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CANDU-6 Heat Transport System Stability Analysis With Canflex Fuel Bundle

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CANFLEX 핵연료를 사용한 CANDU-6의 열수송계통 안정성 분석

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Abstract

The Heat Transport system loop stability of CANDU-6 reactor using the CANFLEX fuel bundle was studied. The Thermal-hydraulic behavior of CANFLEX fuel bundle is similar to the conventional 37-element fuel bundle since the reactor power and the frictional pressure drop through the fuel channel is almost the same each other. However the CANFLEX fuel bundle gives higher critical channel power and more homogeneous enthalpy distributions in the subchannels than 37-element fuel bundle. The SOPHT modelling of the CANFLEX fuel bundle and the Reactor Outlet Header(ROH) interconnection line was made and the stability analysis response of Wolsong-1 reactor with CANFLEX fuel bundle was obtained. Without the ROH interconnection line the Heat Transport system loop using 43-element fuel bundle is unstable like the current 37-element fuel bundle. With the ROH interconnection line, however, the Heat Transport system is stable within ±1% of nominal flow. In the Heat Transport system loop stability point of view for Wolsong-1 plant, therefore, the CANFLEX fuel loading is considered to be acceptable.

요 약

중수로용 개량핵연료집합체인 CANFLEX 핵연료다발의 CANDU-6 원자로 장전시 열수송계통에 대한 유동안정성이 분석되었다. CANFLEX 핵연료다발은 기존의 37개봉 핵연료다발과 원자로출력 및 압력강하 측면에서 거의 일치되며, 이로인해 수력적 거동이 양립하는 반면, CANFLEX 핵연료다발은 기존의 37개봉 핵연료다발 보다 임계채널 출력이 증가하며, 반경방향 출력분포의 평탄화로 인해 균일한 엔탈피 분포를 확보할 수 있게 된다. CANFLEX 핵연료다발 및 출구모관들의 상호연결관에 대한 SOPHT 모델을 개발하였으며, 이 모델을 이용하여 CANFLEX 핵연료다발이 장전된 월성 1호기의 유동 안정성 거동이 해석되었다. 해석결과, 열수송계통의 출구모관들의 상호연결관이 없을 경우에는 기존의 37개봉 핵연료다발과 같이 유동이 불안정함을 보였으며, 출구모관들의 상호연결관이 있을 경우에는

정격출력의 ±1% 내에서 안정함을 보였다. 따라서 CANFLEX 핵연료다발의 월성 1호기 장전시 열수송계통의 유동안정성 측면에서는 건전할 것으로 판단되었다.

1. Introduction

Recently Korea Atomic Energy Research Institute (KAERI) and Atomic Energy of Canada Ltd. (AECL) are developing an advanced fuel bundle, CANFLEX (Canadian Flexible Fuel Bundle) for the CANDU-6 reactor like Wolsong-1, 2, 3 and 4 reactors. The fuel design and analysis have been performed and reported in [1]~[4]. The manufacturing process and quality assurance procedure were prepared by AECL and KAERI and some CANFLEX fuel bundles have been produced for thermal-hydraulic test[5]. Several thermal-hydraulic tests including pressure drop, vibration and endurance tests are being performed at AECL and KAERI laboratories to verify the CANFLEX design and analysis. At the present time, several advantages using the CANFLEX fuel were found such as higher critical heat flux(CHF), lower maximum linear power and flexibility of using slightly enriched uranium(SEU) or recovered enriched uranium(REU). In order to obtain the license for the CANFLEX fuel loading in CANDU-6 like Wolsong reactors, several analyses have been performed since 1987. As one of these tasks the present work is to perform the Heat Transport(HT) system loop stability for the validation of the CANFLEX fuel loading in CANDU-6 reactor. It is expected from the engineering point of view that the change from the conventional 37-element to CANFLEX may not affect the loop stability behavior of CANDU-6 reactor due to similar thermal-hydraulic behavior each other. The present study is to clarify this engineering judgement using the suitable analysis tool and to support the licensing activity as well as investigating the effects from the design differences such as fuel bundle geometry, reactor physics and interconnection line configuration.

2. Heat Transport System Configuration

CANDU-6 reactor core vessel is consisted of a cylindrical stainless steel assembly(calandria) which contains heavy water moderator. The HT system, which carries the heat generated in the reactor core to the steam generators(SG), is a pressurized heavy water closed loop. The calandria contains 380 horizontal fuel channels. The heavy water coolant passes through and around the bundles of natural uranium fuel located within the pressure tube. As shown in Figure 1, CANDU-6 HT system comprises two separate loops which are connected by the pressure and inventory control(PIC) system. Each loop contains two HT pumps, two steam generators, two reactor inlet headers(RIH) and two reactor outlet headers(ROH) in a "figure-of-eight" arrangement. Each loop contains 190 fuel channels. Feeder pipes are connected with the inlet and outlet headers respectively. The feeders are sized such that the coolant flow to each channel is approximately proportional to the channel power. The enthalpy increase of coolant is therefore approximately the same for each fuel channel. During the normal operation, the on-power reactor core is refuelled in accordance with a prescribed refuelling scheme. The ROH conditions are 10 MPa(a), 310°C during the normal operation. In order to increase the unit efficiency, boiling in the core is allowed leading to an outlet header quality of up to 4% at full power. The PIC system is designed to provide a means of pressure and inventory control for the closed HT loop to provide adequate overpressure protection. The major equipment in this system to achieve the pressure and inventory control of the HT system is a pressurizer, liquid relief valves, a degasser condenser and a feed pump. A pressurizer is a pressure vessel to accommodate the HT coolant swells and shrinks caused by various transients as well as an overpressure protection of the HT system. The liquid relief valves are provided to protect the HT system from an overpressurization caused by high pressure transients. A deg-

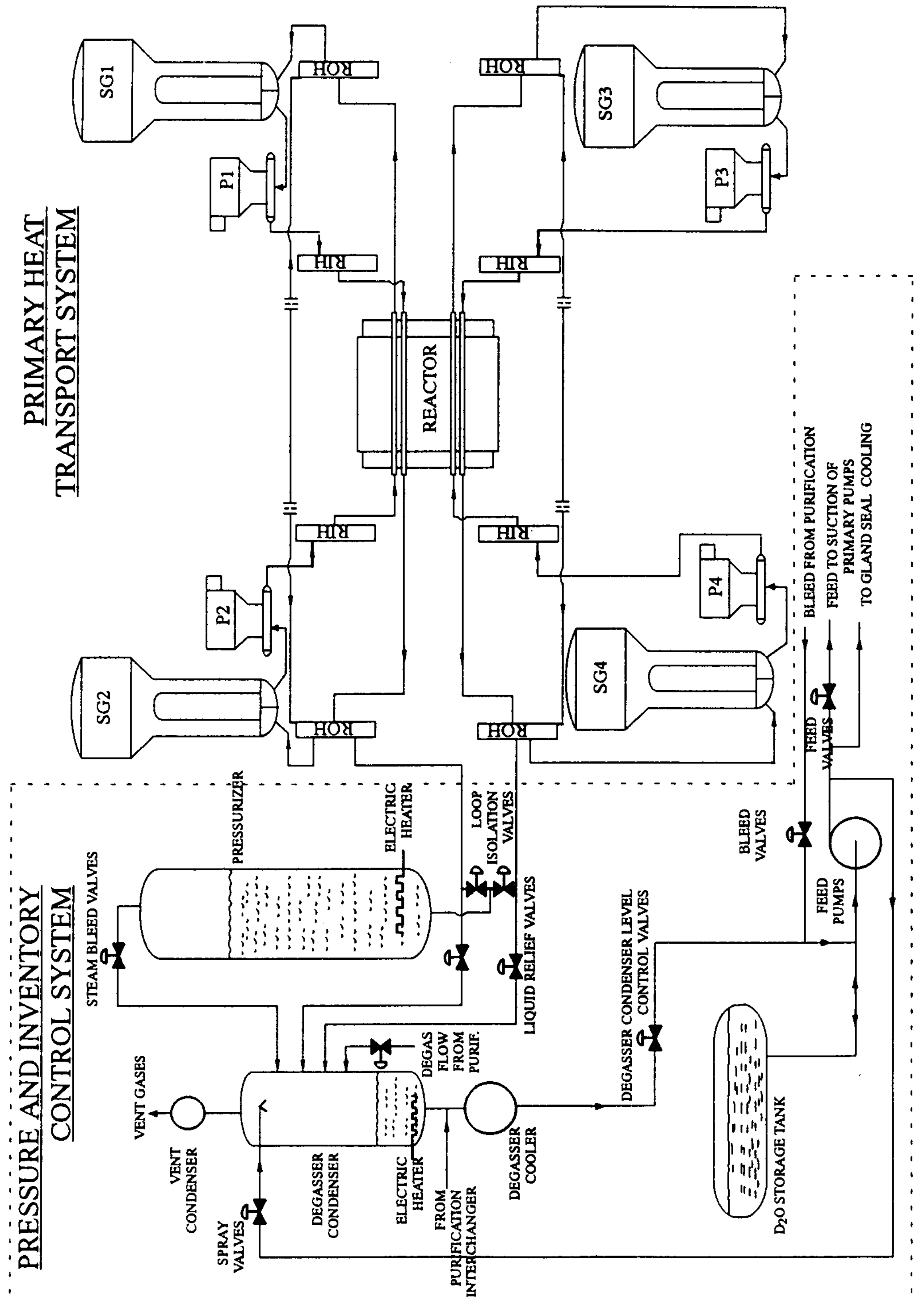


Fig. 1. Wolsong-1 Heat Transport System Configuration

asser condenser is provided to receive D_2O from the HT system through the liquid relief valves during high pressure transients as well as through the steam bleed valves and the degassing valves during various reactor control processes. The feed pump, feed valves and bleed valves maintain the HT system inventory during the normal plant operation and control the HT system pressure. Hydraulic frictional losses in the HT system have been minimized in the interests of pumping efficiency, resulting in low or even negative damping to certain operational asymmetric perturbations such as HT system pressure and flow. Without the interconnection lines, the HT system divergent oscillations occur when the station is operating with quality in the ROH. Although HT system divergent oscillations do not jeopardize the safe operation of the plant, they are operationally unacceptable. AECL established the installation of an interconnection pipe between two ROHs in the HT system configuration with appropriate flow resistance to introduce sufficient damping to eliminate the possibility of any unstable flow oscillation under any operating conditions. This concept is simple, reliable and passive and therefore has been adopted for all CANDU-6 stations.

3. CANFLEX Fuel Bundle Application in CANDU-6

The CANFLEX fuel bundle is different from 37-element bundle as shown in Figure 2. The CANFLEX fuel bundle is composed of 43 elements with two different size elements. The outside diameter of CANFLEX fuel bundle is the same as that of 37 -element bundle in order to assure the compatability with Wolsong-1 fuel channel and existing fueling machine. The CANFLEX bundle provides greater operational flexibility and more operating and safety margins as an alternative of 37-element bundle.

In the fuel performance point of view, two big different design changes, CHF enhancement design

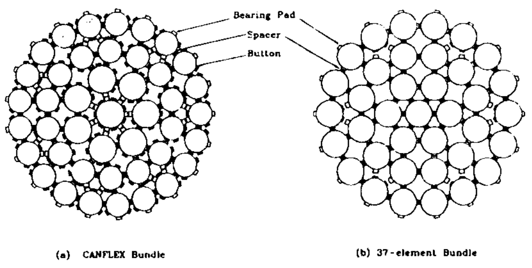


Fig. 2. Cross-Sectional View of CANFLEX and 37-element Fuel Bundles

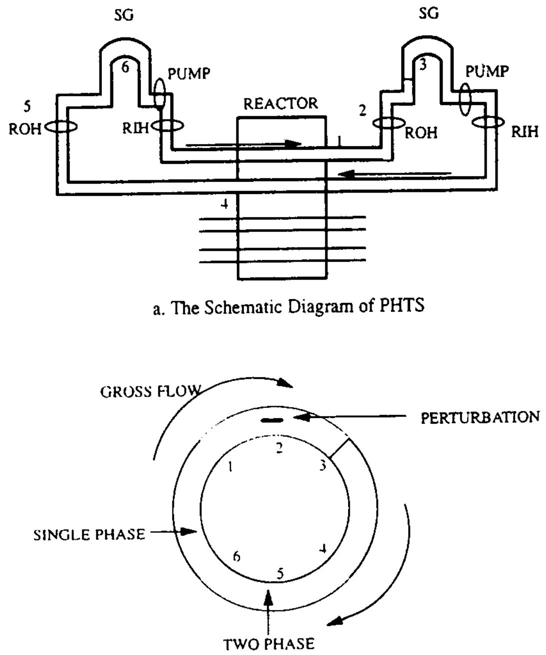
and lower fuel rating or flattened radial power profile of fuel bundle, were made. CHF enhancement design plays mainly a role of giving higher critical channel power than 37-element bundle without excessive pressure drops due to more fuel rods and its appendages compared to 37-element fuel bundle. As a result, CANFLEX bundle has more flexibility and safety of reactor operation. The flattened power profile of CANFLEX bundle gives lower element power rating, more homogeneous enthalpy distributions in the subchannels than 37-element fuel bundle and finally improves the fuel physics and thermalhydraulic performance.

4. Loop Stability

Extensive study about the HT loop stability has been performed by AECL[6][7]. The basic mechanisms can be readily found in common literature[8]. The condition necessary for the initiation of flow oscillation in the loop are sufficient void exit in both ends of the "figure-of-eight" circuit, low inherent system damping and occurrence of an asymmetric disturbance.

As shown in Figure 3, there exists two phase region at ROH and single phase region at remaining area simultaneously in the HT system due to the quality at ROH. Therefore, there may be flow oscillation in the event of system operation perturbation such as; i) power maneuvering up and down at the maximum rate, ii) grid load change, iii) purification flow turned on and off, iv)full steam bleed from the pressurizer as per controller demand, v)full liquid feed and bleed through PIC system as per controller demands.

The figure-of-eight circuit oscillation is a result of the interaction among various effects such as spring-mass effect, positive feedback effect, negative feedback effect and transport delay effect. For the spring-mass effect, the two phase region is compressible and acts like a spring. The single phase liquid region acts predominantly as an incompressible mass, giving substantial inertia to the system. Given a perturbation, say a small pressure reduction in one of the two phase regions, the fluid in the upstream liquid region is accelerated and the fluid in the downstream liquid region is decelerated. The mass flow into the two phase region is, thus, increased, compressing the region and causing the pressure to rise.



a. The Schematic Diagram of PHTS

b. Simplified Schematic of PHTS Loop

Fig. 3. Heat Transport Loop Stability Description

The inertia of the system causes the increased inflow into the perturbed region to continue even after the pressure has returned to normal. An overpressure will result, causing a rebound effect. The upstream liquid now decelerates and the downstream liquid accelerates. With no loss or gains, this oscillation will continue undiminished. For the positive feedback effect, a positive feedback occurs through the interaction of the flow and channel power. For small perturbation, the reactor and channel power remain constant. If the flow is perturbed, the main result is that the enthalpy rise per unit mass of coolant is perturbed. An increase in coolant velocity or flow causes a reduction in specific enthalpy of the two phase region downstream of the reactor channel. The pressure in this region is reduced, causing an acceleration of the upstream flow, all other things being equal. For the negative feedback effects, the main stabilizing mechanism is the resistive losses in the circuit. These losses would tend to oppose increases and decreases in velocity by increasing and decreasing losses, respectively.

None of the above effects occur instantaneously in a distributed system such as the CANDU-6 system. Significant delays occur in energy and density through the reactor channel, the feeders, and the main piping to the steam generator. This transport delay effect and other time-dependent effects such as inertia, heat transfer to pipe walls, differential transit time through the various feeders etc, affect the dynamics of the interaction of the above effects.

If the pressure at point 2 of Figure 3 is reduced by the removal of a small amount of mass, the flow upstream of two-phase region increases and the flow in the downstream region decreases. For a specified liquid region flow perturbation, two effects occur simultaneously. The extra mass tends to compress the fluid and thereby raises the pressure. The second effect is the lowering of enthalpy(per unit mass) by the addition of lower enthalpy fluid. This has a decompression effect as discussed above. Since the flow per turbation is sustained by the inertia, the new core flow yields a new lower enthalpy. Thus, in time, the bulk specific enthalpy moves to this new lower enthalpy and tends to stabilize there and therefore the pressure reduction due to enthalpy reduction is limited. After some characteristic time, the compression effect dominates, causing the oscillation to reverse direction. Simultaneous to these events at point 2, the opposite perturbation is occurring at point 5 of Figure 3.

To prevent these instability and enhance the loop stability, pump flow control or outlet header interconnection line can be used. The interconnection line was chosen and installed as the most appropriate and reliable means to enhance system stability because of its effectiveness, relatively simplicity. The

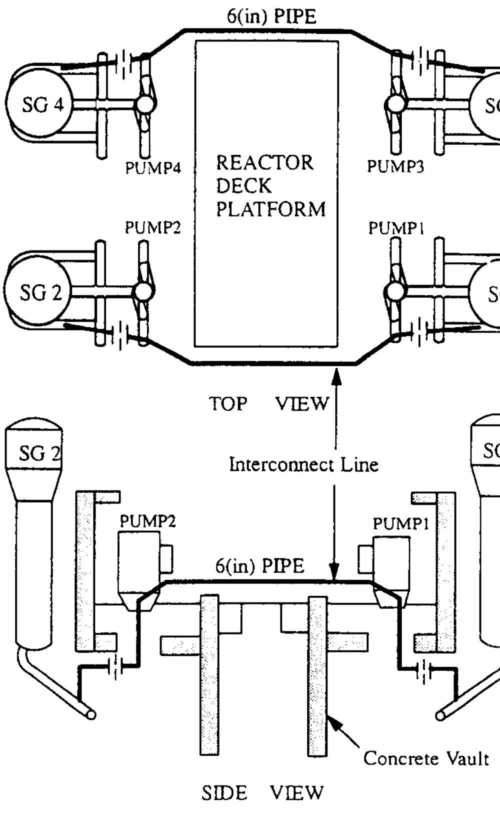


Fig. 4. Wolsong-1 ROH Interconnection Line Configuration

ROH of the same HT system loop are interconnected by a 6 inch line as shown in Figure 1. The interconnection lines are routed above the reactor outlet headers and an orifice is provided at each end of the lines. Figure 4 shows the general arrangement drawing of the interconnection lines. The ROH interconnection line arrangements for Point Lepreau, Gentilly 2, Cordoba and Wolsong-1 plant are the same as shown in Figure 4.

The Point Lepreau reactor HT system stability test [6] indicated that the ROH interconnection line is essential to stabilize the CANDU-6 HT system. With the interconnection line in place, a perturbation at reactor outlet header propagates in much the same manner as described previously. However, the presence of the interconnection line diminishes the effect of the perturbation by allowing fluid to move from the remote header to the perturbed header. A volume of fluid moves into the perturbed header to replace some of the fluid extracted. This directly reduces the driving force for the liquid pass velocity change. In addition, it helps to relieve the subsequent increase in void fraction at the remote header. It is more effective if the inertia is low to begin with. Hence a steam filled interconnection line is preferable to a liquid filled line. To enhance phase separation in the line, and hence increase the amount of steam in the line, provision has been made to elevate the line and to provide liquid drainage.

5. Analysis Code

The loop stability of HT system with interconnection line can be confirmed by computer analysis and plant commissioning test etc. The analysis was based mainly on computer codes such as SOPHT(Simulation of Primary Heat Transport), FIREBIRD and HYDNA-3. Flow instability analysis for Wolsong-1 reactor had been performed using HYDNA-2 code during Wolsong-1 design stage and results were given in Wolsong-1 FSAR. However SOPHT was the primary code used in the loop stability analysis recently and other codes mainly provided verification during the previous study. A stability test was made as a part of the plant reliability check during the Point Lepreau Generating Station(PLGS) commissioning test in early 1980s[6]. Extensive pre-test analysis using SOPHT was carried out to assist in the design of the test procedure as well as to provide feedback analysis as the test progressed. The results of the stability test at 100% FP have conclusively demonstrated that under certain conditions when sufficient void exists in the system and in the absence of the interconnection line and that flow instability can be initiated by a suitable perturbation. Pre-test analysis showed that SOPHT code predictions agreed reasonably well with station data in terms of damping ratio and oscillation period when proper core model was used. Choo[6] reported that the worst condition for flow oscillation was predicted to be at an initial ROH quality of about 3.0%.

The optimal range of the interconnection orifice loss coefficient should be in the range of 20~40.

SOPHT code is a digital computer program for the CANDU Heat Transport system. It is a comprehensive thermal hydraulic analysis package and was developed for simulation of various normal and abnormal operating conditions of CANDU reactor. The mathematical theory and modelling of thermal-hydraulic system employed in SOPHT code are described by Chang[9] in detail. The detailed information about the verification of the initial version can also be found in [10]~[14].

A workstation version of SOPHT code with the single channel model is used in performing the present stability analysis. The validation of this version was made by the comparison of SOPHT results with the site data from the PLGS[6, 7]. It is required to show that SOPHT code predicts thermal-hydraulic performance in, at least, a conservative manner. Figure 5 shows the comparison of test data during PLGS commissioning test with SOPHT prediction. Excellent agreement between SOPHT and the plant data was obtained. The current version of SOPHT code used

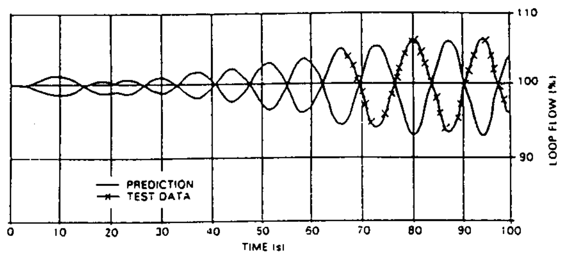


Fig. 5. Comparison of Test Data With SOPHT Prediction Tuned To 65% FP Data

in the present analysis, is the result of continuous effort to improve the code since that time.

6. SOPHT Modelling

The schematic diagram of SOPHT model for CANDU-6 reactor is drawn in Figure 6. The SOPHT model includes Heat Transport(HT) system, Pressure and Inventory Control system, HT Purification system, Main Steam Supply system and Steam Generator Feedwater system. The Shutdown Cooling(SDC) is also connected to cool the HT system during reactor shutdown stage. The SDC system is not modelled in Figure 6 since it doesn't operate during the normal power operation condition. The piping and equipment in systems are divided into several "modules" as shown in Figure 6. Modules have constant volumes same as that of the piping or equipment they modelled. Pressure and temperature(or enthalpy) are the variables in the modules. Modules are connected to each other by "links". A link has a constant length, cross-sectional area, hydraulic diameter, elevation change and flow resistance. For a valve link, the valve discharge coefficient is also included. Pumps are included in links. The only variable for links is a flow rate. Pressure, temperature, enthalpy for modules and flow rate for links are the output data from computer analysis. If the metal heat is considered, the metal wall data is included in the input data. The SOPHT code uses the iteration method to calculate these properties and therefore a set of first guess val-

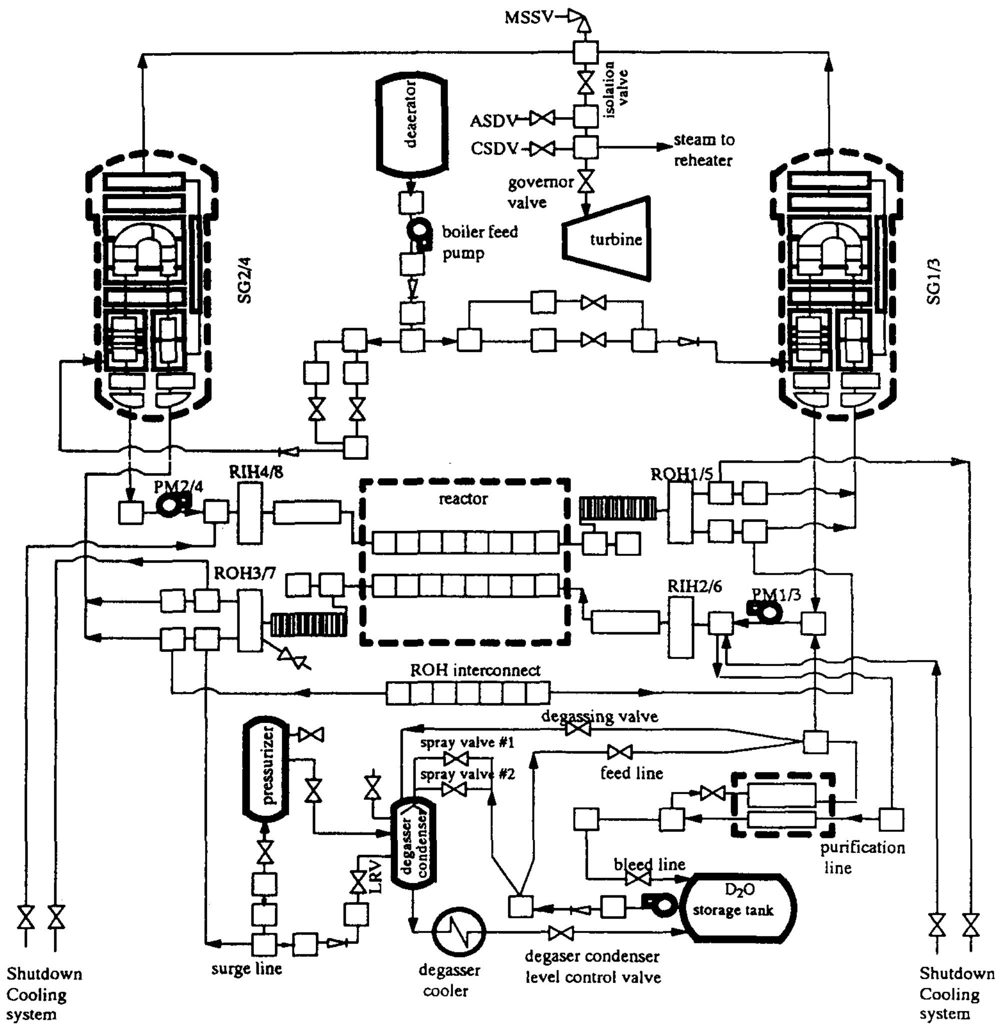


Fig. 6. Wolsong-1 SOPHT Nodalization

ues for these properties must be given in the steady state input data.

The SOPHT model presented in this report as shown in Figure 6 is called "a single channel, two quadrant model" which means that only one loop of the HT circuit is modelled. Therefore one core pass is equivalent to an average value of 190 fuel channels.

In the two quadrant model the flow rate, the cross-section area, the volume, the power generated and the heat transferred are all doubled to represent a full HT circuit. In order to obtain the correct pressure drop, the equivalent diameter of the link must be used. The SOPHT program calculates the flow velocity by dividing the doubled flow rate by the doubled cross-sectional area. The equivalent diameter and the calculated flow velocity are then used to calculate the pressure drop in the link.

The SOPHT input data for the CANFLEX fuel bundle was prepared from the fuel bundle geometry as shown in Figure 2. Detailed modelling information

Table 1. Wolsong-1 Fuel Channel Data for 37-element and CANFLEX Fuel Bundles

Calculation parameters	Unit	Modelling & equation	37-Element	CANFLEX
Density	kg/m^3	saturation state at 288°C D_2O condition	811.9	811.9
Kinematic viscosity	m^2/s	saturation state at 288℃ D_2O condition	1.23×10^{-7}	1.23×10^{-7}
Mass flow rate	kg/s	reference flow rate (1900001b/hr)	23. 94	23.94
Fuel channel total length	m	fuel channel total length, 10.084−2*(1.549−0.864)	5.98	5.98
Flow volume of fuel channel	m^3	volume of F/C-volume of 12 fuel bundles	3.93	4.13
Average flow area of 190 fuel channel	m^2	(P/T volume-F/A volume)*190 from flow volume calculation	0.6572	0.6903
Velocity	m/s	(reference flow rate)/ (ρ*Area of fuel channel)	8.5248	8.116
Rod diameter	m	fuel rod diameter	0.0131	0.0115 0.0135
Pressure tube diameter	m	pressure tube diameter	0.1034	0.1034
Flow area of one fuel channel	m^2	flow area in fuel channel	3.4102×10^{-3}	3.6166×10^{-3}
Wetted perimeter of fuel channel	m	wetted perimeter in fuel channel	1.8476	1.9286
Equivalent diameter of fuel channel	m	equivalent diameter in fuel channel	7.4885×10^{-3}	7.5355×10^{-3}
Reynolds No.		v*De/(Greek Lettw)	519009	497197
Friction factor in SOPHT		$f=0.0056+0.5/Re^{0.32}$ in SOPHT code	0.013015	0.013117
Reference Pressure drop (clean F)	kPa	$\Delta P=\rho(\Delta fL/D+K)*v^2/2$	626.2	627.5
Dynamic head	Pa	$\rho v^2/2$	29501.2	26737.0
Frictional term	Pa	fL/D(for single phase turbulent flow)	10.393	10.410
Resistance for clean fuel (K)		$K=\Delta P/(\rho v^2/2)-(fL/D)$	10.83	13.08

is given by Park et al. [15]. Table 1 shows the difference of major parameters between two fuel bundles. The flow area of CANFLEX fuel channel is slightly larger than that of 37-element channel but the header to header pressure drop is almost the same each other. A number of small pads were attached newly around the 43-element to improve the CHF by promoting turbulence. The reactor physics data such as delayed neutron fraction and fuel reactivity worth for 43-element fuel were also prepared. However the change in reactor physics data shows minor effect on the loop stability behavior.

The SOPHT model of CANDU-6 interconnection line was prepared from the isometric drawing as shown in Figure 7. This ROH interconnection line modelling was based on Wolsong-1 site data. The configuration and input data calculation for the ROH interconnection line are detailed in Park et al. [15]. During Wolsong-2 design stage, however, the elevation of interconnection line was lowered due to the inconvenience for accessing the mechanical deck above the reactor core vessel. Wolsong-2, 3, 4 are identical stations and therefore the same in the stability analysis point of view. However, Wolsong-1 interconnection line configuration is different from Wolsong-2, 3, 4 plants. Also the HT pump characteristic curve[18] was obtained to model the pump head accurately. The polynomial regression of the curve was made to generate the SOPHT input data.

There are two pressurizer models available in the SOPHT code-the adiabatic and the equilibrium model. For pressurizer in-surge, the adiabatic model assumes adiabatic compression while equilibrium conditions are assumed for the equilibrium model. Both models assume the equilibrium condition for pressurizer out-surge. It is our experience that without the ROH interconnection line, the adiabatic model results in less damping than equilibrium model. For the fast flow in-surge, the performance of pressurizer is closer to the adiabatic process; for the slow flow in-surge, it is closer to the equilibrium process. The true pressurizer performance lies somewhere between the two extremes of adiabatic and equilibrium models. Since without the ROH interconnection line, the adiabatic pressurizer model shows less damping, therefore, it is conservative to choose the adiabatic pressurizer model for this HT system stability study.

Reference	Module	Link	Length (m)
F-B	85		16.154
A-B		M85-M86	8.077
B-C	86	M86-M87	2.083
C-D	87	M87-M88	2.496
D-E	88	M88-M49	4.331
A-F		M85-M84	8.077
F-G	84	M84-M83	1.881
G-H	83	M83-M82	2.640
H-J	82	M82-M77	4.287

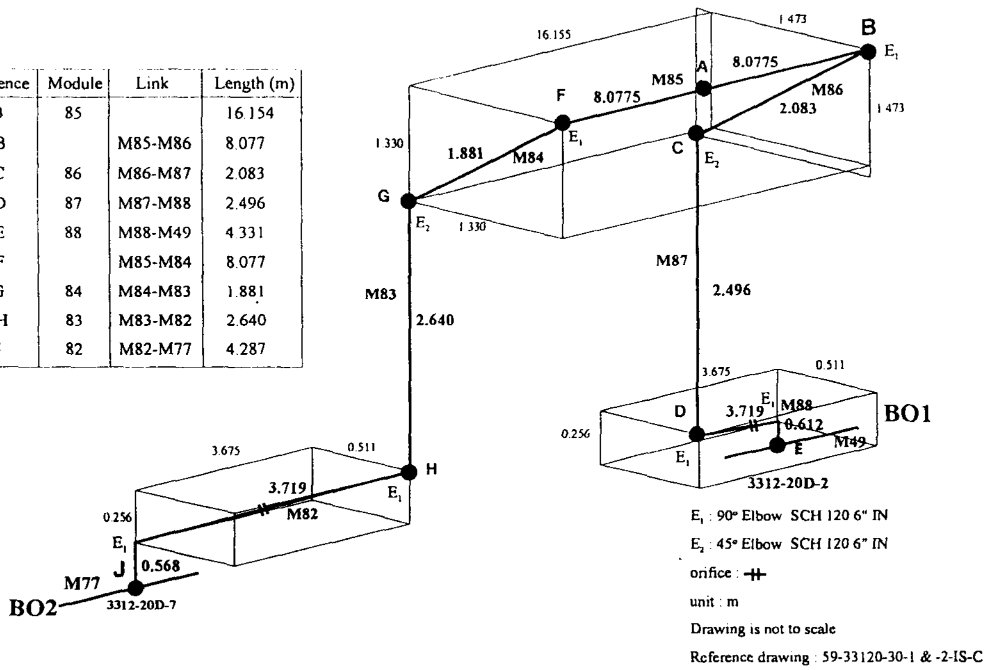


Fig. 7. Wolsong-1 Interconnection Line Nodalization

7. Damping Ratio

The flow at RIH and the pressure at ROH are commonly used to observe the oscillation behavior. For an indication of the relative margin to instability for any oscillation, the damping ratio is used to measure the degree of oscillation. The damping ratio(DR) is defined as a convenient indicator which gives a quantitative measure of the peak-to-peak attenuation of the oscillation[17].

$$D.R. = \frac{-\ln(x)/2\pi}{\sqrt{1 + (\frac{\ln x}{2\pi})^2}}$$

where x is the ratio of the attenuation of the peak-to-peak oscillation. It is noted that the damping ratio for a given flow oscillation may vary with time due to non-linearity. The starting point of the data is the first minimum value after 30 seconds of the transient time. The first 30 seconds of the transient is dominated by the initial perturbation, therefore for the initial 30 seconds the flow pattern is almost the same for all the cases and is not meaningful from the HT system loop stability point of view. An average damping ratio of five consecutive cycles after 30 seconds is typically used in this report. Damping ratios for the cases with or without the interconnection line considered in the present study are listed in Table 2.

8. Acceptance Criteria

The acceptance criteria of the ROH interconnection line are to use the conservative approaches to demonstrate that with the ROH interconnection line the HT system is stable. The worst case causing fast and large divergence without the interconnection line was used for the analysis with the interconnection to observe the stable behavior. As the HT system flow oscillation is used to indicate the HT system stability, the acceptance criterion of the flow is that in the event of a perturbation, the amplitude of the reactor inlet header flow oscillation is less than ±1% of nominal flow[16].

9. Analysis Results

During the steady state condition, the difference of major parameters between 37-element and 43-element is small as shown in Table 3. The mass flow rate through the HT system using CANFLEX fuel is almost the same as that using the 37-element since the reactor power and the header to header pressure drop is similar each other.

Various initial perturbations were studied in the earlier stability studies and it was determined that the most effective initial perturbation is to open/close the

Table 2. Results of Damping Ratio Calculation

Description	Average Damping Ratio
Wolsong-1 Loaded with 37-Element Fuel Bundle Without Interconnection Pipe	−0.06841
Wolsong-1 Loaded with CANFLEX Fuel Bundle Without Interconnection Pipe	−0.06739
Wolsong-1 Loaded with 37-Element Fuel Bundle With Interconnection Pipe	0.101535
Wolsong-1 Loaded with CANFLEX Fuel Bundle With Interconnection Pipe	0.036913
Wolsong-1 Loaded with 37-Element Fuel Bundle With Interconnection Pipe and 103% Pump Power	0.088051
Wolsong-1 Loaded with CANFLEX Fuel Bundle With Interconnection Pipe and 103% Pump Power	0.037647
Wolsong-2 Loaded with 37-Element Fuel Bundle Without Interconnection Pipe	−0.06784
Wolsong-2 Loaded with 37-Element Fuel Bundle With Interconnection Pipe	0.030881
Wolsong-2 Loaded with CANFLEX Fuel Bundle With Interconnection Pipe	0.030419

Table 3. Comparison of the Steady-State Condition Between 37-element and CANFLEX Fuel Bundles

Parameters	Unit	Core Pass I (RIH 4/8 to ROH 1/5)		Core Pass II (RIH 2/6 to ROH 3/7)	
		CANFLEX Bundle	37-Element Bundle	CANFLEX Bundle	37-Element Bundle
Total Core Flow	kg/s	3864.47	3866.478	3864.47	3866.48
Header-Header Pressure Drop	MPa	1.426	1.425	1.423	1.422
Outlet Header Pressure	MPa	9.9868	9.9868	9.984	9.984
Outlet Header Enthalpy	kJ/kg	1394.16	1394.05	1393.40	1393.29
Outlet Header Quality	%	3.49	3.48	3.44	3.43
Outlet Header Temperature	°C	309.96	309.96	309.94	309.94
Inlet Header Pressure	MPa	11.4125	11.4115	11.4073	11.4062
Inlet Header Enthalpy	kJ/kg	1128.62	1128.64	1127.86	1127.89
Inlet Header Temperature	°C	266.58	266.59	266.42	266.43
Reactor Power	MW	1026.2	1026.2	1026.2	1026.2

HT system steam bleed valve from the pressurizer. The initial perturbation same as used in Point Lepreau commissioning test[16] is adopted in the present study. That is, the steam bleed valve is ramped open in 5 sec. → the valve is held open for 5 sec. → the valve is ramped close in 5 sec. → the valve is kept closed after 15 sec. of transient.

The steam bleeding from the HT system to the degasser condenser causes the initial perturbation of the HT system loop. The steam bleed valve action drops the pressure of its connecting ROH while the opposite side ROH of the reactor is not affected immediately. Figures 8, 9, 10 show the HT flow transient after an initial perturbation without the interconnection line for the 37-element fuel bundles of CANDU-6 reactor. The pressure difference of these two ROHs will develop oscillation in less than 100 seconds as shown in Figure 8. According to the previous study the sinusoidal flow variation in time with the maximum amplitude occurs in the single phase regions and the pressure variation with the maximum amplitude occurs in the two phase regions. Figure 8 shows the HT system flow variation at RIH and Figure 10 represents the pressure variation at ROH. This transient result indicates that without the interconnection line the HT system flow and pressure of the conventional 37-element fuel bundle diverges with average damping ratio of -0.06841. As expected the condition at points 2 and 5 in Figure 3 is opposite each other. The ROH quality in this case is shown on Figure 9. The amplitude of flow oscillation grows until the flow quality reaches the lower bound, zero percent.

Based on the sensitivity study of Wolsong-2 reactor[16], the optimized SOPHT model for Wolsong-1 HT system was adopted in the present study. It was

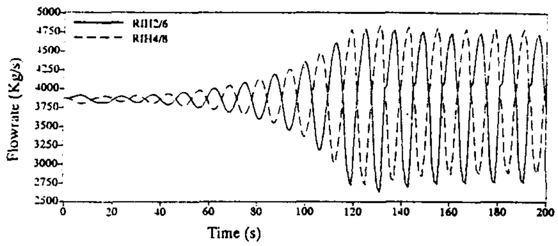


Fig. 8. HT System Flow Variation Without Interconnection Line-W-1 37-element

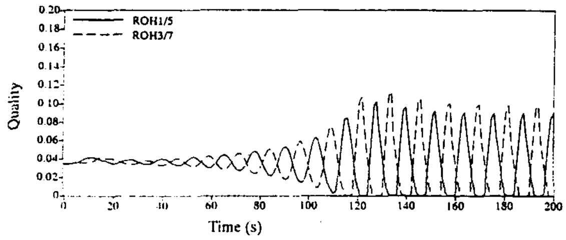


Fig. 9. ROH Quality Without Interconnection Line - W-1, 37-element

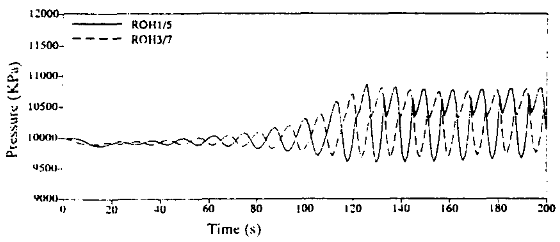


Fig. 10. ROH Pressure Variation Without Interconnection Line-W-1, 37-element

found that the loop stability was sensitive to the number of nodes assigned to the reactor outlet feeder in the SOPHT modelling. The present study used the number of nodes which provides a maximum instability without ROH interconnection line. Also the HT system instability is sensitive to the ROH quality. The ROH quality may increase approximately from 2% to 4% as the steam generator function degrades with the gradual accumulation of dirt or chemical compounds on the surface of steam generator tubes. Based on the sensitivity study, the ROH quality which provides a maximum instability without the ROH interconnection line was used as an input to the SOPHT model for the conservative analysis. That is, the reactor outlet feeder is represented by 25 nodes and the initial steady state operating condition is at 100% FP(full power) with 3.4% ROH quality. The ROH quality was adjusted using the fouling factor of the steam generator.

The input data for Wolsong-1 reactor was developed for both 37-element and 43-element fuel bundles. Figure 11 indicates that Wolsong-1 HT system with CANFLEX fuel bundle is also unstable without ROH interconnection line. Although the interconnection line design is different between Wolsong-1 and 2 reactors, the HT system flow oscillatory behavior should be the same without the interconnection line. The present analysis results were verified by producing the same oscillatory curve reported for Wolsong-2 reactor as shown in Figure 11 without the interconnection line[16]. Most input data are adopted from Wolsong-2 data except the interconnection line model, the friction loss coefficient through the fuel channel and the CANFLEX fuel geometry.

When the ROH interconnection line is installed the initial perturbation dies out and the HT system becomes stable as shown in Figure 12. The ROH interconnect line provides positive damping. Operating experience has already shown that Wolsong-1 plant with 37-element fuel bundle is stable when the interconnection line is installed. Therefore Figure 12 validates the simulation of HT system loop stability using the SOPHT code. The sensitivity study for the effect of geometric factors on the loop stability has been performed during Wolsong-2 interconnection line design. The geometric factors include the elevation and the diameter of the interconnection line, the loss coefficient, K of the orifice installed in the line. It was found that the optimized design would be the K=20~40(K=30 for Wolsong-1), the elevation=4m for 6 inch diameter. The amplitude of the RIH flow oscillation which should be half of the difference between maximum and minimum values is

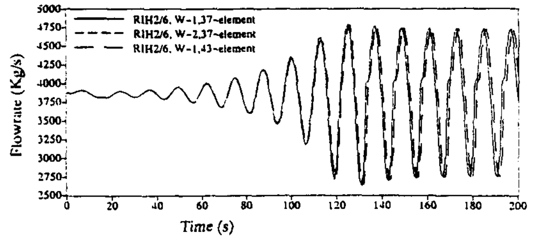


Fig. 11. HT System Flow Variation Without Interconnection Line

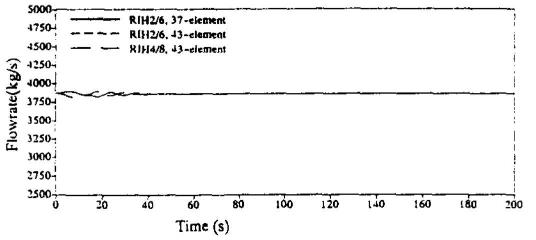


Fig. 12. HT System Flow Variation With Interconnection Line-W-1

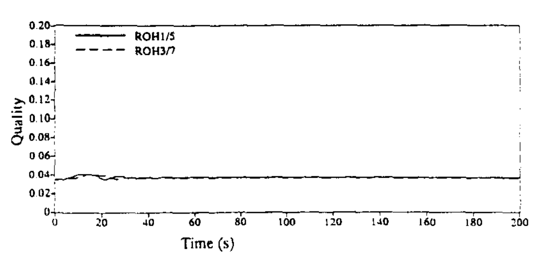


Fig. 13. ROH Quality With Interconnection Line-W-1, 43-element

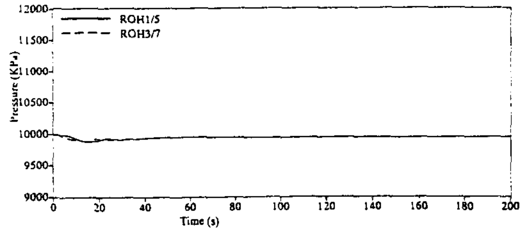


Fig. 14. ROH Pressure Variation With Interconnection Line-W-1, 43-element

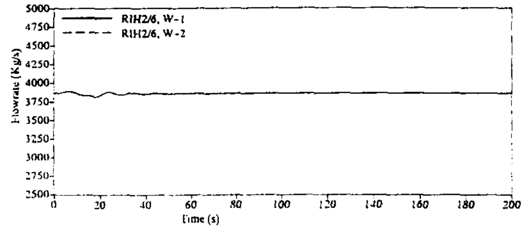


Fig. 15. HT System Flow Variation With Interconnection Line-43-element

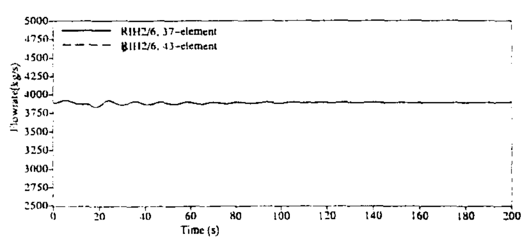


Fig. 16. HT System Flow Variation With Interconnection Line-W-1, Pump Mismatch

less than ±1% of nominal flow as specified in the acceptance criteria before. Figure 12 also shows that the 43-element fuel bundle case is stable like 37-element case. As far as the HT system loop flow stability is concerned the behavior is similar each other due to the same reactor power. Figures 13 and 14 show the stabilization behavior of the ROH quality and pressure for Wolsong-1 reactor with the interconnection line using 43-element fuel bundles. Figure 15 shows the transient result when the CANFLEX fuel bundle is loaded in Wolsong-2 reactor. Similar to Wolsong-1 this result indicates that Wolsong-2 reactor using CANFLEX fuel bundle is also stable.

It was found that the loop stability is sensitive to the HT pump head variation. When the ROH interconnection line is installed, the mismatch of two HT pumps may result in constant coolant flow through the ROH interconnection line which will reduce the capability of the interconnection line to stabilize the HT system. The HT pump head tolerance may affect the loop stability behavior. The maximum head tolerance is limited to +3% and −0% from the design value. The mismatch of two HT pumps will result in constant coolant flow through the ROH interconnection line and may make the HT system less stable. Figure 16 shows the result when one HT pump is operating at 103% while the other one is operating at 100%. For both 37-element and 43-element fuel bundles, the Wolsong-1 HT system is stable in this case too.

10. Conclusion

The HT system loop stability of CANDU-6 reactor as Wolsong-1 with the CANFLEX(43-elements) fuel bundle has been performed. The mechanics of the flow instability caused by two phase flow occerrence inside the closed HT system loop was reviewed. Using SOPHT code which is the generalized thermal-hydraulic analysis package for CANDU reactor, the simulation of HT system in the present study was compared and verified with Wolsong-2 stability analysis result reported previously. The SOPHT modelling of the CANFLEX fuel and the Wolsong-1 interconnection line was made and the stability analysis response of Wolsong-1 reactor with 43-element fuel bundle was obtained. The HT system loop stability behavior in case of using the 43-element fuel bundle is similar to that of the conventional 37-element fuel bundle. Without the ROH interconnection line the HT system loop using 43-element fuel bundle is unstable like the current 37-element fuel bundle. With the ROH interconnection line, however, the HT system is stable within $\pm 1\%$ of nominal flow. In the HT system loop stability point of view for Wolsong-1 plant, therefore, the CANFLEX fuel loading is considered to be acceptable. It is considered that the thermal-hydraulic transient behavior as well as the steady state condition of the HT system using the CANFLEX fuel bundle is similar to that with the current 37-element fuel bundle.

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