AN ADVANCED CANDU REACTOR WITH SUPERCRITICAL WATER COOLANT: CONCEPTUAL DESIGN FEATURES

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ABSTRACT

AECL is studying an advanced CANDU reactor concept, with supercritical steam as coolant. The coolant, being a high density gas, at a pressure above 22 MPa and temperatures above 370°C, does not encounter the two-phase region with its associated fuel-dryout and flow-instability problems. Increased coolant temperature leads directly to increased plant thermodynamic efficiency, thereby reducing unit energy cost through reduced specific capital cost and reduced fuelling cost. The reduced coolant in-core density leads to sufficiently reduced void reactivity, so that light water becomes a coolant option. The use of supercritical water coolant also opens up the possibility of enhanced safety with a natural circulation primary flow, taking advantage of the gas expansion coefficient.

To preserve neutron economy, especially at high coolant temperatures, a fuel channel that is currently being developed has a pressure tube that is thermally insulated from high-temperature coolant and is in contact with the cold heavy-water moderator. Two stages of development of a supercritical-cooled CANDU reactor were identified. The first uses conventional or near-conventional zirconium-alloy fuel cladding with coolant core-mean temperatures near 400°C, and the second uses advanced high-temperature fuel cladding at coolant core-mean temperatures near 500°C.

A first-stage cost reduction of 20% from the CANDU 6 design is estimated as a result of improved thermodynamic efficiency. A large change in coolant density across the core leads to a factor 3 or 4 reduction in heavy-water inventory and a corresponding reduction in coolant void reactivity. The latter leads to improved fuel burnup and reduced demands on the safety shutdown systems.

INTRODUCTION

The dominant objective of the supercritical advanced CANDU reactor is a major decrease in the unit energy costs so that, at the time of introduction, it will be able to compete with combined cycle gas turbine plants. CANDU costs, both capital and fuelling, are to a first approximation inversely proportional to the plant thermodynamic efficiency, which is governed by the core-mean coolant temperature. Significant improvements in the core coolant temperature require either a change in coolant (e.g., molten salt, liquid metal or high-temperature organic) or operation in the supercritical regime with water as the preferred option.

Studies of light-water reactors (LWRs) operating with supercritical light water are currently underway in Japan and Russia and show that such reactors are feasible with current technology or modest extrapolations of current technology. For example, fuel cladding of stainless steel or Inconel 625 is envisaged. The Russian concept (Silin et al., 1993) would utilize primary- and secondary-coolant circuits, whereas the Japanese concepts (Oka et al., 1993, 1995) would utilize a direct cycle. Moreover, the

Japanese studies address both thermal and fast reactors (Oka et al., 1993, 1995; Jevremovic and Oka, 1995).

With a conventional CANDU fuel channel, an increase in coolant pressure would require an increase in pressure-tube thickness and a loss of neutron economy. To preserve neutron economy, especially at high coolant temperatures, an insulated fuel channel, called CANTHERM, is being developed. It has the option of having no calandria tube with the cold pressure tube in contact with the heavy-water moderator, and is insulated from high-temperature coolant. Operating conditions that keep the pressure tube cold increase both the strength and the creep resistance of the pressure tube so that no neutron economy penalty is anticipated as a result of the higher coolant pressure. Such a fuel channel could be employed to increase coolant temperatures and pressures in a conventional CANDU primary-heat-transport system (PHTS) or it could be employed, as envisaged here, in a redesign for supercritical coolant conditions.

Two stages of development of a supercritical-cooled CANDU reactor have been chosen. The first uses conventional or near-conventional zirconium-alloy-clad fuel with coolant core-mean temperatures near 400^{o}C, and the second uses advanced high-temperature, possibly ceramic-clad fuel at coolant core-mean temperatures near 500^{o}C. At fuel-cladding temperatures beyond 500^{o}C, the rate of corrosion of zirconium-based-cladding will be prohibitive requiring significant fuel design change. Stainless steel or nickel-based fuel cladding could be used but would reduce neutron economy. One idea being pursued is to protect the zirconium alloy by means of a corrosion-resistant coating. Recent advances in plasma-spraying technology, for example, permit a uniform and adherent layer to be produced without affecting the properties of the substrate. Another idea for even higher temperatures is an all-ceramic fuel bundle, for example, using the silicon-carbide matrix-composite fuel cladding that is being developed for high-burnup LWR fuel (Tulenko et al., 1997).

A first-step cost reduction of 20% from the CANDU 6 reactor is projected as a result of improved thermodynamic efficiency. A large reduction in the mean coolant density in the core leads to a factor 3 or 4 reduction in heavy-water inventory and a corresponding reduction in coolant void reactivity. The latter leads to improved fuel burnup and reduced demands on the safety shutdown systems.

SUPERCRITICAL CANDU DESIGN

Figure 1, based on the properties of light water, illustrates how the CANDU design 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 reactor have been chosen with coolant core-mean temperatures near 400^{o}C and 500^{o}C, labelled 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 main subject of this paper.

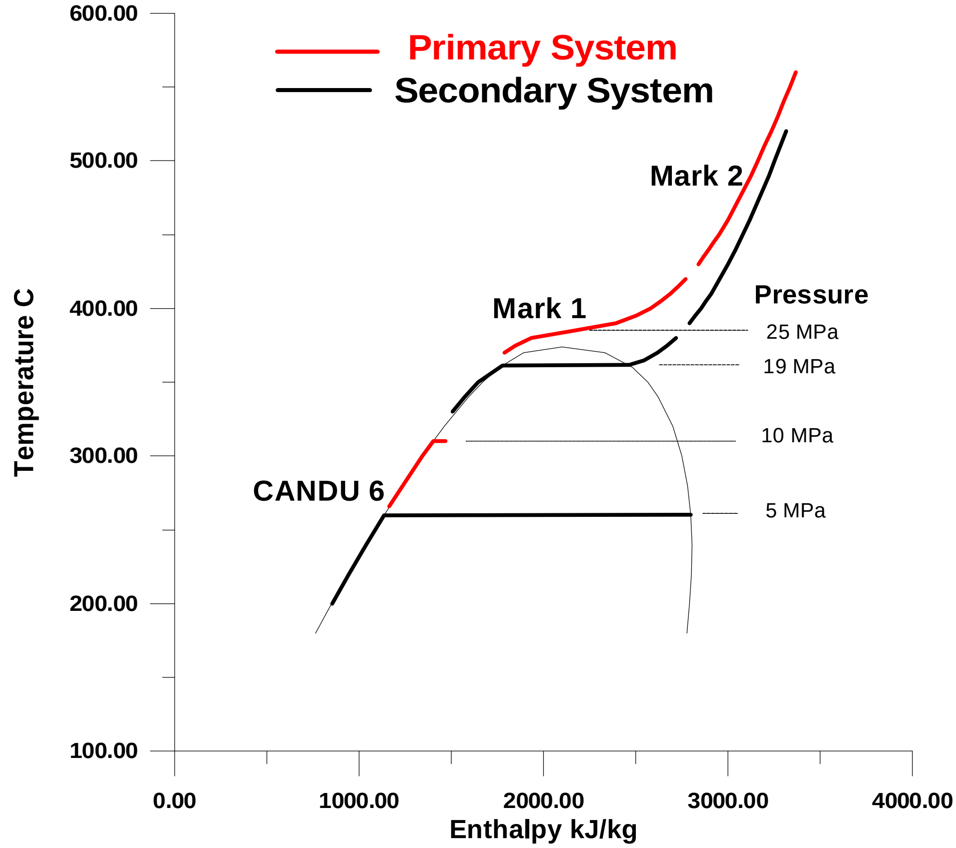

Figure 1: **CANDU Evolution to Supercritical Coolant Conditions**

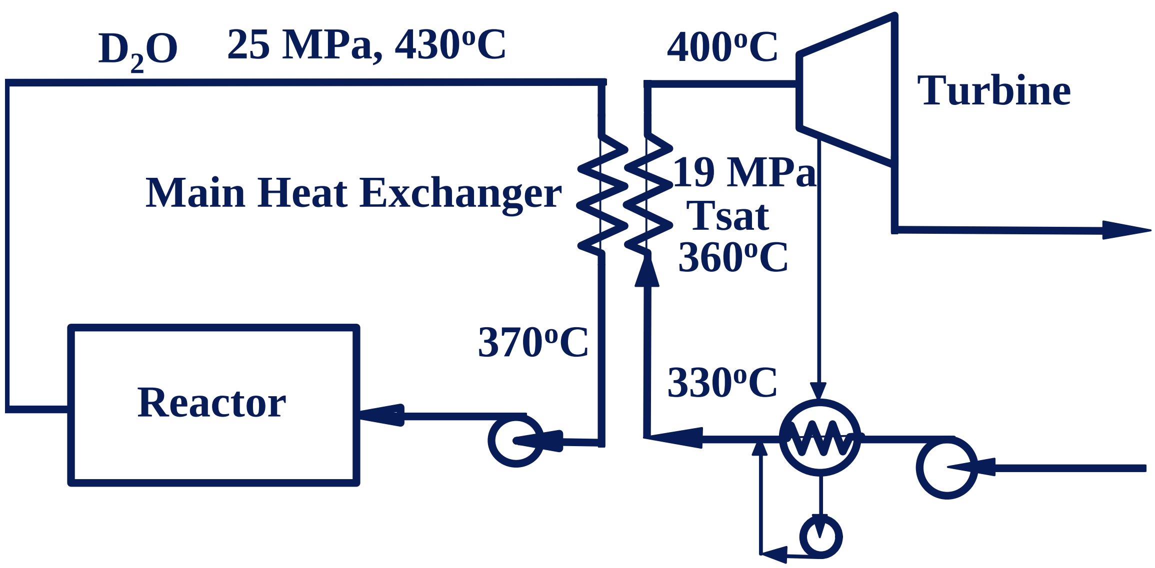

Figure 2: **Indirect Cycle**

The Mark 1 circuit design, shown in Figure 2, is similar to a conventional CANDU circuit design, except for the steam generator, which becomes a supercritical heat exchanger. 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, which was heated from 330°C to 380°C in a once-through counter-current-flow steam generator.

Water has a high specific heat near the critical point, and this feature leads to a factor of 3 increase of the core enthalpy change and a corresponding factor of 3 reduction in channel flow, compared with the CANDU 6 values, for the same channel power and core temperature rise. A small core temperature rise is important because it leads to reduced outlet temperature for a given core-mean temperature, which is important insofar as materials are considered. At 400°C, the mid-core D_2O density of 0.2 g/cc leads to a void reactivity of about 4 mk. The flow reduction leads to reduced pressure drop and greatly reduced pumping power even with the reduced coolant density.

The high specific heat also leads to high heat transfer coefficients from fuel to coolant, and fuel cladding temperatures are expected to remain within the corrosion limits for Zr.

High heat transfer coefficients are also expected in the steam generator leading to economical heat transfer surface area requirements. The steam-generator temperature profiles, shown in Figure 3, are based on a once-through countercurrent flow steam generator.

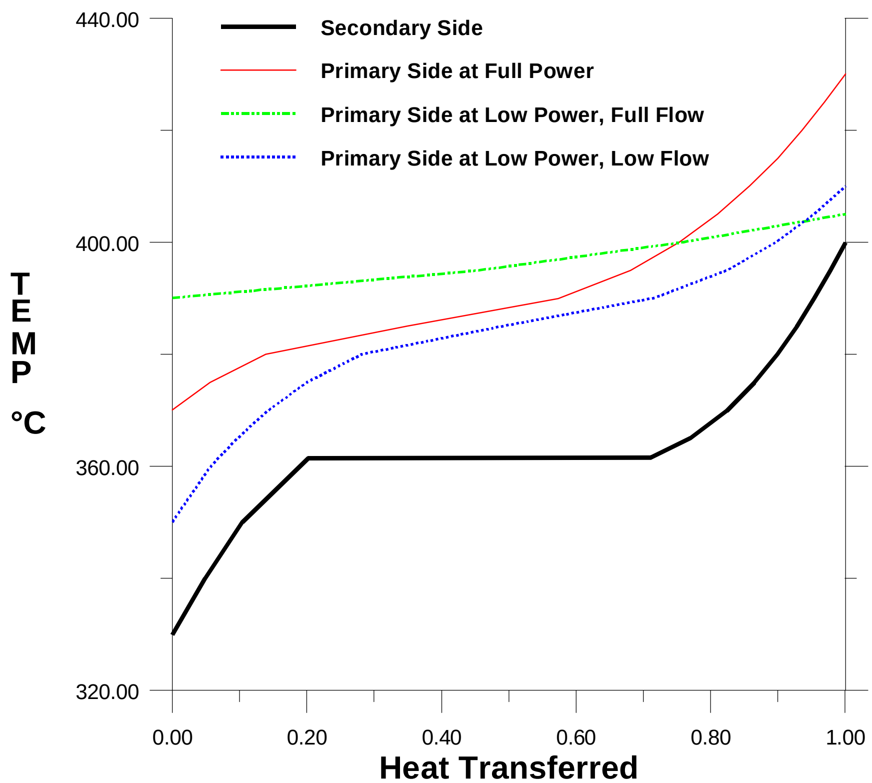

Figure 3 Steam Generator Temperature Distributions

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 1 lead to a channel flow that is 30% of the CANDU 6 value for the same channel power. Channel pressure drop would be similarly reduced. Primary pumping power would be reduced by a factor of 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-Cladding Temperatures

High specific heat near the critical point leads to high heat transfer coefficients and modest fuel-cladding temperatures. The first estimates were made for a standard 37-element bundle geometry operating at a maximum outer-element power of 50.7 kW/m, and a coolant temperature of 400^{o}C. The fuel-to-coolant heat transfer coefficient was calculated from Yamagata et al., 1972. The cladding-to-coolant temperature difference was only 50^{o}C, even at the reduced channel flow, resulting in a cladding nominal maximum temperature of 450^{o}C. The cladding temperatures could be further reduced by using the 43-element CANFLEX fuel.

Void Reactivity and Thermodynamic Efficiency

At the Mark 1 temperatures of Figure 1, the core-mean coolant density is 0.28 g/cc leading to a heavy-water coolant void reactivity of about 4.5 mk. At the thermodynamic mean temperature[1] of 360^{o}C on the secondary side of the steam generator, the Carnot efficiency is 1.21 times that of the CANDU 6 Carnot efficiency leading to, as a first approximation, 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. An option aimed at avoiding such a need and which could lead to a 3% additional capital cost reduction, would use a helium over heavy-water pressurizer. 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. Startup, in this case, would be done with nuclear heat or with an external heat source. With nuclear heat, after going critical, the temperature would be raised at low power. As the heavy water boils at lower pressures, steam and helium would flow to the pressurizer where the steam would be condensed, purging helium from the heat transport system. When operating pressures and temperatures are reached, pumping would start, enabling power to be increased.

Secondary Pressure and Temperature Control

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

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

Primary Flow and Temperature Control

Currently, the preferred option is to maintain full primary-side pumping from low to full power and allow the primary-side temperatures to simply follow secondary-side temperatures. Figure 3 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.

By maintaining full primary-side flow 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 dashed curve of Figure 3. At low power, the core-mean coolant density will be lower than at full power, and the power to reactivity coefficient from coolant density will thus be negative.

VARIATIONS ON MARK 1

The Mark 1 design, as described above, can be varied to improve cost or improve safety. Cost can be improved in a direct-cycle, light-water-cooled design, made possible by increased pumping power permitting increased core inlet temperature. Safety can be improved by employing natural circulation in the primary system.

Direct-Cycle Light Water

Increases in core inlet temperature beyond the 370^{o}C level, discussed above for the Mark 1 design, lead to reduced coolant inlet density and extra pumping power. The return on thermodynamic efficiency is modest leading to modest gains in cost in a heavy-water-cooled indirect cycle. However, gains are more dramatic if the reduced coolant density and reduced void reactivity permit a change in coolant to light water employed in a direct cycle. This possibility has been explored within the CANDU 6 constraints of channel power, pumping power and void reactivity and with fuel cladding temperature limited to 500^{o}C.

A first-order algebraic model of such a plant has been formulated characterizing pressure drop by the sum of pressure drop in the inlet and outlet feeders and using values from Yamagata et al., 1972, for fuel-to-coolant heat transfer. Thermodynamic efficiency was estimated using the thermodynamic mean temperature of heat addition to the working fluid. The direct cycle has the advantage of using the core-mean temperature rather than mean temperature on the secondary side of a steam generator. Void reactivity was calculated using WIMS-CRNL (Donnelly, 1996) and was dependent on light-water coolant density and temperature.

The above constraints are met at a pressure of 25 MPa with coolant inlet and outlet temperatures of 393^{o}C and 450^{o}C respectively or at a pressure of 23 MPa with coolant inlet and outlet temperatures of 382^{o}C and 440^{o}C respectively. The Carnot efficiency is 1.32 times the Carnot efficiency of a CANDU 6 reactor.

With a return to CANDU 6 void reactivity, this design would not have the reduced void reactivity of the heavy-water-cooled Mark 1 design, and the rate of change of void reactivity in for example a LOCA would be an issue to be resolved. However, an eventual relaxation of the fuel temperature restraint would permit reductions in void reactivity, so the direct-cycle light-water option is, at least, of eventual interest.

Natural Circulation Design

The use of supercritical fluid, which approximates a perfect gas at high density, provides a different primary-flow option. Using the conventional analysis for a single-phase thermosyphon, it can be shown that the supercritical fluid provides a much larger thermal expansion coefficient (proportional to the inverse absolute temperature) when utilizing a constant pressure heat exchanger (HE) cycle. The fluid is heated in the core, flows under buoyant forces to the HE, and is there cooled to near the HE outlet temperature.

Thus the design expression for the reactor power Q, in a supercritical loop becomes:

$$Q \approx h^{3/2}\left(\frac{Ac_P P}{G}\right)\left(\frac{2g\Delta L}{K}\right)^{1/2}$$

The reactor power, Q, is given by the expression for a flow area, A, loop loss coefficient, K, operating pressure, P, and elevation difference, ΔL, and the efficiency of the loop appears as $h^{3/2}$ showing the importance of a high thermal efficiency. The reactor power output is then linked directly to the HE outlet temperature, via the primary-side density change coupling with the reactor flow (G).

CHANNEL AND FUEL

CANTHERM 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 (patent pending) insulated fuel channel, shown in Figure 4, 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. In addition to the supercritical application, such a fuel channel could be employed to increase coolant temperatures and pressures in a conventional CANDU PHTS.

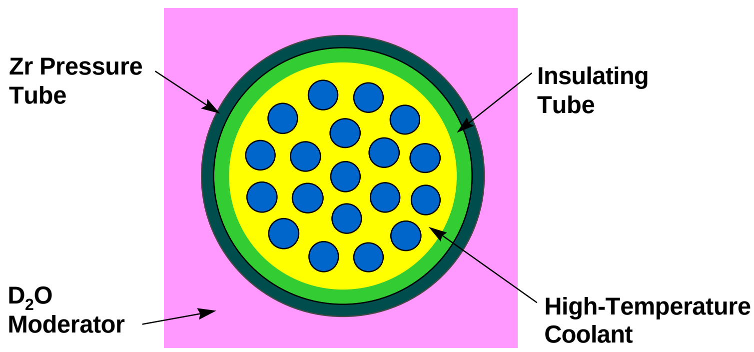

Figure 4: CANTHERM Insulated Fuel

Fuel

The Japanese study uses Inconel cladding to obtain acceptable corrosion rates at fuel-cladding temperatures up to 600°C. Because neutron economy is a requirement, this option is not open to the CANDU design, and thus a supercritical CANDU reactor cannot afford the luxury of Ni- or Fe-based fuel-cladding materials. It is probable that zirconium-based cladding can be used at the lower temperatures, but at higher temperatures more exotic ceramics are utilized.

Zirconium alloy-clad UO_2 pellets

Zirconium at 600°C in steam suffers on one major ground: corrosion caused by oxidation. Creep strength is a secondary issue and could probably be overcome by using fibre (say SiC fibre) reinforcement. Uranium dioxide clad with various zirconium alloys has been operated successfully in superheated steam coolant at a sheath temperature of 500°C. After 6 months of irradiation, the zirconium oxide thickness was 12 μm. This would indicate a metal loss of 5 to 10% of the wall thickness over 2 years.

An alternative possibility is the use of a thin metallic-alloy-coated Zr-alloy cladding. We have had some success with coatings of chromium on Zr-2.5Nb by electroplating or plasma spraying and with coatings of diamond-like carbon on Zr-2.5Nb by laser ablation. These coatings are currently being tested in a high-temperature autoclave.

Ceramic-Clad UO_2

Silicon carbide cladding is being developed for high-burnup LWR fuel (Tulenko et al., 1997). A concern with a ceramic cladding is a lack of toughness and possible failures resulting from tensile forces arising from coolant turbulence, and pellet and fuelling machine interactions. A ceramic cladding would have to be free-standing, or it would crack and fail as a result of fuel thermal expansion. The compressive stresses arising from coolant pressure could well overcome any tensile forces, so the use of ceramics should not simply be precluded on the grounds of brittleness. Also note that toughness can be increased by using fibre reinforcement. Currently, a ceramic-clad fuel design is still in the conceptual stage. It is not expected to be needed for the Mark 1 design but will be necessary if the coolant temperatures are increased to 500°C and beyond.

CONCLUSIONS

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 dryout. 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. Reduced coolant inventory could result in a further 3% cost reduction. It also leads to a void reactivity reduced by a factor of 3 from conventional CANDU values. High coolant specific heat leads to a reduced mass flow, again by a factor of 3, and a pumping power requirement reduced by factor of 6, with an option for natural circulation. High coolant specific heat leads to good heat transfer from fuel to coolant, even at the reduced flow, resulting in a peak fuel-cladding temperature of only 450°C. Materials compatibility problems are severe and will require intensive materials development over a number of years to achieve a practical design.

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