CANDU WITH SUPERCRITICAL WATER COOLANT: CONCEPTUAL DESIGN FEATURES

by
N. Spinks

AECL
Chalk River Laboratories

Introduction

An advanced CANDU reactor, with supercritical water as coolant, has many attractive design features. The pressure exceeds 22 MPa but coolant temperatures in excess of 370°C can be reached without encountering the two-phase region with its associated fuel-dry-out and flow-instability problems. Increased coolant temperature leads to increased plant thermodynamic efficiency reducing unit energy cost through reduced specific capital cost and reduced fueling cost. Increased coolant temperature leads to reduced void reactivity via reduced coolant in-core density. Light water becomes a coolant option. To preserve neutron economy, an advanced fuel channel is needed and is described below. A supercritical-water-cooled CANDU can evolve as fuel capabilities evolve to withstand increasing coolant temperatures.

CANTHERM Fuel Channel

With a conventional CANDU fuel channel, an increase in coolant pressure and temperature would require an increase in pressure-tube thickness and a loss of neutron economy. To preserve neutron economy, especially at high coolant temperatures, a change in fuel channel design is needed. The CANTHERM insulated fuel channel, shown in figure 1, is currently under development at AECL. It has no calandria tube and the pressure tube, in contact with the cool heavy-water moderator, is insulated from the high-temperature coolant. Such a fuel channel could be employed to increase coolant temperatures and pressures in a conventional CANDU primary heat transport system or it could be employed in a redesign at supercritical coolant conditions.

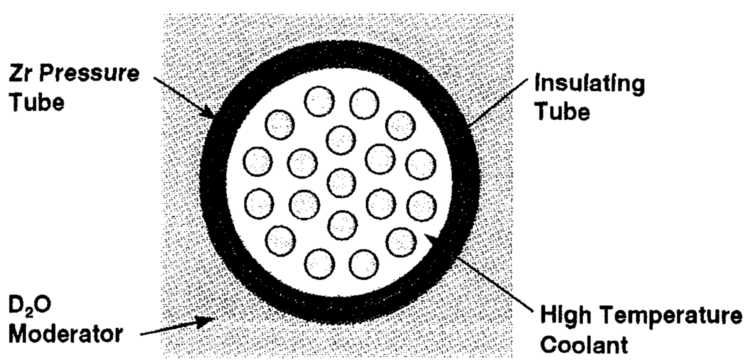

Figure 1: CANTHERM Insulated Fuel Channel

Supercritical CANDU Evolution

Figure 2, based on the properties of light water, illustrates how CANDU could evolve in terms of coolant temperature and enthalpy from conventional pressures and temperatures to supercritical pressures and temperatures. Two stages of development of a supercritical-cooled CANDU have been chosen with coolant core-mean temperatures near 400°C and 500°C. These are dubbed Mark 1 and Mark 2 respectively. They are based on heavy or light water coolant at a nominal pressure of 25 MPa. Mark 1 transfers heat from a heavy water primary system to a light water secondary system at 19 MPa and is expected to operate with conventional or near-conventional zirconium alloy clad fuel. Mark 2 requires advanced fuel and operates with heavy water to light water or light water to light water in an indirect cycle or with light water in a direct cycle. The Mark 1 concept has been developed further and is the subject of this paper.

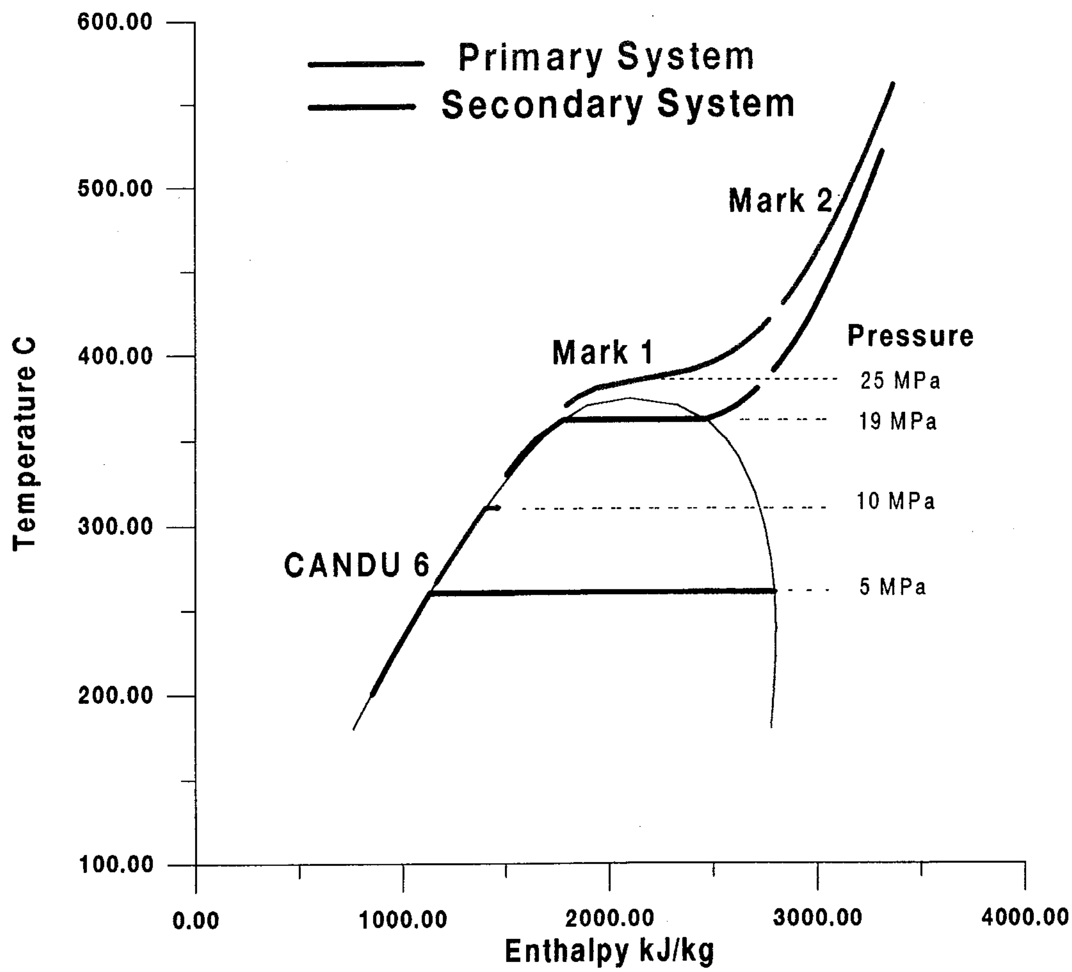

Figure 2: CANDU Evolution to Supercritical Coolant Conditions

Mark 1 Design

The initial calculations for the Mark 1 design were based on heavy water at 25 MPa between 370°C at core inlet and 420°C at core outlet, transferring heat to H_2O at 19 MPa heated from 330°C to 380°C in a once-through counter-current-flow steam generator. These results are reported below. However some advantage in control exists, also discussed below, when the outlet temperatures are increased to 430°C for the core and to 400°C for the steam generator.

Flow, Pressure Drop and Pumping Power

At in-core temperatures around 400°C, i.e. just above the critical temperature of 370°C, the exceptionally high specific heat leads to an attractive heavy-water-cooled design. High specific heat leads to greatly reduced mass flow, pressure drop and pumping power. The enthalpy changes of figure 2 lead to a channel flow 30% of CANDU 6 for the same channel power. Channel pressure drop would be similarly reduced. Primary pumping power would be reduced by factor 6, not only because of the reduced mass flow and pressure drop, but also because of a high coolant density (0.6 g/cc) at the pumps. A rapid density reduction in the core leads to a greatly reduced core-mean density, as discussed below.

Peak Fuel Clad Temperature

High specific heat near the critical point leads to high heat transfer coefficient and modest fuel clad temperatures. These were calculated as follows:
The peak clad temperature was evaluated at the nominal maximum power for a CANDU 6 fuel element and at a coolant temperature of 400°C. From figure 2 it is seen that this temperature will occur at a position towards the outlet end of the channel. The nominal maximum power of 50.7 kW/m for an outer element was taken from a CANDU 6 safety report. Fuel bundle geometric details are for 37 element fuel.

The fuel-to-coolant heat transfer coefficient was calculated using equation 3 of reference 1. The clad to coolant temperature difference is only 50°C, even at the reduced channel flow, leading to a clad nominal maximum temperature of 450°C. Clad corrosion rates should be acceptable at these temperatures, but further investigation is needed on the corrosion and general behaviour of conventional or near-conventional CANDU fuel under such conditions of steam cooling at high pressure and high temperature.

Void Reactivity and Thermodynamic Efficiency

At the Mark 1 temperatures of figure 2, the core-mean coolant density is 0.28 g/cc leading to a heavy-water void reactivity reduced from 15 mk to about 4.5 mk. At the

thermodynamic mean temperature[1] of 360°C on the secondary side of the steam generator, the Carnot efficiency is 1.21 times that of CANDU 6 leading to an 18% cost reduction.

Heavy-Water Inventory and Primary Pressure Control

The coolant core-mean density of 0.28 g/cc could lead to a 70 % reduction of coolant inventory at full power. However, additional heavy water might be needed to fill the PHTS at reduced power, especially in the cold shutdown condition. Two options are discussed below aimed at avoiding such a need and leading to a 3% additional capital cost reduction.

Option 1 Helium

Pressure could be controlled with a helium over heavy water pressurizer as shown in figure 3. On cold shutdown, helium would enter the large piping and steam-generator piping, to accommodate heavy water shrinkage, but there would be sufficient heavy water to fill headers, feeders and fuel channels.

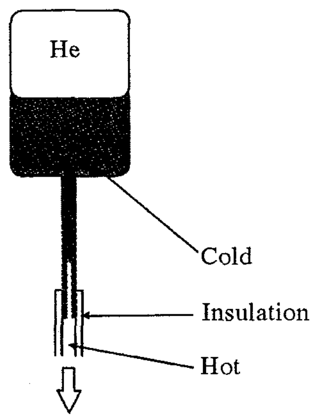

Figure 3: Helium Pressurizer

Start up could be done with nuclear heat or with an external heat source. With nuclear heat, after going critical, the next step would be to raise temperature at low power. As the heavy-water boils at lower pressures, steam and helium would flow to the pressurizer where the steam could be condensed, purging helium from the heat transport system. When operating pressures and temperatures are reached, pumping could start, enabling power to be increased.

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[1] Tmean = change-in-enthalpy / change-in-entropy where the changes apply over the secondary side of the steam generator.

A LOCA, during start up, could be problematic. At lower temperatures, the coolant in-core density is high holding up significant reactivity and, at high pressure, a fast blowdown might be expected. Even starting from low power, the rapid rate of insertion of reactivity could lead to an excessive power pulse.

Cool down is envisaged in a reversal of the start up sequence. Thus, at a decay power sufficiently low to permit fuel cooling by hot stagnant supercritical water, pumps could be turned off and cool down commenced via heat transfer to the moderator. A two-phase coolant condition could be avoided by controlling helium pressure to above the saturation pressure. This may be desirable to avoid, for example, stratified flow in horizontal fuel channels.

At the cold shutdown condition, the additional channel coolant inventory would reduce reactivity by some 10 mk but cold start up could always be done with low xenon levels in the core so there would always be plenty of reactivity available. Reactivity would be gained as operating temperatures are reached but would be readily controlled at low power.

High pressure helium control is likely to lead to diffusion of helium into the heavy water coolant with potentially deleterious effects. For example helium is likely to degrade the heat transfer from fuel to coolant. It could also degrade pump performance but this may not be too important for Mark 1 with its modest flow requirements. Loop tests would be needed in any development of this option.

Another difficulty with helium is its containment. The gas is notorious for diffusing through all materials, including metals, and it will tend to leak out of the pressurizer at the high pressures of Mark 1.

Option 2 Heavy Water Transfer Between Moderator and Primary System

This idea is to transfer heavy water from the moderator to the PHTS to accommodate primary system shrinkage during cool-down. It presents problems with tritium releases from higher PHTS tritium levels and with the cost of higher PHTS heavy water isotopic concentration. However the latter could be compensated by the use of a common heavy-water upgrader. Conventional PHTS pH levels are different than that in the moderator in order to control corrosion of carbon steel PHTS piping. However this may not be an issue with Mark 1 because stainless steel ex-core piping is likely needed at the higher coolant temperatures.

A disadvantage with transfer of heavy water from the moderator is impairment of the moderator heat sink. The CANTHERM fuel channel potentially improves the moderator heat sink to the extent that it could provide effective maintenance cooling. With transfer of heavy water to the PHTS, cooling could still be provided but with sprays and reliance on a/c power. Mark 1 would not be passive.

With reduced moderator inventory, the reactor could not be started on nuclear heat. However the PHTS would be full and could be heated on pump heat augmented if necessary by external heaters. The hot heavy water would have to be cooled during transfer to the moderator. Once operating temperatures are attained, the reactor could go critical, pumps started and power raised.

A conventional electrically-heated pressurizer cannot effect much of a change in pressure for water at the outlet temperature of 420°C. However it could be used at 400°C when connected to the inlet header or pump-suction header. With the inlet water at 370°C and the pressurizer set at 400°C, a small change in pressurizer temperature will effect a big change in pressure. The pump-suction header connection is preferred because, in the event of a pump trip, the hot end of the fuel channel would not see additional pressure.

The pressurizer would not have a liquid level to use for inventory control but the temperature itself might be usable. A loss of inventory would reduce the fluid specific volume in the pressurizer which, at constant pressure, requires an increase of temperature. So if the pressurizer temperature increases, add heavy water.

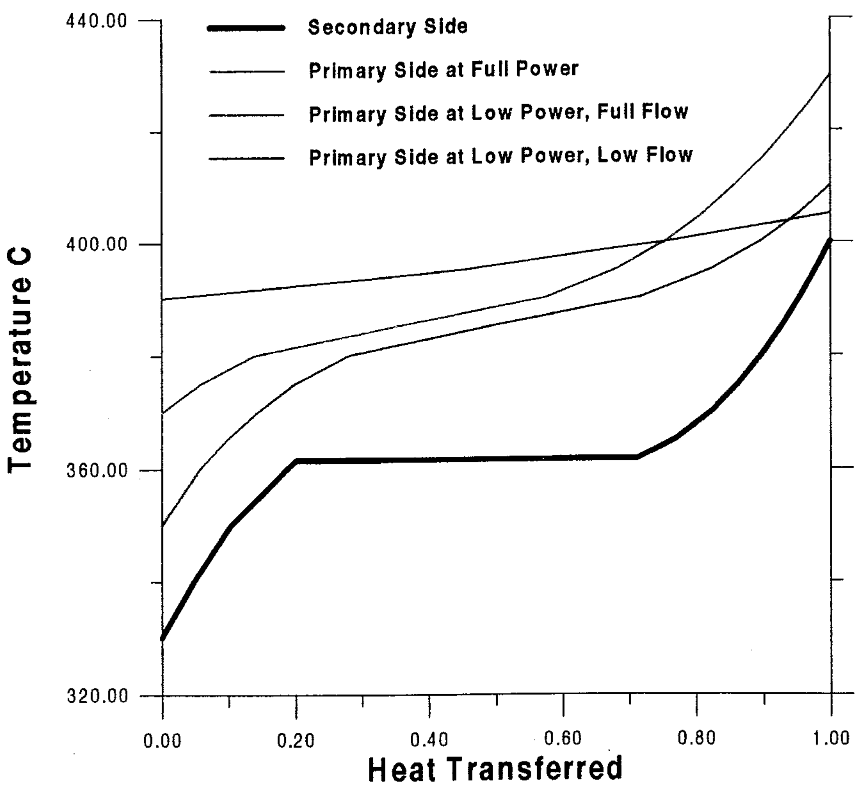
Secondary Pressure and Temperature Control

On the secondary side, pressure control could be done via the usual reactor power or turbine governor-valve control. For the Mark 1 once-through steam generator, in place of conventional boiler level control, feed-water flow could be varied to control the degree of steam superheat thereby maintaining the turbine inlet condition. It is expected that this would lead to a feed-water flow closely proportional to thermal power thereby maintaining a near constant temperature profile on the secondary side of the steam generator.

Primary Flow and Temperature Control

Consider maintaining full primary-side pumping from low to full power and consider permitting primary temperatures to simply follow secondary temperatures.

Figure 4 shows temperature variations in the once-through steam generator. Data are plotted from light-water steam tables for the secondary side at 19 MPa and the primary side at 25 MPa. The primary and steam-generator hot side temperatures are increased somewhat from those considered above. Various primary-side curves are shown in colour with the full-power case shown in red.



Steam Generator Temperature Distributions
Figure 4

By maintaining full pumping throughout the power range, at low power the entire primary circuit will come to a temperature just above the secondary superheated steam temperature, as shown in the green curve of figure 4. The core-mean coolant temperature at low power will be higher than that at full power and the power to reactivity coefficient from coolant density will be negative in spite of the "positive" void coefficient. On the other hand if flow were made proportional to power, the primary temperatures would be reduced, at low power, as shown in the blue curve of figure 4. This would lead to a larger

coolant inventory at low power and an inventory that would be clearly reducing as power is raised. The power to reactivity coefficient from coolant density would be clearly positive.

Conclusion

A heavy-water-cooled CANDU design at supercritical temperatures and pressures becomes possible with the advanced CANTHERM fuel channel and provides a plant with increased thermodynamic efficiency and reduced coolant density without troublesome two-phase flow phenomena such as fuel dry out and flow instability. The reduced density leads to reduced heavy-water inventory and reduced void reactivity.

A first stage "Mark 1" conceptual design of a supercritical heavy-water-cooled CANDU reactor has been described. The coolant core-mean temperature of about 400°C leads to a reduction in unit energy cost of about 20% compared with conventional CANDU designs. It also leads to a void reactivity reduced by a factor 3 from conventional values. Reduced coolant inventory should result in a further 3% cost reduction. High coolant specific heat leads to a reduced mass flow, again by a factor 3, and a pumping power requirement reduced by factor 6. High coolant specific heat leads to good heat transfer from fuel to coolant, even at the reduced flow, resulting in a peak fuel clad temperature of only 450°C. Mark 1 is expected to be able to use near-conventional CANDU fuel.

Reference

1. Yamagata et al, "Forced Convective Heat Transfer to Supercritical Water Flowing in Tubes", Int. J. Heat Mass Transfer, Vol. 15, 1972.