DEVELOPMENT OF OUT-OF-CORE CONCEPTS FOR A SUPERCRITICAL-WATER, PRESSURE-TUBE REACTOR

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Abstract

One of the Generation IV programs at Chalk River Laboratories has as its prime focus the development of out-of-core concepts for the SuperCritical Water (SCW) pressure tube reactor under development in Canada. A number of technical issues associated with the interface of out-of-core components and the pressure tubes of a SCW pressure tube reactor are being investigated. This article focuses on several aspects of out-of-core components and layouts, building upon concepts that have been developed during the past few years. The efforts are strongly focused on concepts for a fuel channel that can be fabricated with the tight lattice pitch (typically 230 to 250 mm) that may be required for some applications such as utilization of a thorium fuel cycle. It is not practical to adapt concepts with a tight lattice pitch while using the thicker materials required for the higher temperatures and pressures required for supercritical operation.

A change in lattice pitch or configuration is required to accommodate the component size increases. This presentation will cover a number of new concepts developed to produce feeders and end fittings for the harsh conditions of a SCW pressure tube reactor. These components are then developed into conceptual models of a Gen IV pressure tube reactor mounted in both horizontal and vertical orientations. Full 3-D solid models of both concepts will be demonstrated as well as a 1/10th-scale model of one face of a horizontal concept that has been built from components made with a 3-D printer.

Keywords: Supercritical Water Pressure Tube Reactor, Out-of-Core Concepts, Channel Closure, Lattice Pitch

1. Introduction

This report describes ongoing efforts to investigate technical issues associated with the interface of out-of-core components and the pressure tubes of the Generation IV (Gen IV) SuperCritical Water (SCW) pressure tube reactor proposed by AECL. One of the main focuses of this development has been to produce a concept that includes the thicker pressure tubes and end fittings required for a Gen IV pressure-tube reactor operating at much harsher conditions of temperature and pressure. The out-of-core components must also interface with the proposed High-Efficiency Fuel Channel (HEC) [1]. The HEC fuel channel proposes the use of a thicker pressure tube (compared to the ACR® or CANDU 6® reactors) made from the zirconium alloy, Excel, in contact with the moderator so the pressure boundary remains at the moderator temperature of less than 100°C. A cylindrical insulator is placed between the fuel bundles (and coolant) and the pressure tube.

This report focuses on the development of out-of-core concepts that enable end fittings to be connected to the HEC pressure tubes. These concepts are then used to build up a complete fuel channel assembly that can be assembled with a lattice pitch as tight as 230 mm for a fuel channel with a nominal inside diameter (ID) of 103 mm, identical to the ID of present CANDU fuel channels. Other lattice pitches are being investigated for different fuel channel sizes. The complete fuel channel is then used in the conceptual layout of a reactor core, demonstrating that all the required components can be located in such a manner that the input and output feeders can be connected to a header that in turn, can be connected directly to a high-pressure turbine.

Work has ben done to develop the ideas for both a horizontal and vertical orientations for the reactor. Full 3-D layouts are presented for both orientations.

2. The High-Efficiency Fuel Channel

The HEC that has been proposed for use with the Generation IV reactor is illustrated in Figure 1. It uses a pressure tube mounted directly in the moderator. The present concept is to use Excel, an alloy of zirconium, for the pressure tube [1, 2]. An insulator, presently specified as made from Yttrium-Stabilized Zirconia (YSZ) [2], is used between the high-temperature coolant used in the Heat Transport System (HTS) and the pressure tube. The insulator has small holes or other porous features that permit the coolant to apply full pressure to the inside of the pressure tube while maintaining a temperature drop as high as 500°C between the inside surface and the pressure tube. The liner tube shown in Figure 1 is a thin cylindrical tube, likely of a corrosion-resistant stainless steel that contains the ceramic and isolates it from the passage of fuel bundles.

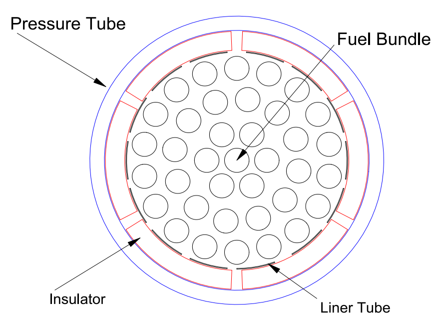

Figure 1 Illustration of High-Efficiency Fuel Channel.

This approach to the fuel channel has been adapted for several reasons. The various zirconium alloys are the only practical materials for use as pressure tubes because they have a low thermal neutron absorption cross section. Essentially all of the other possible structural materials that could contain the high pressures and temperatures of the coolant used in the heat transport system are based upon alloys of iron, nickel, cobalt, chrome or titanium. These alloys have much higher (factors of five to ten or worse in some cases) neutron absorption cross section that leads to significantly higher enrichment requirements for the fuel. However, the ultimate and tensile strength of zirconium alloys tends to drop quickly at temperatures above about 350°C.

There is also a significant increase in strength as the temperature is lowered from around 300°C, typical of present use, to temperatures below 100°C. By using the pressure tube at low temperature, one can utilize the higher tensile properties and the low neutron cross section of zirconium alloys.

However, this concept requires that the pressure tubes be mounted directly in the moderator. This, in turn, leads to the elimination of calandria tubes that have been a feature of all previous CANDU designs.

3. End Fittings

3.1 General

The supercritical coolant used for a SCW pressure tube reactor will enter the fuel channel at a nominal 300°C and exit at about 600°C at a pressure of about 25 MPa. These harsh conditions for the HTS coolant lead to requirements for the fuel channel that includes a thicker pressure tube plus the insulator (see Figure 1) and a thicker end fitting of higher yield material than used in present CANDU reactors. The usual design approach for the present generation of CANDU reactors is illustrated in Figure 2

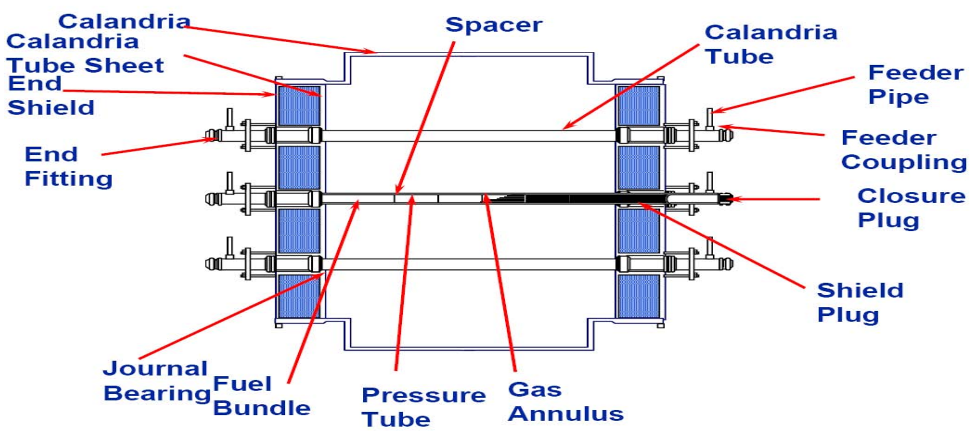

Figure 2 Basic Components of a CANDU Core.

The reactor is made up from a large cylindrical vessel called the calandria that has two separate tube sheets on each end. The inner tube sheet is called the Calandria Tube Sheet and it marks the beginning of the reactor core. The outer tube sheet is the Fuelling Tube Sheet. The calandria is filled with heavy water at low pressure that acts as the moderator and the fuel bundles are contained in the pressure tubes that are cooled by the Primary Heat Transport System (PHTS). The coolant is transferred from the PHTS pumps through end fittings and the fuel channel and then through the steam generator to complete the closed loop. Each fuel channel requires coolant that is coupled from a large header through individual pipes called feeders and these are connected to the input of the fuel channel using a transition piece called an end fitting. Each end fitting uses a channel closure to seal the end fitting. The channel closures are removed and replaced during each on-power fuelling operation. The shield plug provides radiation shielding inside each end fitting and the space between the tube sheets is also filled with metal shielding that is water cooled. The combined effect of the two shields reduces the neutron fields at the external face of the reactor to levels that do not produce severe induced radiation fields after the reactor is shut down. This is important for maintenance activities. These same basic features will be required for a SCW reactor.

Figure 3 (a) shows more details of an end fitting in the vicinity of the tube sheets for a CANDU 6 reactor. The two tube sheets are connected by lattice tubes as shown. Calandria tubes are connected to the calandria tube sheet on both sides of the reactor core and the end fittings are inserted into the lattice tubes and are connected to the pressure tubes near the inner face of the calandria tube sheet by using rolled joint technology. One end of each end fitting is free to move axially to accommodate both thermal expansion and radiation-induced axial creep and there are bearing surfaces between the lattice tubes and the end fittings that enable the axial motion. The bellows connects the end fitting to the fuelling tube sheet and seals the volume contained between the pressure tube and the calandria tube. The four circles at the left of the figure represent the approximate size of the penetrations through the fuelling tube sheet for the connections to either the lattice tube or bellows. There is a necessity that the amount of material between the penetrations be reasonably thick because the high forces required to roll-expand the calandria tubes into the tube sheet can distort tubes sheets if there is not sufficient material.

The example shown in Figure 3 (a) is representative of a CANDU 6 reactor that uses heavy water for both the moderator and the coolant. If light water is used as coolant as in the Advanced CANDU Reactor (ACR) and also for the proposed SCWR, there is a necessity to reduce the lattice pitch for a number of core-physics reasons when using the current fuel and fuel channel designs. This leads to significant challenges, especially for the SCWR. Figure 3 (b) shows the basic details of the HEC (Figure 1) rolled into an end fitting and mounted into the lattice tube as shown in Figure 3 (a). The lattice spacing used for this figure was 240 mm. For this conceptual development, the end fitting is taken as fabricated from Inconel 718 that has much higher yield than the stainless steel used in the present CANDU reactors and the thickness of the pressure tube and insulator are representative of the material thicknesses that would be required to withstand the conditions of the SCW coolant. There is very little space between adjacent penetrations in the fuelling machine tube sheet for this configuration.

Figure 3 (c) shows a potential solution to the problem – extend the pressure tube through the tube sheets and make the rolled joint outside of the fuelling tube sheet. This permits the extra material of the fuel channel and end fitting to be used and still maintain reasonable webs of material between the penetrations through the tube sheets.

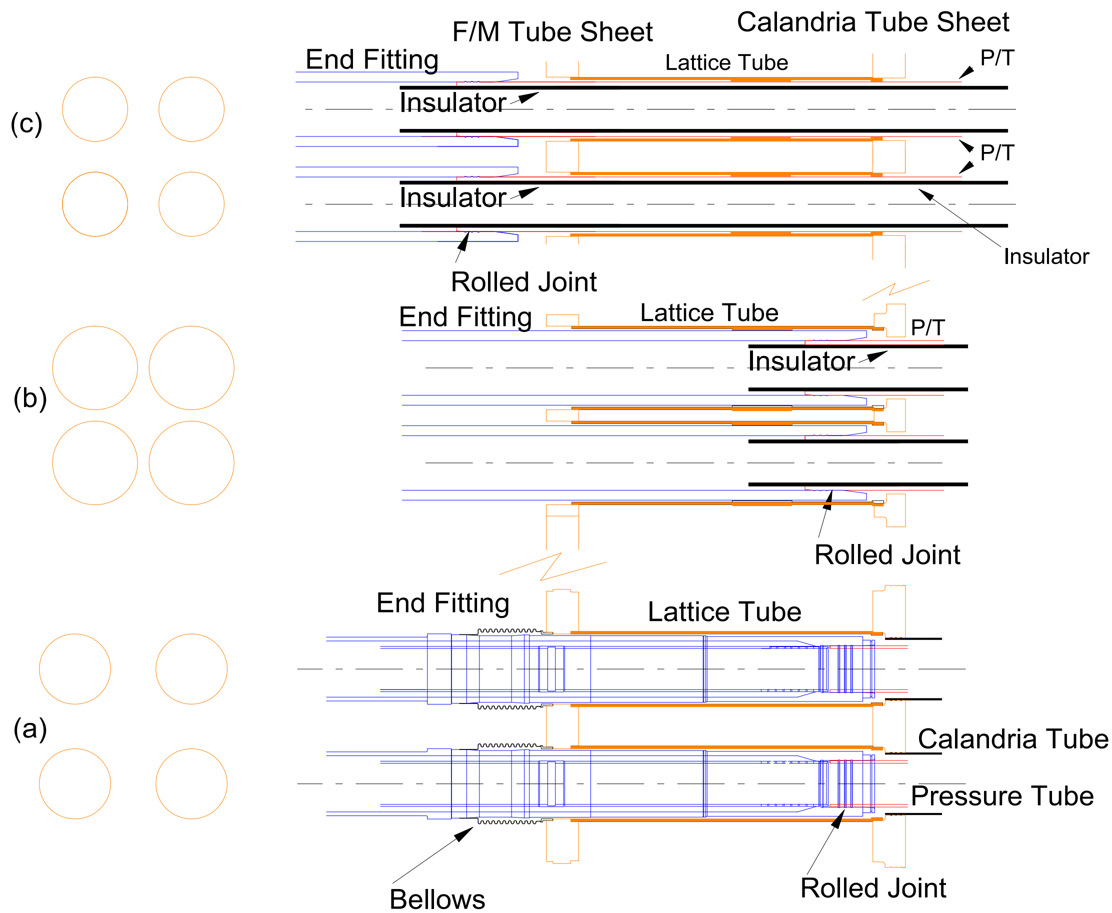

Figure 3 Key out-of-core components of CANDU reactors.

This concept has been further developed with new end fittings designs for both the inlet and outlet ends of the fuel channel. In present CANDU reactors there is a near symmetry between the inlet and outlet ends of a fuel channel. For a SCW pressure tube reactor, the coolant undergoes a very large change in density and enthalpy as it passes through the fuel channel that leads to a greatly reduced total mass flow (about 3 kg/s for a high-power (about 8 MW) fuel channel compared to 25 to 30 kg/s for a present CANDU reactors). The decreased density requires a corresponding increase in flow velocity to compensate. The effect of this is to require quite different designs of the input and output end fittings, feeders and headers. The design concepts that have been developed for each end of the fuel channel reflect those differences. These concepts are described in the next two sections.

3.2 Inlet end fitting

Figure 4 shows the present concept for the input end of the fuel channel in which the rolled joint between the end fitting and the pressure tube is outside of both tube sheets as illustrated in Figure 3 (c). The two tube sheets and the lattice tube are similar to present CANDU technology. The HEC pressure tube extends through the lattice tube and is connected to the inlet end fitting using a rolled joint. The insulator that is part of the HEC extends the length of the pressure tube and beyond the rolled joint by about 300 mm to ensure that there is a reasonable temperature gradient between the region where the coolant enters the insulator and the area of the rolled joint. Figure 5 shows ANSYS calculations of the temperature gradient along this insulator. This ANSYS model shows a length of end fitting made from Inconel, extending from the rolled joint into the region beyond the insulator that sees the coolant temperature. This calculation was done for a rather generic temperature of 420°C, significantly higher than the expected inlet temperature and lower than the outlet temperature. The end fitting is the top rectangular piece in this calculation, as noted on Figure 5. The pressure tube and a 10-mm thick insulator are shown below the end fitting. The inner face of the insulator is maintained at the coolant temperature of 420°C and the cool end of the end fitting is maintained at the moderator temperature of 80°C while the outboard end (right-hand end) is at 420°C. The middle rectangular piece is the pressure tube. The maximum temperature reached in the pressure tube inside the rolled joint is about 130°C. There is only a small change in ultimate strength for a temperature increase to 130 compared to 80°C, showing that the estimate of extending the insulator about 300 mm beyond the rolled joint is a reasonable starting point. At the higher temperatures being evaluated at present (up to about 600°C at the outlet), the insulator will need to be extended about 400 mm beyond the rolled joint.

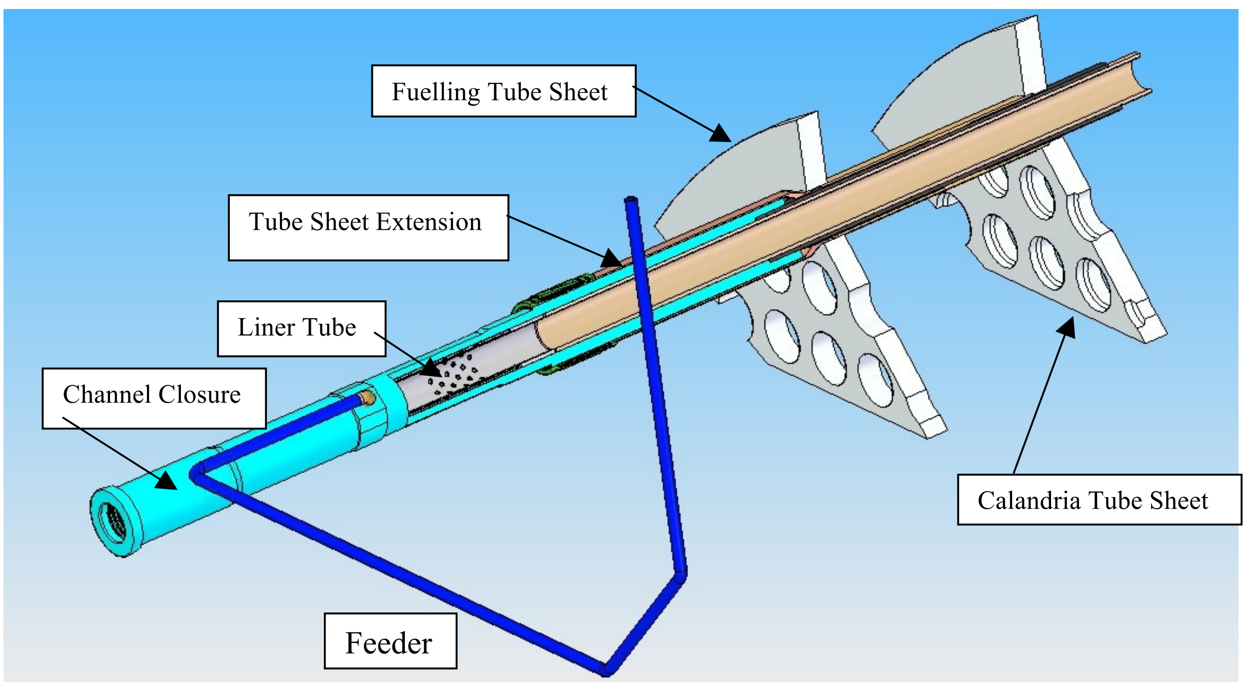

Figure 4 Solid model of one concept of the input end of a SCWR fuel channel.

With reference to Figure 4, the lattice tube is welded into each tube sheet during construction of the calandria vessel. The bearing pad (that may be either at one location as shown or at two locations toward each end of the lattice tube) supports the pressure tube. The bearing pad will need to have several axial passages to enable coolant from the moderator circuit to pass from the fuelling tube sheet into the moderator. A rough estimate of the required water flow is given by

assuming a uniform temperature of the coolant as it passes between the two tube sheets. The amount of energy passing through the cylindrical insulator is given by:
$q_r = 2\pi Lk(\Delta T)/\ln(r_2/r_1)$

Where L is the length of the insul;ator between the two tube sheets (m)
r_1, r_2 are the inner and outer radii of the insulator (m)
k is the thermal conductivity of the insulator (W/m-^{o}K)
ΔT is the temperature difference between the inner and outer surfaces (^{o}K)

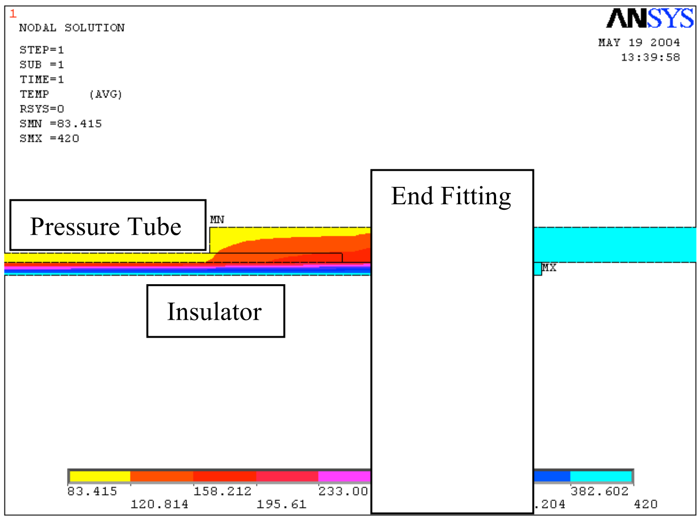

Figure 5 Temperature distribution at the rolled joint region for the insulated pressure tube to end fitting transition.

An estimate of the heat transferred is made by using a value of k of about 0.5 W/m-^{o}K for a Yttrium Stabilized Zirconia insulator, in a one-meter long section of insulated pressure tube between the tube sheets and a 10-mm thick insulator. If the coolant temperature is 500 (600) ^{o}C (for the outlet end) and about 300 ^{o}C for the inlet end, and the pressure tube is maintained at about 80^{o}C, the amount of heat transferred through the insulator in the outlet section is about 7 (9) kW and about 3 kW at the inlet end. This will need to be removed by moderator water passing between the pressure tube and the lattice tube. If the moderator is maintained at about 80^{o}C then the minimum flow rate to keep it below boiling is less than 60 (80) g/s at the outlet end and 30 g/s at the inlet end. This can be transferred with a small diameter line connected to the tube sheet extension outside of the fuelling tube sheet.

Other features of the design concept include the extended lattice tube extension attached to the fuelling tube sheet and the bellows that is then connected to the end fitting

3.3 Channel closure

In general, pressure tube reactors require a channel closure at one or both ends of each fuel channel to seal the end of the fuel channel. It must also be removable using remote handling equipment such as a fuelling machine that removes the closure and stores it temporarily while fuel is changed. The sealing elements of the channel closure must be made from metal components to withstand the high temperatures and pressures. The present CANDU reactors use a seal disk as illustrated in Figure 6 [3]. This has been a remarkably successful technology, in use in CANDU reactors for over 40 years. It may be difficult to use this same technology at the harsher conditions of the Gen IV reactor.

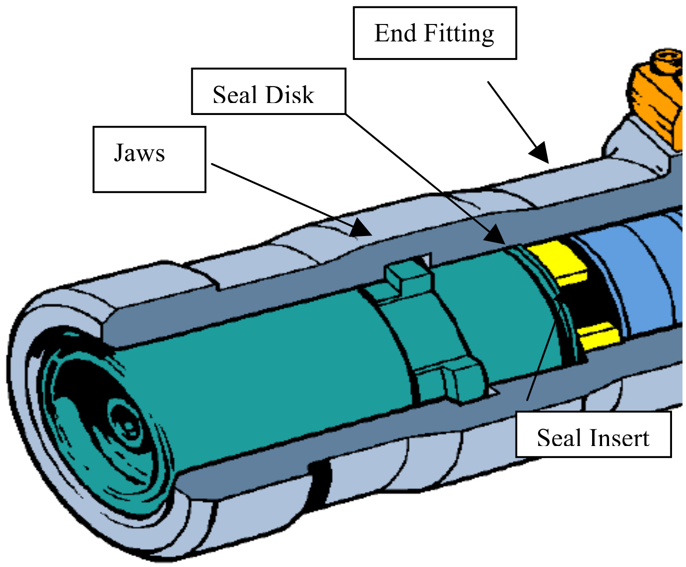

Figure 6 The CANDU 6 Channel Closure [3].

AECL did some work about 10 years ago on a potential new channel closure called the bore seal channel closure [4]. This seals by using a metal seal element that is a section of a cone as illustrated in Figure 7. The diameters shown are designed for use in an end fitting with an internal diameter of 104 mm. The seal element is normally a circular conical section. If high-yield material such as Inconel 718 is used for the seal element, it can be pulled into the elliptical shape shown within the elastic limits of the material, rotated for installation into the end fitting and rotated back to circular shape in a cut-out in the end fitting. Figure 8 shows some details of the seal element and a seal disk mounted in an end fitting. This design concept permits the load produced by the HTS coolant to be applied initially through the seal element into the end fitting. As the pressure is increased the seal element is deflected until it contacts the front of the channel closure body and then shares the load between them. This keeps the stress on the various metal components within reasonable limits.

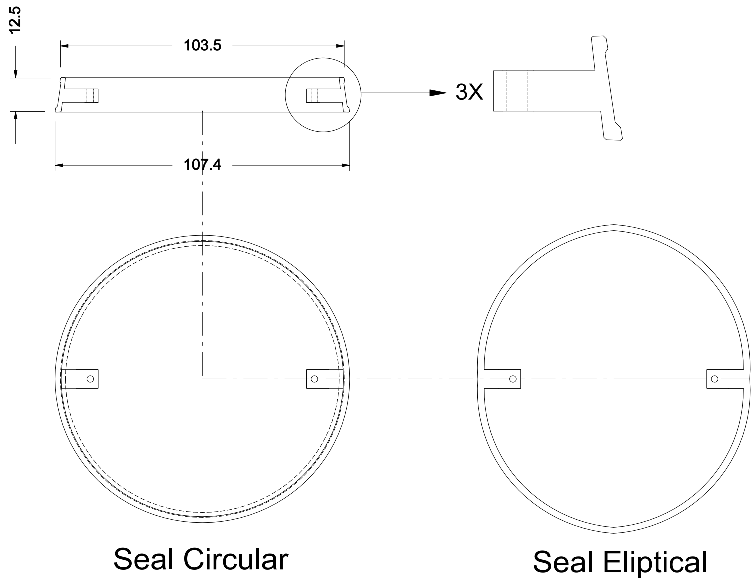

Figure 7 Principle of bore seal element.

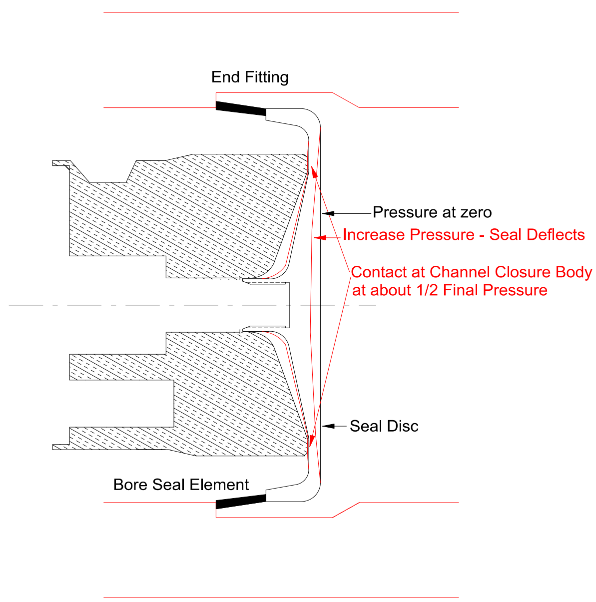

Figure 8 Application of the bore seal.

Figure 9 shows an ANSYS calculation of the components shown in Figure 8 used at a pressure of 25 MPa. The maximum stress is about 875 MPa, below the yield of INCONEL 718 when used at the input of a fuel channel. The seal element has a maximum stress of about 450 MPa.

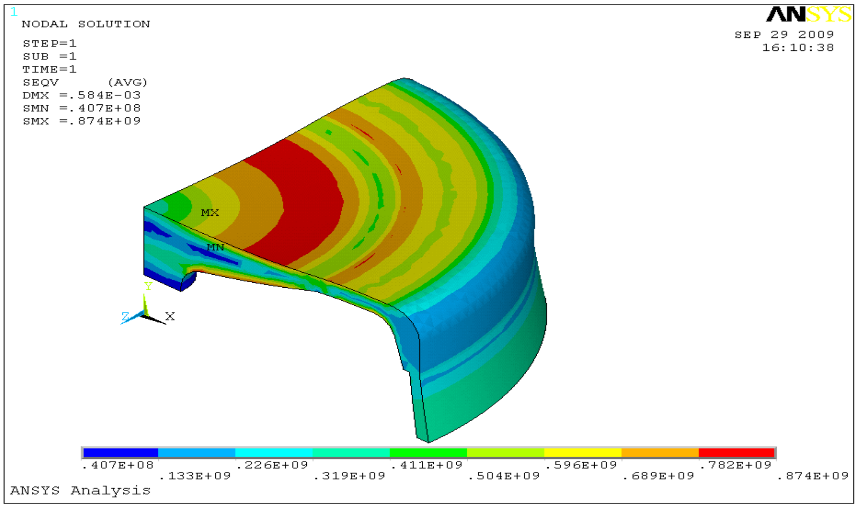

Figure 9 ANSYS calculation of the stress on the seal element and seal disk shown in Figure 8.

3.4 Outlet end fitting

Figure 10 shows the present concept for the outlet end of the fuel channel in which the rolled joint between the end fitting and the pressure tube is outside both tube sheets. This concept was developed in parallel with work on the inlet fuel channel. The HEC pressure tube is rolled into a short (about 500 mm) outlet end fitting. The insulator is inserted from the inlet end of the fuel channel to a position about 400 mm beyond the rolled joint. The length of the outlet end fitting is determined by the requirement to extend from the rolled joint area to a position beyond the insulator by at least another 120 mm. This region is used to support the outlet shield plug and produce a prepared region for the weld to the reducer shown on Figure 10. The reducer is used to reduce the channel diameter from the nominal 104 mm to about 60 mm (ID) that will be used for the outlet feeders. There is also a prepared region on the outlet end fitting to weld to the outlet tube sheet extension. This secures the fuel channel in the tube sheet extension and into its final position in the reactor. Because of the high temperature at the outlet of the fuel channel, a different channel closure design is needed for the harsh conditions of both temperature and pressure. Fuel handling will be done from the input end of each fuel channel, likely at shutdown conditions.

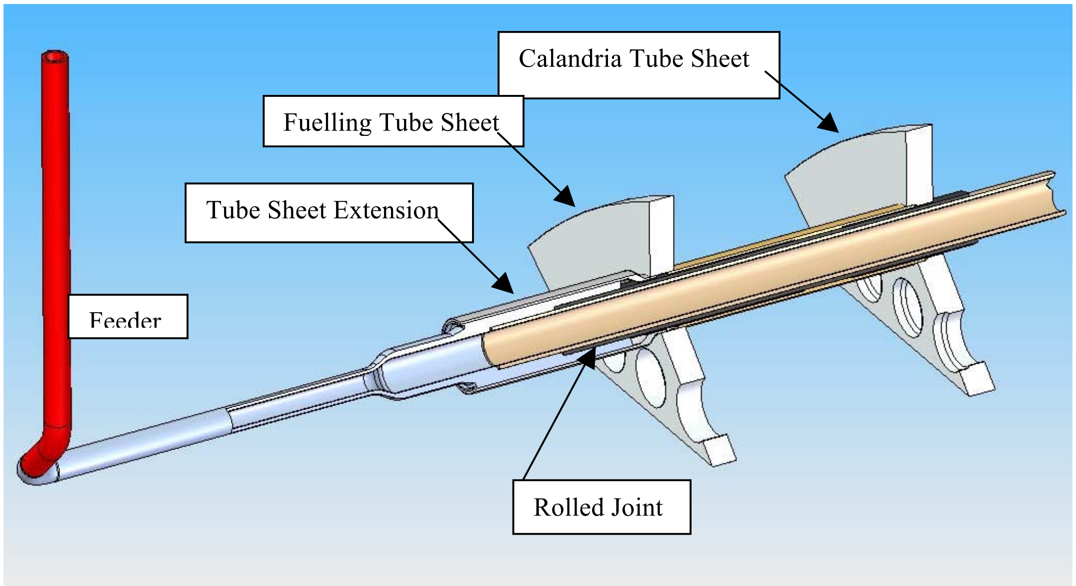

Figure 10 Solid model of one concept of the input end of a SCWR fuel channel.

3.5 Outlet shield plug

The outlet shield plug is another component of a SCW pressure tube reactor that requires careful design. It shields the line-of-sight area at the back of the channel closure from the intense neutron and gamma-ray fields inside the reactor core and also holds the fuel bundles in place. The design of the outlet shield plug is more complex than for the inlet plug. The coolant density is about 1/10th of the inlet density and provides very little attenuation of either the neutrons or gamma rays. In the SCW pressure tube reactor there is an insulator that extends beyond the rolled joint by at least 400 mm and the rolled joint is already outboard of the fuelling tube sheet. Therefore the shield plug cannot be secured near the fuelling tube sheet and must be secured in the first metal beyond the insulator, a location that is nearly 1.5 m from the face of the fuel bundles instead of approximately one meter as in present CANDU reactors. The outlet shield plug will not be removed as part of fuel handling and could be installed during construction of the fuel channel and remain in place for the life of the reactor.

Figure 11 shows a first concept of the outlet shield plug. It is shown in this figure as a single piece of 1.5 m long. There is a length of about 450 mm of solid stainless steel to attenuate both neutrons and gamma rays near the inboard end of the shield plug. The coolant passes in an annular region at the outer radius of the fuel channel in this section. It then passes through a highly transparent section of the shield plug (section A-A) into the central region and the outer part of the shield plug is made from solid stainless steel to provide the attenuation at the outer region. The outlet end shows catches that will secure the shield plug in place in the outlet end fitting. No details of these components or an activation method has been developed at this time.

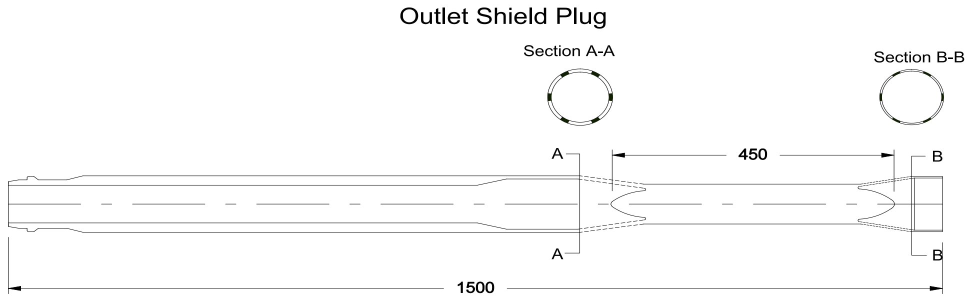

Figure 11 Outlet Shield Plug. The design is meant to provide substantial line-of-sight shielding with high-density stainless steel with minimal flow resistance to the outlet coolant.

4. Assembly of a fuel channel

In order to assemble the fuel channel that has been developed in Sections 3, the pressure tube is first rolled into the short outlet end fitting. The next stage is to weld the reducer and the straight section of the outlet feeder and first bend to the end fitting. The assembly of the pressure tube, end fitting and short section of feeder is then inserted into the reactor face in the appropriate tube sheet site. The end fitting is located into the tube sheet extension and is welded to it. Next the inlet end fitting is rolled into the pressure tube. The next step is to insert the insulator from the inlet end. It will likely be in several overlapping sections. The next step is to weld the inlet end fitting to the bellows and then make the field weld to the feeder. The final step will be to roll the liner tube into the end fitting and add the shield plug and channel closure.

5. SCW reactor concepts – horizontal orientation

In order to build up a complete model of the out-of-core components of the SCWR, all of the end fittings and feeders must be located so that they can be led from the face of the reactor to the appropriate header above the reactor core without interference. They must also be able to tolerate the expected fuel channel axial growth during the lifetime of the reactor and the mechanical design must be tolerant of that growth. A full 3-D solid model of one face of the reactor with the fuel channels mounted in a horizontal orientation has been developed based on the components shown in Sections 3.2 and 3.4.

Figure 12 shows a view of the diagonal row of outlet end fittings (Figure 10) and a horizontal row of inlet end fittings (Figure 4). This figure shows how the two groups of feeders are located to avoid interference and the paths of the feeders away from the reactor face. The outlet feeders use large elbows to minimize flow-induced erosion from the high-velocity coolant flow. Each successive feeder is ported outside of the reactor face along a diagonal line starting from the centre of the reactor. Each of these feeders passes between the rows of input end fittings without any interference. One other strong feature of this design concept is that there is also excellent access to the inlet end fittings for connections to a snout of a fuelling machine.

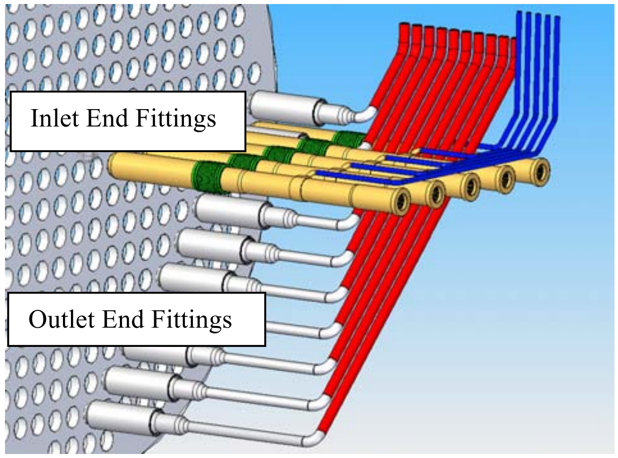

Figure 12 The assembly of inlet and outlet end fittings and feeders.
This figure shows how the channels are added without interfering with neighboring channels.

Figure 13 shows an isometric view of the entire face of the reactor. These model drawings provide a complete conceptual layout of the face of a Gen IV SCW reactor using a horizontal orientation with coolant flow in alternating directions. This horizontal layout enables the use of a very tight lattice pitch of about 230 mm.

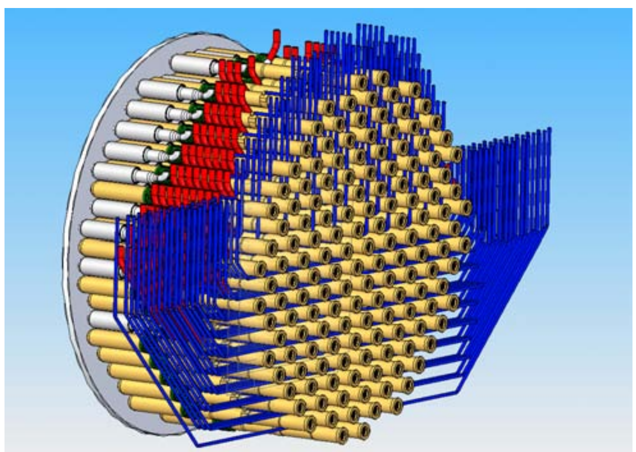

Figure 13 Solid 3-D model of the face of a SCW reactor built in a horizontal orientation.

6. SCW reactor concept – vertical orientation

At this stage of conceptual development, both horizontal and vertical orientations are being considered. Figure 14 shows the initial concept for a vertical reactor using the same input and output concepts for the ends of the HEC. Off-power (batch fuelling) is being considered as an option to minimize the challenge in designing a fuelling machine to connect to a pressure tube at SCW conditions. The preferred approach to locating the fuel channels is with the input at one end and the output at the other end of the reactor. If the direction of coolant flow is alternating such as shown in the horizontal configuration (Figure 13) then there will be a requirement for different fuelling machines at both ends.

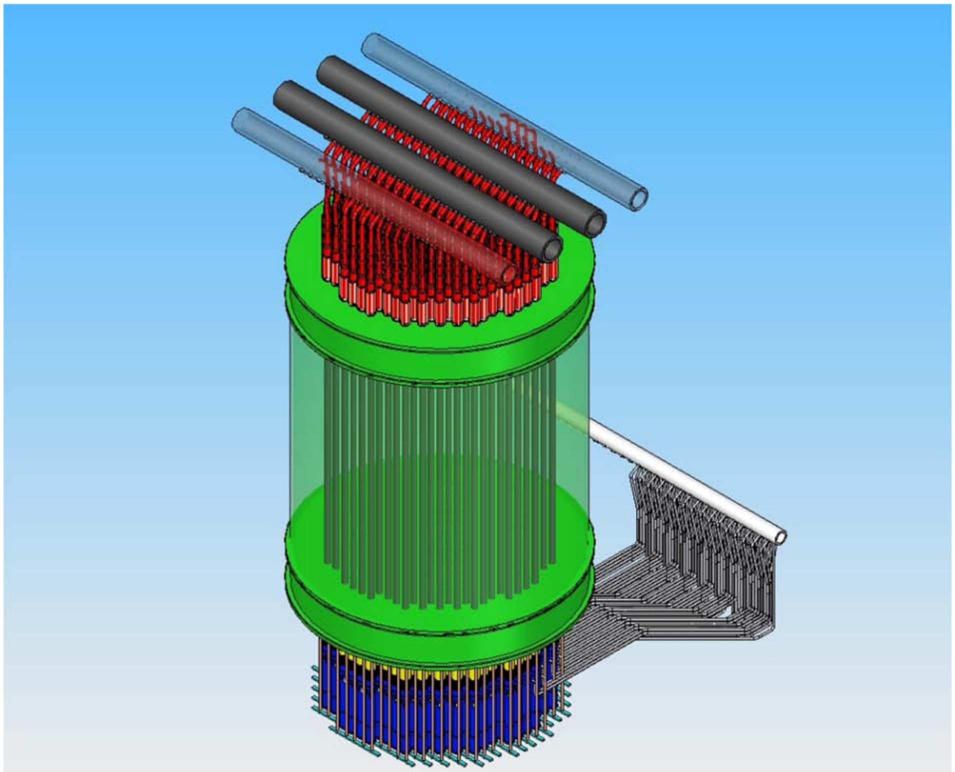

Figure 14 SCW Reactor Concept – Vertical Orientation

This figure shows the input header at the bottom of the reactor. It can also be moved to the same elevation as the outlet headers if required. This figure also shows the outlet end fittings welded to the tube sheet extensions as shown in Figure 10. A technique is being developed to accommodate the thermal expansion of the outlet end fittings and feeders. One option being considered is that the whole fuel channel floats using bellows connections at both ends. Other options and initial concepts for fuel handling will be addressed during the next phase of development of the out-of-core components of the SCW reactor.

7. Summary

This report provides preliminary conceptual designs of out-of-core components and the pressure tubes of a Generation IV (Gen IV) SuperCritical Water (SCW) pressure tube reactor. Basic concepts such as connection to the HEC pressure tube at both the input and output end of the fuel channel have been developed. The HEC is the present concept of an insulated fuel channel proposed for use in a Gen IV pressure tube reactor. It uses a pressure tube made from Excel (an alloy of zirconium) in direct contact with the moderator and an insulator between the coolant and fuel bundles and the pressure tube. The novel approach of extending the pressure tube outside of the tube sheets to enable connections between the fuel channel and the end fittings is proposed as one possible solution to the demanding space requirements and heavier components required for SCW operation. The HEC pressure tube is interfaced with the input and output fuel channel hardware to make up an initial concept of a complete fuel channel.

Basic layouts of the key components of the out-of-core hardware are then developed into both horizontal and vertical configurations of a SCW reactor. The efforts were focused on concepts for a fuel channel that can be fabricated with the tight lattice pitch that may be required for some applications such as utilization of a thorium fuel cycle. The lattice pitch used for the horizontal layout proposed is only 230 mm and for the vertical layout is 245 mm.

The present model provides the first reasonably complete conceptual layout of a Gen IV pressure tube reactor mounted in either horizontal or vertical orientation. This is considered part of the conceptual design of the CANDU SCWR core.

8. References

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