MEASURING STEAM GENERATOR PERFORMANCE USING NON-INTRUSIVE DOWNCOMER FLOW MEASUREMENTS

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ABSTRACT

Nuclear plant reliability depends directly on steam generator performance. Downcomer flow is a good monitor of steam generator performance. It provides information critical to the efficient and safe operation of steam generators as determined by the recirculation ratio and water inventory. In addition, reduced downcomer flow may indicate steam generator crudding or inadequate chemical cleaning.

This paper describes recent advances in the application of ultrasonic technology to measure flow velocity in the downcomer annulus during operation. This technique is non-intrusive since the measurements are taken with ultrasonic transducers mounted on the outer shell of the steam generator. New transducers and improved installation techniques have resulted in increased transducer reliability.

Through on-site testing, it was determined that some CANDU steam generators are experiencing carry-under (steam from the separators is carried into the downcomer). To measure the downcomer flow under these conditions, a different ultrasonic technique was required. A new technique became available in 1995 and was successfully adapted for high-temperature application. This transflection method was attached to a Bruce A steam generator in January of 1996. Whereas previous installations provided data for two to three months, this installation was still operating when the reactors were shut down in 1997.

Options for movable measuring systems and simpler surface preparation have also been examined. This research has determined several obstacles and some possibilities for the use of magnets in temporarily holding the transducers at a given location. This would allow for measurements to be taken in a larger number of locations using the same flow measurement system. In addition, the need for minor welding on the surface of the steam generator shell would be eliminated.

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1. INTRODUCTION

Nuclear plant reliability depends on good steam generator performance. Without a continuous monitoring technique, steam generator performance has only been monitored by opening up the vessel and observing the amount of fouling. A non-intrusive system now exists for determining the recirculation ratio of an operating steam generator on a continuous basis. This system consists of transducers and a flow meter that are commercially available and a method of installation that has been developed within the Vibration and Tribology unit at Chalk River Laboratories.

Downcomer flow measurements provide the following health and performance indicators for operating steam generators:

- a measure of recirculation ratio, and indirect measure of water inventory (i.e., heat sink capability of the boiler) The recirculation ratio is a measure of how much water is circulating throughout the steam generator relative to the amount of steam that is being produced. Downcomer flow velocity is directly related to the recirculation ratio, from which you can infer the rate of tube support fouling. Fouling will increase the hydraulic resistance and reduce the recirculation ratio. In turn, a low recirculation ratio causes more crud to deposit on the tube supports, increasing the problem.
- a sensitive indication of changes in operating characteristics of the secondary side (e.g., anticipate and respond to broached plate blockage problems, before they become a major source of maintenance and repair)
- a definite indication of any significant presence of void (carryunder from the drum to inadequate steam separator capacity, or leakage through the shroud ports)
- a direct indication of crud build-up in the steam generator (loss of flow velocity, decreased efficiencies and loss of production)
- a means for the operator to monitor long-term fouling trends and plan for a clean at the most convenient outage, or possibly avoid tube support cleaning entirely through a modified chemistry program
- a comparison before and after a clean provides a measure of the effectiveness of the clean, confirming return to design conditions ... or not.
- a validation for computer codes used in the design of steam generators

This measurement technology will enable nuclear power stations to ensure their steam generators are operating at peak efficiencies with minimized production losses. This paper describes the ultrasonic technique, summarizes some of the recent technical developments and provides actual flow measurement results.

2. ULTRASONIC TECHNIQUES

Transit-Time Technique

Ultrasonic flow measurement is based on a knowledge of the speed of sound in various mediums. For reflective-mode flow measurement in a steam generator, ultrasonic pulses are alternately fired and received between upstream and downstream transducers, using the downcomer shroud wall as a reflector (see Figure 1). Because the sound waves travelling from the upstream transducer are moving with the water flow, they will reach the opposite transducer faster than those travelling from the downstream transducer. The difference in time of flight between upstream and downstream pulses, Δt, is used to determine the downcomer flow velocity, V_f, as follows:

$$V_f = \frac{\Delta t}{2} \frac{a_f^2}{W \tan\theta_f} \tag{1}$$

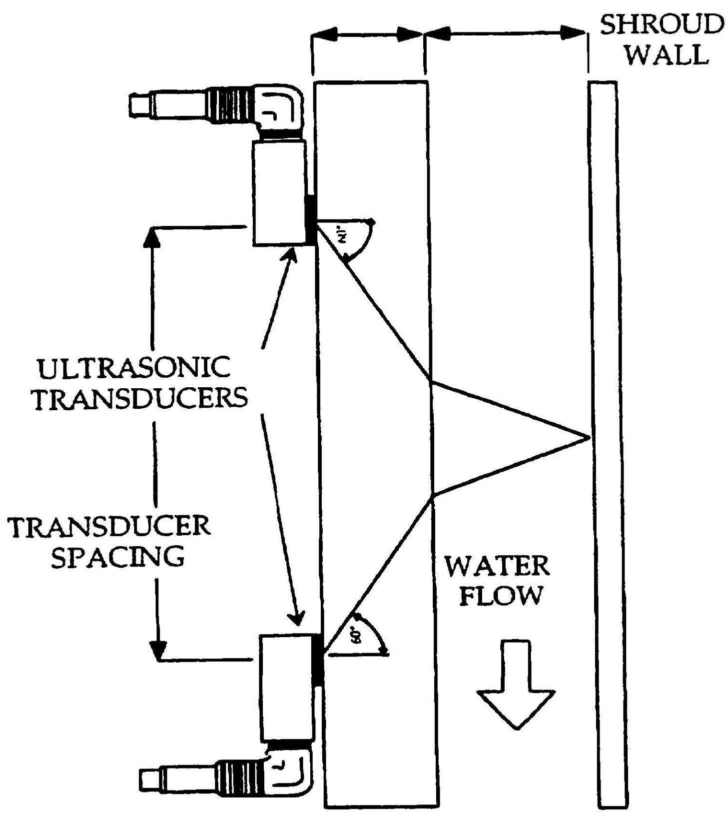

Figure 1: Transit-time Technique

where, W is the annulus width, a_f is the speed of sound in the fluid, and θ_f is the angle of refraction from the shell to the annulus as measured from the normal to the shell.

The flow meter searches for pulses in a time window that has been calculated internally from user-provided information about the temperature and geometry. User input includes types of media, medium thicknesses, number of passes, distance between transducers and temperature. If pulses are detected within the calculated window, the signal quality must be verified. After a significant number of successful transmit and receive cycles, the flow meter will calculate and output flow data. Reference 1 provides a detailed description of the operational theory behind the transit-time technique.

Transflection Technique

With the transit-time technique, an object (e.g., vapour bubble) that obstructs or absorbs the transmitted pulse, will cause the measurement technique to fail. In contrast, the transflection technique requires the presence of a reflective second phase to be able to measure flow velocity. As with the transit-time technique, a sound pulse from the transmit transducer enters the steam generator shell and refracts as it enters the flowing water. Any signals reflected back to the receive transducer are analyzed and filtered to remove background noise, retaining only the signal due to the moving bubbles or particles (see Figure 2). The time required for a bubble to move a specified distance is used to calculate downcomer flow velocity (see Equation 2).

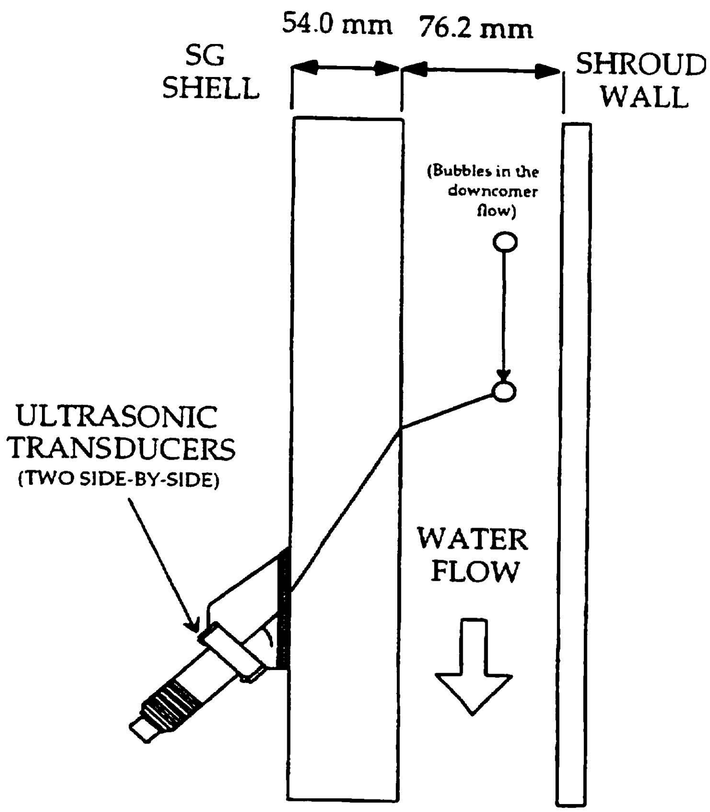

Figure 2: Transflection Technique

$$V_f = \frac{c_1}{4F \sin\phi_1 \Delta t} \quad (2)$$

where: F is the ultrasonic transducer frequency, c_1 is the speed of sound in the transducer wedge, ϕ_1 is the transducer wedge angle (measured normal to the shell), and Δt is the time required for the bubble to travel a specified distance (usually $1/2\lambda$). Reference 2 provides a detailed description of the operational theory behind the transflection technique, and the basis for this velocity calculation.

3. APPLYING ULTRASONIC TECHNIQUES TO STEAM GENERATORS

Several factors associated with nuclear steam generators create a difficult environment for ultrasonic measurements. High temperatures, thick outer shells and radiation fields were obstacles that had to be overcome in the development of a suitable measurement device.

High temperatures affect transducer lifespan, couplant selection and differential thermal expansion of the system attaching the transducers to the outer shell. To prolong their lifespan, current transducers must be cooled with a constant air stream when attached to steam generators. Room-temperature couplants (liquids and pastes) cannot be used at steam generator temperatures. If the transducer and shell surfaces are smooth and flat, and if sufficient force can be applied to mold the couplant to the micro-contours of these surfaces, soft metals can be used as a couplant.

Considerable development was required before suitable surface preparation and clamping techniques were established. With soft metal couplants, flat and smooth surfaces are needed to minimize signal loss due to absorption and scattering at the couplant/wall and couplant/transducer interfaces. In addition, parallel surfaces are required to ensure that the signal initiated at one surface is sent directly toward the second surface. Consequently, a portable machining device was found that could be used to produce flat, parallel surfaces by removing less than 0.5 mm from the outer wall. In addition, the surface is polished to remove surface imperfections.

Transducer mounting hardware consisting of clamped steel rails was designed to allow higher forces to be applied to the transducers. The steel rails also keep the transducers aligned vertically and allow for easy adjustment of the spacing between the transducer pair. The clamping hardware is spring-loaded to allow for thermal expansion effects while maintaining a constant pressure. Laboratory testing showed that significant signal loss would occur if the original mounting pressure was not maintained.

Wall thickness affects the signal strength due to natural diffusion/absorption of the sonic pulse as it passes through the carbon steel. The steel walls of CANDU nuclear steam generators are typically more than 54 mm (2 in.) thick to safely contain shell-side pressures of about 4.5 MPa (260 °C). Because the steam-generator walls are much thicker than the pipe walls generally encountered in ultrasonic flow measurement, the signal strength for this application is low. Faced with a signal of limited strength, it is even more important to be sure that the transducer-to-shell couplant is minimizing the signal loss.

Flow-meter parameter settings suggested by the manufacturer of the flow meter were not suitable for steam generator applications. Laboratory tests were undertaken to determine appropriate parameter settings and to understand the limitations of the flow meter device. Further details are provided in References 1 and 2. In addition, laboratory tests were carried out to confirm the calibration of the ultrasonic flow meter techniques at room-temperature and at steam generator operating conditions [2]. These tests indicate that the measurement system is accurate to about ±10 percent of the flow at velocities above about 0.2 m/s. Room-temperature tests indicated that upstream flow disruptions (producing eddies and vortices) had little impact on the transit-time signal. However, as little as 0.3 percent void fraction was sufficient to disrupt the flow measurement process with the transit-time technique. In contrast, the transflection technique was found to require about 0.1 percent void fraction and was still operational at 30 percent void fraction. Figure 3 shows the combined transit-time and transflection measurement system that was used in laboratory tests.

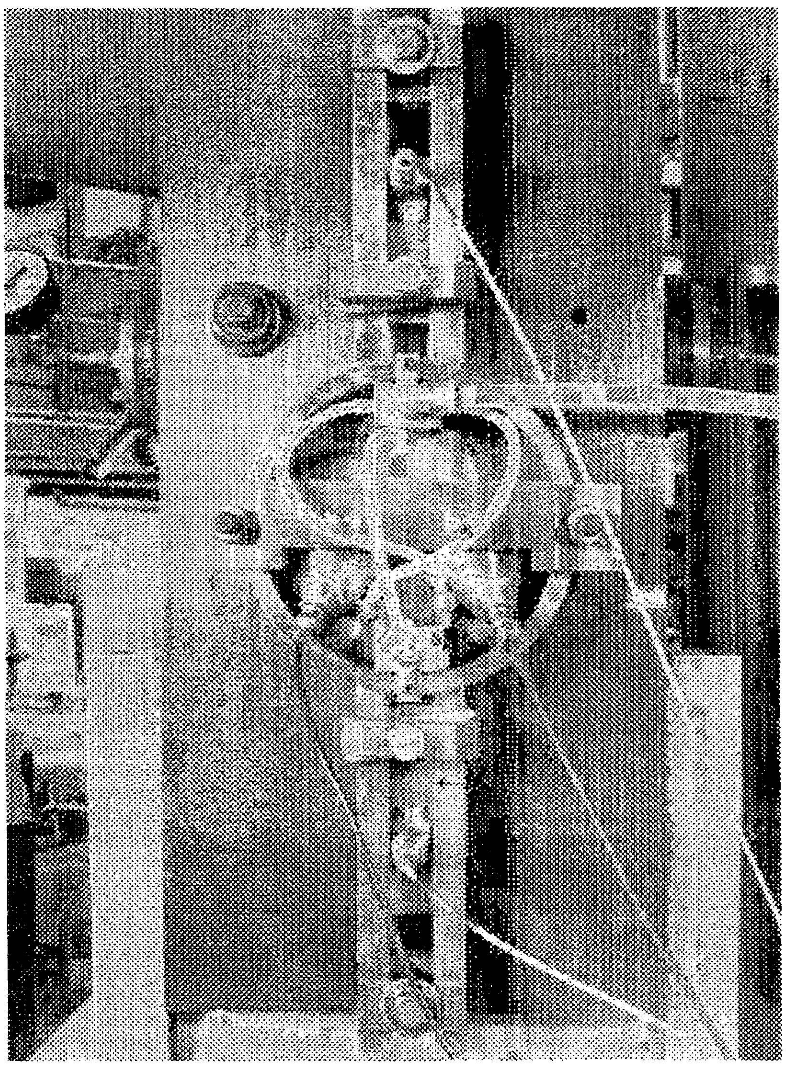

Figure 3: Transit-time and transflection combined measurement system used in laboratory tests and subsequently installed at Bruce NGS 3

Radiation fields of 1.5 R/hr during reactor operation restrict access of personnel to the boiler face. This restriction precludes the possibility of performing minor tests and adjustments of installed equipment while the reactor is operating. The inability to make adjustments after the steam generator was at operating temperature caused significant time delays in the development of this ultrasonic measurement system.

4. RECENT RESEARCH

4.1 Optimizing Surface Finish Techniques

During actual steam generator installations, it has been observed that the force required to obtain an adequate signal strength varied from site-to-site. This was believed to be due to variations in the surface preparation produced while machining and polishing the transducer contact areas.

A test program was conducted to assess the effect of surface preparation on signal strength. Eight test disks were machined from a carbon steel plate. The top and bottom surfaces were made parallel with a surface grinding process. The bottom surfaces were then flat lapped to ensure consistent signal transmission characteristics at the water/steel boundary. Additional top surface treatments were performed on all disks except Disks A and B (see Table 1).

For all of the tests, a 25.4 mm test plate was positioned over 76.2 mm of room temperature water (see Figure 4) to simulate a downcomer geometry. The bottom of the tray acted as the downcomer shroud wall to reflect the signals. Disk A was set into the left-side opening and was

Table 1: Summary of Top Surface Conditions for the Carbon Steel Disks

Disk	Type of Finish	Details	Ra (μm)	Rz (μm)	Curvature
A	ground	machine shop	1.19	8.54	flat
B	ground	machine shop	1.91	15.0	flat
C	lapped	lapping plate with 14 μm abrasive	0.455	3.44	convex 5.0 μm
D	milled/lapped	current portable milling technique	0.361	2.80	convex 2.5 μm
E	polished	metallographic 3 μm abrasive	0.361	1.65	convex 3.0 μm
F	machine lapped	5 μm abrasive	0.509	4.37	flat
G	machine lapped	14.5 μm abrasive	1.85	2.93	flat
H(a)	milled	portable mill	1.85	15.5	saw-tooth profile 30 μm variation
H(b)	polished	previous technique used before Sept 95	0.217	3.23	wavy profile with 26 μm variation

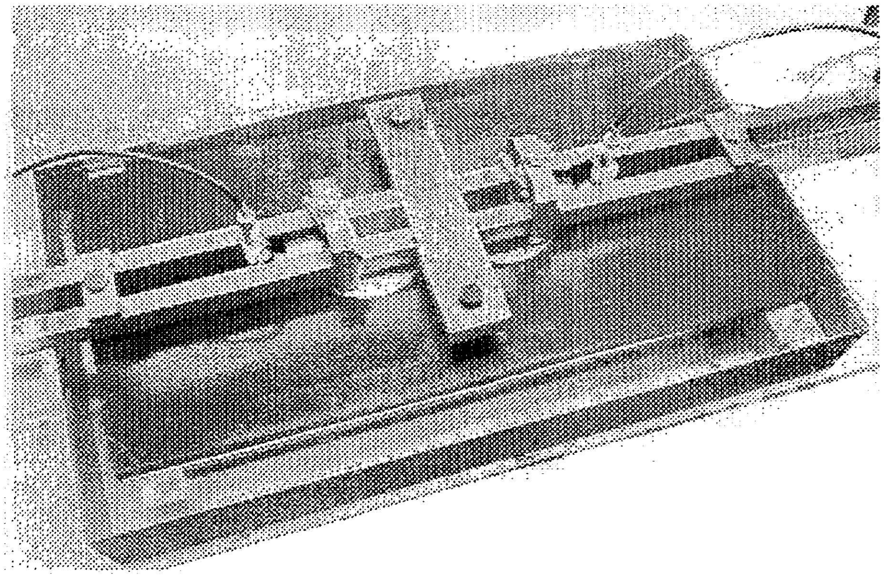

Figure 4: Photograph of Test Plate with Transit-Time Transducer Hardware

left in place as a reference while disks were changed and forces were measured on the right side of the test plate. Signal transmission through Disks B to H was tested as the transducer clamping force was adjusted from 0 to 11,000 N. The results of these tests are shown in Figure 5.

The current portable milling/lapping technique (Disk D) provides signal strength results that are similar to those of a highly polished disk (Disk E). The previous portable milling techniques did not produce a flat surface and therefore resulted in significantly lower signal strength. The results show that flatness variations up to 5.0 μm, peak to valley surface roughness(Rz) of 5.0μm and clamping forces of 6000 N are sufficient to produce efficient signal transmission.

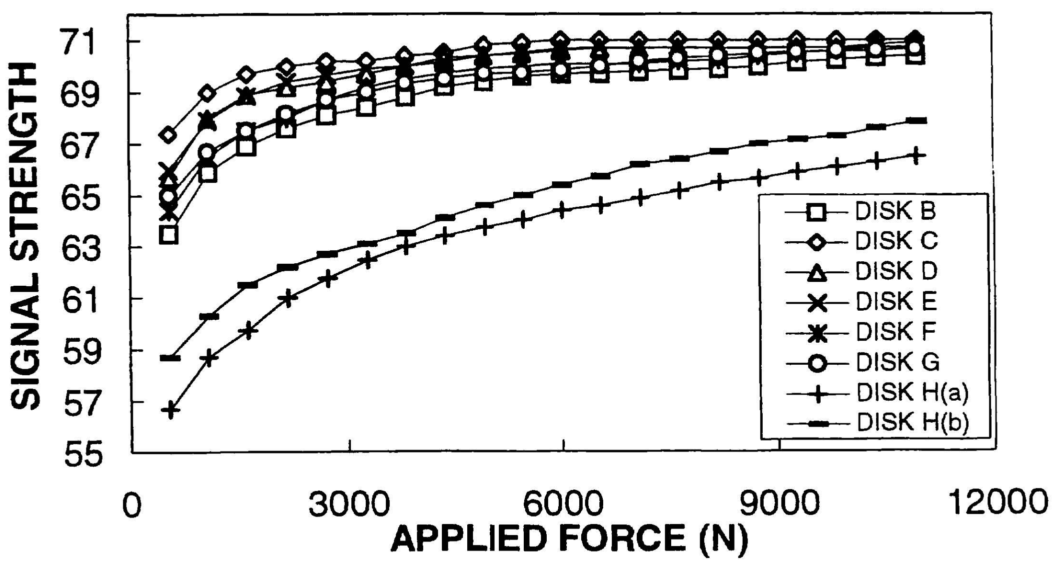

Figure 5: Signal Strength vs Coupling Force for all Test Disks

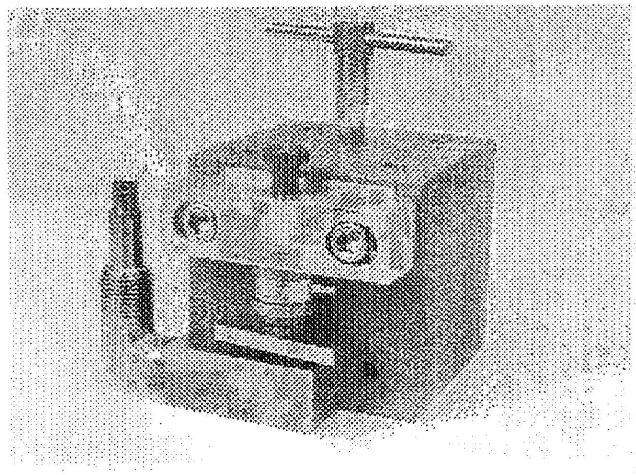

Figure 6: Single Magnetic Clamp with Transducer Force Measurement Set-Up

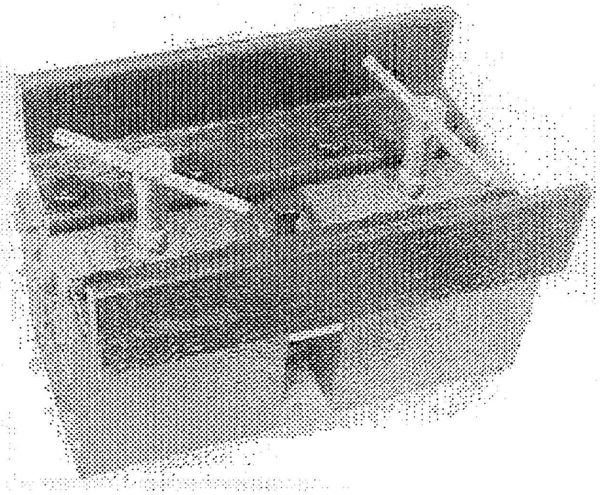

Figure 7: Tandem Magnetic Clamp

4.2 Magnetic Transducer Attachment

The possibility of high-temperature magnets replacing welded studs on the sides of steam generators was tested by considering the effect the wall curvature on the clamping strength. Two magnetic clamps were set up with a piezoelectric force transducer fitted between the clamping bracket and a transit-time transducer (see Figures 6 and 7). Brass shim stock was placed between the magnets and a test plate to measure the relationship between magnet gap and coupling force (see Figure 8).

Clamping force from the single magnetic clamp was limited to 700 N due to off-axis loading. With the tandem clamp, a clamping force of 4600 N was achieved without a shim. The manufacturer's specified maximum holding force of 4198 N was exceeded when the gap between

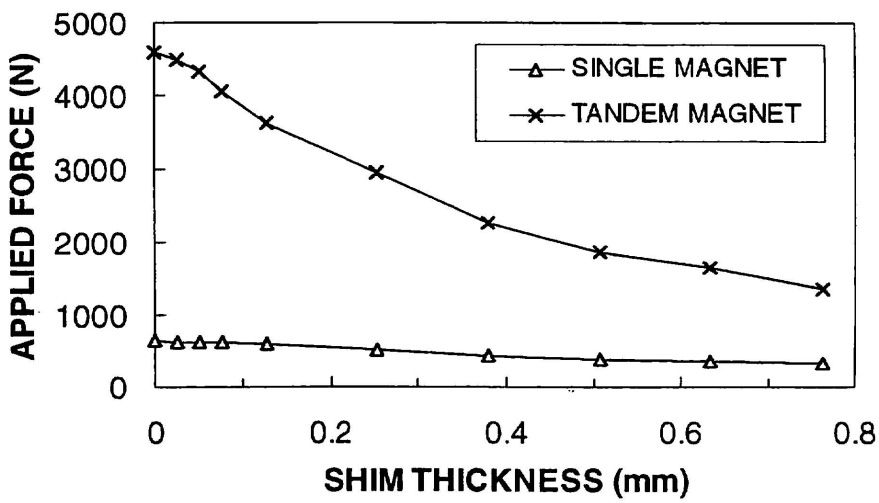

Figure 8: Magnetic Clamp Coupling Force vs. Gap between Magnet and Surface

the magnet and the steel plate was less than 0.00762 mm. To obtain this gap specification with a steam generator, the magnet would have to be machined to fit the curve of the outer wall. In addition, a more powerful magnet would have to be used to produce the required clamping force of 6000 N, as measured in Section 4.1. A possible alternative that has not yet been tested is a custom manufactured electronically switched permanent magnet. The estimated weight for this magnet would be 15 kg and a clamping force of 10,000 N would be possible. The milling equipment also uses the welded studs and, therefore, this equipment would have to be redesigned to use magnetic clamping.

4.3 Improved Transducer Lifespan

Previously available transducers used at CANDU steam generator temperatures would fail within a few months if no cooling was applied. Therefore, methods to cool these transducers were developed. Recently, more reliable high-temperature transducers have been developed by the manufacturer, but have not yet been used in steam generator applications. These longer lifespan transducers are scheduled to be installed at Bruce NGS 8 in the summer on 1998. This new development in transit-time transducers will eliminate the need for air-cooling if the steam generator is not susceptible to carryunder in the downcomer. Research is now underway to determine if these new "waveguide" transducers can be welded directly to the outer wall of the steam generator. Welding directly would significantly simplify transducer installation.

5. FIELD APPLICATIONS

The first successful in-service application of the transit-time technique was at Bruce Nuclear Generating Station (NGS) 3 in the spring of 1993. Since then, installations have taken place in Bruce-4, Darlington-2, and most recently again at Bruce-3 where both transit-time and transflection equipment were installed. As well, the transit-time transducers have been installed at Gentilly-2 on feedwater piping to accurately monitor the flow of water to the steam generator. In all cases, the flow measurement system worked well, with the following results:

- A crudded steam generator gives results indicating a recirculation ratio well below design specifications[1].
- The transit-time technique worked well at Bruce at lower powers on both a crudded and a chemically-cleaned steam generator. However, at high powers the technique failed, probably because of steam carryunder, hence the need for the transflection technique[2]. As reactor power increases, more steam is forced through the separators and the likelihood of carryunder increases. A cleaned steam generator will have the potential for more carryunder than when it's fouled, because the separators have more load when the steam generator is clean.
- Successful transit-time flow measurements up to 100 percent power were achieved at Darlington NGS 2 (see Figure 9)[2]. The velocity at full power shows excellent agreement with the value predicted using THIRST, a thermalhydraulic computer code for analyzing steam generators.

- A 1996 dual mode installation (transit-time and transflection) at Bruce worked well [3]. Transflection flow measurements up to 75% reactor power were achieved (previously unattainable with transit-time alone). The system was still working when the reactor was shut down (~1.5 years of operation).

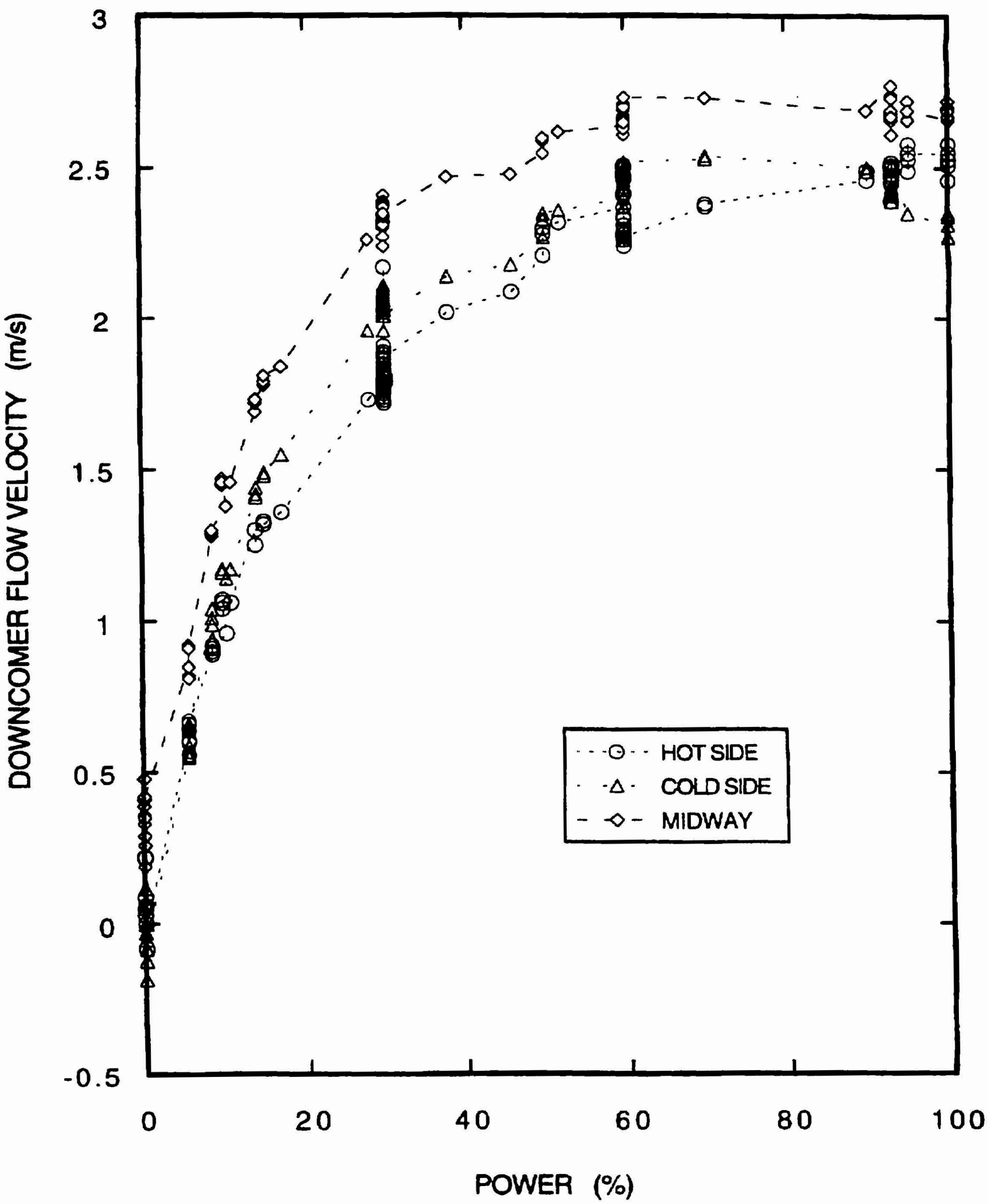

Figure 9: Downcomer Flow Velocity as a Function of Reactor Power

6. CONCLUSIONS

A non-intrusive ultrasonic flow measurement system has been successfully used to measure downcomer flow velocities in operating steam generators. Predicted velocities using the THIRST code (a thermalhydraulics computer code) are in agreement with the measured velocities.

Recent advances in transducer technology have overcome earlier limitations and resulted in a transit-time transducer that does not require cooling and will last for many years. Research is underway to determine if this transducer can be welded directly to the surface of the steam-generator outer wall.

The transflection technique has been used successfully to measure downcomer flow in a steam generator with carryunder. With air-cooling, this technology can provide reliable measurements indefinitely.

Recent research has shown that significant development would be required to use magnets to replace welded studs in the installation of ultrasonic measurement systems. Even in short term applications, the permanent magnets have not been shown to be reliable.

Many laboratory tests have been carried out to perfect the surface preparation so that a strong signal is obtained. The test specimens prepared with the current portable/milling technique performed as well as highly-polished, laboratory-prepared test specimens.

7. ACKNOWLEDGEMENTS

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