EXPERIMENTAL AND ANALYTICAL STUDIES ON THE INSTABILITY IN THE LZCS FOR CANDU REACTORS

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When reactivity insertion such as refueling occurs in CANDU reactors, the power and the water levels are tilted in the upper outer zone of the LZCS (Liquid Zone Control System) and fluctuate unstably for a certain period of time (1-5 days). The instability described above is observed in most CANDU reactors in service around the world, but its root cause is unidentified and no solutions to this problem have been established. Therefore, this study attempted to prove experimentally and analytically that the root cause lies in the hold-up of light water on the top of the TSP (Tube Support Plate) due to the mismatch between net volumetric flow rate of light water and helium crossing the narrowed porous TSP installed within the LZCS compartment. Our method was to perform a hydrodynamic simulation of in/outflow of light water and helium. Two solutions for the aforementioned instability of LZCS are suggested. One is to regulate the compartment for both inflowing helium gas and outflowing light water; the other is to enlarge the flow paths of helium and light water within TSP. The former may be applicable to nuclear reactors in service and the latter to those planned for construction.

KEYWORDS : LZCS, Cycling, CCFL, Liquid Zone Control System, CANDU Instability

1. INTRODUCTION

Since the CANDU-type nuclear reactor uses natural uranium as its fuel, which leaves little room for extent excess of reaction, one should use heavy water (D_2O) with a small neutron absorption cross-section and a large scattering cross-section as a moderator and a coolant, and also overmoderate the reactor before operating it. Thus, if light water (H_2O) is inserted into the reactor core, no effects of velocity reduction are produced, only the effects of neutron absorption (the role of the control rod). Also, due to the nuclear characteristics of natural uranium (creation of Pu), the reactor locally increases the extent of reaction (power output) after replacing fuel. Thus, an H_2O compartment should be installed in the reactor core to adjust light water level, thereby controlling local power tilt caused by the replacement of reactor fuel. This is referred to as the liquid zone control system (LZCS).

2. LIQUID ZONE CONTROL SYSTEM CONFIGURATION

CANDU, which as it uses natural uranium does not have a significant margin in terms of excess reactivity, is operated in an over-moderated state with D_2O used as moderator and coolant for its small neutron absorption cross-section and large scattering cross-section. Therefore, when H_2O is fed into reactor core, only neutron absorption effect (of control rod) is shown without moderation effect. In addition, reactivity (power output) rises locally for a certain period of time following refueling due to

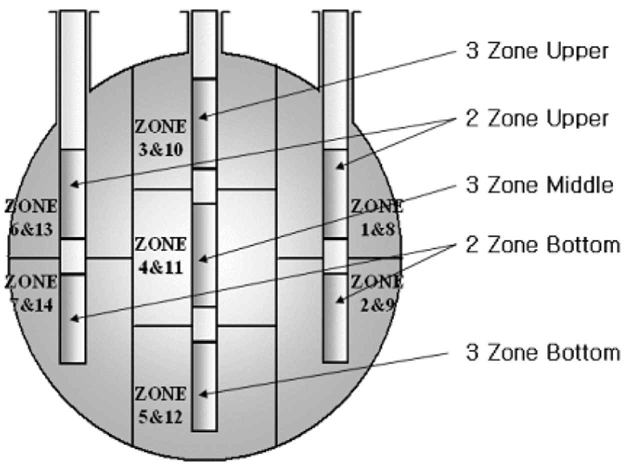

Fig. 1. Cross Section of Compartments in Calandria

nuclear characteristics (Pu generation). Therefore, H_2O compartment is installed within reactor core to adjust H_2O level and thereby control local power tilt following nuclear refueling, which is referred to as LZCS (Liquid Zone Control System).

LZCS is installed at six locations within reactor core, each consisting of two or three zircaloy compartment assemblies, or 14 in total. Six compartment assemblies are installed at south bank and north bank of Calandria, three for each respectively and each assembly consists of two compartments outward and three in the center as shown in Fig. 1.

3. ANALYSIS OF INSTABILITY EXPERIENCES

3.1 Instability Events

In most CANDU-type reactors, in Korea and elsewhere, power output and LZCS water level fluctuated sharply above 80% during initial operation following nuclear refueling. As Fig. 2 indicates, such events happened in upper zones of Calandria, notably in Zones #1, 6, 8, 13. In other words, power output and compartment water level of upper outer zones went out of normal control range following refueling in such zones.

Most CANDU-type reactors suffer similar phenomenon, but even the original designers, AECL (Atomic Energy of Canada Limited) and COG (CANDU Owner Group), have yet to identify causes and clearly suggest solutions.

Instability within LZCS occurs as the water level in upper outer compartments is TSP (65%) or more and the water level and the power output surges for 4~5 days before falling sharply to normal level. If helium compressor runs in an on-off mode, water level and power output cycle in synchronization with the helium compressor operation (on-off) cycle. Phase 1 analysis has already revealed that H_2O standing on the top of TSP is attributable to the instability of LZCS.

3.2 Effect on Power Distribution

In terms of water level control logic for applicable compartments of LZCS, water level rises as H_2O influx increases as per reactor core output signal. However, if the water level exceeds 80%, it is fixed at 80% by phasing out in reference to water level meter signal.

However, if the flow of H_2O and helium becomes abnormal within compartment, water level meter indicates that water level stays at 80%. However, H_2O stands on the top of TSP in effect until it reaches water spreader at the top edge of compartment. Helium layer at the bottom of TSP also rises from the bottom until it fills a little less than 30% of the compartment.

In the end, reading of water level meter differs from actual H_2O level. In other words, water level meter sends a signal to control system, indicating that H_2O fills 80% of compartment from the bottom, but the actual H_2O and helium levels are as in Fig. 6. In Fig. 6, helium layer at the bottom of TSP displaces H_2O, which is a neutron absorber in proportion to its length (20~65% water level). As such region is not only closer to the center of Calandria but also carries great importance, reactivity control performance deteriorates significantly. On the other hand, some H_2O standing on the top of TSP (100~125% water level) is pushed out of the boundary of fuel loaded in Calandria, making little contribution to reactivity control.

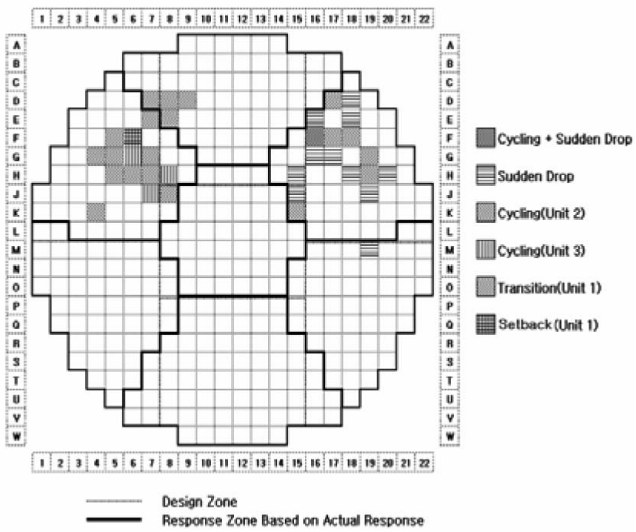

Fig. 2. Instability-Affected Zones in the Wolsong Plant and Fuel Channels Replaced Prior to the Instability Event

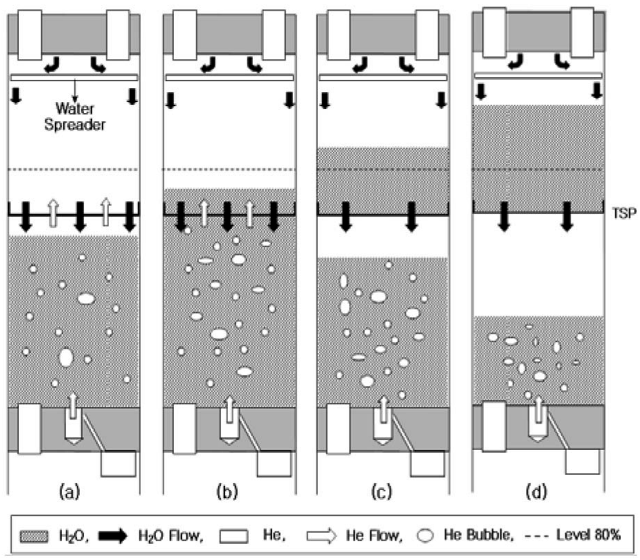

Fig. 3. How Abnormality Occurs within Compartment

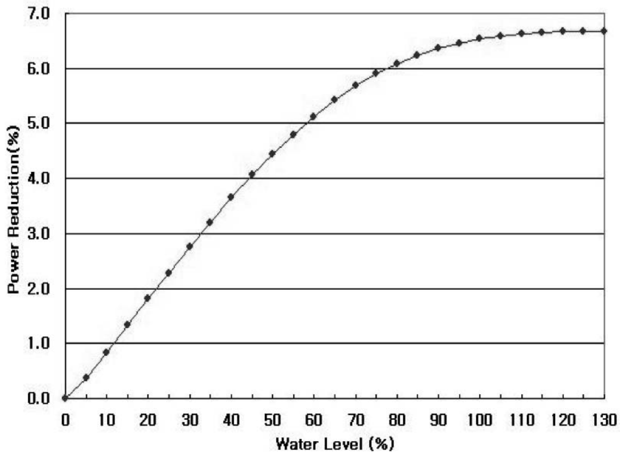

Fig. 4. Power Reduction Subject to Water Level in the Upper Outer Compartment

For the reason above, actual water level in compartment rises, but local power output increases out of control.

To prove the statement above, we used RFSP (Reactor Fuelling Simulation Program), which is a reactor physic code for CANDU-type reactors to calculate power reduction (%) subject to compartment water level; we compared the outcome with power output data of instability event. Power reduction calculation outcome subject to compartment water level is as in Fig. 4.

As Fig. 4 indicates, power reduction (control worth) at normal water level from 0~80% within compartment is 6.09% in the absence of abnormality. However, if abnormality develops fully as in Fig. 3, H_2O (0~20% water level) at the bottom of TSP reduces power by 1.75%, H_2O (65~100% water level) from TSP to the boundary of nuclear fuel loaded in Calandria reduces power by 1.11%, and H_2O (100~125% water level) beyond the boundary of nuclear fuel reduces power by 0.14%, resulting in total power reduction (control worth) by only 3%.

Therefore, power is estimated to increase by about 3.09% in comparison with normal control conditions if H_2O and helium flow within compartment becomes abnormal. Power output was about 1.01 FP (Full Power) and 1.04 FP at maximum, respectively, before and after instability developed, indicating a rise of about 3%. As the estimation outcome and the actual power output data are consistent with each other, abnormality within compartment seems to blame for sudden surge of power output.

3.3 Effect on Geometrical Location in Compartments

As CANDU-type reactors have fuel channels surrounding Calandria which is a horizontal cylinder, neutron speed is relatively higher in the center than in the outer perimeter. Fig. 5 shows the size and location of Calandria nuclear fuel channels and compartments with lattice pitch. The figure also indicates the location of H_2O

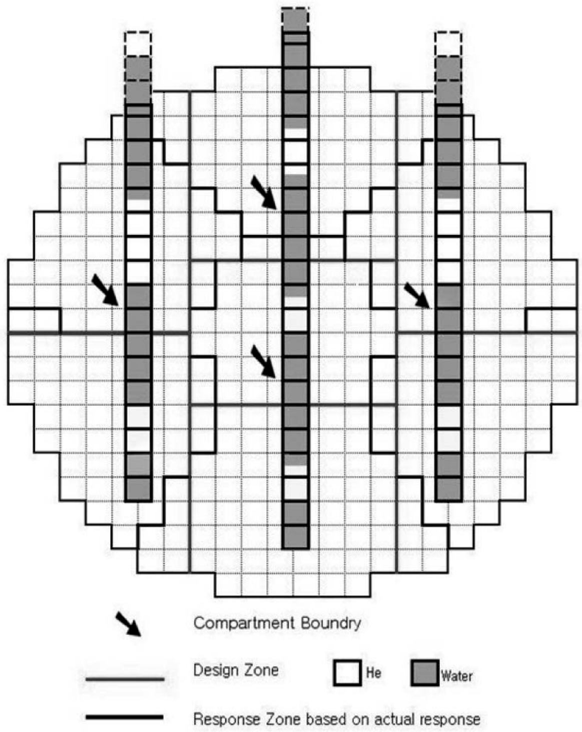

Fig. 5. Anticipated Light Water and Helium Relocation in each Compartment

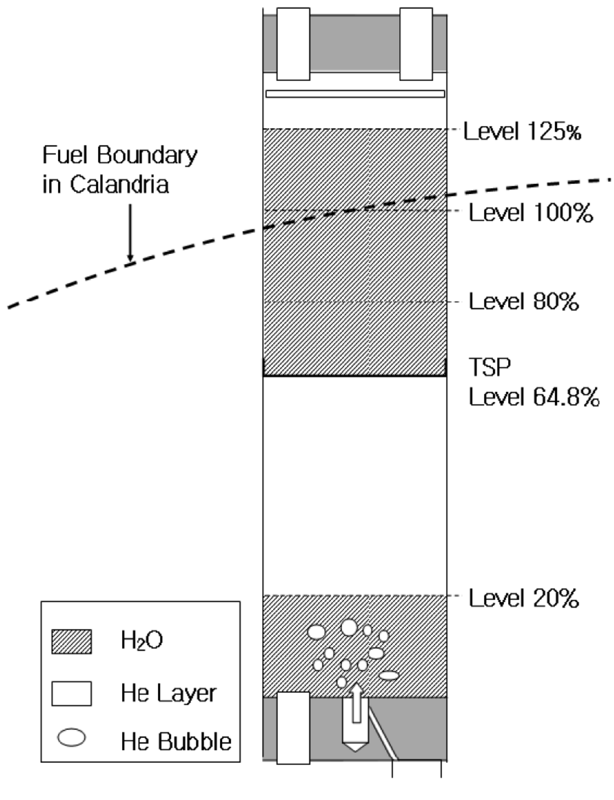

Fig. 6. Relocation of Light Water and Helium

and helium on the assumption that unstable flow of H_2O and helium develops in all compartments.

If abnormality develops within compartments of upper outer zones (#1, 6, 8, 13), H_2O within compartment moves toward the perimeter side, where importance and neutron speed is low and some H_2O stands at the perimeter of reactor core not loaded with nuclear fuel, hampering normal power control and rather increasing power.

On the other hand, if abnormality develops in lower outer zones (#2, 7, 9, 14) and lower central zones (# 4, 5, 11, 12), H_2O moves toward the center of Calandria where importance and neutron speed is high, contributing significantly to power control. When abnormality develops in upper central zones (#3, 10), some H_2O moves beyond the fuel boundary. However, as neutron speed is not significantly lower in outer area of Calandria than in upper outer zones, and abnormality in upper outer and central compartments leads to relocation of H_2O in a manner to impact the power control of upper central zones, power control is deemed to be determined by the existence of abnormality in the compartments of adjacent zones. Therefore, instability rendering normal power control impossible develops mostly in the upper outer zones of Calandria. (Fig. 6)

3.4 Cause of Cycling

Fig. 7 illustrates fluctuation of power output and water level subject to change in the pressure of delay tank in cycling range. Increase/decrease range is small at the beginning of instability, but the amplitude of fluctuation increases over time. The following explanation is valid for such fluctuations of water level. When compressor runs, pressure within compartment drops, causing helium bubble at the bottom of support plate to expand in terms of volume. As helium bubble accounts for more space within compartment, control worth of H_2O will decrease proportionally, resulting in a momentary rise in power. On the contrary, if compressor stops, pressure will rise and bubble area will shrink, causing more H_2O to contribute to power control, increasing control worth of H_2O and leading in the end to power reduction. In addition, if pressure rises by helium compressor, water level rises as well to control such pressure. However, when abnormality has developed within compartment, water level within compartment does not increase above 80% without any significant amplitude. Power (reactivity) decreases gradually over time due to the unique characteristics of nuclear reactor and reactivity control, with compartment water level falling as well. From the moment compartment water level falls below 80%, helium compressor kicks in to increase power. Then, compartment water level rises to 80% again to control power. In other words, water level falls gradually below 80% as local power decreases. But, power output increases and decreases in a cyclic pattern subject to helium compressor operation; water level controlling power output shows the same cyclic behavior as the amplitude of power output between the level subject to gradual reduction of local power and 80%.

Therefore, cycling pattern of local power and compartment water level as a part of instability event is attributable to the intermittent operation (on/off) of helium compressor.

In effect, compartment water level and local power fluctuation disappeared in several CANDU-type nuclear plants in Korea and elsewhere after they changed helium compressor operation mode from intermittent to continuous.

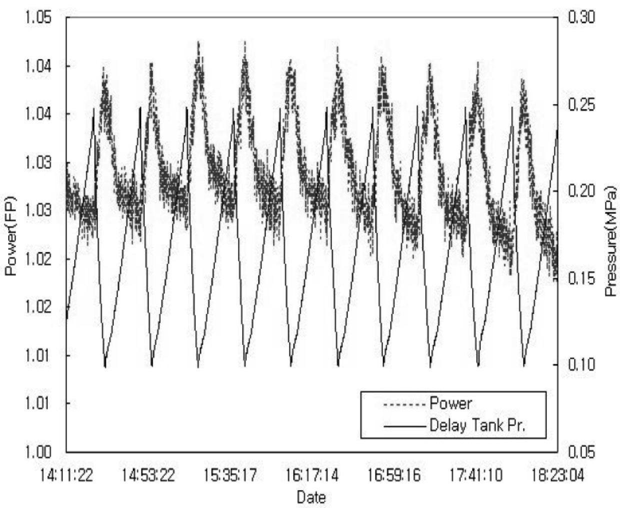

Fig. 7. Power and Delay Tank Pressure in Cycling Range (October 30, 2002, 14:11:22 –18:23:04)

4. EXPERIMENTAL ANALYSIS

4.1 Experiment Description

Previous research into the cause of instability in LZCS concluded that instability develops as H_2O stands on the top of TSP since the flow path of H_2O and helium narrows significantly when H_2O level is at or above TSP. To reproduce such an instability event theoretically, a theoretical model for flow behavior of each liquid within compartment is necessary.

To that end, basic data for calculation of pressure distribution within compartment, in/outflow volume, and remaining volume of liquid are necessary. Therefore, we designed and built a test loop in Fig. 8 and conducted an experiment. First of all, we set the outflow volume of H_2O at the normal volume rating of a nuclear power plant and fixed it so as to maintain H_2O standing above TSP at constant level. Since the flow volume that passes through support plate and falls downward is the same as the inflow volume from the top, flow volume passing through TSP

Table 1. Comparison of Operation Parameters between Experiment and Reactor

		Reactor	Experiment
Availability Flow cross section,(cm^2)		85.24	97.89
Flow	H_2O(l/s)	0.45	0.533~0.9
	Air(l/s)	0.042	0.055~0.065

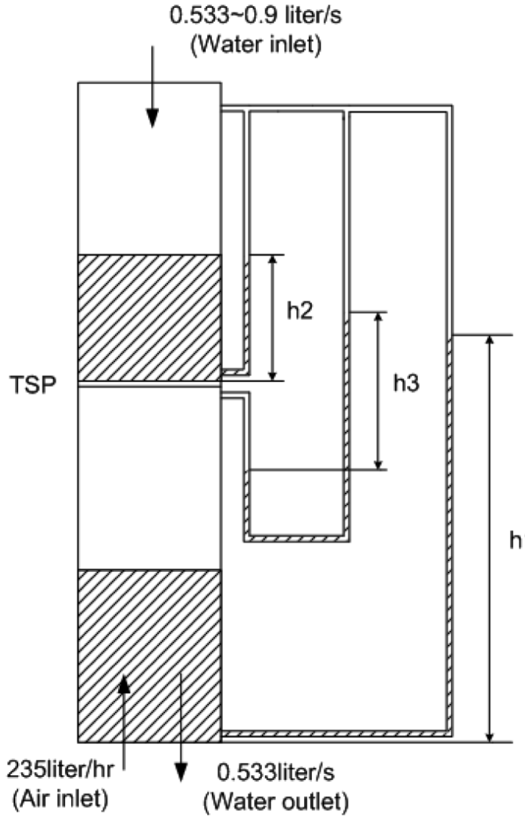

Fig. 8. Test Loop and Compartment

is measured with ease by measuring the H_2O inflow volume from the top (outside). As the pressure inside compartment is also measured, the relationship between flow volume and pressure can be accounted for.

Accordingly, it was proven that the flow path of H_2O and helium narrowing down at TSP was the fundamental cause of the instability event. In addition, a solution that could prevent instability event by widening the flow path of H_2O and helium around TSP was also clarified.

As commercial off-the-shelf acrylic pipe that was closest to the specifications of pipe actually used in a power plant was used to produce a pressurized compartment, the experimental model was slightly different from actual dimensions. (Table. 2).

$A_s/A_e = \dot{m}_s/\dot{m}_e$ Therefore, the flow volume of H_2O and air was adjusted in proportion. Since the gap in area was not significant, flow volume was adjusted in a way to ensure reliability.

4.2 CCFL (Counter-Current Flow Limit) Model

The first and foremost mechanism that merits consideration is CCFL (Counter-Current Flow Limit) of He (air) and H_2O. In other words, He and H_2O form a counter-current flow in a support plate with narrow flow path, limiting the volume of H_2O down flow. As the experiment indicated, when abnormality develops, air stands still at the bottom, failing to pass through support plate, and only H_2O forms the down flow. The Wallis Correlation, which is the empirical formula of CCFL, is $\sqrt{j_g^*}+\sqrt{j_l^*}=C$. C is a value between 0.75-1; air stands still; therefore, $j_g^*=0$ and only j_l^* remains.

On the other hand, C for the experimental conditions herein is 1.0. $j_l^* = j_l\rho_l^{\frac{1}{2}}\left[gd_0(\rho_l-\rho_g\right]^{-\frac{1}{2}}$ is given in theoretical formula and ρ_0 can be ignored as it is very small in

Table 2. Matrix for Experiment

Experiment Matrix		Object	Method	code
Pressure Distribution Experiment	Increase Water Level	Time dependent water level, pressure, flow velocity measurement	Into the zone flow fixing after Instability	AI
	Water level fixing	TSP Top & Bottom pressure measurement	TSP Top water level fixing after Instability	AF
Instability examined experiment		Instability examined at ATM	Measurment pressure 20cm space 50~100cm From TSP Top	B
LZCS experiment		Instability examined at 3bar		C

comparison with ρ_l. Simply put, it is $j_l^* = j_l(gd_o)^{-\frac{1}{2}}$.

In the formula $j^*_1=Q_1/A=V_1A_1/A=(1-\alpha)V_1$ which is Superficial Velocity.

Furthermore, as TSP is formed in one cylindrical flow path in the center and six crescent ones around, equivalent diameter can be used instead. In addition, flow volume passing through TSP is 0.933*l*/s (932.7cm^3/sec). From this value, flow velocity experiment and theoretical formula of H_2O passing through a support plate corresponding to CCFL conditions are 0.26*l*/sec and 0.43*l*/sec respectively.

Comparison of such values with the experimental outcome herein of 0.260m/sec, which is the velocity of flow passing through TSP, reveals a significant gap.

4.3 Verification of the Experimental Results

To predict H_2O distribution within compartment, it is important to determine the volume of H_2O passing through TSP. In addition, Bernoulli's Equation can be applied simply to the mechanism controlling the flow volume passing through TSP, but a correction factor could be applied.

Therefore, control volume to apply Bernoulli's Equation to H_2O standing on the top of TSP is as in Fig. 9, below.

As the above figure illustrates, if applying Bernoulli's Equation between point ① and ②,

as actual value is obtained by multiplying theoretical value with correction factor C,

P_A=101.3kPa, P_C=104.1486kPa for example with water level 30cm,

Actual flow velocity is 0.260m/sec as in Table 3.

The above value is deemed to be very realistic since C is usually between 0.5~0.7.

4.4 Verification of Experiment Outcome

Let us suppose that H_2O and helium flow normally within compartment. When water level rises to 80% in the wake of power increase, inflow H_2O volume, outflow volume and flow volume passing through TSP are all equal.

$Q_{ext}=Q_{in}=Q_{out}$

H_2O outflow volume in terms of CANDU-6 specification rating is 0.45*l*/sec. Due to numerical errors and experiment outcomes of the experiment rig, abnormality did not develop at such flow volume. But, it is our judgment that several errors increase H_2O outflow volume, resulting in abnormality in the end. Therefore, let us assume that the H_2O outflow volume of 0.55*l*/sec is the maximum flow volume passing through TSP, (Q_{in})max.

Supposing that abnormality occurs in the flow of H_2O and helium within compartment and fully develops, H_2O and helium relocate as in Fig. 10. Hence, the relation among flow volumes below TSP then is:

$Q_{He}=Q_{out}-Q_{in}$

Supposing steady status in relation to the above equation, the relation among volumes below TSP is:

$V_{He}=V_{out}-V_{in}$

Abnormality develops since the flow volume of H_2O passing through TSP (Q_{in}) is smaller than the outflow volume of H_2O at the bottom of compartment (Q_{out}). On the assumption that the maximum H_2O flow volume

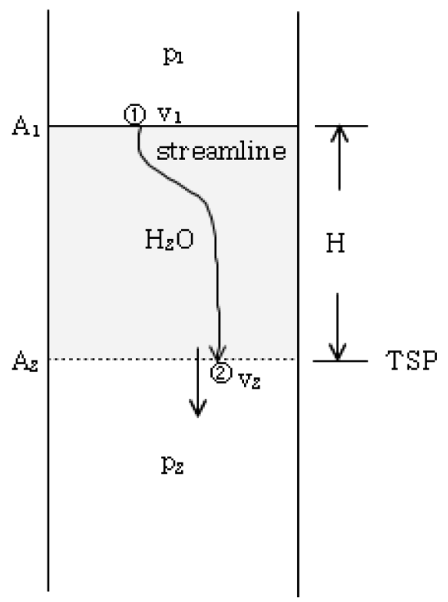

Fig. 9. Control Volume around TSP

Table 3. Results of Experiment & Theory

Water level (TSP Top) (cm)	A-C pressure (Δp, kpa)	$V_{l,th}$ theory (m/sec)	$V_{l,ac}$ Practice (m/sec)	$C\left(\frac{V_{l,th}}{V_{l,ac}}\right)$
30	2.8486	0.260	0.47	0.56
50	4.8181	0.260	0.44	0.59
70	6.7808	0.260	0.44	0.59
90	8.7526	0.260	0.40	0.65
110	10.6902	0.260	0.46	0.57
Ave.(C_{av})				0.59

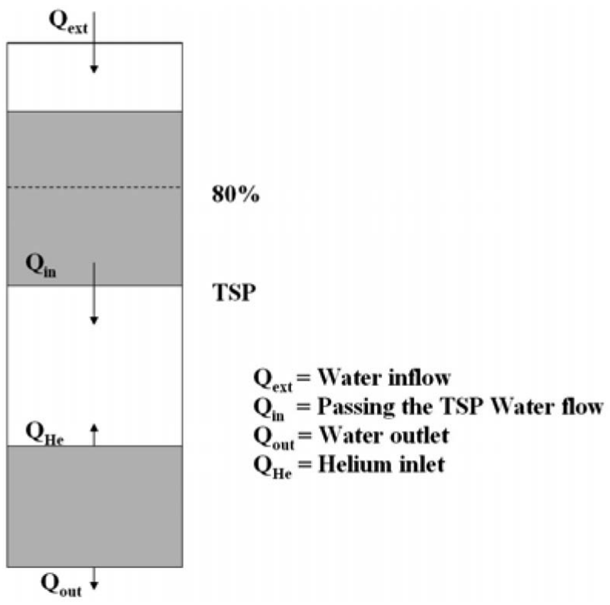

Fig. 10. Relocation of Water & Helium

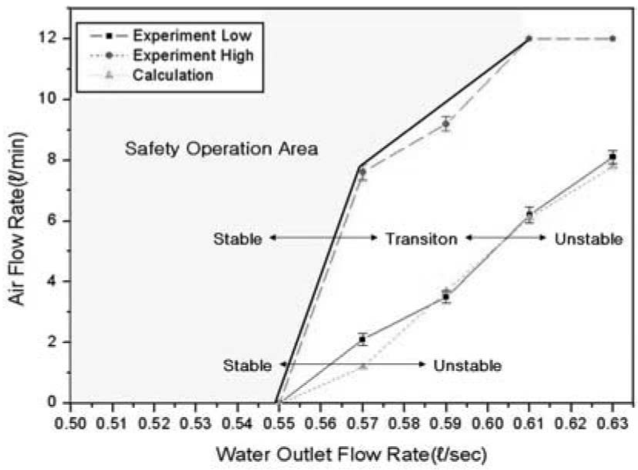

Fig. 11. Abnormality Pattern Map

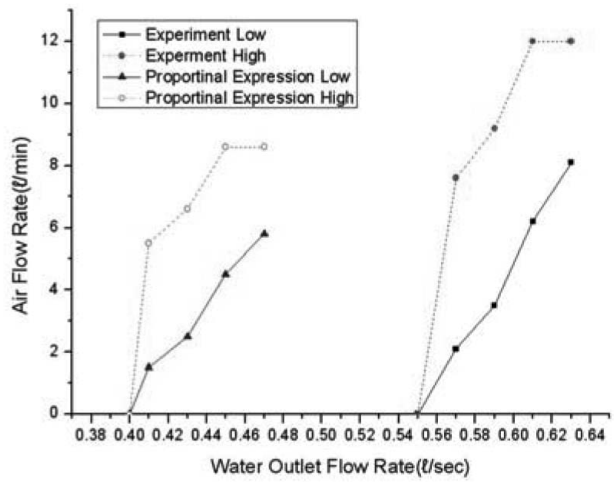

Fig. 12. Abnormality Pattern Map for Improved TSP Design

Table 4. Comparison of Parameters

	Experiment	Reactor	etc
Flow Cross section	$40.67cm^2$	$29.24cm^2$	
Water Outlet	$0.55l/s$	$0.40l/s$	

passing through is $0.55l$/sec or (V_{in}) max=$0.55l$/sec, for abnormality to develop, V_{out}-(V_{in}) max>0 must be true. In addition, if the volume of H_2O in short below TSP is greater than the volume of helium, helium passes through TSP and abnormality does not develop. Therefore, as the 2nd condition for abnormality to develop, $V_{out}-(V_{in})max \geqq V_{He}$ must be true. In short, for abnormality to develop, in the relation applicable to flow volume below TSP or $Q_{He}=Q_{out}-Q_{in}$, both $Q_{out}-(Q_{in})max>0$ and $Q_{out}-(Q_{in})max \geqq Q_{He}$ must be true. We applied the experimental value of H_2O outflow volume (Q_{out}) and helium inflow volume (Q_{He}) to the above instability determination formula and performed calculation. As for comparison between experimental outcomes and calculation outcomes from determination formula, Fig. 11 superimposes calculation outcomes over the instability map based on experimental outcomes.

In the comparison, experimental outcomes and calculation outcomes are considerably similar to each other in terms of abnormality development within compartment at the same helium (air) inflow volume and H_2O outflow volume. Therefore, the experimental outcomes are found to be feasible.

The comparison between experimental outcomes herein and calculation outcomes of determination formula has revealed that conditions in Fig. 11 are necessary to ensure operation in a steady state.

We installed pressure gauges at Points A, B, C, C`, D as in Fig. 11, pressurized at 3bar, and obtained the following experimental outcome.

The experimental outcome was not significantly different from the outcomes of pressure distribution experiment at atmospheric pressure, but the above experiment was significant in that it simulated the actual operational conditions of power plant.

From a proportional expression including the gap between actual power plant and experiment rig in reference to the above flow cross-section and H_2O outflow volume, we derived the following data (as in Fig. 12).

4.5 Instability Event Improvement Experiment

When we used TSP with 10% wider flow path (Fig. 16), abnormality that appeared in the existing TSP did not develop even at the same H_2O outflow volume and helium inflow range, which proves that narrowing of H_2O and helium flow paths through TSP is the fundamental cause of instability, and that increasing the flow path of H_2O and helium in TSP can prevent instability from developing.

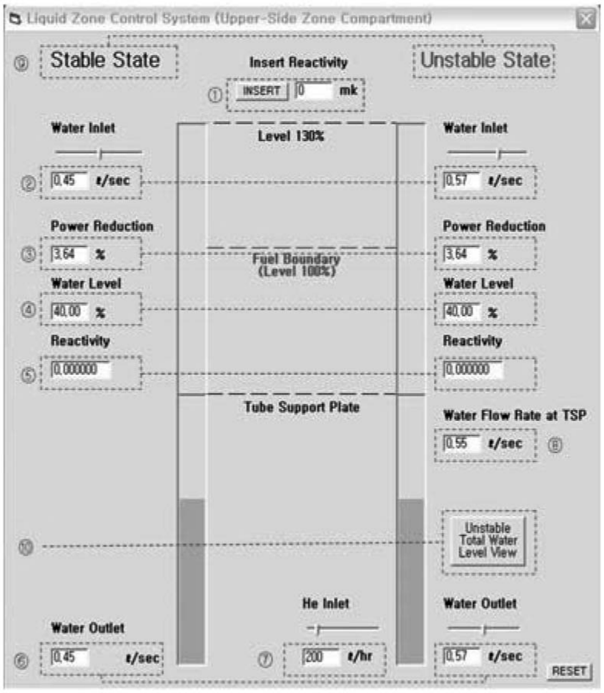

Fig. 13. Program Interface

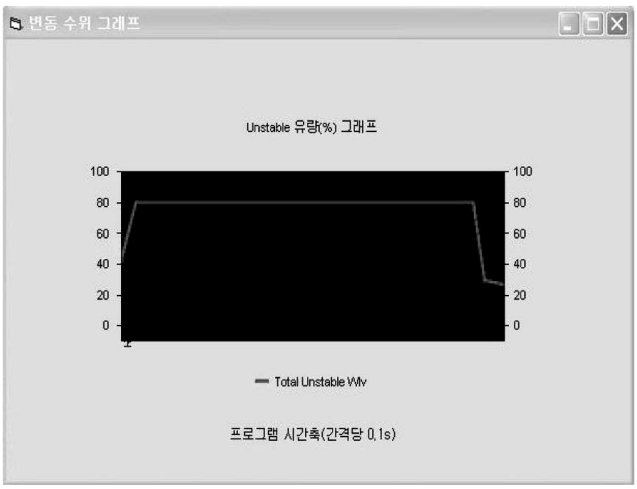

Fig. 14. Simulation Result

5. PREDICTION MODEL DEVELOPMENT

5.1 Prediction Model

The following program is a prediction model for overall instability event in LZCS of CANDU-6 nuclear reactor that develops a theoretical model reproducing a hydraulic instability event with experimental outcomes and basic thermal liquid equation and links the outcome to RFSP. As it is possible freely to adjust H_2O outflow volume and helium inflow volume, the above mapping and the instability event prediction model will be highly instrumental in verifying adequate operation range and evaluating safety in response to permit/authorization request.

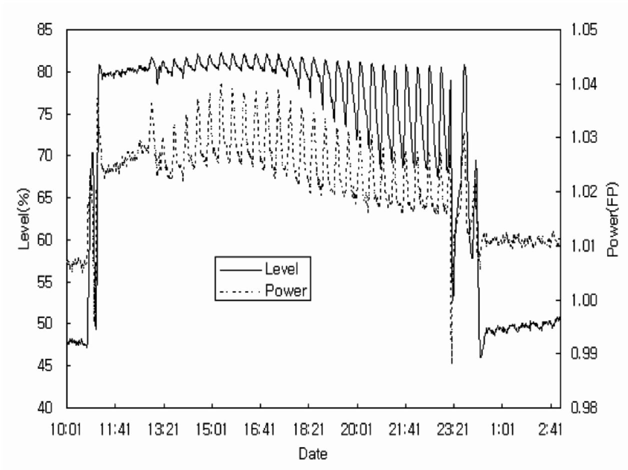

Fig. 15. Fluctuation of Compartment Water Level and Power Following G19 Channel Refueling in the Wolsong Reactor 2 October 30, 2002 10:00–October 31, 2002, 02:48

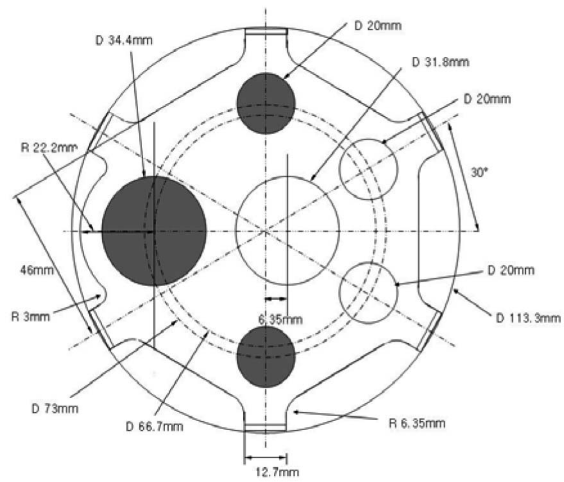

Fig. 16. TSP Increased 10% of Net Flow

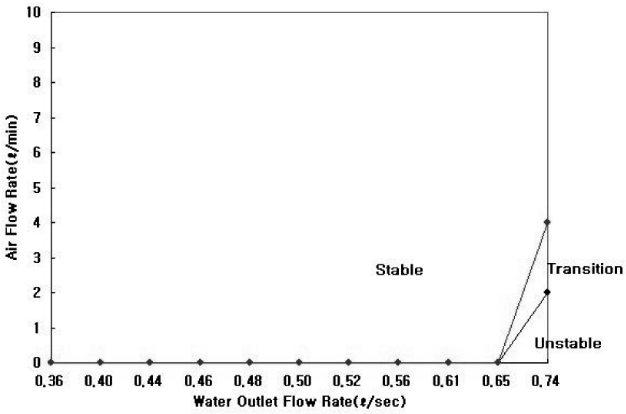

Fig. 17. Stable Area TSP increased 10% of net flow Experiment

5.2 Prediction Model Trial

Abnormality developed over about 16 hours in actual power plant. However, we set the time to about 5 minutes to expedite experiment outcome in the program. Comparison between the compartment water level and local power output fluctuation graph following G19 channel refueling in Wolsung Reactor 2 (Fig. 15.) and the simulation outcome (Fig. 14) indicates similar behaviors. Oscillation in Fig. 15 is due to the operation of compression pump; future program upgrades will include addition of oscillation effect.

6. CONCLUSION

After studying the cause of instability (sudden rise in power output and water level which went on over time before dropping abruptly) within LZCS that developed frequently after nuclear refueling in CANDU-6 reactor, we arrived at the following conclusions.

6.1 Cause of Instability Event

Following is the fundamental cause of instability frequently developing in CANDU-type reactor or the cycle of sudden rise in LZCS compartment water level and local power output and abrupt drop.

Narrow flow path in TSP intended to prevent liquid-induced vibration of H_2O and helium pipes running through compartments hampers the flow of H_2O and helium within compartment, causing helium layer to form below TSP and H_2O to stand on the top and disrupting normal power control.

6.2 Improvement Suggestions for Prevention of Instability

Instability event in LZCS is an abnormality of control system attributable to hydraulic abnormality of LZCS. If it is possible to prevent such instability, fluctuation and sudden drop of compartment water level and local power output will not happen.

Therefore, we suggest two ideas to prevent instability.

First, it is practically impossible to modify facilities directly in case of nuclear power plants currently in service. Therefore, instability can be prevented by maintaining H_2O outflow volume and helium inflow volume within the steady range suggested in the map of Fig. 16.

Second, since it is possible to improve facilities from ground up in case of new reactors under construction or power plants undergoing Calandria replacement, H_2O and helium flow paths in TSP can be expanded.

Of course, several verification processes, such as stability analysis, must be performed in advance to apply suggested improvement approaches to nuclear power plants actually in operation.

6.3 Pressurized State Verification Test

System test in pressurized state yielded the same outcome as the previous experiment conducted at atmospheric pressure.

6.4. Theoretical model & simulation program

Theoretical model for inside of compartment, RFSP and experimental outcomes were aggregated to develop a program simulating the abnormality event within LZCS; the accuracy and applicability of the program was verified in a trial simulation.

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