LOFA ANALYSIS OF CANDU-SCWR

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Abstract

CANDU SCWR is a pressure-tube type supercritical water cooled reactor under research based on the existing knowledge of operating water-cooled CANDU reactors and fossil fuel Super Critical Water (SCW) plants.[1] Although CANDU reactors have the well proven features of large passive heat sinks, such as a separate low temperature and pressure moderator, the loss of main feedwater accident (LOMF) still could make a great challenging event since it results a rapid loss of coolant inventory in the reactor core. In the present study, a safety configuration similar to the SCWR design of Westinghouse Company is employed to the CANDU SCWR system and the passive safety characteristics of this design during a loss of main feedwater accident (LOMF) is evaluated with RELAP5/MOD4.0 computer code. The result confirms the potential of this safety design for mitigating the consequences of LOMF accident alone without using any other safety facilities.

1. Introduction

The conventional SCWR designs, including the CANDU SCWR, normally applied the "once-through direct cycle" concepts, in which the coolant flows through the core at supercritical pressure where it gets heated and turns into "steam", and flows to the turbine directly through the steam line. There are no recirculation loops in the once-through direct cycle system.

Although the special feature of CANDU reactors, namely the separation between the low-pressure moderators and the high-pressure coolant, allows the decay heat to be emitted by heat radiation and conduction through the surrounding isolated pressure tube to the heavy water moderator during the postulated phase of severe accidents, the LOMF still could become a great challenging event for CANDU SCWR with "once-through direct cycle". Hence, to prevent the core from being over heated, significant auxiliary feedwater flow is required to be initiated rapidly.

To mitigate LOMF events for SCWR, the Westinghouse Company has developed a new system using additional loops with feedwater tanks connected to the outlet and inlet of the pressure vessel to increase the reserve of coolant in the system.[2] In the present study, a safety configuration similar to the SCWR design of Westinghouse Company is employed to the CANDU SCWR system and its safety characteristics during LOMF events have been evaluated.

2. System Designs

As mentioned above, the key concept of this new CANDU SCWR design is to add a circulation loop with a feedwater tank to each loop of the reactor core cooling system so as that a more inherent safety response can be obtained. As illustrated in Figure 1, the system has 2 identical loops. In each loop, one feedwater tank is connected to the steam line upstream and the feedwater line downstream. Two coolant pumps are located between the feedwater tank and the inlet of pressure vessel to maintain inventory in the tank and provide core flow during normal operation. An isolation condenser is located between the cold leg and hot leg of one loop, and is isolated from the system during the normal operation.

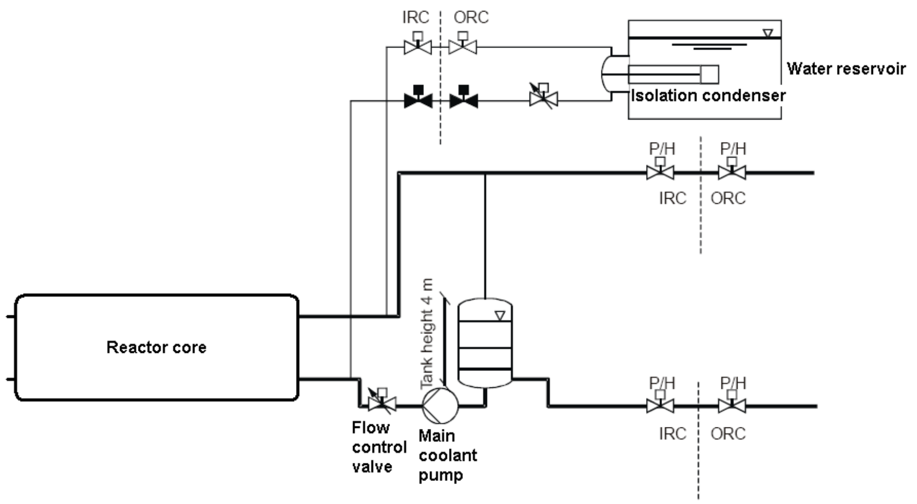

Figure 1 Conceptual flow diagram for CANDU SCWR reactor core cooling system.

This kind of design could increase the reserve of coolant in the system. During LOMF accident, the main coolant pumps would coast down providing sufficient flow from the feedwater tanks to the reactor in the short term, while the long-term consequences of LOMF would be mitigated by the isolation condenser, which could provide sufficient decay heat removal.

3. Model Description

In order to estimate the behavior of this CANDU SCWR design during a LOMF accident, RELAP5/Mod4.0 computer code has been adopted for both the short-term and long-term simulations. Figure 2 shows the system node diagram.

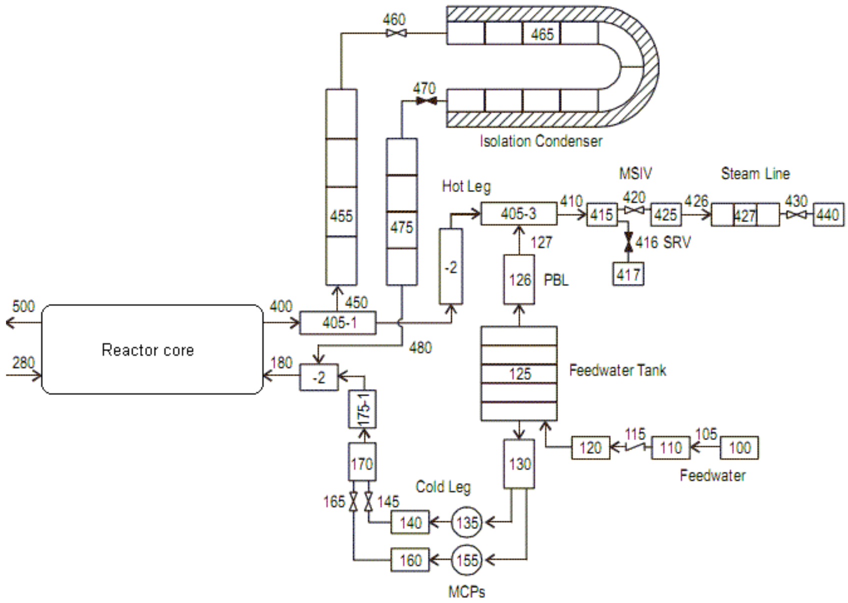

Figure 2 RELAP5 model of the CANDU SCWR cooling system.

In the loop shown in Figure 2, the feedwater line flow and temperature are controlled by a time-dependent junction (105) and a time-dependent volume (100), respectively. The main coolant pumps (135 and 155) are sized to provide the desired flow at rated operating conditions. The rated head compensates for the pressure drop across the reactor core, cold legs, and hot legs at rated flow. The safety relief valve (416) provides overpressure protection, while the isolation condenser (465) could provide decay heat removal in the late of LOMF accident. The isolation condenser was located 10 m above the hot leg to provide the driving head for natural circulation during operation. The tube bundle in the isolation condenser contained 100 10-meters long tubes, each with an inner diameter of 0.012 m. To simplify the analysis, the outside surface temperature of the isolation condenser was set 393K, near the temperature expected during nucleate boiling.

Because the RELAP5/Mod4.0 is not capable to carry out transient calculation between supercritical conditions and subcritical conditions, the working pressure is set to 19 MPa so as to carry out a similar calculation. The principal parameters are given out in Table 1.

Pressure	19 MPa
Coolant flow rate	1320 kg/s
Number of coolant loops	2
Thermal power	2540 WM
Coolant inlet/outlet temperature	553/723 K

Coolant inlet/outlet density	501.76/71.837 kg/m^3
Core area/length	0.33 m^2/6 m
Inner diameter/length of IC tube	0.012 m/10 m
Number of tubes in IC	100

Table 1 Principal characteristics of CANDU SCWR Model

4. LOMF accident simulation

With the RELAP5 model described above, LOMF simulation has been carried out. Calculated sequences of events are given as shown in Table 2.

Event	Time (s)
Loss of main feedwater	0.0
Main coolant pumps tripped	0.0
Reactor trip signal	1.1
Reactor emergency shutdown	1.8
Turbine stop valves closed	2.3
Isolation condenser activated	434.0

Table 2 Sequences of events for LOMF.

The transient was initiated by a complete, instantaneous loss of main feedwater flow and a simultaneous main coolant pump trip at 0 s. A reactor scram signal was generated at 1.1 s because the velocity of the main coolant pumps dropped lower than 267 rad/s, and it initiated a turbine trip as well. The turbine trip caused the turbine stop valves to begin closing. The turbine stop valves ware fully closed at 2.3 s, and the control rods began to drop into the core at 1.8 s. In the late of LOMF accident, the water level in feedwater tank dropped below 0.7 m and activated the isolation condenser at 434.0 s.

4.1 Short-term LOMF simulation

In the short term, the feedwater tanks provide sufficient inertia to delay the effects of the loss of main feedwater until late in the transient, so the loss of main feedwater does not have a significant impact on the system. Results and analysis are presented below.

4.1.1 Reactor power

In this model, reactivity feedback has been considered to simulate the effects of changes in the fuel temperature and fluid density. The Doppler and density feedback coefficients are -3.54x10-3 $/K and +2.046x10-2 $/(kg/m3), respectively. Thus, the power initially decreased due to reactivity feedback and then more rapidly near 2.3s when the control rods was released beginning reactor shutdown.

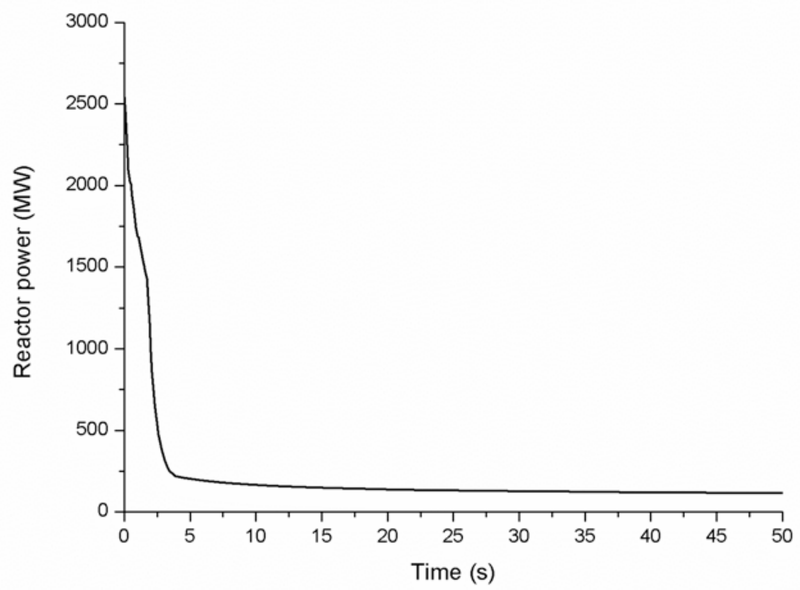

Figure 3 Reactor power following a total loss of flow.

4.1.2 Pressure

Figure 4 shows the calculated pressure in the reactor core. The pressure immediately decreased following the instantaneous loss of feedwater due to the continuing flow through the steam lines to the turbine. The response of the turbine control valves, which the control system would throttle in an attempt to maintain pressure, was neglected. Thus, the calculated depressurization is expected to be somewhat faster would actually occur in the plant. The pressure increased following the turbine trip at 2.3 s until the pressure reached 20.5 MPa at 2.9 s and the bank of safety relief valve open on both steam line. Pressure gradually decreased until reaching the closing set point of the safety relief valves, and then rose again.

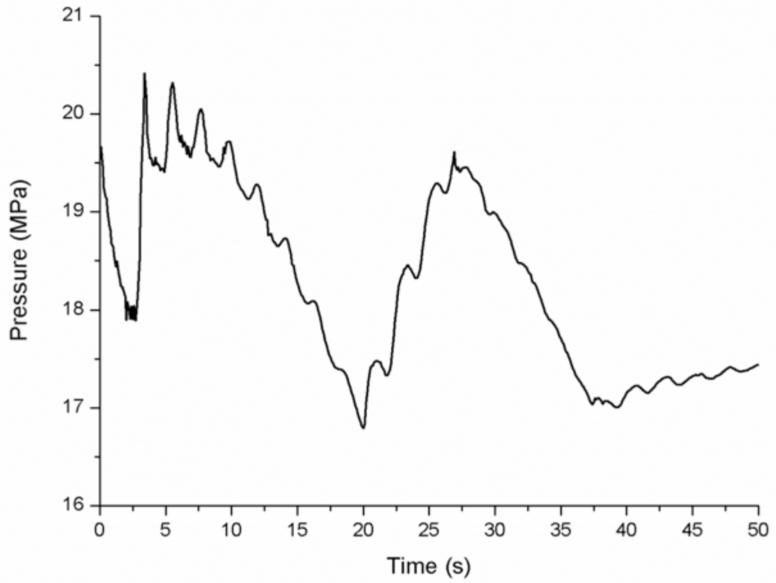

Figure 4 Reactor pressure following a total loss of flow.

4.1.3 Mass flow

The mass flow is shown in the figure 5. After LOMF happened, the main coolant pumps would coast down providing sufficient flow from the feedwater tanks to the reactor in short term, and the mass flow in the core kept decreasing as the velocity of the main coolant pumps decreased.

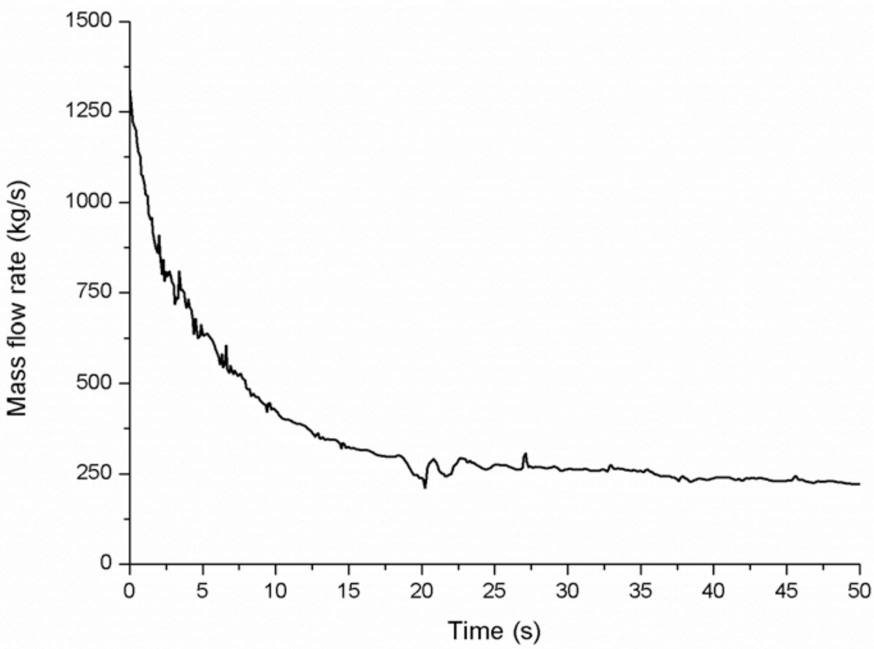

Figure 5 Core flow rate following a total loss of flow.

4.1.4 Cladding temperature

Since in the very beginning of accident, the flow decreased much more rapidly than the reactor power, the maximum cladding temperature initially increased due to this mismatch. Later, the emergency shut down system was initiated, and the power dropped sharply. Thus, the peak cladding temperature was reached near about 15 s, and then decreased throughout the remainder of the calculation.

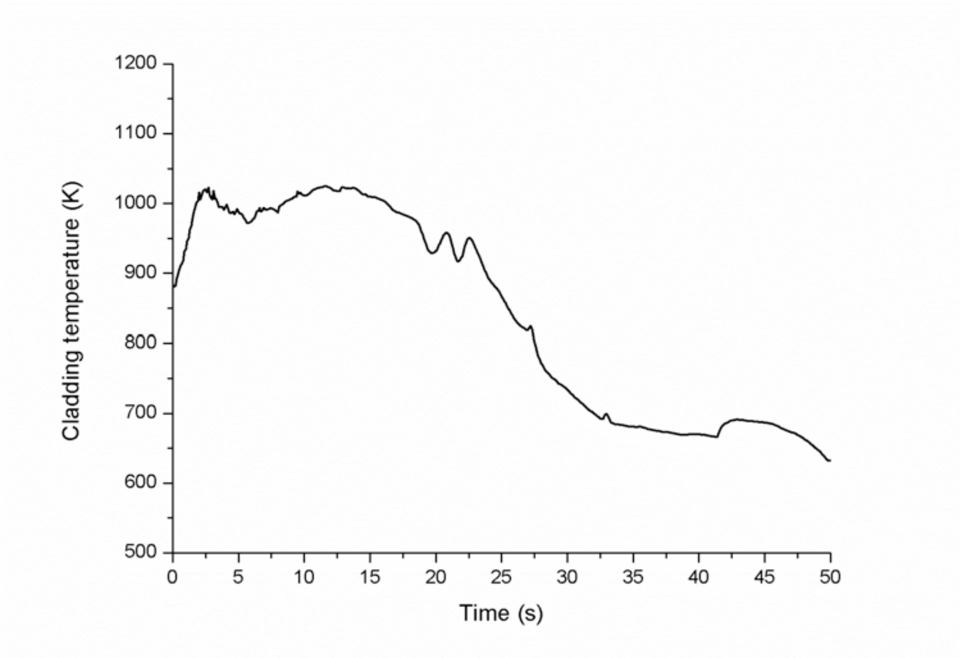

Figure 6 Maximum cladding temperature following a total loss of flow.

4.2 Long term LOMF simulation

In the long term, if the startup feedwater system, which is not a safety grade system, is not available, the decay heat generated by the core could not be moved out from the system except by safety relief valves keeping releasing high pressure steam to the suppression pool. In this case, the water level in the feedwater tanks would keep dropping and finally lead to lack of sufficient coolant in the system and damage of fuel rod.

The isolation condenser is added to the system for avoiding this kind of accident. The loss of mass though the safety relief valves caused the level in the feedwater tanks to continue to decrease. The feedwater tank level reached 0.7 m at 434 s as shown in figure 7. An isolation signal was generated, which opened the valve in the discharge line of the isolation condenser and allowed flow through the isolation condenser due to natural circulation.

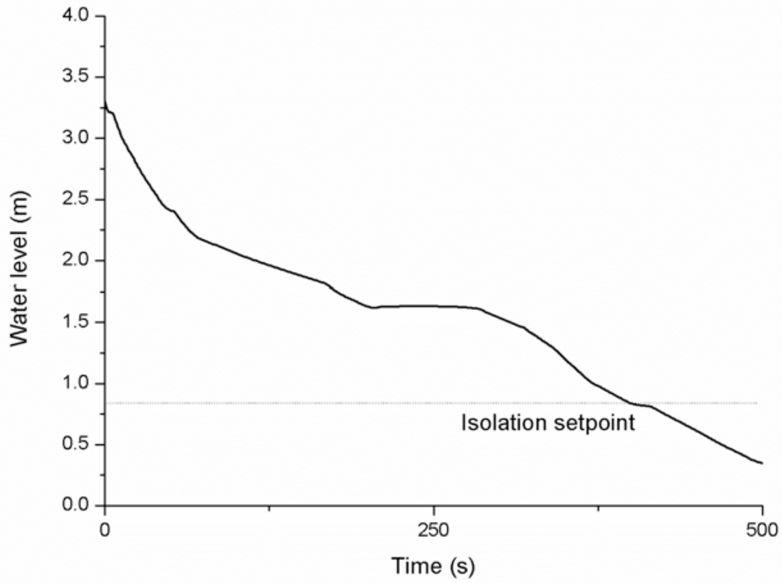

Figure 7 Feedwater tank level following a total loss of flow.

As the number of tubes in the isolation condenser determines directly the coolant mass flow rate during its operation, and influences its heat-removal capacity consequently, a series of calculations was performed in which the number of tubes were 50, 100 and 200 respectively in order to study its impact on the system. Results and analysis are presented below.

4.2.1 Mass flow rate through the isolation condenser

Figure 8 shows the flow rate through the isolation condenser during long-term LOMF. The flow rate was clearly determined by the number of tubes, and they were nearly proportional in the beginning. For the case with 50 tubes, the isolation condenser could not move out enough decay heat efficiently; thus, the pressure in the system kept rising and caused the safety relief valves releasing high pressure steam, so the mass flow rate through the isolation condenser decreased as well.

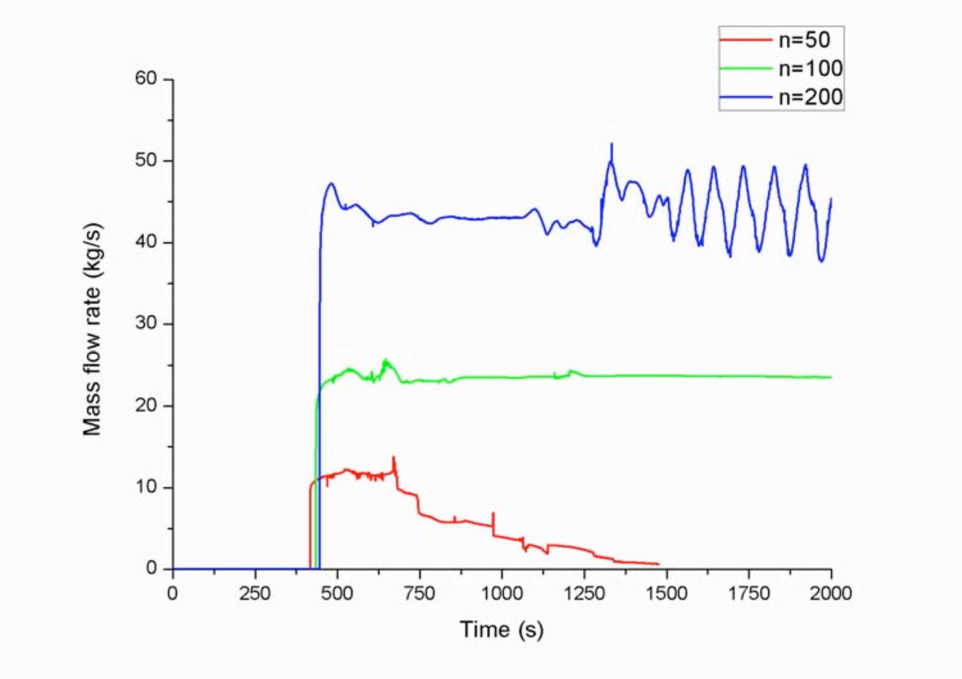

Figure 8 The flow rate through the isolation condenser during a long-term LOMF.

4.2.2 Heat removed by the isolation condenser

Figure 9 shows the heat removed by the isolation condenser during a long-term LOMF, and the reactor power as well. For the cases with 100 and 200 tubes, the heat removed by the isolation condenser eventually exceeded the core decay heat, while for the case with 50 tubes, the heat removed decreased with the decrease of mass flow coolant through the isolation condenser.

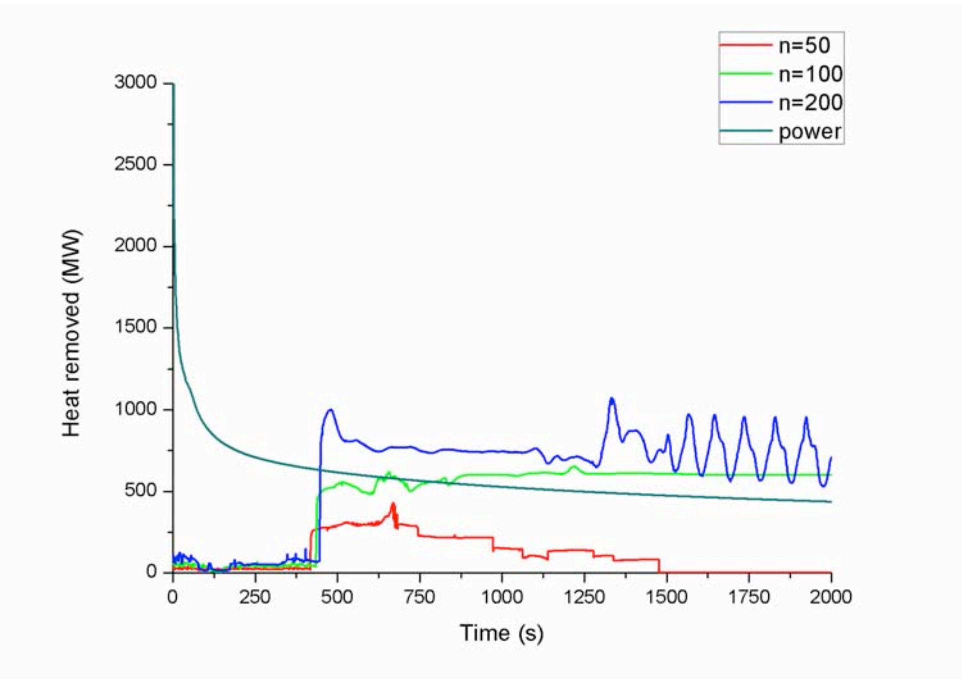

Figure 9 The heat removed by the isolation condenser during a long-term LOMF.

4.2.3 Reactor pressure

Figure 10 shows the reactor pressure during the event. The reactor pressure was generally maintained between the opening and closing set points of the safety relief valves. For the case with 100 and 200 tubes, the reactor pressure began to fall after a delay since sufficient heat was removed, and with more tubes, the fall of pressure began more early. For the case with 50 tubes, the pressure kept rising as we have anticipated.

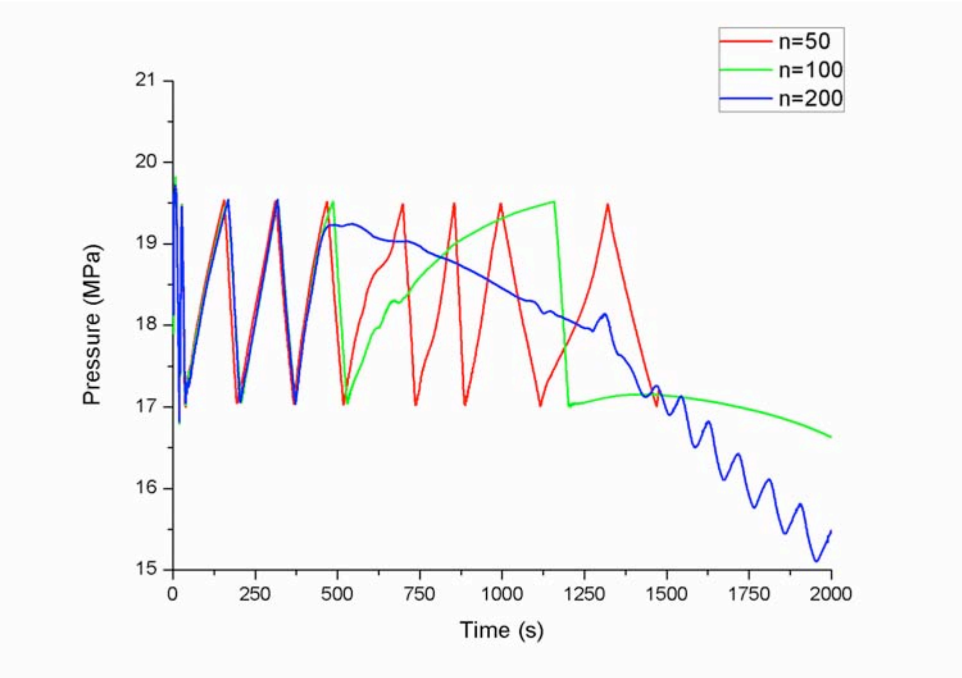

Figure 10 The reactor pressure during a long-term LOMF.

4.2.4 Maximum cladding temperature

Figure 11 shows the effect of the long-term LOMF on the maximum cladding temperature in the core. The cladding temperature decreased rapidly following the reactor trip at 15 s. The number of tubes affected the results after the isolation signal at 434 s. For the case with 100 and 200 tubes, enough decay heat was removed constantly by the isolation condenser, the cladding temperature was always kept less than 700 K. For the case with 50 tubes, the maximum cladding temperature increased rapidly after the isolation signal because he heat removed by the isolation condenser was not enough and the system kept losing coolant.

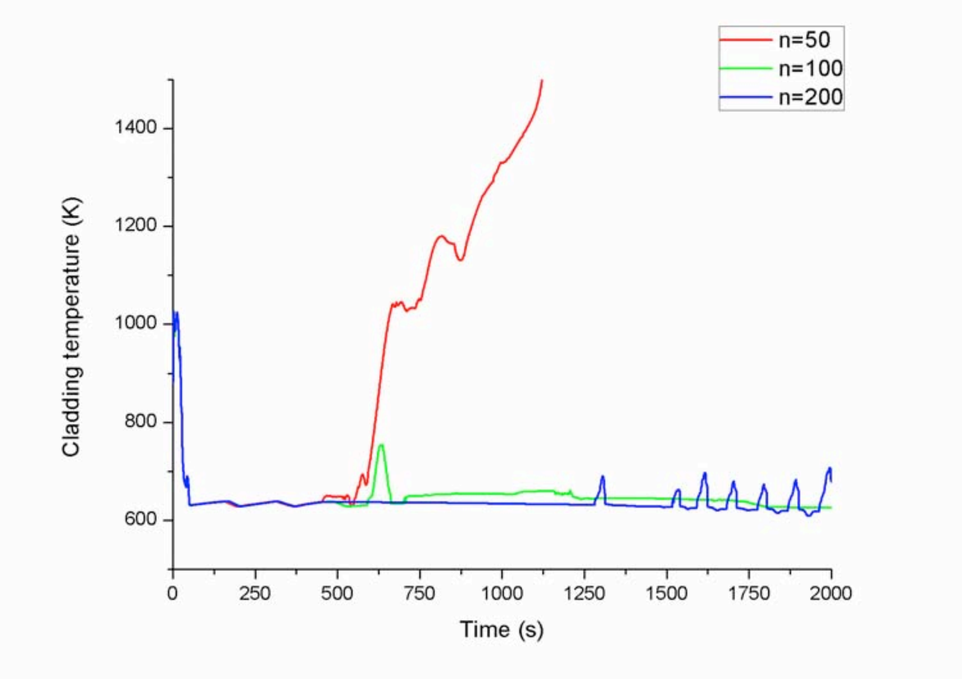

Figure 11 The maximum cladding temperature during a long-term LOMF.

5. Conclusion

A new safety concept was applied to CANDU SCWR and a RELAP5/Mod4.0 model of the proposed design was developed. The simulation results confirmed the potential of the new design for mitigating the loss-of-flow events. The combination of the liquid inventory in the feedwater tanks and the flow provided by the main coolant pumps during coastdown, and the circulation between the hot and cold legs allow the proposed design to passively meet cladding thermal limits following a LOMF transient, while an isolation condenser could provide long-term decay heat removal.

6. References

[1] D.F. Torgerson, “CANDU technology for Generation III+ and IV reactors” , *Nuclear Engineering and Design*, Vol. 236, 2006, pp.1565–1572

[2] Westinghouse Electric Co., “Feasibility study of supercritical light water cooled reactors for electric power production”, INEEL/EXT-04-02530, 2004, pp.106-108