield tubesheet was not practical because there is no suitable tapped hole in the tubesheet. The positioning assembly being used is welded to the cut-off stub of the stop attachment collar. During channel removal, the stopcollar will be cut off about 44 mm outboard of the face of the fuelling side tubesheet. This will leave the annulus gas system tubing untouched.

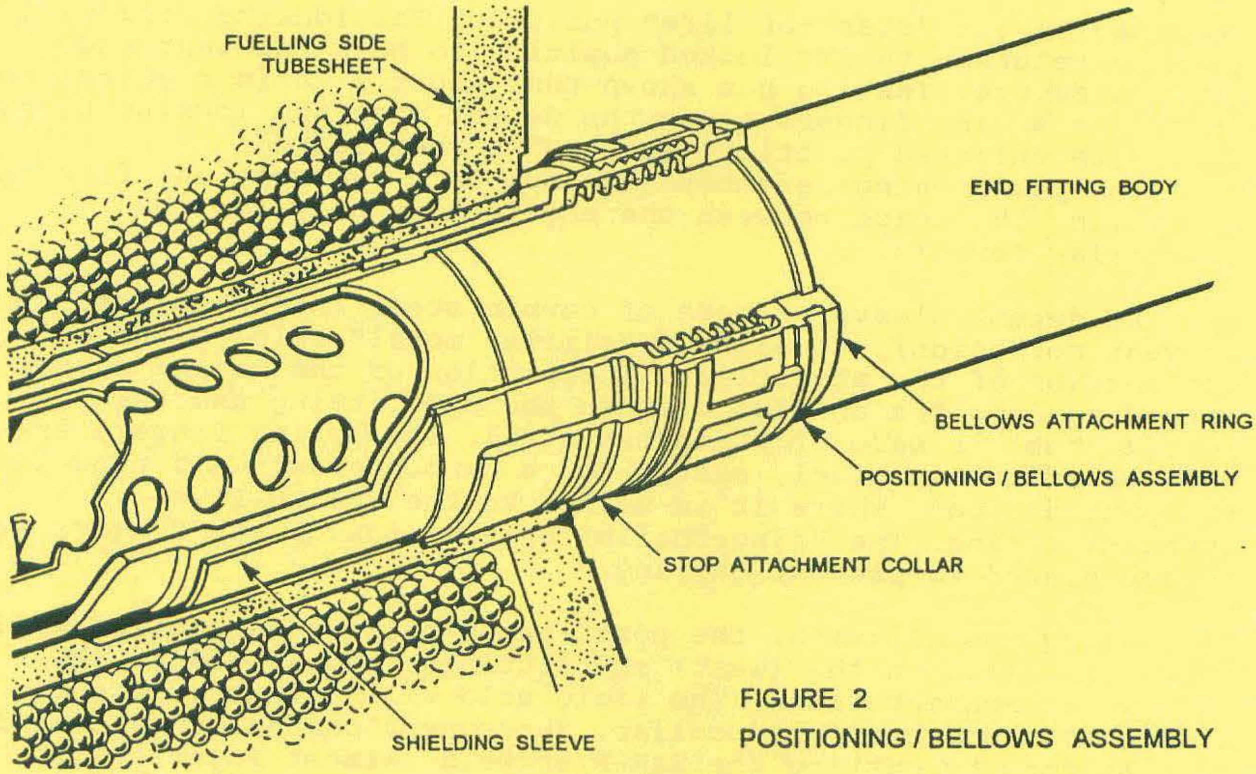

FIGURE 2
POSITIONING / BELLOWS ASSEMBLY

The new positioning/bellows assembly is a spring finger detent positioning assembly integrated with the bellows. The assembly will be welded to the end fitting bellows attachment ring before channel installation.

If the fuel channel is subsequently replaced, the positioning bellows assembly will be left in place when the end fitting is removed.

a) The bellows is a three ply Inconel 600 bellows, similar to the conventional channel annulus bellows. It has diameters and a convolution height to fit in the space between the end fitting body and the detent sleeve. This makes it smaller than the conventional bellows. Instead of being welded to ferrules at its ends, it is welded to parts of the positioning assembly.

b) The positioning assembly is a spring finger detent with a movable locking sleeve. The detent sleeve is welded to the cut off stub of the old stop attachment collar, and to the inboard end of the bellows. The spring fingers are part of a ring that is welded to the bellows attachment ring on the end fitting. The fingers engage in a series of grooves in the detent. When the locking sleeve is in its "locked" position (as it will be except when a channel shift operation is happening), it prevents the fingers from disengaging themselves from the groove in the detent, and no end fitting movement will occur.

After half the design life (13 years), the locking sleeve will be moved so it doesn't restrict flexing of the fingers, the fuel channel will be shifted so that the east end fitting is returned to its "start-of-life" position. The locking ring will then be returned to its locked position to hold the west end fitting secure. Testing has shown that about 2 kN is required to shift the spring fingers along the detent when the locking sleeve is in its unlocked position, and 180 kN when locked.

The positioning assembly also supports the west end fitting, by filling the space between the end fitting body and the stopcollar ferrule.

c) The detent sleeve is made of carbon steel (nickel plated to prevent corrosion), to allow a "similar metal" weld to the cut off portion of the stopcollar. The portion of the detent sleeve extending into the annulus between the end fitting and the lattice tube is made of stainless steel. The spring fingers are made of stainless steel, except for a carbon steel weld ring at the outboard end, where it is welded to the E/F bellows attachment ring. The "fingernails" on the ends of the fingers are chrome plated to prevent galling.

d) During installation, the positioning/bellows assemblies will be preinstalled on the (west) end fittings, and welded to the bellows attachment rings. The field weld will join the detent sleeve to the cut off stopcollar. Subsequent channel replacement will be done by cutting the BAR-P/BA weld (almost identical to the BAR-bellows weld on the east) during removal, and rewelding the replacement component in the same location.

6. EAST BELLOWS

As noted above, the original channel design had a bellows at the east end only. Since these bellows have not deteriorated in service, they will not be replaced in the LSFCR outage, except as a contingency operation if they are damaged.

The east bellows has 15 convolutions of 3 ply (each 0.33 mm thick) Inconel 600. A ferrule, made of type 304L stainless steel, is roll expanded into the endshield lattice tube. On the outboard end, a carbon steel flange sleeve is welded to the end fitting bellows attachment ring during fuel channel installation.

7. E/F BEARINGS

The E/F bearings support the end fittings in the calandria endshield lattice tube. Each bearing set consists of a bearing sleeve (in the lattice tube) and a journal ring (on the end fitting). The bearing sleeves (two on the east end and only one on the west) will not be replaced in the LSFCR outage. They will, however, be brush cleaned to remove any loose corrosion. New design journal rings will be installed with the new end fittings.

The inboard journal ring on the end fitting body overhangs the end of the end fitting body, in a manner similar to those on the Pickering retube channels, to increase the bearing travel. As on Pickering, it is retained by a ring of stainless steel balls that fit in two matching semicircular grooves in the end fitting and journal.

The outboard journal ring on the east end fitting is held in position by the shielding sleeve, which in turn is retained by a snap ring. Two ridges on the outer surface of the journal will contact the bearing sleeve, one ridge at a time. Both journal rings will be made from type D2 tool steel, the standard material for CANDU reactor end fitting journal rings.

At the west end, end fitting support is provided by an inboard extension of the positioning assembly. This will fill the annular space between the end fitting body and the stop attachment collar ferrule. Since the only movement this component will see will be during the mid-life channel repositioning, it does not have to be a hard, wear resistant material, and type 304 stainless steel was selected. Axial grooves on the outside of this extension provide flow passages for gas flow to the Annulus Gas System tubing.

8. ANNULUS SPACERS

Four annulus spacers separate the pressure tube from the calandria tube, preventing direct contact between the two. A garter spring design is used because these roll when the pressure tube moves relative to the calandria tube, and there is no sliding motion that might scratch the pressure or calandria tubes.

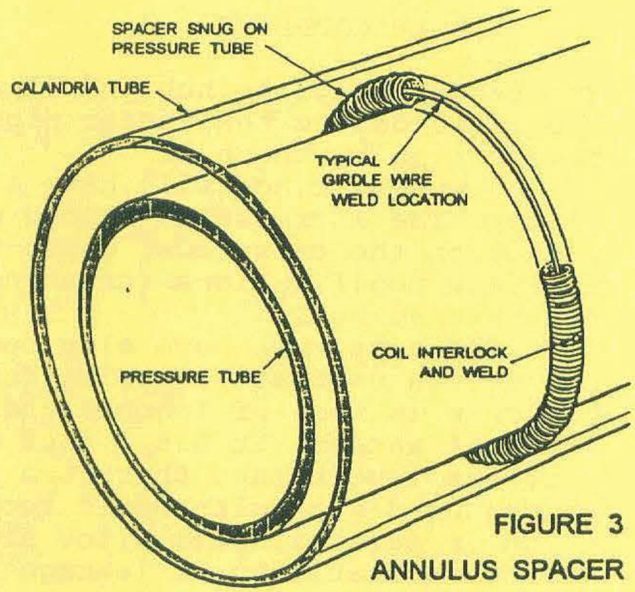

FIGURE 3
ANNULUS SPACER

The annulus spacers (commonly called "garter springs"), are a new design. The original Bruce A spacers were made of zirconium alloys, and are loose on the pressure tube. This looseness enabled them to move out of position before the weight of the fuel caused the pressure tube to sag enough to pinch them in place.

The new spacers currently being developed are made of Inconel X-750, are tight to the pressure tube and have a welded Zircaloy girdle wire. The Inconel coil is also joined to itself with a weld.

Spacers of the current (Darlington, Pickering LSFCR) design are tight to the pressure tube, but have an overlapping girdle wire which does not provide a dependable electrical connection with itself, making eddy current detection unreliable. The welded girdle wire of the new design retains its detectability by eddy current methods permanently. The welded coil design was adopted to improve the installability of the garter spring using a new installation tool.

Four spacers are installed, centered in the reactor core, about 1 m apart.

9. SHIELDING SLEEVES

The shielding sleeves fill the gas filled annular space between the end fittings and the endshield lattice tube and absorb radiation streaming through the gap.

The shielding sleeve on the east end fitting is used to retain the outboard journal ring, and is itself held in position by a snap ring. On the west, the shielding sleeve is attached to the end of the positioning assembly, and will stay in the lattice tube if the end fitting is subsequently removed. The west shielding sleeve covers the snap ring groove in the end fitting body (provided to retain the east shielding sleeve) so that a snap ring is not inadvertantly put in it. Both shielding sleeves are made of stainless steel.

10. FEEDER COUPLING

The feeder coupling hub and flange are not being replaced - the hub is welded to the feeder pipe and the flange is trapped on the feeder pipe by the hub.

New seal rings will have a larger diameter and thicker flange. The increase in flange diameter reduces the opening moment on the capscrews, while the flange thickness is increased to allow modifications (creating "specials") to accomodate refurbished hubs.

The capscrews have also been redesigned, based closely on the design used at Pickering for the P3/P4 retube. The new capscrew is made of Inconel and has a hexagonal head with an integral washer. It has a flat smooth surface on both ends, so that its length (and therefore its axial strain and stress) can be measured with ultrasonic techniques. No locking is used. The stronger material will allow higher torque at assembly, and a reduced probability of leakage later in life.

11. LINER TUBES

The liner tubes have been redesigned by G.E. Canada to allow installation in different rotational positions, in order to reduce the number of different end fitting bodies. This has been done by adding extra keyways in the end fitting body. This is similar to the method used for replacement end fittings provided for Bruce A. Restraint in the axial direction will be provided by a lock wire. The latch is a one piece design, similar to the Bruce B latch, rather than the original Bruce A two piece design. Recent replacement end fittings supplied to Bruce A have also featured liner tubes with one piece latches.

The inboard end of the latch was enlarged and lengthened to allow the rolled joint to be made with the liner-latch assembly installed. This modification does not affect the support of the end fuel bundle nor the passage of fuel through the region.

The redesign also makes liner tubes easier to remove and install after operation. Clearances between liner tube and end fitting body were increased in some areas (to prevent jamming), and tightened in others (to prevent crud ingress). Additional chrome plating was added to prevent galling. Tools to remove and reinstall liners were designed, because past problems in removing liner tubes were likely due as much to inadequate tooling as to the detail design of the components.

As before, the outlet liner has a fuel latch that supports the fuel string against the hydraulic force of the coolant flow, and the inlet liner has a spacer ring. Both liner tubes have lugs to which the shield plugs can be latched. These details are unchanged from the original design.

12. CHANNEL CLOSURE

The channel closures seal the ends of the end fittings, forming parts of the Primary Heat Transport System pressure boundary. They are removed and reinstalled by the fuelling machines during fuel changing operations. During the LSFCR operation, the Channel Closures will be removed, refurbished, stored and reinstalled. A test program yet to be completed will establish the nature of the refurbishing - one possibility is the replacement of all seal disks.

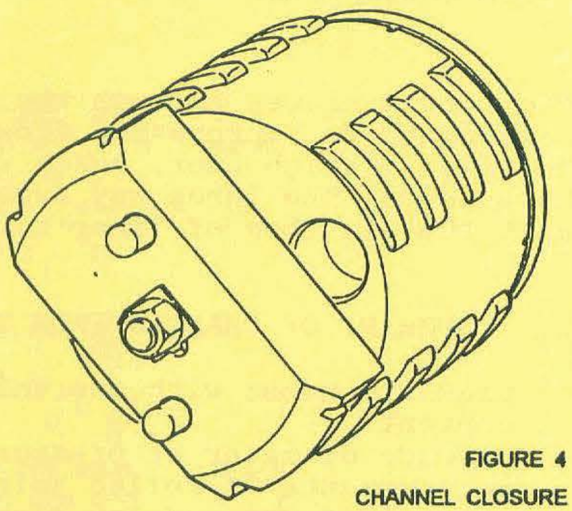

FIGURE 4
CHANNEL CLOSURE

13. SHIELD PLUGS

Shield plugs fill the space inside the end fitting liner tubes to absorb radiation originating in the reactor core. They are removed and reinstalled by the fuelling machines during fuel changing operations.

The outlet shield plugs will be replaced with new ones of the same design as the originals, to avoid the difficulty of reinstalling the radioactive components.

A new inlet shield plug was designed by G.E. Canada and tested at AECL SPEL. This design incorporates a flow straightener at its inboard end to reduce the turbulence of the coolant flow as it approaches the fuel. Testing shows the vibration of the inlet fuel bundle has been reduced to about 50%. This is expected to reduce the probability of fuel fretting the pressure tube.

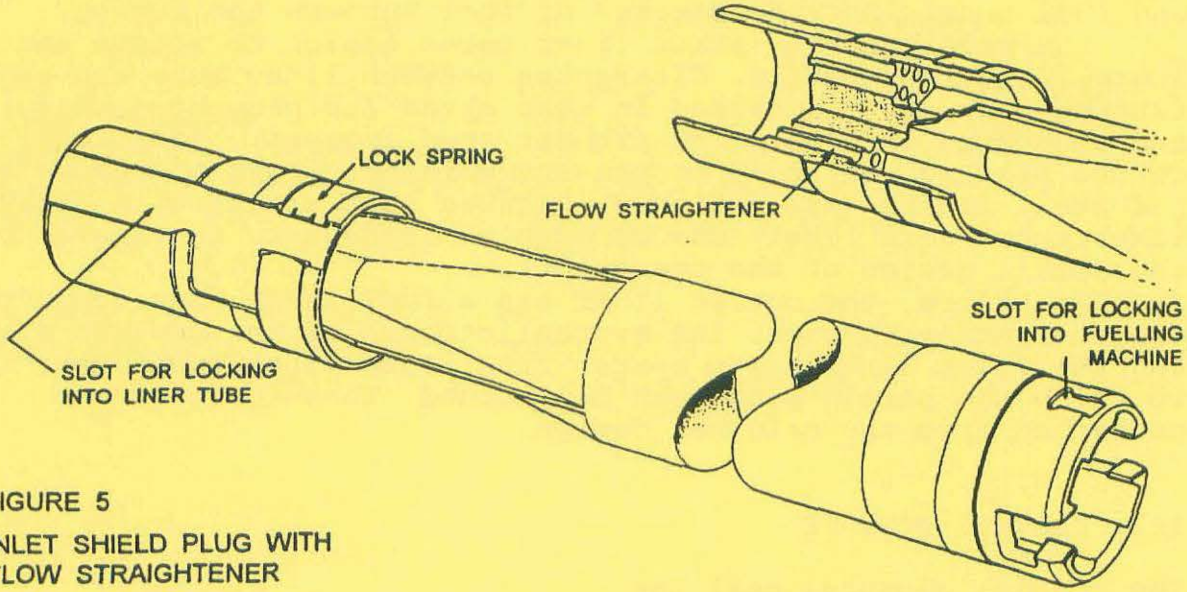

FIGURE 5

INLET SHIELD PLUG WITH FLOW STRAIGHTENER

The flow passages through the shield plug have also been redesigned to improve the flow from the liner tube flow holes to the flow straightener, again with the intention of reducing turbulence. The three way symmetry of the shield plug webs aligns with the six rows of liner tube holes.

14. SUMMARY OF CHANGES FROM THE ORIGINAL DESIGN

- pressure tubes with one thick end, and with reduced hydrogen content
- outside diameter of pressure tubes machined to suit clearance requirements of rolled joints
- zero clearance and low clearance rolled joints used, with expander rollers positioned accurately
- flush rolled joint used on inlet end fitting
- rolled joints will be made on reactor through liner tubes

- 3 end fitting body types that can be installed in two or three rotational positions, on east and west reactor faces, and at inlet or outlet (in the original design, fourteen different types were necessary)
- only one rolled joint bore diameter used
- index hole added to E/F body for inclinometer
- stainless steel used for E/F shielding sleeves
- E/F liner tubes will be more easily replacable
- inboard journal rings will overhang the end of the end fitting for increased axial travel

- replacement of the stop attachment collar with a positioning/bellows assembly
- use of spring finger detent type of positioning assembly
- support of west end fitting by positioning/bellows assembly.

- four garter springs rather than two
- garter springs tight to P/T, with welded Inconel coil and welded Zircaloy girdle wire (note: still under development)

- E/F bellows attachment ring with (blind) auxiliary AGS connection, identical on both E/Fs

- Inconel feeder coupling capscrews with (external) hex head
- feeder coupling seal ring with larger, thicker flange

- inlet shield plug with improved flow passages and a flow straightener.

15. CONCLUSIONS

Close cooperation between the tooling designers and the fuel channel designers made possible our success in designing a fuel channel that will be easier and quicker to install. As well, this new channel is expected to provide the station with twenty-five years of trouble-free operation, due to the elimination of many large and small problems in the original design.

16. ACKNOWLEDGEMENTS

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As well, this new fuel channel is the result of the labours of a team of engineers and technicians, and not the the exclusive property of the author. Contributors to the design include:

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