RIH 35% LARGE BREAK LOCA WITHOUT ECC FOR THE RUFIC CORE

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ABSTRACT

CATHENA models for a PHTS circuit and fuel channel analyses have been developed for a CANDU-6 reactor loaded with CANFLEX-RU (Recycled Uranium) fuel, and a demonstration analysis for a RIH 35% LBLOCA/LOECC has been performed.

The major difference of the CATHENA circuit and slave fuel channel models for the CANFLEX-RU core from those for a standard 37-element NU core came from the different power distributions in the bundle and core resulting from the increase of the fuel fissile content, average discharge burnup, and axial power shape change due to the change in the refueling scheme. The minimum CPR is found to be M-19. However the M-04 channel, a twin channel to M-19 channel, is chosen as the hypothetical limiting channel for a Large LOCA accident analysis. As for the results of the reactor power pulse calculation, the peak reactor power and the peak power of the limiting channel are found to be 1.485 times, and 1.986 times as big as those of a standard 37-element fuel case. It is expected that the breakup criterion of the fuel, 840 J/g, is not exceeded at the hottest bundle in the limiting channel. The fuel channel blowdown analysis result shows that the portion of the pressure tube corresponding to bundles 2 to 8 is predicted to be ballooned contact during 22 to 32 sec into the accident, similar to the NU core case. As for the results of a demonstrative post-blowdown analysis for the inlet steam flow condition of 10 g/s, the center fuel temperature at bundle number 5, reaches 2057.6°C at about 331.5 sec. In general, the results of the CATHENA circuit analysis including the power pulse analysis, blowdown and post-blowdown fuel channel analyses for the CANFLEX-RU core fall within the foreseeable expectations with reasonable trends.

1. INTRODUCTION

As a part of a feasibility study on the use of recovered uranium for a CANDU reactor, an accident analysis has been carried out for a RIH 35% Large break LOCA. CATHENA models for the PHTS circuit and fuel channel analyses have been developed for a CANDU-

6 reactor loaded with CANFLEX-RU (Recycled Uranium) fuel, and a demonstration analysis for the RIH 35% LBLOCA/LOECC has been performed.

The major difference of the CATHENA circuit and slave fuel channel models for a CANFLEX-RU core from those for a standard 37-element NU core came from the different power distributions in the bundle and core resulting from the increase of the fuel fissile content, average discharge burnup, and axial power shape change due to the change in the refueling scheme. The minimum CPR channel for the high power channels is found to be M-19 as shown in Fig.1. However as M-19 belongs to the intact loop in the existing CATHENA 10 parallel channel core model, the M-04 channel which is the twin channel of the M-19 channel is chosen as the hypothetical limiting channel for a Large LOCA accident analysis as it belongs to the critical core pass of the CATHENA core model for a Large break LOCA. The core model for the CATHENA circuit analysis uses the same 10 parallel channel model and channel grouping as that for the Wolsong 2,3,4 Large LOCA analysis without any necessary justification.

As a result of the reactor power pulse calculation, the peak normalized reactor power and the peak channel power of the limiting channel M-04 are found to be 3.826 and 6.321 as can be seen in Fig.2, thus 1.485 and 1.986 times as big as that of a standard 37-element fuel case, which are 2.557 for total reactor power, and 3.182 for the O6 channel respectively. As shown in Table 1, it is expected that the breakup criterion of the fuel, 840 J/g, is not exceeded at the peak power pin of the hottest bundle in the limiting channel.[1]

2. FUEL CHANNEL BLOWDOWN ANALYSIS

Hypothetical limiting fuel channel, M-04_mod

A hypothetical limiting fuel channel, M-04_mod, is made and assumed to have a channel power of 7.3 MW, and maximum bundle power of 935kW at the peak power locations, i.e., bundles 4 and 5, as shown in Fig.4. These channel and bundle power limits are assumed to be the same as those for Wolsong 2,3,4, without any proper justification for the CANFLEX-RU core. The variation of the ring element rating with bundle average burnup is shown in Fig. 3, and the axial power profile for this M-04_mod channel devised from the requirements of having 7.3 MW channel power, 935kW maximum bundle power as well as keeping the basic shape of the axial power profile of the highest power channel group, group 6, is found to be as shown in Fig. 4.

Slave Channel Blowdown Analysis

For a RIH 35% Large LOCA condition, blowdown fuel channel analysis is carried out for this M-04_mod channel using the header boundary conditions from the 10 parallel channel circuit analysis based on the CANFLEX-RU core and flow distribution. Figures 5,6 show the behavior of the center element and outer element fuel temperatures during the blowdown stage. The fuel temperature at bundles 5 and 6 of the outer ring element show the highest peak at about 2.5 sec reaching 1380°C, and this is due to the highest power rating among the 4 fuel rings at the zero bundle burnup condition, for which this study is performed. The analysis result in Figures 7, 8 shows that the portion of the pressure tube corresponding to bundles 2 to 8 is predicted to be ballooned contact during 22 to 32 sec into the accident similar to standard 37-element NU fuel, starting from bundle 4, as a result of the high channel pressure of 3.8 to 4.2 MPa, and the high pressure tube temperature above 600°C reaching up to 820°C for the period from 15 to 25 sec. The Fig. 9 shows the corresponding variation of the calandria tube temperature.

The major results of the fuel channel blowdown analysis are the temperatures of the fuel, pressure tube, and the calandria tube, and the pressure tube deformation as shown in Figs. 5 to 8, and these are used as the initial boundary conditions for the following post-blowdown analysis.

The analysis for checking the occurrence of dryout at the calandria tube outer surface at the time of ballooning contact cannot be performed as the transient local subcooling of the moderator at the corresponding locations is not available because a separate 3-D moderator temperature for the local heat flux calculation is not carried out as a part of this study.

According to the summary of the experimental results of the dryout on the CT outer surface[2], the minimum local subcooling of the moderator necessary to avoid the dryout of the calandria tube with contact temperature higher than 800°C is 28°C. However as no transient temperature analysis of the moderator has been carried out for this CANFLEX RU loaded CANDU-6, no assessment can be made of the pressure tube integrity for a PT/CT ballooning contact.

3. FUEL CHANNEL POST-BLOWDOWN ANALYSIS

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

Fuel Channel Hydraulic Model

The fuel channel model for CATHENA post-blowdown fuel channel analysis uses the 4 subchannel post-blowdown model. 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.

Heat Transfer Solid Component Model

The heat transfer model is divided into two parts, one the solid component model, and the other the auxiliary model. The former includes the geometry of the fuel, pressure tube, calandria tube, the boundary conditions, material properties, heat generation, initial temperature, and the print options for each model. On the other hand, the latter is divided into 3 subcomponents; the radiation model, solid-solid contact model, and 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 a fuel element, a pressure tube and a calandria tube. Each fuel element is divided into 4 regions radially, i.e., fuel meat, gap, zircaloy tube, and 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 topmost element has 18 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 determined as is described in the following section.

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

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 this 6th highest channel power group as described in the paragraph of "Hypothetical limiting fuel channel, M-04_mod" in the previous chapter.

Radiation Heat Transfer Model

This model simulates the radiative heat transfer between the solid components, i.e., between the fuel and pressure tubes, and the pressure tubes and calandria tubes. The view factor matrix is obtained using an utility program, MATRIX, and an emissivity of 0.8 is used for the fuel outer surface, internal surface of the pressure tube, and an emissivity of 0.325 for the outer surface of the pressure tube and both side surfaces of the calandria tube.

Pressure Tube Deformation Model

This model 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. And the contact conductance between the two tubes is calculated after the contact. The high temperature pressure tube creep rate, or expansion rate are calculated based on the Shefelt's creep rate correlations[3], and the maximum and minimum bound failure criteria. The contact conductance between the pressure tube and calandria tube are assumed to be 11 $kW.m^2.^oC$ based on the contact boiling experiments.

Fuel/PT, PT/CT Contact Conductance Model

This model simulates the heat transfer coefficient due to the direct contact between the metal surfaces.

Analysis Results

As for the results of the post-blowdown analysis for the inlet steam flow condition of 10 g/s, the center fuel temperature at the bundle number 5, reaches to 2057.6^oC at about 331.5 sec as shown in Fig.10, and the fuel temperature of the outer ring fuel reaches to 1327.5 ^oC at 391.5 sec. The times at which PT/CT contact occur coincide those of peak values of the convective heat transfer from the calandria tube to the moderator denoted by Q, conv to mod. in Figs 11, 12. Also note that the peak heat generation by $Zr\text{-}H_2O$ reaction occurs when the center pin fuel temperature is highest, which is physically reasonable. The observation in Fig.12 that the time when the peak of the heat transfer to moderator by convection across the PT and CT follows the peak in Zr-H2O reaction heat generation with some time lag makes sense physically, too. The general trend of the center pin fuel temperatures with time shows similar to those of standard NU fuel case, while reaching the peak at about 330 s, 90 sec earlier as compared to 420 s of standard 37-element NU fuel case. The reason for this earlier peak fuel temperature is not figured out yet.

As most portions of the pressure tube are already contacted with the calandria tube at the high power middle region before the pressure tube temperatures reach 780^oC, the fuel and pressure tube temperatures in the post-blowdown stage are found to be lower than that of the standard NU fuel case, and unless the calandria tube experience dryout at the time of a ballooning contact of the pressure tube due to insufficient local subcooling, the condition of the fuel channel could be safer than that of the standard fuel case considering the fact that the pressure tube temperatures at PT/CT contact do not reach as high as that of the standard NU case, which is about 800°C, as proven in Fig. 7.

4. CONCLUSION

CATHENA models for the PHTS circuit and fuel channel analyses have been developed for a CANDU-6 loaded with CANFLEX-RU (Recycled Uranium) fuel, and a demonstration analysis for a RIH 35% LBLOCA/LOECC has been performed. The peak reactor power and the peak power of the limiting channel are found to be 1.485 and 1.986 times larger than those of a standard 37-element fuel case. It is expected that the breakup criterion of the fuel, 840 J/g, is not exceeded at the hottest bundle in the limiting channel. The fuel channel blowdown analysis result shows that the portion of the pressure tube corresponding to bundles 2 to 8 is predicted to be ballooned contact during 22 to 32 sec into the accident, similar to the NU core case. However the pressure tube temperatures at PT/CT contact do not reach as high as 800°C, like the case of the standard NU case, which means larger moderator subcooling is necessary for the onset of calandria tube dryout for RU core than NU core. In general, the results of the CATHENA circuit analysis including the power pulse analysis, blowdown and post-blowdown fuel channel analyses for the CANFLEX-RU core fall within the foreseeable expectation with reasonable trends.

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Table 1. Margin to Fuel Breakup Threshold

Break	Initial-Power Seconds (MW.s)	Pulse Energy* (J/g)	Total Energy Deposition** (J/g)	% Margin to Breakup
35% RIH	6.943	359.0	605.4	27.9

* Pulse Energy = Initial Power Seconds × 23.48/454 J/g

** Total Deposition Energy = Pulse Energy + 246.4 J/g

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									1.718	1.744	1.709	1.709	1.746	1.722									A
B						1.854	1.707	1.751	1.670	1.605	1.641	1.641	1.606	1.672	1.760	1.715	1.860						B
C					1.772	1.632	1.607	1.575	1.516	1.549	1.567	1.568	1.549	1.519	1.577	1.614	1.637	1.776					C
D				1.720	1.642	1.541	1.504	1.521	1.500	1.503	1.528	1.528	1.504	1.502	1.526	1.513	1.544	1.645	1.724				D
E			1.867	1.632	1.590	1.527	1.487	1.475	1.481	1.491	1.546	1.547	1.491	1.484	1.479	1.494	1.530	1.594	1.635	1.873			E
F			1.717	1.596	1.567	1.503	1.485	1.480	1.504	1.529	1.547	1.546	1.531	1.504	1.485	1.488	1.509	1.571	1.600	1.721			F
G		1.782	1.631	1.542	1.547	1.521	1.491	1.498	1.519	1.533	1.549	1.550	1.533	1.522	1.498	1.495	1.523	1.549	1.544	1.634	1.785		G
H		1.710	1.584	1.551	1.530	1.502	1.492	1.506	1.524	1.530	1.542	1.542	1.531	1.523	1.509	1.494	1.504	1.531	1.552	1.585	1.709		H
J	1.758	1.624	1.554	1.515	1.549	1.556	1.547	1.557	1.565	1.574	1.564	1.565	1.574	1.567	1.559	1.552	1.556	1.549	1.516	1.554	1.622	1.761	J
K	1.702	1.573	1.510	1.494	1.545	1.552	1.554	1.566	1.571	1.588	1.602	1.602	1.589	1.572	1.568	1.555	1.552	1.545	1.494	1.509	1.569	1.703	K
L	1.749	1.589	1.511	1.499	1.534	1.530	1.552	1.578	1.583	1.599	1.605	1.605	1.598	1.584	1.578	1.552	1.529	1.534	1.498	1.510	1.585	1.749	L
M	1.752	1.578	1.501	1.466	1.502	1.523	1.532	1.561	1.601	1.596	1.633	1.633	1.596	1.601	1.562	1.532	1.522	1.501	$\boxed{1.465}$	1.499	1.573	1.749	M
N	1.811	1.601	1.507	1.470	1.499	1.494	1.512	1.560	1.564	1.582	1.594	1.594	1.583	1.564	1.561	1.512	1.493	1.498	$\boxed{1.469}$	1.506	1.597	1.808	N
O	1.883	1.650	1.559	1.487	1.485	$\boxed{1.478}$	1.501	1.529	1.546	1.555	1.537	1.537	1.556	1.547	1.530	1.502	1.479	1.485	1.490	1.559	1.648	1.882	O
P		1.742	1.651	1.545	1.528	1.503	1.498	1.513	1.532	1.534	1.521	1.523	1.538	1.535	1.516	1.499	1.505	1.527	1.547	1.653	1.740		P
Q		1.809	1.671	1.624	1.618	1.546	1.500	1.510	1.524	1.540	1.521	1.521	1.540	1.523	1.510	1.503	1.546	1.616	1.630	1.681	1.819		Q
R			1.820	1.688	1.687	1.590	1.503	1.493	1.515	1.516	1.524	1.525	1.519	1.516	1.493	1.506	1.592	1.692	1.696	1.835			R
S			1.886	1.786	1.701	1.599	1.521	1.479	1.484	1.513	1.531	1.531	1.513	1.486	1.480	1.521	1.600	1.702	1.787	1.890			S
T				1.920	1.755	1.630	1.527	1.501	1.480	1.469	1.492	1.493	1.470	1.480	1.501	1.527	1.631	1.756	1.921				T
U					1.880	1.684	1.600	1.599	1.505	1.511	1.518	1.518	1.511	1.505	1.599	1.599	1.684	1.880					U
V						1.942	1.745	1.669	1.542	1.501	1.475	1.475	1.501	1.542	1.668	1.745	1.942						V
W									1.833	1.739	1.739	1.739	1.739	1.833									W
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Fig. 1. Critical Power Ratio (CPR) Map of CANFLEX-RU Core

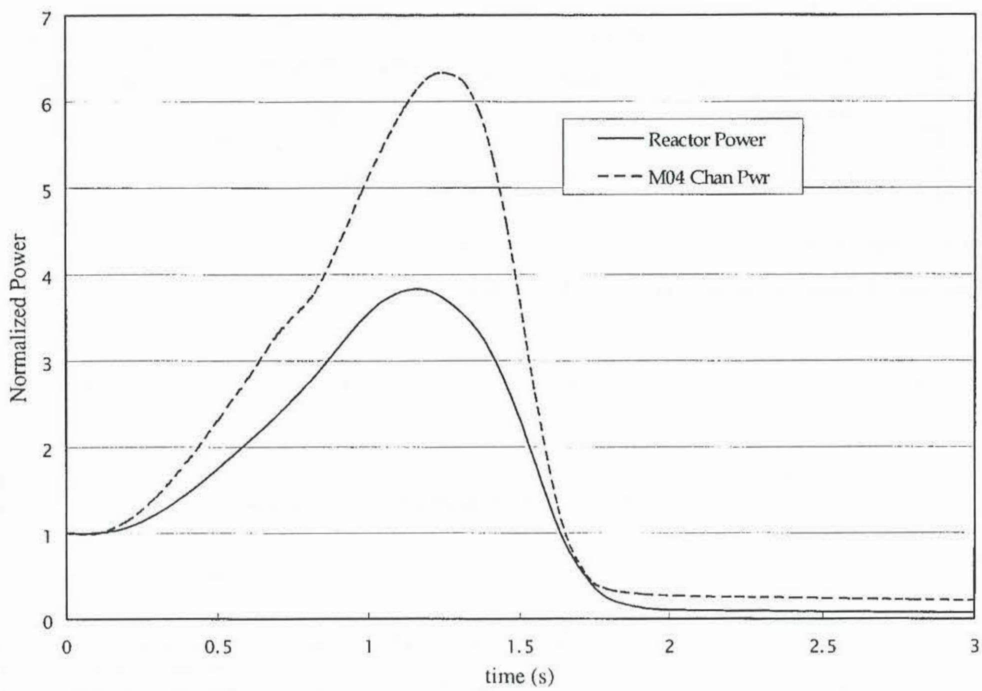

Fig.2. Reactor and M-04 Channel power pulse during RIH 35% Break for RUFIC Core

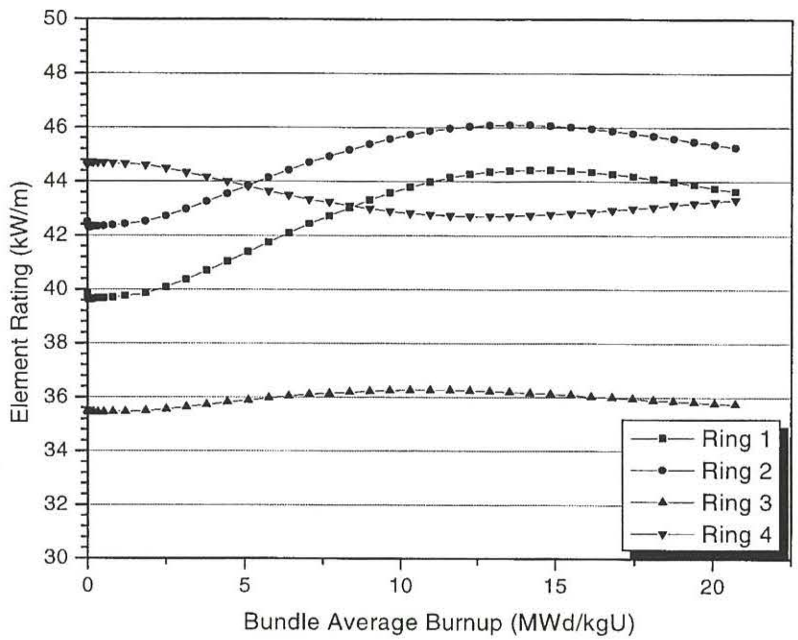

Fig. 3. Linear Element Rating vs. Bundle Average Burnup for CANFLEX-RU

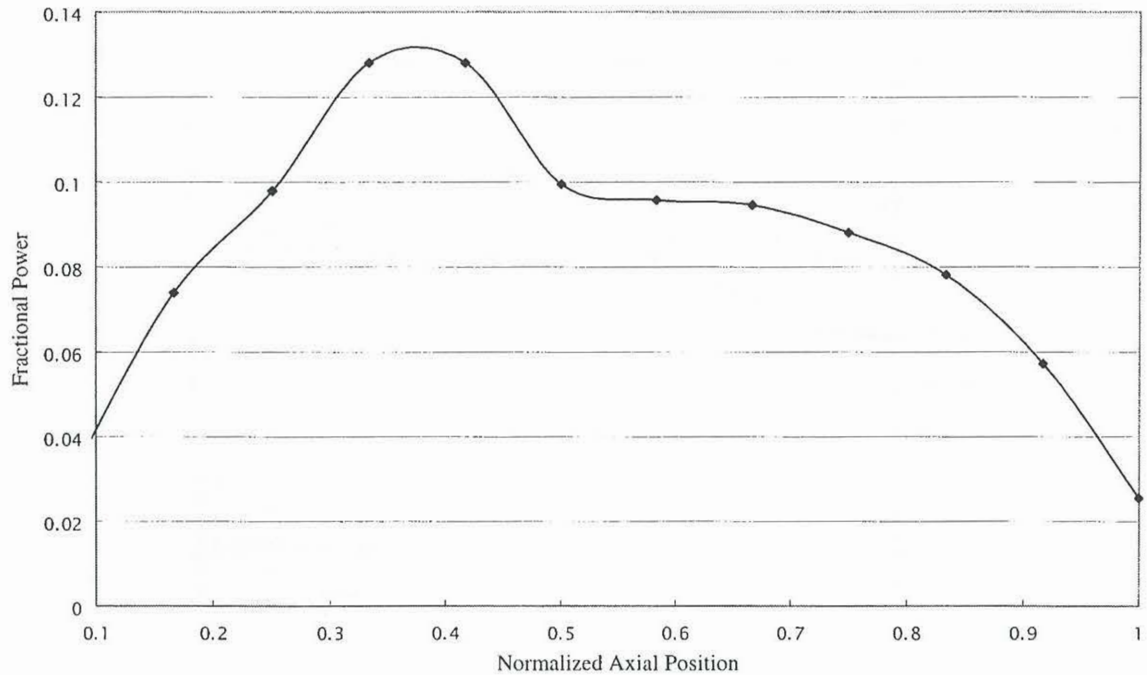

Fig.4. Axial Power Profile of the Hypothetical Limiting Channel based on Highest Power Channel Group Data

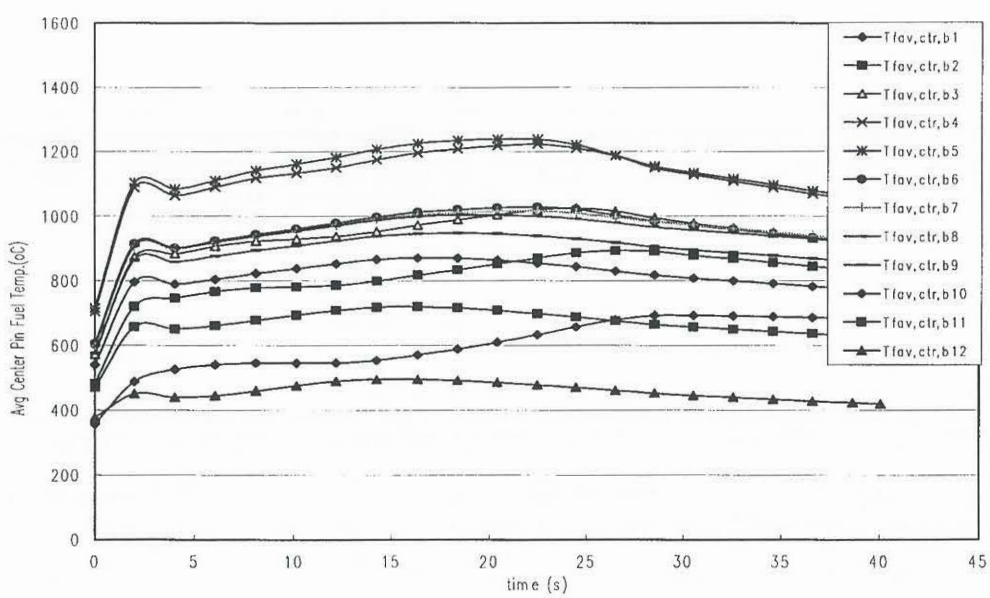

Fig. 5. Center Element Fuel Centerline Temperature at Various Bundle Positions

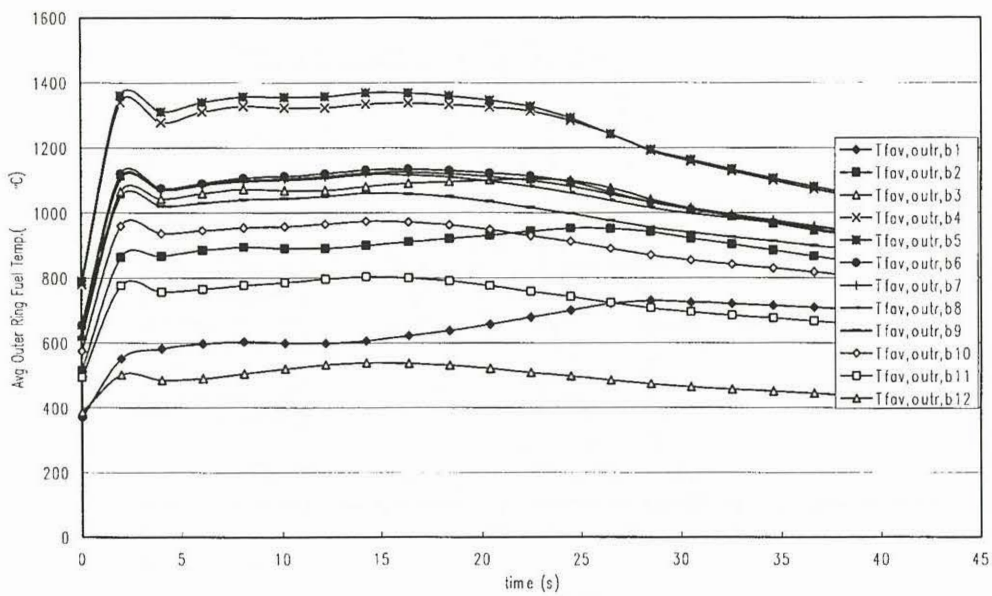

Fig. 6. Outer Element Fuel Centerline Temperature at Various Bundle Positions

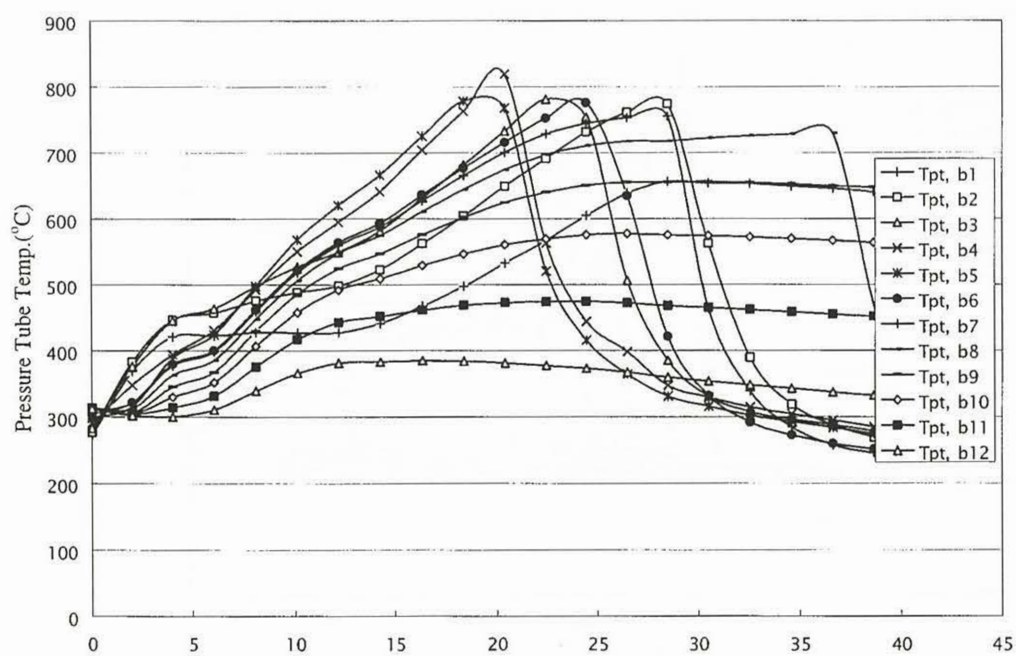

Fig.7. Pressure Tube Temperature of channel M-04 for various Bundle during RIH 35% Break

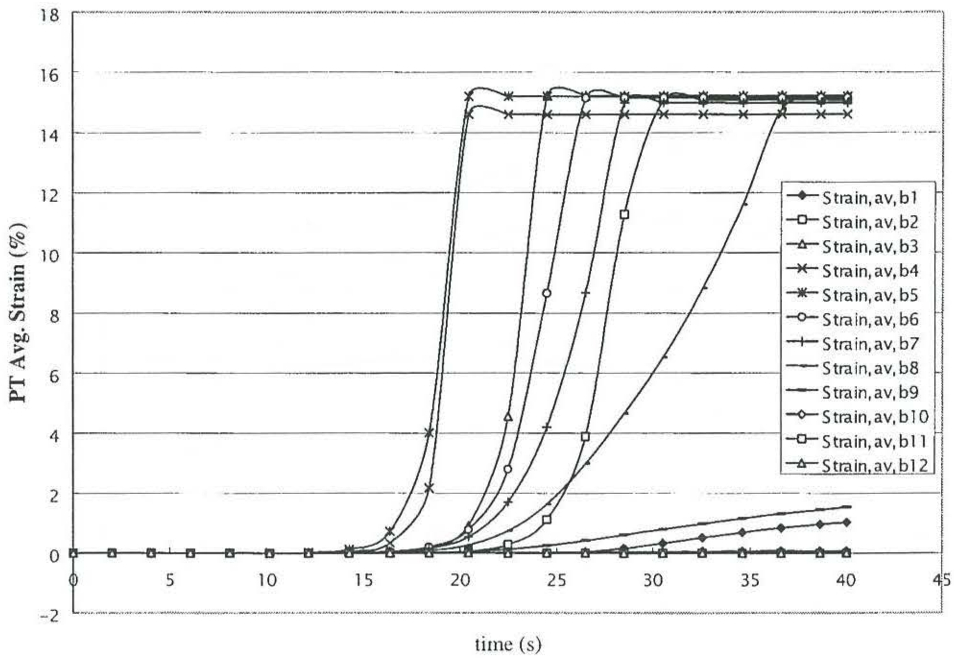

Fig.8. Pressure Tube Average Strain of channel M-04 for various Bundle during RIH 35% Break

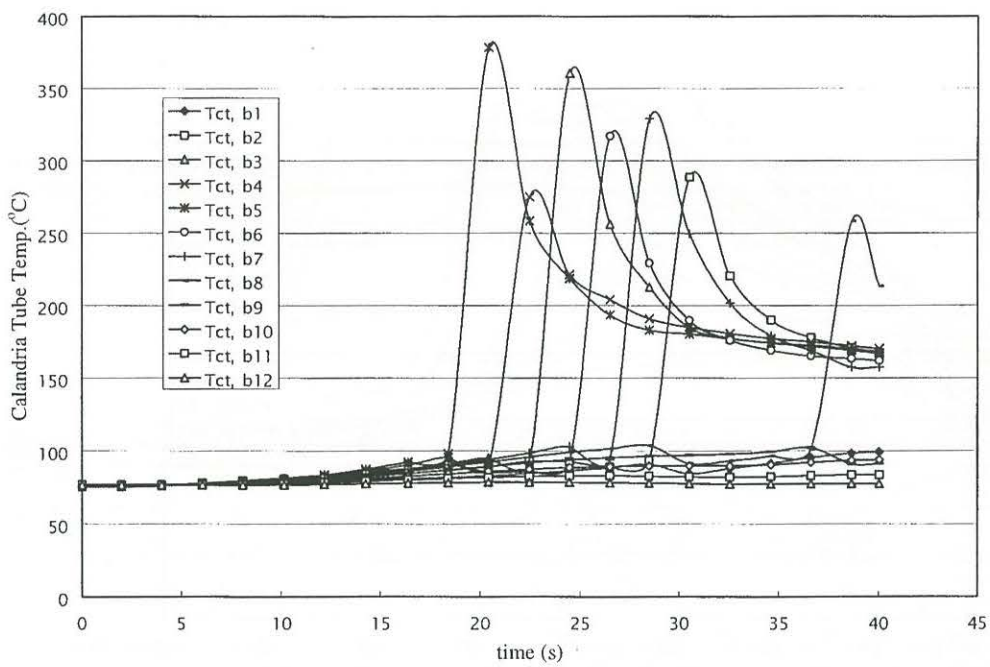

Fig.9. Calandria Tube Temperature of channel M-04 for various Bundle during RIH 35% Break

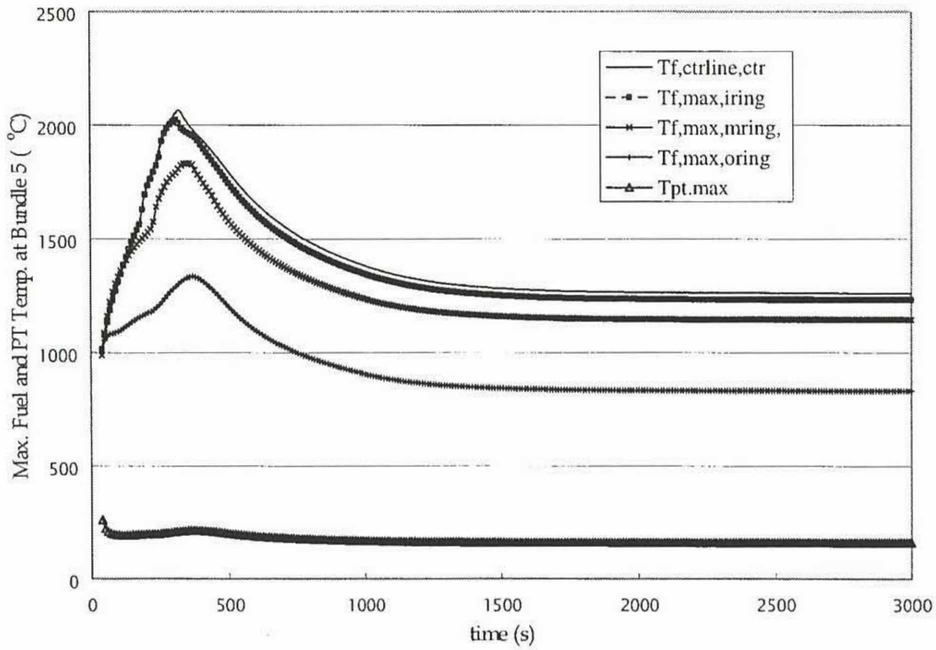

Fig.10. Fuel and Pressure Tube Temperatures of channel M-04 at Bundle 5 for RIH 35% Break

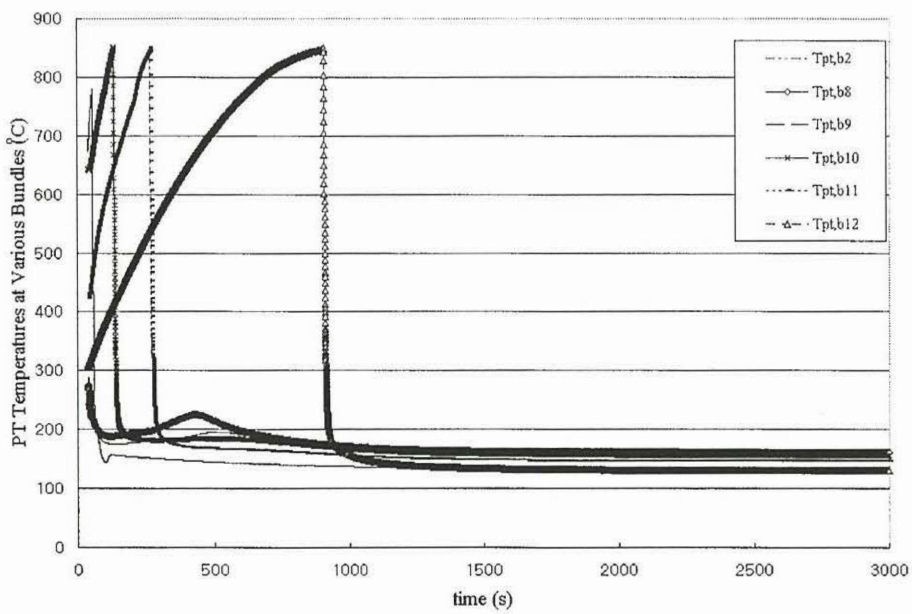

Fig.11. Pressure Tube Temperatures of channel M-04 at Bundles not experienced ballooned contact during blowdown for RIH 35% Break

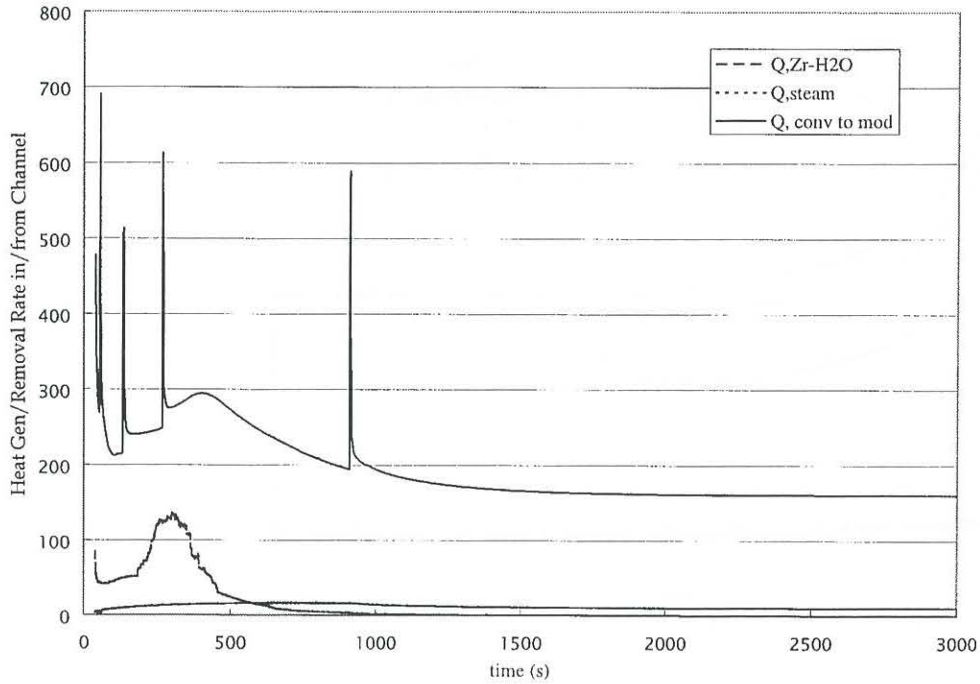

Fig.12. Heat Gen/Removal Rate in/from channel M-04 during post-blowdown for RIH 35% Break without ECC