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Sensitivity Analysis of RCW Temperature on the Moderator Subcooling Margin for the LBLOCA of Wolsong NPP Unit 1

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1. Introduction

Heat removal from the Primary Heat Transport System (PHTS) to Moderator by Pressure Tube/ Calandria Tube (PT/CT) contact in the CANDU reactor is one of valid heat removal methods when the Large LOCA with LOECI (Loss of ECC Injection) occurs [1]. Moderator subcooling margin has to be ensured in order that heat removal through the moderator is available. Thus, moderator subcooling margin has been analyzed using the MODTURC_CLAS code in the Large LOCA FSAR PARTs C & F.

Performance of moderator heat exchangers depends on RCW (Raw reCirculated Water) temperature. And also the temperature is affected by sea water temperature. Unfortunately, sea water temperature is gradually increasing by global warming. So it will cause increase of RCW temperature inevitably. There is no assessment result of moderator subcooling with increasing RCW temperature even if it is important problem. Therefore, sensitivity analysis is performed to give information about the relation between RCW temperature and moderator subcooling in the present study.

2. Methodology and Assumptions

In this section introduction of the code, methodology and assumptions used to analyze the moderator subcooling are described.

2.1 MODTURC_CLAS code

A computational fluid dynamics (CFD) software package, MODTURC_CLAS V2.9-IST, was used to analyze moderator subcooling margin following a large LOCA with LOECI in the Wolsong unit 1. This code was developed to predict the CANDU moderator temperature distributions in normal operation, or available subcooling during postulated LOCAs for which the moderator is required to act as a heat sink. It is a customized version of the more general code TASCFLOW [2, 3], which includes additional moderator specific models and parameters described in detail in References 4 and 5.

CANDU specific features included in MODTURC _CLAS are concept of porosity, pressure loss, buoyancy, and mass/momentum/energy sources and so on. The effect of the calandria tube matrix on the flow distribution is approximated using the porous media concept.

Buoyancy forces can be modeled using one of two models in this code: one is the Boussinesq' approximation in which density difference is assumed to a linear function of a local fluid temperature and a reference temperature, and the other is calculating a density difference based on a temperature difference and a volumetric expansion coefficient, either constant or variable.

The standard k-ε model was employed to model turbulence generation and dissipation within the vessel.

2.2 Methodology

In the present study, the same methodology used in Large LOCA PART F (Large LOCA with LOECI and Loss of Class IV Power) is used to assess the moderator subcooling.

PT/CT contact time, maximum PT temperature at contact time, and heat load to the moderator are calculated in single channel analysis using the CATHENA. The heat load to the moderator is used as an input in MODTURC_CLAS code, and other two results are used in the moderator subcooling margin assessment.

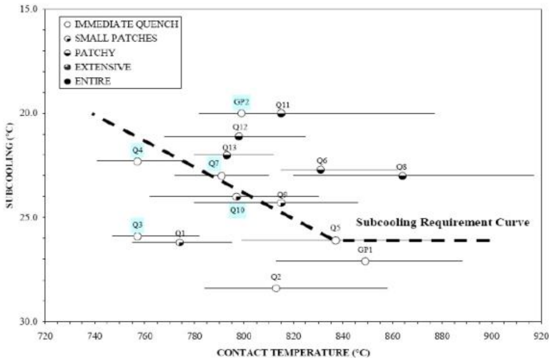

Figure 1 Moderator Subcooling Requirement Curve using Glass-peened Calandria Tubes

Required subcooling with above two parameters (PT/CT contact time, maximum PT temperature at contact time) is indispensable parameter to calculate the moderator subcooling margin. The required subcooling is estimated by using the "Subcooling Requirement

Curve” depicted in Figure 1. Figure 1 presents the Subcooling Requirement Curve for early heat-up due to PT/CT ballooning contact that was obtained using experimental results from full-scale tests plotted in terms of subcooling versus pressure tube temperatures at the time of PT/CT contact.

The objective of the moderator analysis using the MODTURC_CLAS is to calculate the minimum available subcooling at elevations encompassing the top 10 rows of channels. The transient of the maximum core and global temperatures and outlet and bulk temperatures are also predicted. The limiting case for this analysis is the case with the maximum extent of PT/CT contact from the single channel analysis, because that maximizes the heat load to the moderator.

The previous analysis results (FSAR LBLOCA PART F) are yielded based on RCW temperature of 35℃. In the present study, 38℃ and 39℃ RCW temperature are also assumed to predict the moderator minimum subcooling margin. Lastly, these three results will be compared.

2.3 Assumptions

The assumptions used in the analysis are summarized below:

1) The moderator heat load is 100 MW initially and is distributed based on the bundle power map at an initial or equilibrium operating condition at 103% full power.
2) The calandria wall is assumed to be thermally adiabatic.
3) The moderator outlet temperature is set to the moderator outlet temperature setpoint (69℃) plus 1.6℃ for uncertainty [6]. For quasi-steady state simulations, the inlet temperature (boundary condition) is specified to keep the outlet temperature at a given value, based on moderator heat load and inlet flow rate. For transient, the Moderator Temperature Control (MTC) model in MODTURC_ CLAS controls the outlet temperature (by adjusting the opening of RCW valves).
4) The moderator circulation remains at its full flow rate of 1019 kg/s.
5) The moderator cover gas pressure is 21 kPa(g).
6) Class IV power is assumed to be unavailable when the turbine begins to unload. This is assumed to occur 15 seconds after the break.
7) When Class IV power is lost, the main moderator pump runs down and simultaneously service water flow to the heat exchangers stops. The main moderator pump is assumed to rundown to zero rpm linearly over a period of 60 seconds. Thus 75 seconds after the break there is no moderator flow.
8) 15 seconds after termination of main moderator pump flow (90 seconds after the accident) the pony motors which are on Class II power start up and increase the moderator flow linearly from 0 to 256 kg/s over a period of 10 s (equally distributed to the eight nozzles).
9) 3 minutes after the loss of Class IV power (195 seconds after the accident) service water flow is restored to the heat exchangers.
10) During the main pump rundown period (from 15 seconds to 75 seconds) the inlet temperature is calculated by MTC logic of MODTURC_CLAS.
11) Following 195 seconds, at which time the service water is restored to the heat exchangers.
12) At 1000 seconds, the operator re-establishes the normal (100%) moderator flow by connecting the main motor to one of the Class III buses.

The thermalhydraulic boundary conditions are described in Table 1.

Table 1 Thermalhydraulic Boundary Conditions for the Moderator Subcooling Analysis

Parameters	Value
Total moderator heat load	100 MW
Fraction of heat load in the core region of the moderator	0.939
Outlet temperature	70.6℃
Total inlet mass flow rate	1019 kg/s
Ratio of mass inflow at two inlet nozzle banks	49/51
Ratio of mass flow per inner/outer inlet nozzle compartments	38/62
Cover gas pressure	21 kPa(g)
Recirculating service water per heat exchanger	1125 kg/s
Recirculating service water temperature	35, 38, 39℃

3. Analysis Results

3.1 Available Subcooling Transient

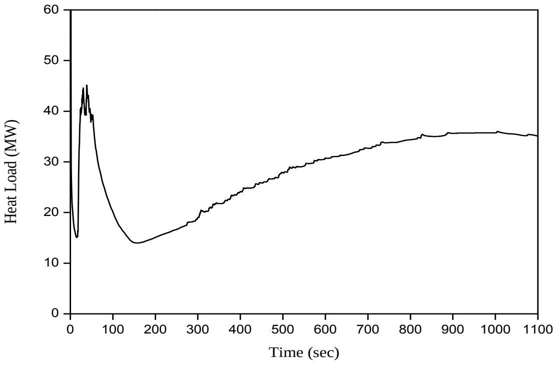

Figure 2 Heat Load to Moderator Following a 35% RIH Break with LOECI and Loss of Class IV Power

The total heat load to the moderator is shown in Figure 2 when the Large LOCA with LOECI and Loss of Class IV Power is occurred. The reactor trip occurs at about 0.43 s. There is an initial peak in the heat load corresponding to the power pulse. This initial peak is terminated by reactor shutdown. Shortly after 14 seconds, PT/CT contact begins due to PT strain, causing a second increase in heat load to the moderator. There is an initial "spike" in the contact heat load to the moderator corresponds to the rapid transfer of stored heat in the pressure tube across the PT/CT ballooning interface, to the calandria tube and then to the moderator. This results in a second peak, which turns around after the phase of PT/CT contacts ends. In the longer term the heat load rises slowly to a third peak as more pressure tube segments sag into contact with their calandria tubes, reaching a third peak at about 1000 s.

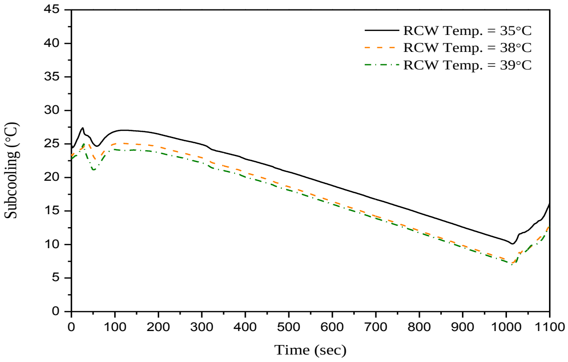

Figure 3 Minimum Available Subcooling at Row A for 35% RIH Break with LOECI and Loss of Class IV Power

Local temperature variations are predicted by the MODTURC_CLAS code. The minimum available subcoolings at fuel channel row A as a function of time for each RCW temperature conditions are shown in Figure 3. The reason of showing only the row A is that this row is placed the top of the calandria and has higher temperature than other lower rows. Since the moderator temperature is increased as the RCW temperature increases in quasi-steady state, the initial subcoolings are different each other. The initial subcoolings at row A of RCW temperature 35℃, 38℃, and 39℃ are 25℃, 23.5℃, and 23℃ respectively. After reactor trip, the heat load to the moderator decreases until PT/CT contact begins at around 20 seconds. Thus moderator subcooling initially increases (or local temperature decreases), then decreases as the heat load from PT/CT contacts increases. After about 60 seconds the moderator head load decreases again, and subcooling increases. As the moderator pump runs down (completely stopped at 75 seconds), the flow in the calandria becomes buoyancy - dominated. The moderator pony motors start at 90 seconds, but deliver only one-quarter of the normal flow. The jets from the calandria inlet nozzles are too weak to penetrate the hotspot at the top of the calandria. Thus, subcooling continuously decreases until the operator re-starts the main motors at 1000 seconds.

3.2 Subcooling Margin

Method of assessment of subcooling margin is divided into four steps: CATHENA single channel analysis results arrangements, required subcooling estimation, minimum available subcooling estimation, and subcooling margin calculation.

First of all, PT/CT contact time and PT maximum temperature at contact time for each channel and bundle location should be extracted from CATHENA single channel analysis results. Secondly, required subcooling estimation is performed by using the Figure 1, "Moderator Subcooling Requirement Curve". In third step, the minimum available subcooling corresponding to contact time for each channel and bundle location should be searched in the MODTURC_CLAS available subcooling results. Finally, subcooling margin is derived by subtracting required subcooling from available subcooling. An example of subcooling margin result in accordance with above procedure is shown in Table 2. And also subcooling margins for each RCW temperature condition are shown in Table 3.

Table 2 Example of Subcooling Margin Result

Channel Power (MW)	7.3
Bundle Location	7
Highest Row Location	Row M
PT/CT Contact Time (s)	14.4
Max PT Temp. @ contact time (℃)	800
Required Subcooling (℃)	23.5
Available Subcooling (℃)	33.11
Subcooling Margin (℃)	9.61

As a result of this analysis, if RCW temperature exceeds 39℃ the subcooling margin may not be ensured when Large LOCA with LOECI and Loss of Class IV Power occurs.

Table 3 Minimum Subcooling Margin of Critical Pass

RCW Temp. (℃)	**Channel Power (MW)**	**Bundle Location**	**Highest Row Location**	**PT/CT Contact Time (s)**	**Max PT Temp. @ contact time (℃)**	**Required Subcooling (℃)**	**Available Subcooling (℃)**	**Subcooling Margin (℃)**
35	4	10	Row A	884	sagging	10	12.95	2.95
38	4	10	Row A	884	sagging	10	10.23	0.23
39	5	6	Row B	41.2	788	22.75	22.40	-0.35

4. Conclusions

The moderator subcooling margin has to be ensured to establish the moderator heat removal when Large LOCA with LOECI and Loss of Class IV Power occurs.

However, sea water temperature is increasing gradually due to global warming. So it is necessary that sensitivity analysis of RCW temperature on the moderator subcooling margin to estimate the availability of the moderator heat removal.

In the present paper, the moderator subcooling analysis is performed using the same methodology and assumptions except for RCW temperature used in FSAR Large LOCA PART F. As a result of this analysis, it is conclude that the moderator subcooling margin may not be ensured when Large LOCA with LOECI and Loss of Class IV Power is occurred if RCW temperature exceeds 39℃.

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