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CONCEPTUAL DESIGNS FOR VERY HIGH-TEMPERATURE CANDU REACTORS

by

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ABSTRACT

Although its environmental benefits are demonstrable, nuclear power must be economically competitive with other energy sources to ensure it retains, or increases, its share of the changing and emerging energy markets of the next decades. In recognition of this, AECL is studying advanced reactor concepts with the goal of significant reductions in capital cost through increased thermodynamic efficiency and plant simplification. The program, generically called CANDU-X, examines concepts for the future, but builds on the success of the current CANDU designs by keeping the same fundamental design characteristics: excellent neutron economy for maximum flexibility in fuel cycle; an efficient heavy-water moderator that provides a passive heat sink under upset conditions; and, horizontal fuel channels that enable on-line refueling for optimum fuel utilization and power profiles. Retaining the same design fundamentals takes maximum advantage of the existing experience base, and allows technological and design improvements developed for CANDU-X to be incorporated into more evolutionary CANDU plants in the short to medium term.

Three conceptual designs have been developed that use supercritical water (SCW) as a coolant. The increased coolant temperature results in the thermodynamic efficiency of each CANDU-X concept being significantly higher than conventional nuclear plants. The first concept, CANDU-X Mark 1, is a logical extension of the current CANDU design to higher operating temperatures. To take maximum advantage of the high heat capacity of water at the pseudo-critical temperature, water at nominally 25 MPa enters the core at 310 ^{o}C, and exits at ~ 410 ^{o}C. The high specific heat also leads to high heat transfer coefficients between the fuel cladding and the coolant. As a result, Zr-alloys can be used as cladding, thereby retaining relatively high neutron economy.

The second concept, CANDU-X NC, is aimed at markets that require smaller simpler distributed power plants (~300 - 500 MWe). The steam cycle and coolant conditions are proposed to be the same as CANDU-X Mark 1. The major difference between the reactors is that natural convection would be used to circulate the primary coolant around the heat transport system. This approach enhances cycle efficiency and safety, and is viable for reactors operating near the critical point of water because of the large increases in heat capacity and thermal expansion coefficient across the core.

The third concept, CANDUal-X, is a dual cycle concept, with core conditions similar to the Mark 1 and NC. In this concept, coolant leaving the core is first expanded through a VHP

turbine in a direct cycle. Employing a dual steam cycle avoids a high-pressure steam generator. The conditions of the core and the VHP expansion can be designed such that the exhaust from the turbine is used as the heat source for an indirect cycle; that is, the secondary side can be equivalent to that presently employed in conventional CANDU plants. An advantage of this concept over conventional direct cycle nuclear plants is that only one relatively small turbine is exposed to radioactive coolant, and it is located within containment.

In summary, the reactors described above represent concepts that evolve logically from the current CANDU designs to higher efficiency, with only modest extensions of current technology. This paper presents a technical overview of the different conceptual designs, as well as a brief discussion of the enabling technologies that are common to each, which is the focus of current R&D.

INTRODUCTION

It is expected that in the future, the energy and electricity markets will change rather dramatically from their present state. Environmental concerns regarding the emission of green-house gases (GHGs) are growing and this, plus the prospect of dwindling fossil fuel reserves, and privatization and deregulation of much of the electricity sector will strongly affect the decisions that governments, utilities and investors will make when considering energy options.

From an environmental perspective, it is generally accepted (Bertel, 1999, Fetter, 1999) that increasing the amount of electricity generated by nuclear plants is a viable option toward meeting the CO_2-reduction targets set in Kyoto in 1997 at the third Conference of the Parties (CoP-3) for the UN Framework Convention on Climate Change. Although its environmental benefits are demonstrable, nuclear energy must be economic to ensure its place in the emerging energy markets of the next century. New nuclear plants will only be built if the initial capital costs, and risks associated with plant operation and performance are shown to compete favourably with competing regional energy sources. In most areas of North America, this competition is fossil-fired combined cycle gas turbines (CCGT).

AECL has a program in place, generically called CANDU-X, that examines new, innovative, reactor concepts that can be built and operated at significantly reduced capital and unit energy costs. In addition, the reactors should also possess enhanced safety features, and a flexible, proliferation-resistant fuel cycle.

The most significant cost reductions for the CANDU-X concepts are expected through an increase in thermodynamic efficiency by raising the coolant temperature, and any simplification in plant design that may result. Although numerous high-temperature coolants were examined early in the CANDU-X project, water at supercritical pressure and temperatures has been adopted as the coolant of choice. The concept of utilizing supercritical water (SCW) in a power plant is not a new one; fossil-fired plants cooled by SCW have been in operation for over 30 years. Supercritical-water-cooled reactors were first studied seriously in the late 1950's and early 1960's (Keyfitz, 1964, Marchaterre and Petrick, 1960). With the drive toward increased economic competitiveness, this interest has been renewed in a number of countries in the 1990's (Silin et al., 1993, Dimmick et al, 1998, Bushby et al, 1999, 2000, Oka and Koshizuka, 1993). In each case, these reactors are believed to be very competitive economically because of the higher thermal efficiency and the possibility of plant simplification. As an example of the latter, steam separators and dryers are not required in a direct cycle because SCW is a high-density gas, which does not encounter the two-phase region. Independent of steam cycle, the absence of a second phase alleviates concerns of fuel dryout, thereby enabling an increase in channel power. This, in combination with the enhanced thermodynamic efficiency, yield reductions in fuel, specific capital and O&M costs.

The use of SCW also enhances safety because of the possibility of using natural circulation for the primary coolant (Dimmick et al, 1998), taking advantage of the gas expansion coefficient and large density change with temperature around the critical point. At an average in-core temperature of around 400°C (i.e., just above the pseudo-critical temperature of 370°C), the high specific heat leads to a greatly reduced mass flow, and thus pressure drop. The large density change between the core inlet and exit results in sufficient driving head, with a moderate elevation difference to permit natural circulation.

Three design variants of a supercritical cooled CANDU are described and are shown in Figure 1. The first is the logical extension of the current CANDU design to higher pressure and temperature. The second utilizes natural circulation for the primary coolant, and the third is a variant of the first but utilizes the innovative idea of a very high pressure (VHP) turbine in the primary circuit inside of containment. Although only conceptual at present, the possibility of stretching the third variant to the limit currently set by steam turbine materials is also considered. These various design concepts are compared to the CANDU-6 in Table 1.

CANDU-X Mk 1

The CANDU-X Mk 1 is a logical extension of the present CANDU design. An indirect cycle is employed, but the temperature of the primary coolant at 25 MPa is increased to 380 °C at the inlet and 430 °C at the outlet, yielding an increase in thermodynamic efficiency of roughly 20 % over conventional water-cooled reactors. The core would consist of 380 channels, each running at an average power of 6 MW(t), or 2280 MW(t) for the entire reactor. At an assumed overall cycle efficiency of 41 %, the electrical output is 910 MW. The conditions for the CANDU-X Mark 1 were chosen to take maximum advantage of the marked increase in enthalpy, and thus heat capacity, that occurs at ~ 385 °C (the pseudo-critical temperature). The high heat capacity leads to a three-fold increase in core enthalpy change, and a corresponding three-fold reduction in channel flow (compared with current CANDU values) for the same channel power and temperature rise. Channel pressure drop is similarly reduced. The relatively high coolant density at the pumps (~0.6 g/mL), in addition to the reduced mass flow and pressure drop, results in a six fold reduction in the primary pumping power for the Mark 1 compared to current CANDU values (Dimmick et al, 1998).

The core design will be horizontal and employ interlaced flow in adjacent channels, similar to the approach used in conventional CANDU plants. Thus, even though there is a large density gradient along each channel, the average core density will be the same on each side of the reactor because each face contains an equal number of channel inlets (where the coolant density is highest) and outlets (where the coolant density is lowest). This will significantly simplify the physics and control aspects of the reactor compared to a unidirectional vertical core design (Dobashi et. al., 1998).

The high specific heat at the pseudo-critical point leads to high heat transfer coefficients between fuel cladding and coolant (Yamagata et. al. 1972, Koshizuka et. al. 1994). As a result, cladding temperatures are predicted to be only 60-70 ^{o}C above the coolant temperature which is within the range of Zr-alloys. In in-reactor tests, uranium dioxide clad with various zirconium alloys has been operated successfully in superheated steam coolant at sheath temperatures of up to 500^{o}C. After six 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 two years. In addition, out-reactor experiments have revealed that some Zr-alloys exhibit acceptable corrosion resistance at the proposed burnups of the different fuel types, if the temperature of the cladding is kept below roughly 475 ^{o}C. Acceptable corrosion rates are achieved at higher temperatures when the surface of the cladding is treated with a thin corrosion-resistant layer.

Options for the thermodynamic cycle of Mark 1 are illustrated in Figure 2. The first option under consideration is a very high pressure (VHP) turbine with the exhaust directed toward a conventional LWR turbine set that operates under typical LWR conditions. In the dry region, efficiencies lie between 94 and 96%, but drop off to 82% near the exit from the HP turbine where the steam quality is reduced to 0.85.

Expansion into the wet region for both the high pressure and low pressure turbines results in a reduced cycle efficiency, which for Mark 1, is estimated to be ~ 6 %. Most of these losses could be recovered by employing multiple (2 or 3) stages of reheat, thereby avoiding expansion into the two-phase region. A cycle employing three stages of reheat (i.e. a single high pressure reheat and two lower-pressure (PWR type) reheats) avoids the wetness in the HP expansion, and reduces the wetness in the LP expansion. A similar result could be obtained with two high-pressure reheats, whereas wetness could be avoided completely with two high pressure and one lower pressure reheats; however, it needs to be determined whether the proposed reheating could be done efficiently, without excessive heat degradation. A more efficient option would be to perform the high-pressure reheat using heat directly from the primary system. The flow from each outlet header would divide to supply a steam generator and a reheater in parallel.

CANDU-X NC

To meet the needs of markets that require smaller, distributed power plants, the output of the CANDU-X NC reactor is approximately 350 MW(e). The reactor is smaller since this output can be accommodated by a reduced number of channels running at a lower average channel power (232 channels at ~ 4 MW vs 380 at 6 MW for the Mark 1). The smaller core will have a reduced amount of heavy water in the moderator, and fewer loops and steam generators (2 compared to 4 in current CANDU designs). These differences lead directly to reduced construction and capital costs.

The principal difference between the Mark 1 and the CANDU-X NC is that natural convection is employed for 100 % of the heat removal from the core under normal operating conditions. This represents an improvement in passive safety compared to forced convection; most notably, accident scenarios involving loss of Class IV power are no longer a concern. Cycle efficiency is improved since a percentage of the reactor power is not required to drive the heat transport pumps during operation (Figure 1b).

To investigate the feasibility of natural convection, a simple steady-state, natural-circulation program was written. This program included the full physical variations of the thermophysical properties of supercritical water. The initial and boundary conditions to the core, the operating pressure and temperature, along with the circuit resistance coefficients and the elevation difference between the core and the heat exchanger were specified. With an initially assumed flow, the program, using a supercritical water property routine, iterated around the loop on flow to calculate the steady-state density and enthalpies at each node in the circuit. To understand the parametric trends, many thousands of these calculations were done for different input conditions and the output data were plotted against each other to display the trends as shown in Figure 3. The effect of the large density and enthalpy changes around the critical temperature can be seen in this Figure where the inlet temperature is a parameter. Below about 370°C the outlet temperature/channel power surface is relatively flat (except for high loss coefficient combined with high power), whereas as soon as the inlet temperature exceeds 380°C the outlet temperature rises very sharply regardless of the channel power and loss factors. If the fluid enters the core below the critical temperature, it is at relatively high density and low enthalpy, and exits above the critical temperature at low density and high enthalpy. The large density difference gives a large natural-convection driving force, and the large enthalpy change allows a high channel power with relatively low flow and, hence, pressure drop.

This illustrates that to utilize the maximum design flexibility of elevation and loss coefficients within a maximum outlet temperature limit with a high-powered channel, it is necessary to keep the inlet temperature below the critical temperature and the outlet above the critical temperature. If the inlet temperature is allowed to rise above the critical temperature, the much-reduced density and enthalpy changes result in a very much higher outlet temperature. Although this would lead to higher thermodynamic efficiency, it also would require low neutron cross-section materials capable of operating in the 600°C range, beyond the capability zirconium alloys without a corrosion-resistant coating.

For the CANDU-X NC concept, it is proposed for coolant to enter the core at 350 °C and exit at 400 °C, thereby allowing cycle options similar to those for Mark 1 shown in Figure 2. These temperatures were also chosen because they provide ideal conditions for natural circulation. The coolant enters the core below the critical temperature at a relatively high density and low enthalpy; whereas, it exits the core above the critical temperature, at low density and high enthalpy. From calculations performed to-date, natural convection of the primary flow in a CANDU-X NC will be possible with a heat exchanger that is 10-20 m above the core, and if pressure losses around the primary circuit are minimized.

To address the thermalhydraulic issues with the CANDU-X reactor, experimental and analytical programs are underway. A large pumped loop using supercritical CO_2 is being commissioned to study heat transfer and pressure drop, and for fluid-to-fluid modelling studies of supercritical fluids. This loop will subsequently be converted to natural circulation to study instabilities, both in single and multiple parallel channels. In addition, a small natural-convection supercritical water loop is operational as a materials test facility. This loop operates between 360°C and 450°C, i.e. across the critical temperature, in a stable manner. Current plans are to extend the loop to multi-channel and to add an active chemistry control system.

CANDUAL-X

The CANDUal-X concepts utilize a dual steam cycle to take maximum advantage of proven systems used in conventional water-cooled reactors. As shown in Table 1, conceptual designs for two CANDUal-X reactors operating at different temperatures have been developed. In both cases, the coolant leaving the core drives a VHP turbine in a direct cycle. For CANDUal-X1, expansion of the coolant through the VHP turbine produces steam at temperature of 306 °C, which is fed directly into the primary side of a CANDU 6 steam generator. This approach avoids the expense and uncertainty associated with a steam generator operating at a shell-side pressure of 18 or 19 MPa (c.f. Mark 1). Also, because the primary side of the steam generator is now condensing, a smaller steam generator is required to transfer the same amount of heat. The dual-cycle concept also makes use of proven turbine technology that is presently being used in SCW-cooled fossil-fired plants (Smith, 1999). The addition of the VHP turbine onto a conventional CANDU indirect cycle in this manner adds 310 MW(e) to a standard CANDU 6 station output, to yield a net efficiency of 40.6 %.

For CANDUal-X2, the intent is to achieve the highest possible efficiency by operating the core at the maximum temperature achievable with existing steam turbine technology. At an outlet temperature of 625 °C, CANDUal-X2 would produce 1143 MW(e) of electricity at 45 % efficiency. In this case, exhaust from the VHP turbine (yielding 500 MW(e)) is first fed into a high-pressure regenerator prior to the steam generator. The regenerator reduces the steam temperature from 415 °C to ~ 315 °C, making it suitable for the standard CANDU indirect cycle. The core temperature is beyond the operating envelope for Zr-alloys; thus, cladding made from a Ni-based alloy or stainless steel could be used, although a high temperature ceramic with a low neutron cross section would be preferable on the basis of neutron economy.

It is possible to locate the VHP turbine in the containment because of its relatively small size compared to low pressure turbines. The conditions of the core and the VHP expansion have been chosen such that the exhaust from the turbine can be used as the heat source for an indirect cycle, equivalent to that employed in conventional CANDU plants. Moreover, the radioactive coolant remains wholly within containment, unlike a conventional BWR. There is a potential safety implication of having a turbine within containment and also a potential problem of deposition of activated corrosion products on the turbine and these are being evaluated.

DESIGN FEATURES COMMON TO ALL CONCEPTS

Core Design and Primary Coolant

Significant cost reductions will be achieved with CANDU X by reducing the inventory of heavy water. If natural uranium is the fuel of choice for a future customer, the primary coolant should be heavy water to achieve sufficient fuel utilization. However, since the density of SCW is much lower than water at ~ 300 ^{o}C and 10 MPa, there is a considerable reduction in D_2O inventory compared to current CANDU designs. An added benefit of the lower density coolant is the reduction in the coolant void reactivity (CVR). Depending on the design of the CANDU X core, reductions in CVR of three to five times present values can be achieved.

If slightly enriched uranium is used as fuel, the primary coolant can be light water which results in a significant reduction in heavy water inventory as well as a simplification in the heavy water recovery systems. With light water coolant the lattice pitch of the channels needs to be reduced to between 20 and 21 cm to get a near zero coolant void reactivity which results in additional heavy water savings because of the reduced size of the calandria. Initial indications are that this lattice pitch is achievable especially with bi-directional flow and single ended refuelling as described below.

Fuel Channel Design

For a conventional design to be used in SCW conditions, the thickness of the pressure tube would have to be approximately doubled because the operating pressure is much higher, and because the ultimate tensile strength of Zr-alloys decreases sharply above 400 ^{o}C. Such a large increase in tube thickness is contrary to the design premise of neutron economy, and will almost certainly necessitate fuel enrichment, or depletion of the ^{91}Zr isotope from Zr-containing components in the core to achieve acceptable fuel burnup. The absolute rates of corrosion and deuterium would also be greater at SCW temperatures, but it needs to be determined whether this would affect the projected lifetime of a much thicker pressure tube.

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 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. Thermally insulating the pressure tube removes the need for an annulus gap, and consequently, the calandria tube. In the CANTHERM design, the pressure tube will be in direct contact with the moderator, and, therefore, operate cold. At moderator temperatures, corrosion and deuterium ingress into the pressure tube should be greatly reduced. Moreover, the strength, and likely the creep resistance, of commercially available Zr-alloys will be such that the thickness of the pressure tube can be roughly equal to the present CANDU design; i.e., a significant neutron penalty is not expected. In addition to the supercritical application, such a fuel channel could be employed to increase coolant temperatures and pressures in a conventional CANDU PHTS.

Fuel and Refueling

With conventional CANDU plants, on-line refueling is used to achieve optimum power profiles and fuel utilization. The best profile from the fuel cooling aspect has the peak power skewed toward the core inlet and can be accomplished by positioning new bundles at the channel inlet and the highest burnup bundles at the outlet. Fuel defects associated with power ramping will be reduced because generally a bundle is subjected to a declining power history over its lifetime. To prevent a large flux asymmetry across the core bidirectional flow would be used so that adjacent channels have the channel inlet at opposite sides of the core. Two fueling machines are employed in present CANDU designs: one to load new fuel bundles, and the second, on the opposite end of the channel, to receive spent bundles. For CANDU-X, single-ended refueling from the inlet side of the channel will be adopted, since elastomeric seals within the fueling machine (F/M) perform better at the lower inlet temperature. Two F/Ms will still be required, but they will access different channels on opposite sides of the core because of the interlaced flow. Because access by the F/M to the outlet end of the channel is not required, the diameter of the outlet end fitting can be reduced, allowing smaller lattice pitches to be achieved. This design was originally proposed for the CANDU-3 design reactor (Anon.) although with the fueling machine accessing the outlet of the channel rather than the inlet.

Single-ended refueling from the inlet side of the channel requires that all bundles are extracted against the coolant flow. After the spent bundles are removed, the channel is refueled with the coolant flow, using the remaining extracted bundles first, followed by the new ones. Extraction of the fuel from the inlet requires the individual bundles to be tied together, probably using a central tie rod. This is standard procedure for experimental fuel string irradiations in the NRU reactor and was also used in the Gentilly-1 boiling light water reactor. An alternative option would be to design a bundle with a coupling on the end plates to connect adjacent bundles. This development would simplify the design of the fueling machine because a long receiving chamber and tie rod may not be required; individual bundles could be separated from the rest of the fuel string as they exit the core. For both systems the bundles would be aligned to reduce the pressure drop across the core. This is especially useful for CANDU-X NC, where the reduced pressure drop will facilitate natural circulation of the flow.

Passive Moderator cooling.

The separation of the coolant and moderator is an attractive safety feature of all CANDU designs. The moderator provides an excellent heat sink for long term cooling of the core under a postulated accident involving a loss of coolant combined with a loss of emergency core cooling. Presently, heat is removed by a forced convection loop, which is also employed under normal operating conditions.

For CANDU-X, it is proposed that heat be removed from the moderator by natural convection with a passive moderator circulation system (PMCS). In the PMCS design, the moderator is maintained close to saturation at the calandria pressure, and heat is transported from the calandria to an elevated passive heat exchanger in a natural-circulation loop (Khartabil et al. 1995). Under normal operating conditions, heat has to be continuously removed from the moderator. This is done in existing plants by using a forced convection loop. An attractive feature of the PMCS is that flashing occurs close to the calandria exit. This proximity provides a large driving force, because of the large density difference between the cold-leg subcooled liquid and the hot-leg two-phase mixture. This design feature makes it possible to remove moderator heat under both normal and accident conditions using natural-convection flow. Moreover, having the moderator temperature close to saturation provides the option of utilizing the moderator heat for feedwater heating, which improves plant efficiency.

The main feature of this design is that vapour is generated by flashing. Simulations using the CATHENA code (Hanna, 1998) have shown that a flashing-driven natural-circulation loop can be used to remove moderator heat under normal operating conditions without any flow instabilities. Under some conditions, limit-cycle oscillations were observed experimentally. With a few exceptions, the experimental results were successfully described by the CATHENA code (Dimmick et al., 1999). Experiments with two-phase flow in large diameter vertical pipes (Shoukri et al., 2000) have shown that slug flow does not occur eliminating one of the design concerns with this concept.

CONCLUSIONS

A CANDU reactor cooled by supercritical water has significant potential to be competitive in future energy markets through increased thermal efficiency and plant simplification. Three reactor concepts cooled by SCW have been developed that span the entire power range for future competitive markets. The three concepts all use the same flexible horizontally-oriented core design, and can be matched to both direct and indirect steam cycles. Thus the concepts build on the successful heavy-water moderated, pressure tube reactors that represent the existing CANDU designs. This approach takes maximum advantage of the existing experience base, and enables technological and design improvements developed for the CANDU-X program to be spun off and incorporated into evolutionary CANDU plants in the short to medium term, as part of AECL's continuing program to develop and improve the CANDU design. Enabling technologies that are generic to each of the reactor concepts will remain the focus of the

CANDU-X program. These include development of a CANTHERM fuel channel, SCW thermalhydraulics, chemistry, materials compatibility, and safety.

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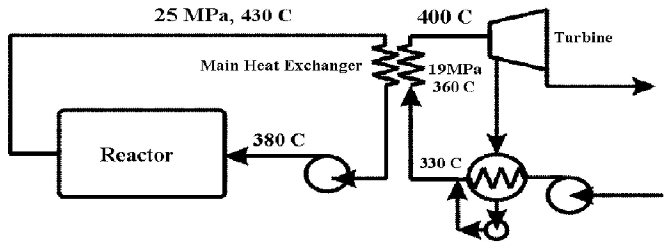
Table 1

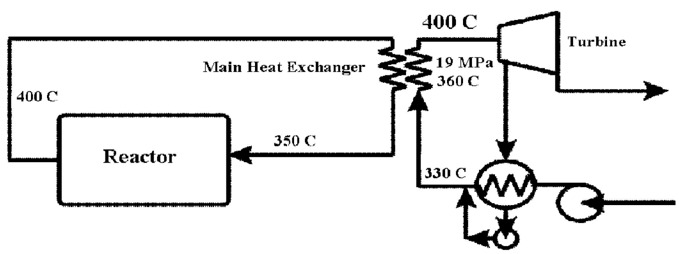
CANDU-X Design Numbers

	CANDU 6	CANDU-X Mark 1	CANDU-X NC	CANDUal-X1	CANDUal-X2
Thermal Power (MW)	2064	2280	930	2340	2536
Gross Electric Power (MW)	725	910	370	950	1143
Eff. (%)*	35	41	40	40.6	45
Press. (MPa)	10	25	25	25	25
Inlet Temp (^oC)	266	380	350	312	353
Outlet Temp(^oC)	310	430	400	450	625
Inlet Density (g/mL)	0.780	0.451	0.624	0.720	0.615
Outlet Density (g/mL)	0.690	0.122	0.167	0.109	0.068
Core Flow (kg/s)	7700	2530	976	1504	1321
Number of Channels	380	380	232	~300	~300
Ave. Channel Power (MW)	5.4	6	4	7.8	8.5

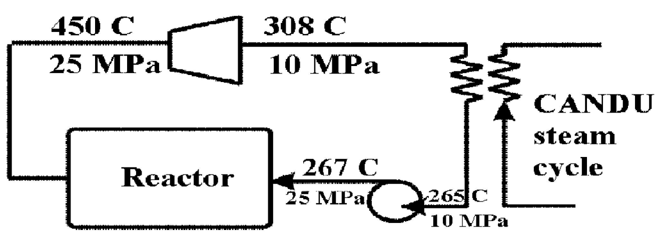
NOTE: *estimated



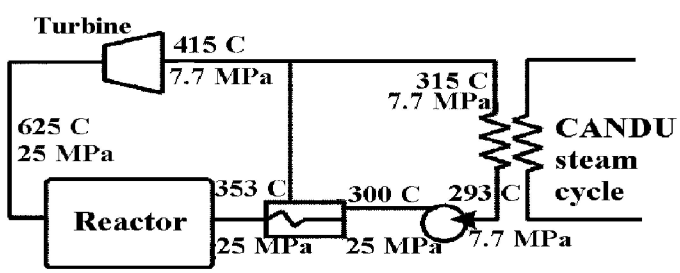
a) CANDU-X Mark 1



b) CANDU-X NC



c) CANDUal - X1



d) CANDUal - X2

Figure 1 CANDU-X Designs.

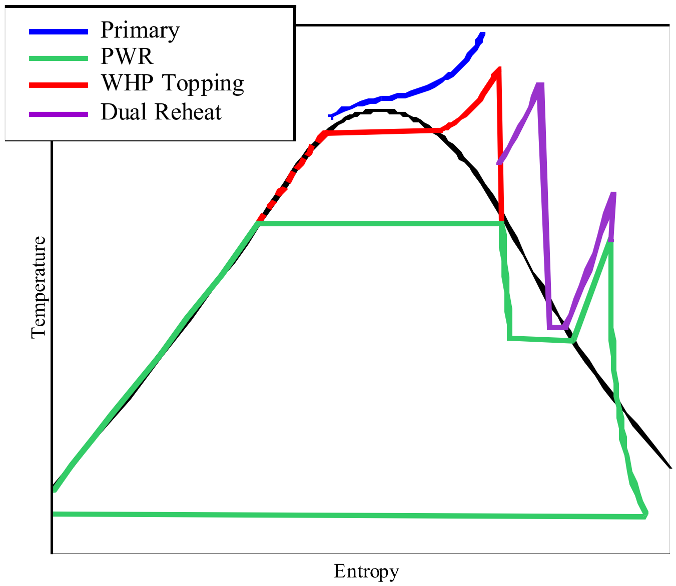


Figure 2 Possible Cycle options for CANDU-X Mark 1.

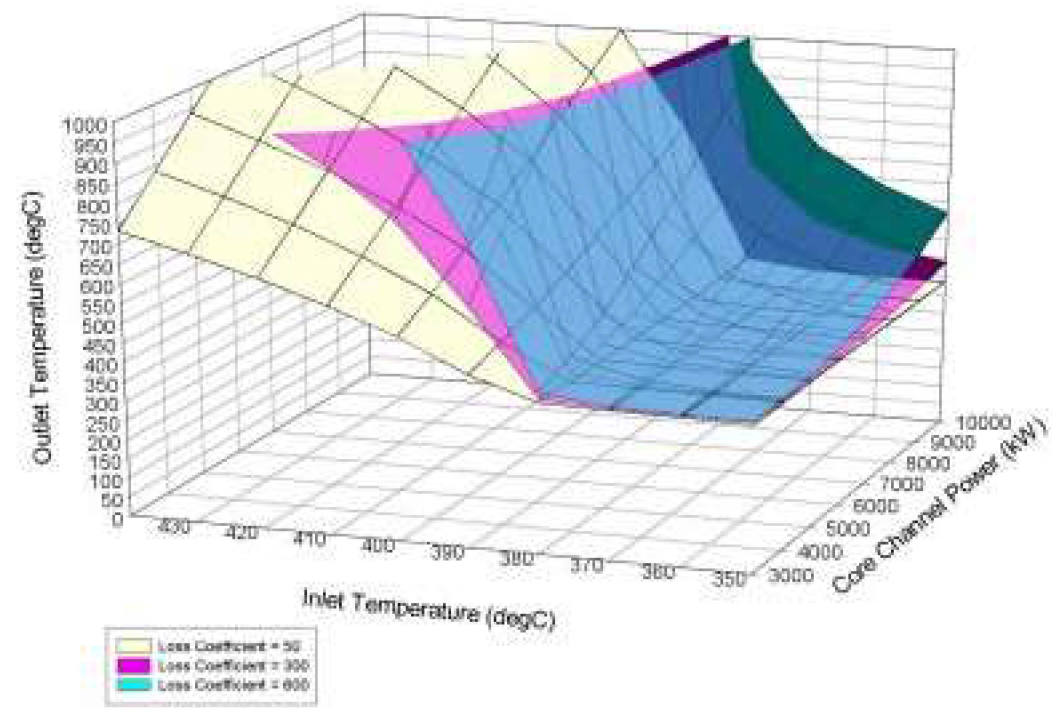


Figure 3 **CANDU-X Natural Circulation. Significance of T_{crit}**

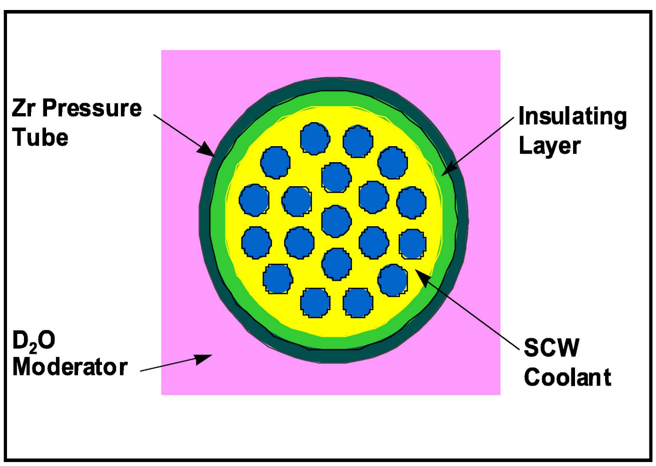


Figure 4 **Schematic of CANTHERM fuel channel design. The pressure tube is insulated from the hot coolant, removing the need for a calandria tube and an annulus gap.**