Pressure-Tube Super-Critical Water Reactor Design Features Affecting Station Blackout Response

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Abstract

The primary focus of generation IV nuclear reactor designs in Canada is a pressure-tube super-critical water reactor (PT-SCWR), a design that maintains the key aspects of the Canadian Deuterium (CANDU) reactors. However, the higher temperature, higher pressure and lower density of the super-critical water coolant during normal operations imply new initial conditions for the accident analysis, and impose new design requirements on the pressure tubes. This paper examines the potential effect these design changes have on the response to hypothetical situations that could lead to severe core damage.

1. Introduction

In recognition of the increased role nuclear power will play in a future with increased energy demands and greater concern over greenhouse gas emissions, the Generation IV International Forum (GIF) was formed to promote the development of nuclear power plants with improved economics, reliability, safety, sustainability, and proliferation resistance. Six reactor concepts were select for cooperative development by for the thirteen member countries. One of these designs, the super-critical water reactor (SCWR), was chosen to be the primary focus in Canada since the design can be seen as an evolution of the current CANDU designs [1].

The general concept of the SCWR is to use super-critical water as both the coolant and the working fluid in order to reap the improved thermal efficiency available from the increased temperatures. The Canadian SCWR conceptual design employs the same design principle used in existing CANDU reactors where the coolant is separated from the low temperature, low pressure heavy water moderator using pressurized channels. The higher temperature and pressure of the coolant impose new requirements on the reactor that manifest into key design features.

Reduced probability of severe core damage is also one of the primary safety goals of the GIF. A station blackout combined with the unavailability of back-up diesel generators is a postulated initiating event leading to severe core damage in existing Canadian reactors. The design changes and new operating conditions in the SCWR, may alter the severe accident phenomena expected and the progression of events.

2. Background

2.1 Key design features of the Canadian SCWR

The design of the Canadian SCWR is still in the conceptual design stages. In general, the key principles of the CANDU reactor will be maintained. The fuel is contained and cooled in pressure tubes that run through the Calandria Vessel containing the heavy water moderator. This allows the moderator to be at low temperature and low pressure, simplifying the design and construction and providing a large mass of cool liquid to serve as an inherent emergency heat sink. The Calandria Vessel sits in the Reactor Vault filled with cool light water acting as a radiological shield that can also serve as heat sink during severe accidents. The pressure tube concept is also favourable because it enables the use of the on-line-re-fuelling machines – a signature component of the CANDU reactors.

The use of horizontal fuel channels in the core allows for bi-direction cooling, as employed in current CANDU reactors. This may be particularly useful in a super-critical water reactor, as it will balance the large density gradients that may be encountered as the coolant crosses the pseudo critical line. The inclination of the fuel channels, however, is one of the many design aspects that has not yet been determine. There may be benefits in having vertical fuel channels in the SCWR : improving the natural circulation capability, or, reducing the load on the re-entrant fuel channel, one option for re-design of the fuel channel [2].

The high temperature and pressure of the coolant affects the material selection throughout the reactor design. This is particularly important for the fuel cladding and pressure tube – traditionally manufactured from zirconium-alloys due to their good neutron economies and resilience when irradiated. However, at the temperatures expected in the SCWR, zirconium-alloys experience excessive corrosion and the ultimate tensile strength deteriorates to the point where the thickness required for the super-critical pressures tubes would be unfeasible.
Figure 1 represents the cross-sections of the pressure tubes used in a typical CANDU reactor. A possible redesign of the pressure tubes, known as the 'High Efficiency Channel', is represented in
Figure 2. In this design, the pressure tube is internally insulated, and expected to operate at moderator temperatures of about 80 °C, allowing the use of a Zr-alloy for the pressure tube.

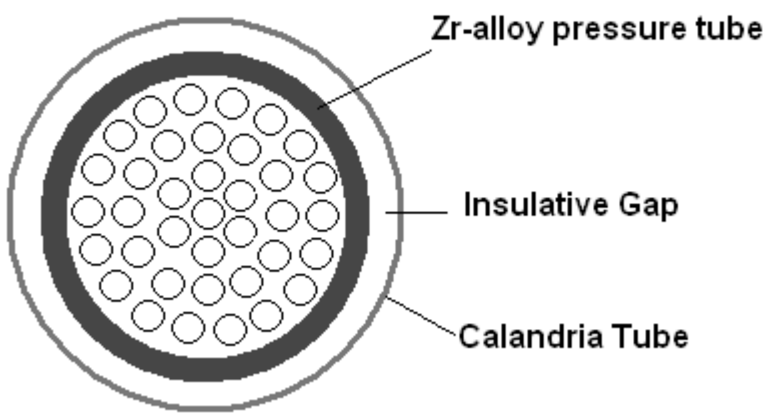

Figure 1   Pressure tubes in existing reactors

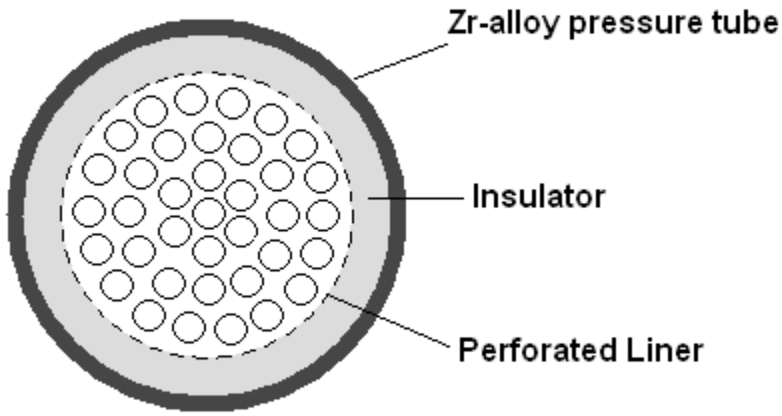

Figure 2 Proposed High Efficiency Channel

The perforated liner and insulation must only bear the load of the weight the fuel elements, and not the pressure of the coolant. The selection of the materials for the perforated liner and insulator is still undecided. The liner must show good low corrosion and swelling from irradiation. Since the liner can be very thin, the neutron absorption of the liner is not of high concern. A leading candidate for this component is coated ferritic-martensitic steel [2]. There is greater uncertainty in the choice of material for the insulator. This section must show good corrosion resistance, low neutron absorption and low thermal conductivity. Some form of Zirconium-ceramic (Zirconia) is a likely material to be used [2]

Another fuel channel option proposed is the Re-entrant fuel channel, shown in an axial-cross-section in Figure 3. In this case, a thin inner tube, similar to the liner of the HEC, would guide the coolant along the wall of the pressure tube before turning around at the end and passing over the hot fuel in the centre of the channel. The coolant would thus enter and exit from the same end of the core [1]. Since the inner tube would be unrestrained at one end, a vertical orientation would be favourable in order to avoid the cantilever forces on a horizontal tube supported from only one end.

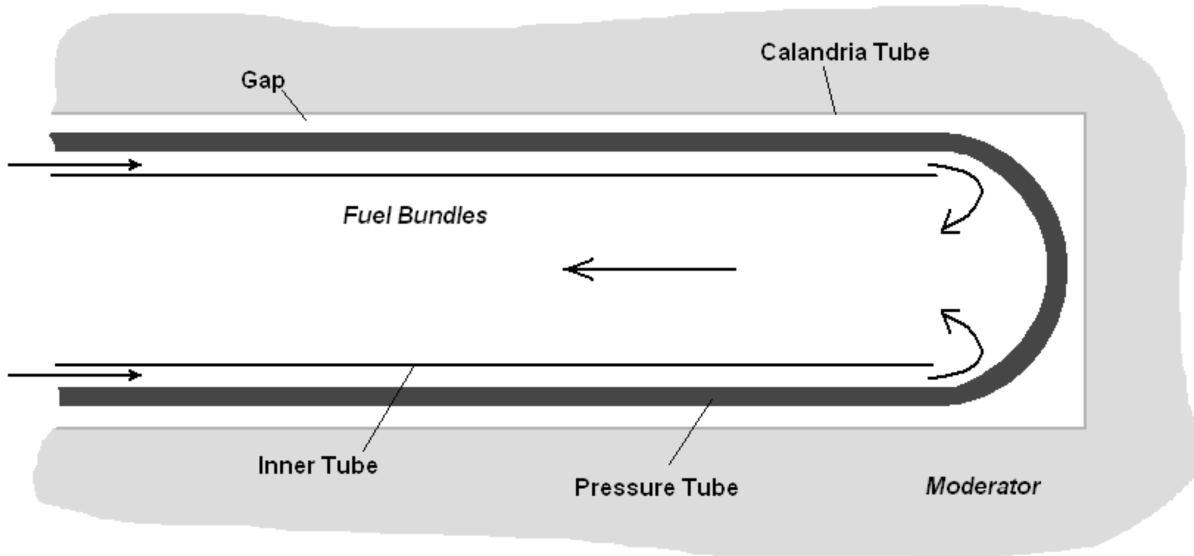

Figure 3 Re-entrant fuel channel

Another significant evolution from the existing Canadian reactors is the move to slightly enriched fuel – a step that has already been incorporated into the generation III Advanced CANDU Reactor (ACR) design. Using slightly enriched uranium enables the use of light water as the coolant, and provides great economic savings by reducing the size of the core and quantity of heavy water moderator.

There are also plans to introduce a greater amount of passive systems into the reactor design. The mass flow of super-critical water is expected to be lower than an equivalent existing Candu reactor. This may facilitate the application of a natural circulation loop for the primary heat transport system. Existing reactors are capable of maintaining natural circulation for the primary loop in decay power situations provided the inventory of the steam generators does not deplete. The SCWR design may forgo the steam generators in favour of a direct cycle where the coolant is used as the working fluid for a gas turbine located inside containment. In such a case, it is possible that the SCWR will incorporate a passive system such as the isolation condenser used for natural circulation in the direct cycle boiling water reactors [3].

The ACR design incorporates a PEWS (Passive Emergency Water Supply) that will also be incorporated into the SCWR. The PEWS is a large tank of water held near the top of the containment that can provide make-up water to the various heat sinks during emergencies: the steam generators, the Calandria vessel and the reactor vault, as well as providing water for condensing spray in the containment. Existing reactors provide forced circulation for the cooling of the moderator. A key feature expected to be introduced in the SCWR is the addition of a passive flashing-driven moderator cooling system [4].

2.2 Response to a station blackout in existing CANDU reactors

During a postulated station blackout accident (loss of Class IV power) and unavailability of back-up diesel generators (loss of Class III power) in existing Canadian reactors, the coolant flow is lost and the reactor is shutdown automatically. The power drops to the decay heat levels, thus the pressure and temperature of the primary coolant system drop. The fuel continues to produce heat due to the decay of the fission products, and this heat is transported away from the fuel by the coolant. Although there is no forced circulation since pump power is lost, sufficient coolant flow is maintained by natural circulation driven by the large temperature difference and static pressure difference between the core and the steam generators.

The decay heat is transferred to the steam generators, but lack of feed-water pump power means there is a limited inventory in the steam generators. The pressure rises in the steam generator and the steam is slowly released to the atmosphere through the main steam relief valve.

With the loss of the steam generator inventory, the natural circulation deteriorates. Some density driven flow is maintained. The coolant pressurizes, and the feed/bleed system accommodates. Again, since there is no feed-pump power, the coolant inventory cooled in the feed/bleed system cannot be returned to the main loop. The heavy water storage tank and the bleed condenser fill with coolant and eventually the relief valve opens to containment. The coolant inventory slowly leaks through the relief valve as it continues to remove the decay heat from the fuel. Fuel channels near the top of the core, where the density driven flow is the lowest, are the first to void. When the vapour and liquid phases separate in these channels, the coolant temperature rises above saturation. The pressure tube will thermally expand (balloon) into contact with the calandria tube. In this state, there is a more direct path for the heat to travel from the fuel to the moderator. The moderator receives the decay heat from the fuel. When film boiling begins on the outer wall of a ballooned pressure tube, the excess heat combined with the hydride-embrittlement of the interior wall cause the pressure tube to rupture.

The coolant blows down into the calandria. The excess steam is too much for the calandria vessel relief valves, and the rupture disks burst. A large amount of moderator is ejected into containment, uncovering several levels of fuel channels. As the fuel channels are uncovered, they fail and rest on the lower, intact channels. Eventually, enough fuel channels fail that the load on the lower channels is too great, and the core collapses. The moderator continues to boil off and discharges through the relief ducts. The debris is kept relatively cool and contained within the calandria vessel by the shield water cooling of the outer calandria vessel wall. The containment may be compromised about one day after the incident when the pressure rises due to the shield water evaporation. The calandria vessel will remain intact until the shield water drops to a level adjacent with the level of the debris. This isn't expected to occur until two or three days following the incident, allowing time for make-up water supply to be added to the calandria vessel or the reactor vault.

3. SCWR Design Features Affecting the SCDA response

As discussed above, a typical pressure-tube heavy water reactor will progress through various heat sinks in response to a complete loss of power. These heat sinks are summarized in Table 1. In order to ascertain the response of a SCWR to the same incident, the development of the heat transfer pathways to these heat sinks must be analysed. Improved safety in response to a complete loss of power will be available if the SCWR design is able to counter the challenges each of these heat sinks face in the course of events. The proposed counter-measures are summarized in Table 1.

Heat Sink	Existing Reactor Response in loss of Class IV and Class III Power	SCWR Design Mitigations
Steam Generators	Feed-water pumps unavailable - limited SG inventory	PEWS supplies make-up water to the steam generators.
	Hold-up inventory is gradually released to the environment	If no steam generators: potential use of isolation-condenser or similar system that can maintain natural circulation without forced feed-water flow
Coolant	Bleeds off to Feed/Bleed system, but with no feed-flow, primary heat transfer system pressurizes and is released to containment through relief valves	No proposed counter-measure: heat transfer system will also over pressurize and coolant will be released to containment
	Increasing temperature will cause pressure tube thermal deformation	Presence of internal insulator may protect pressure tubes from deformation
Moderator	Moderator absorbs decay heat through new heat path created by thermal expansion of pressure tubes into contact with the calandria tubes	No deformation, but pressure tube design is proposed to allow decay heat to conduct through insulator to the moderator without any deformations
	Moderator cooling system fails without pump power; Moderator evaporates through pressure relief ducts	Passive moderator cooling and PEWS moderator make-up ensure that this heat sink does not evaporate
	Severe core damage ensues: ▪ Fuel channels are uncovered, ▪ Core collapses.	If no moderator evaporation: no fuel channels are uncovered, **no severe core damage**
Shield Water	Terminal debris bed at the bottom of the calandria vessel is contained by cooling from the shield water on the outer wall of the calandria.	
	The shield water will boil off slowly - pressure increase from shield water evaporation challenges containment integrity.	PEWS supplies sprinklers to condense the steam in the containment and reduce the pressure
	Shield water level drops to point where not enough cooling provided to calandria and corium melt penetrates calandria wall, leading to ex-vessel molten-core-concrete and molten-core-water interactions which will most likely lead to fission product release.	PEWS supplies make-up water to the reactor vault mitigating corium breach of the calandria vessel.

Table 1 Heat sink progression in response to a loss of class III and class IV power

The first challenge to the system is the loss of forced flow. Natural circulation will transport the decay heat through the coolant in both the existing reactors and the SCWR. The natural circulation in the SCWR, however, may not be reliant on the feed-water flow and thus not limited to the time until depletion of the steam generator hold-up inventory as it is in existing reactors. If natural circulation can be sustained indefinitely, the SCWR will not suffer any appreciable damage in response to a station blackout.

If natural circulation degrades, the coolant will pressurize, and evaporate. The next line of defence against the decay heat causing fuel damage is the heat sink available in the moderator. A direct heat path must be developed that will transfer sufficient amount of energy away from the fuel. The re-entrant fuel channel can be designed to undergo a similar deformation as the existing reactors – where the inner tube separating the flow would expand into contact with the pressure tube. Since coolant flow will have degraded significantly by this point, isolating a cooler flow along the wall of the pressure tube is not as critical as establishing a path for the heat to travel from the fuel to the moderator. It has been proposed that the high efficiency channel will enable sufficient heat transfer to the moderator without any deformation [1]. The mechanism for this heat transfer needs to be investigated. If the heat conduction path can be formed without any deformation of the pressure tubes, and if the moderator does not uncover the channels, there will not be any limited or severe core damage experienced in the reactor. However, if this heat transfer path cannot be established, there may be early fuel failure or pressure tube rupture without the failure of the moderator as a heat sink: increasing the probability of core damage.

The passive moderator cooling system will have a great effect in reducing the probability of severe core damage. Even if some deformation of the pressure tubes, classified as limited core damage, occurs to create a heat transfer path, the accident should not progress into severe core damage where the pressure tubes rupture and the core collapses. The passive emergency water system proposed will allow for make-up water at any stage of the accident progression without the need for operator action.

4. Future work and conclusion

The design of the pressure tube is identified as a key aspect that will affect the outcome of a station blackout. The pressure tubes must allow sufficient heat transfer to the moderator in order to prevent early melting of the fuel. The characteristics of the high efficiency channel need more investigation. Thermal-hydraulic system analyses will be conducted for a loss of forced flow transient with parametric analysis of the thermal properties of the fuel channel materials. The effectiveness of the moderator cooling system will be studied as well.

Due to the increased reliability of natural circulation, as compared to diesel generators, the passive systems incorporated into the design of the SCWR should greatly reduce the probability of severe core damage. If the new pressure-tube design are able to provide heat transfer from the fuel to the moderator without any deformation of the pressure-tube or over-heating of the fuel, a complete station blackout combined with the loss of back-up generators may not even lead to limited core damage.

5. References

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