

## **Assessment of Leak Detection Capability of CANDU 6 Annulus Gas System Using Moisture Injection Tests**

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### **Abstract**

The CANDU 6 reactor assembly consists of an array of 380 pressure tubes, which are installed horizontally in a large cylindrical vessel, the Calandria, containing the low pressure heavy water moderator. The pressure tube is located inside the calandria tube and the annulus between these tubes, which forms a closed loop with CO<sub>2</sub> gas recirculating, is called the Annulus Gas System(AGS). It is designed to give an alarm to the operator even for a small pressure tube leak by a very sensitive dew point meter so that he can take a preventive action for the pressure tube rupture incident. To judge whether the operator action time is enough or not in the design of Wolsong 2, 3 & 4, the Leak Before Break(LBB) assessment is required for the analysis of the pressure tube failure accident. In order to provide the required data for the LBB assessment of Wolsong Units 2, 3, 4, a series of leak detection capability tests was performed by injecting controlled rates of heavy water vapour. The data of increased dew point and rates of rise were measured to determine the alarm set point for the dew point rate of rise of Wolsong Unit 2. It was found that the response of the dew point depends on the moisture injection rate, CO<sub>2</sub> gas flow rate and the leak location. The test showed that CANDU 6 AGS can detect the very small leaks less than few g/hr and dew point rate of rise alarm can be the most reliable alarm signal to warn the operator. Considering the present results, the first response time of dew point to the AGS CO<sub>2</sub> flow rate is approximated.

### **1. Introduction**

The Canada Deuterium Uranium(CANDU) 6 reactor utilizes the pressure tube concept and uses natural uranium dioxide fuel and heavy water for both heat transport system and moderator system,

as compared to Pressurized Water Reactor(PWR). The reactor consists of an array of pressure tubes, which contain reactor fuel bundles and are installed horizontally in a large cylindrical vessel, the Calandria, filled with low pressure heavy water moderator[1]. The coolant, passing through the

pressure tube at temperatures between approximately 250°C and 300°C, is pressurized to approximately 10 MPa[2]. Each pressure tube is surrounded by the calandria tube and the annular space between these tubes is filled with dry carbon dioxide in order to reduce heat transfer from the primary coolant to the moderator. The dry carbon dioxide in the annulus gas system, is circulated by one or two compressors to improve the leak detection capability and prevent corrosion in fuel channel components as compared to stagnant AGS.

In early CANDU reactors such as Pickering Unit 3 and 4 and Bruce Unit 2, some pressure tubes have failed due to delayed hydride cracking(DHC) [3-4]. Most of these failures initiated at a rolled joint due to high residual stresses, which remained from improper rolling procedures. It was recognized that more deuterium might ingress into the pressure tube at the rolled joint and hydride precipitation caused by deuterium diffusion inboard might cause DHC in the high stress region of the rolled joint at reactor operating temperatures. Predicting deuterium buildup in the rolled joint region was found to be essential to assure reliable plant operation.

The structural integrity of the pressure tube is assured by applying conservative criteria for the initiation of DHC. The presence of moisture in the AGS indicates that a crack may be present in the pressure tube. If a crack develops in a pressure tube at a rolled joint, unstable crack propagation can be avoided by the application of LBB, which requires that: (a) the crack length at wall penetration be less than the critical crack length(CCL) for unstable propagation, (b) the leak is detected and (c) appropriate operator action is taken before the length of the growing DHC crack exceeds CCL.

The LBB concept has been developed for CANDU nuclear reactors as a defence in depth for

unstable, catastrophic pressure tube rupture [5]. The LBB concept requires timely detection and confirmation of a leak, appropriate operator intervention to shutdown, cooldown and depressurize the reactor before the crack length exceeds the critical crack length(CCL). A probabilistic methodology is used to calculate the time between leak and break [6] and is being implemented by using a computer code called MARATHON [7], written in Fortran-77. The risk associated with unstable fracture can be estimated. A review of the LBB for CANDU heat transport piping system was given by Kozluk, etc [5], with the conclusions that the response time and sensitivity of the AGS to abnormal amounts of moisture in the system are important parameters for the LBB analysis. The response was evaluated analytically by a computer model which simulates the transport of moisture in the AGS.

The presence of moisture due to the leakage is first detected by dew point meters. The dew point reading in the annulus is known to gradually increase due to moisture accumulation in the annulus, and if there is a leak from the pressure tube the dew point reading increases abruptly due to the leak[8]. In case of pressure tube leak, the expected leak rate is about 0.5 kg/hr with the initial crack length.

A test program was undertaken in Wolsong Unit 2 during June 1997 to determine the response of the AGS instrumentation and to confirm the dew point response in LBB assessment. Heavy water vapour was injected at known and controlled rates at the inlet end of the longest and the shortest AGS strings. The tests showed that the AGS is sensitive to the presence of even a small quantity of moisture, *i.e.* an order of a few g/hr.

The objective of present moisture injection tests was to demonstrate that the AGS dew point meters were capable of detecting leaks in a timely manner such that LBB can be assured for the

postulated pressure leak and to demonstrate the validity of models predicting the response of the system. The test results will be used for LBB assessment within the broad range of plant operating conditions. The appropriate alarm setpoint of low AGS flow rate will be examined.

## 2. Annulus Gas System(AGS) Description

The AGS instrumentation is located inside the containment except the gas supply line, which consists of beetles, leakage flow indicators, drain tank level transmitter and dew point meters, as shown in Figure 1. The beetle makes use of electrical conductivity of water between electrodes to detect the presence of liquid water, which was drained from the leakage flow indicator. The leakage flow indicator is used to identify which string of channels has a leak. A cold finger trap was implemented to obtain moisture samples to identify the source of the heavy water from the moderator system or primary heat transport system(PHTS). If the dew point reading is over a certain high dew point value during normal operation; it is suggested to purge the system, whenever necessary, to stay below the suggested value. During the normal operation, one compressor is working while the others are in standby or in maintenance. The moisture detection capability of the AGS is well verified for the dew point range from 0 °C to -35 °C. The dew point value and the rate of rise are monitored continuously and the rate of rise is compared with that value obtained from the computerized rate of rise algorithm.

In the event of a pressure tube leak, the dew point reading will increase at a rate faster than the gradual increase, which normally occurs due to natural moisture buildup in the system. The abnormal increase of moisture in the system will annunciate high dew point alarm and high dew

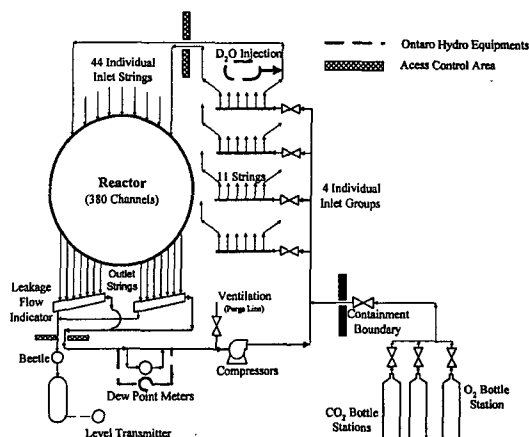


Fig 1. Draft Flow Sheet of Annulus Gas System

point rate of rise alarm. If the dew point rate of rise alarm annunciates by both dew point meters, it is considered that a leak has started. In this case, the operator should switch operation mode to zero power hot(ZPH) condition and depressurize PHTS to 8 MPa [9]. The operator should shut down the reactor within the prescribed time from the initial receipt of alarm signal and he should search out leak location during the holdup at ZPH condition. The dew point rate of rise alarm will normally be followed by a beetle alarm and the duration of alarms depends on the size and leak location.

Three different PHTS operating conditions are given in Table 1 for Wolsong Units 2, 3 & 4. Usually, the operating conditions of the reactor are determined by the measurements taken at the Reactor Outlet Head(ROH). Even though cold pressurized(CP) state is not a normal operating condition, the tests were conducted since the data are used in the stress analysis of pressure tubes. For Zero Power Hot (ZPH) condition, the value of nominal CANDU 6 operating pressure was taken and it was assumed that the operating temperature was constant from the pressure tube inlet to ROH. At normal operating condition of AGS, the recirculating gas flow rate was measured to be

**Table 1. Operating PHTS Conditions [2]**

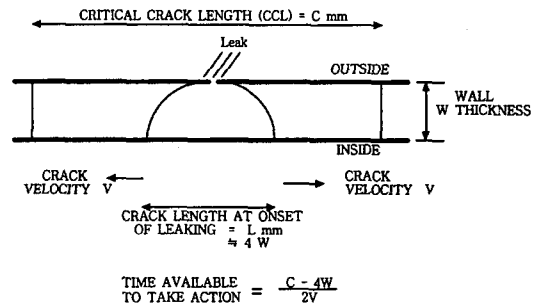
Condition	PT Inlet Temperature (°C)	PT Inlet Pressure (MPa)	PT Outlet Temperature (°C)	PT Outlet Pressure (MPa)	ROH Temperature (°C)	ROH Pressure (MPa)
FPH	266.3	11.08	311.8	10.24	310	9.99
ZPH	261	8.13	261	7.25	261	7
CP	37.8	11.43	37.8	10.25	37.8	9.99

approximately 3 L/s(STP) with one compressor and 5.1 L/s(STP) with two compressors. At ZPH condition, the temperature and pressure near the dew point meter are about 40°C and 0.04 MPa(g), respectively.

**3. Generic Leak Before Break Assessment**

To ensure structural integrity of the pressure tube in CANDU 6, conservative criteria will be applied to minimize the risk of DHC initiation at flaws. In early CANDU reactors, improper rolling procedure between end fitting and pressure tube produced excessive tensile residual stresses in the pressure tube. In some cases, due to sufficiently large tensile hoop stress, the crack initiated at the inner surface of the pressure tube. Eventually, the crack grew in the radial direction and penetrated the tube wall, causing the leak of pressurized heavy water into the annulus gas.

The semi-elliptical shape of a crack has an initial crack length  $L_o$  when it penetrates through the wall of the pressure tube and starts leaking. The centre of the crack is a distance  $A$  from the rolled joint. Figure 2 shows geometrical parameters for the crack. The crack will grow at both ends until it reaches the critical crack length (CCL). The crack propagation may be unstable and when it reaches CCL, the pressure tube rupture is expected to occur. In general, the crack growth rate  $V$  is known to be temperature dependent and CCL as



**Fig. 2. Schematic Diagram to Show Crack Dimensions at Onset of Leakage**

well as  $V$  will change with time during plant shut down and startup manoeuvres, due to the changes in temperature and pressure [7].

As a general LBB assessment with a known crack velocity, the time  $t_{LBB}$  took from the start of penetration to reach CCL

$$t_{LBB} = (CCL - L_o) / 2V \quad \text{for } L_o < CCL < 2A \quad (1)$$

Generally, the initial crack length is 4 times the wall thickness. Using this approach, the time available for operator action is approximately 15.43 hr with  $V = 0.972$  mm/hr (at test temperature below 200°C),  $CCL = 50$  mm for typical outlet conditions at 310°C and 150 MPa hoop stress. The  $L_o = 20$  mm is taken as a conservative value since measured length in Pickering and Bruce accidents was about 16 mm. The mass flow rate  $Q$  (kg/hr) of PHTS coolant leakage through the crack is calculated [2] by

$$Q = 0.7618L - 14.86 \quad (2)$$

Where  $L$  is crack length in mm. It was developed based on the measured leak rate data at different crack lengths of pressure tube removed from the Canadian reactors.

Whenever the collection rate is greater than 2 kg/hr, the beetle alarms for the reactor cool down. To assure LBB in pressure tube, it is required that; (a) the crack length at wall penetration is less than CCL, (b) whenever the leak occurs, it is detected and (c) action is taken before the crack length exceeds the CCL. To estimate how much time it takes to detect a leak and to take action, one needs to perform a series of moisture injection tests to evaluate the leak detection capability of AGS [10].

#### 4. Moisture Injection Tests

As mentioned before, the purpose of the AGS is to provide the operator with sufficient time to take an appropriate action to prevent unstable rupture of a leaking pressure tube. A series of tests was conducted to demonstrate the moisture leak detection capability of the AGS in Wolsong Unit 2 and to verify the performance of computer algorithm for the dew point rate of rise. The responses of the AGS to the presence of moisture were confirmed by injecting heavy water vapour at controlled rates to simulate pressure tube leak and the test results were utilized for LBB assessments. The design values for alarm set points for the dew point rates of rise will be suggested by analyzing test results [11].

There are a number of preparatory works before the moisture injection test, which are as follows; (a) the AGS must be fully commissioned and must be purged and dried to a dew point of  $-35\text{ }^{\circ}\text{C}$  to  $-40\text{ }^{\circ}\text{C}$  for an extended period of time, (b) the PHT system must be functional at zero power

hot(ZPH) condition and at steady state operation (i.e. no transient) (c) the moderator and shield cooling systems must be circulating at ZPH condition. For a case of large  $\text{D}_2\text{O}$  leak test, condensation is assumed to occur at some part of the end shield system where the wall temperature is about  $60\text{ }^{\circ}\text{C}$ , however, such a condensation was not detected in the present tests with small leak rates.

The dew point response of the AGS is dependent upon the gas flow rate, system pressure,  $\text{D}_2\text{O}$  leak rate,  $\text{CO}_2$  leak location if there is any. However, in these tests, it was assumed during the tests that the AGS is almost  $\text{CO}_2$  leak tight. In the present work, two types of test were performed depending on the reactor condition. As the first type, the test equipment (four hygrometers, moisture injection system and work station) after site installation was commissioned during four cold tests when the reactor was at cold condition. Then,  $\text{D}_2\text{O}$  moisture was injected into the AGS while the reactor was at ZPH condition. Here, the results of three hot tests with various  $\text{D}_2\text{O}$  injection rates will be discussed. Table 2 shows the test matrix. The system was in recirculation mode with one or two compressor/s during the tests. In purge mode, the vent valve is opened to release moisture buildup in the system to the environment and dry carbon dioxide is continuously supplied from the  $\text{CO}_2$  bottle station so that  $\text{CO}_2$  circulation can be driven by gas supply pressure even when the compressor does not run.

A schematic diagram of the AGS for Wolsong Unit 2 is shown in the Figure 1, which shows also that  $\text{D}_2\text{O}$  injection system was connected to one of 44 inlet strings while 4 dew point meters were connected after leakage flow indicators in parallel with the station hygrometer. All these instrumentation was located inside the Access Control Area.

**Table 2. Test Matrix**

Test No	D <sub>2</sub> O Injection Rate (g/hr)	Number of Compressors Running	Number of Inspection Channels in Series	Notes
Cold Test 1	12.8	1	all	External Circuit Injection
Cold Test 2	2.9	1	11	
Cold Test 3	3.3	2	11	Injection at Purge Mode
Cold Test 4	2.5	1	11	Leak Location/Search
Hot Test 1	1.25	1	11	Injection at Purge Mode
Hot Test 2	3.05	2	11	
Hot Test 3	2.48	2	3	Captions of Figures

To simulate actual leak in the AGS system, moisture was introduced into the inlet end of the shortest string (3 channels in series) or of the longest string (11 channels). The fastest dew point response is expected to be measured in the case of 3 channels in series with two compressors running (Hot Test 3). For Hot Test 1, in case of 11 channels in series with one compressor running, the slowest dew point response was measured.

The following four calibrated dew point meters were connected to the AGS as close to the station dew point probes as possible; (a) "Panametrics" probe similar to the station dew point meter which detects moisture by its effect on the electrical impedance of aluminium, (b) "MCM" probe which is a silicon-based sensor and detects the change in capacitance and (c) "EG&G" and "GED2" probes which are chilled mirror optical hygrometer detecting moisture on a constant frost layer. The most accurate indication of dew point is provided by the last dew pointer meters when conditions are not changing rapidly.

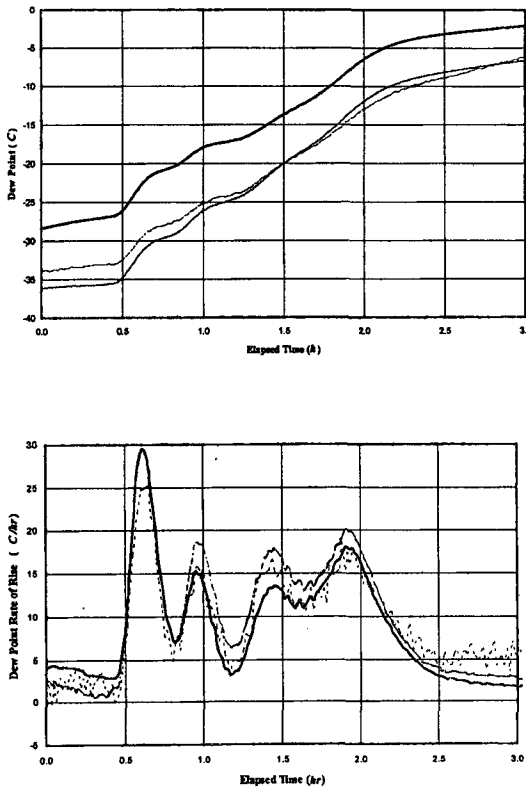
Essentially, the same test procedure was used for all the tests: Before the test, the system was operated under recirculation mode with identical system flow rate, temperature, pressure and system dew point. Moisture was injected at a constant rate until the system dew point reached about -10°C and then a purge was initiated to dry

the system for the next test or to obtain dew point response in purge mode. The followings are general test procedure.

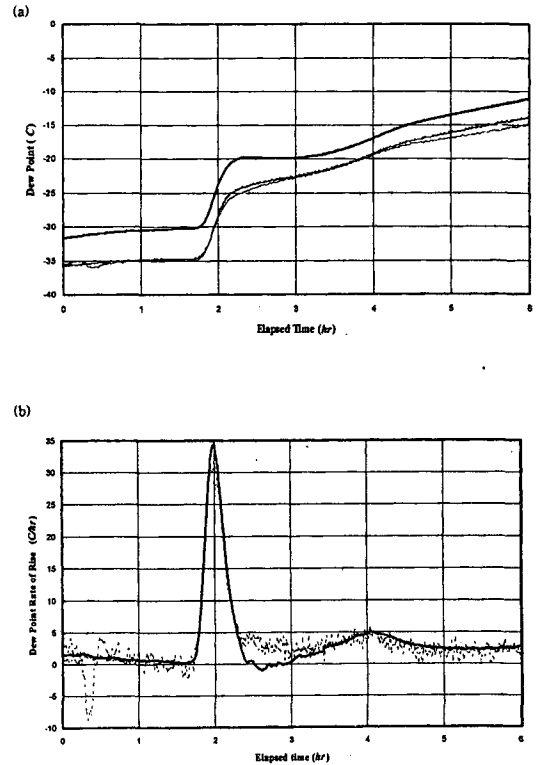
- a) Prepare the system for the purge mode
- b) Continue purging until the dew point reaches -39 °C for the Cold Test and -37 °C for the Hot Test
- c) If the dew point does not reach -35 °C within 60 minutes after the start of the purge regards as AGS leak and follows the reactor operating manual procedure
- d) If the dew point does not reach -39 °C or -37 °C within four hours after the start of the purge, inform KEPCO system engineer
- e) If the dew point reaches -39 °C or -37 °C, switch to recirculation mode and keep in operation for four hours
- f) After four hours from the start of recirculation, collect data while injecting at determined rate
- g) When the dew point reaches -10 °C, stop injection

## 5. Test Results

Since the moisture from the leaking channel in a particular string is mixed with the dry gas flowing from the other string, the dew point measured by the instrumentation does not represent overall moisture content for the AGS. At the inlet after



**Fig. 3 (a) Dew Point Response and (b) Dew Point Rate of Rise for Cold Test 1;**  
**1 Compressor ( $Q_s=3.0$  sL/s) , ECI (12.8 g/hr)**  
 \_\_\_\_\_, Pana ; ..... MCM ; - - - - , GED2



**Fig. 4 (a) Dew Point Response and (b) Dew Point Rate of Rise for Cold Test 2;**  
**1 Compressor ( $Q_s=3.0$  sL/s), 11 Channels (2.9 g/hr)**  
 \_\_\_\_\_, Pana ; ..... MCM ; - - - - , GED2

the first pass, the combined moisture is equally distributed to all of the strings. It is only after a long period of time that the moisture content through the system becomes more or less homogeneous. However, it is important to detect a sudden increase in measured dew points when the injected moisture reaches the hygrometers. After a sudden increase in the measurement, the dew point rise is more gradual because much more moisture would be necessary to obtain the same level of change in measured dew point.

Cold Test 1 was performed with one compressor running and after moisture was injected through the main circuit with the rate of injection of 12.8

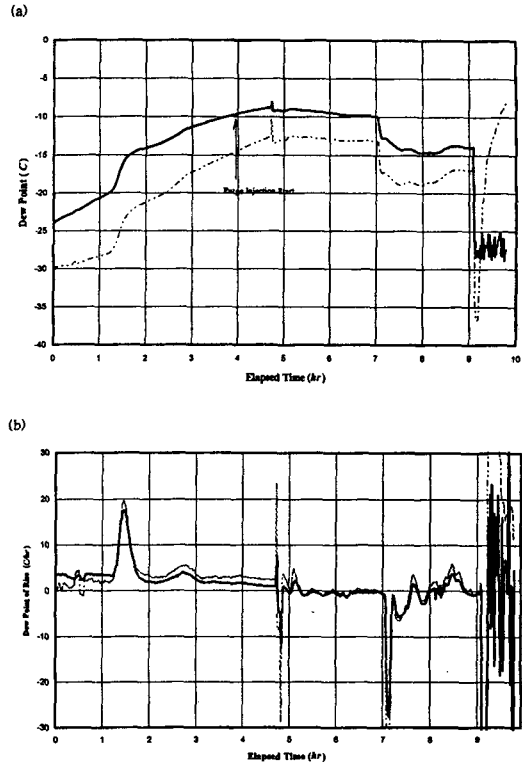
g/hr, the injected moisture travelled through all the strings. Therefore, injected heavy water vapour was distributed to all the 44 strings. Figure 3 shows dew point response and dew point rate of rise for Cold Test 1.

Figure 3(a) shows that it took about 30 minutes for the injected moisture to arrive at the location where the hygrometers were connected. The sudden increase in dew point measurements was measured by all four hygrometers when the injected moisture reaches them through the three channel string. After the first sharp increase, the following sudden increases in measured dew points are caused by the moistures coming

through 5, 7, 9 and 11th channel strings. After two hours from the start of injection, the circulating moisture may be distributed to all strings with different lengths in proportion as the volume flow in each string. This is the start of the second round pass of moisture through the system and the dew point rate of rise during the second pass is more gradual than that during the first pass of the response. The dew point rate of rise is calculated from the measured dew point and the results are shown in Figure 3(b). Only four peaks in measured rate of rise were observed and it is judged because the recirculating moisture was distributed in all strings and then, the mixed moisture in three channel strings reached the hygrometer earlier than the initially injected moisture, which was passing through longer channel strings. It is shown that GED2 hygrometer is most sensitive than the other ones.

Cold Test 2 was conducted with  $D_2O$  injection rate of 2.9 g/hr when one compressor was running. The moisture was injected into the inlet end of the longest string. The first sharp increase in measured dew point appears after two hours from the start of the injection, as shown in Fig. 4(a). It took about four hours after the injection for mixed moisture to travel through the eleven channel annuli and to arrive at the hygrometers. After the two sharp increases (however, the first sharp increase is predominant), the rise in measured dew point is more gradual.

Cold Test 3, as shown in Figure 5, was performed for eleven channel string with the moisture injection rate of 3.3 g/hr and with two compressor running. When the dew point temperature of  $-10\text{ }^\circ\text{C}$  was achieved, the AGS was switched to the purge mode operation by purging  $CO_2$  gas through the annuli in the reactor in order to see the change in the dew point reading during this mode and by stopping a compressor while the injection was continued. The time for the injected

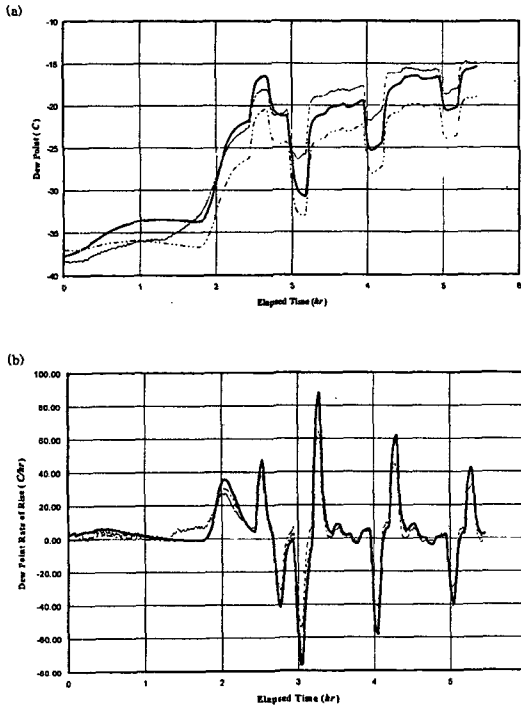


**Fig. 5. (a) Dew Point Response and (b) Dew Point Rate of Rise for Cold Test 3; 2 Compressors ( $Q_s=5.1$  sL/s), 11 Channels (3.3 g/hr), Purge Injection**  
 —, Pana ; - - - - - , MCM

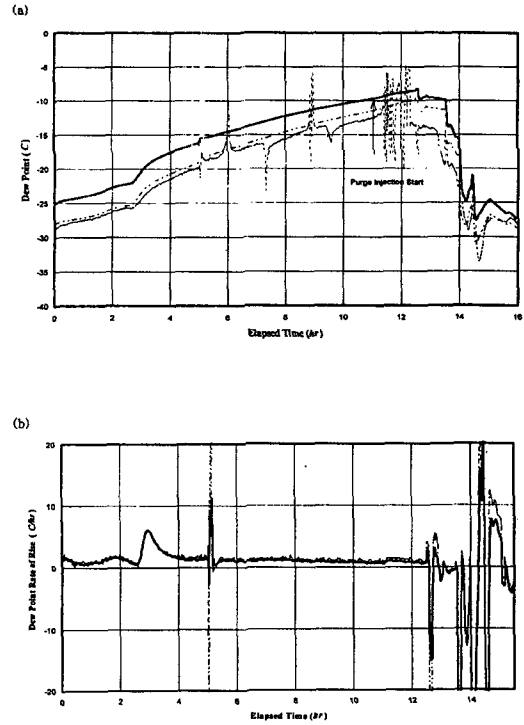
moisture to arrive at the hygrometer was about 90 minutes. The second increase in the dew point readings, but not dominant, appears around three hours. It is expected that the reason for quicker instrument response time for the Test 3 is mainly due to higher  $CO_2$  gas flow rate, compared to the Test 2. The expected behaviour is for dew point, after purge starts, to remain steady decrease. However, the dew point shows stepwise change. Some of this was due to inadequate purge operation.

To locate the leaking bank/string, an additional cold test was conducted with one compressor running and the moisture was injected into the





**Fig. 6. (a) Dew Point Response and (b) Dew Point Rate of Rise for Cold Test 4; 1 Compressor ( $Q_s=3.0$  sL/s), 11 Channels (2.5 g/hr), Leaking Location Test**  
 \_\_\_\_\_, Pana ; ..... MCM ; ---- GED2



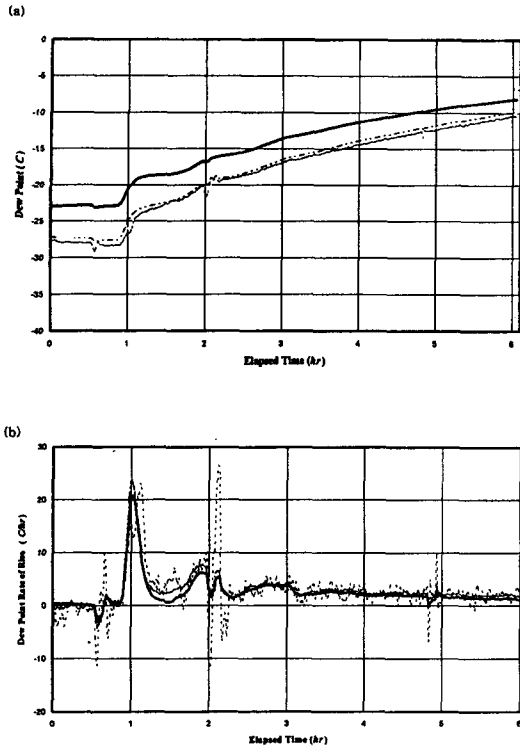
**Fig. 7. (a) Dew Point Response and (b) Dew Point Rate of Rise for Hot Test 1; 1 Compressor ( $Q_s=1.6$  sL/s), 11 Channels (1.25 g/hr), Purge Injection**  
 \_\_\_\_\_, Pana ; ..... MCM ; ---- GED2

inlet end of the longest string with the injection rate of 2.5 g/hr. The first response was recorded in the hygrometer in about 108 minutes after the start of the injection, as shown in Figure 6.

When the dew point increases gradually, the leak location/search activities were carried out with compressor running continuously. According to dichotomization process, two of the four header valves were closed at a time and the moisture level was observed by the dew point meters. After identifying the banks that showed high dew point readings, one of the two banks was isolated and the dew point temperatures were monitored. This will narrow down the location to one of the four banks. Using the same procedure, the leaking

channel was identified. For example, when the dew point increases during the process, the leaking banks valved-in while the non-leaking channel was isolated. It took about five hours as the longest time to identify the leaking string with worst case in probability sense.

Figures 7, 8 and 9 illustrate the dew point responses for the hot tests. The procedure for each of hot tests was the same as for the cold test, except that the reactor was in Zero Power Hot condition as shown in Table 1. For the Hot Test 1 with one compressor running, as shown in Table 2, the moisture injection rate into the longest string was 1.25 g/hr. The normal flow rate of AGS is about 3.0 sL/s with one compressor

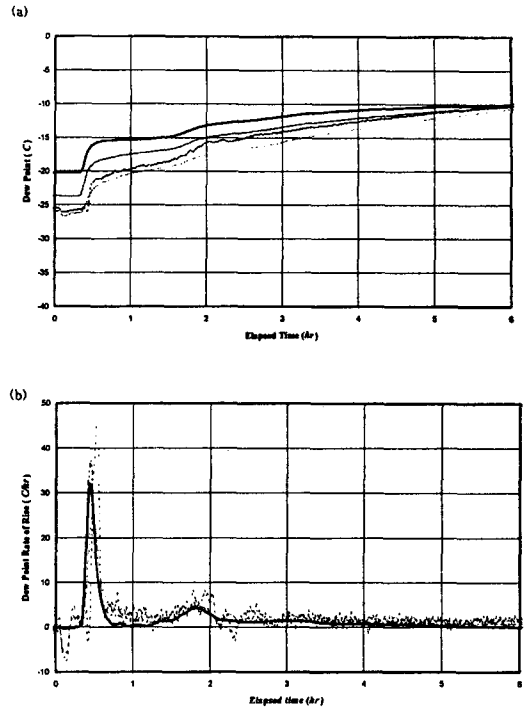


**Fig. 8. (a) Dew Point Response and (b) Dew Point Rate of Rise for Hot Test 2;**  
**2 Compressors ( $Q_s=5.1$  sL/s),**  
**11 Channels (3.05 g/hr)**  
 \_\_\_\_\_, Pana ; -.-.-.-, MCM ; - - - - , GED2

running. However in the Hot Test 1, flow rate was readjusted to 1.6 sL/s using valve. The first moisture front was detected after 2.7 hours from the start of injection, as shown in Figure 7. The second moisture front appeared at four hours indicating the circulation time of two hours in the system. Injection was continued during the purge mode.

Figure 7(b) shows a plot of the dew point rate of rise calculated every six minutes interval. The ground peak, in conservative sense, of the calculated values will be used for the design value of the alarm set point for the dew point rate of rise.

Figure 8 shows the dew point responses for the



**Fig. 9. (a) Dew Point Response and (b) Dew Point Rate of Rise for Hot Test 3;**  
**1 Compressors ( $Q_s=3.0$  sL/s),**  
**3 Channels (2.48 g/hr)**  
 \_\_\_\_\_, Pana ; -.-.-.-, MCM ;  
 - - - - , EG&G ; - - - - , GED2

Hot Test 2 with two compressors running and at 3.05 g/hr moisture injection rate. The response time of the first step increase in the reading is shorter than for the Hot Test 1 mainly because of the higher AGS flow rate. The circulation time might be one hour with two compressors running. As expected, the rate of rise for this test was higher than for the case of Hot Test 1 because of higher  $CO_2$  gas flow rate and more moisture injection rate.

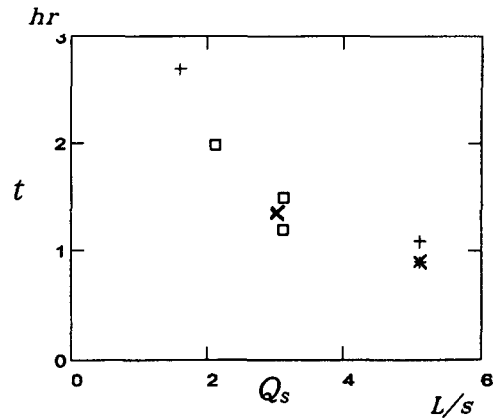
Hot test 3 was conducted with two compressors running and injection was performed into the shortest string (3 channels) with the injection rate of 2.48 g/hr. It took about 30 minutes to detect the first moisture front, as shown in Figure 9. The

second front was detected in just before two hours from the start. The rate of rise was very high compared to the results of the other hot tests.

As shown in the test results, it is noted that the first peak of the dew point rate of rise is strongly dependent on the rate of moisture injection while the first dew point response is influenced by the number of channels and by the AGS CO<sub>2</sub> flow rate. In general, the value of the peak increases with the injection rate and the response time is more or less proportional to the annulus volume of the passing channels. By inspection of Figs 5 & 8 where both tests were performed in almost same test conditions, the response time for hot test is shorter than that for cold test. Since the volume of gas is expanded with temperature, the gas flow velocity in annulus for hot test might be larger than that for cold test, even though the standard flow rates are same. The conversion factor of the response time from cold test to hot test is about 0.77. Based on the above assumptions, the response times can be converted to the case of 11 channels string (hot test). As a result, the approximated response times, from the results of the other cases, can be calculated, as shown in Fig. 10. Some of the results for Bruce Unit 3 & 4 [12] are compared to the present results, however both configurations of Wolsong and Bruce are slightly different. The response time to the AGS CO<sub>2</sub> flow rate is more or less in parabolic, in the range of the both tests. If two hours is available for the first dew point response based on the LBB assessment, the alarm setpoint for very low flow rate might be, at least, 2.1 sL/s.

**6. Conclusions**

In order to confirm how quickly the station dew point meters respond to the leak from the pressure tube, leak detection capability tests were performed under both reactor hot and cold



**Fig. 10. The First Response Time, *t* (sec), versus AGS Flow Rate, *Q<sub>s</sub>* (sL/s).  
Present Results ; +, Hot Test  
x, Converted Result from Cold Test  
Bruce Results ; □, Hot Test**

conditions. These results will be used for LBB assessment and for establishing reactor operating criteria for Wolsong Unit 2. The moisture injection rates used for the tests were less than the value of the lowest discriminable leak rate (no condensation in annuli). The responses of the dew point depend on the moisture injection rate, the system carrier gas flow rate and the leak location.

The tests show that AGS can detect and give alarms even for the very small leaks. Even though tests shows that the the leak detection time with two compressors running is shorter than the case with one compressor running, the AGS is in normal operation with one compressor running and this is related to the efficiency of existing piping size. It was realized that the dew point rate of rise might be the best indicator to warn the operator of maneuvering reactor condition to protect unstable fracture of pressure tubes. Considering the test results, it is suggested that leak location/search activities via selective string isolation be performed during the recirculation

mode rather than purge mode because during the purge mode, it is difficult to obtain a constant flow rate in the AGS and the dew point reading is unstable.

It took about five hours from start of injection to search the leak location based on dichotomization process under the recirculating mode. So the required action will be taken before the crack length exceeds the critical crack length for LBB assessment. Without enough time to search the leak location, it is expected for the searching to have inspection of each channel during reactor shutdown; however, it takes long time and it is tedious.

In general, thermal hydraulics analysis and dew point analysis might be carried out prior to the tests in order to make a comparison between test results and for the actual abnormal operation. It is also suggested to do the post-test analysis to make corrections for differences in assumed test temperature, flow rate and pressure values. To support the interpretation of dew point trend by the operator after the high dew point level alarm, it is recommended to add an algorithm to the computer program. This algorithm will give an additional annunciation which reflects the  $D_2O$  leak size. The algorithm should be based on three parameters; dew point, dew point rate of rise and the system carrier gas flow rate. However, considering the present results, the response time to the AGS  $CO_2$  flow rate is approximated. The response time to the AGS  $CO_2$  flow rate is more or less in parabolic, in the range of the present tests.

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#### Nomenclature

- $t_{LBB}$  : LBB Time, hr  
 CCL : critical crack length, mm  
 $L_0$  : initial crack length, mm  
 $V$  : crack growth rate, mm/hr  
 $Q$  : Leak flow rate, kg/hr  
 $Q_s$  : Standard flow rate of Annulus Gas System, sL/sec  
 $L$  : crack length, mm

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