LIQUID ZONE CONTROL SYSTEM INSTABILITY TEST PROGRAM

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Abstract

CANDU® operators have observed occasional reactor control instabilities that are clearly linked to the operation of the Liquid Zone Control System. AECL has undertaken a program to take a comprehensive look at system experience and focus on the root cause of the instabilities. A full-scale experimental program covering a range of representative flows, temperatures and gas densities was undertaken to define the nature of the instability and test design fixes. This work confirmed that support plate restrictions lead to instability and defined the range of conditions. It has led to an improved plate design that has sufficient open area to avoid water "separation". It can be considered in new stations or refurbishment projects.

1. Introduction

A number of operating anomalies with the Liquid Zone Control (LZC) System (LZCS) in CANDU® reactors have been observed. The most notable have occurred in CANDU® reactors of more recent vintage. When reactivity in the CANDU® reactor is disturbed after refueling, the water level in the liquid zone control system in the top reactor region sometimes shows local instability if the initial water level in the compartment is 50% or higher. This phenomenon has been experienced at Darlington Units 3 and 4, Wolsong Units 2,3 and 4 and most recently at Qinshan Units 1 and 2.

Liquid hold up on the Tube Support Plate (TSP) and creation of gas void below the plate has been suggested as a possible cause for the observed instabilities [1]. A more recent paper [2] identifies the holdup of liquid light water on top of the TSP and the creation of gas void below the plate, observed under the experimental conditions, as the key-contributing factor of instability. It also proposed an increase in the perforation area available for counter-current gas liquid flow in the TSP as a potential solution to the water column separation under LZCS operating conditions.

The water column separation (WCS) phenomenon appears to be associated almost solely with the uppermost LZC Compartments (LZCCs) in 2-zone LZC Assemblies (LZCAs). The same phenomenon has not been reported for lower LZCCs and rarely for the top LZCCs in three-zone LZCAs.

A review of operational experience associated with the LZCS suggests WCS as the major cause of instability. A detailed experimental investigation of LZCS operation has not been performed in the past and the cause of WCS is not well understood. The focus of this study, part of a multidiscipline team effort including designers and system analysts, is the hydrodynamic phenomena related to WCS at the TSPs.

2. Background

2.1 System description and function

The primary means of reactivity control in CANDU® reactors is the LZCS. The LZCS is based on adding negative reactivity to the core by varying the amount of a neutron absorbing material, namely light water, in LZCCs. A reactor face (end) view of the zones and LZCAs is shown in Figure 1. The in-core part of the system comprises six LZCAs divided into fourteen compartments, which correspond to the fourteen zones within the reactor. The compartments are filled with and drained of demineralized light water either independently (to control the neutron flux spatially) or simultaneously (to control the bulk neutron flux). Functional requirements of the liquid zone control include:

- Providing bulk and spatial reactivity control,
- Removal of heat from the compartments (via a heat exchanger external to the core),
- Purification of LZC water by ion-exchange, and
- Providing radiation shielding to the top of the reactor

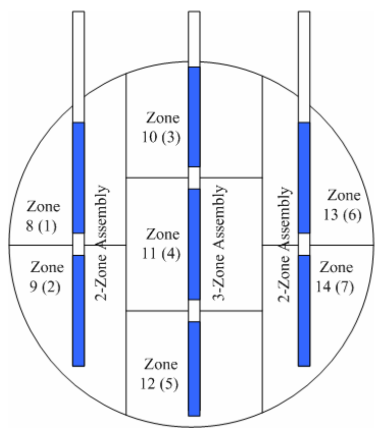

Figure 1: Face View of the Zones and Zone Controllers.
(Zones at the other end are numbered in brackets)

The LZCAs have multiple tubes within each assembly (either 2-zone or 3-zone) to provide inlet and outlet pathways for light water and helium. To reduce the number of individual tubes running through the assembly, some of the fluid pathways are tube-in-tube designs (thus minimizing the number of perforations along the cross section of the assembly, at the top and bottom of the assembly, and the bulkheads). To minimize vibrations and fretting of the tubes, a TSP is installed in each zone at 60% of the zone height.

A simplified schematic of the LZCS is shown in Figure 2. Figure 2 also shows the typical arrangement of a LZCC. The LZCCs range in size from 18 to 29 L. The controlled range of reactivity from all compartments (from all empty to all full of light water) is about 7 mk. The outflow of water from the compartment bottom is maintained at a constant value of 0.45 L s^{-1} while inflow of water from the compartment top is regulated between 0 and 0.9 L s^{-1}. When the water inflow to the compartment is equal to water outflow, the level of water in the compartment remains unchanged. The level of water rises when the inflow of water is greater than the outflow of water or falls when the inflow is smaller than outflow. The rate of level change in LZCCs permits a maximum reactivity rate of approximately ±0.14 $mk.s^{-1}$.

The space above the light water in a LZCC is pressurized with helium gas to maintain a constant outflow of water from the compartment. The light water outflow is maintained constant (0.45 L s^{-1}) by regulating actions of the feed and bleed control valves to maintain the pressure difference between the top of the LZCC and the delay tank constant at 300 kPa. The pressure in the LZCC is controlled by injecting helium gas at the bottom and removing it at the top of compartment. Water flows downwards while helium gas flows upward, countercurrent to the water flow.

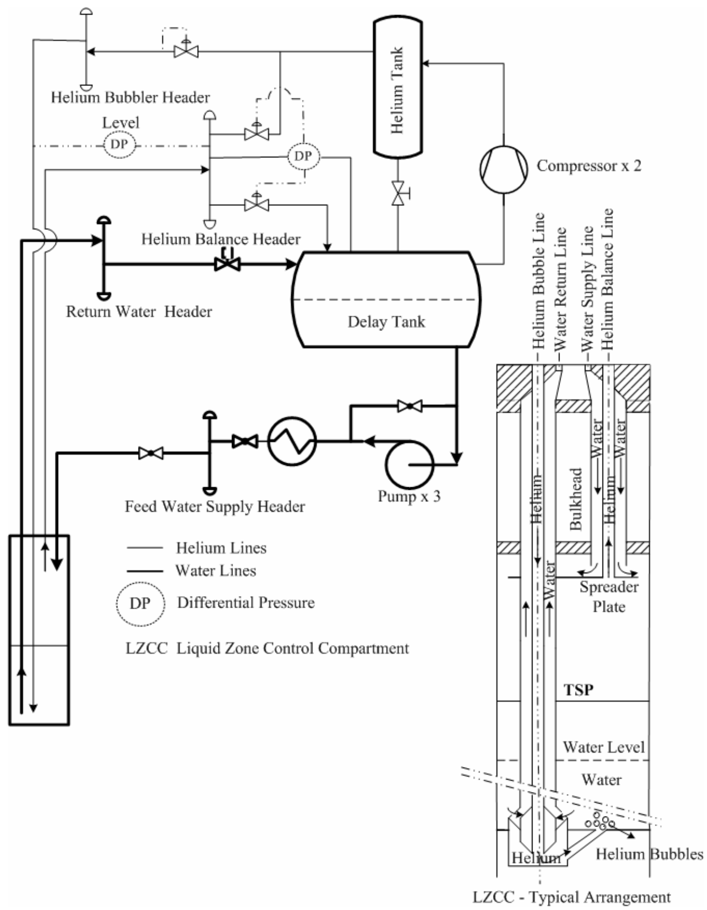

Figure 2: Simplified Schematic of LZCS

2.2 Operating experience

An assessment of all reported operational events on this system, across the CANDU® reactor fleet, was carried out. The distribution of events was organized into two distinct categories: events concerning level control and instabilities (Figure 3), and events unrelated to level control and instabilities. It should be noted that the available OPEX came principally from Canadian NGSs. As such, the flooding phenomenon seen in Wolsong 2/3/4 and Qinshan 1&2 is underrepresented in this analysis.

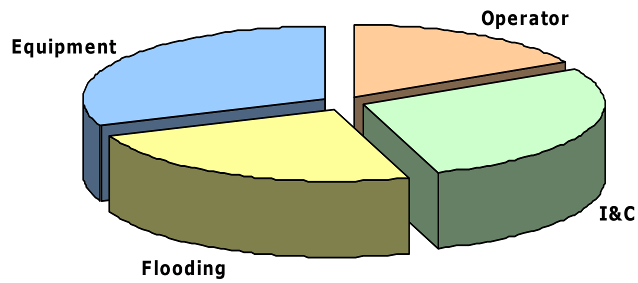

Figure 3: Distribution of LZCS Operating Events

Other than operator errors or specific equipment problems (e.g., gas compressors), it was found that the majority of problems were directly or indirectly associated with column separation (sometimes called 'flooding'). This leads to the subject test program with a focus on hydrodynamic effects surrounding the tube support plate.

2.3 Design Requirement for the Tube Support Plate

The test program was intended to assess not only the current design but alternatives that would eliminate the problem. Prior to considering new design options, it was necessary to revisit and rethink a complete set of design requirements for support plate. These include:

- Capable of minimizing vibration of the internal tubes. Fretting caused by internal and external flows shall be minimized or eliminated.
- Allow passage of gas and liquid phases with minimal pressure drop
- Structurally strong enough to handle static and dynamic pressure differentials from flow streams or impingement loads.
- Materials compatible with other reactor internal components (eg, not susceptible to corrosion, minimal effect on reactivity, resistant to embrittlement by nuclear hardening) and have comparable design life.
- Ability to withstand all conditions (temperature, pressure, seismic) that the overall compartment must meet.
- Easy to install, assemble or retrofit and require little or no maintenance and inspection.
- Without sharp corners or protrusions that can pierce or damage assembly components.
- Tolerant of thermal expansion and creep of zone assemblies during transient conditions.

These restrictions required the test program to focus on the current plate design and modest modifications to the plate, which would not challenge the aforementioned requirements. If a satisfactory solution was not determined contingency plans would have us look at more substantive modifications. These include plate elimination or relocation and radical redesign such as bubble caps or a conical shape or an annular perforated plate. The latter concepts were intended to divert the water to the wall and maintain a clear central passage.

3. Experimental program

3.1 Test set-up

An experimental program was defined to investigate the hydrodynamics of gas-liquid, counter-current, two-phase flow through the TSP. An assessment of the expected hydrodynamics in an LZCC was done to define the experimental parameters and test conditions.

The test column is a full-scale replica of the two-phase flow region in the top zone of a 2-zone LZCA. It was fabricated from Plexiglas® to ensure that all phenomena that are taking place at the TSP during the experiments can be visually observed and recorded. The test equipment was designed specifically to investigate the two-phase flow phenomena through the TSP. The experimental set-up was also designed to investigate different TSPs and the test-column design ensured easy replacement of the TSP during the test campaign. Dummy tubes were used inside the test column to simulate helium and water carrying lines inside the top LZCC in a 2-zone LZCA. Experiments were performed, according to the hydrodynamic assessment, over a range of flows, temperatures and gas densities to cover the full range of relevant conditions in the real LZCA.

The test set-up is shown in Figure 4, schematically, along with a photograph of the installed column. Also shown is a schematic of the TSP (TSP #1) used in the top zone of a 2-zone LZCA. The test set-up essentially consisted of a recirculating-water circuit and a once-through gas system. The water was fed from the top of the test column and drained from the bottom while gas was fed from the bottom of the column and vented through the top. Water flows were measured and controlled appropriately as shown. The water temperature was adjusted using an immersion heater in the tank and measured at the top column feed point. The gas feed flow was controlled near the feed point and volumetric flows in this paper are referenced to 21°C and 101.3 kPa(a). Differential pressure measurements allowed separate measurements of the water level above and below the TSP. A video camera was installed outside of the test column at the level of the TSP to record the gas-water countercurrent flow through the TSP.

3.2 Experimental tests

The tests consisted of identifying the gas and liquid flow rate conditions necessary for onset of water column separation (OWCS). In these tests, the differential water flow rate (inlet-outlet) was maintained constant at ~5 $L.min^{-1}$ (constant rate of rise of the water level). The tests were carried out as a function of the inlet water flow rate, in the range 0 to 80 $L.min^{-1}$, and in the gas flow rate range 0 to 20 $L.min^{-1}$.

The objective of these tests was to develop WCS curves for different TSP designs, investigate the effects of parameters such as temperature, initial water and gas distribution and gas density (He and Air). Six different TSP designs were tested. The TSP designs tested allowed for investigating the effect of the shape of perforations in the TSPs and the total perforation area on WCS.

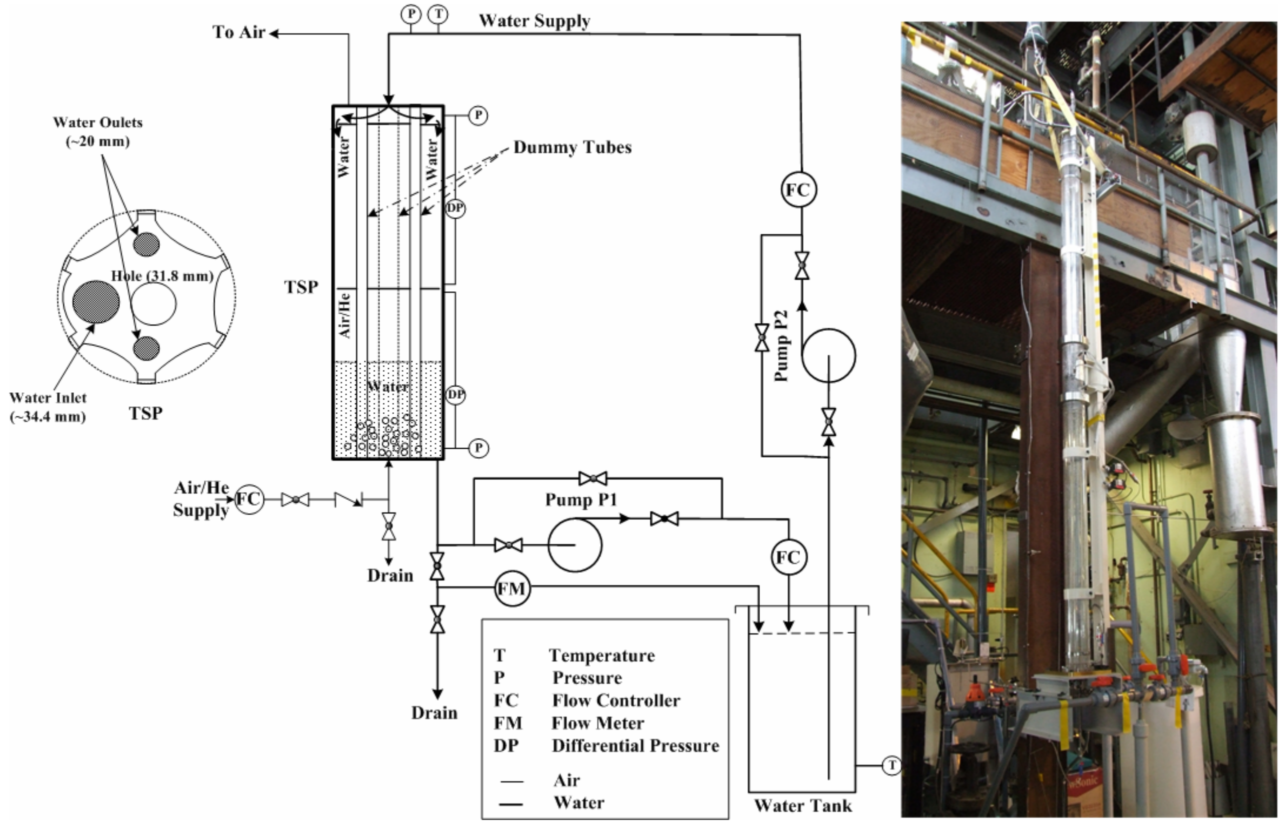

Figure 4: Schematic of the Experimental Set-up

4. Results

The WCS curves obtained for the air-water system with TSP #1 at ambient temperature (29 - 34ºC), are shown in Figure 5. The data are plotted as a function of the outlet water flow rate. WCS occurred only when the water level was above the TSP. This was found to be a necessary condition for WCS to occur. During WCS, defined by the formation of an air column below the TSP, water continues to flow through the TSP while arriving air bubbles coalesce and become stratified below the TSP. Under certain conditions, the air gap remains stable and continues to grow with time. Under these conditions, no gas bubbles ever pass through the TSP. This condition is termed "complete separation" in the text. This condition is shown in Figure 6 (photograph taken during complete WCS). Under some conditions, the air gap becomes unstable with the appearance of secondary bubbles that escape primarily through the perforations in the periphery of the TSP. This condition, at times, was also observed to lead to the collapse of the air column with subsequent re-formation. The highest values of air and water flow conditions that lead to WCS without complete separation were treated as upper-bound conditions for OWCS and these points are represented by Curve 1 in Figure 5. The highest values of air and water flow conditions leading to complete separation were treated as upper-bound conditions for complete separation. Curve 2 in Figure 7 represents these data. Complete WCS characterizes the region below Curve 2.

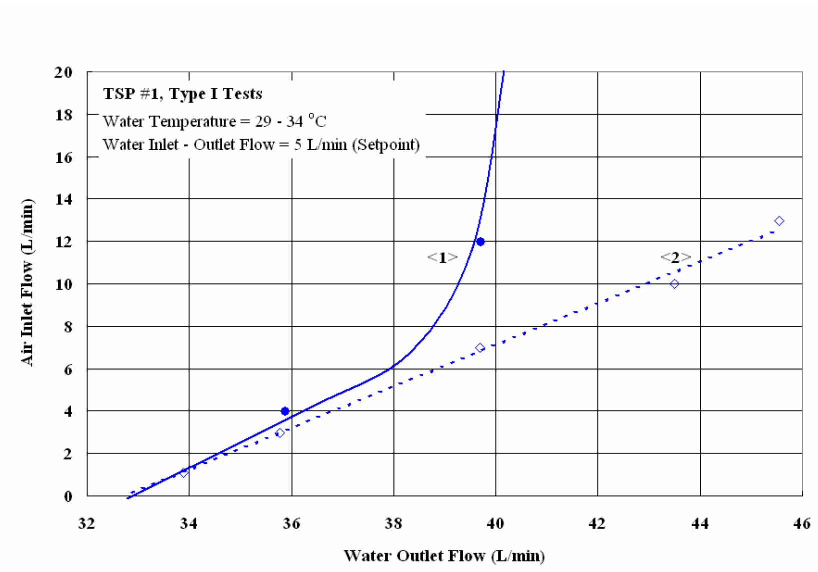

Figure 5: Water Column Separation Curve Obtained with TSP #1

The two curves (Curves 1 and 2) merge at low flow rates. The point of intercept of these curves with the “X” axis at zero airflow defines the minimum water flow rate required for OWCS. This value can be found from the linear plot to WCS data with complete separation. This point represents a key parameter that defines the boundary between WCS-free and WCS conditions. The experimentally-observed WCS characteristics are shown schematically in Figure 7. As Figure 7 shows, Region A (the region left of the point of minimum air flow rate required for OWCS) is WCS-free under all operating conditions (air and water flow rates) tested. Under operating conditions to the right of Region A the system is prone to WCS. This region can be further subdivided into a transition region (Region B) and WCS region (Region C). In Region B, Curve 1 defines the boundary between WCS-free and WCS conditions. Under conditions to the right of Region B (Region C), WCS-free operation is not possible.

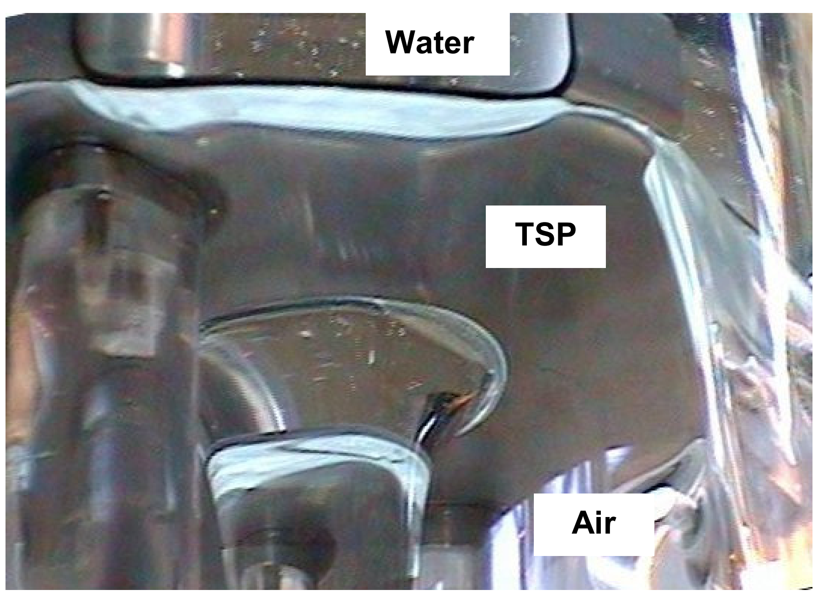

Figure 6: Complete Water Column Separation

As Figure 5 shows, for TSP #1, the minimum outlet water flow rate required for OWCS was observed at ~33 L.min^{-1}. Below this water flow rate, WCS was not observed in the airflow-rate range 0 to 20 L.min^{-1}.

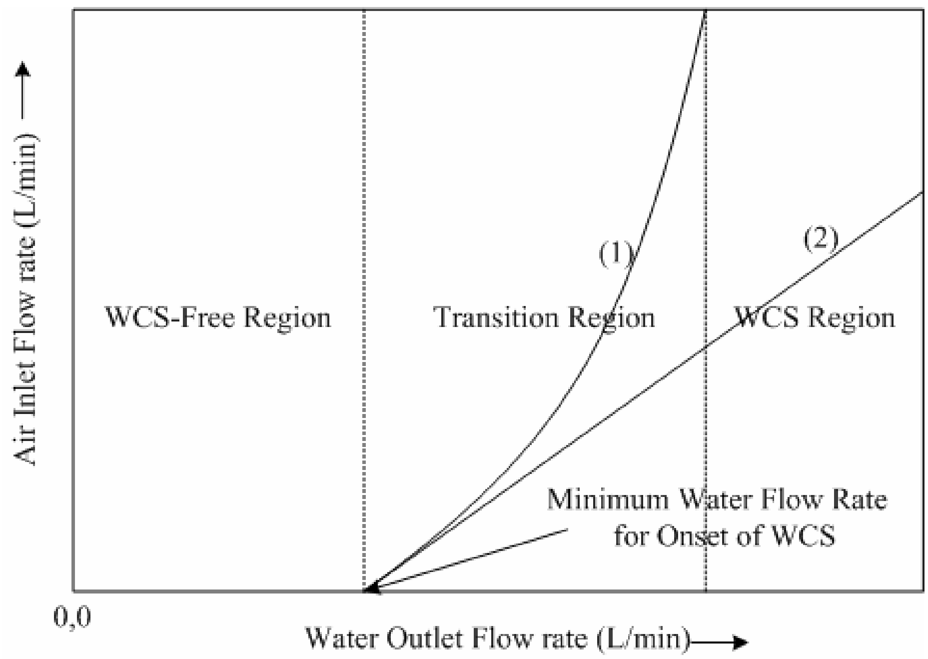

Figure 7: Water Column Separation Curves

Some tests were done using a variable difference between inlet and outlet flow similar to the method in reference [2]. No difference was observed.

4.1 Effect of temperature

Temperatures between about 27 and 50°C were found to have no effect on the WCS curves.

4.2 Effect of inlet water and gas distribution

The effect of inlet water distribution was investigated using a spreader plate arrangement that preferentially channelled the water flow down only one side of the LZC tube. This was found to have no effect on the WCS curves. It appears that once the liquid level is above the TSP, which is a necessary condition for WCS to occur, flow of liquid and gas through the TSP is unaffected by the manner in which the liquid arrives at the surface of the liquid.

Three gas injectors were tested, each designed to produce a different range of bubble sizes. Under the test conditions, no difference between the WCS curves for the three gas distributors was observed.

4.3 Effect of gas density

The effect of gas density on WCS was investigated using helium and air. These two gases allowed observation of any trends in the gas density range 0.16 to 1.17 $kg.m^{-3}$. A discernible effect of gas density on the WCS was not observed with He-water and air-water systems.

4.4 Effect of perforation shape

The effect of perforation shape on WCS was investigated using three different TSPs (TSP #1, TSP #4 and TSP#5) with different perforation geometries but similar perforation area. The perforation shape was found to have little effect on WCS

4.5 Effect of perforation area

The effect of perforation area on WCS was investigated using four different TSPs (TSP #1, TSP #2, TSP #3 and TSP #6). Three TSPs (TSP #1, TSP #2 and TSP #6) have circular perforations with different areas. An open-structure TSP design (TSP #3) approaches closest to an obstruction-free (95% open area) configuration for gas-liquid flow. WCS was not observed for TSP #3 under the experimental conditions tested.

Figure 8 shows the WCS curves obtained for three TSPs (TSP #1, TSP #2 and TSP #6). The minimum outlet water flow rate required for OWCS was found to increase with increasing perforation area in the TSP, increasing the WCS-free operating region with increasing perforation area. Figure 9 shows a plot of the TSP perforation area against the minimum outlet water flow required for OWCS for all TSPs tested, indicating that the minimum outlet water flow rate required for OWCS is directly proportional to the perforation area.

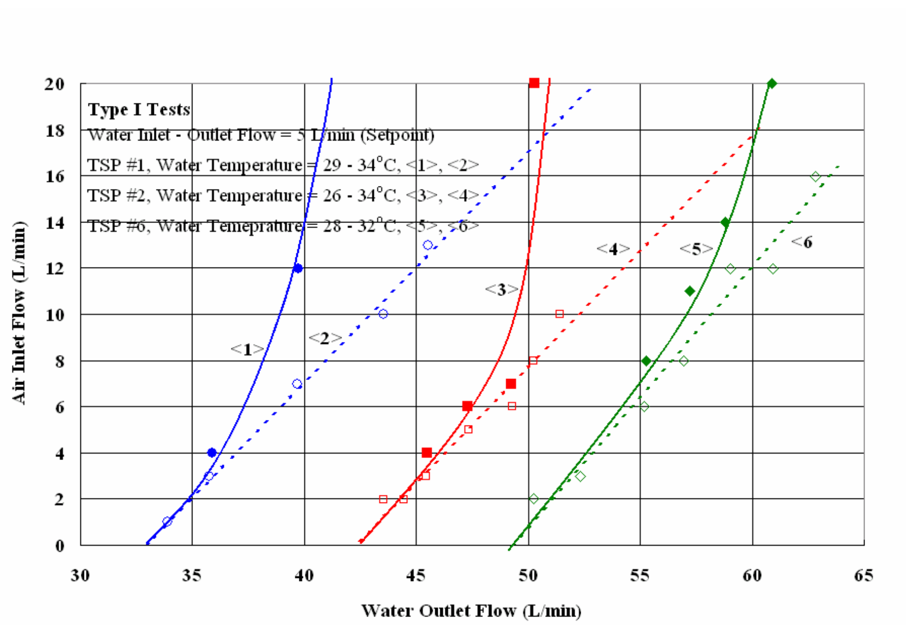

Figure 8: Effect of Perforation Area on WCS

Figure 10 shows a plot of WCS data, in terms of superficial velocities of air and water through the TSP. The superficial velocities were calculated assuming that the total perforation area is available for both air and water flows. This figure was constructed using only the data representing the upper-bound conditions for complete separation for TSP #1, TSP #2 and TSP #6 and a straight line appears to fit the data well. This plot represents a generalized curve representing all TSPs for complete separation. The correlations shown in Figures 9 and 10 can, therefore, provide a means of estimating the minimum outlet water flow rate required for OWCS for any given TSP.

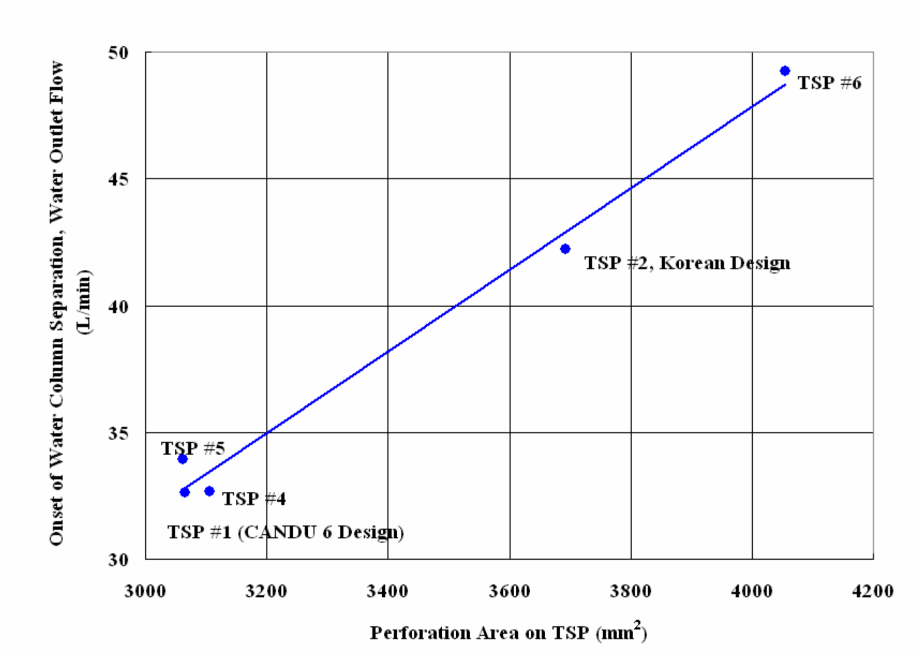

Figure 9: Effect of Perforation Area on OWCS

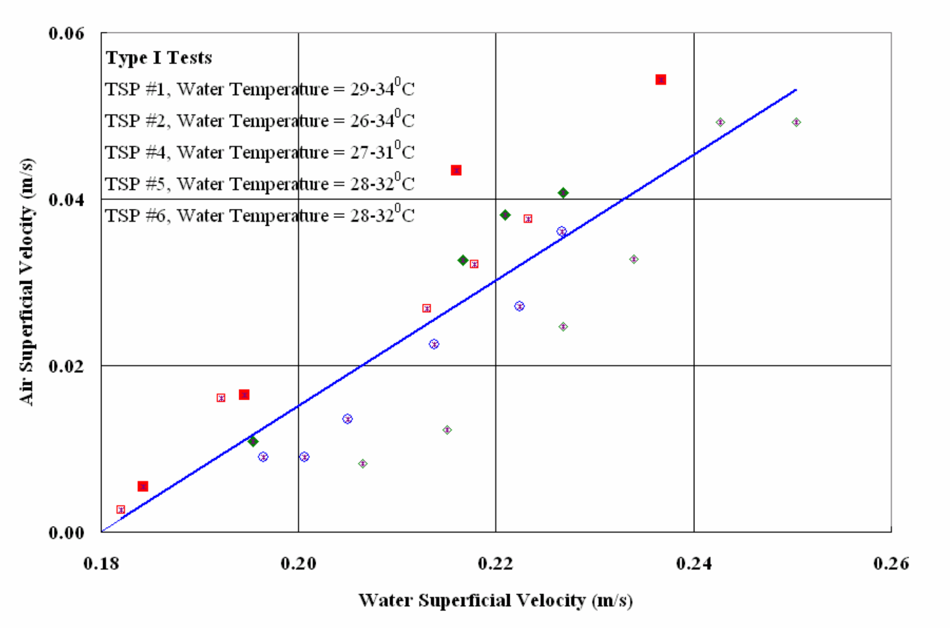

Figure 10: A Generalized WCS Curve for Complete Separation

5. Related Work

While the test rig is full scale and can reproduce a full range of flow conditions, a limitation is the extent to which the dynamic system behaviour can be represented. The actual LZC in an operating reactor is always responding to signals from the Reactor Regulation System (RRS) to provide fine control of bulk and spatial reactivity. This information is updated typically every 0.5 seconds for bulk power control and every 2 seconds for spatial control.

In order to optimize system performance and have the ability to track normal and abnormal transients AECL is developing dynamic control system simulation. Given the region of instability defined by the subject experimental program, the transient analysis will enable us to optimize the control system in order to avoid or alert the operator to the region of instability.

6. Conclusions

From a design perspective, even though we were focussing on a specific component part, it was valuable to prepare a complete set of design requirements prior to testing new designs.

An understanding of the conditions necessary for WCS in LZCCs was obtained from the experimental program. Under certain gas-water flow conditions, the WCS phenomenon was observed when the water level was above the TSP. The TSP provides a restriction to counter-current gas flow through the TSP when the water level is above the TSP. At sufficiently high liquid flows, WCS occurs as a result of stratification of gas at the TSP. This decreases the upper zone's ability to add negative reactivity since water is added at the top of the compartment, outside of the core.

Parameters such as temperature, initial distribution of gas and water, and density of the gas on WCS were found to have no effect on the observed WCS phenomenon. The only parameter that affects WCS was found to be the area available in the TSP for counter-current gas-water flow. The minimum water flow rate required for OWCS was found to increase with increasing perforation area, increasing the WCS-free operating range of gas-water flow rates. The best performing plate (TSP #6) is a simple modification. It meets specified design requirements while allowing 43% more flow before the onset of instability.

Two generalized correlations were obtained that can be used to predict the minimum outlet water flow rate required for OWCS for any given TSP. This offers the possibility for designing a suitable TSP with sufficient open area for gas-liquid flow to avoid WCS phenomenon over the expected range of flows encountered during LZCS operations.

7. References

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8. Acknowledgements

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