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Thermalhydraulic Characteristics of CANDU 9 Moderator System

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Introduction

The CANDU moderator plays an important role beyond the normal function of moderating fast neutrons. It assumes the function of heat sink for the heat accumulated and produced in the fuel, following a postulated Loss Of Coolant Accident (LOCA) with loss of Emergency Core Cooling (ECC) injection. Analysis of this function is of special importance in the licensing process (Safety Analysis Report) and as a proof of adequacy of the system design [1, 2].

This paper assesses the thermalhydraulic behavior of the CANDU 9 moderator. The objective is to demonstrate that sufficient subcooling is available for LOCA with loss of ECC injection to prevent calandria tube dryout.

CANDU 9 Moderator System

The CANDU 9 moderator system is illustrated in Figure 1. The main component in CANDU 9 moderator system is a horizontal cylindrical vessel called the calandria. The vessel contains 480 horizontal fuel channels. Each channel consists of a pressure tube (PT) containing the fuel and the recirculated primary coolant, and a calandria tube (CT) surrounded by the moderator. The two tubes are separated by an annulus gap. The moderator coolant is circulated in the moderator system to remove heat from moderator. The coolant enters the calandria through twelve down-facing inlet nozzles along the wall and leaves the calandria through four outlet ports about ten degree above the inlet nozzles. The inlet/outlet nozzles are symmetrical to the cylinder axis. Such an inlet/outlet layout results in the coolant flow upward in the reactor core region.

The moderator circulation system consists of two main moderator pumps and four plate-type heat exchangers. The pumps extract the moderator from outlet ports and circulate it through the primary side of heat exchangers. The heat carried by moderator is rejected to the recirculated cooling water (RCW) in the secondary side of heat exchangers. The coolant returns to the calandria after being cooled.

The water flow rate to the secondary side of heat exchangers is governed by the Moderator Temperature Control (MTC) system. In normal operation, the moderator circulation system with the MTC logic maintains the moderator temperature by controlling the Moderator Outlet Temperature (MOC) to the nominal setpoint.

During a Loss-Of-Coolant Accident, the MTC lowers the setpoint on LOCA signal to give the maximum RCW flow rate at the secondary side of the heat exchangers. This is called Moderator Crash Cooling and will increase the heat sink capacity of the moderator.

Accident Scenarios and Analysis Objective

When a LOCA occurs in the primary heat transport system (PHTS), coolant is discharged into the containment. The PHTS inventory and consequently the PHTS pressure decrease. The reactor is tripped and energy deposition to the moderator from neutronic and fission product decay power decreases rapidly. Since ECCS injection is assumed not to occur, the fuel temperature will increase. Eventually the PT will be heated up and PT deformation occurs. This results in the pressure tube and calandria tube (PT/CT) contact either by ballooning due to high PHTS pressure or by sagging due to gravity. The moderator therefore functions as the heat sink for the heat in the fuel that is transferred through PT/CT contact. If the heat transfer is adequate, i.e., no CT dryout (film boiling on CT surface), fuel channel integrity is ensured. The results of contact boiling experiments [3] show that CT dryout will not occur if sufficient subcooling in moderator is maintained.

The present analysis addresses the out-of-core LOCA. The case of a 100% Reactor Outlet Header (ROH) break with loss of ECC injection is simulated. This case is selected because it is the limiting case in terms of heat load to the moderator. The objective of the analysis is to examine the dynamic thermalhydraulic characteristics of the moderator system when it functions as the core heat sink and to demonstrate the fuel channel integrity.

MODTURC_CLAS Computer Code

The computer code, MODTURC_CLAS, was used for the analysis. MODTURC_CLAS is a 3-D Computational Fluid Dynamics code with the heat exchanger and the MTC logic models [4] to predict temperature and hence subcooling distributions in a CANDU moderator.

MODTURC_CLAS makes use of the most recent advances in computational methods to provide greater flexibility and economy in prediction of moderator temperature and flow of a single-phase turbulent incompressible fluid. The use of the code allows calculations of detailed 3-D distributions of moderator velocity and temperature inside the calandria vessel, and simulation of transient inlet/outlet temperatures using the heat exchanger and MTC logic models.

Modelling Conditions

The calandria consists of the reactor core and the reflector region. In the reflector region a polar grid is used with fine mesh in the vicinity of the inlet jets. In the reactor core a non-orthogonal grid is employed. The effect of the calandria tube matrix on the flow distribution in the core is modeled by using the porous media concept. The total number of nodes is 135792.

A CANDU 9 heat exchanger model is incorporated into the MODTURC_CLAS code. The RCW rate on the secondary side of heat exchangers is adjusted every two seconds depending on both the neutron power change rate and the deviation of the MOT from the setpoint.

The simulation starts from the steady-state normal operating conditions. For conservatism, the heat load to moderator of 129MW which corresponds to 103% full power operation, was used in the simulation. The initial power distribution is proportional to the bundle power map at steady state. The total inlet nozzle mass flow rate of nominal value is assumed equally distributed to the 12 inlet nozzles. The initial inlet temperature is taken from the energy balance calculation based on the nominal setpoint of outlet temperature, heat load and flow rate.

The dynamic boundary conditions used in the simulation include the energy deposition directly from neutronic power and fission product decay power, and heat load from fuel due to pressure tube/calandria tube contact. The simulation assumes that the cover gas pressure is maintained at the nominal value and the moderator crash cooling is not credited during the transient process.

The simulation was performed for 1200 seconds at which time, the moderator temperature increase has already been arrested.

Results

Figures 2 and 3 present initial (steady-state) velocity and temperature distributions. Figure 2 shows the velocity field in the plane X=2.54 m that is an inlet plane. As can be seen from this figure, the jets coming out from the nozzles travel along the vessel wall meeting at the bottom of the vessel. The jet flow then moves upwards through the core with some of the flow at the top being directed towards the outlet and the remainder being deflected at the top of the vessel. The flow in this plane is seen to be symmetrical. Figure 3 shows temperature isotherms in the Y-Z planes at distance 2.54 m from the sub-shell axial face. As can be seen from the figure, the temperature in these planes increases monotonically from the bottom of the vessel to the top. This phenomenon is observed for any given axial plane (X=constant). The highest temperature is about 70°C on the top row of channels in the core region. The temperature difference between the bottom and the top in the core is around 12°C, which reflects a good moderator mixing capability inside the calandria as per design intent.

Figures 4 and 5 respectively show the velocity and temperature distributions in the plane X=2.54 m at the end of the transient simulation. The velocity and temperature distributions at any given time are similar to those under normal operating conditions. Figure 6 shows the moderator temperature transients. As can be seen, the inlet temperature closely responds to the control logic, giving a maximum temperature of 68°C at 320 seconds and a minimum temperature of 43°C at 450 seconds. The moderator temperatures at the core region and at the outlets decrease in the early stage of the accident due to the reactor trip that reduces heat load to the moderator. When the Pressure Tube/Calandria Tube contacts occur, the moderator temperature increases due to increased heat load to the moderator. However, the moderator heat exchangers are able to remove the heat and arrest the temperature increase. The temperature spikes occur shortly after the beginning of each PT/CT contact and are smeared out very quickly by forced and natural convection of moderator in the vessel. The highest core temperature is about 74°C on the top row of channels, giving a subcooling of 34°C. Figure 7 shows the subcooling for top 10 rows, Rows A to K. As can be seen, the minimum subcooling is approximately 34°C that occurs at row A and at around 400 seconds. Therefore, CT dryout is precluded with a large margin, based on the results of contact boiling experiments [3] which determine the limiting condition for CT dryout.

Conclusion

It can be concluded that the design of the CANDU 9 moderator system provides robust and stable thermalhydraulic characteristics both in normal operating conditions and during the transient after a large LOCA combined with loss of ECC injection. The calculated temperature distribution shows that there are no localized hot spots in the moderator. The large subcooling margin precludes the occurrence of dryout of calandria tube, thereby ensuring that channel integrity is maintained.

References

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2. M. Bonechi and A.L. Wight, “CANDU 9 Safety and Licensing Update”, paper presented at the 14th KAIF/KNS Conference, Seoul, Korea, April 1999.
3. GE. Gillespie, R.G. Moyer and P.D. Thompson, “Moderator Boiling on the External Surface of a Calandria Tube in a CANDU Reactor During a Loss-of-Coolant Accident”, AECL-7664, 1982 October.
4. MODTURC-CLAS Version 2.3, User Documentation, January 1994, Advanced Scientific Computing Ltd., Waterloo, Ontario, Canada.

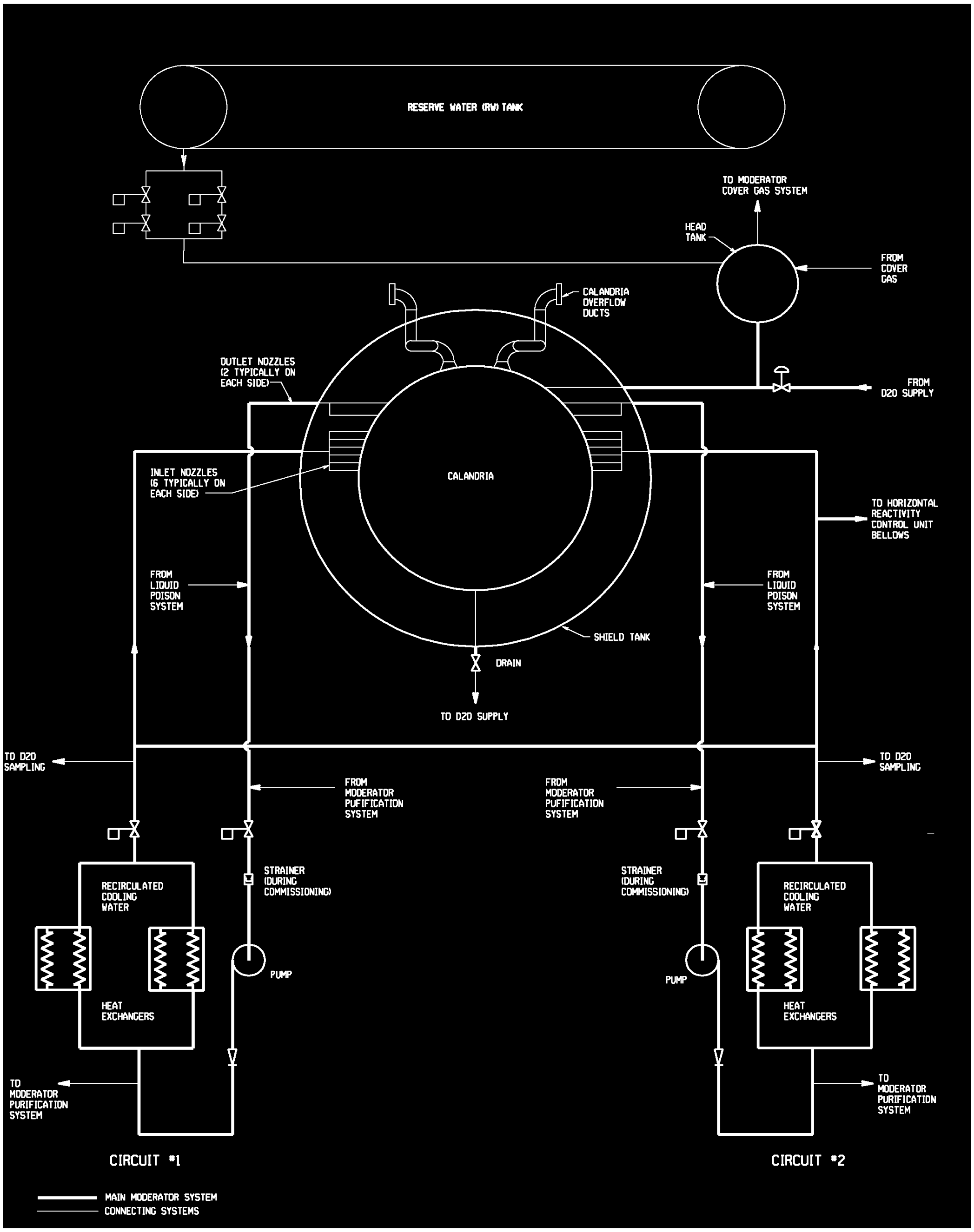

Figure 1 CANDU 9 Moderator System

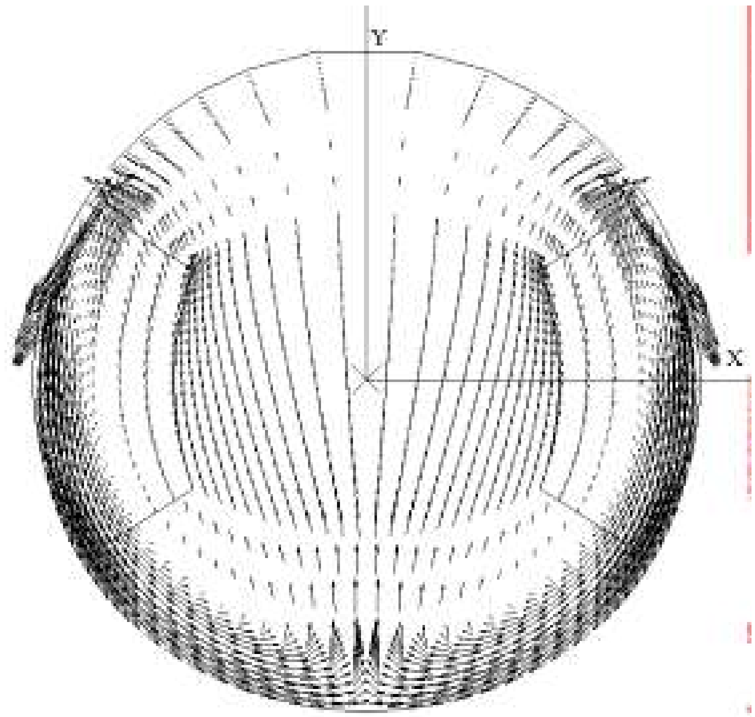

Figure 2 **Initial Velocity Field in a Inlet Flow Plane (X=2.54 m)**

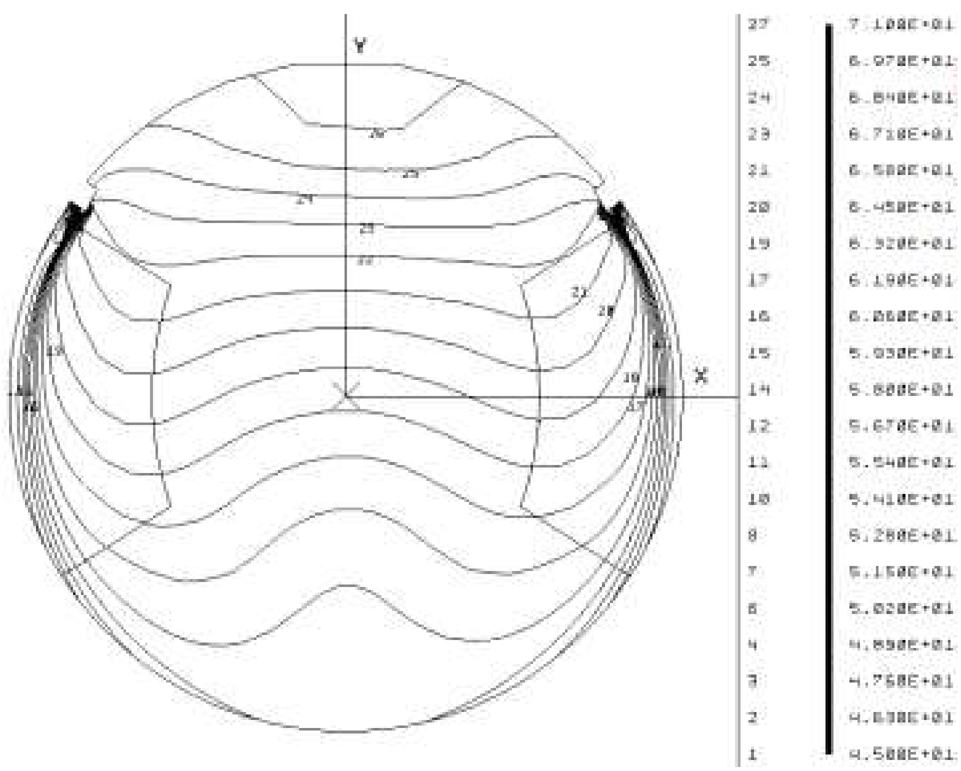

Figure 3 **Initial Temperature Isotherms in a Inlet Flow Plane (X=2.54 m)**

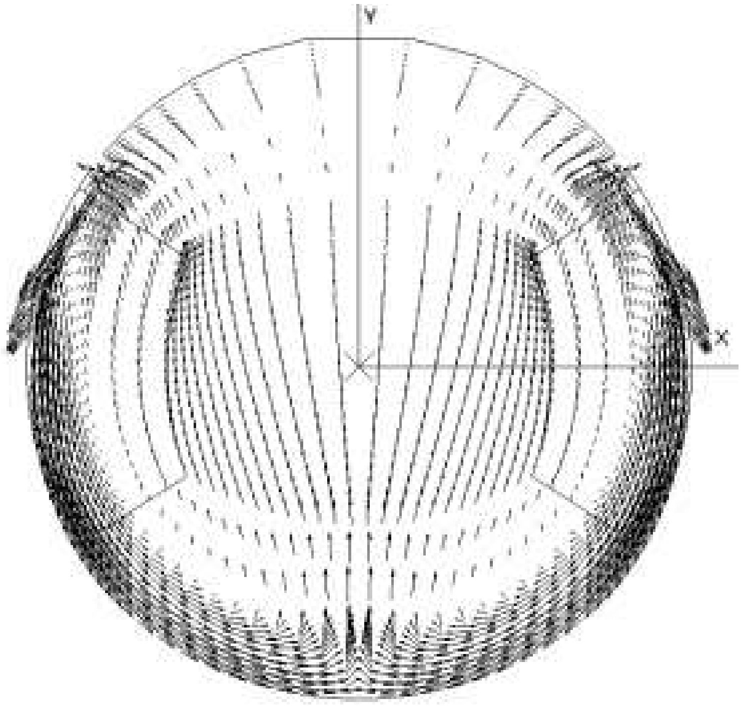

Figure 4 **Velocity Field in a Inlet Flow Plane (X=2.54 m), at 1200 s**

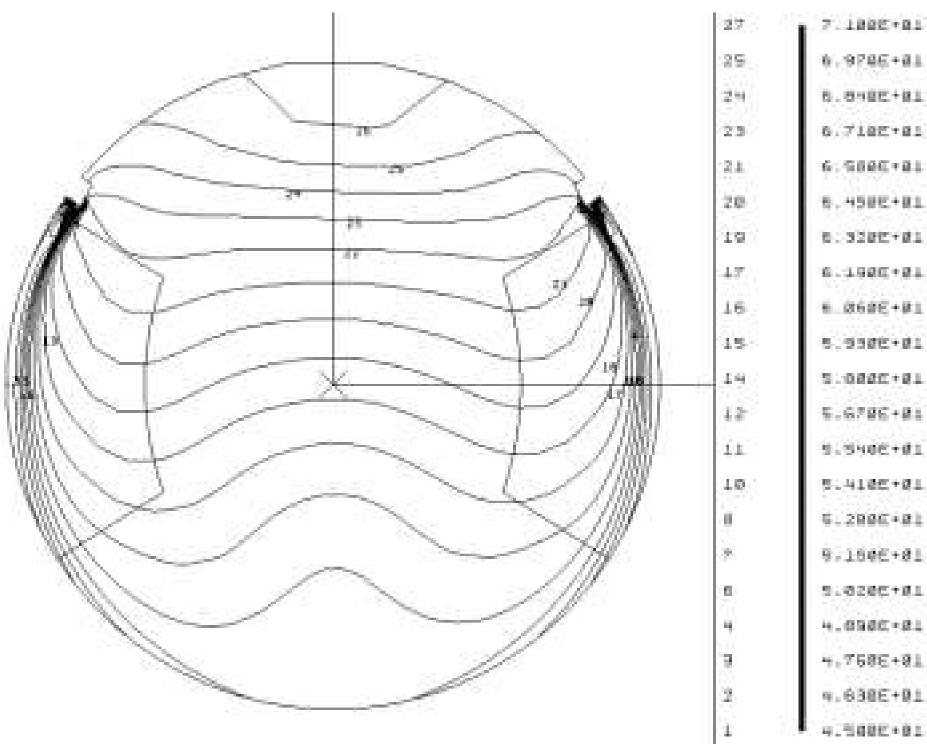

Figure 5 **Temperature Isotherms in a Inlet Flow Plant (X=2.54 m), at 1200 s**

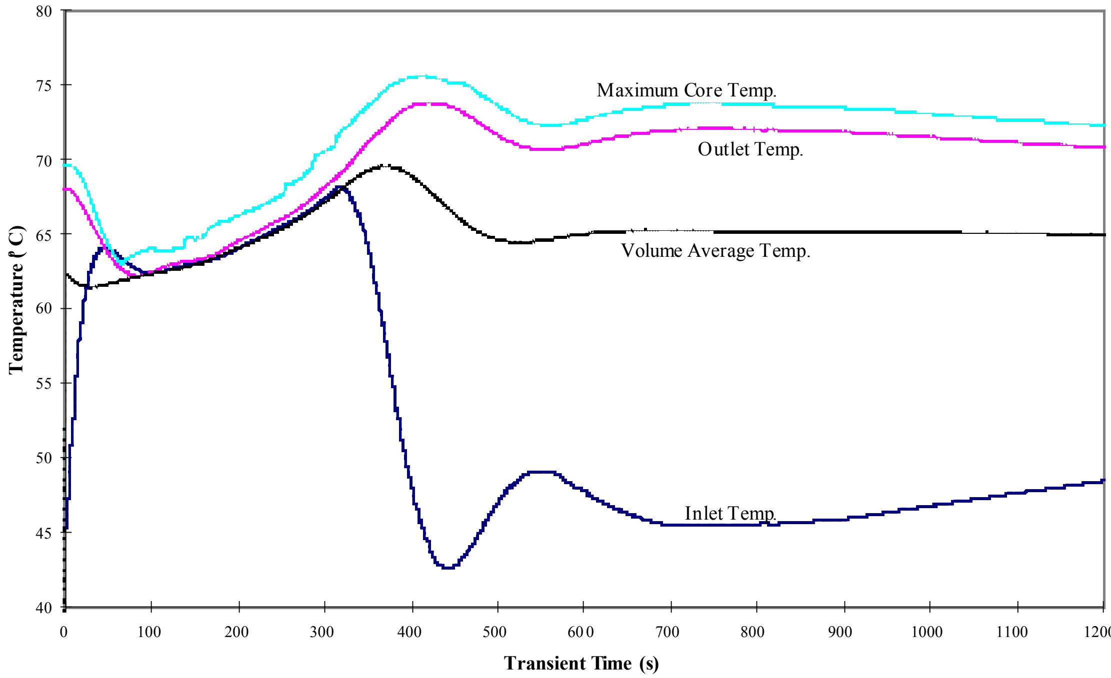

Figure 6 Moderator Temperature Transients

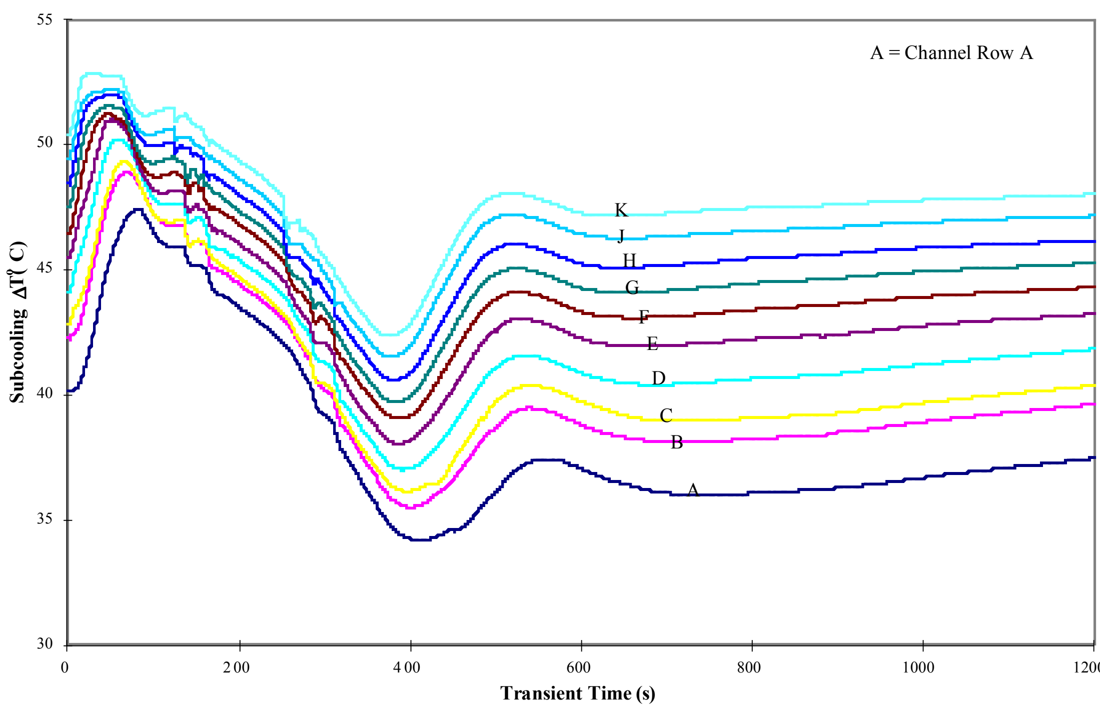

Figure 7 Moderator Subcooling Transients