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Wolsong 2,3&4 Fuel Channel Analysis during a Large Break Loss of Coolant Accident with Loss of ECCS Injection

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Abstract

Wolsong 2,3&4 fuel channel analysis during a large break loss of coolant accident with loss of ECCS injection (LOCA/LOECC) is performed to obtain the heat load to moderator. Because the single channel analysis requires the establishment of the safety codes and their input decks, the present study follows the same safety analysis methodology found in FSAR of Wolsong 2,3&4. From this work we obtain the safety tools such as CATHENA MOD3.5b/Rev.1 and CHAN-II/A MOD2 codes, and their code modeling in a form of code input deck. The analysis consists of two parts: front-end (blowdown period) and back-end. For the front-end analysis the fuel and pressure tube (PT) temperatures, and PT circumferential strains at the end of front-end as well as fuel channel depressurization are calculated using CATHENA code and used as initial and boundary conditions for back-end analysis. The back-end period under the conditions of prolonged low steam flow is analyzed by CHAN-II code to determine parametrically the limiting steam flow rate that maximizes the fuel temperatures.

Finally, the heat load from a single channel to moderator is calculated by CATHENA for front-end and by CHAN-II for back-end, which is used as input to a moderator analysis.

1. Introduction

The Wolsong 2,3&4 single channel analysis is divided into two parts 1) the front-end analysis for blowdown phase and 2) the back-end analysis for the late heat up phase (post-blowdown).

The front-end is defined as the period up to the time at which the fuel is cooled by single-phase superheated steam at a very low flow. A detailed calculation of the fuel and PT temperatures for a specific channel is performed by CATHENA MOD3.5b/Rev.1 code [2]. The CATHENA single channel model includes feeders, end-fitting, PT, CT, and fuel bundles. The boundary conditions such as the inlet and outlet header pressure, enthalpy and void fraction are provided by the CATHENA MOD3.5b/Rev.1 circuit analysis for a “slave” CATHENA single-channel analysis.

Fuel channels in half of the core are divided into six channel power groups as shown in Table 1. The behavior of each channel in a given group is represented by one channel at the maximum power for the group. The distribution of channels with each group is determined from a fuel management study [1].

The fuel model in the single channel contains 10 groups of fuel elements per bundle and models radiation heat transfer and PT deformation. In this paper more detailed fuel model is also considered to investigate the effect of fuel grouping on the fuel transient behavior. For the 1st channel power group the channel power and the maximum bundle power (bundle 6 and 7) of channel O6 are normalized to the maximum operating limits of 7.3 MW and 935 kW, respectively. The fuel and PT temperatures and PT circumferential strains at the end of front-end as well as fuel channel depressurization are used as initial and boundary conditions for back-end analysis.

The back-end analysis starts at the end of front-end and covers a long period, typically about 2500 sec, until Zircaloy/steam reaction termination occurs and heat generation balances heat loss. In this period the fuel elements are expected to heat up and fail, fission products are released from the fuel matrix, hydrozen is generated in the channels and pressure tubes heat up and deform. The back-end analysis is performed by using the CHAN-II/A MOD2 code [3] and a parametric study to determine the worst steam flow rate which maximizes the Zircaloy/steam reaction and at the same time minimizes the heat removed by the flowing steam and hydrozen.

In the present study, CATHENA calculation during the back-end period is also performed to compare the fuel behavior by CHAN-II MOD2 calculations. For this purpose CATHENA calculation is extended to the back-end period using the flow boundary condition model corresponding the specified steam flow rate.

The heat load from O6 channel to moderator is calculated by CATHENA for front-end period and by CHAN-II for back-end period. The same procedure can be applied to other power groups shown in Table 1 to provide the heat source boundary conditions for the moderator analysis.

Table 1 Representative Channel and Number of Channels for Each Power Group

Channel Power Group	Channel Power Range (MW)	Channel Numbers	Representative Channel and Power (MW)
1	7.0-7.3	2	O6(7.3)
2	6.6-7.0	9	S10(7.0)
3	6.0-6.6	37	L3(6.6)
4	5.0-6.0	16	G5(6.0)
5	4.0-5.0	14	B10(5.0)
6	0.0-4.0	17	W10(4.0)

2. Front-end Channel Model

The O6 channel is modeled for the highest power group which has the minimum critical channel power ratio. The CATGEN utility program [4,5] is used to assemble the relevant geometry data in the CATHENA fuel channel models, CATHENA end fitting models and feeder models to generate the CATHENA input data file for the single channel from header-to-header.

2.1 Header Boundary Conditions

The transient thermal-hydraulic header boundary conditions such as pressure, enthalpy and void fraction are provided by CATHENA MOD3.5b/Rev.1. Figure 1 gives the pressure transient and gas enthalpy for RIH 35% break.

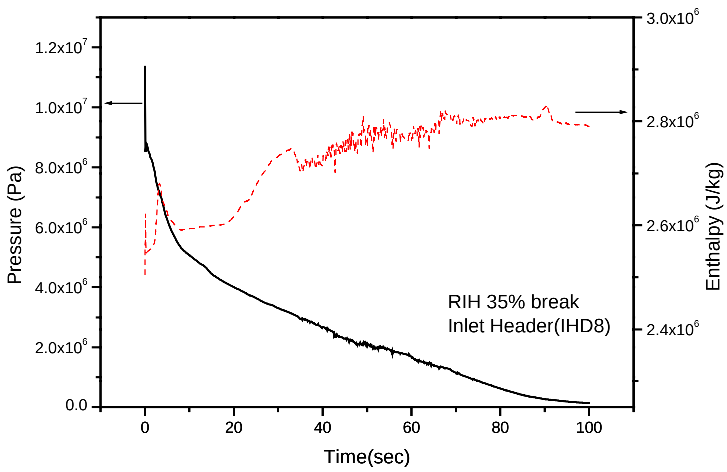


Figure 1 Header BC.s from Circuit Analysis (Critical Pass: RIH 35% break)

2.2 Reactor Power Transient

The reactor power transient (normalized) will be provided by reactor physics calculation [6] in a file readable by CATHENA. The channel axial and radial power distributions are given in the fuel input data of the heat transfer package.

2.3 Hydraulic Model

In the CATHENA slave channel model of O6 [7], a total number of twenty pipe components is used across the inlet feeder, inlet end fitting, fuel string, outlet end fitting, and outlet feeder. A schematic diagram of the hydraulic model is shown in Figure 2. The number of feeder nodes is selected for each channel depending on the orientation and cross sectional area of two successive elements.

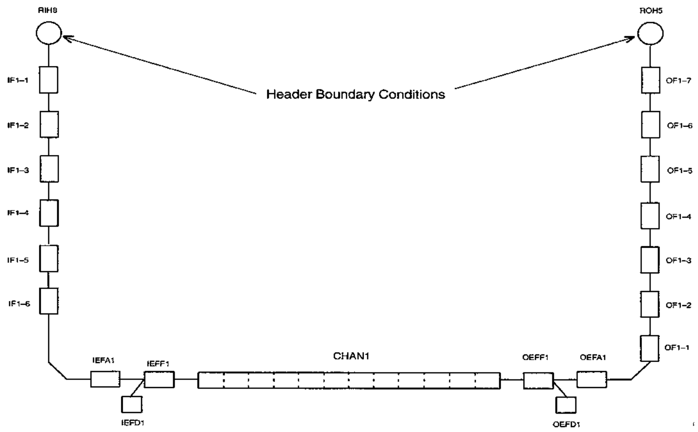


Figure 2 Nodalization of CATHENA Slave Channel Model

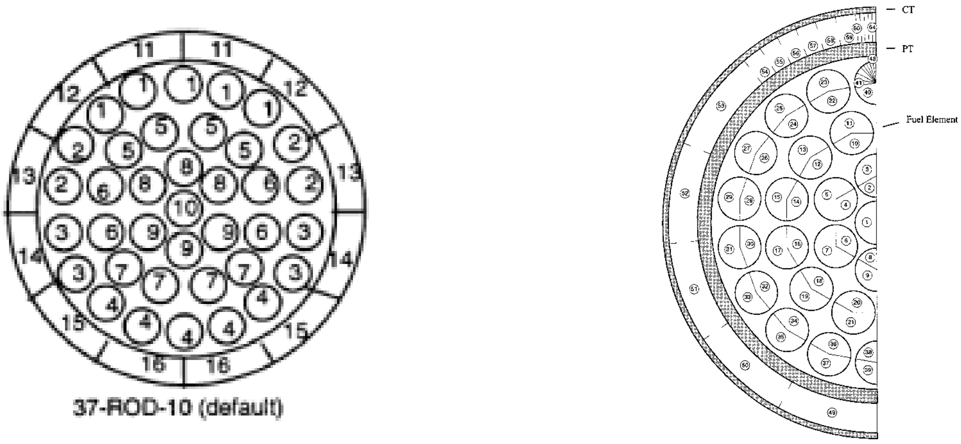
2.4 Fuel Input Data

The inlet and outlet feeder is divided into a number of sections, the inlet and outlet end-fittings are also divided into sections, and the fuel channel is divided into 12 sections (i.e., 12 bundles residing within the channel). The 4 cylinder grouping (37-ROD-10) from the fuel channel model [8] is chosen for the slave models. That is, each ring (center pin, inner ring, intermediate ring, and outer ring) is modeled separately accounting for the radial power distribution.

Each fuel element is typically divided into 4 radial regions: fuel, gap, Zircaloy sheath and oxide layer. The fuel element model consists of a detailed radial nodalization with radial nodes in the fuel pellet region, in the gap region, in the sheath region, and in the oxide region. The thermal radiation among the fuel elements, between the fuel elements and the PT, and between the PT and CT is modeled in the CATHENA single-channel analysis; therefore, a thermal radiation view factor matrix defines which solid surfaces may radiate heat between each other. This matrix is generated from matrix utility program in CATHENA. The heat transfer associated with a particular surface under flow stratification in the channel is also modeled by the alpha-wet and alpha-dry values which provide the void fraction limits for submerged or exposed conditions. These are generated form the bundle untility program in CATHENA.

In this paper more detailed fuel model [9] is also considered to investigate the effect of fuel grouping on the fuel transient behavior. In the detailed fuel model, the separation of the top element from the outer ring is performed to model the bearing pad/PT contact, each fuel element except center pin is divided into 2 sectors, and the number of sectors for pressure tubes and calandria tubes are increased.

Figure 3 gives a cross sectional view of the fuel pin grouping and sectoring for both of the fuel models.



(a) 37-ROD-10 (b) Detailed model

Figure 3 Fuel Pin Grouping for Channel O6

The channel power and the maximum bundle power (bundle 6 and 7) of channel O6 are normalized to the maximum operating limits of 7.3 MW and 935 kW, respectively. All fuel bundles in the channel are assumed to have a bundle radial power profile at a burnup corresponding to the plutonium peak.

3. Back-end CHAN-II/A MOD2 Model

The back-end analysis provides the fuel and PT temperatures, and the heat load to moderator from PT/CT contact due to PT deformation. The CHAN-II/A MOD2 is used for the back-end analysis.

The code contains a single fuel channel model with nodalization and geometry similar to that of the CATHENA slave model. The channel is divided axially into 12 nodes, each axial node length corresponds to one fuel bundle. For each axial segments, the fuel elements, PT and CT are modeled as a system of concentric rings. Modeling of a center pin, inner ring (6 elements), intermediate ring (12 elements) and outer ring (18 elements) simulates a regions, contact and non-contact zones depending on PT deformation.

Under the conditions of prolonged low flows, CHAN code evaluates the thermal and chemical response of fuel channels. The code quantifies the effects of steam flow, Zircaloy/steam reaction, and thermal radiation on fuel, PT and CT, and estimates the hydrogen production from the Zircaloy/steam reaction. The inlet steam temperature and flow are specified as input parameters.

The input assumptions for CHAN-II/A MOD2 model are as follows:

- Contact conductance between the PT and CT is assumed to be constant at 6.5 kW/m^{2}K for sagged pressure tubes and 11 kW/ m^{2}K for ballooned PT.
- The moderator temperature is taken as 66°C.
- The Urbanic and Heidrick correlation is used for the Zircaloy/steam reaction calculation.

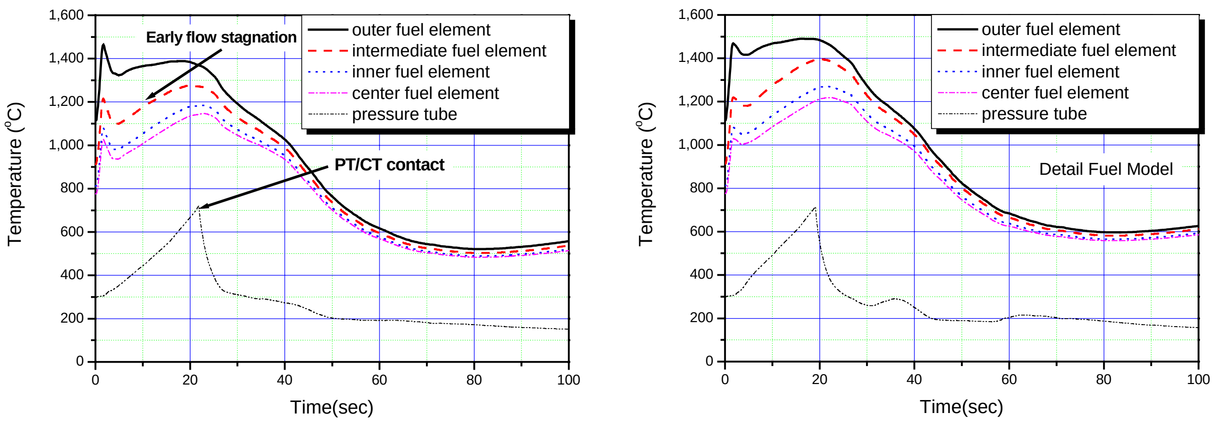
4. Fuel Channel Analysis Results

4.1 Results of Front-end Calculation

Figures 4 and 5 show fuel and pressure tube temperatures at bundle 6 of a O6 channel for 35% RIH break and 100% ROH break, respectively.

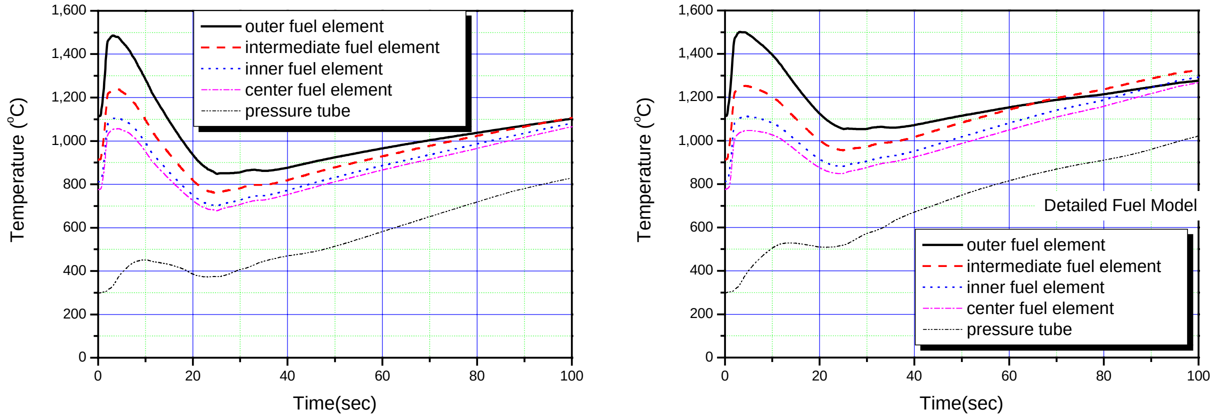
The effect of grouping is not sensitive to the maximum fuel temperature during the front-end. Therefore, there is no need to use detailed fuel model and 10 group fuel model is appropriate for the front-end assessment.

PT/CT contact is predicted to occur in the RIH 35% break. Fuel element temperatures in bundles near PT/CT contact locations decreases rapidly after PT/CT contact due to the improved heat transfer to the cooler pressure tube. However, the PT temperature for ROH 100% break is continuously increased and the late heatup rate by ROH 100% break is higher than that by RIH 35% break, because there is no PT/CT contact prior to start of fuel heatup. Therefore, the fuel and pressure tube conditions for 35% RIH break are used in the CHAN simulations to represent all breaks which result in significant PT/CT ballooning contact in the critical pass during front-end. PT contact does not occur in the critical pass for ROH 100% break with loss of ECC injection during front-end due to a small flow in the forward direction and rapid depressurization.



(a) 37ROD-10 (b) Detailed Model

Figure 4 Fuel and Channel Temperatures in the Critical Pass for a 35% RIH Break with Loss of ECC Injection (Bundle 6 of 7.3 MW Channel)

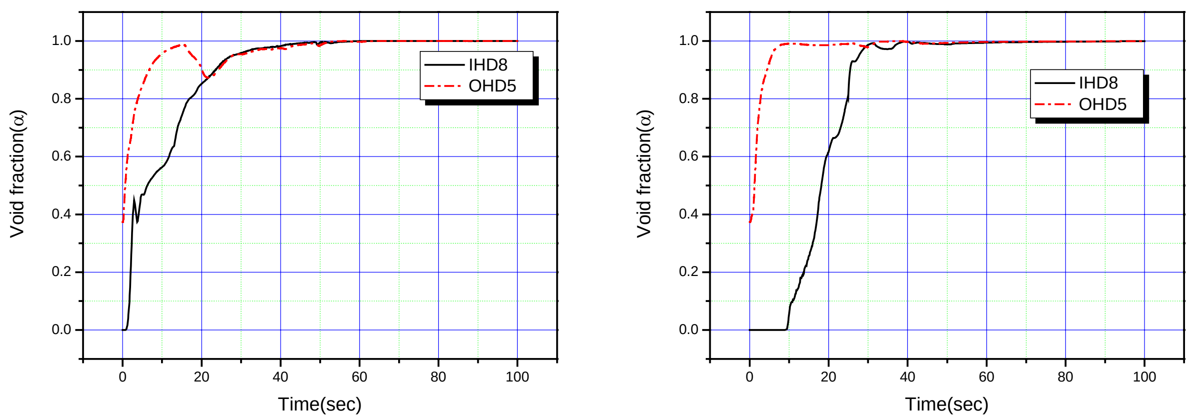


(a) 37ROD-10 (b) Detailed Model

Figure 5 Fuel and Channel Temperatures in the Critical Pass for a 100% ROH Break with Loss of ECC Injection (Bundle 6 of 7.3 MW Channel)

4.2 End of Blowdown

Although the CATHENA calculation is continued up to 100 seconds, the end of blowdown is assumed at 40 seconds. As we can see in Figure 6 the void fraction at inlet and outlet headers are nearly 1.0 at 40 seconds after initiation of break. From this point the critical pass is under the conditions of prolonged low steam flows.



(a) 35% RIH Break (b) 100% ROH Break

Figure 6 Inlet and Outlet Header Void of Critical Pass for LOCA with Loss of ECC Injection

4.3 Results of Back-end Calculation

Table 2 shows the detailed information of a representative channel (O6) calculated by CATHENA at the end of blowdown, which required as input data of CHAN-IIA simulations. This data includes bulk-average fuel temperatures in each fuel segment, PT temperatures for each segment, initial PT strain in each segment.

Table 2 7.3 MW Channel Axial Temperature and PT Strain Distribution at End-of-Blowdown Time for 35% RIH Break with Loss of ECC Injection (Critical Pass)

Bundle Number	Outer Ring (°C)	Intermediate Ring (°C)	Inner Ring (°C)	Center Pin (°C)	PT (°C)	PT Strain (%)
1	714.1	710.0	707.2	706.0	713.7	3.3
2	853.7	841.1	829.4	824.3	296.4	16.0
3	957.5	937.4	917.6	908.7	305.7	15.8
4	1017.6	991.3	965.5	953.7	304.6	16.1
5	1051.4	1019.4	987.7	973.1	293.8	16.4
6	1026.4	988.5	951.3	934.3	272.8	16.2
7	952.4	912.0	872.8	855.2	237.8	16.2
8	848.7	813.1	776.1	759.2	199.8	16.2
9	747.3	721.4	688.4	673.5	472.2	0.5
10	631.6	619.3	592.1	580.0	372.8	0.0
11	475.3	475.5	462.1	455.3	307.7	0.0
12	314.2	317.4	314.4	312.7	257.6	0.0

Figure 7 shows the CHAN-II/A calculations of average ring temperatures for 35% RIH break. The radial temperature distribution among fuel rings are compared in this figure, which shows that the fuel near the PT is more effectively cooled than that near the center of channel because of radiation and PT/CT contact heat transfer to the cooler moderator. However, the fuel temperature of outer ring is higher than that of center pin in the front-end calculations (Figures 4 and 5).

CATHENA calculation during the back-end is also performed to compare the fuel behavior by CHAN-II/A calculations. For this purpose CATHENA calculation is extended to the back-end period using the flow boundary condition model corresponding the specified steam flow rate. Figure 8 compares the center element fuel temperatures for steam flows of zero (adiabatic), 5, 8, 10, 20 and 100 g/s for 35% RIH break cases. The bundle position which results in the highest predicted fuel temperatures is shown for each steam flow rate.

In the CHAN-II/A calculations, convective heat transfer rate is the highest at steam flow of 100 g/s, which results in the lowest temperature. While the zero steam flow does not show the highest temperature, because there can be no Zircaloy/steam reaction at zero steam flow. The limiting flow rate which maximizes the fuel temperature is 8 g/s.

In the CATHENA calculation we cannot see the parametric effect of steam flow rate on the fuel temperature. Furthermore, the CATHENA predictions are lower than those of CHAN-II/A, since the fuel heat up by Zircaloy/steam reaction is not well represented.

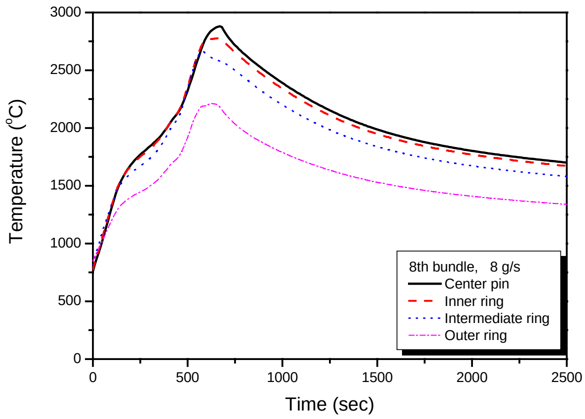
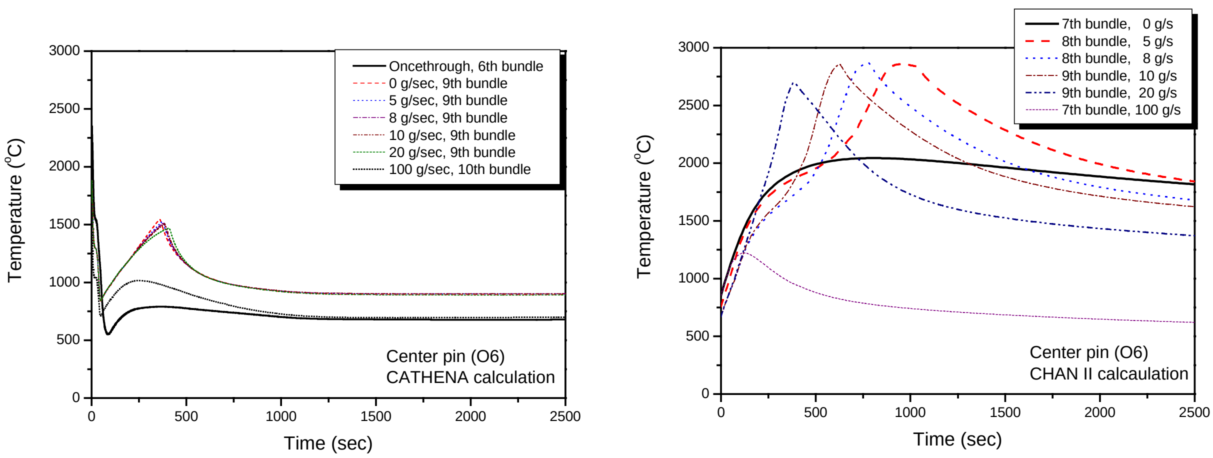


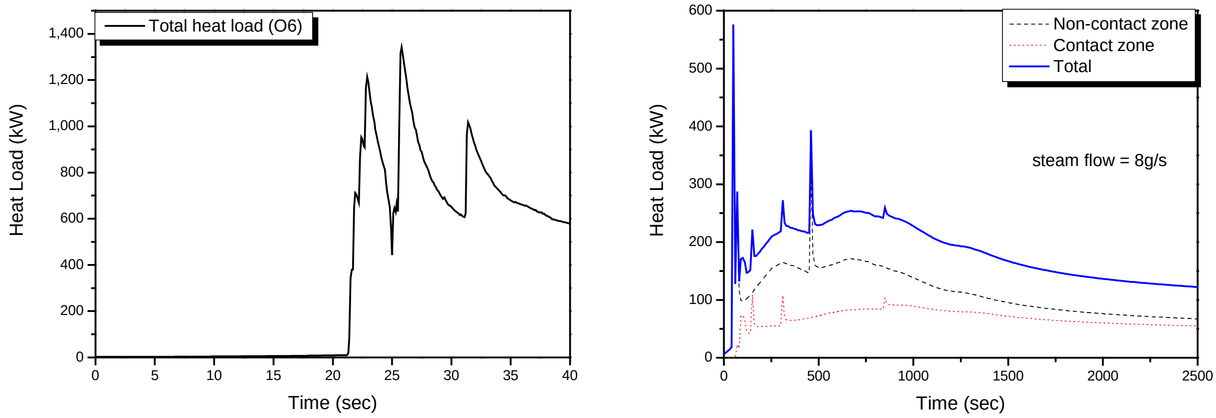
Figure 7 Ring Average Temperatures for a 35% RIH Break with Loss of ECC Injection (Critical Pass of 7.3 MW Channel)



(a) CATHENA calculation (b) CHAN-II/A calculation

Figure 8 Maximum Fuel Temperature for Various Steam Flow Rates for a 35% RIH Break with Loss of ECC Injection (Critical Pass of 7.3 MW Channel)

Figure 9 shows the transient heat load to the moderator both for front-end and back-end. The reasons for the heat load spikes are due to the PT/CT contacts occurring at different times and by different mechanisms. The same procedure can be applied to other power groups shown in Table 1 to provide the heat source boundary conditions in the moderator analysis.



(a) CATHENA (front-end) (b) CHAN-II/A (back-end)

Figure 9 Heat Load from Calandria Tube to Moderator: 35% RIH Break with Loss of ECC Injection (Critical Pass of 7.3 MW Channel)

5. Conclusions

From the present study we can obtain the safety tools such as CATHENA MOD3.5b/Rev.1 and CHAN-II/A MOD2 codes, and their code modeling in a form of code input deck for the single channel analysis with LOCA/LOECC. The analysis consists of two parts: front-end and back-end.

In the front-end assessment a detailed calculation of the fuel and pressure tube temperatures for O6 channel is performed by CATHENA code.

- PT/CT contact is predicted to occur in the RIH 35% break, however there is no PT/CT contact in the ROH 100% break.
- The different fuel grouping between 10 group fuel model (37ROD-10) and the detailed fuel model has no effect on the prediction of the maximum fuel temperature during the front-end.

In the back-end analysis CHAN-II code is provided with CATHENA conditions at the end of front-end and performs the calculations for the late heat up phase.

- CHAN-II calculations of average ring temperatures for 35% RIH break shows that the fuel near the PT is more effectively cooled than that near the center of channel because of radiation and PT/CT contact heat transfer to the cooler moderator.
- Parametric study of steam flow by CHAN-II calculations shows that the limiting flow rate which maximizes the fuel temperature is 8 g/s.
- In the CATHENA calculation for back-end we cannot see the parametric effect of steam flow rate on the fuel temperature. Furthermore, the CATHENA predictions of fuel temperatures are lower than those of CHAN-II, since the fuel heat up by Zircaloy/steam reaction is not well represented.
- For use of moderator analysis the heat load from a single channel to moderator is calculated by CATHENA for front-end and by CHAN-II for back-end.

Acknowledgements

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