RECENT ADVANCES IN ULTRASONIC DOWNCOMER FLOW-MEASUREMENT TECHNIQUES FOR RECIRCULATING STEAM GENERATORS

Victor Janzen, Brian Luloff, Sujin Wren, Will Luff,
Atomic Energy of Canada Ltd.
Ken Sedman, Greg Galan,
Bruce Power

Non-intrusive ultrasonic measurements of downcomer flow velocity have been successfully used in the past to determine recirculation ratios and water inventory in CANDU steam generators. Knowledge of these process conditions allows operators to assess the effectiveness of maintenance programs, monitor the effects of tube fouling, and observe flow conditions following component modifications. It also provides designers with a means to verify or improve code predictions.

Ultrasonic measurement systems have recently been installed on sixteen steam generators at the Bruce B Nuclear Generating Station, as part of an investigation into the possible effects of long-term boiler degradation. The most recent version of AECL's downcomer-flow technology was used, which features high-temperature transducers that are attached magnetically and then welded to the steam-generator outer shell. This method eliminates the complications of precision surface preparation, high-temperature couplants and awkward mechanical attachments. The paper will outline the method and summarize flow velocities measured during normal operation, over extended periods of time. It will also describe how the information might be used, e.g., to assess thermalhydraulic conditions, verify design calculations and support the case for reactor uprating. Further improvements that may allow the reliable measurement of flow in steam generators with steam carry-under are suggested, and preliminary results are presented from a dual-purpose single- and two-phase flow-measurement system.

KEYWORDS: Steam Generator, Downcomer, Flow Measurement, Ultrasonic Flowmeter

1. INTRODUCTION

The performance of steam generators is critical to the overall efficiency and reliability of nuclear power plants. Generally speaking, steam-generator thermalhydraulic performance is inferred from parameters measured elsewhere in the plant, e.g., the Reactor Inlet Header Temperature, and the condition of steam-generator components is monitored by periodic visual and non-destructive-examination (NDE) inspections. The flow velocity in the outer downcomer annulus (see Figure 1) can serve as a direct, dynamic measure of steam-generator performance, since it can be continually measured during operation and can be directly linked to recirculation ratio and water inventory with the use of simple thermalhydraulic correlations. However, the flow in operating steam generators is often not monitored as a general practice, partly because standard intrusive flow-measurement techniques present many practical problems and safety concerns. Without a demonstrated robust flow-measurement system capable of low maintenance and high reliability factors over the long term, shell-side flow measurements have often only been considered necessary after steam-generator performance has become a significant issue.

Recently, there has been increased interest in assessing the performance of steam generators (SGs), in particular those being considered for refurbishment or life extension and those in mid-life with degradation problems. Over the past two years AECL, Bruce Power and Babcock & Wilcox Canada have teamed up to measure downcomer flow velocities in a total of sixteen steam generators (boilers) at the Bruce B Nuclear Generating Station (NGS). The installation of flow-measurement systems was initiated as part of a Root Cause Investigation into the tube support plate degradation observed in some Unit 8 boilers, and subsequently in boilers belonging to other Units. The intent was to convert downcomer flow velocities to recirculation ratios, which could then be compared with theoretical calculations and used as input to thermalhydraulic analyses of the condition of the boilers.

A limited number of non-intrusive methods are available to measure flow in reactor components, chief among them being ultrasonic (UT) methods, e.g., References [1] to [5]. For the cases described here, downcomer flow velocities were measured with an upgraded version of the non-intrusive ultrasonic system previously used in Darlington and Bruce NGS [1,2]. For Bruce B steam generators, the relatively simple "transit-time" technique was chosen because it is appropriate for single-phase (liquid) flow, i.e., for SGs where there is no steam carry-under in the downcomer flow. Previous measurements at Bruce B Unit 8 Boiler 8 (U8B8) had shown that this was the case.

This paper summarizes the development of the flow-measurement systems at Chalk River Laboratories and their installation of the downcomer flow-measurement systems at Bruce B NGS. It updates results previously presented at an earlier stage of the project. This information can be used to validate thermalhydraulic codes, investigate correlations with boiler operating parameters, establish long-term trends in SG performance and support cases for reactor uprating.

Most recently, there has been some interest in measuring flow in Bruce A boilers, in which the downcomer flow path likely contains a certain amount of steam carry-under. This paper describes some of the methods that could be used for carrying out these measurements, and presents preliminary results from prototype systems capable of measuring two-phase flow at high temperatures.

2. ULTRASONIC TRANSIT-TIME FLOW MEASUREMENT SYSTEMS

Ultrasonic transit-time flow measurement is based on knowledge of the flow-channel geometry and the speed of sound in various media. A typical steam generator geometry for transit-time flow measurements is shown in Figure 2. Ultrasonic pulses are alternately sent and received between upstream and downstream transducers attached to the exterior of the shell. A number of sound-wave paths are possible; the two of interest are the "short-circuit" path along the shell directly between the two transducers, which can be used for diagnostic purposes, and the path shown by the dashed line in Figure 2 that twice traverses the downcomer annulus. For the portion of that path through liquid the sound pulses travelling from the upstream transducer will reach the opposite transducer faster than those travelling from the downstream transducer, because the pulses travelling from the upstream transducer are moving with the water flow. The difference in the time-of-flight between upstream- and downstream-travelling pulses is directly proportional to the downcomer flow velocity [1].

The microprocessor-controlled flow meter sends pulses alternately from the upstream and downstream transducers, searching each time for pulses received within a time window that is based on input geometry and soundspeed parameters that include the effects of temperature. User input includes type and thickness of media (transducer wave guide, SG shell and downcomerfluid), number of passes, distance between transducers, and temperature. If pulses are detected within the calculated window, the signal quality must be verified according to criteria set by the user. After a preset number of successful transmit and receive cycles, the flow meter will calculate and output flow data including the flow velocity and various diagnostic messages and/or parameters.

User inputs such as the steam generator shell thickness and the width of the downcomer annulus must be accurate to ensure that the velocity reading is correct. The shell thickness is required to properly calculate the transducer spacing. The annulus width is particularly important since it is inversely proportional to the measured flow velocity [1]. For example, if the annulus width that is input to the flow meter is 10% larger than the actual annulus width, the measured flow velocity will be 9% lower than the actual flow velocity. For this reason, and as an independent check on the ultrasound transmission properties, the annulus width (and the shell wall thickness) are now measured independently with a normal-beam UT probe, as described in Section 4.1.

An OKS™-type[1] ultrasonic transducer, the type now commonly used to measure downcomer flow, is shown in Figure 3, along with a custom-made mounting bracket used to attach a Resistive Thermal Device (RTD). The RTD measures the temperature partway along the thermal-standoff buffer (steel shaft) connecting the UT crystal housing (low temperature) to the welded "foot" (high temperature). These temperature measurements provide a check that the boilers are at or near operational temperature and that the UT crystals are at a safe operating temperature.

The GE Infrastructure Sensing (formerly Panametrics) DF868 flowmeters used in these measurements have a front-panel display and a built-in data logger which records up to three user-defined flow parameters and any error/diagnostic messages at pre-set time intervals. Generally, for this application the measured flow velocity, measured RTD temperature and the fluid soundspeed calculated by the flowmeter were logged. The soundspeed, derived from the average velocity for the upstream and downstream traverses, serves as a check that the flowmeter has properly identified the timing pulses used for calculating the flow velocity. Flow velocities obtained in this manner typically have measurement uncertainties of approximately ±10% [1] for velocities of the order of 2 m/s, with a repeatability of ±5% or better.

3. TRANSDUCER ATTACHMENT TO BOILERS

The interface between the transducers and the boiler shell is critical to the successful passage of ultrasonic pulses to and from the OKS transducers. Even a very small gap or the presence of small voids between the transducer and the vessel wall leads to unwanted scattering and

[1] OKS™ is a product designation of GE Infrastructure Sensing, the developer and manufacturer of this particular type of high-temperature ultrasonic transducers.

absorption of the signal energy, lowering signal strength and producing background noise. Earlier installations (ca. 1997-99) relied on achieving a smooth and parallel mounting surface that was obtained by painstaking grinding and polishing in the field, and they used a soft metallic foil sandwich as an ultrasonic couplant. Since that time it has become clear that for high-temperature, long-term applications, welding transducers directly to the shell could be accomplished with much less surface preparation and, if done properly, would result in at least as high signal transmission and a more rugged, semi-permanent, installation.

Although welding ultrasonic transducers to steel piping has become a preferred choice for standard flowmeter applications, particularly at high temperature, it had not been used for steam generators prior to the development phase of this project. The accepted procedure now is to fasten transducers to the boilers with a custom-made magnetic welding fixture that holds a pair of transducers precisely in place during the welding process. The welding fixture was designed around a high-strength permanent magnet with one surface machined to match the curvature of the Bruce B boilers. The type of weld expected is shown in Figure 4. Babcock & Wilcox Canada performed the welding of the transducers to the identified steam generators. For the recent Bruce B installations, the location was chosen to be the same as the location of the 1999 installation on Boiler 8, i.e., between the 6th and 7th tube-support plates on the hot side (inlet side).

4. SYSTEM CHECKS – FLOW VERIFICATION AND SHELL WALL / ANNULUS MEASUREMENTS

To verify the accuracy of downcomer flow measurements made in the field, it was necessary to verify the boiler shell wall thickness and downcomer annulus gap width in the field, and to verify the accuracy of the transit-time technique and equipment by carrying out flow measurements in the lab.

4.1 Boiler Shell Wall Thickness and Downcomer Annulus Width Measurements

A normal-beam UT spectrum is shown in Figure 5 for a filled Bruce B boiler. The first four regularly spaced peaks on the left-hand side of the spectrum correspond to successive internal reflections in the boiler shell, with the spacing (time delay) determined by the shell-wall thickness and the soundspeed in the shell. In this time spectrum, obtained with an Epoch III UT diagnostic instrument, the number in large print near the top right of the display represents the time, in microseconds, of the peak selected by the horizontal gate centred on the third peak from the left on the display.

The peaks in the right-hand half of the spectrum (Figure 5), starting with the fifth from the left, are multiplets, the result of a single pass of the UT signal through the water-filled annulus and reflected back combined with multiple reflections in the shell wall. The appearance of the first "water" peak nearly coincident with the fifth internal reflection "shell wall" peak is consistent with an annulus gap width approximately the same as the wall thickness, since at ambient temperature the soundspeed in steel is very close to four times the soundspeed in water.[2]

[2] The time delay of the first "water" peak corresponds to one traverse of the water gap plus one traverse of the steel wall.

Typically two sets of normal-beam UT measurements are made, the first with the boilers empty, to measure only the shell wall thickness, and the second, with the boilers filled, to measure the annulus gap width. Assuming the soundspeed is accurately known, the thickness of the shell or the annulus width can be accurately determined from the slope of the time delay vs. peak number, as illustrated in Figure 6. Theoretical points correspond to the predicted time delay based on the boiler dimensional specifications and tabulated soundspeeds at ambient temperature. The experimental shell wall thickness is obtained from the slope of the carbon-steel (CS) trend line (in theory, equal to the slope of the carbon-steel-plus-water (CS+W) trend line) while the experimental annulus gap width is obtained from the difference in y-intercepts between the CS and carbon-steel-plus-water (CS+W) trend lines.

Table 1 lists the results of UT measurements for filled and for empty Bruce B Unit 5 and Unit 7 boilers. In both cases the UT equipment was checked with a calibration block of known thickness, and found to be accurate to better than 0.5%. For each Unit, the two sets of wall-thickness values agree on average within 0.2 mm (0.3%), sufficiently accurate for our purposes. The average of all the wall thickness measurements is 76.3 mm, confirming that the nominal wall thickness of 76.0 mm used in the downcomer flowmeter setup is sufficiently accurate.[3]

The average value of the downcomer annulus gap width for the four Unit 5 boilers given in Table 1 is 76.2 ± 1.2 mm, compared with the nominal gap width of 76.2 mm and so the flow-velocity values need not be adjusted on this account. This average value also agrees with the value obtained for Unit 7 Boiler 7 of 77.5 ± 1.0 mm within experimental uncertainty.

4.2 Flow Verification Tests

The design of the test section used to verify the downcomer flow measurements in the lab is shown in Figure 7. The flow direction is upward. The section designed to mock up the downcomer flow channel is fabricated of commercially available 3”-by-5” rectangular carbon-steel channel, 120” long. The inside dimensions are nominally 2.5” by 4.5”. The 120”-long rectangular channel was welded to transition flanges at either end and mounted in a vertical leg attached to the VIBFLO hydraulic loop at AECL’s Chalk River Laboratories. The rectangular section extends approximately 60” upstream (below) and 42” downstream (above) the location of the UT transducers, to allow for proper flow development from and to the 4” loop piping.

Not shown in Figure 7 are a flow conditioner (mixer + straightener) upstream of the rectangular test section, and a 48”-high vertical section of 4” clear acrylic piping downstream of the test section, so that air bubbles in the flowstream could be observed.

Two sets of flow-verification tests were carried out. In the first, the measurement section reproduced the geometry used at Bruce B NGS. The section consisted of a pair of OKS-type transducers mounted 12.1” apart, welded to a 3”-thick bar of carbon steel (CS), simulating the SG outer shell. The CS bar was inserted into an opening in the face of the rectangular

[3] Note that the accuracy of the flow-velocity measurements does not depend directly on the wall-thickness accuracy, since the wall thickness cancels out for contra-propogating UT pulses, to first order.

section, with welded brackets and boltholes located so that the 2.5" flow-channel depth was maintained throughout the measurement section.

In the second set of tests, another pair of OKS transducers was mounted on a 2⅛"-thick CS block (nominal thickness for a Bruce A boiler) using room-temperature couplant. One advantage of this system is that the spacing between the transducers could be optimized for room temperature, as opposed to the welded units whose spacing was optimized for boiler operating temperatures.

The two sets of flow velocities are summarized in Table 2 and Table 3. Note that although the standard deviations listed in Table 3 are statistical measures only, and do not reflect the absolute accuracy of the measurements, they do indicate that the scatter in the reported flow rates is quite similar for the two types of flow measurements being compared. That is, under these test conditions the UT flowmeter results are reproducible to a precision similar to that of the loop vortex-shedding flowmeter FT-6.

The results of this part of the test program verify that at flow velocities up to 3.8 m/s the accuracy of the ultrasonic flowmeter system consisting of OKS-type transducers and the DF868 flowmeter is, on average, within 4.4% and, at worst, within 7% of the correct value. The statistical variability in the UT data is low, and is comparable to that of the more accurate loop vortex-shedding flowmeter.

In summary, these results confirm that the 10% level of uncertainty suggested by AECL as appropriate for this type of UT flow measurement with is reasonable. The results also suggest that the intrinsic accuracy of the room-temperature UT measurements when optimized at room temperature may be somewhat better than 10%.

5. DATA ACQUISITION, LOGGING AND ANALYSIS

Typically the flowmeter data-acquisition and automatic-logging parameters are set up for continuous operation prior to the reactor being brought to zero-power hot status. In order to eliminate false readings, the firmware is configured to perform several checks on the data obtained from series of sent and received pulses, including an acceptance window for the derived fluid soundspeed, which is a function of temperature.

To verify the correct operation of the flowmeters and to allow the measurements to follow the relatively rapid changes in process conditions during reactor start-up, values of the flow velocity, RTD temperature, and calculated soundspeed are normally logged every minute for the reactor start-up period. The time interval is changed to every 12 minutes for longer periods of unattended operation as the reactors near operating power.

After each set of data has been downloaded to a PC, further checks and filters are applied for errors in calculated fluid soundspeed, signal quality, and any anomalous fluctuations in signal characteristics or in flow-velocity ranges. The RTD temperatures are used to confirm the boilers are at normal operating temperature. Following error checks the flow velocity, RTD temperature and fluid soundspeed values obtained from downloaded data logs are plotted vs. time, with average values taken over selected time periods during which the reactor was operating at a steady power level.

The resulting sets of analysed flow-velocity, RTD temperature and calculated soundspeed data are later consolidated into a single database including reactor power and boiler operating conditions such as feedwater flow rate and boiler water level. Additional sets of data logged by the flowmeters are downloaded to a PC as required while the reactor is operating.

6. RESULTS AND APPLICATIONS

Apart from their use as a diagnostic tool to assess the general condition of the boilers, the downcomer flow data have several applications including thermalhydraulic code validation, correlation with boiler thermalhydraulic parameters, continuous monitoring of boiler performance including long-term trends, and field data that can be used to support the case for changes to reactor operating conditions. Two of these applications are discussed in this paper; information on all four of these applications can be found in Reference [6].

6.1 THIRST Code Validation

THIRST (Thermal-Hydraulic In Recirculating Steam Generator) is a three-dimensional computer code that calculates flow and heat transfer in vertical, recirculating steam generators (SGs) under steady-state conditions [7]. Such computer codes are invaluable as steam-generator design tools and as modeling tools. For example, they are used to assess the effects of various degradation mechanisms and/or changes in process conditions. To perform these functions properly, they require validation to determine the accuracy of code predictions.

For this purpose, average values for flow velocities at different levels of reactor power were extracted from data logs over selected time periods during which the reactor was operating at a steady power level. In Figure 9 and Figure 10 these values are plotted as a function of reactor power for two boilers at the Bruce B NGS. These velocities can be used to determine riser flow rates, and thus boiler recirculation ratios. This calculation is particularly straightforward in the present case, since, in the absence of an integral preheater and reheater drains, the riser flow equals downcomer flow. Measured downcomer flow rates from the Bruce B boilers have been used to validate downcomer flow predictions made with the THIRST code as a function of reactor power [8].

6.2 Long-Term Trends

Average values of flow velocity while the reactor was operating at 90% full power over an eight-month period are summarized in Figure 11. Overall averages are shown as horizontal lines and range from 1.67 m/s for Boiler 2 to 2.10 m/s for Boiler 8. The statistical uncertainties as represented by the standard deviations range from 0.03 m/s (2% of overall average) to 0.10 m/s (6% of overall average). These uncertainties are somewhat less than the experimental uncertainty of ±10% associated with individual downcomer flow measurements.

For Boiler 8, the long-term average flow velocity value at 90% reactor power is 2.10 m/s, compared to the average velocity of 2.0 m/s measured for the same boiler in 1999. Although this is a measurable difference, and may reflect a change in boiler conditions over the intervening five years, it is also of the same order as the experimental uncertainty of ±10%.

7. MEASUREMENTS OF TWO-PHASE DOWNCOMER FLOW

AECL's development of downcomer flow technology is currently focused on testing flow-measurement techniques and transducer combinations capable of measuring flow that includes steam carry-under. The basic transit-time system as described earlier is useless in the presence of any significant (greater than approximately 0.2% by volume [2]) void fraction in the flow stream, largely because the soundspeed and transmission properties vary dramatically with void fraction [9,10].

There are a number of commercially available systems that could, in principle, measure steam-water flow, although none claim to function at CANDU temperatures for extended periods of time. Virtually all of these systems rely on sound waves propagating from a transmitting to a receiving ultrasonic transducer.

Systems using the following three techniques have been tested with air-water mixtures at room temperature in the downcomer-flow vertical test rig:

1. An “enhanced transit-time” technique, with the same geometry as described above, but in which the sound transmission is boosted by optimizing the ultrasound frequency and using high-repetition-rate sound bursts with an optimized sample rate.
2. A Doppler technique, in which a pair of transducers are mounted at the same horizontal location and the frequency shift due to sound waves reflected off moving particles or bubbles is measured.
3. A “speckle-tracking” technique, also requiring a pair of transducers at the same horizontal location, in which pairs of pulses “interrogate” a medium that contains acoustically reflecting particles or bubbles, and the echoes are correlated.

Doppler and speckle-tracking methods are similar in that they are used with media that contain particles or bubbles that reflect ultrasound, and the response is proportional to v/c, where v is the velocity of the particle or bubble and c is the speed of sound in the medium.

For the present application, the speckle-tracking method offers some advantage over the Doppler technique because it can easily be ranged down to relatively low flow velocities by increasing the time delay between the interrogating pair of pulses [10]. A commercially available speckle-tracking (Transflection™) technique has been used in the past to measure SG downcomer flow [2], albeit with some difficulties, e.g., transducer mounting at high temperatures. The purpose of this particular development phase was to investigate alternative technologies and look at possible improvements to the Transflection™ method that could solve problems related to installation and high temperatures.

Bench-top tests were carried out with air bubbled through a vertical column of water, followed by flow tests in the downcomer-flow test rig with acoustically reflecting particles and with air bubbles. Figure 12 shows the modified test-rig mount designed to accomodate four transducers, attached to the thick steel bar that replicates the boiler outer shell. As in the flow-verification tests, one pair of OKS transducers is mounted in the transit-time geometry, spaced approximately 10” apart vertically (only the top transducer is shown in Figure 12). A second pair of OKS transducers is mounted near the center of the steel bar in the geometry required for the Transflection™ technique, spaced a few inches apart horizontally.

This “quartet” arrangement allows the two pairs of transducers to sample nearly identical flow volumes, and allows both transit-time and Transflection™ data to be acquired simultaneously under conditions of very low void fraction in which they may both be operational [2]. For these room-temperature tests, the transducers were not welded to the steel bar but were fastened with screw-type mounts, with a gel-type acoustic couplant placed between the transducer and the bar.

During bench-top tests and flow tests the enhanced transit-time and Doppler systems failed to reliably produce reasonable flow-velocity results. At least part of the problem lies with conditions that are specific to SG installations: for example, it is impossible to mount transducers facing each other – the optimum Doppler geometry – on a CANDU boiler, and the thick steel shell causes high signal losses. Although it is conceivable that these two techniques could be used to measure downcomer flow, based on the results of these tests success would require extensive development programs.

Of the three techniques tested, only the speckle-tracking method consistently produced results with the geometry and signal intensity required for measuring SG downcomer flow. Preliminary results are shown in Figure 13 and verify that the speckle-tracking / Transflection™ method with OKS high-temperature transducers can produce reliable signals in two-phase air-water flow. Additional tests are planned to optimise the design, e.g., transducer frequency, transducer separation and angle, signal-processing parameters. Note that the speckle-tracking technique will not work in single-phase flow (c.f., Figure 13 with no air injected). A system with both transit-time and speckle-tracking capability would therefore be versatile in that downcomer flow could be measured under single-phase and two-phase flow conditions and any switching between the types of flow could be detected. Earlier tests suggested that the SG downcomer flow at some CANDU stations is single-phase liquid flow at low reactor power but is steam-water flow at full power [2].

8. SUMMARY

Non-intrusive downcomer-flow measurement systems have been recently installed on sixteen steam generators at the Bruce B NGS. An improved, semi-permanent installation method was used in which buffered ultrasonic transducers were welded to the boiler shell, eliminating the complications of surface preparation and high-temperature couplants. For downcomer-flow applications of this type, a set of detailed installation instructions has been developed to cover preparation, testing, installation and verification of the equipment.

Apart from their immediate diagnostic value related to thermalhydraulic performance, possible uses of this information include validation of thermalhydraulic codes, investigating correlations with boiler operating parameters, establishing long-term trends in SG performance, and supporting cases to be made for reactor uprating.

A prototypical two-phase flow-measurement system based on the high-temperature OKS-type transducers combined with a commercially available speckle-tracking technique has been developed and tested. Preliminary results show that such an installation will work under the conditions relevant to SG downcomer flow, notably the geometry arising from the large-diameter, thick-shelled boiler, low velocity range, and low-to-medium void fraction.

9. ACKNOWLEDGEMENTS

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Table 1
Boiler Shell-Wall Thickness and Annulus Gap Width Values from UT Measurements

Boiler	Shell-Wall Thickness (mm)		Annulus Gap Width (mm)
	Normal-Beam – I	Normal-Beam – II	Normal-Beam
U5B1	75.92	76.14 ± 0.65	75.20 ± 1.9
U5B2	76.93	76.77 ± 0.08	77.66 ± 0.2
U5B3	75.90	76.08 ± 0.06	73.22 ± 0.2
U5B4	75.51	75.56 ± 0.03	78.82 ± 2.8
Average:	*76.06*	*76.14*	*76.23*
U7B5	75.90	75.99 ± 0.09	--
U7B6	76.14	76.56 ± 0.13	--
U7B7	76.68	76.33 ± 0.28	77.5 ± 1.0
U7B8	76.91	76.96 ± 0.02	--
Average:	*76.41*	*76.46*	

Table 2
Flow Verification Measurements – Transducers Fastened to 2⅛” Test Bar

Flow Velocity from VIBFLO Loop FT-6 Meter (m/s)	Number of Readings (DF868)	Average Flow Velocity (m/s)	Adjusted Average[4] (m/s)	Percent Difference
4.0	136	3.80	3.98	0.6%
2.5	131	2.20	2.38	4.7%
“	66	2.28	2.47	1.1%
2.0	156	1.75	1.93	3.3%
“	119	1.80	1.99	0.4%
1.5	144	1.29	1.46	2.4%
“	120	1.30	1.49	0.6%
1.0	168	0.80	0.97	2.6%
“	108	0.78	0.98	2.3%

Table 3
Flow Verification Measurements – Transducers Welded to 3” Test Bar

Expected Velocity (m/s)	Number of Readings (DF868)	UT DF868 Flowmeter			VIBFLO FT-6 Flowmeter			Percent Difference
		Average Velocity (m/s)	Adj. Avge. Velocity[4] (m/s)	*2*Std. Dev’n*	Average Flow Rate (L/s)	Average Velocity (m/s)	*2*Std. Dev’n*	
2.5	108	2.47	2.50	*0.09*	17.76	2.50	*0.07*	0.2%
2.0	113	1.84	1.87	*0.02*	14.15	1.99	*0.03*	6.4%
1.5	106	1.36	1.39	*0.01*	10.58	1.49	*0.02*	6.9%
1.0	107	0.92	0.95	*0.02*	7.03	0.99	*0.02*	4.2%

[4] Adjusted for zero-flow offset.

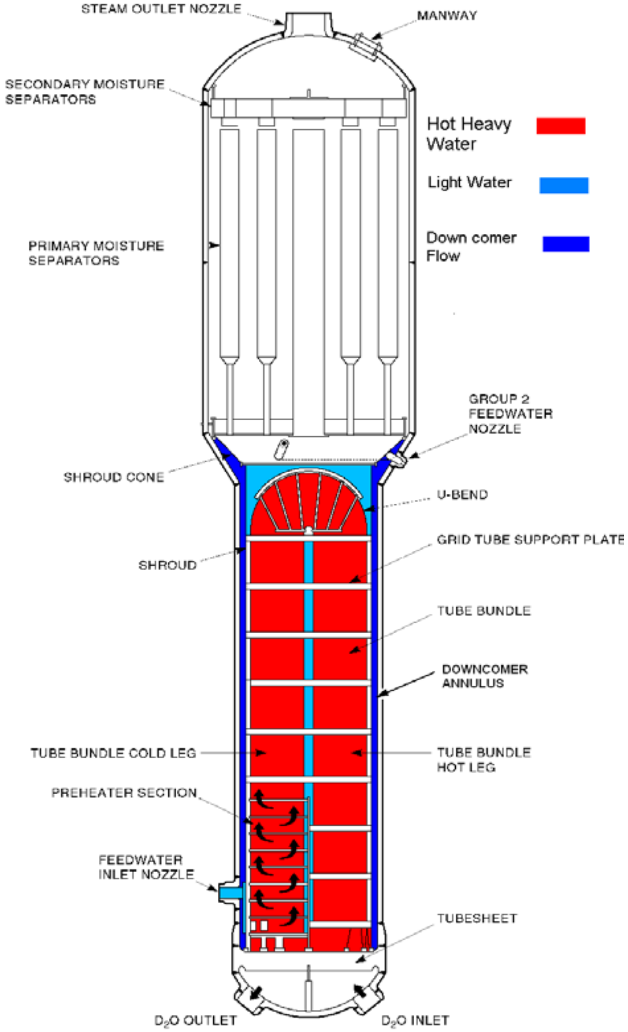

Figure 1 Typical CANDU SG layout. The downcomer annulus is a typically 3-in. wide annulus which serves as the flow path for fluid being recirculated from the (hot) phase separation region near the top to the inlet windows in the bottom of the shroud.

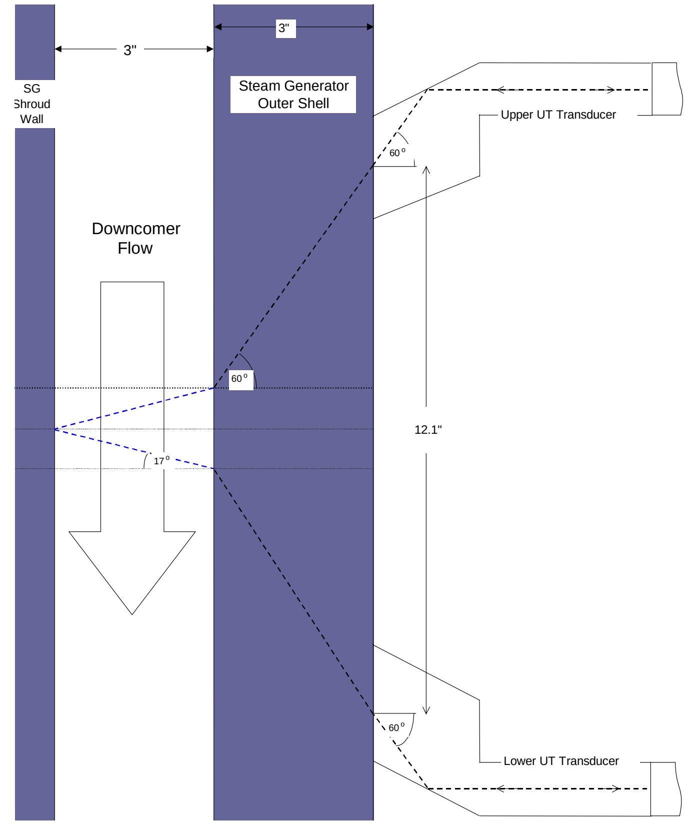

Figure 2 Geometry of UT transducers, spaced vertically 12.1 in. apart, and signal path (dashed line) through the boiler shell and the downcomer annulus. Nominal dimensions are given for Bruce B steam generators. The angle of refraction at the shell-downcomer interface is calculated from the speed of sound in steel and water at the reactor operating temperature of nominally 270 ºC.

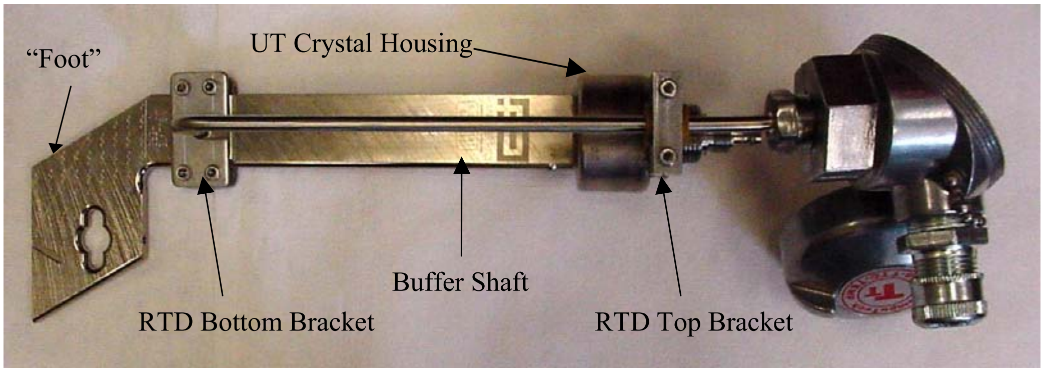

Figure 3 OKS transducer and RTD assembly. During installation, the RTD assemblies were attached after the transducers had been welded to the boiler shell.

Figure 4 A completed weld.

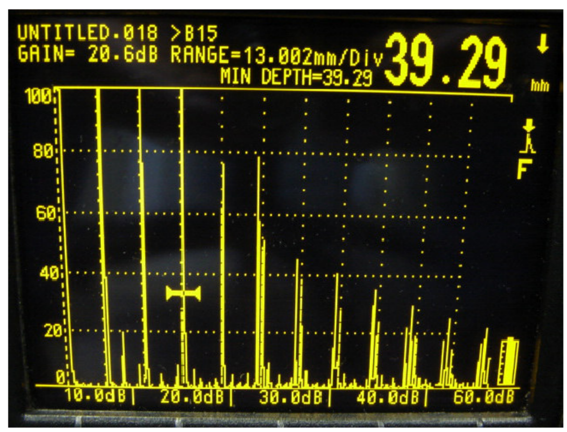

Figure 5 Normal-beam UT time spectrum for a Bruce-B boiler filled with water.

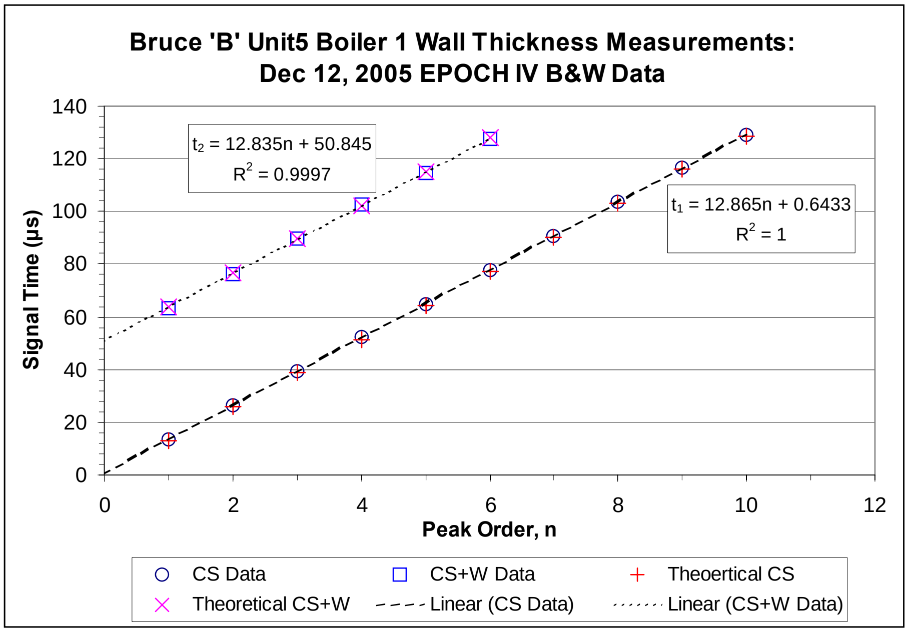

Figure 6 Delay time vs. peak number for UT normal-beam probe spectrum from Bruce B Unit 5 Boiler 1 filled with water.

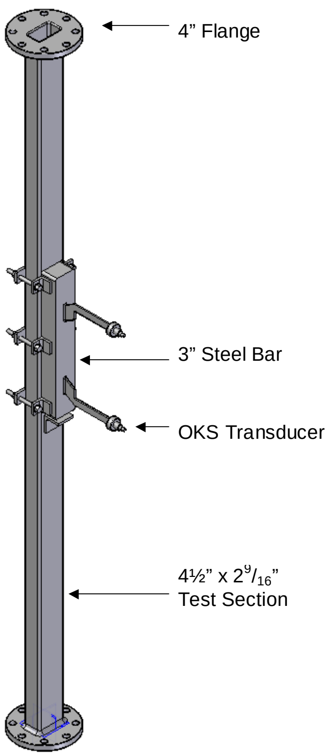

Figure 7 Downcomer flow test section.

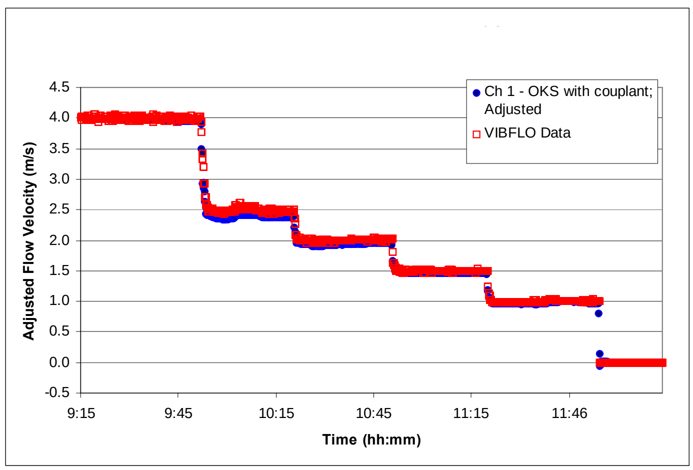

Figure 8 Results of flow verification tests – downcomer flow system c.f. VIBFLO loop flowmeter.

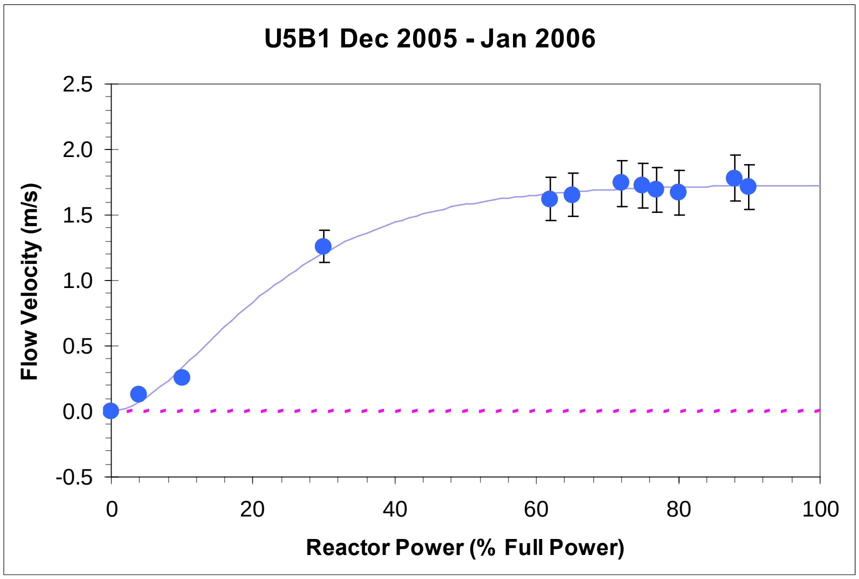

Figure 9 Bruce B Unit 5 Boiler 1 measured flow velocity as a function of reactor power.[5]

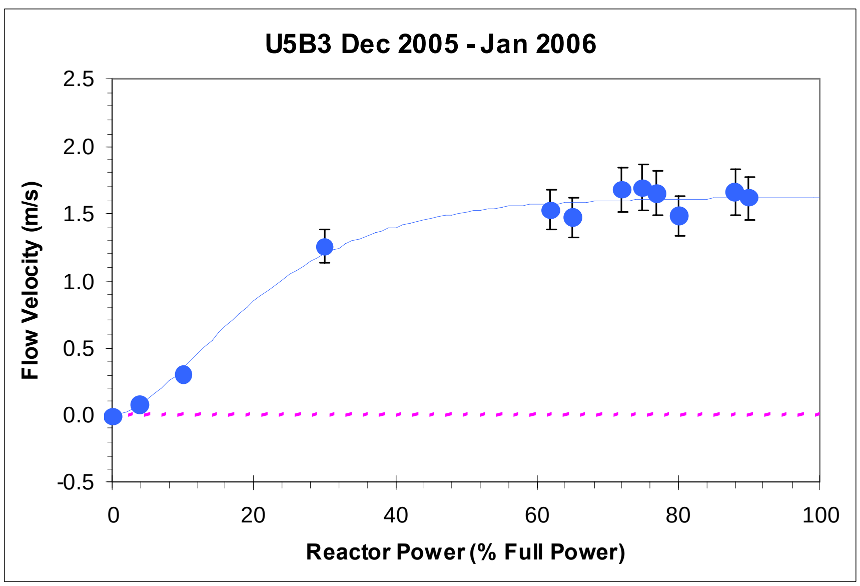

Figure 10 Bruce B Unit 5 Boiler 3 measured flow velocity as a function of reactor power.[5]

[5] The curve is drawn only as a guide and does not represent an established correlation between flow velocity and reactor power.

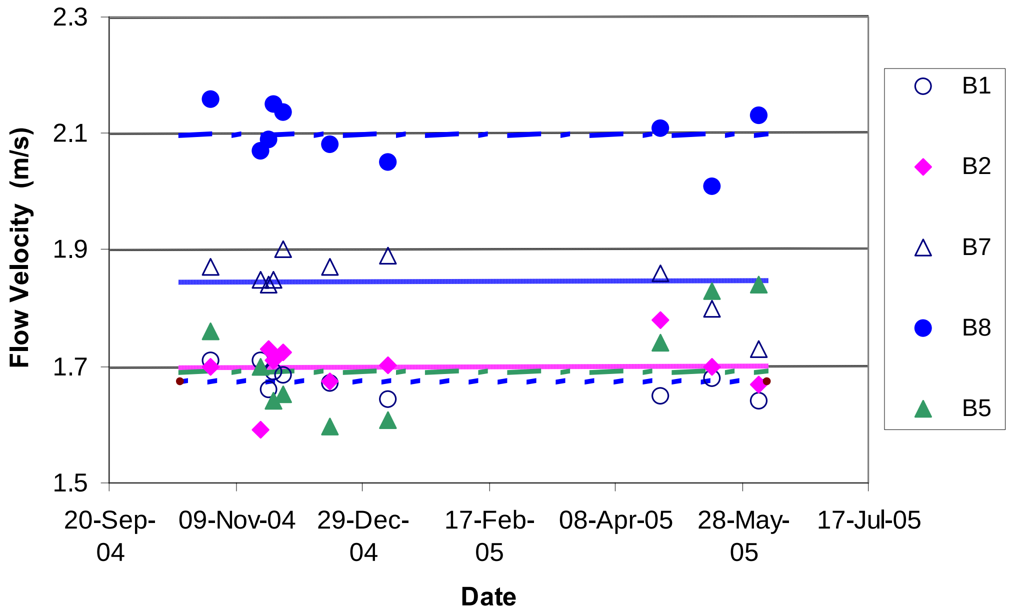

Figure 11 Downcomer flow velocity over time for the five Bruce B Unit 8 instrumented boilers, at 90% full reactor power. The horizontal lines represent overall average values.

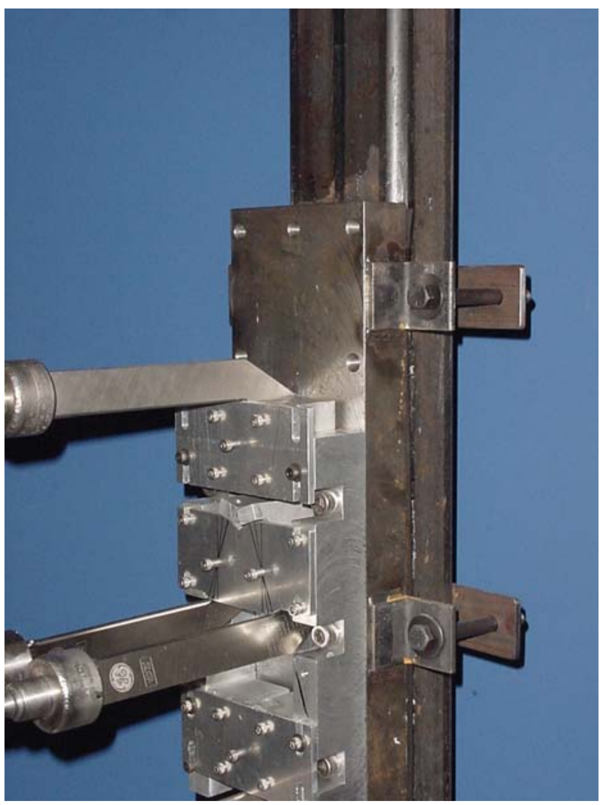

Figure 12 OKS-transducer mounting assembly fastened to the test rig, showing the top transit-time transducer and the pair of Transflection™ transducers (side-by-side).

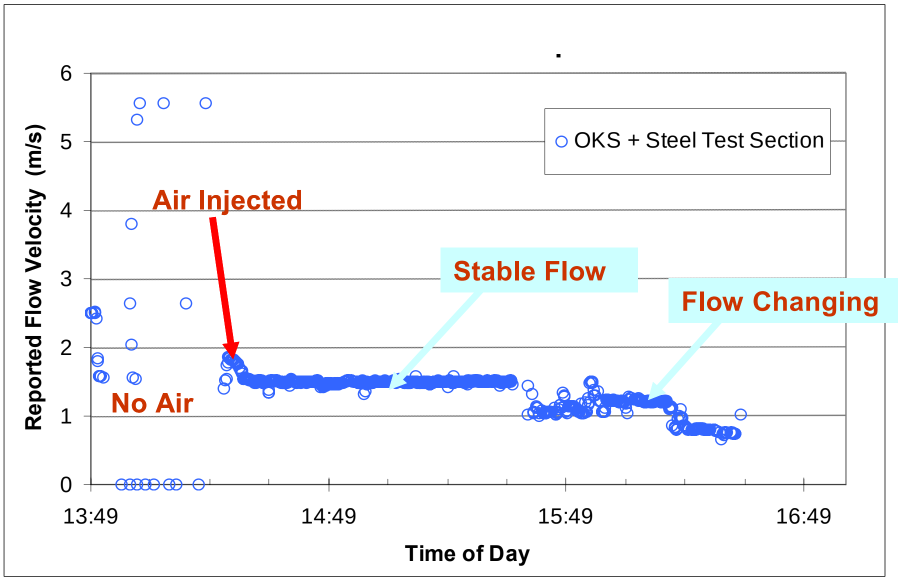

Figure 13 Preliminary results obtained with OKS high-temperature transducers in "Transflection™" mode with downcomer-flow test section – two-phase flow.