CONCEPTUAL MECHANICAL DESIGN FOR A PRESSURE-TUBE TYPE SUPERCRITICAL WATER-COOLED REACTOR

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Abstract

This paper presents a conceptual mechanical design for a heavy-water-moderated pressure-tube supercritical water (SCW) reactor, which has evolved from the well-established CANDU®[1] nuclear reactor. As in the current designs, the pressure-tube SCW reactor uses a calandria vessel and, as a result, many of today's technologies (such as the shutdown safety systems) can readily be adopted with small changes. Because the proposed concept uses a low-pressure moderator, it does not require a pressure vessel that is subject to the full SCW pressure and temperature conditions. The proposed design uses batch refueling and hence, the reactor core is orientated vertically. Significant simplifications result in the design with the elimination of on line fuelling systems, fuel channel end fittings and fuel channel closure seals and thus utilize the best features of Light Water Reactor (LWR) and Heavy Water Reactor (HWR) technologies. The safety goal is based on achieving a passive "no core melt" configuration for the channels and core, so the mechanical features and systems directly reflect this desired attribute.

1. Introduction

The supercritical water (SCW) cooled nuclear reactor is one of six new system concepts selected by the Generation-IV International Forum (GIF), and as a GIF member, Canada is developing a channel type SCW reactor. Key design goals of the GIF include improving economics (and hence reduce electricity cost) and sustainability, as well as enhancing safety and proliferation resistance. The Canadian SCWR concept can potentially meet all of these goals.

Based on the mechanical design of pressure retaining components of the reactor core, commercial nuclear reactors are grouped as either "pressure-vessel" or "pressure-tube" reactors. The most common pressure-vessel reactor designs are the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR). In these reactor designs, nuclear fuel is contained in a large pressure vessel. In pressure-tube reactor design, nuclear fuel is contained in a number of small pressurized fuel channels. The most common pressure-tube reactor used in commercial power plants is the HWR, where common features are the fuel channel (including a pressure-tube, channel end closure and shield plug), a low-pressure heavy water moderator, a calandria vessel containing the moderator and fuel channels, and feeder pipes that transport coolant in and out of fuel channels.

Increased pressure and temperature, needed to operate the reactor in supercritical water conditions, impose significant challenges to the reactor design. For example, under SCW reactor conditions, a typical reactor core material strength reduces by about a factor of two to three due

[1] CANDU (CANada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited (AECL).

to increased temperature (up to 625ºC) while the operating pressure increases by about a factor of two as compared to the current water-cooled reactors. The reduction in material strength and the increase in operating loads could limit the vessel size of a pressure-vessel type SCW reactor because of a need for a much thicker-walled vessel. The current manufacturing limit for a nuclear-grade SCW vessel size is about 4.5 metres in inner diameter with 0.5-m wall thickness. On the other hand, a pressure-tube based SCW reactor has no such manufacturing limitations. In fact, today's coal-powered supercritical reactors employ piping that can operate at SCW conditions at temperatures higher than 650ºC and this enables existing superalloy materials, thermal operating cycles, and turbines to be directly adapted to nuclear conditions [1],[2].

This paper presents a conceptual mechanical design for a heavy-water-moderated pressure-tube SCW reactor, which has evolved from the well-established pressure-tube type reactor. As in current designs, the pressure-tube SCW reactor uses a low-pressure calandria vessel and, as a result, many of today's technologies (such as the control and safety systems) can readily be adopted with some changes. Because the proposed concept uses a low-pressure moderator as in traditional HWR reactors, it does not require a pressure vessel that is subject to SCW pressure conditions. Unlike current HWRs, the proposed design uses batch refueling, and to simplify fuelling process, the reactor core is orientated vertically. Significant simplifications result in the design with the elimination of on line fuelling systems, fuel channel end fittings and fuel channel closure seals, thus utilizing the best features of LWR and HWR technology. The safety goal is based on achieving a passive "no core melt" configuration for the channels and core, so the mechanical features and systems directly reflect this desired attribute.

Typical mechanical design requirements include meeting all applicable Codes and Standards, while being able to sustain a long operating and economic life with suitable allowance for maintenance compatible with decreased cost of generation.

2. Canadian Direct-Cycle Supercritical Water Nuclear Reactor Concept

The Canadian SCWR concept adopts a direct thermal cycle offering high efficiency and simplified system. Figure 1 illustrates the typical SCWR layout (which is similar to that of the boiling-water reactors (BWRs)) and thermal cycle. The direct cycles directly pass steam into high pressure turbine generators eliminating the need of steam generators as in the PWRs or PHWRs. Moisture separator and reheater (MSR) are used to remove water droplets prior to low-pressure turbines. A 48% thermal efficiency can be achieved with the reactor outlet temperature of 625°C.

The Canadian SCWR takes advantage of the well-developed balance of plant (BOP) layout of the SCW fossil-fire power (FFP) plants (which are operating at conditions similar to the Canadian SCWR). This would reduce significantly the design and development efforts. A noticeable difference in the BOP configuration between current SCW FFP plants and BWR plants is the use of the reheat option, which eliminates the need of the MSR and increases the thermal efficiency further. To match a SCWR to a reheat SCW turbine, the flow from the back end of the high pressure (HP) turbine must be returned at a lower pressure through the core in the second pass. The steam is then reheated to the required superheat and fed to the intermediate pressure (IP) section of the turbine. For a channel reactor, the reactor exit temperature can be established by either changing the channel length, the flow rate, or the number of passes through the core, or some combination. Reheat steam cycle version of the design uses channels to superheat steam which are placed at the periphery of the reactor core and have about 1.5 times lower heat flux compared to the average heat flux.

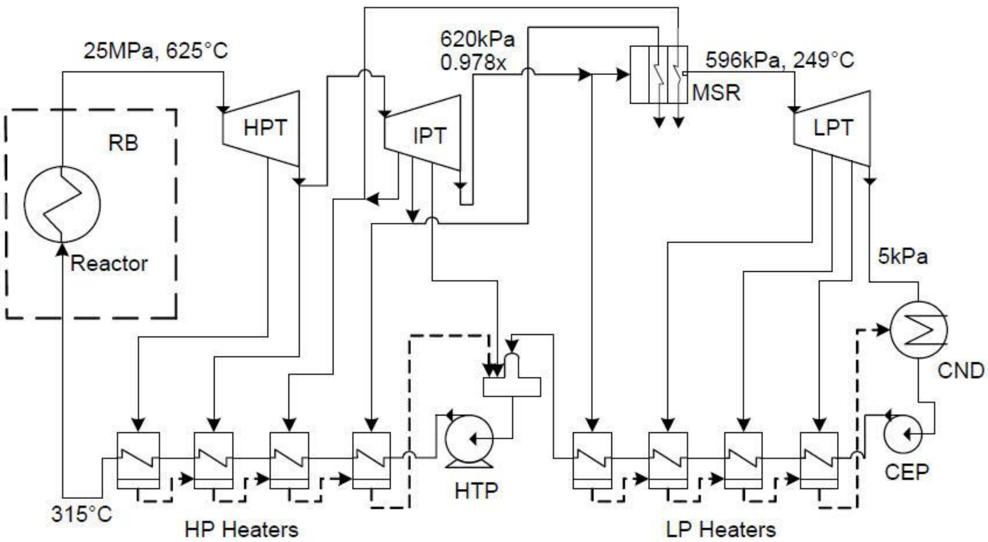

Figure 1 Typical Supercritical Water-Cooled Reactor Layout and Thermal Cycle.

A maximum calculated efficiency of 50% is achievable using the direct cycle with the reheat option. This represents a major improvement of 40% in efficiency over current LWR designs (at about 35% efficiency), satisfying the economic design goal of the SCWR. Hence there is an equivalent increase in the energy extracted from the same amount of fissile material, a result consistent with analyses of the fuel irradiation and reactor core physics for SCWR using special high-efficiency pressure tubes with an optimized lattice. The reheat capability is being explored as a design option for the final Canadian SCWR concept.

While the overall BOP layout of the Canadian SCWR plant remains similar to that of the SCW FFP plant, the high pressure (HP) and, possibly, the intermediate pressure (IP) turbines will be installed inside the reactor building to enhance the plant safety. Optimization of the piping layout is required, and further safety enhancement can be introduced using Dual Cycles, which utilize a steam generator or HX, but with increased cost and loss of some thermal efficiency. Table 1 compares thermal efficiencies of various thermal cycles with and without the reheat option [3].

Table 1 Summary of typical efficiency results (25 MPa/625°C/2540 MW(th)).

Cycle	Direct	Direct	Dual	Dual
Option	Reheat	Moisture Separator	Reheat	Moisture Separator
Reheat (MPa/°C)	6.1/625		6.1/625	
Efficiency %	50	48	49	47

3. On-Power Fuelled Horizontal Core Pressure-Tube Reactor

Traditionally, CANDU reactor cores have been placed horizontally, specifically to accommodate on-line refueling which maintains criticality while using natural uranium as fuel. Substantial work has already been done on developing horizontal SCW concepts because this was the natural evolution from the Generation II and III+ channel HWR reactor designs (CANDU 6, PHWR and Advanced CANDU Reactor (ACR[2])). For the channel type horizontal or vertical core SCWR concepts to be feasible, the high efficiency fuel channel (HEC), (discussed in Section 4.3), is preferred as it allows for fuelling from both ends of the core. Changes in fuel channel design and operating conditions necessitated modifications or new concepts in the conventional out-of-core fuel channel components interfacing with the HEC. Concepts of key fuel channel hardware such as a channel closure and the shield plugs were also developed at the concept stage. Details of the horizontal reactor concept and development are described in a paper on the development of SCWR out-of –core components [4].

4. Batch Fuelled Vertical Core Pressure-Tube Reactor

Because of the challenge of the stresses and safety issues of connecting a fuelling machine to a pressure tube at SCW conditions, a vertical core design with off-power batch fuelling has been introduced [4]. In addition, the global move to a sustainable recycled fuel cycle using enriched fuels eliminates the necessity to use on-line fuelling, which is needed to maintain reactivity with natural uranium fuel. These considerations have led to the preference for the vertical orientation of the reactor core that allows more efficient batch refueling as well as other design changes that simplified the reactor concept mechanical design.

Figure 2 illustrates the current vertical-core pressure-tube SCW reactor. The proposed design uses a pressurized inlet plenum attached to a traditional channel-type core. This design differs from traditional HWR designs in three major features: (1) using an inlet plenum instead of inlet feeders, (2) adopting a vertically oriented reactor core, and (3) refuelled off-line. A cross-section of the reactor is shown in Figure 3 which provides a perspective of the entire reactor layout where the primary components are labelled.

A simple schematic describing just the coolant flow is given in Figure 4. The light water coolant enters the inlet plenum through inlet nozzles (inlet pipes are not shown) and then enters the fuel channels that are connected to the tubesheet at the bottom of the inlet plenum. Because the pressure losses in fuel channels are significantly larger than in the inlet plenum, inlet coolant will tend to divide reasonably uniformly into the fuel channels. However, further control of flow rates in each individual channel is needed with the appropriate use of orifices in fuel channels to obtain a more uniform exit temperature distribution. Inlet conditions are specified to be subcritical at a pressure of 25 MPa and a temperature of 350ºC [7]. As the coolant is forced vertically downwards in the fuel channel, it gradually becomes supercritical with the energy generated by the fuel. The supercritical water exiting from the fuel channels is collected in the outlet header at an average 625ºC temperature chosen specifically to match existing and expected SCW turbines in thermal power plants.

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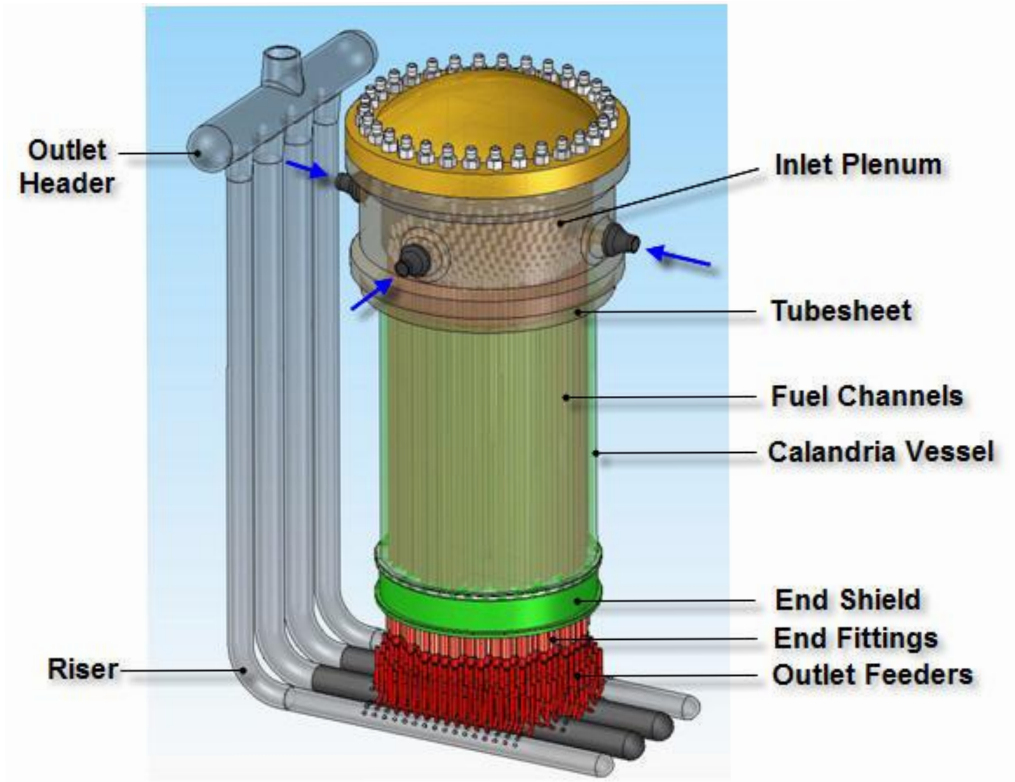

Figure 2 Preliminary Concept of the Pressure-Tube Type SCWR.

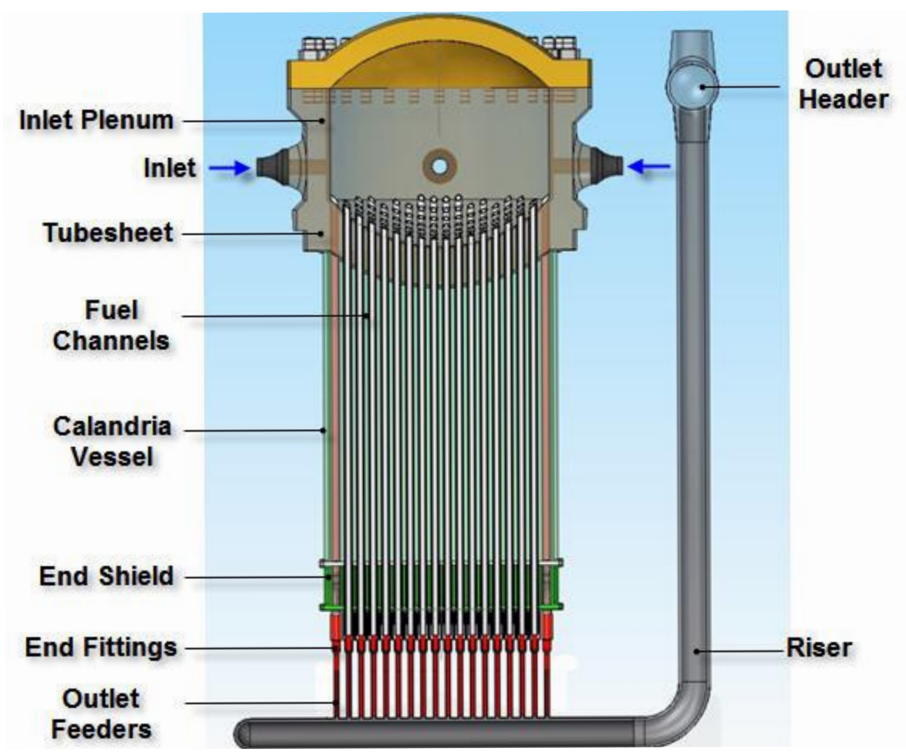

Figure 3 Cross Sectional View of the Pre-Conceptual Pressure-Tube Type SCWR.

4.1 Inlet Plenum

Inlet plenum replaces inlet feeders, end fittings, and end fitting internals (shield plug, liner tube, channel closure seal and channel closure plug) and, as a result, significantly reduces the number of components as compared to the CANDU pressure-tube reactor.

The inlet plenum material is forged SA508, a high-temperature steel, and the bottom of the inlet plenum, called the tubesheet, is machined to form a square array of holes about the same size as pressure tubes. For optimal physics purposes, the pressure tube material is a Zirconium alloy [7] with low neutron cross-section. Because welding Zirconium alloys (pressure tube) to steels (tubesheet) is not possible without causing brittle material structure, pressure tubes are attached to the tubesheet using rolled joints. An alternative method of joining pressure tube to tubesheet is explosion bonding. This method has not been used in current HWRs but has been used for sealing steam generator tubes at the tube sheet .

The rolled joint between pressure tube and tubesheet provides a leak-tight joint. Under SCWR conditions, increased wall thickness and possible exposure of the rolled joint to high temperature/high pressure coolant introduces challenges in the development of a leak-tight rolled joint. Although using a thicker pressure tube is a challenge, there have been successful rolled joints between 10 mm thick pressure tubes and end fittings. There does not appear to be a large step between these developments and rolled joints between 10 to 13 mm thick pressure tubes and perhaps 25 mm thick end fittings of Inconel as proposed here. An R&D program has been initiated at AECL to study this enabling technology for this future application to SCWR.

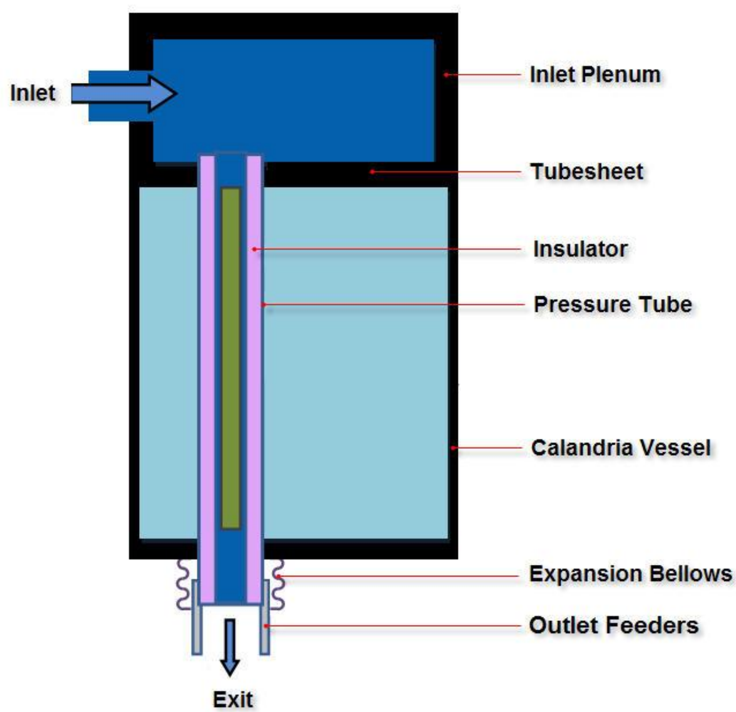

Figure 4 A Simplified Schematic of the Pre-Conceptual Pressure-Tube Type SCWR.

4.2 Calandria Vessel

The tank holding the moderator surrounds the channels, and is conventionally called the calandria vessel (CV) and includes most standard CANDU features. The calandria vessel is a relatively low-pressure tank that includes heavy water moderator, the number of fuel channels needed for a given power, reactivity control mechanisms and emergency shutdown devices. The moderator is heavy water (D_2O) at low pressure and low temperature because of its superior neutron moderation . The moderator operates slightly sub-cooled which makes it possible to use a flashing-driven natural circulation loop to passively remove moderator heat [5]. An attractive feature of this design is that this moderator system functions as a heat sink during both normal and off-normal operation and potential accident conditions, without active pumping; therefore, it provides additional safety margin and complete decay heat removal capability in case of emergency. The end shield at the bottom of the reactor is a neutron reflector filled with spherical steel balls as in current HWR designs.

4.3 Fuel Channels

Fuel channels are small diameter (125mm to 175mm) pressure tubes containing nuclear fuel bundles. Because Zirconium alloy material strength reduces sharply and corrosion rates increase at temperatures beyond 400 ºC, the higher temperatures in SCW fuel channels require special consideration. A ceramic insulator (placed between the fuel bundles and the pressure tube) is introduced to maintain the pressure tube temperature close to the moderator temperature [6]. The insulator material selected is Yttrium-Stabilized Zirconia (YSZ), which has low neutron absorption properties and excellent thermal resistance. This fuel channel with zirconia insulator is called the High Efficiency Fuel Channel (HEC) [7] and is illustrated in Figure 5. Because of added insulator thickness and higher operating pressures, the HEC pressure tube is larger and thicker (as compared to current HWR reactors), and because the pressure tube is in contact with the moderator, this pressure boundary remains at the low moderator temperature. At this temperature, the zirconium alloy Excel has superior properties [9][10] and, hence, is the selected material. The insulator has small holes and/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^{o}C between the inside surface and the pressure tube. The perforated liner tube shown in Figure 5 is a thin cylindrical tube, made of a corrosion-resistant stainless steel that contains the YSZ insulator and isolates it from the main coolant flow and fuel bundles. Since the physics, thermal hydraulics and mechanical aspects are coupled, fuel bundle optimization studies are ongoing to ensure burn up, enrichment, reactivity coefficients, axial and radial power profiles, fuel and clad temperatures, linear power rating, reactivity (k_{eff}), and stability are well behaved during the fuel cycle. The current reference fuel channel dimensions are listed in Table 2.

This insulated approach to the fuel channel has been adapted for several reasons, and is predicated on safety plus the performance limits of known materials under SCW conditions [8]. 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 ten or larger in some cases) neutron absorption cross section that leads to significantly higher enrichment requirements for the fuel and, also, increases in activation products. However, the ultimate and tensile strength of zirconium alloys tends to drop quickly at temperatures at about 400°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 both the higher tensile properties and the lower neutron cross section of zirconium alloys. The challenges are anticipated in maintaining the pressure tube temperature below 100°C depending on the insulator performance and natural circulation flashing decay heat removal. The test programs with Zirconia insulator at supercritical temperatures and on flashing flow heat removal address these challenges.

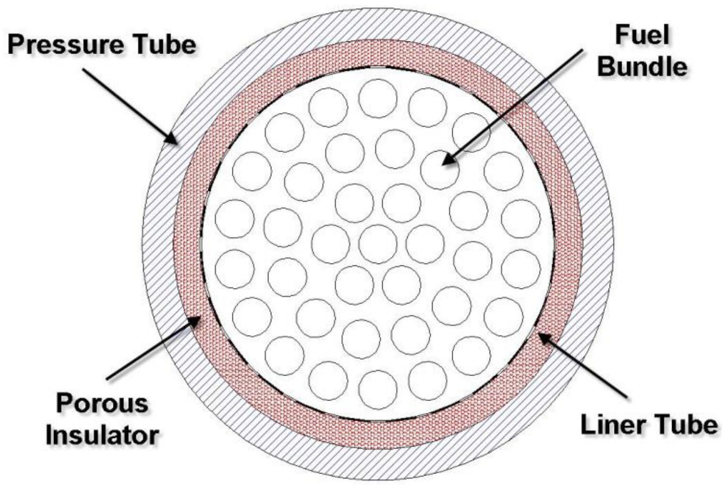

Figure 5 Illustration of High-Efficiency Fuel Channel.

Table 2 Pre-Conceptual HEC Dimensions.

	Fuel Channel Dimensions
Liner Inside Diameter (mm)	136
Liner Thickness (mm)	0.7
Insulator Thickness (mm)	10
Pressure Tube Thickness (mm)	12
Pressure Tube Outside Diameter (mm)	181.4

The major passive safety argument is rejecting decay heat to the moderator without fuel melting, and direct contact of the pressure tubes and the heavy water moderator allows the natural circulation cooling of pressure tubes during both normal and accident conditions. Following an accident, radiation heat transfer from the fuel elements is then conducted through the insulator and the pressure tube to the moderator that is effectively cooled by the flash-driven naturally-circulated moderator. This increased safety feature satisfies one of the GIF goals of "improved safety" and this objective is a key constraint on the design concept in terms of channel design, bundle power and moderator heat removal.

4.4 Outlet Feeders

At the outlet end, see Figure 6, fuel channels are connected to small diameter outlet feeder pipes through transition pieces that are rolled to the pressure tube on one end and welded to the outlet feeder pipes on the other end. It is important to protect the rolled joint from the high temperatures of the HTS coolant to ensure leak-tight functionality. Hence, the rolled joint is placed inside the calandria vessel and is in direct contact with the moderator to keep it cool. Also, the zirconia insulator 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 HTS coolant exits the insulator and the region/elevation of the rolled joint. An expansion bellow at the end of the fuel channel allows for axial thermal expansion and creep growth of the fuel channel.

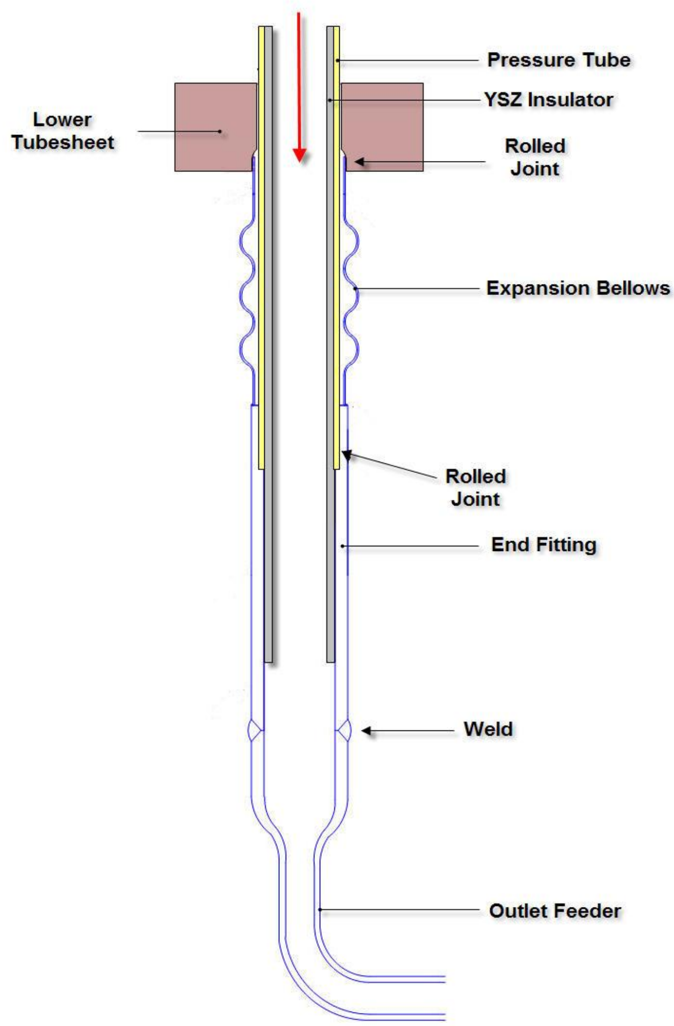

Figure 6 Details of Pressure Tube to Outlet End-Fitting Connection.

Outlet feeder pipes provide flexibility to the fuel channel/outlet pipe structure so that the differential growth of fuel channels caused by material creep and thermal expansion can be accommodated. The large diameter outlet pipes, called risers, are anchored such that their downward thermal expansion is about the same as the thermal expansion of fuel channels. This configuration minimizes in-service stresses of both the outlet piping and the fuel channels. Outlet flow from risers is collected in the headers before it is transported to turbines.

At the outlet, materials are selected based on the operating experience of existing supercritical coal plants, a possible selection is T/P91(2) class of high-temperature alloys commonly used in conventional supercritical coal plants.

4.5 Fuel Channel Layout

Fuel channel layout for the reference design is shown in Figure 7. The thermal power of the concept can be easily varied to meet the need by varying the channel count, and has been set at 2540 MW for the nominal reference design. This has resulted in the electric power of about 1200 MW, assuming a 48% thermodynamic cycle efficiency of the plant. The resulting number of fuel channels is 336, obtained from the considerations of average fuel channel power of 6.5 MW(t), and a radial power profile factor of 1.2. The number of fuel channels is selected to be a multiple of 12 to allow flexible refueling and shuffling the positions of 1/3rd of the fuel bundle assemblies. Lattice pitch is selected to be 250 mm based on the optimization of fuel to moderator ratio to achieve a negative void coefficient, and high fuel burnup.

4.6 Refuelling and Maintenance Activities

The proposed design simplifies refuelling and fuel channel replacement activities and uses conventional LWR technology. For refuelling or fuel channel replacement, the head of the inlet plenum is removed with the help of an overhead crane. This provides direct access to all fuel channels. This configuration is also simpler than those in existing PWRs and BWRs in which control rods and other reactor internals need to be removed first before getting access to fuel bundles. Prior to refuelling, the inlet plenum is depressurized and drained below the head seal level. During refuelling, the light water coolant is circulated at a lower rate and naturally circulated (gravity driven) into the fuel channels to keep fuel elements cool and to prevent the coolant from boiling.

5. Conclusions

A conceptual supercritical water cooled pressure-tube reactor design is presented. When compared to present (Gen III) pressure-tube based CANDU reactors, the present design offers the following advantages in mechanical design and operations:

- Eliminates inlet feeders.
- Eliminates channel closure plugs (two for each fuel channel).
- Eliminates channel closure seal (two for each fuel channel).
- Allows batch fuelling with simultaneous multi-channel fuelling and convenient access through a hollow inlet plenum.
- Easier pressure tube replacement with convenient access to fuel channels by removing the inlet plenum head.

- Enables a compelling safety case.
- Passive core cooling is possible through natural convection of heavy water moderator.
- Small LOCA of an outlet has a small impact due to the common coolant inlet.
- Provides 40% higher efficiency.
- Has a compact footprint and layout.

Refinement of this conceptual design via, optimization of the fuel, safety and layout is proceeding.

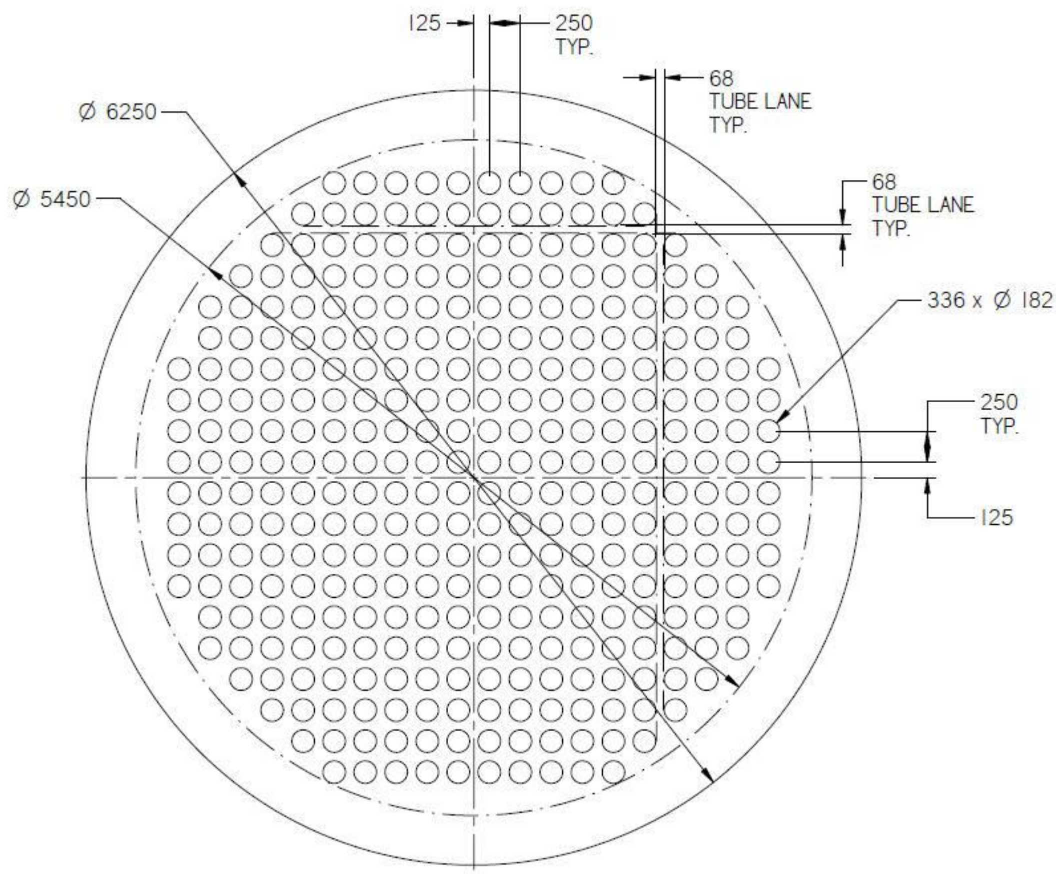

Figure 7 Cross-Section of the Calandria Vessel Showing the Fuel Channel Layout.

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