THE UNBALANCED DISTRIBUTION OF DEUTERIUM IN THE TWO HEAT TRANSPORT LOOPS AND THE FLOW THROUGH THE PRESSURIZER INTER-CONNECT PIPE AT POINT LEPREAU GENERATING STATION

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ABSTRACT

The measurement of dissolved deuterium in the two loops of the primary heat transport system of the Point Lepreau Generating Station has consistently shown that loop 2 has, 20%-100%, higher concentration that loop 1. It was proposed that this difference in concentration was caused by the transfer of a deuterium rich stream through the pressurizer inter-connect pipe. A plant experiment forcing flow through the pressurizer inter-connect pipe in each direction verified this mechanism. A model is presented which can explain the difference in concentration normally maintained between the two loops.

Presentation at
The 19th Annual Conference of the Canadian Nuclear Society

1998 October

1.0 INTRODUCTION

The dissolved deuterium data from the Point Lepreau Nuclear Generating Station (PLNGS) show that there has been consistently more deuterium (by 20% to 100%) in loop 2 than in loop 1 of the Primary Heat Transport System (PHTS) (Figure 1). The data from the Gentilly Nuclear Generating Station (GNGS) also showed[1] that dissolved deuterium concentration is higher in one loop than in the other. As part of the effort to understand this behavior, the dissolved deuterium data from the Orbisphere analyzer in the PHTS at PLNGS were continuously monitored and analyzed from December, 1995 to September, 1996. According to the observed behavior of dissolved deuterium in the two loops, especially the response of dissolved deuterium concentration in one loop to the addition of hydrogen into the other loop, it was proposed[2] that a flow from loop 2 to loop 1 through the pressurizer inter-connect pipe could cause such an unbalanced distribution of deuterium in the two loops. To verify this proposed mechanism, a test was recently conducted at the station by deliberately changing flow direction through the pressurizer inter-connect pipe and measure the response of the dissolved deuterium in the two loops. This report describes the proposed mechanism and presents the test results for the verification of this mechanism.

2.0 DISSOLVED DEUTERIUM IN THE PHTS AND THE ADDITION OF HYDROGEN

The sampling system and the instruments used for the analysis of the dissolved deuterium and hydrogen addition were described in a previous report[3]. In addition to the Hydran 102B analyzer mentioned in the previous report, a Hydran 101 analyzer was also used for the data presented in this report. The results from the two analyzers for samples from the same source often differs slightly. Sometimes the difference could be as much as 2 cc/kg. In the routine analysis, the two analyzers were used whichever was available. There was no differentiation as to which data were obtained with the Hydran 101 or with the Hydran 102B in the routine analysis. Compared with the results obtained with the Hydran analyzers for samples obtained from the same source, the results from the Orbisphere on-line analyzer were usually higher by 5% to 40%. One possible cause for this discrepancy is that some deuterium initially in the sample might be lost by diffusion through the wall of the hypodermic syringe sampler during sampling. Another possible cause might be that oxygen trapped inside the syringe sampler might lower the readings of dissolved deuterium as oxygen in the samples may interfere with the measurements of dissolved deuterium using the Hydran analyzers[4]. To minimize the loss of deuterium during sampling, the samples were taken to the laboratory and injected into the Hydran analyzers immediately after they were taken from the sampling room (Room S147). The time duration was typically 5 minutes.

3.0 VERIFICATION OF THE UNBALANCED DISTRIBUTION OF DEUTERIUM IN THE TWO PHT LOOPS

The data presented in Figure 1 were obtained with the Hydran analyzers using grab samples. There is a large degree of scatter within the data. To verify the difference between the dissolved deuterium concentrations in the two loops, the dissolved deuterium concentrations from the two loops were measured with the on-line Orbisphere analyzer by valving the analyzer to different sampling lines respectively.

Figure 2 shows the dissolved deuterium results obtained with the on-line Orbisphere analyzer. It can be seen from Figure 2 that the dissolved deuterium concentration in loop 1 (sampled from the discharge of pump 2) was confirmed to be lower than that in loop 2 (sampled from the discharge of pump 4). The values are about 9.4 cc/kg and 11.2 cc/kg for loop 1 and loop 2 respectively, or the deuterium concentration in loop 2 is approximately 20% higher than that in loop 1.

Figure 2 also shows that the dissolved deuterium concentration in the sample from the inlet of boiler 2 was significantly lower than that in the sample from the discharge of pump 2. This will be discussed in Section 5.1.

4.0 THE RESPONSE OF DISSOLVED DEUTERIUM CONCENTRATION IN THE TWO LOOPS WHEN HYDROGEN WAS ADDED INTO ONE OF THE LOOPS ALONE

4.1 The Observed Responses

On several occasions during the monitoring period, the dissolved deuterium in loop 1 fell below the action point (4 cc/kg). However the dissolved deuterium in loop 2 remained above 5 cc/kg and therefore hydrogen was injected into loop 1 alone according to the operating procedure[5]. Figures 3 and 4 show the responses of the dissolved deuterium in loop 1 and in loop 2 to the injections of hydrogen into loop 1 respectively. The dissolved deuterium was measured with the on-line Orbisphere analyzer. Figure 3 shows that immediately after the injection of hydrogen, the dissolved deuterium concentration in loop 1 increased rapidly by 3.5 cc/kg which is approximately the theoretical value if all the hydrogen (approximately 150 L) stayed in loop 1 (about 60 m^3, 48 t). After the increase, the dissolved deuterium concentration gradually decreased by 2.5 cc/kg in 3 hours. The decrease was slightly more than half of the original increase. Figure 4 shows that shortly after the injection of hydrogen into loop 1, the dissolved deuterium concentration in loop 2 started to increase, gradually reaching a steady state value (8.1cc/kg) within 3 hours. The increase was 1.4 cc/kg, which is about half of the increase in loop 1 upon the hydrogen injection.

4.0 THE RESPONSE OF DISSOLVED DEUTERIUM CONCENTRATION IN THE TWO LOOPS WHEN HYDROGEN WAS ADDED INTO ONE OF THE LOOPS ALONE (Cont'd)

4.1 The Observed Responses (Cont'd)

Based on this analysis, the response of the dissolved deuterium concentration in loop 2 to the addition of hydrogen in loop 1 must have involved the transport of deuterium from loop 1 to loop 2. According to the design of the PHTS in the CANDU 600 stations, mixing between the two loops should take place in the purification circuit. However, Figures 3 and 4, shows that during the increase of dissolved deuterium in loop 2, the dissolved deuterium concentration in loop 1 was lower than that in loop 2. The following analysis shows that such a transport of deuterium from loop 1(which has a lower concentration) to loop 2 (which has a higher concentration) can not take place in the purification system.

4.2 Theoretical Response

Figure 5 shows a schematic diagram for the transport of dissolved deuterium if the purification system is the only place where mixing between the coolant from the two loops takes place.

Mass balance on dissolved deuterium in the purification system (neglecting the volume of the purification system which is approximately 14 m^3) yields

$$C_1 F_1 + C_2 F_2 = C_p (F_1 + F_2) \tag{1}$$

Where C_1, C_2 and C_p are the concentrations of dissolved deuterium in cc/kg, F_1 and F_2 are the flow rates in kg/s. A mass balance on dissolved deuterium in loop 1 and loop 2 gives

$$C_1 + C_2 = C_1^o + C_2^o \tag{2}$$

$$W \frac{dC_1}{dt} = F_1 (C_p - C_1) \tag{3}$$

$$W \frac{dC_2}{dt} = F_2 (C_p - C_2) \tag{4}$$

4.0 THE RESPONSE OF DISSOLVED DEUTERIUM CONCENTRATION IN THE TWO LOOPS WHEN HYDROGEN WAS ADDED INTO ONE OF THE LOOPS ALONE (Cont'd)

4.2 Theoretical Response (Cont'd)

where W is the mass of the coolant in each loop and C^o_1 and C^o_2 denote the concentrations in loop 1 and loop 2 immediately after the hydrogen injection. From Equs (1) and (2), the solutions of Equs (3) and (4) are:

$$C_1 = \frac{C_1^0 + C_2^0}{2} + \frac{C_1^0 - C_2^0}{2} \exp\left(- \frac{2 F_1 F_2}{W(F_1 + F_2)} t \right) \tag{5}$$

$$C_2 = \frac{C_1^0 + C_2^0}{2} + \frac{C_2^0 - C_1^0}{2} \exp\left(- \frac{2 F_1 F_2}{W(F_1 + F_2)} t \right) \tag{6}$$

Equs (5) and (6) describe the responses of the dissolved deuterium concentration in the two loops (C_1 and C_2) to the perturbation of dissolved deuterium concentrations in the two loops. Immediately after the hydrogen was injected into loop 1, the dissolved deuterium concentration in loop 2 should remain unchanged (C_2^o) and the dissolved deuterium in loop 1 should increase to a new value (C_1^o) due to the exchange reaction between H_2 and D_2O to form D_2. Figure 6 shows the responses of dissolved deuterium concentration in the two loops according to Equs (5) and (6) at two different purification flow rates. It can been seen from Figure 6, after the injection, the dissolved deuterium concentration in loop 1 should instantly increase and then gradually decrease, the dissolved deuterium concentration in loop 2 should gradually increase. After a certain period of time, a steady state should be reached and the dissolved deuterium concentrations in the two loops should be equal to the average of the two initial concentrations. The transition time, or the time it takes to reach a steady state is dependent upon the total purification flow (F_1+F_2) and the relative values of F_1 and F_2. The transition time is shorter if the purification flow is high and the F_1 and F_2 are similar ($F_1 = F_2$ is the best case).

5.0 THE CAUSE FOR THE UNBALANCED DISTRIBUTION OF DISSOLVED DEUTERIUM IN THE TWO LOOPS

A comparison between the observed responses (Figures 3 and 4) and the theoretical response (Figure 6) of dissolved deuterium to the addition of hydrogen into loop 1 reveals that the two responses do not agree. Therefore, the net transport of deuterium from loop 1 to loop 2 as shown in Figure 4 can not take place in the purification system. It must have occurred by another mechanism.

5.0 THE CAUSE FOR THE UNBALANCED DISTRIBUTION OF DISSOLVED DEUTERIUM IN THE TWO LOOPS (Cont'd)

5.1 The Transport of deuterium by the Flow Through the Pressurizer Inter-connect Pipe

The observation at GNGS by Elliot et al[6](see Appendix) and a later observation at PLNGS (Figure 3) during this work show that the concentration of dissolved deuterium in the sample taken from a non-boiling section (pump discharges for instance) of a loop is higher than that in a sample taken from a boiling section (boiler inlets for instance) of the same loop. This was explained by the pattern of the two phase flow in the boiling section of a main pipe and the distribution of deuterium in the two phases. It was considered that the flow pattern of the coolant in the boiling section of the pipe where the sampling line is connected is such that steam bubbles flow mostly in the core and the condensed liquid flows mostly in the annulus near the wall of the pipe. In this case, the flow which enters the sampling line is mostly from the condensed liquid near the wall of the main pipe (Figure 7).

The distribution of deuterium in the two phases depends on both thermodynamics (Henry's Law) and mass transfer. The Henry's law constant[7] for D_2 in D_2O is 1234 MPa per mole fraction of D_2 at 310 °C. Calculations show that at equilibrium, the ratio of the D_2 in one gram steam bubbles to the D_2 in one gram liquid water is about 123 at the reactor outlet pressure (1450 psia). Thus, deuterium is concentrated more in the steam bubbles than in the liquid water. Under the header outlet conditions, there is approximately 4% (weight) steam quality, the ratio of the deuterium in steam bubbles to the deuterium in liquid should be $(0.04 \times 123)/(0.96 \times 1) = 5.125$ at equilibrium. Therefore the dissolved deuterium in the liquid should be decreased by 83.7%, or to 16.33% of the original value after the boiling if equilibrium is achieved.

As a result of the flow pattern and the distribution of the deuterium in the system bubbles and liquid water, the deuterium concentration in the sampling line is less than the average deuterium concentration in the main pipe. This principle was also used to determine the dissolved deuterium concentration in the condensed phase in a two phase flow section of the NRU test reactor at Chalk River Laboratories[*].

Based on this principle, it was proposed[2] that a continuous flow of liquid from the boiling section of loop 2 to loop 1 would cause the unbalanced distribution of deuterium in the two loops as shown in Figures 1 and 2. Discussions with the station personnel[**] indicated that such a flow could be through the pressurizer inter-connect line. The return of this flow would be the purification circuit (see Figure 5). The following analysis shows that such a continuous flow would cause an unbalance distribution of deuterium between the two loops:

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[*] Personal conversation with J. Elliot, at CNER, Summer, 1995.

[**] Personal discussion with R. Gibb, September, 1996, Pt. Lepreau Generating Station.

5.1 The Transport of deuterium by the Flow Through the Pressurizer Inter-connect Pipe (Cont'd)

The total flow rate of the coolant in the horizontal 18 inch-diameter boiler inlet pipe to which the 10 inch-diameter pressurizer inter-connect/shutdown cooling pipe is connected is approximately 1000 kg/s. The steam quality in the pipe is approximately 4% by weight. Calculation shows that the flow pattern in the 18 inch pipe is in the bubbly flow regime according to the modified Baker Plot for adiabatic steam-water system at 1500 psia[8]. Measurements of the local void fraction in bubbly flow pipes generally indicate that the void fraction near the wall surface is close to zero[9], that is, the fluid near the wall surface is mostly condensed liquid.

To simplify the analysis, an extreme case was assumed: the flow through the pressurizer inter-connect pipe equals the total purification flow which is equivalent to closing valves MV1 and MV4 (or vice versa, MV2 and MV3). Figure 8 shows the simplified follow diagram when MV1 and MV4 are closed. In Figure 8, k is referred as a partition constant; It equals to the ratio of the average deuterium concentration in the side line to the deuterium concentration in the main loop. If $k=1$, there is no partition; the amounts of deuterium in unit mass of D_2O in the side line and in the main loop are the same. If $k<1$, there is relatively less deuterium going into the side line and more deuterium stays in the main loop.

As mentioned earlier, In the CANDU 600 stations, there is no boiling at the discharge of the pumps and the deuterium concentration in the sampling lines from these locations should be the same as the deuterium concentration in the main loop. The sampling lines from the boiler inlet pipes is, like the 10 inch pressurrizer inter connect pipe, side lines off two phase flow pipe. The Appendix shows that the ratio of the deuterium concentration in the sampling line from the boiler inlet to the deuterium concentration in sampling line from the pump discharge, or deuterium concentration from the main loop, is 0.735. Therefore, the k value near the sampling lines from the boiler inlets at GNGS is approximately 0.735. Similarly, Figure 2 shows that dissolved deuterium concentration was 9.8 cc/kg for the sample from Pump 2 discharge and 7 cc/kg for the sample from the Boiler 2 inlet. The k value for the sampling line from Boiler 2 inlet at PLGS is approximately 0.714. Obviously, the k value is much less than 0.1633 which is the equilibrium ratio of deuterium concentration in the condensed phase and the deuterium concentration before phase separation under normal operation (see discussions at the beginning of this section). The difference between the measured k value and the thermodynamic k value indicates that either some steam bubbles also entered the sampling line or the distribution of D_2 among the two phases did not reach equilibrium at the boiler inlet locations. Based on Figure 2, 0.7 will be used as the estimated k value for the pressurizer interconnect pipe in the following analysis.

Mass balance on dissolved deuterium in loop 2 yields

$$W\frac{dC_2}{dt} = F(C_1 - k\,C_2) \tag{7}$$

where W is the mass in each loop (kg), F, the mass flow rate (kg/s), C_1 and C_2, the concentrations of dissolved deuterium (cc/kg), and

$$k = \frac{C_3}{C_2} \tag{8}$$

from (7) and (8),

$$W\frac{dC_2}{dt} = F(C_1 - kC_2) \tag{9}$$

Since

$$(C_1 + C_2)W = (C_2^0 + C_1^0)W \tag{10}$$

Where C_1^o and C_2^o are the initial concentrations. From (1),

$$C_1 = C_1^0 + C_2^0 - C_2 \tag{11}$$

Substitution of Equs (11) in to (9) yield

$$W\frac{dC_2}{dt} = F[C_1^0 + C_2^0 - (1 + k)C_2] \tag{12}$$

the solution to Equs (11) and (12) are:

$$C_2 = \frac{1}{1+k}\left[C_1^0 + C_2^0 - (C_1^0 - kC_2^0)\exp[-\frac{F}{W}(1 + k)t]\right] \tag{13}$$

$$C_1 = \frac{1}{1+k}\left[kC_2^0 + kC_1^0 + (C_1^0 - kC_2^0)\exp[-\frac{F}{W}(1 + k)t]\right] \tag{14}$$

5.0 THE CAUSE FOR THE UNBALANCED DISTRIBUTION OF DISSOLVED DEUTERIUM IN THE TWO LOOPS (Cont'd)

5.1 The Transport of deuterium by the Flow Through the Pressurizer Inter-connect Pipe (Cont'd)

when t equals infinity and a steady state is achieved

$$C_2 = \frac{C_1^0 + C_2^0}{1+k} \tag{15}$$

$$C_1 = \frac{k(C_1^0 + C_2^0)}{1+k} \tag{16}$$

The combination of Equs (15) and (16) yields

$$C_2(t=\infty)/C_1(t=\infty) = 1/k \tag{17}$$

Equs (17) indicates that under steady state conditions, the ratio of C_2 to C_1 is 1/k (1.45), or the dissolved deuterium concentration in loop 2 is 45% higher than in loop 1 when the purification flow equals the pressurizer inter-connect pipe flow. This is consistent with the observed differences as shown in Figures 1 and 2, although, in the case of Figure 1 & 2, the purification flow was probably higher than the inter-connect pipe flow.

Figure 9 shows the response of C_1 and C_2 to a flow of 10 kg/s and 24 kg/s respectively under the condition, F=0 prior to t=0 and $C_1^0=C_2^0=C^0$ when t=0. Figure 9 shows that the time it takes to reach the steady state depends on the flow rate through the pressurizer inter-connect pipe.

5.2 Tests to Verify the Proposed Mechanism

5.2.1 Dissolved Deuterium Concentrations in the Two Loops When There Was No Boiling

At low reactor powers (<77%), there is no boiling in the PHT loops. The partition factor, k should be unity and the concentrations in the two loops should be the same (Equ 17) when there is no boiling. To verify this prediction, the hydrogen Orbisphere Analyzer for the PHTS was valved in between loop 1 (Boiler 2 inlet) and loop 2 (Pump 4 discharge) to measure the dissolved deuterium concentration during the 1996 October start-up. Measurements were made at the different reactor powers: 1%, 5%, 30%, 50% and 77%. Grab samples were also taken from the two loops analyzed for dissolved deuterium concentration to verify the measurements by the Orbisphere Analyzer.

5.2.2 The Response of the Dissolved Deuterium Concentration in the PHTS to a Forced Flow through the Pressurizer Inter-connect Pipe

As demonstrated in Section 5.1, at steady state and under normal reactor operating conditions, C_2 should be higher than C_1 ($C_2 = C_1/k$, Equ 17) when there is a flow through the pressurizer Inter-connect pipe from loop 2 to loop 1. On the other hand, C_1 should be higher than C_2 ($C_1=C_2/k$) when there is a flow through the pressurizer Inter-connect pipe from loop 1 to loop 2.

To verify this prediction, a test was performed to deliberately force changes in the directions and the flow rates of the flow through the pressurizer Inter-connect pipe and measure the response of C_1 and C_2. Since refueling might cause unpredicted changes in dissolved deuterium concentration in the PHTS[2] and hydrogen addition may cause complications, the test was scheduled on a day when there was no refueling and no hydrogen addition prior to and during the experiments. The test was conducted on August 13, 1997 according to the following procedure:

10:00	Test started; normal conditions, the purification flow was at normal 24 kg/s, with one purification ion exchange column in service. Part of this flow is suspected to flow from loop 2 to loop 1 through the pressurizer inter-connect pipe. Orbisphere analyzers for hydrogen calibrated; the performances of the Hydran analyzers verified. Orbisphere analyzer valved to P2 discharge (loop 1) from P4 discharge (loop 2).
10:15	MV2 & MV3 closed, the purification flow was 24 kg/s; all of the flow was forced to go from loop 1 to loop 2 through the pressurizer inter-connect pipe. Valve Orbisphere analyzer to P2 discharge (loop 1).
10:22	Flow reduced to 10 kg/s from 24 kg/s.
11:00	Orbisphere analyzer valved to P4 discharge (loop 2).
11:50	Orbisphere analyzer valved to P2 discharge (loop 1).

5.0 THE CAUSE FOR THE UNBALANCED DISTRIBUTION OF DISSOLVED DEUTERIUM IN THE TWO LOOPS (Cont'd)

5.2.2 The Response of the Dissolved Deuterium Concentration in the PHTS to a Forced Flow through the Pressurizer Inter-connect Pipe (Cont'd)

12:00	Flow increased to 24 kg/s.
12:20	Orbisphere analyzer valved to P4
13:20	Orbisphere analyzer valved to P2
13:30	MV2 & MV3 opened; flow returned to normal; part of the 24 kg/s is suspected to flow from loop 2 to loop 1 through the pressurizer inter-connect pipe.
13:50	Orbisphere analyzer valved to P4
14:50	Orbisphere analyzer valved to P2
15:00	MV1 & MV4 closed, the purification flow was reduced to 10 kg/s from 24 kg/s; all of the flow (10kg/s) was forced to go from loop 2 to loop 1 through the pressurizer inter-connect pipe.
15:30	Orbisphere analyzer valved to P4
16:30	Orbisphere analyzer valved to P2
17:00	Flow increased to 24 kg/s.
17:20	Orbisphere analyzer valved to P4
18:20	Orbisphere analyzer valved to P2
18:30	MV1 & MV4 opened; flow returned to normal; part of the 24 kg/s is suspected to continue to flow from loop 2 to loop 1 through the pressurizer inter-connect pipe.
19:00	Orbisphere analyzer valved to P4
19:30	Orbisphere analyzer valved to P2
20:00	Orbisphere analyzer valved to P4 Test terminated.

5.0 THE CAUSE FOR THE UNBALANCED DISTRIBUTION OF DISSOLVED DEUTERIUM IN THE TWO LOOPS (Cont'd)

5.3 Results and Discussions for the Test to Verify The Proposed Mechanism

5.3.1 Dissolved Deuterium Concentrations in the Two Loops When There Was No Boiling

Typical measurements of dissolved deuterium concentrations in the two loops before the reactor power went beyond 77% is shown in Figure 10. Since there was no boiling, the concentration measured from the boiler inlet sample should be the same as the concentration measured from the pump discharge sample for the same loop (See Section 5.1). Compared with Figure 2, the dissolved deuterium concentration in the two loops are essentially the same when there was no boiling. The measurements at other reactor powers: 1%, 5%, 50% and 77% showed the same behavior. The results obtained with the Hydran Analyzers from the grab samples are consistent with the results from the on-line Orbisphere Analyzer within experimental error. Therefore, this experiment demonstrated that C_1 is equal to C_2 when there is no boiling.

5.3.2 The Response of the Dissolved Deuterium Concentration in the PHTS to a Forced Flow through the Pressurizer Inter-connect Pipe

The results from the pressurizer Inter-connect flow experiments are shown in Figure 11. The two Hydran Analyzers were compared both at the beginning and in the middle of the test using the samples obtained from the same source (see Table I).

Table I Comparisons between the two Hydran analyzers for samples from the same source

Time	**Aug 12 14:30***	**Aug 12 17:00***	**Aug 12 19:00***	**Aug 13 07:40***	**Aug 13 18:25****
Hydran 101	7.47	7.84	7.57	7.30	5.59
Hydran 102B`	5.00	5.86	6.40	6.22	5.73

Notes: * samples from pump 4 discharge; ** samples from pump 2 discharge.

5.3 Results and Discussions for the Test to Verify The Proposed Mechanism (Cont'd)

5.3.2 The Response of the Dissolved Deuterium Concentration in the PHTS to a Forced Flow through the Pressurizer Inter-connect Pipe (Cont'd)

In general, the readings from the Hydran 102 B were lower than from Hydran 101 by about 1.5 to 2 1.5 cc/kg. Figure 10 shows that the readings from the Orbisphere Analyzer were consistently higher than the readings obtained from the two Hydran analyzers, especially at high concentrations. The following conclusions are drawn from Figure 11:

1) Under normal conditions, (at both the beginning and the end of the test), the dissolved deuterium concentration was higher in loop 2 than in loop 1 by 40% to 60%, which is consistent with Figures 1 and 2.

2) When MV2 and MV3 were closed and the purification flow was forced to go from loop 1 to loop 2 through the pressurizer inter-connect pipe, the deuterium in loop 2 started to move from loop 1 to loop 2. At a flow rate of 10 kg/s, the changes in dissolved deuterium concentrations in the two loops had reached more than 60% of the total change (according to the Orbisphere data) within 80 minutes. This demonstrates that a flow as low as 10 kg/s through the pressurizer inter-connect pipe is sufficient to cause the observed unbalanced behavior.

3) Deuterium was transported back to loop 2 from loop 1 after the valving conditions returned to normal. This indicates that there is a flow from loop 2 to loop 1 under normal conditions.

4) When valves MV1 and MV4 were closed and the purification flow was forced to go completely from loop 2 to loop 1 through the pressurizer inter-connect pipe, the deuterium in loop 1 continued to move back to loop 2 and the dissolved deuterium concentrations in the two loops returned to the values prior to the closing of valves MV2 and MV3.

5) No significant change was observed when valves MV1 and MV4 were re-opened. This, also implies that the flow direction under normal conditions was the same with the flow direction when valves 1 and 4 were closed. There was a decrease in dissolved deuterium concentration in loop 2 from 17:00 to 20:00. It is not known what caused the decrease.

5.0 THE CAUSE FOR THE UNBALANCED DISTRIBUTION OF DISSOLVED DEUTERIUM IN THE TWO LOOPS (Cont'd)

5.3 Results and Discussions for the Test to Verify The Proposed Mechanism (Cont'd)

5.3.2 The Response of the Dissolved Deuterium Concentration in the PHTS to a Forced Flow through the Pressurizer Inter-connect Pipe (Cont'd)

The above response verified the behavior predict in Sections 5.1 and 5.2.2.

In the experiments, no significant difference was observed when the flow rate was changed from 10 kg/s to 24 kg/s.

In Figure 11, when MV2 and MV3 were first closed and the purification flow rate was controlled at 10 kg/s, the deuterium concentration in the two loops should obey Equs 13&14. In that case, the purification flow was a constant and equal to the inter-connect pipe flow. Figure 12 gives the comparison between the data from the measurement and the data from the model. For loop 1 (P2), the two agreed well. However, for loop 2 (P4), the two did not agree. The discrepancy is probably due to the performance of the on-line Orbisphere analyzer, especially when it was used back and forth between the two sampling lines. To compare the calculated values from the model with the data from the measurements, the Orbisphere analyzer should be continuously connected to one sampling line. It is preferable that two Orbisphere analyzers be used at the same time, one for each sampling line.

6.0 CONCLUSIONS

Station data show that the dissolved deuterium concentration in loop 2 has been consistently higher than that in loop 1 by about 40% to 100%.

The data obtained during hydrogen addition into loop 1 alone show that deuterium was transported to loop 2 from loop 1 even though the concentration in loop 2 was higher than that in loop 1. Analysis show that such a transport can not take place in the purification circuit.

The theoretical analysis shows that the flow from loop 2 to loop 1 through the pressurizer inter-connect pipe can cause the observed unbalanced deuterium distribution in the two PHT loops. A flow in the opposite direction would cause the deuterium concentration in loop 2 to be lower than that in loop 1.

The experiments deliberately forcing a flow through the pressurizer inter-connect pipe in both directions verified the theoretical analysis.

The experiments suggest that under normal operating conditions, there is a flow through the pressurizer inter-connect pipe. This flow causes the observed unbalanced distribution for deuterium in the two PHT loops.

7.0 IMPLICATIONS

The flow rate through the pressurizer inter-connect pipes under normal operating conditions can be derived by a reliable real time measurement of dissolved deuterium concentrations from the purification, Pump 2 and Pump 4 discharges using the existing sampling lines.

The initiation of steam in the outlet headers can be detected by the changes in dissolved deuterium concentrations at both the boiler inlet and the pump discharge. When steam starts to form, the two concentrations starts to differ from each other.

The unbalanced distribution of dissolved deuterium in the two PHT loops can be corrected by adjusting valves 3335-MV1, MV2, MV3 or MV4.

ACKNOWLEDGMENTS

The authors would like to thank the following people for their assistance and support during this work:

F. Steward, C. MacNeil, T. Underhill, K. MacGibbon, S. Groom, K. Verma, R. Gibb, E. Young, H. Tang, J. Elliot and E. Moskal

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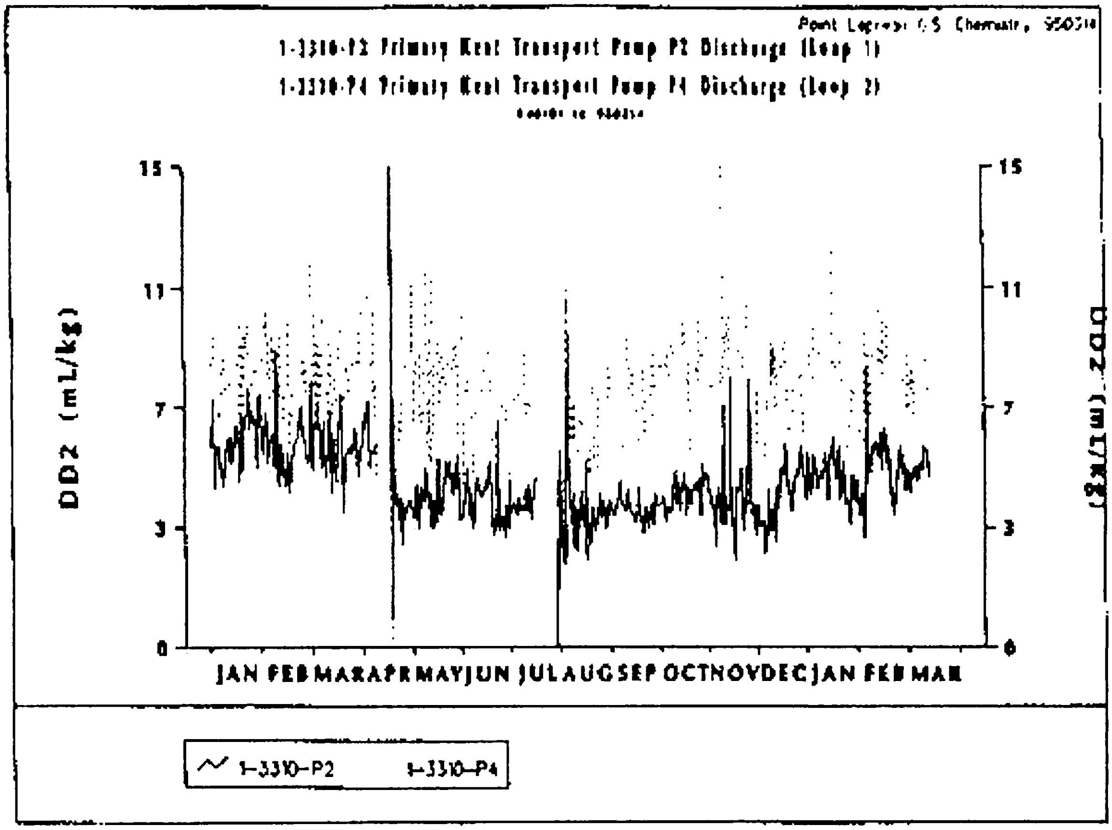


Figure 1 The dissolved deuterium data analyzed with Hydran Analyzers in the laboratory for using grab samples.

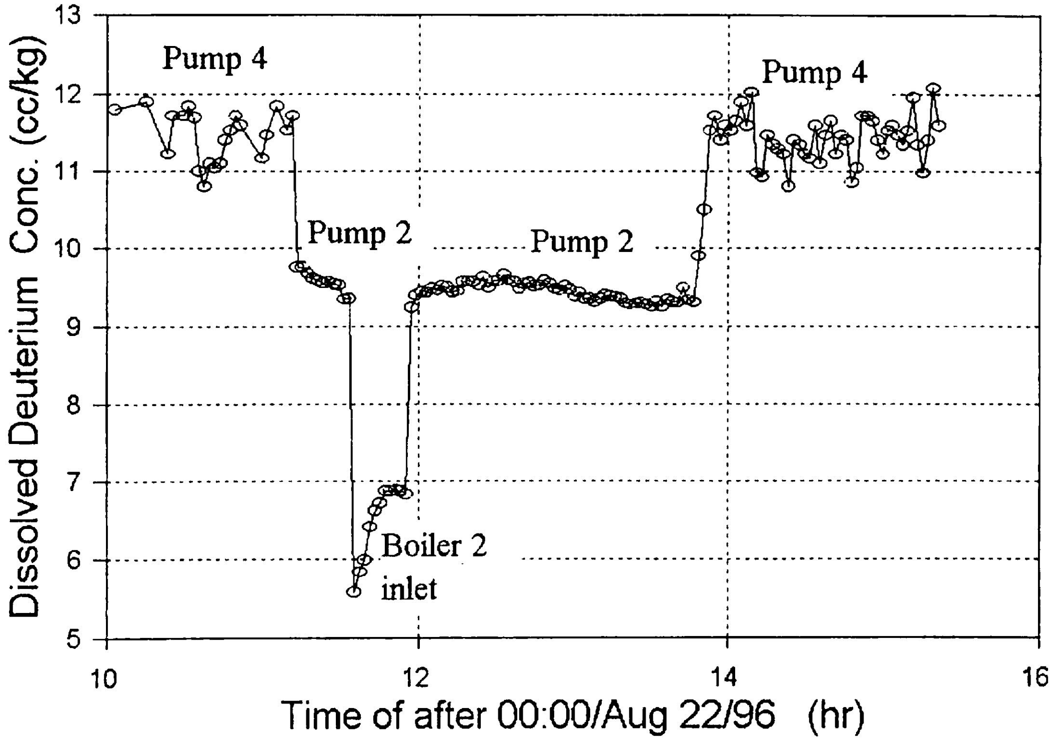


Figure 2 The dissolved deuterium data obtained with an on-line Orbisphere Analyzers

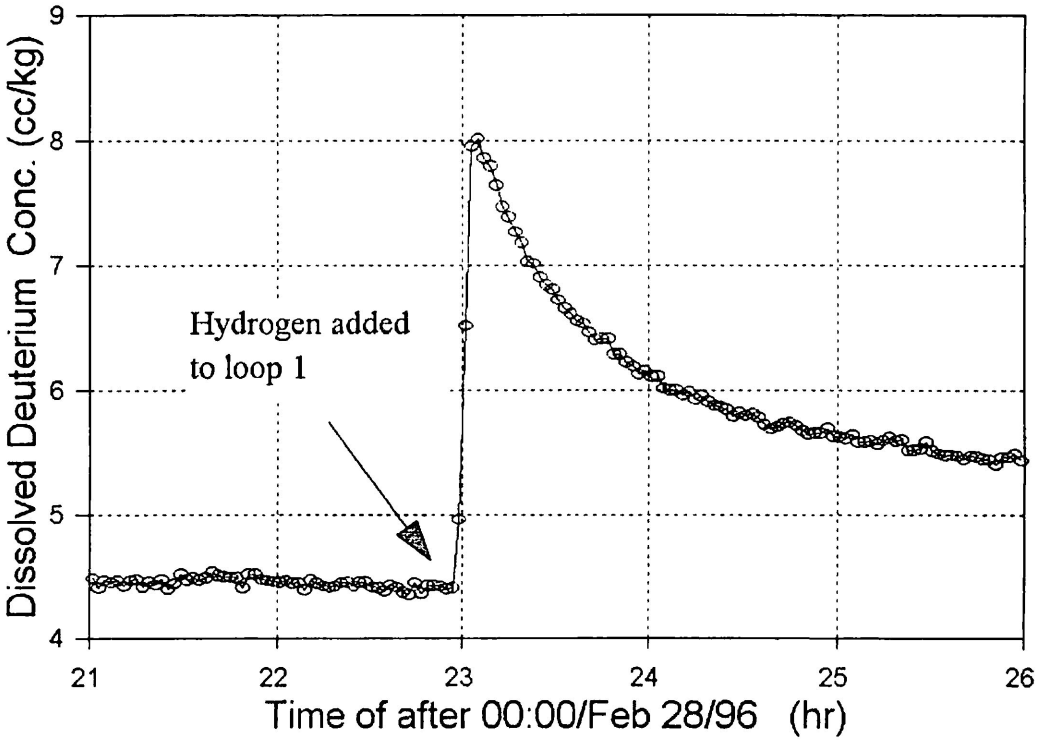
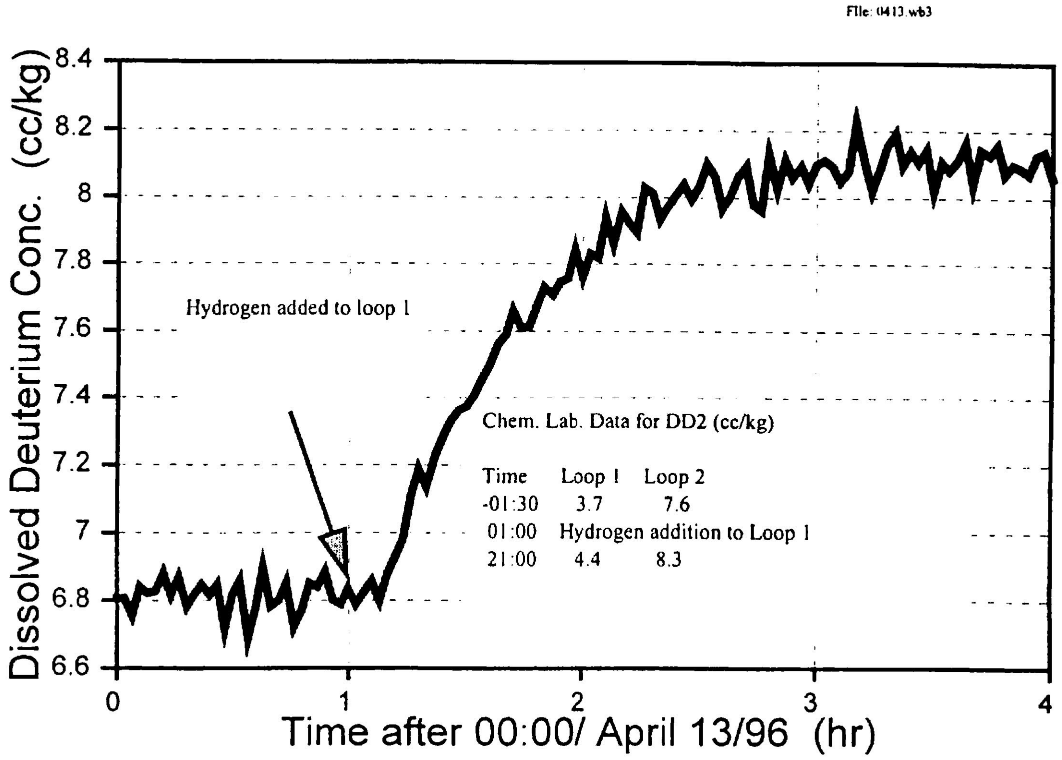


Figure 3 The response of dissolved deuterium concentration in loop 1 (boiler # 2 inlet) to hydrogen addition into loop # 1. Hydrogen addition for approximately 5 min at 30 L/min flowrate.



Chem. Lab. Data for DD2 (cc/kg)

Time	Loop 1	Loop 2
-01:30	3.7	7.6
01:00	Hydrogen addition to Loop 1	
21:00	4.4	8.3

Figure 4 The response of dissolved deuterium concentration in loop 2 (pump # 4 discharge) to the hydrogen addition into loop # 1, the sample for loop 1 data analyzed in the laboratory was from the discharge of pump # 2. Hydrogen addition for approximately 5 min at 30 L/min flowrate.

File:loop-rat2

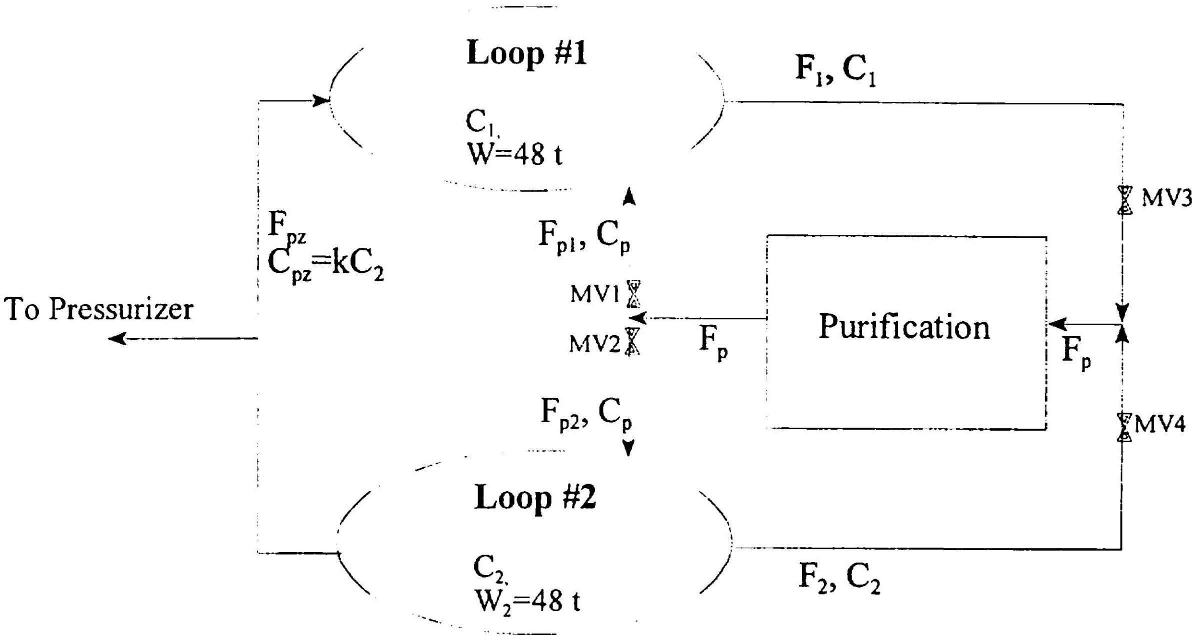


Figure 5 Schematic diagram for the transport of deuterium through the purification circuit.

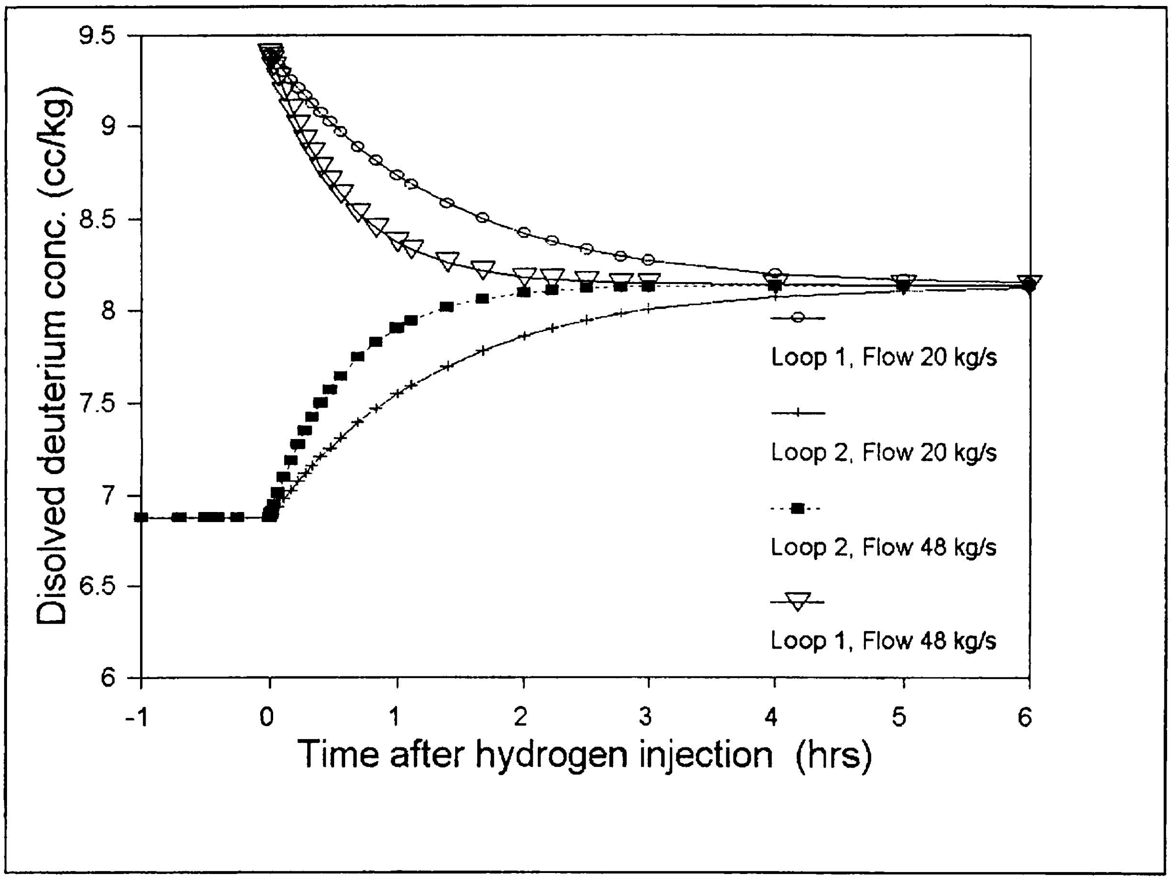


Figure 6 Theoretical responses of dissolved deuterium concentration in the two loops when hydrogen is added into loop 1 if purification is the only place where mixing between the two loops takes place ($C_1^o = 6.88$ cc/kg, $C_2^o = 9.4$ cc/kg).

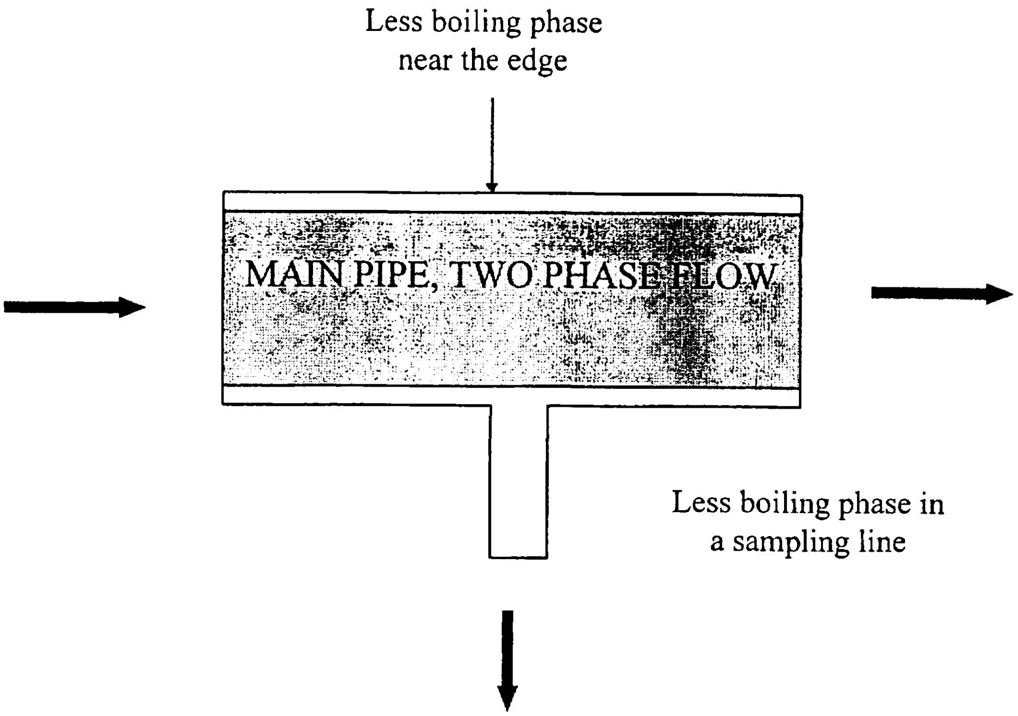


Figure 7 Schematic representation for the distribution of bubbles in a main pipe in a sampling line.

File:loop-mi3

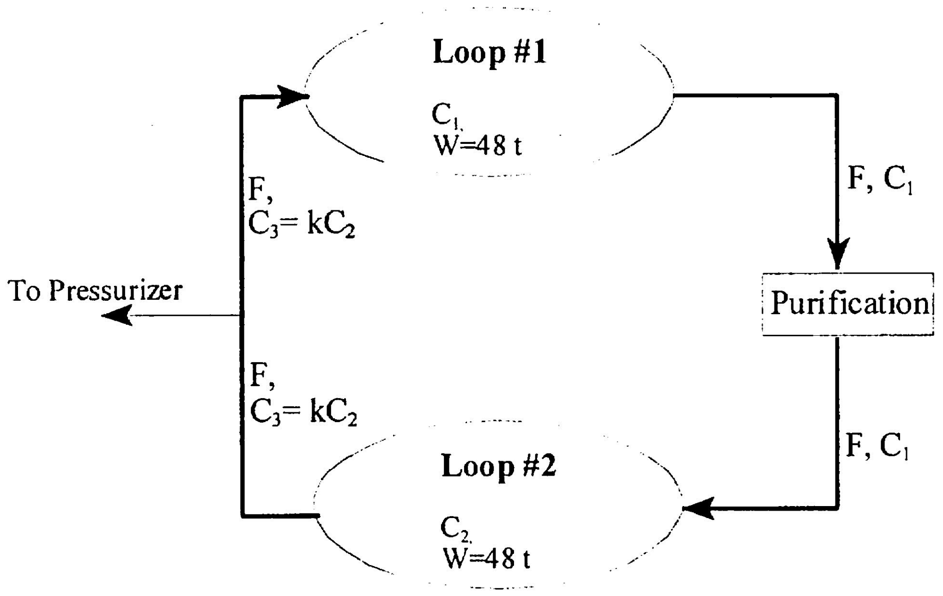


Figure 8 Schematic diagram for the flow and the transport of dissolved deuterium through the pressurizer inter-connect pipe.

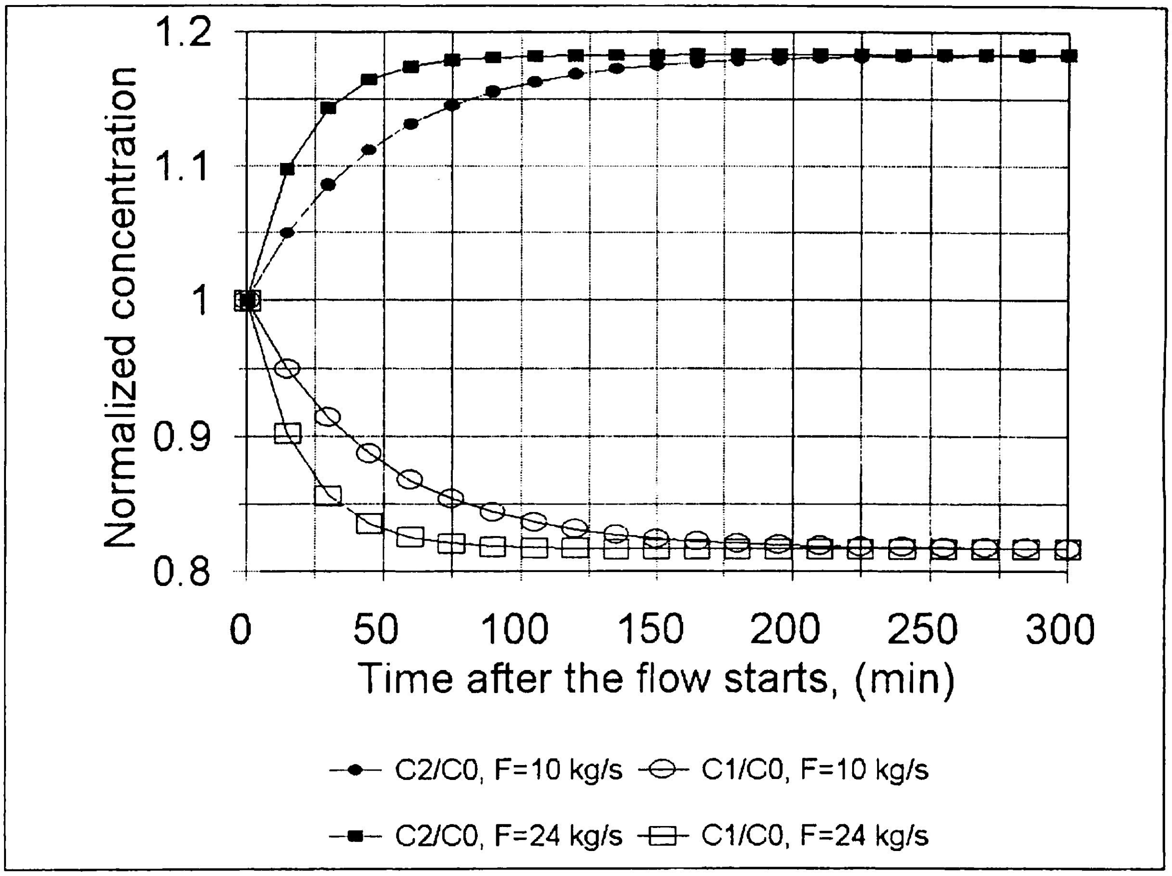


Figure 9 Theoretical responses of dissolved deuterium concentrations in the two loops after the initiation of constant flows through the pressurizer inter-connect pipe. (Purification flow = Pressurizer inter-connect pipe flow, $C_1^o = C_2^o = C^o$).

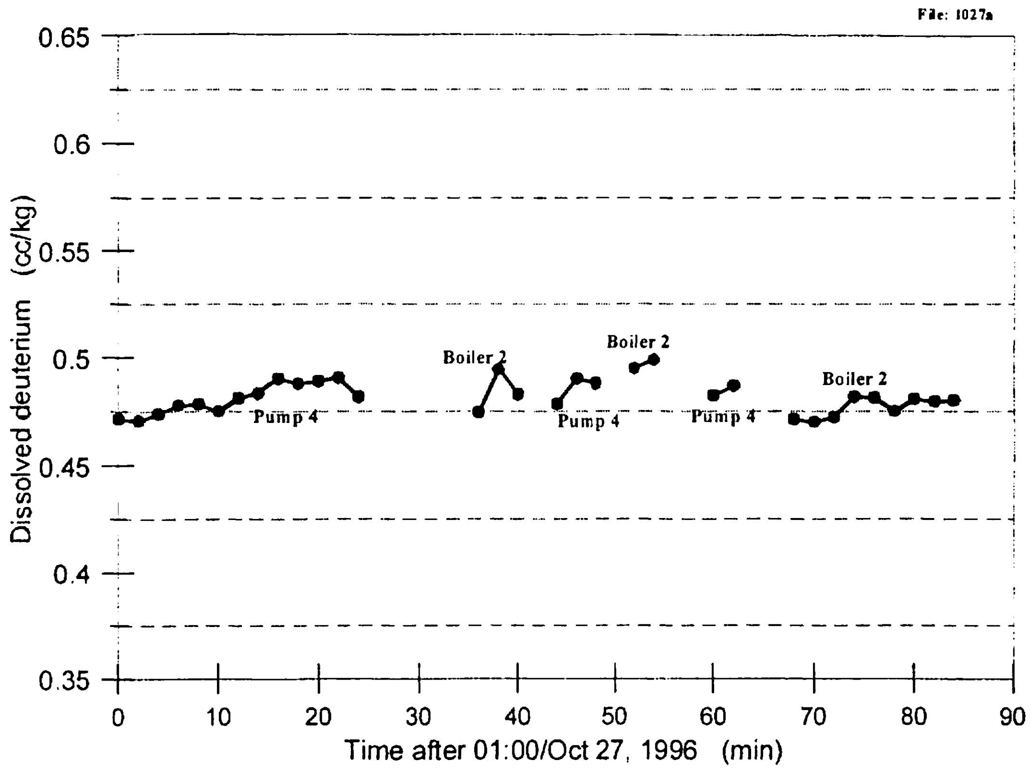


Figure 10 Typical dissolved deuterium data obtained with an on-line Orbisphere Analyzer when there was no boiling in the PHT loops.
Reactor power: 30%

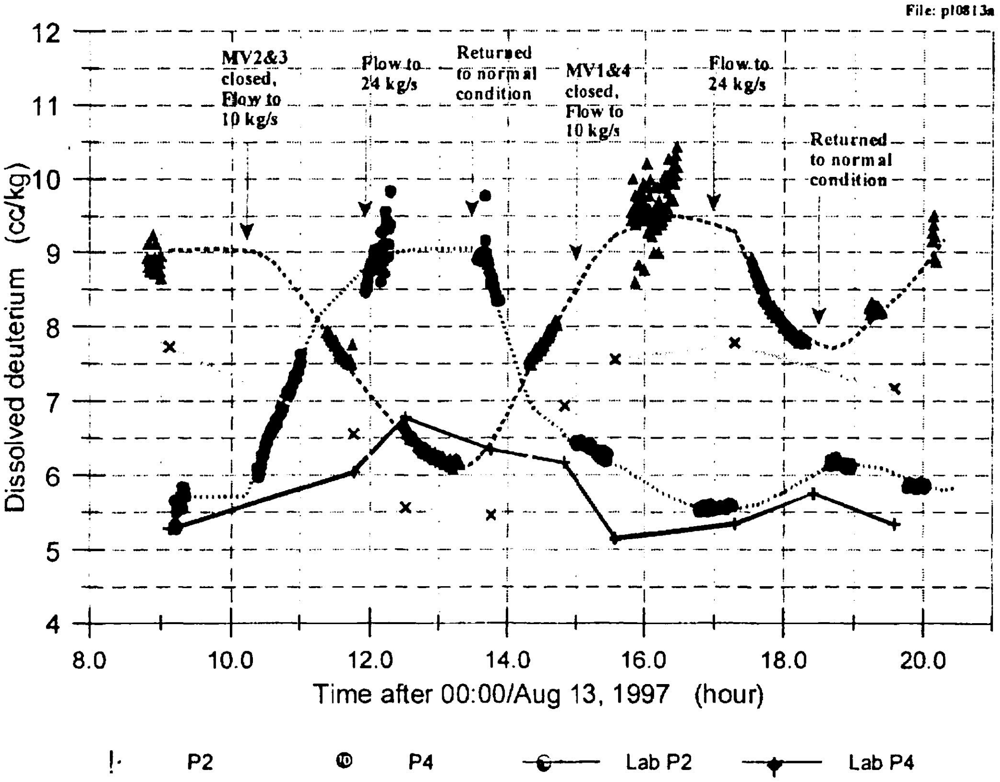


Figure 11 Measured responses of dissolved deuterium concentrations in the two loops to the direction and rate of the flows through the pressurizer inter-connect pipe.

NOTES:

1. The dashed lines are the projected values;
2. The pressurizer flow was equal to the purification flow and the direction is from loop 1 to loop 2 when MV2 and MV3 were closed. Similarly the direction was from loop 2 to loop 1 and the pressurizer flow was equal to the purification flow when MV1 and MV4 were closed.

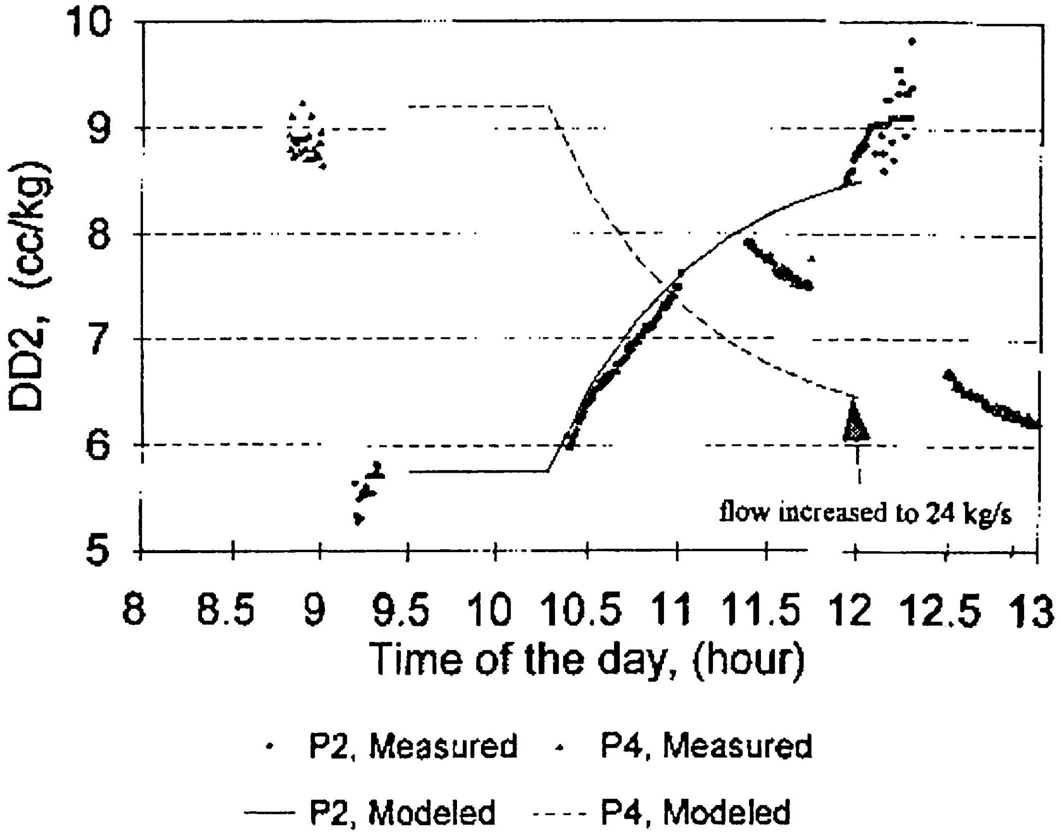


Figure 12 Comparison between the theoretical and measured responses of dissolved deuterium concentrations in the two loops after the initiation of a constant flow from loop 1 to loop 2 through the pressurizer inter-connect pipe.

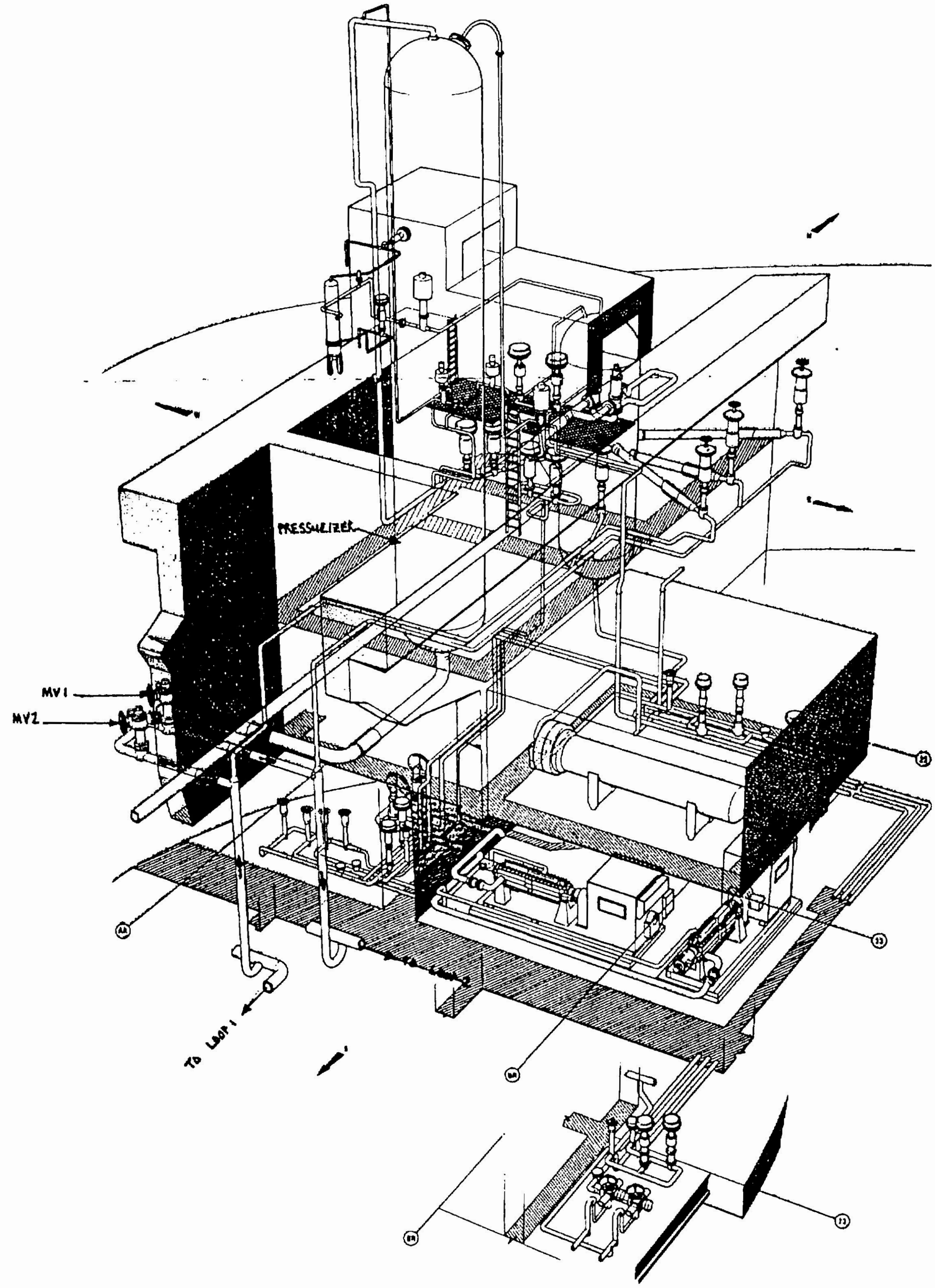


Figure 13 - General Arrangement of Pressurizer Interconnect Piping

Appendix A

Dissolved Deuterium Concentration in the Samples from Boiler Inlet and Pump Discharge Measured at GNGS[7]

Time of measurements	LOOP 2 Boiler Inlet	LOOP 2 Pump Discharge	RATIO, Boiler Inlet to Pump Discharge
1995 June 13 at 15:00	1.70	2.53	0.672
1995 June 14 at 08:20	2.2	2.76	0.797
Average			0.735