DEVELOPMENT OF THE CATHENA FUEL CHANNEL MODEL FOR AN INTEGRATED BLOWDOW AND POST-BLOWDOWN ANALYSIS FOR A 37-ELEMENT CANDU FUEL CHANNEL

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Abstract

The objective of this study is to develop a new fuel channel safety analysis system for covering both the blowdown analysis including the power pulse and the post-blowdown analysis with the same safety analysis code, CATHENA[1] in a consistent manner. This new safety analysis methodology for a fuel channel analysis is expected to be better than the previous one used for the Wolsong 2,3,4 licensing[2] which used CATHENA for the blowdown analysis and CHAN-II[3] for the post-blowdown analysis, in several areas; consistency in the computer codes used and the modeling methods, the degree of uncertainty in the modeling and calculation. For this aim the existing CATHENA subchannel fuel channel model for a post blowdown analysis[4] has been modified, and thus improved, and a processing program that conveys all the final state of the fuel channel at the end of blowdown analysis to the post-blowdown analysis as the initial conditions[5] has been developed, and tested for its proper implementation for the intended purposes. A comparison of the results of this new analysis method with those of the Wolsong 2/3/4 Safety Analysis[2] confirmed that the total heat transfer rate matches well up to 1000 sec, and then that of the new method begins to under-predict it consistently. On the other hand, the fuel

temperatures of the center pin, inner ring fuel and the middle ring fuel are predicted by this new method to be lower than the old method by about 200 – 250 ^{o}C at the peak time. Considering the differences in these two analyses methodologies, especially the modeling of the fuel ring, a subchannel flow passage with an intermixing, and the radiation among the solid structures by considering every fuel individually, this trend of the results seems to be physically reasonable. However considerable future validation works are necessary to justify this new methodology for a licensing

I. INTRODUCTION

In the case of a Large LOCA without an ECC in CANDU-6 reactor, the 95 fuel channels at the downstream of the break, called the critical core pass, will undergo a severe loss of coolant, significant channel voiding resulting in a rapid power pulse in the order of several seconds, and then after a proper reactor trip it will undergo a blowdown phase and then a post-blowdown phase of a LOCA. In this case the safety concern is twofold, one is the fuel breakup and the other pressure tube rupture due to a PT/CT contact. Thus these two concerns are manifested in terms of the acceptance critieria of the fuel channel design; the prevention of the fuel channel integrity impairment by an abrupt fuel breakup during a power pulse. The prevention of an impairment of the pressure tube integrity by an overheating of the fuel channel during a post-blowdown period. One of the most probable ways of jeopardizing the fuel channel integrity is a dryout of the calandria tube on the moderator side due to a contact of the pressure tube and the calandria tube, whether a ballooning contact or sagging contact. Thus ensuring the prevention of this condition throughout the LBLOCA transient by analysis has been one of the goal of generic safety issues of the CANDU reactors. These safety analyses involve two major parts, one to find the transient heat flux of the calandria tube on the moderator side throughout the accident, the other to find the local moderator subcooling adjacent to the calandria tubes during the transient. The first part consists of carrying out the blowdown and post-blowdown fuel channel analyses for most of the foreseeable transient conditions, and thus it involves a lot of analyses cases, e.g. the blowdown and post blowdown analyses for the 6 channel groups of the critical and the noncritical core passes. Due to the difficulty in justifying the uncertainties in the coolant flow rates involved in the final condition of the blowdown analysis, a series of sensitivity studies on the incoming steam flow rate, which results in many cases of code simulation for the post-blowdown phase. Because of the many laborious engineering works involved in carrying out this analysis, it was attempted to improve the efficiency as well as the accuracy of the simulation by changing the post-blowdown analysis code from the CHAN-II code to the CATHENA code, and by developing an interface processing program that automatically transfers the necessary input data from the results of the blowdown analysis to the post-blowdown analysis input deck for the pre-prepared sensitivity cases.

The objective of this study is to develop a new fuel channel safety analysis methodology for covering both the blowdown analysis including the power pulse and the post-blowdown analysis with the same safety analysis code, CATHENA in a consistent manner. This new safety analysis methodology is expected to be better than the previous one which used CATHENA for the blowdown analysis and CHAN-II for the post-blowdown analysis, in many respects, such as a consistency in the computer code as well as the modeling methods, reducing the area of uncertainties in the modeling and calculation. For this aim the existing CATHENA subchannel fuel channel model for a post blowdown analysis has been modified, and thus improved, and a processing program that conveys all the final states of the fuel channels at the end of a blowdown analysis to the post-blowdown analysis as the initial conditions, has been developed, and tested for its proper implementation for the intended purposes.
A comparison of the results of this new analysis method with those of the Wolsong 2/3/4 Safety Analysis[2] confirmed that the total heat transfer rate matches well up to 1000 sec, and then that of the new method begins to under-predict it consistently. On the other hand, the fuel temperatures of the center pin, inner ring fuel and the middle ring fuel are predicted by this new method to be lower than the old method by about 200 – 250 ^{o}C at the peak time. Considering the differences in these two analyses methodologies, especially the modeling of the fuel ring, a subchannel flow passage with an intermixing, and the radiation among the solid structures by considering every fuel individually, this trend of the results seems to be physically reasonable. However considerable future validation works are necessary to justify this new methodology for a licensing

II. FUEL CHANNEL POST-BLOWDOWN ANALYSIS MODEL

Under a low steam flow and a high fuel temperature condition, which is expected after the blowdown phase of a LOCA ends in severe accidents such as LOCA/LOECC accidents, the heat transport in the CANDU fuel channel is affected by a thermal radiation, a steam convection, a heat conduction in the solid components and a heat flux in the moderator. In addition, at a high temperature, the zirconium sheath reacts chemically with the steam producing an additional heat and hydrogen gas. Also the arrangement of the fuel elements in concentric rings results in different flow rates between the different rings of the elements(i.e., coolant subchannels). Under this condition, the pressure tube weaken and subsequently contacts with the calandria tube. On the basis of these phenomena, a CATHENA post-blowdown model for a subchannel hydraulic modeling and a local solid-to-solid contact modeling has been developed successfully

II.A. Fuel Channel Hydraulic Model

The fuel channel model for the CATHENA post-blowdown fuel channel analysis uses the 5 subchannel post-blowdown model as shown in Fig.1. Here each flow subchannel is treated as a horizontal pipe with a different flow and hydraulic diameter. Flow mixing is assumed to take place at the ends of the fuel bundles called junctions. The mixing is modeled by discretizing the heated portion of the whole fuel channel into 12 equal-length pipe components and inserting small mixing nodes between the discretized hydraulic nodes as shown in Fig.2.

II.B. Heat Transfer Solid Component Model

The heat transfer model is divided into two parts, one is the solid component model, and the other is the auxiliary model. The former includes the geometry of the fuel, the pressure tube, the calandria tube, the boundary conditions, the material properties, the heat generation, and the initial temperature. On the other hand, the latter is divided into 3 subcomponents; the radiation model, the solid-solid contact model, and the fuel channel deformation model. These models are included in the heat transfer package, GENHTP, of the CATHENA input file. The solid component model is composed of the fuel element, the pressure tube and the calandria tube. Each fuel element is divided radially into 4 regions, i.e., fuel meat, gap, zircaloy tube, and the zircaloy-oxide layer. All the other elements besides the center and the topmost outer element, are divided into 2 circumferential sectors. The center element has 1 circumferential sector whereas the top most element has more circumferential sectors to simulate the FE/PT contact. The heat generation from each element is determined based on the ring power ratio based on a zero bundle burn up condition and the bundle power. The axial bundle power distribution is conservatively determined based on the fuel management analysis as explained in the next section.

The Zr-Steam reaction rate and the heat from this reaction are computed based on the Urbanic-Heidrick correlation[6]. The pressure tube is divided into radially 2 regions, one a metal and the other an oxide layer, and many circumferential sectors as shown in Fig.1. The annulus region filled with CO_2 gas is modeled as a thermally insulated region. The moderator to which the heat is discharged from the fuel across these two tubes is modeled as a largecooling reservoir.

II.C. Axial Power Profile

After the axial power profiles of all the fuel channels in the core are analyzed, they are grouped into 6 groups. All the axial power profiles of all the fuel channels of the 6-th group are found to fall between two representative limiting axial power profiles. Among these profiles the most limiting axial power profile is found through a sensitivity study in terms of the final fuel temperatures from the post-blowdown analyses. Thus one profile is selected as the representative axial power profile for the highest channel power group, the O-06 channel group, and it is used for all the other lower channel power groups.

II.D. Radiation Heat Transfer Model

This model simulates the radiation heat transfer between the solid components, i.e., between the fuels, the fuels and the pressure tube, and the pressure tube and the calandria tube. The view factor matrix is obtained by using an utility program, MATRIX, and an emissivity of 0.8 is used for the fuel outer surface, the internal surface of the pressure tube, and an emissivity of 0.325 is used for the outer surface of the pressure tube[7] and both side surfaces of the calandria tube. No feedback of the geometry change for the radiation heat transfer calculation during a transient is considered.

II.E. Pressure Tube Deformation Model

This model circumferentially calculates the plastic deformation of the pressure tube caused by the internal pressure and high temperature at various fuel bundle locations. The calculation of the plastic deformation rate of the pressure tube continues until the pressure tube contacts with the calandria tube. The contact conductance between the two tubes is calculated after a contact. The pressure tube creep rate, or the expansion rate at high temperature are calculated based on Shewfelt's creep rate correlations[8,9], and the maximum and minimum bound failure criteria.

PT axial straining is considered by using sagging temperature criterion. The temperature at which a PT sag contact occurs is assumed to be 850^{o}C with a maximum contact angle of 60^{o} at the bottom of the channel, which was used in previous Safety Analysis Reports[2] based on the results from large-scale experiments[10,11].

II.F. Fuel Gap Conductance, Fuel/PT, PT/CT Contact Conductance Model

The fuel-to-sheath gap conductance is assumed to be 10 kW/m^{o}C to account for a sheath lift-off from the fuel due to a depressurization of the fuel channel. This is conservative because during the first several seconds of a transient for a large break LOCA, the fuel channel has not depressurized enough to cause a sheath lift-off from the fuel and lower the gap conductance. The chosen conductance value is consistent with Ross and Stoute's experimental measurements [12].

This model simulates the heat transfer coefficient due to a direct contact between the metal surfaces. 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 pressure tubes, which are consistent with those used in the Safety Analysis Reports[2].

II.G. Metal-Water Reaction and Hydrogen/Heat Generation

The Urbanic and Heidrick correlation [6] is used for the zircaloy/steam reaction calculation on the fuel sheath and inner surface of the PT. This zircaloy/steam reaction adds more heat generation both on the sheath outside surface and the inside surface of the PT, on top of the channel decay power. The thickness of the oxide layer, the volume of the hydrogen produced, and the heat generation for the metal water reaction is calculated. The effect of the generated hydrogen in reducing the amount of steam available for the reaction is modeled. This "steam starvation" calculation is not fed back to the channel thermohydraulic calculation.

II.H. Selection of A Pessimistic Inlet Flow Condition for the Most Limiting LOCA Scenario, RIH 35% Break

The postulated 35% RIH Break event was selected as the accident scenario for this study as this scenarios has significant PT/CT contact in the downstream core pass (called the critical pass) in the broken loop owing to a continual relatively high internal pressure in the order of 3 to 4 MPa for about 20 sec during which the weakened pressure tube balloons, whereas no significant pressure tube ballooning occurs due to a rapid system depressurization for the other typical large LOCA scenarios such as a PSB 55% break and a ROH 100% break. The most pessimistic channel inlet steam flow condition from the view point of a pressure tube heat up due to a metal-water reaction and subsequent sagging contacts, i.e., mass flow rate of 10 g/s, is used for all the fuel channels in this analysis. This steam flow is high enough to contribute to the zirconium/steam reaction but low enough that a steam cooling is not very effective.

III. Results and Discussion of the Post-Blowdown Analysis for Channel O6 for the RIH35% Break LOCA/LOECC

The results of the blowdown and post-blowdown analyses for the representative fuel channel of the highest channel power level group among the 6 channel groups (O-06, S-10, L-03, G-05, B-10, W-10) is presented in Table 1 and Fig.3 for the Reactor Inlet Header (RIH)

35% Break of a Large Loss of Coolant Accident without an ECC Injection.

The times at which the pressure tube ballooned to contact with the calandria tube at various axial bundle locations for the 4 highest channel power level groups as well as the pressure tube contact temperature and the corresponding internal pressure are tabulated in Table 1. The total heat load to the moderator from each fuel channel group during the RIH35% Break LOCA w/o an ECC are shown in Fig.3. After performing a similar calculation for all the 6 representative fuel channels and summing all the heat transfer rates to the moderator from the 95 fuel channels belonging to the critical core pass which is 1/4 of the 380 core fuel channels located at the downstream of the broken inlet header, the total radiation heat transfer rate to the moderator from the critical core pass was obtained as shown in Fig.4 for both the blowdown phase and the post-blowdown phase. In.Fig.5 and Fig.6 the fuel temperatures of the center element, and the inner, the middle, and the outer ring and the temperatures of the pressure tube and the calandria tube are shown for the bundle no. 6 at a steam Flow of 10 g/s, a 7.0 MW Channel Bundle 6 for the RIH35% Break w/o an ECC case for both the fuel channel analysis methodology, the new one and the previous one.

A comparison of these results with those of Wolsong 2/3/4 Safety Analysis[2] confirmed that the total heat transfer rate matches very well up to 1000 sec, and then that of the new method begins to under-predict it consistently. On the other hand, the fuel temperatures of the center pin, inner ring fuel and the middle ring fuel are predicted by this new method to be lower than the old method by about 200 – 250 ^{o}C at the peak time. Considering the differences in these two analyses methodologies, especially the modeling of the fuel ring, a subchannel flow passage with an intermixing, and the radiation among the solid structures by considering every fuel individually, this trend of the result was expected. The rationale is that both the radiation heat transfer and the convective heat transfer would be more effective in the fuel channel model of the new method than the old CHAN-II method which models all the fuel pins in each ring as one annularly shaped solid tube. Even though these results are deemed physically reasonable and consistent, justification of them for licensing is another matter. So a validation of this new fuel channel analysis methodology has been under way for the past years, which involves a validation of a similar CATHENA post-blowdown model against the CS28-1,2 experiments, and developing and validating a 3-D CFD model for a post-blowdown analysis for a 37-element fuel channel. It is hoped that these efforts can be useful for justifying the new methodology including the above mentioned under-prediction of the fuel temperatures in the post-blowdown phase of a LBLOCA.

IV. CONCLUSION

A CATHENA model for a post-blowdown fuel channel analysis have been improved from an existing one for a CANDU-6 reactor, and an analysis for a RIH 35% LBLOCA without an ECC has been performed.

A comparison of the results of this new analysis method with those of the Wolsong 2/3/4 Safety Analysis[2] confirmed that the total heat transfer rate matches well up to 1000 sec, and then that of the new method begins to under-predict it consistently. On the other hand, the fuel temperatures of the center pin, inner ring fuel and the middle ring fuel are predicted by this new method to be lower than the old method by about 200 – 250 ^{o}C at the peak time. Considering the differences in these two analyses methodologies, especially the modeling of the fuel ring, a subchannel flow passage with an intermixing, and the radiation among the solid structures by considering every fuel individually, this trend of the results seems to be physically reasonable. However considerable future validation works are necessary to justify this new methodology for a licensing

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Table 1. PT/CT Contact Results During the Blowdown Period for the Critical Pass of 35% RIH Break with Loss of ECC Injection

Channel id and Power	PT/CT Contact Time [s]	Bundle Location	Max. PT Temp. [^{o}C] at Contact Time	Internal Pressure at Contact Time [Mpa(a)]
O-06 7.3 MW	21.3	5	809.6	4.0
	21.9	6	812.7	4.0
	22.2	7	808.1	3.9
	22.7	4	805.8	3.9
	25.1	8	780.2	3.7
	25.7	3	801.4	3.7
	31.2	2	789.2	3.3
S-10 7.0 MW	24.1	5	802.0	3.8
	25.0	6	790.8	3.7
	25.1	4	797.7	3.7
	26.5	7	777.4	3.6
	28.0	3	794.2	3.5
	34.0	2	776.3	3.2
L-03 6.6 MW	24.3	6	803.7	3.8
	24.6	5	804.5	3.8
	24.7	7	796.9	3.8
	26.7	4	799.8	3.6
	28.9	8	760.7	3.5
	30.5	3	795.2	3.3
	38.4	2	782.1	2.9
G-05 6.0 MW	29.6	5	793.3	3.4
	30.0	6	782.2	3.4
	33.8	4	779.9	3.2
	37.5	3	764.4	3.0

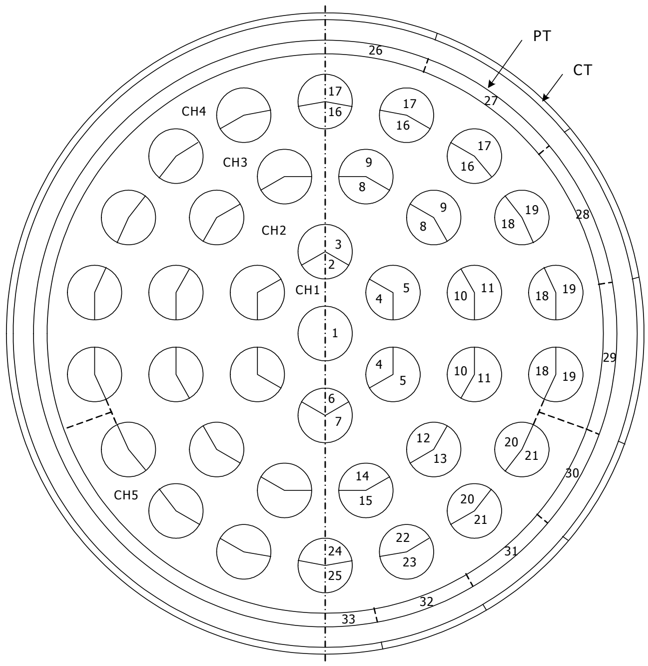

Fig.1. Fuel Rod Power Grouping, Solid Structure and Coolant Subchannel Modeling in the Post Blowdown Analysis Model of a CANDU 37-Element Standard Fuel Bundle

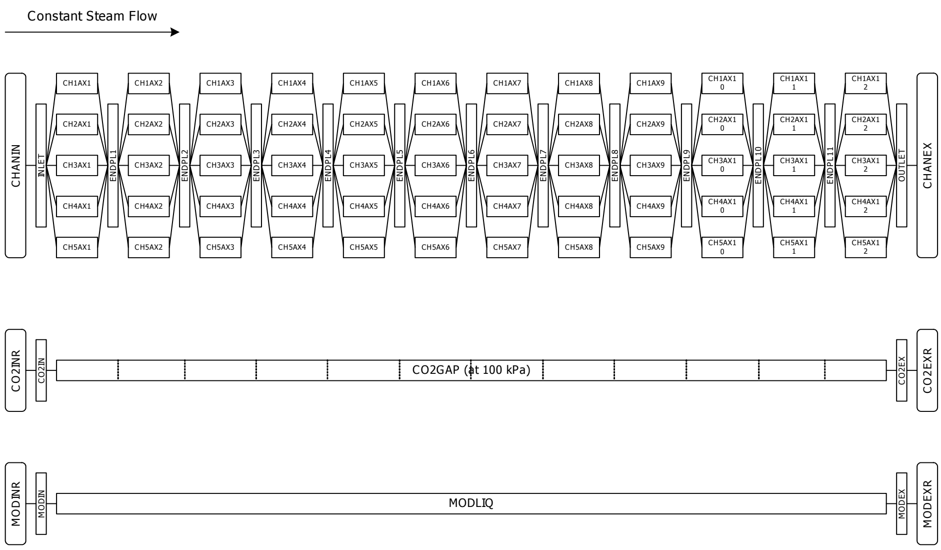

Fig.2. Coolant Subchannel Hydraulic Node Arrangement for the Post Blowdown Analysis Model for a CANDU 37-Element Standard Fuel Bundle

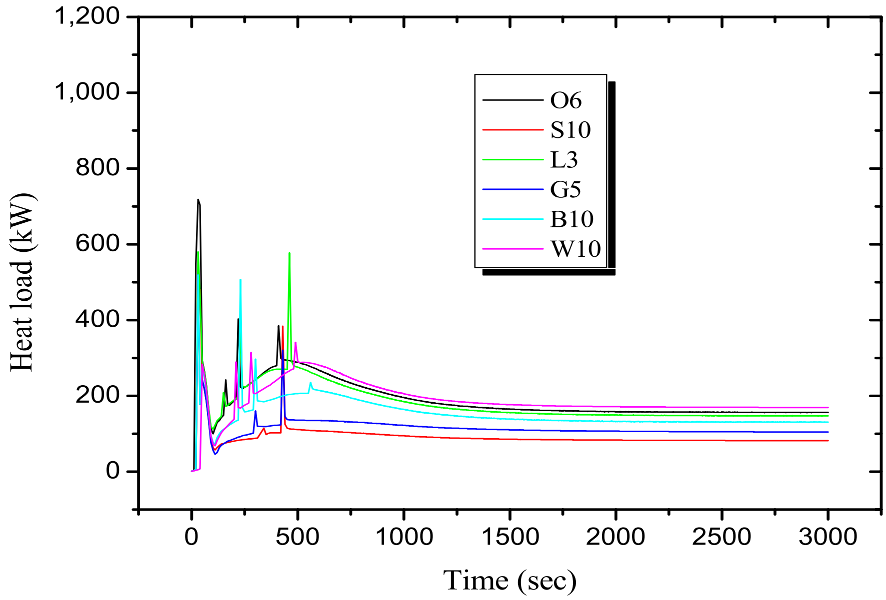

Fig. 3. Heat Load to the Moderator from Each Fuel Channel Group during the RIH35% Break LOCA w/o an ECC.

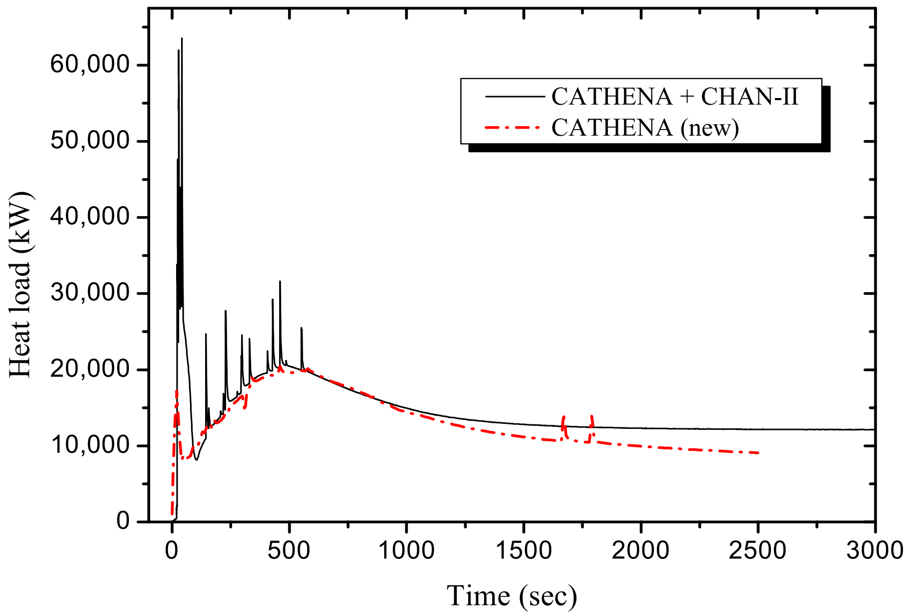

Fig. 4. Comparison of the Total Heat Load of the Critical Pass to the Moderator between the New Method and the Previous Method for RIH35% Break w/o an ECC [2].

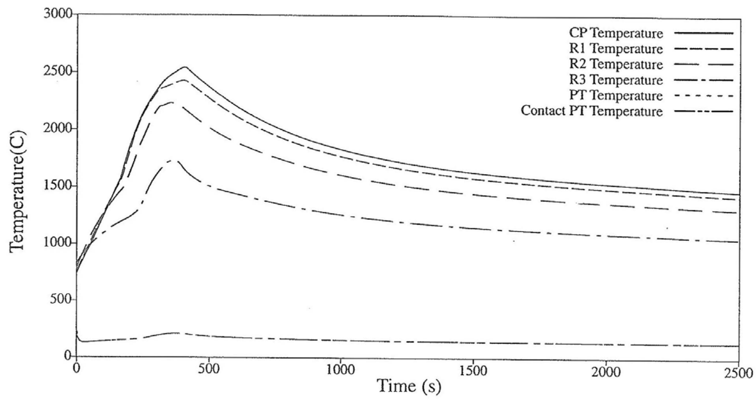

Fig. 5. The Ringwise Fuel Temperature, PT and CT Temperature Prediction obtained by the Previous Method for the Bundle at a Steam Flow of 10 g/s, a 7.0 MW Channel for a RIH35% Break w/o an ECC [2].

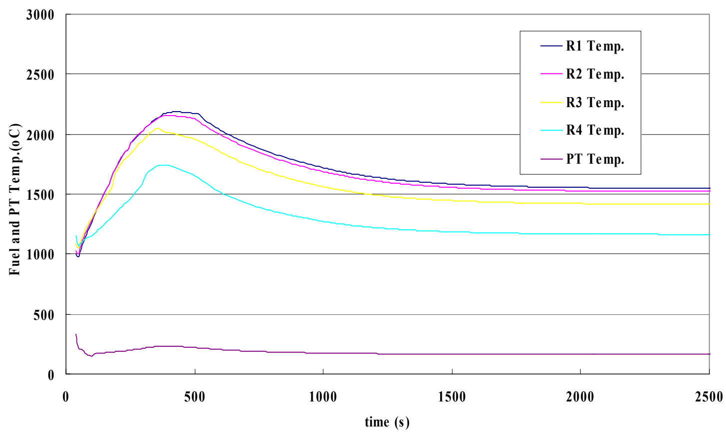

Fig. 6 The Ringwise Fuel Temperature, PT and CT Temperature Prediction obtained by the New Method for the Bundle at Steam Flow of 10 g/s, 7.0 MW Channel for a RIH35% Break w/o ECC.