CONCEPTUAL FUEL CHANNEL DESIGNS FOR CANDU – SCWR

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This paper presents two of the fuel channel designs being considered for the CANDU-SCWR, a pressure-tube type supercritical water cooled reactor.

The first is an insulated pressure tube design. The pressure tube is thermally insulated from the hot coolant by a porous ceramic insulator. Each pressure tube is in direct contact with the moderator, which operates at an average temperature of about 80°C. The low temperature allows zirconium alloys to be used. A perforated metal liner protects the insulator from being damaged by the fuel bundles and erosion by the coolant. The coolant pressure is transmitted through the perforated metal liner and insulator and applied directly to the pressure tube.

The second is a re-entrant design. The fuel channel consists of two concentric tubes, and a calandria tube that separates them from the moderator. The coolant enters between the annulus of the two concentric fuel channel tubes, then exits the fuel channel through the inner tube, where the fuel bundles reside. The outer tube bears the coolant pressure and its temperature will be the same as the coolant inlet temperature, ~350°C.

Advantages and disadvantages of these designs and the material requirements are discussed.

KEYWORDS : Generation IV, GIF, Supercritical-Water Cooled Reactor, CANDU, SCWR, Fuel Channel

1. INTRODUCTION

Concepts of nuclear reactors cooled with water at supercritical pressures were studied as early as the 1950s and 1960s in the USA and Russia. However, no supercritical water-cooled power reactor has been built. Recently the idea of developing such reactors has become active again. One of the six reactor concepts being considered by the Generation-IV International Forum (GIF) for international collaborative R&D is the Super Critical Water-cooled Reactor (SCWR) [1]. With SCW as a coolant, the thermodynamic efficiency is increased to over 40%. The CANDU-SCWR concept falls under this category. Although SCWR can be designed as fast or thermal reactors, [2, 3] the CANDU-SCWR is a thermal reactor.

Similar to the current CANDU®[1] design, the CANDU-SCWR is moderated using heavy water and it has fuel bundles residing inside horizontal pressure tubes. The coolant, however, is light water at 25 MPa, with an inlet temperature of 350°C and an outlet temperature of up to 625°C (Table 1). The feasibility and significant benefits of SCW pressure-channel nuclear reactors are given by Duffey et al. [4], [5]. Calculations examining the feasibility of using SCW as reactor coolant in a pressure tube type SCWR have also been published [6, 7, 8]. The thermophysical properties of water for the CANDU-SCWR, the current CANDU-6 and the Pressurized Water Reactor (PWR) are given in Table 2.

Because of the high temperature and high pressure of the coolant for a CANDU-SCWR, the standard CANDU pressure tube design cannot be used. There have been several conceptual designs for the CANDU-SCWR fuel channel [9, 10, 11]. Section 2 describes two of the designs AECL is actively pursuing.

2. FUEL CHANNEL DESIGNS FOR THE CANDU-SCWR

Using SCW as a coolant requires a major design change to allow continued use of the low neutron absorbing material currently used in CANDU fuel channels. Many designs have been considered. This paper concentrates on the two designs: the High Efficiency Channel (HEC) and the Re-

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

Table 1. Preliminary Specifications of CANDU-SCWR

Spectrum	Thermal
Moderator	Heavy water
Coolant	Light water
Thermal Power	2540 MW
Flow Rate	1320 kg/s
Number of Channels	300
Electric Power	1220 MW
Efficiency	48%
Fuel	UO_2 / Th
Enrichment	4%
Inlet Temperature	350°C
Outlet Temperature	625°C
Cladding Temperature	< 850°C
Calandria Diameter	4 m

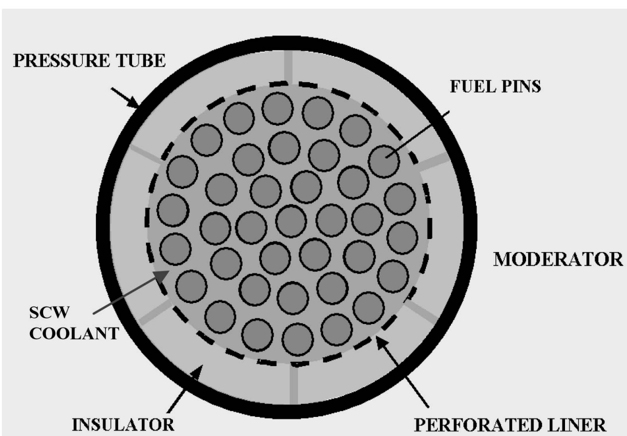

Fig. 1. An Insulated Pressure Tube Design of the CANDU-SCWR Fuel Channel.

Entrant Channel (REC). The designs and the material requirements are given in the following sections.

2.1 The High Efficiency Channel

The High Efficiency Channel (HEC) is shown in Figure 1. Unlike current CANDU reactors, this design does not use a calandria tube to separate the pressure tube from the moderator. Each pressure tube is in direct contact with the moderator, which operates at an average temperature of about 80°C. The pressure tube is thermally insulated from the hot coolant by an insulator. A perforated metal liner protects the insulator from being damaged by the fuel bundles and from erosion by the coolant flow. The coolant pressure is transmitted through the perforated metal liner and small openings in the insulator and directly applied to the pressure tube. The insulator does not need to support the coolant pressure, although it must be able to withstand the weight of the fuel bundles.

2.1.1 Material Selections for the HEC

The material selection for each fuel channel component depends on its function. The pressure tube is the pressure boundary, so its material must have high strength to contain the coolant. The insulator must have high thermal resistance and corrosion resistance in SCW, plus sufficient strength to bear the weight of the fuel bundles without significant thickness reduction during its design life. The perforated liner and the fuel sheaths must have high corrosion resistance in SCW, although their resident times are significantly different. The fuel sheaths must be able to withstand the pressure differences between the coolant and fuel sides. One common requirement for all in-core fuel channel components is that they should be as neutron transparent as possible. The irradiation deformation of all these components must also be considered in their design.

No alloy or material has received enough study to ensure its viability in an SCWR. Extensive R&D on materials will need to be conducted on candidate materials in the following areas [1], [12]:

- Oxidation, corrosion and stress corrosion cracking,
- Radiolysis and water chemistry,
- Strength, embrittlement, fracture toughness,
- Dimensional and microstructural stability.

In the following, the preliminary CANDU-SCWR fuel channel design and its material selection are reviewed.

2.1.1.1 Pressure Tube Materials

The pressure tube is a pressure boundary component. In the HEC design, the pressure tube is in contact with the moderator and it would operate at about the moderator temperature (~80°C). At this low temperature (compared to the proposed coolant outlet temperature of ~ 625°C), the strength of Zr alloys would be much greater, and the corrosion rate much lower so that such low neutron absorbing alloys would be suitable for the pressure tube to retain neutron economy.

A high strength, creep resistant zirconium alloy Excel (Zr - 3.5%Sn - 0.8%Nb - 0.8%Mo - 1130 ppm O), developed by AECL in the 1970s [13, 14, 15] is a candidate material for the HEC design. In the HEC design, Excel would be used in the annealed condition to minimize the irradiation creep and growth rates.

The properties of Excel have been reviewed in [16]. Only a brief summary will be presented here. Figure 2 shows that the UTS of Excel is about 700 MPa at the low operating temperature (~100°C). ASME Code requires that the design stress of the pressure boundary component be

Table 2. Comparison of the Values of Thermophysical Properties of Water* and Values of Heat Transfer Coefficient for the Conditions of CANDU-SCWR, CANDU-6 and PWR [6]

Parameter	Unit	CANDU-SCWR		CANDU-6		PWR	
Pressure	MPa	25**		10.5		15	
Temperature	ºC	Inlet 350	Outlet 625	Inlet 265	Outlet 310	Inlet 290	Outlet 325
ΔT from inlet to outlet	ºC	275		45		35	
Density	kg/m^3	625.5	67.58	782.9	692.4	745.4	664.9
Enthalpy	kJ/kg	1624	3567	1159	1401	1285	1486
Increase in enthalpy	kJ/kg	1943		242		201	
from inlet to outlet	kJ/kg·K	7.06		5.38		5.74	
Specific heat	J/kg·K	6978	2880	4956	6038	5257	6460
Expansivity	1/K	$5.17\cdot10^{-3}$	$1.74\cdot10^{-3}$	$2.09\cdot10^{-3}$	$3.71\cdot10^{-3}$	$2.54\cdot^{-3}$	$4.36\cdot10^{-3}$
Thermal conductivity	W/m·K	0.481	0.107	0.611	0.530	0.580	0.508
Dynamic viscosity	Pa·s	$7.28\cdot10^{-5}$	$3.55\cdot10^{-5}$	$10.12\cdot10^{-5}$	$8.24\cdot10^{-5}$	$9.23\cdot10^{-5}$	$7.81\cdot10^{-5}$
Kinematic viscosity	m^2/s	$11.63\cdot10^{-8}$	$52.47\cdot10^{-8}$	$12.93\cdot10^{-8}$	$11.90\cdot10^{-8}$	$12.38\cdot10^{-8}$	$11.75\cdot10^{-8}$
Diffusivity	m^2/s	$11.02\cdot10^{-8}$	$54.72\cdot10^{-8}$	$15.75\cdot10^{-8}$	$12.68\cdot10^{-8}$	$14.80\cdot10^{-8}$	$11.83\cdot10^{-8}$
Surface tension	N/m	–	–	$22.5\cdot10^{-3}$	0.0121	$16.7\cdot10^{-3}$	$8.77\cdot10^{-3}$
Prandtl number	–	1.06	0.96	0.82	0.94	0.84	0.99
Reynolds number ($\times10^6$) at G***=860 kg/m^{2}s, D_{hy}=8 mm	–	0.946	1.940	0.680	0.835	0.745	0.881
Nusselt number**** ($=0.023\cdot Re^{0.8}\cdot Pr^{0.4}$)	–	1418	2425	985	1225	1068	1308
Heat transfer coefficient	W/m^2·K	8527	3228	7522	8114	7744	8303

* All thermophysical properties of water were calculated according to NIST (2002).
** Critical point for water is 374°C and 22.12 MPa.
*** This value of mass flux corresponds to CANDU-SCWR operating conditions. Mass flux values in subcritical nuclear reactors are much higher; therefore, values of Reynolds number, Nusselt number and heat transfer coefficient will be also much higher in subcritical reactors.
**** Nusselt number is calculated using the Dittus-Boelter correlation (1930) for forced convective heat transfer in a circular tube as a first estimate only.

less than 1/3 of the UTS of the material. For an operating pressure of 25 MPa, and for a pressure tube of 120 mm inside diameter, the required wall thickness is about 6.5 mm.

Hydrogen from the coolant and deuterium from the moderator will enter a zirconium alloy pressure tube as a by-product of oxidation. Reference [16] showed that due to the low ingress rate at the low operating temperature and the high Terminal Solid Solubility (TSS) for hydrogen of Excel (Figure 3) [17], TSS will not be exceeded for the design life of a CANDU-SCWR pressure tube (assumed to be 30 years at 90% capacity factor). This eliminates one of the necessary conditions for Delayed Hydride Cracking (DHC), the only cracking mechanism that has been observed in zirconium pressure tubes in service.

Irradiation deformation of annealed Excel has shown much lower creep rates than cold-worked Zr-2.5Nb, the standard CANDU pressure tube material. At 300°C, the creep rate of annealed Excel is about 0.3 that of cold-worked Zr-2.5Nb (Table 3). Growth data also show that annealed Excel is about 30% more resistant compared with Zr-2.5Nb at this temperature [14].

A few in-reactor, bent-beam type stress relaxation tests were conducted at ~60°C, to a fluence of about 8×10^{24} n/m^2. Figure 4 plots the data of Excel and compared that with data from Zr-2.5Nb [15]. The creep coefficient, C, can be derived from these data, which is defined by the following equation:

$$\dot{\varepsilon} = C\sigma\phi \tag{1}$$

where

- $\dot{\varepsilon}$ is the plastic strain rate,
- ϕ is the irradiation flux and
- $\sigma = E\varepsilon$ is the stress in a specimen with modulus E, deformed to an elastic strain ε.

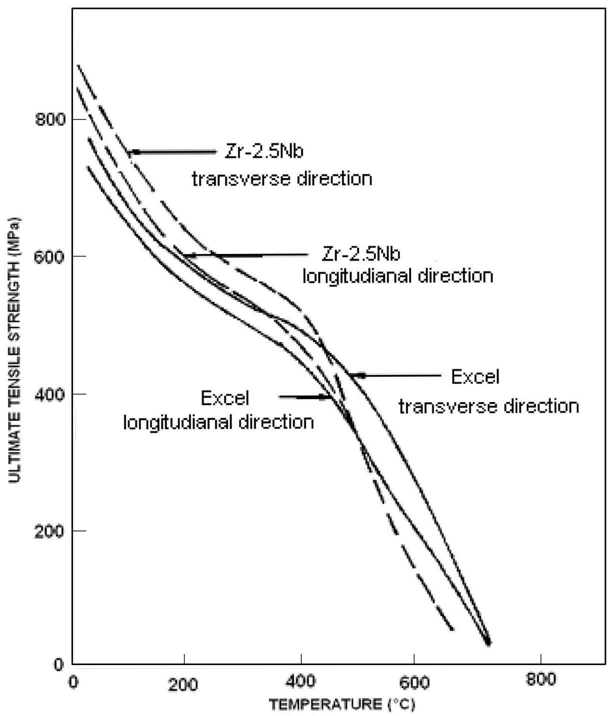

Fig. 2. Typical Ultimate Tensile Strengths of an Annealed Excel Tube as a Function of Temperature. Typical Curves for Cold-Worked Zr-2.5Nb are Also Shown

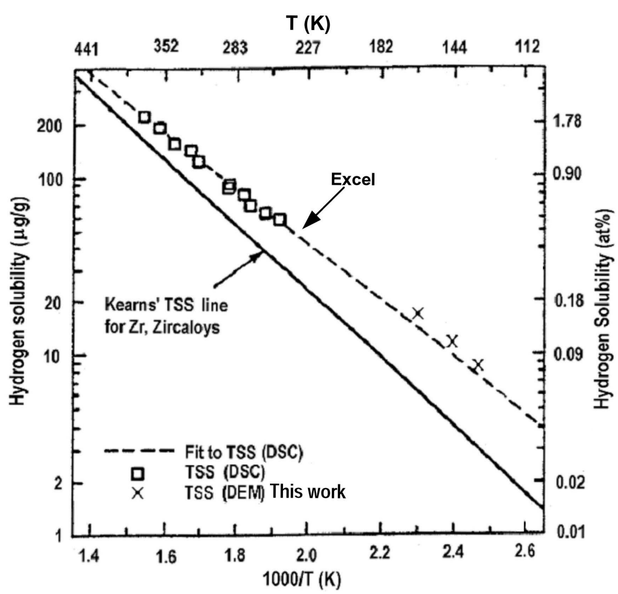

Fig. 3. TSSD for Excel Compared With That for Zr and Zircaloy [17]

The data show that the ratio of creep rate at this temperature is even lower at about 0.15. The significant reduction of the creep rate at 60°C from 300°C for annealed Excel is surprising, as most other materials show slight negative temperature dependence in this temperature range.

Although preliminary data indicate that the dimensional changes due to irradiation would be lower than the present CANDU reactors, systematic in-reactor tests are planned at low temperature to obtain the required data. Bent-beam type stress relaxation specimens and internally pressurized capsules will be tested at ~100°C.

2.1.1.2 Insulation Materials

The detailed performance requirements for the insulator will depend on the final design of the HEC. In general, the insulator must have excellent corrosion resistance and provide an effective thermal barrier that can withstand thermal stresses and cycling. It should also be dimensionally stable during irradiation. The insulator in the HEC design does not need to support the coolant pressure, but it must be able to bear the load of the fuel bundles.

Porous Yttria Stabilized Zirconia (YSZ) has been selected for further studies because it has low neutron cross-section, low thermal conductivity and very high corrosion resistance in SCW [18]. Many studies have shown that stabilized zirconia is exceptionally resistant to irradiation damage from fast neutrons and energetic ions. Limited data showed

Table 3. Ratios of Creep for CW Zr-2.5Nb and Annealed Excel at ~300°C [14]

	Ratio of Creep Rate
Cold Worked (CW) Zr-2.5Nb	1
Annealed Excel, longitudinal	0.32
Annealed Excel, Transverse	0.28

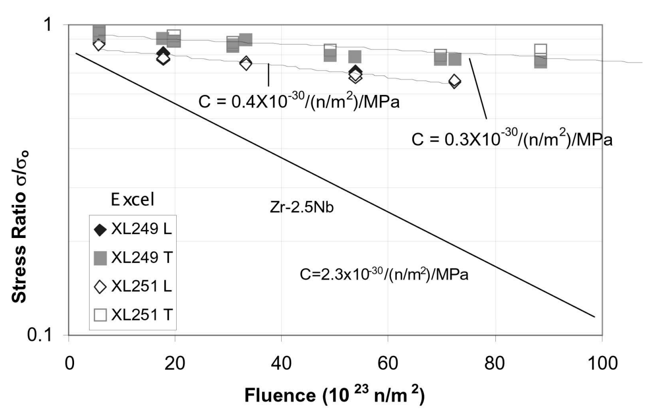

Fig. 4. Stress Relaxation Tests of Annealed Zr-2.5Nb [15] and Annealed Excel at 60°C. L and T indicate the Longitudinal and Transverse Direction of the Tube. C is the Creep Coefficient [15]

that irradiation would not significantly embrittle YSZ, at least at high temperatures [19]. No amorphization was observed in stabilized zirconia under neutron [19] or ion irradiation to a high displacement level [20, 21, 22]. These results are also supported by naturally existing radioactivity sources [23].

To increase the thermal resistance and improve on thermal shock resistance, porous YSZ with open pores is selected. As SCW has very low thermal conductivity (Figure 5) [24], changing the porosity of the YSZ can vary its strength and thermal conductivity. Experiments show that the yield strength of YSZ with 70% porosity is about 5 MPa, strong enough to bear the weight of the fuel bundles.

The thickness of the insulator will be chosen to meet the requirement that only about 1 to 2% of the thermal energy would be transferred to the moderator. No satisfactory correlations exist for predicting the effective thermal conductivity of porous material. Experimental determination will be necessary. A HEC test facility is available to measure the thermal properties of the HEC design, Figure 6.

A detailed heat lost calculation requires the dimensions of the fuel channel components and the effective thermal conductivity of the insulator as a function of temperature. As these are not yet available, a rough upper-bound estimate of the thermal conductivity and the thickness of the insulator can be as follows. It is assumed that the effective thermal conductivity k_e of a porous material is given by:

$$k_e = v_1 k_1 + v_2 k_2 \tag{2}$$

where

k_i is the thermal conductivity and

v_i is the volume fraction of the i^{th} component.

Using this assumption, the effective thermal conductivity of the YSZ (70% porosity) is:

$$k_e = 0.3 \cdot k_{ZrO_2} + 0.7 \cdot k_{H_2O} \tag{3}$$

where

k_{ZrO2} = 2.7 W/(m · K) is fairly constant in the temperature range of interest, and

k_{H2O} is a strong function of temperature as given in Figure 5.

Solving the heat transfer problem numerically, a wall thickness of about 7 mm will be required to restrict the heat lost to the moderator to about 1.5% of the thermal power of the fuel channel.

As the fuel bundles rest on the insulator, its creep properties need to be studied. The creep properties are a function of porosity, the microstructure of the material, and neutron flux. A systematic study to measure these parameters is underway, in the temperature range from 100 to 650°C.

2.1.1.3 Liner Tube Materials

The metal liner protects the insulator and provides a hard surface for the fuel bundles to slide and rest on. The metal liner is perforated so that the coolant pressure can be transmitted to the pressure tube. The metal liner will not be stressed other than from bearing the load of the fuel bundles. The material need not be overly strong, but it should have sufficient resistance to wear and fretting. The two most important requirements for this material are low corrosion and swelling rates. As there is no external stress on the liner tube, irradiation creep is not a concern.

There are several stainless steels that have adequate corrosion resistance. A large amount of work is being done world-wide on the corrosion of materials in SCW under the Generation IV programs [25, 26, 27, 28], mainly on Ni based alloys, ferritic-martensitic (F/M) materials and low-swelling stainless steels. Most Ni based alloys would

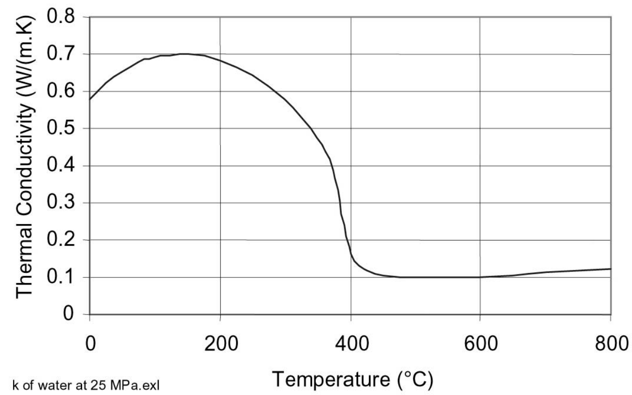

Fig. 5. Thermal Conductivity of Water as a Function of Temperature at 25 MPa [24]

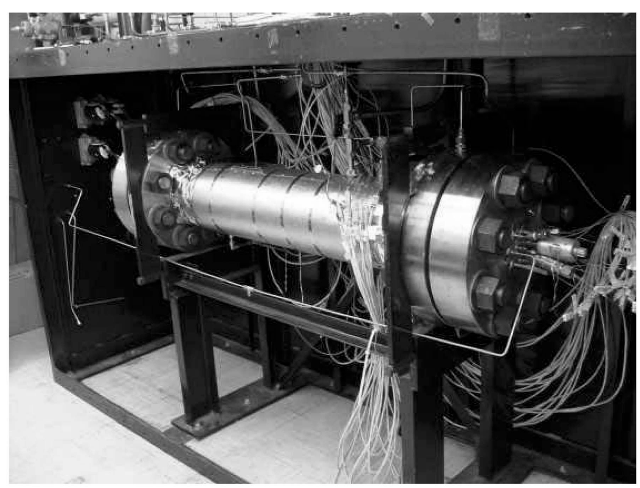

Fig. 6. HEC Test Facility to Test the HEC Design

become embrittled due to neutron irradiation. However, as there is no large load on the inner tube, irradiation embrittlement may not be a concern. F/M steels do not embrittle as much as Ni alloys, but they have higher oxidation rates compared with Ni based alloys. If corrosion rate is at a acceptable level, F/M steels are promising candidate materials for the liner tube. It has been shown that for irradiation between 300 - 710°C, void swelling is below 1% up to about 100 dpa [29]. Coating may be required to reduce the oxidation to acceptable levels. AECL is investigating corrosion resistant coating for SCWR applications [30].

So far, corrosion tests have been performed out of flux. In-flux studies with appropriate coolant chemistry will be required, as neutron irradiation can have significant effects on the behaviour of metals in SCW coolant.

2.2 The Re-Entrant Fuel Channel

AECL is also considering other fuel channel designs including the re-entrant type fuel channel shown in Figure 7.

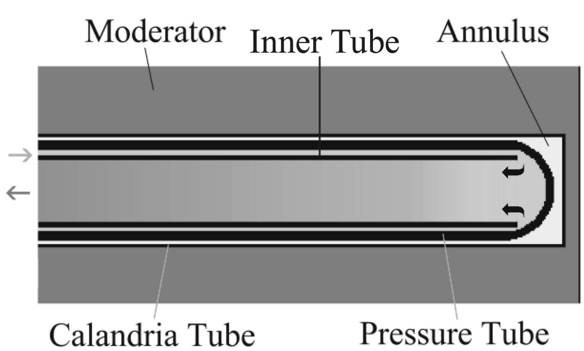

Fig. 7. Re-Entrant Type Fuel Channel for CANDU-SCWR.

The fuel channel consists of a pressure tube and a concentric inner tube. Similar to the current CANDU reactors, the pressure tube of this design is separated from the heavy water moderator by a gas annulus. SCW coolant flows first between a pressure tube and the inner tube. It turns around and flows through the inner tube, where the fuel resides. This design keeps the pressure tube at a temperature of about 350°C to 400°C.

2.2.1 Pressure Tube

Figure 2 shows that this temperature, zirconium alloys are possible candidates for the pressure tube material in terms of strength. The UTS of Excel is about 450 MPa at 400°C, and thus the pressure tube with 120 mm inside diameter would be about 10 mm thick to satisfy the ASME Codes. However, corrosion, hydrogen ingress, delayed hydride cracking and irradiation deformation require studies, as very little data on these properties are available at this temperature range. Corrosion increases with temperature. Coating would be required to reduce the corrosion rate and hydrogen ingress rate to acceptable level. AECL has shown that Cr plating is effective in reducing oxidation and hydrogen ingress at these temperatures [16]. Hydrogen ingress can also be controlled by alloying [31] or surface treatments (shot-peening, for example) other than coating.

Irradiation deformation is a strong function of temperature in this temperature range. However, there are little data for irradiation creep and growth at these high temperatures and more data are required for the final design of the fuel channel.

2.2.2 Inner Tube

The inner tube requires a high temperature corrosion resistant material similar to the liner tube of the HEC. As it is not required to bear any significant pressure difference, the inner tube can be made as thin as possible to improve neutron economy. However, because of that, a vertical fuel channel may be more practical for this fuel channel design, as the inner tube does not have the support of the insulator like that in the HEC. Similar materials as the liner tube in the HEC can be used for the inner tube, thus discussions in Section 2.1.1.3 also apply to the inner tube. As stated in Section 2.1.1.3, coating may be required to reduce the oxidation rate [30]. Although the main function of the coating is to reduce the oxidation rate, it can also be used to reduce the heat transfer to the SCW in the annulus, which would in turn, reduce the temperature of the pressure tube.

Another design to reduce thermal conductivity of the inner tube is to have a double-wall design for the inner tube. The thin double-walled inner tube wall will not be able to stand the pressure of the coolant without support. One conceptual design is to use the SCW as support. Small openings in the inside wall will allow SCW to get between the walls to equalize the pressure. The openings should be small enough to limit any significant movements of the SCW within the walls, but large enough that the water trapped between the walls should have enough time to move in and out due to temperature swing during start-up/shut-down, and operation of the reactor. Exact dimensions and numbers of these openings will depend on the heat-up and cool-down rates of the reactor. Stagnant SCW is a poor thermal conductor (Figure 5), and thus a thick insulating layer is not required.

3. FUEL CLADDING MATERIALS

The peak fuel clad temperature for the CANDU-SCWR is expected to be ~850°C [5]. At this temperature, zirconium alloys will not be suitable because of the low strength and high oxidation rate.

If neutron economy can be relaxed due to uranium enrichment, stainless steel can be used as a fuel cladding material. AECL is studying the corrosion properties of various alloys including F/M steels. For fuel sheathing applications, high Cr alloys may provide higher strength and better corrosion resistance. Oxide Dispersion Strengthened (ODS) F/M alloys may also provide the required low swelling rate and strength for fuel claddings [32].

Welding of ODS can be a challenge. Properties of the weld and the heat affected zone after irradiation will require study. In-reactor corrosion tests and irradiation creep and growth data are also required for these alloys.

4. DISCUSSION

Neither the insulated pressure tube nor the re-entrant fuel channel concepts are completely new ideas. The ideas have been proposed by AECL and other organizations since 1960s. Two prototype reactors were constructed using these ideas.

The insulated pressure tube design was used in the EL4 reactor in France. The EL4 reactor was a CO_2 cooled, heavy water moderated, 250 MW thermal, 70 MW electrical reactor [33] operated from 1967 to 1985. The heavy water moderator operated at ~60°C and was in contact with the pressure tube, the same as for the HEC. The CO_2 coolant pressure was ~6 MPa [33] much less than the 25 MPa proposed for CANDU-SCWR. A decree authorized partial dismantling of the EL4 reactor in 1996 and decommissioning is still ongoing today.

Re-entrant type fuel channel design have been constructed and operated in Russia [34]. These vertical fuel channels operated at temperatures up to 550°C and the design life of these fuel channels is only 5 to 7 years. With advances in the development of materials, it is expected that the operating temperatures and design life can be extended.

The reactor design of the REC is more complicated than the HEC. As the inlet and outlet are at the same side of the channel, the piping and fittings of the REC are more congested than the HEC design. As indicated in the forgoing, it is more practical to use vertical fuel channels for this design, as the thin inner tube is not supported. To take advantage of natural circulation as a passive safety measure under accident conditions, the outlet of a vertical channel should be at the upper end. In such a case, the coolant density variations in the reactor core need to be taken into account in the reactor core design, which makes the reactor design more complex.

5. SUMMARY

This paper reviews two fuel channel designs of the CANDU-SCWR and their preliminary material selections. Data supporting these material selections are presented and R&D plans to obtain the yet unavailable data are outlined.

The preliminary data for the selected materials indicate that the CANDU-SCWR fuel channel designs are feasible.

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