NATURAL CIRCULATION IN AN INTEGRAL CANDU TEST FACILITY*

P.J. INGHAM[1], J.C. LUXAT[2], A.J. MELNYK[3], T.V. SANDERSON[1]

[1]Safety Thermalhydraulics Branch, AECL Whiteshell Laboratories, Pinawa, Manitoba

[2]Nuclear Safety Technology, Ontario Hydro Nuclear, Toronto, Ontario

[3]Emission Management Technology, AECL Chalk River Laboratories, Deep River, Ontario

Canada

Abstract

Over 70 single- and two-phase natural circulation experiments have been completed in the RD-14M facility, an integral CANDU thermalhydraulic test loop. This paper describes the RD-14M facility and provides an overview of the impact of key parameters on the results of natural circulation experiments. Particular emphasis will be on phenomena which led to heat up at high system inventories in a small subset of experiments. Clarification of misunderstandings in a recently published comparison of the effectiveness of natural circulation flows in RD-14M to integral facilities simulating other reactor geometries will also be provided.

1. INTRODUCTION

Under certain postulated accident conditions decay heat is removed from the core of a nuclear reactor by single- or two-phase natural circulation of the primary coolant. An important nuclear safety consideration is to establish that decay heat can be adequately removed in these situations.

Experiments have been conducted in the RD-14M integral test facility located at AECL's Whiteshell Laboratories, Manitoba, Canada, to gain a better understanding of the probable behaviour of natural circulation in a CANDU® type heat transport system. The data collected from these tests is used to identify and examine relevant phenomena and assist in model development. An electronic database of all experiments has been developed to aid in the validation of computer models used for safety analysis and licensing.

2. FACILTY DESCRIPTION

Figure 1 shows a simplified schematic of RD-14M, a multiple-heated channel, full-elevation, scaled, integral test facility, possessing most of the key components of a CANDU Primary Heat Transport System (PHTS). The facility is arranged in the standard CANDU two-pass figure-of-eight configuration. The facility is designed to produce similar fluid mass flux, transit time and pressure and enthalpy distributions as those typical of CANDU reactors under both forced and natural circulation conditions [1].

---

* Funded by the CANDU Owners Group (COG) through the Safety Thermalhydraulics Working Party 5

** Nuclear Safety Technology, Ontario Hydro Nuclear, Toronto, Ontario, Canada, M5G 1X6

***Emission Management Technology, AECL Chalk River Laboratories, Deep River, Ontario, Canada, KOJ 1JO

® CANDU is a registered trademark of Atomic Energy of Canada Limited (AECL)

The reactor core is simulated by ten, 6 m-long horizontal test sections. Each test section has simulated endfittings and seven electrical heaters, or fuel element simulators (FES), designed to have many of the characteristics of a CANDU fuel bundle. Test sections are connected to headers via full-length insulated feeders. Feeders are equipped with trace heating tapes to minimise heat losses

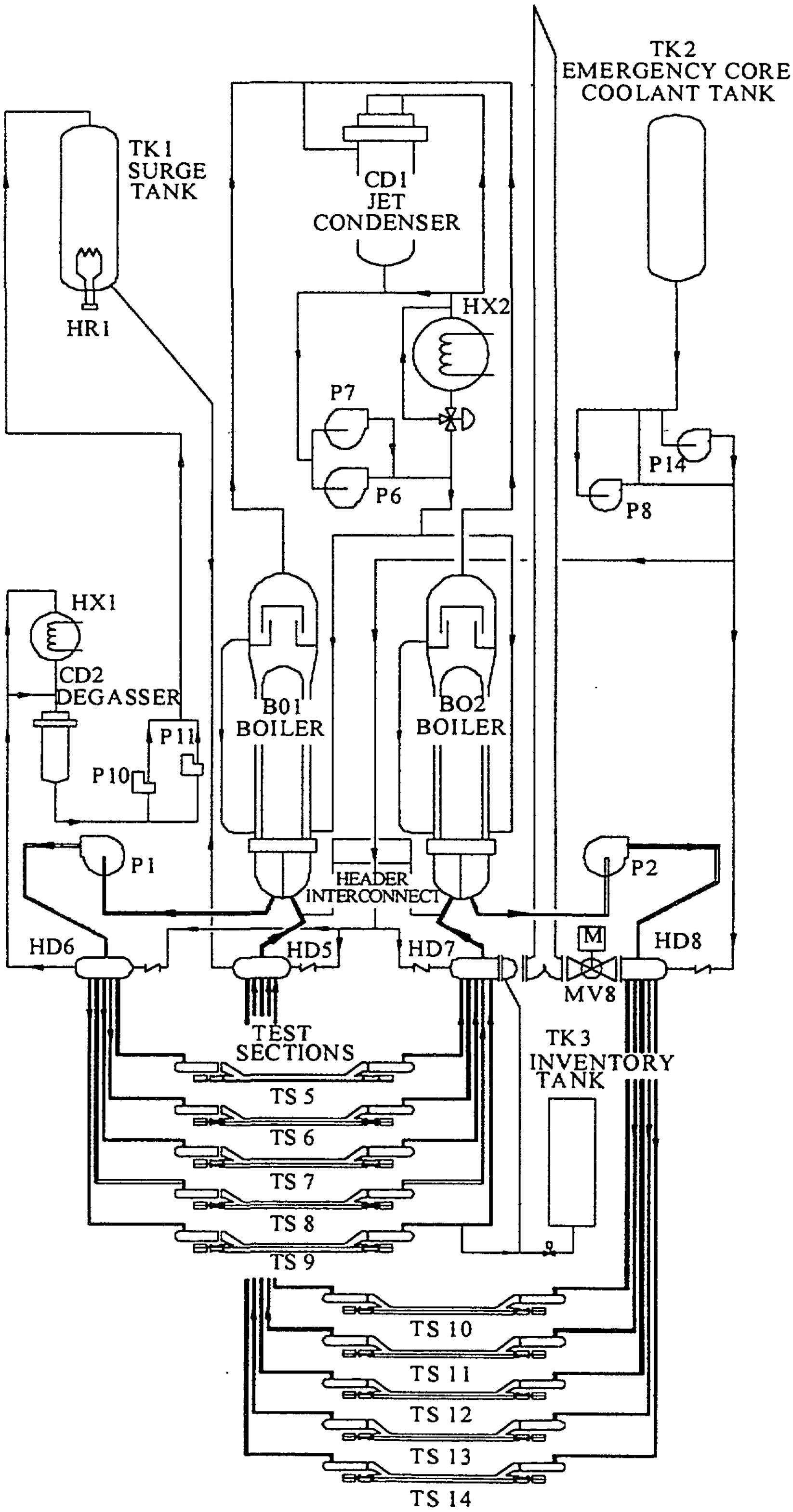

FIG. 1. Schematic of the RD-14M integral CANDU test facility

under natural circulation conditions. Pipework connecting outlet headers can also be valved in to study the effect of outlet header interconnect geometry on mitigating oscillatory behaviour at full and low power conditions.

Above header piping is also CANDU-typical including two full-height, U-tube steam generators or boilers (BO1 and B02) and two bottom-suction centrifugal pumps (P1 and P2). Steam generated in the secondary, or shell, side of the steam generators is condensed in a jet condenser (CD1) and returned as feedwater to the boilers. For natural circulation experiments conducted post 1990 a customised secondary system, designed to operate at reduced power levels typically encountered under natural circulation conditions, was utilised.

The primary-side pressure is controlled by a pressurizer/surge tank (TK1) using a 100-kW electric heater (HR1). The facility operates at typical CANDU primary system pressures and temperatures (typically 10 MPa(g) and 310°C at the outlet header).

For the natural circulation experiments described in this paper, fluid removed from the primary circuit at header 7 (HDR7) is cooled and stored in an inventory tank (TK3). Level monitoring of the inventory tank provides a record of the quantity of primary fluid removed.

The RD-14M facility is extensively instrumented. FES sheath and centre line temperatures up to 1000 °C can be measured axially in five of the seven heaters in each simulated fuel channel to provide a comprehensive picture of the FES temperature distribution. In addition flow, temperature, pressure and the void fraction of the fluid entering and leaving each test section is measured. Gamma densitometers are used to measure the void fraction of fluid at the entrance and exit to both steam generators and at the discharge of both pumps. Fluid temperature, pressure and flow rates are measured at regular intervals throughout the facility. In addition, over 50 differential pressure measurements provide an accurate picture of the pressure distribution throughout the facility. Key secondary-side measurements such as pressure, steam flow rate and temperature, feed water temperature and flow rate and internal shell-side recirculation rate are also recorded. Overall, approximately 600 instruments are scanned and recorded using a dedicated data acquisition system.

3.0. NATURAL CIRCULATION EXPERIMENTS

3.1. Test conditions

To date over 70 natural circulation experiments have been completed in RD-14M. Various parameters have been investigated as summarised in Table I.

TABLE I. RD-14M NATURAL CIRCULATION EXPERIMENTAL TEST CONDITIONS INVESTIGATED

CONDITION VARIED	RANGE INVESTIGATED
POWER	160,100 and 60 kW/pass
SECONDARY-SIDE PRESSURE	4.5, 4.0, 1.0, and 0.1 MPa(g)
SURGE TANK	on/off
DRAIN RATE	0.03 to 0.2 L/s
SECONDARY-SIDE SYSTEM	High / Low Power
OUTLET HEADER INTERCONNECTS	Dynamic and Geometric Scaled
ECI ADDITION	15-33 L/s
MAKE-UP WATER ADDITION	0.08 kg/s
ECI ISOLATION VALVES	open/closed
TRACE HEATING	on/off

3.2. Test procedure

Prior to the start of each test single-phase natural circulation was established and maintained for several hours at the required test conditions. When steady-state conditions were reached, data collection was initiated and several minutes of steady-state data were collected. The primary inventory was then reduced through a series of discrete drains, from header 7 into the inventory tank. Drains were separated by periods where no perturbations were intentionally introduced to allow steady-state conditions to re-establish. The drains continued until a process protection trip on high FES sheath temperatures, 600°C, was reached terminating the experiment. Slower drain rates with longer periods between drains were used in tests conducted after 1990.

4. NATURAL CIRCULATION BEHAVIOUR

In all RD-14M natural circulation tests the individual channel flows were uni-directional at the start of the test. Once draining started and saturation pressure was reached void was detected in the hot leg regions of the loop. The presence of void increased flow rates throughout the loop due to an increase in the buoyancy driving force. As the primary inventory was further reduced a maximum flow rate through the steam generators was eventually reached. Subsequent reduction in the primary inventory resulted in a decrease in flow rates. In tests conducted at the higher pressures and powers, unidirectional flow was maintained throughout this stage. It is suspected that the reduction of flow resulted from a degradation in the steam generator buoyancy driving force component arising from the penetration of void into the cold leg regions of the steam generators. This phenomenon has also been postulated to explain similar behaviour in integral PWR experiments [2]. In RD-14M high pressure, high power tests (>4 MPa(g) and at 160 kW/pass), further reduction of the primary inventory lead to the establishment of an adverse pressure gradient in the steam generators. This adverse pressure gradient eventually offset the forward buoyancy driving component in the highest elevation feeders resulting in flow reversal in these channels in some tests at about 85% inventory. In all cases, core cooling was maintained even after the onset of bi-directional flow. Tests conducted at these conditions have been captured using existing simple models [3].

In tests carried out at lower secondary-side pressures ($P \leq 1.0$ MPa(g)), flows were highly oscillatory at high primary inventories and exhibited highly dynamic behaviour. Flow reversed preferentially in some channels at primary inventories of 95-90% as a result of statistically characterised lags between steam generator and feeder pressure drop components. Channels having long horizontal feeder sections immediately adjacent the end-fittings generally had the largest lags and were most vulnerable to flow reversal.

In all tests, at high and low pressures, continued reduction in primary inventory was accompanied by additional channel flow reversals. While bi-directional flow in the channels caused a break down in net flow through the loop as measured through the steam generators, it did not cause a simultaneous breakdown in core or channel cooling as shown in Figure 2. This suggests that reflux-condensation in the steam generators became the prime heat rejection mechanism at lower inventories. Similar behaviour is also reported for PWR integral tests [2].

In the overwhelming majority of tests FES heatup did not occur until primary fluid inventories were reduced to less than 70%. A small subset of tests carried out at powers of 160 kW/pass and a secondary-side pressure of 1.0 MPa(g) has been the focus of particular interest as FES heatup occurred at primary fluid inventories greater than 85%.

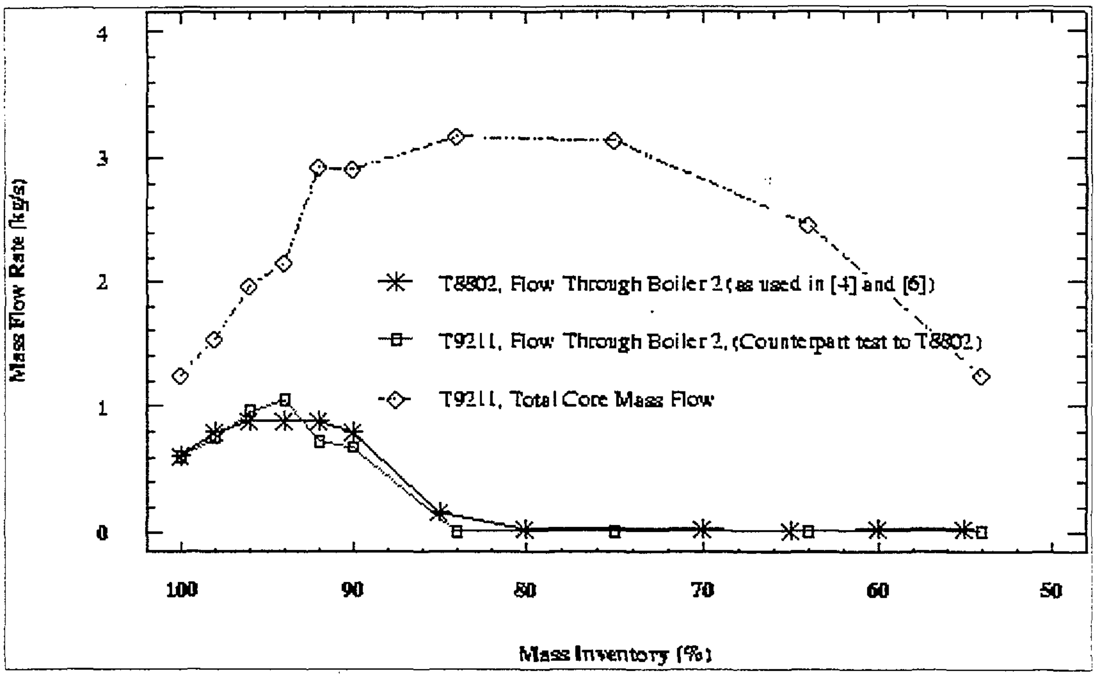

FIG. 2. Comparison of above header and total core flow in RD-14M

4.1. Dryout at high primary fluid inventories

Dryout at primary inventories greater than 85% resulting in FES temperature excursions in excess of 600°C only occurred in 3 natural circulation experiments carried out at primary powers of 160 kW/pass and a secondary side pressure of 1.0 MPa(g). Six other tests conducted under similar conditions did not experience dryout at inventories greater than 70%. In all cases dryout did not occur until the flow in at least 2 of the 5 channels in a pass was reversed.

At these test conditions, the net buoyancy driving force component from the steam generators becomes negligible by about 90% inventory. Individual channel flow is driven by the feeder buoyancy component, which is made up of the liquid filled inflow feeder and a highly voided outflow feeder. In these 3 tests, dryout occurred following a continuous reduction in the pressure drop in the inflow feeder which caused a proportional reduction in the flow through the channel. Inflow feeder gamma densitometer and pressure drop measurements indicate this reduction was caused by void penetration of the inflow feeder (VPIF). Gamma densitometers are located on the feeder piping near the inlet and outlet of each channel. Since void is observed in the feeder, as inferred from pressure drop measurements, prior to being detected by the gamma densitometers, the void does not seem to have originated in the test section (Fig. 3).

All 9 tests showed evidence of void in an inflow feeder at some time following the onset of flow reversal. In fact, a review of natural circulation experiments conducted at other test conditions showed
VPIF to be a common phenomenon. However, in all but these 3 tests the extent of void penetration of the inflow feeder was limited to an intermediate level and only resulted in a partial degradation of channel flow. In some cases, inflow feeders appeared to refill after a period of several minutes, in other cases inflow feeders remained partially voided for several hours. In these latter situations flow through the channels was reduced but did not totally break down. In

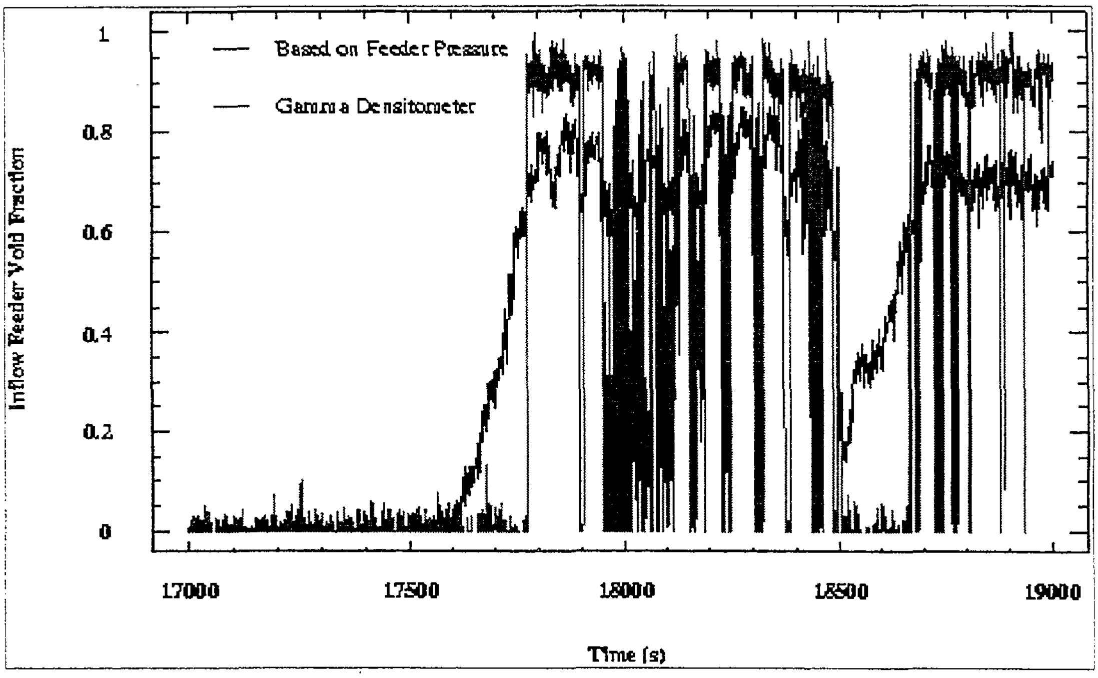

FIG. 3. Appearance of void in the inflow feeder

the three tests experiencing dryout at high inventories, void penetrated the inflow feeder until there was no net buoyancy driving flow in one channel. Flow in all other channels remained sufficient to provide channel cooling. In tests T8809, T8810 and T9308, VPIF, and subsequent dryout, was induced by a depressurization caused by a draining operation as shown in Figure 4.

To obtain more information on conditions leading to dryout at high primary inventories and to establish limits of FES temperature excursions additional tests were carried out. These tests were conducted at power levels of 160 kW/pass and a secondary side pressure of 1.0 MPa(g). FES trips were set at 800 °C as an extrapolation of these earlier results suggested that the FES temperatures would have approached an asymptotic limit close to 700 °C had a process protection trip at 600 °C not occurred. Primary inventories were limited to greater than 80%. Primary coolant draining and/or small changes to the secondary side (10%) were used to induce dryout. Although 69 of the previous 70 natural circulation experiments had trace heating applied to the inlet and outlet feeder piping in these tests feeder trace heating was initially off.

Results from these tests showed that without trace heating only limited VPIF of Test Section 7 (TS7) and TS12 inflow feeders could be induced (Figure 5) and FES temperature excursions were limited to less than 300 °C. Turning on the trace heating resulted in immediate but limited VPIF in some inflow feeders (Figure 5). Further VPIF phenomena were then readily induced by secondary side perturbations (Figure 6). A maximum FES temperature of 675 °C was reached prior to quenching in TS 11 at a primary inventory greater than 85% (Figure 7).

4.2. VPIF mechanisms

It still is not clear why dryout occurred in only T8809, T8810 and T9308. However, it should be noted that T88 tests had a drain rate three times that of subsequent tests and an unplanned secondary side pressure transient during the drain prior to dryout occurred in T9308. It should also be noted that dryout only occurred at these test conditions in a reversed channel

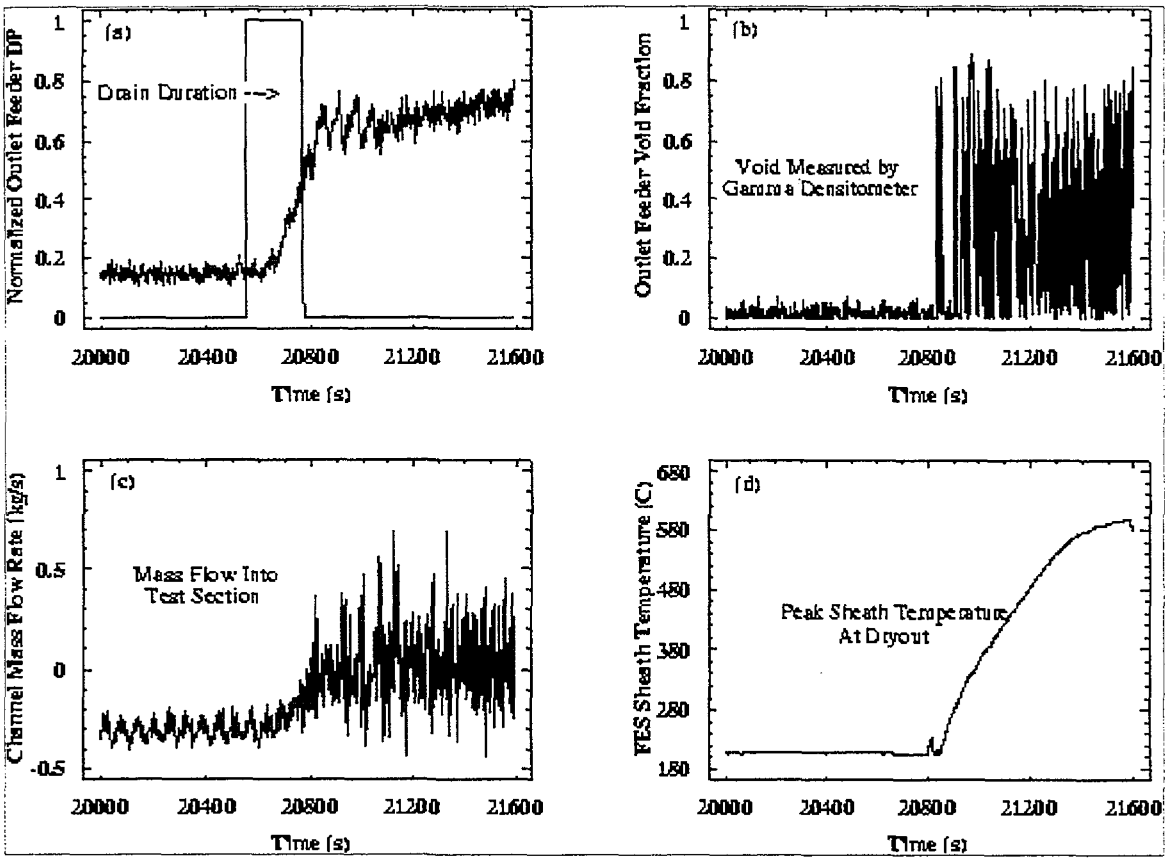

FIG. 4. RD-14M test T9308 (a) VPIF induced by draining, (b) void measured at the inflow of the test section, (c) mass flow through the channel is reduced, (d) dry out occurs at 87% mass inventory

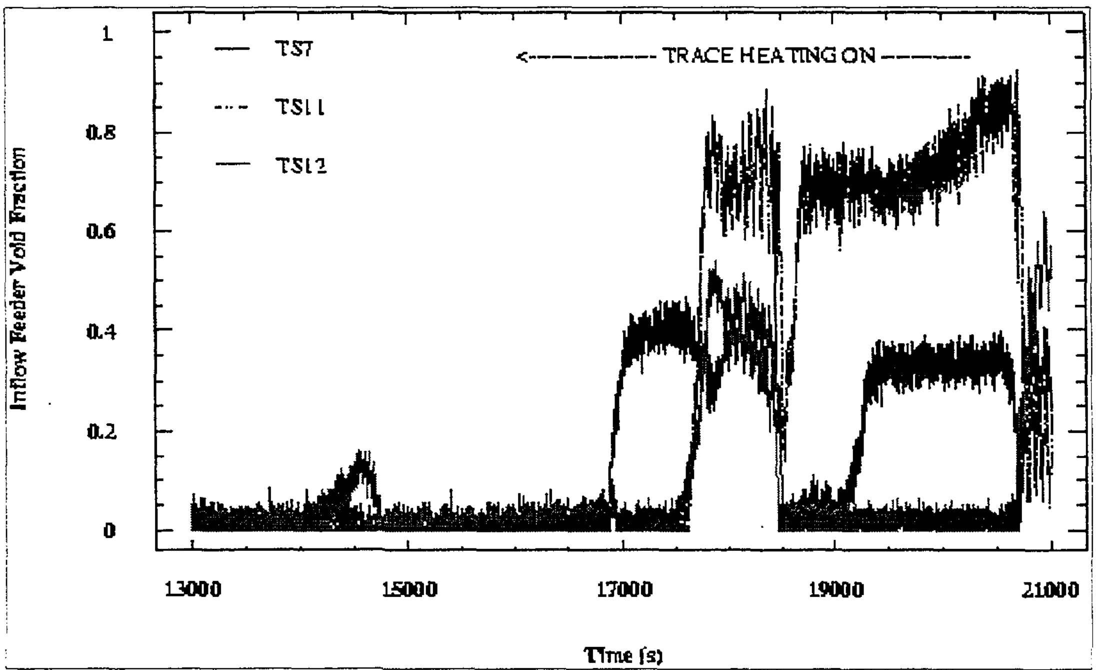

FIG. 5. The effect of feeder trace heating on VPIF

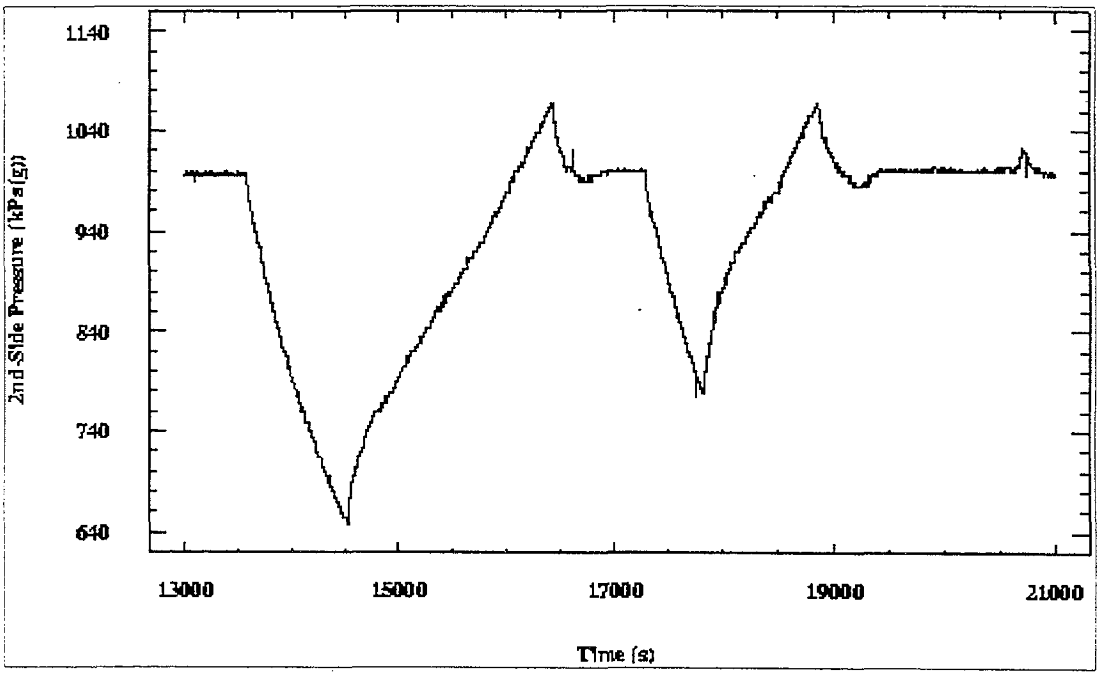

FIG. 6. Secondary side pressure transient

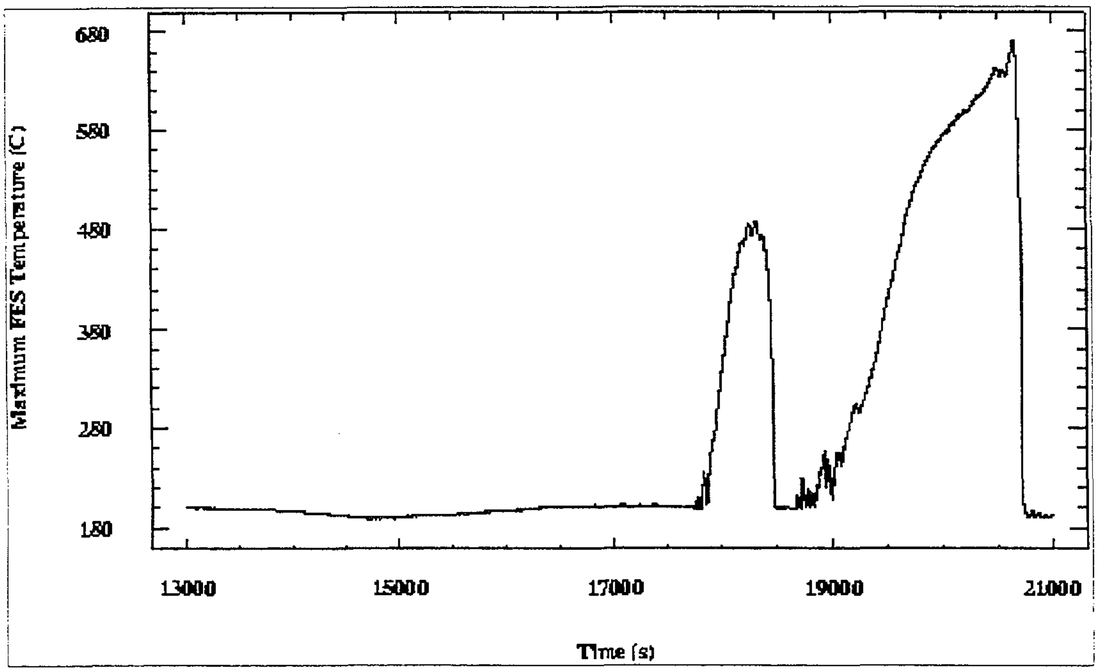

FIG. 7. Test section 11 FES temperature transient

following the second channel flow reversal. Under this circumstance fluid entering the inflow feeder is at saturation temperature. A brief explanation of the various hypotheses as to the cause of VPIF follows.

Steam bubble entrainment and flashing were mechanisms considered. For steam bubble entrainment, the drag forces exceed buoyancy forces causing steam bubbles to be dragged from the header into the feeder. This mechanism should be self limiting and self correcting as a result of reduction in drag forces caused by flow reduction and bubble coalescence. Flashing would imply that void production is solely due to depressurization. This is highly unlikely since all saturated feeders should be effected instead of only a few. Flow induced flashing was also considered. This is attributable to frictional pressure drop and is highly unlikely due to the very low flow rates. This is a self correcting and non sustainable mechanism.

Liquid starvation is a mechanism where an adverse distribution of void in the headers exists such that insufficient liquid is available at the header/feeder interface to offset the flow from the feeder into the channel. Depending on the availability of liquid from the header, the liquid level in the feeder and consequently the flow into the channel will drop until a new steady-state is reached, or in extreme cases, until total flow breakdown occurs and dryout results.

Test data suggests the void entering the feeders originates from the headers and indicates that the void distribution inside the header is extremely complex. Both axial and radial variations must occur with more void present at lower elevations within the header. No direct measurements of void in the RD-14M headers are currently available. However, recent separate effect tests using an instrumented RD-14M inlet header, although not conducted at conditions expected during natural circulation, confirm these variations are possible. Work is presently continuing to extend the study of the distribution of void in RD-14M headers to conditions more typical of natural circulation.

4.3. Complicating factors affecting VPIF mechanisms

Trace heating has a marked effect on VPIF. The trace heating used for natural circulation tests in RD-14M is fixed at the start of the test and is not controllable. Following the onset of bi-directional flow, the added energy may exceed the actual heat losses and void may be generated in the inflow feeder. Trace heating also inhibits void collapse. Experiments are planned to examine this effect.

Feeder metal mass temperature can also effect VPIF. As the primary pressure drops with each subsequent drain, the saturation temperature of the fluid is reduced, possibly below the temperature of the metal pipe. Additional void production may result as stored energy from the pipe walls is transferred to the fluid. Pressure vessel requirements have resulted in an increase in the relative metal to fluid mass ratio from that expected in typical CANDU headers and feeders. Experiments are planned to study this effect as well.

5. CLARIFICATION OF A RECENT COMPARISON OF NATURAL CIRCULATION FLOWS IN OTHER INTEGRAL FACILITIES

Differences in the geometrical configuration between the CANDU PHTS and other reactor systems make direct comparison of natural circulation results difficult. Although many similarities in natural circulation phenomena between CANDU and PWR's have been identified, the multiple, horizontal-channel reactor core allows phenomena like individual channel flow reversal to occur which do not have a counterpart in other systems.

Recently, a quantitative comparison of the effectiveness of natural circulation flows in the CANDU type RD-14M facility and integral facilities simulating PWR and WWER geometries was published [4]. The RD-14M data presented in this comparison was inappropriately extracted and interpreted from an early paper for test T8802 [5]. The authors of this comparison incorrectly

TABLE II. INITIAL CONDITIONS, BOUNDARY CONDITIONS AND KEY EXPERIMENTAL RESULTS FOR COUNTERPART EXPERIMENTS T8802 AND T9211

PARAMETER / RESULT	T8802	T9211
INITIAL PRIMARY PRESSURE (MPa(g))	8.0	7.0
SECONDARY-SIDE PRESSURE (MPa(g))	4.3	4.0
PASS 1 - TOTAL POWER (kW)	100.0	101.9
PASS 2 - TOTAL POWER (kW)	101.5	101.7
INITIAL HEADER 5 TEMPERATURE (°C)	264.2	259.5
INITIAL HEADER 6 TEMPERATURE (°C)	246.9	242.9
INITIAL HEADER 7 TEMPERATURE (°C)	264.8	260.4
INITIAL HEADER 8 TEMPERATURE (°C)	248.0	244.1
TRACE HEATING (kW)	22.0	22.0
BOILER FEEDWATER TEMPERATURE (°C)	57.1	164.9
% MASS INVENTORY OF FIRST CHANNEL TO REVERSE (CHANNEL NUMBER) - PASS 1	84% (HS5)	91% (HS7)
% MASS INVENTORY OF SECOND CHANNEL TO REVERSE (CHANNEL NUMBER) - PASS 1	84% (HS7)	82% (HS7)
% MASS INVENTORY OF FIRST CHANNEL TO REVERSE (CHANNEL NUMBER) - PASS 2	89% (HS10)	91% (HS12)
% MASS INVENTORY OF SECOND CHANNEL TO REVERSE (CHANNEL NUMBER) - PASS 2	84% (HS11 & HS14)	82% (HS14)
% MASS INVENTORY WHERE FLOW THROUGH BOILERS BREAKS DOWN[a]	84%	82%
% MASS INVENTORY AT DRY OUT[b] (CHANNEL NUMBER)	48% (HS7)	48% (HS8)

[a] Breakdown of flow through the boilers based on stalling of above header turbine flow meters. These meters stall at flows below 0.4 L/s.

[b] Dry out based on first channel to have at least two fuel element simulator temperatures exceed 600°C.

assumed the core flow for the RD-14M test was equivalent to the reported flow through only one of the steam generators [6]. Because of the figure-of-eight configuration, this assumption is a factor of two too low under strictly unidirectional flow conditions. The error in this assumption becomes even greater following the onset of channel flow reversal. The RD-14M experimental data used is not consistent with the author's analysis methodology. As a consequence, the magnitudes of RD-14M natural circulation flows are severely underestimated.

Core mass flow rates for the RD-14M test used in this comparison, T8802, cannot be calculated due to insufficient instrumentation in this early test. However, a more recent, better instrumented test, T9211, was conducted at the same nominal conditions as T8802. Test T9211 was the only test conducted using similar conditions and test procedure. Experimental results for T9211 are comparable to T8802 as shown in Figure 2. The similarity between these two tests is also illustrated in Table II where initial conditions, boundary conditions and key experimental results are compared. Important results to note include the similarity of inventory for the first and second flow reversals, breakdown of flow through the boilers and break down of flow in one of the channels (dry out).

The core mass flow rate is obtained by adding the mass flow rate through each channel. Individual channel mass flows are determined by correcting single-phase inflow feeder flow rate measurements made at steady-state conditions at each inventory for density.

To make an accurate comparison of RD-14M with other facilities, the total core mass flow as shown in Figure 2 should have been used in Ref. [4] instead of the flow through only one of the steam generators. As illustrated in Figure 2, both the effective range and the magnitude of the core mass flow rates are significantly larger than the values used in assessing RD-14M results. The referenced comparison implies significant core flow rates only occur over a narrow range of primary inventories (82 to 100%), whereas in reality effective core flow rates were measured at inventories as low as 48%. Similarly, the actual maximum core mass flow rate is a factor of three higher than that in the data used in the referenced comparison. It is unfortunate that the differences in facility configurations and the nature of the data used in this comparison were misunderstood. The impact of these oversights is a gross underestimation of the core cooling effectiveness of natural circulation in CANDU geometries. Superimposition of the correct data on the published comparison clearly demonstrates that natural circulation flows in a CANDU type facility are quantitatively as high, if not higher, than flows encountered in integral facilities representing PWR and WWER geometries.

6. SUMMARY

The key features of RD-14M, an integral CANDU test facility, have been described. An overview of the general behaviour observed in RD-14M natural circulation experiments has been discussed. Void penetration of inflow feeders (VPIF) has been identified as the mechanism responsible for early heatup in a small subset of tests. For these tests, heatup is limited to FES temperatures less than 700 °C and is followed by quenching. VPIF probably originates in the RD-14M headers and is strongly coupled with both header conditions and feeder trace heating.

Natural circulation flows in RD-14M, when accurately compared on a quantitative basis to those found in integral facilities representing PWR and WWER geometries, are as good if not better.

In essence, RD-14M natural circulation results are understood and explainable. They provide a valuable experimental data base for development and validation of physical models.

REFERENCES

[1] INGHAM, P.J., et al, "Scaling laws for simulating the CANDU heat transport system", Proc. 2nd Intern. Conf. Sim. Meth in Nucl. Engrg.,Montreal, Canada (1986)

[2] DUFFEY, R.B., SURSOCK, J.P., "Natural circulation phenomena relevant to small breaks and transients", Nucl. Engrg. Des., 102,115-128. (1987)

[3] WAN, P. T., et al, "Modelling of RD-14M partial-inventory thermosiphoning tests using the OHAT code", 4th Intern. Sim. Meth. Conf., Montreal, Canada, (1993)

[4] D'AURIA, F. and GALASSI, G.M., "Code validation and uncertainties in system thermalhydraulics", Progress In Nuclear Energy, Vol. 33. No.1/2. Pp175-216, (1998)

[5] MELNYK, A.J.,AECL, D'AURIA, F., University of Pisa, personal communication, 1997 February 20

[6] INGHAM, P.J., et al., "Natural circulation experiments in RD-14M with emergency coolant injection", ANS Intern. Top. Meetg.-Safety of Thermal Reactors, Portland, Oregan, USA (1991)