MODERATOR FLOW MEASUREMENTS AT DARLINGTON AND BRUCE-B NUCLEAR GENERATING STATIONS

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ABSTRACT

Moderator flow measurements were performed on Units 2 and 4 of Darlington NGS and Unit 5 and 8 of Bruce B NGS during their respective maintenance outages in 1999. Heat exchanger outlet and calandria inlet flows were measured with each of the pumps running. Measurements were performed using the ultrasonic cross-correlation flow meter, and the results demonstrate that the total moderator flow with either of the main pumps running is substantially higher than the value assumed in the Safety Analysis confirming conservatism in present safe operating margins for moderator sub-cooling. The paper describes the ultrasonic cross-correlation flow meter, presents details of plant measurements and calibration work used to analyze measurement results, and provides rigorous evaluation of the measurement uncertainty.

MODERATOR FLOW MEASUREMENTS AT DARLINGTON AND BRUCE-B NUCLEAR GENERATING STATIONS

1.0 INTRODUCTION

It was identified in the fall of 1998 that the total moderator flow rate is one of the boundary conditions that can have significant effect on the minimum available moderator subcooling in certain ranges of the parameters involved in defining a nuclear unit's Safe Operating Envelope. Although engineering judgement indicated that operation even at the highest allowable power levels would support previous licensing submissions, a clear confirmation of the judgement was required by performing direct measurements of the moderator flow rate.

In order to address this issue, Reactor Performance Monitoring (RPM) Section was contacted to perform moderator flow measurements on the four units of Bruce-B NGS and Darlington NGS. Over the years RPM has been involved in the development, calibration and station use of the Ultrasonic Cross-Correlation Flow Meter (USCCFM), mainly for reactor power verification through boiler feedwater flow measurements. However, USCCFM has also been used for such diverse measurements as CANDU channel flows, low pressure service water flow, moderator secondary side flow, etc. USCCFM has been shown to be one of the most accurate and versatile non-intrusive flow measuring devices available anywhere (Refs. 1, 2).

Ultrasonic transducers were installed inside the reactor vault at Bruce B and Darlington and in the moderator heat exchanger rooms at Darlington in order to measure both heat exchanger outlet flows and calandria inlet flows. Coaxial cables connected the transducers to four data acquisition systems to allo all four flows to be measured simultaneously. Advantages of USCCFM over other available meters such as ease of transducer installation and on-line capabilities of the data acquisition systems played a significant role in the measurement success

The other definite advantage of the USCCFM manifested itself in its ability to measure flows with reasonable accuracy even in the vicinity of bends, t-junctions, and other flow disturbances. The locations available for measurements at Darlington were downstream of 90° elbows. There is sufficient data available from extensive calibration of the USCCFM downtream of 90 degree elbows (Ref. 3) that no further calibration tests were considered necessary to obtain accurate results. On the other hand, the only locations available for measurements at Bruce B were in the immediate vicinity of 135° elbows and a few feet downstream of t-junctions. In order to improve measurement accuracy, a full-scale carbon steel model was constructed, and USCCFM calibration was performed at the OPG Flow Testing Laboratory.

Measurements were done in several distinct steps performed on two separate days several weeks apart. First, equipment was brought into the reactor vault and the heat exchanger rooms, pipe outside diameter and wall thickness measurements were done, transducers were mounted on the pipes, data acquisition systems were set up and tested, and finally, flow data were collected with each of the two auxiliary pumps running. Transducers were left on the pipes, and on the second day of testing about two weeks later, during reactor approach to critical, main pump flows were measured and equipment was removed from the heat exchanger rooms and from the reactor vault.

The results of these measurements successfully demonstrate that the total moderator flow with either of the main pumps running is substantially higher than the value assumed in the Safety Analysis confirming conservatism in present safe operating margins for moderator sub-cooling. The rest of the paper is organized as follows. Section 2 briefly discusses USCCFM design and operation. Section 3 describes the Darlington and Bruce-B moderator system and the relevant piping configuration. Section 4 deals with USCCFM calibration set-up and summarizes calibration results. Section 5 describes plant measurements and presents measurement results. Section 6 contains measurement uncertainty analysis, followed by conclusions in Section 7.

2.0 USCCFM DESIGN AND OPERATION

A detailed discussion of the USCCFM design and operation is contained in a number of reports (see e.g. Ref 3). Here, we will give a brief overview of the meter, concentrating on the issues relevant to the rest of the report. A photograph of the USCCFM and of the transducer mounted on a pipe is shown in Fig. 2.1 and 2.2.

2.1 Ultrasonic Flow Measurements

All ultrasonic flow meters measure the time that it takes for the fluid in the pipe to travel over the distance equivalent to the effective transducer spacing. The volumetric flow (in L/sec) can then be calculated using the following expression:

$$\mathbf{W = FPCF*A*d/\Delta t} \qquad \textbf{(2.1)}$$

where

FPCF is the so-called flow profile correction factor
A is the pipe flow area (m^2)
d is the effective transducer spacing (m)
Δt is the time measured by the flow meter (sec)

The more commonly calculated mass flow in (kg/s) is obtained by multiplying the above expression by the fluid density.

Clearly, the difference in meter designs is reflected in the way it measures Δt, and, to some extent, in the value of the FPCF. By far the most common meters available on the market are transit-time meters, which operate in a "pulse mode". This means that a high frequency, high intensity (several hundred volts) ultrasonic beam is sent at a certain angle to the pipe axis so that there is an axial component that propagates with the flow and opposite to the flow. The difference in the ultrasound travel times is then used to determine fluid travel time or velocity.

2.2 Principle of USCCFM Operation

On the other hand, the USCCFM operates in a "continuous mode", which means that two high frequency (about 1 MHz) but relatively low intensity (about 10 volts) ultrasonic beams are propagated simultaneously across the pipe. Both beams are modulated by the turbulence eddies, and when the high frequency component is removed, the remaining modulation is in the low frequency range (below about 100 Hz). The two low frequency signals are further filtered in the range, which depends on flow characteristics but is typically between 10 Hz and 50 Hz. Fluid travel time is then obtained by performing cross-correlation calculations of the two demodulated and filtered signals, which is done by a PC-based program based on the LABVIEW package. Therefore, the USCCFM directly measures fluid transit time, whereas the traditional transit time meters infer the fluid transit time from differences in ultrasound travel times.

For the purpose of this report, it is sufficient to mention that the main advantage of the USCCFM and its superior accuracy and repeatability is due to the fact that ultrasonic beams propagate directly across the pipe and, therefore, there is no refraction of ultrasound. This, in turn, means that transducer design and maintenance requirements are less stringent than in the case of transit-time meters.

The key to achieving high accuracy in ultrasonic flow measurements is clear understanding of the FPCF for different piping configurations and different flow regimes, and repeatable measurements of the fluid travel time, Δt. Each term in Eq. (2.1) and the corresponding measurement uncertainty will be discussed in Section 6. However, in order to provide better understanding of the calibration work presented in Section 4, a brief discussion of the FPCF is given below.

2.3 Flow Profile Correction Factor

Due to boundary layer effects, the velocity distribution of the flow in a pipe is not uniform but has a specific shape determined by the flow Reynolds number and pipe geometry (see Ref. 3). The FPCF is defined as the ratio of the true volumetric (or mass) flow over the volumetric (or mass) flow measured by an ultrasonic flow meter. In terms of the flow velocity, it is the ratio of the true flow velocity averaged over the pipe flow cross-section to the velocity measured by an ultrasonic flow meter.

For the transit-time meter, the velocity measured ultrasonically is the average of the flow velocity distribution over the ultrasonic path. Therefore, calculation of the theoretical flow profile correction factor is relatively simple, at least when the shape of the flow profile in the pipe is known, as is the case for the fully developed flow (high Reynolds numbers, long runs of straight pipe). Of course, in practice, accurate values of the flow profile correction factor can only be obtained by calibrating a meter for a specific Reynolds number and a specific pipe.

Similar theoretical calculations for the USCCFM are extremely difficult because there is no reliable description of turbulent properties of fluid flow in a pipe. Derivation of the FPCF for the USCCFM would involve first-principle treatment of the interaction of the ultrasonic beam with turbulence eddies in the fluid. However, accurate values of the FPCF for USCCFM for more common piping configurations have been obtained from the meter calibration in high precision flow testing laboratories (Ref. 3).

In particular, the established behaviour of the FPCF downstream of a 90° elbow can be used to analyse Darlington NGS moderator flow measurements (Fig.2.3). However, the piping configuration in the Bruce-B moderator loop is very different from standard configurations, and uncertainty in the FPCF would have been unacceptably high without additional calibration work. The next section describes moderator system at each station and the relevant piping configuration, and Section 4 presents calibration results for Bruce B test model.

3.0 MODERATOR SYSTEM DESCRIPTION

3.1 Darlington Moderator System

The moderator system is a heavy water recirculating system consisting of two main pumps, two auxiliary pumps, two tube-in-shell heat exchangers, and associated valves and piping. The piping isometrics between the heat exchangers and the calandria is shown in Fig. 3.1 and 3.2

During normal operation, heavy water is pumped by one of two pumps (P1 or P2) through the two heat exchangers (HX1 and HX2). Auxiliary pumps (P3 and P4) circulate heavy water when reactor is shutdown or in the event that the main pumps are lost. The moderator system is designed so that each of the main pumps provides the same flow, which is almost equally split between the two heat exchangers. The two auxiliary pumps are also supposed to provide equal flows.

Ultrasonic measurements were performed, primarily, to determine the total flow through the calandria; however, the flow distribution between the two heat exchangers and between the two calandria inlet lines were also of interest. For this reason, measurements were performed in four locations, denoted as “x1” through "x4" in Figs. 3.1-3.2. Locations 1 and 4 were on the two heat exchangers outlet lines and locations 2 and 3 were on the two calandria inlet lines. All the lines involved in the measurements are stainless steel 12" pipes. If the moderator system had perfect hydraulic balance there would be no flow in the balance header (line L8), and the flows measured in the other four locations would be all equal to each other. Although in systems of this complexity perfect hydraulic balance is almost impossible and the four flows are not all the same, the total of the heat exchanger outlet flows must be equal to the total of the two calandria inlet flows. This provides an additional check on the flow and can be used to increase measurement accuracy for the total flow.

3.2 Bruce B Moderator System

The diagram of the Bruce-B moderator system piping isometrics between the heat exchangers and the calandria is shown in Fig. 3.3. Measurements were performed in five locations, denoted as "x1" through "x5". Locations 1 and 3 were on the two calandria inlet lines, locations 2 and 4 were on the two heat exchangers outlet lines, and location 5 was on the balance header.

As was mentioned in the Introduction, the only locations accessible for transducer installation were immediately downstream of 135° elbows on heat exchanger outlet lines and just over two feet downstream of t-junctions on calandria inlet lines. In addition, the system piping configuration upstream of 135° elbows and t-junctions also introduces significant flow disturbances. Since no calibration curves were available for this specific configuration, USCCFM calibration was performed in the OPG Flow Testing Laboratory on a full-scale model that closely approximated the actual piping configuration.

4.0 USCCFM CALIBRATION FOR BRUCE-B MODERATOR MEASUREMENTS

4.1 OPG Flow Testing Laboratory

OPG Flow Testing Laboratory is a flow calibration facility, which incorporates a 10-meter head tank capable of providing gravity fed flow up to 300 L/s and an 8,000 kg weight tank for accurate measurements of mass flow. A flow measuring device such as the USCCFM is calibrated by measuring flow at a particular pipe location and then comparing the meter reading with the mass flow obtained by the static weighing method. The total quality assured 2σ flow measurement uncertainty of the static weighing method varies from 0.12% at the National Institute of Standards and Technology to 0.25% at Alden Research Laboratories, to <0.5% at the National Research Council of Canada Hydraulic Laboratory. The OPG Flow Testing Laboratory is very similar in design and operation to the NRC Hydraulic Laboratory and therefore the same overall uncertainty of 0.5% is achievable.

4.2 Bruce-B Moderator Piping Model

Modelling of a piping configuration for the purpose of calibrating a flow measuring device involves a trade-off between reproducing the actual piping arrangement as close as possible, on one hand, and practical considerations such as the model size, its cost, etc., on the other hand. Model design for Bruce-B moderator flow calibration was based the following considerations:

- previous USCCFM calibration data (Ref. 3) indicate that the FPCF is within about 2% of its fully developed value past ten diameters downstream of a flow disturbance;
- sufficient information is available to be able to extrapolate the FPCF for a particular piping configuration from a lower mass flow provided in the OPG Flow Testing Facility to the higher plant flow;
- since the cost of manufacturing a model from stainless steel is several times higher than from carbon steel, some accuracy will have to be sacrificed due to effect of pipe roughness on the FPCF;
- although the cost of PVC piping is even lower than the cost carbon steel piping, PVC does not lend itself to manufacturing joints and elbows geometrically similar to those existing in the plant.

The two deviations from the ideal calibration tests were the fact that the model was manufactured from carbon steel and that calibration flow was significantly lower than the actual plant flow. The model fully reproduced the moderator system piping configuration close to measurement locations, as indicated in Fig. 3.3. Due to the system symmetry only measurement locations 1 and 2 were modelled. The FPCF in location 3 must be identical to the FPCF in location 2, and the FPCF in location 4 must be the same as that in location 1. As was mentioned before, only very low flow or no flow at all was expected in location 5 (balance header). Therefore, the pipe that modelled the balance header terminated in a dead end, which had two small drain lines (1" and 2") and a valve on each drain line. By performing calibrations with the valves closed and open it was hoped that sensitivity of the FPCF to the flow in the balance header could be determined.

Three views of the model installed at the OPG Flow Testing Facility are shown in Fig. 4.1. The t-junction and the dead end with the two drain lines are seen in the foreground of Fig.4.1a. Due to the Testing Facility layout, the pipe which models the calandria inlet line (measurement location 2) is below the t-junction, rather than above it, as is the case in the plant piping configuration (see Fig. 3.3). The white PVC pipe in the right-hand half of Fig. 4.1a is the 11-foot straight pipe connected to the model by a 135° elbow. Measurement location 1 is just upstream of the elbow. The opposite end of the white PVC pipe is connected by another 135° elbow to a long 80-

foot straight run to ensure that the flow is fully developed before it enters the white pipe. Figures 4.1b and 4.1c give better views of the model upstream of the t-junction.

4.3 Calibration Measurements

As was mentioned in Section 3, there was very little flexibility in terms of transducer locations on the pipes during station measurements. However, calibration tests were performed prior to station measurements, and exact positions of transducers on the pipes in the field were not yet known. Therefore, calibration was done for a number of transducer locations downstream of the 135° elbow and of the t-junction, as well as for several transducer orientations, i.e. the angle between ultrasonic beams and the plane of the elbow or the t-junction.

4.3.1 Pipe Flow Area Measurements. In order to increase measurement accuracy pipe flow area was evaluated from the measurements of the outside diameter using a high-precision traceable calliper and measurements of the wall thickness using an ultrasonic thickness gage Panametrics Model #26DL.

4.3.2 Elbow Calibration. Downstream of the elbow, 11 positions were measured between about 2.5 and 4.5 pipe diameters away from the centre line of the elbow for one particular transducer orientation. Most of the readings were taken about one meter or four pipe diameters downstream of the elbow. For that location, the transducer was rotated around the pipe, and measurements were taken in four different planes. For most locations two or more sets of readings were taken on different days to check measurement reproducibility.

4.3.3 T-junction Calibration. Downstream of the t-junction, 7 positions were measured between about 2 and 3.5 pipe diameters away from the centre axis of the upstream pipe. Most of the readings were taken close to 35 inches or 3.5 diameter from the t-junction. For that location, the transducer was also rotated around the pipe, and measurements were taken in three different planes. For most locations two or more sets of readings were taken on different days to check measurement reproducibility.

4.3.4 Reference Flow Measurements. The flow was also continuously monitored in a reference pipe immediately upstream of the model (white PVC pipe at the bottom of Fig.4.1b). The transducer was mounted about 8 feet downstream of a 135° elbow and about 3 feet upstream of the other 135° elbow (see Fig. 3.3 for approximate correspondence to the station configuration). The reason for monitoring the flow in a reference pipe was twofold. First of all, continuous monitoring ensured that the calibration loop flow was constant over 10-15 minute time intervals, which are normally used to obtain average USSFM data, in spite of fluctuations in the weighing tank readings. Secondly, it provided information on the FPCF before the flow entered the region where station measurements were going to be done. Most of the calibration tests were performed at the maximum achievable loop flow of between 225 L/s and 230 L/s. A few runs were done at lower flows of about 150L/s and 100 L/s in order to verify the Reynolds number dependence of the FPCF.

Of course, Bruce-B moderator piping configuration upstream of the 11-foot pipe is much more complicated than a long straight pipe in the calibration setup. However, calibration measurements done earlier (Ref. 3, 4) indicate that, if pipe elbows are almost 10 diameters apart, the effect on the FPCF is dominated by the upstream elbow closest to the measurement location. From this point of view, flow measurements in the reference pipe provide confidence that the model reproduces well the FPCF in the plant measurement locations.

4.4 Calibration Results

The value of the FPCF in the reference location varied between 0.960 and 0.965 over 5 days of testing. This value is about 3-3.5% higher than the FPCF for the fully developed flow at the test Reynolds number of 1.1×10^6, and agrees well with the expected value 9 pipe diameters downstream of a 90° or 180° elbow (Ref. 3). Since the flow at the station was expected to be about twice as high as in calibration tests, sensitivity of the FPCF to the flow velocity was also verified. However, because higher velocities could not be achieved at the calibration facility, measurements were also done at about 30% and 50% lower velocities. Selected results of calibration measurements are summarized in Table 4.1 for the locations downstream of the elbow and in Table 4.2 for the locations downstream of the t-junction.

4.4.1 FPCF Downstream of the 135° elbow. As the distance from the elbow is increased, there is a rapid increase in the FPCF very close to the elbow, followed by a maximum at approximately 3.5 pipe diameters away from the elbow, and then by a slower decrease. There is a very strong dependence of the FPCF on the transducer orientation very close to the elbow. The dependence almost disappears past about four pipe diameters downstream of the elbow and it is clear that in order to apply calibration results to field measurements the transducer must be mounted at least four pipe diameters away from the elbow. Unfortunately, the only position on the pipe available at Bruce-B was immediately downstream of the elbow. Therefore, elbow calibration results can not be used for analysing station measurements without incurring a significant penalty on measurement uncertainty.

4.4.2 FPCF Downstream of the T-junction. The FPCF downstream of the t-junction (Table 4.2) shows a monotonic decrease as the distance from the junction is increased. The decrease is much more rapid than downstream of the elbow and there also seems to be no dependence on the transducer orientation. This behaviour makes calibration results directly applicable to station measurements, when there is no flow through the balance header. To get an even more accurate value of the FPCF for the station transducer location at 28" downstream of the t-junction, additional calibration runs were done after Unit 5 measurements.

To determine the effect of the balance header flow on the FPCF, calibration was repeated with the transducer mounted in one of the locations close to three pipe diameters downstream of the t-junction and drain valves open. By comparing the weighing tank readings and the reference meter measurements with drain valves closed and open, the flow in the pipe modelling the balance header was estimated to be about 7 L/s, or close to 3% of the flow into the t-junction. The effect on the FPCF was significantly larger than expected and was found to be about 1.5-2%. Having just one value on the curve for the dependence of the FPCF on the balance header flow does not allow an accurate prediction of the FPCF if the flow in the field is significantly higher.

It turned out that there was no measurable flow through the balance header in both Unit 5 and Unit 8 with pump P1 running, but the flow with pump P2 running was close to 20% of the flow into the t-junction. Clearly, calibration results are insufficient to derive accurate values of the FPCF for the latter case. However, if the flow in the balance header with pump P1 running is, in fact, identically zero, then calibration results can be used to determine calandria inlet flows, and heat exchanger outlet flows must be equal to the corresponding calandria inlet flows.

5.0 MEASUREMENTS RESULTS

5.1 Darlington Unit 2 and Unit 4

Measured time delays and the derived flows in L/s for various pump configurations are given in Table 5.1 for Unit 2 and in Table 5.2 for Unit 4. Pipe flow areas are also given in the Tables. The transducer separation was set to d=0.1m for auxiliary pump measurements and d=0.3m for main pump measurements. As was mentioned earlier, values for the FPCF were obtained from the calibration curve downstream of a 90° elbow (see Fig. 2.3) and adjusted for higher Reynolds numbers with the main pumps P1 and P2 running and for lower Reynolds numbers with the auxiliary pumps P3 and P4 running.

The distance from the elbow to the heat exchanger outlet measurement locations was less than six pipe diameters and to the calandria inlet – about ten pipe diameters. There is also a check valve in the heat exchanger outlet line just upstream of the elbow. Both the fact that the curve shown in Fig. 2.3 is very steep for L/D<10 and the presence of a check valve make it difficult to get an accurate value of the FPCF for heat exchanger outlet measurements. Therefore, heat exchanger outlet flows are derived by equating the total heat exchanger outlet and the total calandria inlet flows. The FPCF for calandria inlet measurements are obtained by taking the value of 0.95

from Fig. 2.3 and increasing it by about 0.01 for the main pumps ($Re=2.5*10^6$) or reducing by about 0.015 for the auxiliary pumps ($Re=0.3*10^6$).

The main result of the measurements is that the total flows in both units with the main pumps running are close to each other and are significantly higher than that assumed in the Safety Analysis. The total flows with auxiliary pumps running are also close to each other. Finally, the flows through the heat exchangers are about the same but the flows into the calandria differ by up to 10%.

5.2 Bruce B Unit 5 and Unit 8

Measured time delays and the derived flows in L/s for various pump configurations are given in Table 5.3 for Unit 5 and in Table 5.4 for Unit 8. Pipe flow areas are also given in the Tables. Transducer separation d was set to 0.1m for auxiliary pump measurements, 0.2m for main pump measurements of heat exchanger outlet lines and 0.3m for main pump measurements of calandria inlet lines.

As mentioned earlier, the only values of the FPCF directly applicable to station measurements are for measurements downstream of t-junctions (calandria inlet flows) with the main pump P1 running if there is no flow through the balance header. In this case, calandria inlet flows are calculated using the values of the FPCF from Table 4.2, and heat exchanger outlet flows must be equal to the corresponding calandria inlet flows. These were the first two steps in the following procedure that was adopted to calculate FPCF for all the measurement locations and pump configurations.

- Calandria outlet flows (P1 running) – FPCF from calibration results
- Heat exchanger outlet flows (P1 running) – FPCF are determined from equating heat exchanger outlet flows to the corresponding calandria outlet flows
- Heat exchanger outlet flows (P2 running) – FPCF are the same as for P1 running
- Calandria outlet flows (P2 running) – FPCF are determined by equating the sum of heat exchanger outlet flows to calandria inlet flows
- Auxiliary pumps (P3 and P4) – FPCF for all locations are determined by appluing Reynolds number correction to P1 results.

The main result of the measurements is that the total flows in both units with the main pumps running are close to each other and are significantly higher than that assumed in the Safety Analysis. Also, the flows through the heat exchangers are about the same, and the flows into the calandria with pump P1 running are also very similar to each other. However, the flows into the calandria with pump P2 running differ by about 30%. All the flows with auxiliary pumps running are within measurement uncertainty.

6.0 MEASUREMENT UNCERTAINTY ANALYSIS

In this Section, uncertainties in each of the terms in Eq. 2.1 are considered separately and the total flow measurement uncertainty is derived. All the uncertainties are evaluated at the 95% or 2σ confidence level. The pipe dimensional uncertainties derived here are for the Bruce B piping. The uncertainty for Darlington piping is less due to the large diameter piping.

6.1 Pipe Flow Area

6.1.1 Pipe Outside Diameter. The uncertainty in the pipe flow area is derived by combining measurement errors in the pipe outside diameter and in the wall thickness. The measurement procedure is the same as described in Section 4.3.1 for calibration measurements. Four measurements around the pipe in each of the two planes along the pipe were done on Unit 5 and three measurements around the pipe in each of the three planes along the pipe were done on Unit 8. Therefore, the total of at least eight measurements were done, and the largest standard deviation among measurements was σD=0.2%. Precision of the calibrated calliper is 0.001". However, because of difficult measurement conditions the error of a single measurement of the outside diameter is conservatively taken as δD=0.005". Since due to manufacturing process there is real variation in the pipe outside diameter, the 2σ uncertainty (in %) in the average value is calculated according to

$$\varepsilon_D = \mathrm{sqrt}((\delta D/D_{aver})^2 + (\sigma D/D_{aver} x St(8-1)/\mathrm{sqrt}(8))^2) x 100\% \qquad \text{or}$$

$$\varepsilon_D = \mathrm{sqrt}((0.005/10.8)^2 + (0.002\, x 2.36/2.83)^2) x 100\% = 0.17\%,$$

where St(8-1) is the student-t distribution for eight measurements.

6.1.2 Pipe Wall Thickness. The wall thickness is measured by an ultrasonic thickness cage calibrated for the same material (stainless steel) and at the same temperature as the moderator piping. The manufacturer specified accuracy of the ultrasonic thickness gage Panametrics Model #26DL is δWT=0.001", which gives the random error for the average thickness based on 8 measurements around the pipe for each transducer location as

$$\varepsilon_{WT} = \mathrm{sqrt}((\delta WT/WT_{aver})^2 + (\sigma WT/WT_{aver} x St(8-1)/\mathrm{sqrt}(8))^2) x 100\% \qquad \text{or}$$

$$\varepsilon_{WT} = \mathrm{sqrt}((0.001/0.375)^2 + (0.003 x 2.36/2.83)^2) x 100\% = 0.37\%$$

Although, in the case of Unit 8, 24 measurements around the pipe were done at each transducer location, the additional systematic error due to the velocity of sound not being exactly the same as in the calibration block dominates the total uncertainty.

Variation in the velocity of sound, depending on the type of stainless steel, is about 1% (Ref. 11), which is then the highest possible systematic error in wall thickness measurements. The total error in pipe thickness measurements is then about ε_{WT}=1.4%.

6.1.3 Pipe Flow Area. The error in the pipe flow area is calculated according

$$\varepsilon_A=2(\varepsilon_D D_{aver}+2\varepsilon_{WT} WT_{aver})/D_{aver} x 100\%$$

and gives **$\varepsilon_A=\pm 0.58\%$.**

6.2 Transducer Spacing

For the specific transducer design used in Ontario Power Generation, manufacturing tolerances of about 1 mm for the 300 mm spacing result in the uncertainty of about ±0.06%. This uncertainty should be increased slightly due to the possible transducer misalignment during installation. The resulting uncertainty is conservatively estimated at **±0.1%.**

6.3 Time Delay Measurements

The two sources of uncertainty in the time delay measurements are due to measurement repeatability and measurement reproducibility. Measurement repeatability is simply the amount of scatter among the readings in each set of data. A typical data set contained between 50 and 100 points, with one standard deviation between 2% and 3%. Based on these numbers, the upper bound on the 2σ repeatability of the average value is about **±0.5%**.

Measurement reproducibility refers to the effect of changes in measurement conditions such as transducer mounting and/or changes in the system configuration on the measured flow. Extensive laboratory and plant tests (Ref. 3) indicate that the 2σ value for meter reproducibility is under **±0.3%**.

6.4 Flow Profile Correction Factor for Darlington Masurements

The uncertainty in the FPCF is calculated from the combined uncertainty of calibration measurements downstream of a 90° elbow performed in the OPG Flow Testing Laboratory and the additional uncertainty due to the difference in measurement conditions between the laboratory and the plant. The uncertainty in the reference flow is estimated at 0.5% as discussed in Section 4.1. This uncertainty must be combined with other contributions to USCCFM uncertainty to derive the total final value for the uncertainty in the FPCF.

Since calibration tests were performed on a plastic pipe with a very uniform outside diameter and wall thickness, the uncertainty in the flow area is at most 0.1%. One standard deviation in a particular data set of at least 50 points is always less than 0.5% and, therefore, the upper bound on the 2σ repeatability of the average value is 0.1%. Reproducibility was also shown to be better than 0.1% (Ref. 6), and the error in transducer separation is the same as above (0.1%). Combining these uncertainties in quadratures, results in a value of ±0.54**%** for the uncertainty in individual points on the calibration curve in Fig. 2.3.

An additional contribution to the uncertainty in the FPCF used for analysing station measurements is due to its dependence on the Reynolds number. Since station flows are twice as high as flows in calibration tests with main pumps running and about four times lower with auxiliary pumps running, the value of FPCF obtained from calibration tests must be extrapolated to station flows.

According to the reasonably well known dependence of the FPCF on the Reynolds number (or velocity) for the fully developed flow (see Ref 3), its value changes from about 0.93 for v=4.5 m/s ($Re=1.1*10^6$) to between 0.935 and 0.94, depending on the model, for v=10 m/s ($Re=2.5*10^6$). On the other hand, the value at low velocities v=1 m/s ($Re=2.5*10^5$) is between 0.91 and 0.92. The additional uncertainty is conservatively assumed to be 0.5% and is combined with 0.54% to give εC_{FPCF}=**±0.74%**.

6.5 Total Measurement Uncertainty for Darlington Measurements

Table 6.1 lists individual components and the total measurement uncertainty for calandria inlet flows and heat exchanger outlet flows. The uncertainty in individual flows is determined by combining the terms given in Sections 6.1-6.5 in quadratures and is equal to **±1%**. The total moderator flow is the sum of the two calandria inlet flows or the two heat exchanger outlet flows. Therefore, in determining the total flow uncertainty, contributions from all the individual terms, except the FPCF are divided by sqrt(2). The total moderator flow uncertainty is then lower than the uncertainty in individual flows and is equal to **±0.88%**.

6.6 Flow Profile Correction Factor for Bruce B Measurments

The uncertainty in the FPCF is calculated from the combined uncertainty of calibration measurements performed in the Flow Testing Laboratory and the additional uncertainty due to the difference in measurement conditions between the laboratory and the plant.

6.6.1 Calibration Measurement Uncertainty. The uncertainty in the FPCF derived from calibration measurements is a combination of USCCFM flow measurement uncertainty and the uncertainty in weighing tank readings, based on the expression obtained from Eq. (2.1)

$$\mathbf{C_{calib} = W_{tank}/(A*d/\Delta t)} \qquad \textbf{(6.1)}$$

Except for the uncertainty in the flow area and in repeatability, other uncertainties are the same as quoted above (εW_{tank}=0.5%; εd=0.1%; $\varepsilon \Delta t$=0.3%). Since in calibration tests one standard deviation in a particular data set of at least 50 points is always less than 0.5%, the upper bound on the 2σ repeatability of the average value is 0.1%.

The outside diameter of the carbon steel pipe used in fabrication of the Bruce-B model is much more uniform than that of the stainless steel pipe in the moderator loop. As a result, the uncertainty in the outside diameter at each transducer location, based on eight measurements, is about 0.05%. However, the wall thickness is less uniform than that of a stainless steel pipe with one standard deviation up to 1%. Since speed of sound variation in carbon steel pipe is less than 0.5%, the total uncertainty in the wall thickness, based on 16 wall thickness measurements around the pipe, is then about 1.1%. Estimated uncertainty in the flow area is then 0.27% and the total uncertainty in the FPCF derived from calibration measurements is equal to **±0.66%**.

6.6.2. Application to Station Measurements. As was discussed in Section 4, the only case when calibration results would be directly applicable to station measurements is when the balance header flow is zero. However, there will be an additional contribution to the uncertainty from the fact that only an upper bound on the balance header flow is known (about 25 L/s or 5% of the individual flows). The additional uncertainty can be estimated from calibration data, where a low flow in the model balance header resulted in a 1.5-2% change in the FPCF. Assuming a linear dependence on the flow in the balance header, the FPCF at Bruce-B can be as much as 3% higher than obtained in calibration results.

Another contribution to the uncertainty comes from the sensitivity of the FPCF to the exact transducer position downstream of the t-junction. We estimate this contribution to be about 1%.

Finally, there is also a contribution to the uncertainty in the FPCF due to its dependence on the Reynolds number. Since station flows are twice as high as flows in calibration tests with main pumps running and about four times lower with auxiliary pumps P3 and P4 running, the value of FPCF obtained from calibration tests must be extrapolated to station flows. The additional uncertainty is conservatively assumed to be 0.5% as discussed in Section 6.4.

Combining the above uncertainties, results in the value of **±3.27%** for the uncertainty in the FPCF for calandria outlet flows with pump P1 running. Since heat exchanger outlet flows is obtained by equating them to the corresponding calandria outlet flows , the uncertainty will be similar. For pump P2, the same values of FPCF are used for heat exchanger outlet flows as for pump P1; therefore, the same uncertainty can be used. However, calandria inlet flows are derived by equating the total calandria inlet flow to the total heat exchanger outlet flow. Since the FPCF in this case is obtained from the following expression

$$C_{P2}=W_{P1}/(A*d/\Delta t) \qquad (6.2)$$

εC_{P2} will be higher than εC_{P1} and will incorporate the total uncertainty in W_{P1}, as well as individual uncertainties in A, d and Δt. In Table 6.1 below, the total uncertainty for W_{P1} is given as 3.37% so that $\varepsilon C_{P2}=\pm$**3.47%**.

6.7 Total Measurement Uncertainty for Bruce B Measurements

Table 6.2 lists individual components and the total measurement uncertainty for calandria inlet flows and heat exchanger outlet flows for pump P1 and pump P2 running. The total moderator flow is the sum of the two calandria inlet flows or the two heat exchanger outlet flows. Therefore, in determining the total moderator flow uncertainty, contributions from all the individual terms, except the FPCF are divided by sqrt(2) to give an uncertainty of **±3.32%** for pump 1 and **±3.56%** for pump 2.

7.0 CONCLUSIONS

Moderator flow measurements have been performed at Darlington on units 2 and 4 and at Bruce NGS-B on units 5 and 8 using the Ultrasonic Cross-Correlation Flow Meter. The total moderator flow on both units at both stations is found to be significantly higher than the value assumed in the Safety Analysis. Darlington piping configuration was more suitable for high accuracy measurements and rigorous uncertainty analysis indicates that the uncertainty is slightly above 1% for individual flows and is better than 1% for the total moderator flow. Meter calibration in the OPG Flow Testing Laboratory was performed on a full-scale piping model to improve measurement accuracy at Bruce B due to the very difficult piping arrangement. Calibration work and careful in-plant measurements have resulted in reasonable accuracy of the measured flows. Rigorous uncertainty analysis indicates that the uncertainty is close to 3.5% for both individual flows and total moderator flow.

8.0 ACKNOWLEDGEMENTS

The staff of the OPG Flow Testing Laboratory Martin Greenall, Dave Lowther and Andy Lemyk provided invaluable help in designing and procuring the moderator piping model and made significant efforts to fit calibration tests into their busy schedule.

9.0 REFERENCES

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4. Panametrics Thickness Gauge User Manual.

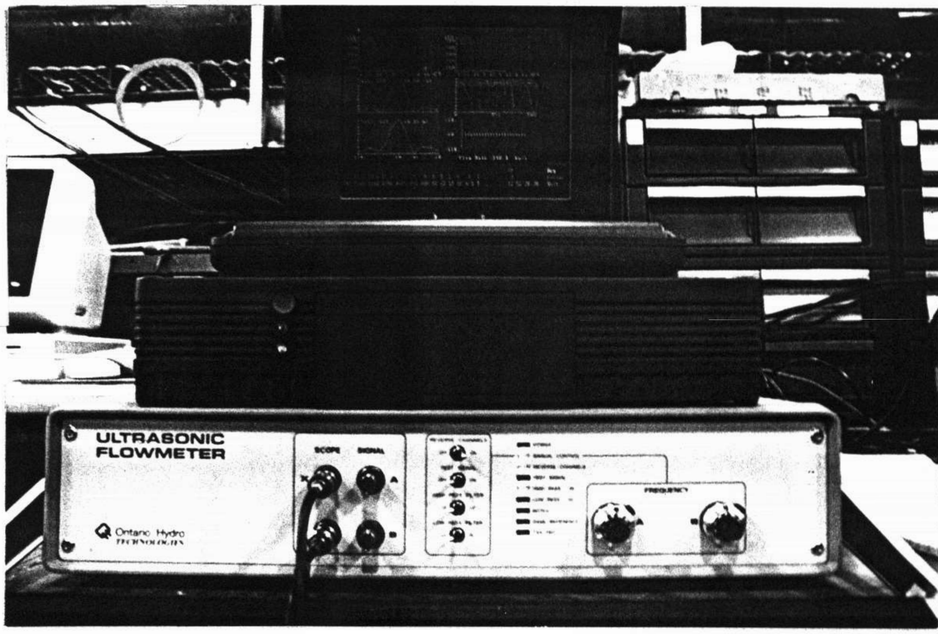

Figure 2.1

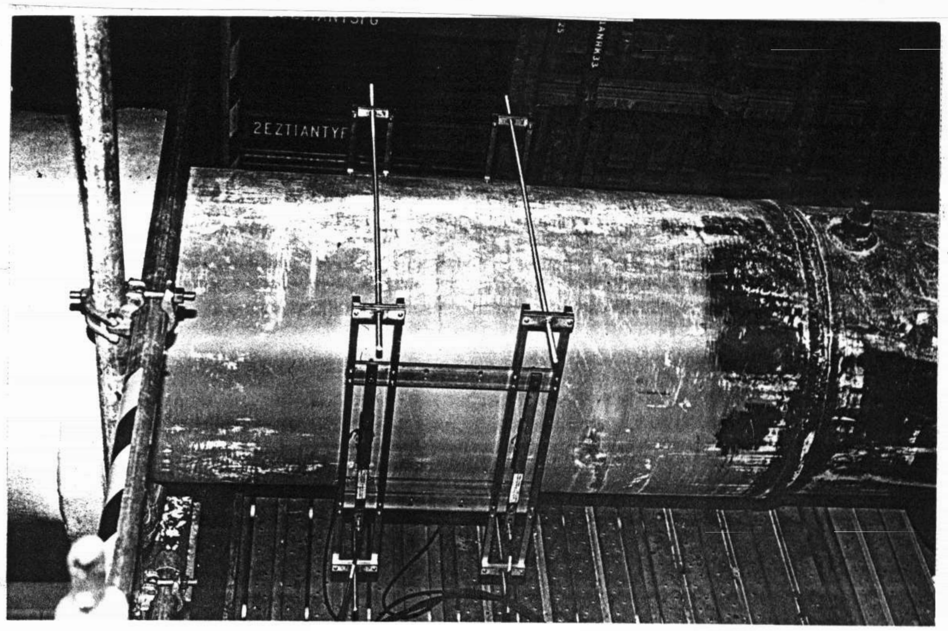

Figure 2.2

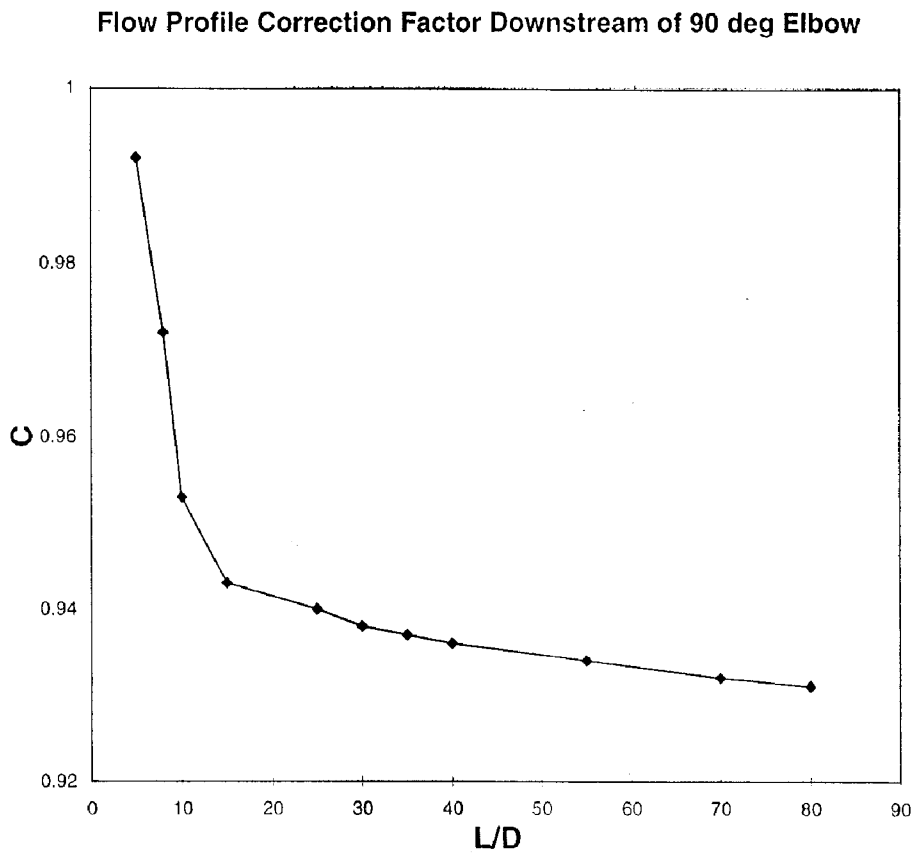
Flow Profile Correction Factor Downstream of 90 deg Elbow
1
0.98
C
0.96
0.94
0.92
0
10
20
30
40
50
60
70
80
90
L/D

Figure 2.3

DARLINGTON MODERATOR SYSTEM PIPING EAST

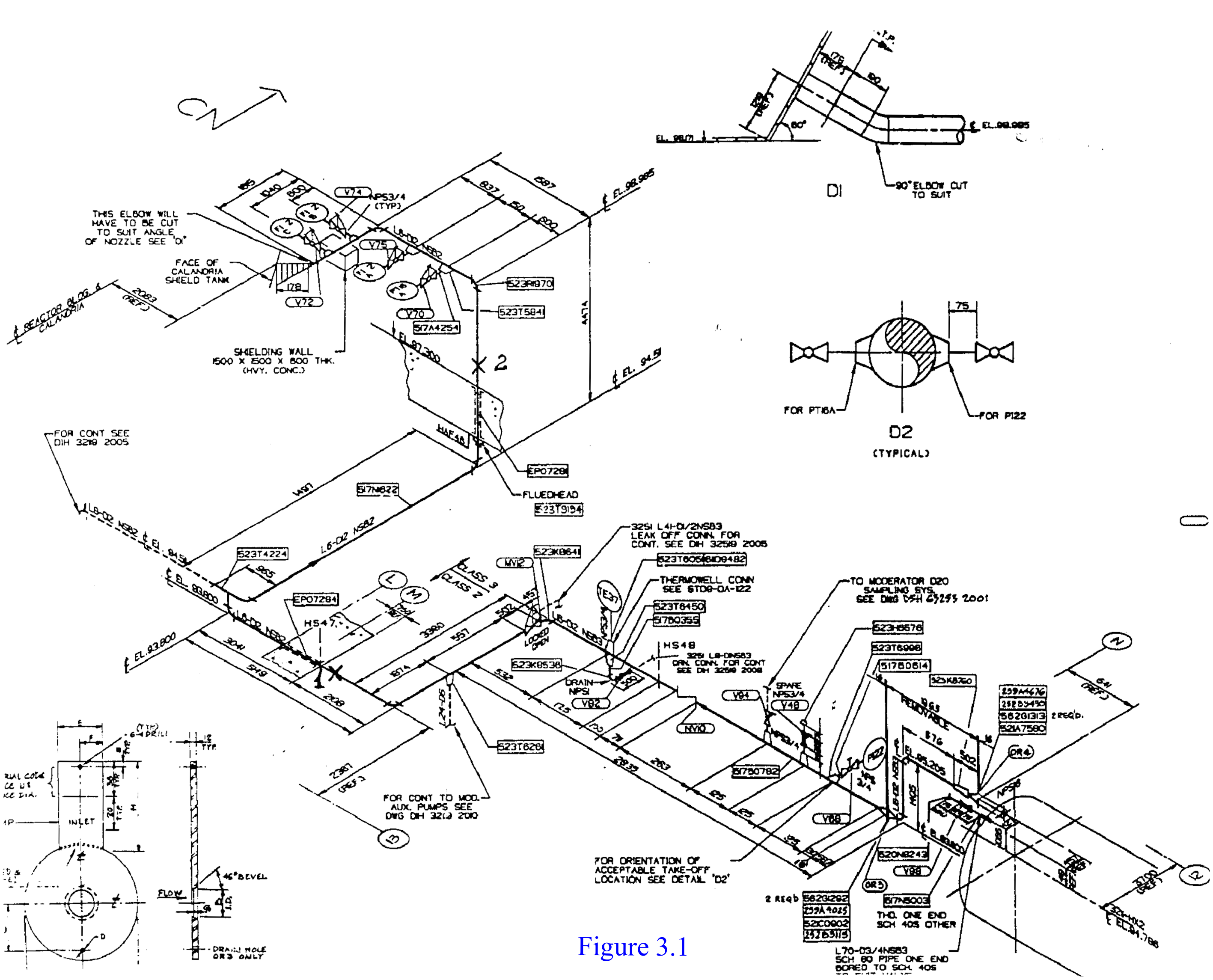

Figure 3.1

DARLINGTON MODERATOR SYSTEM PIPING WEST

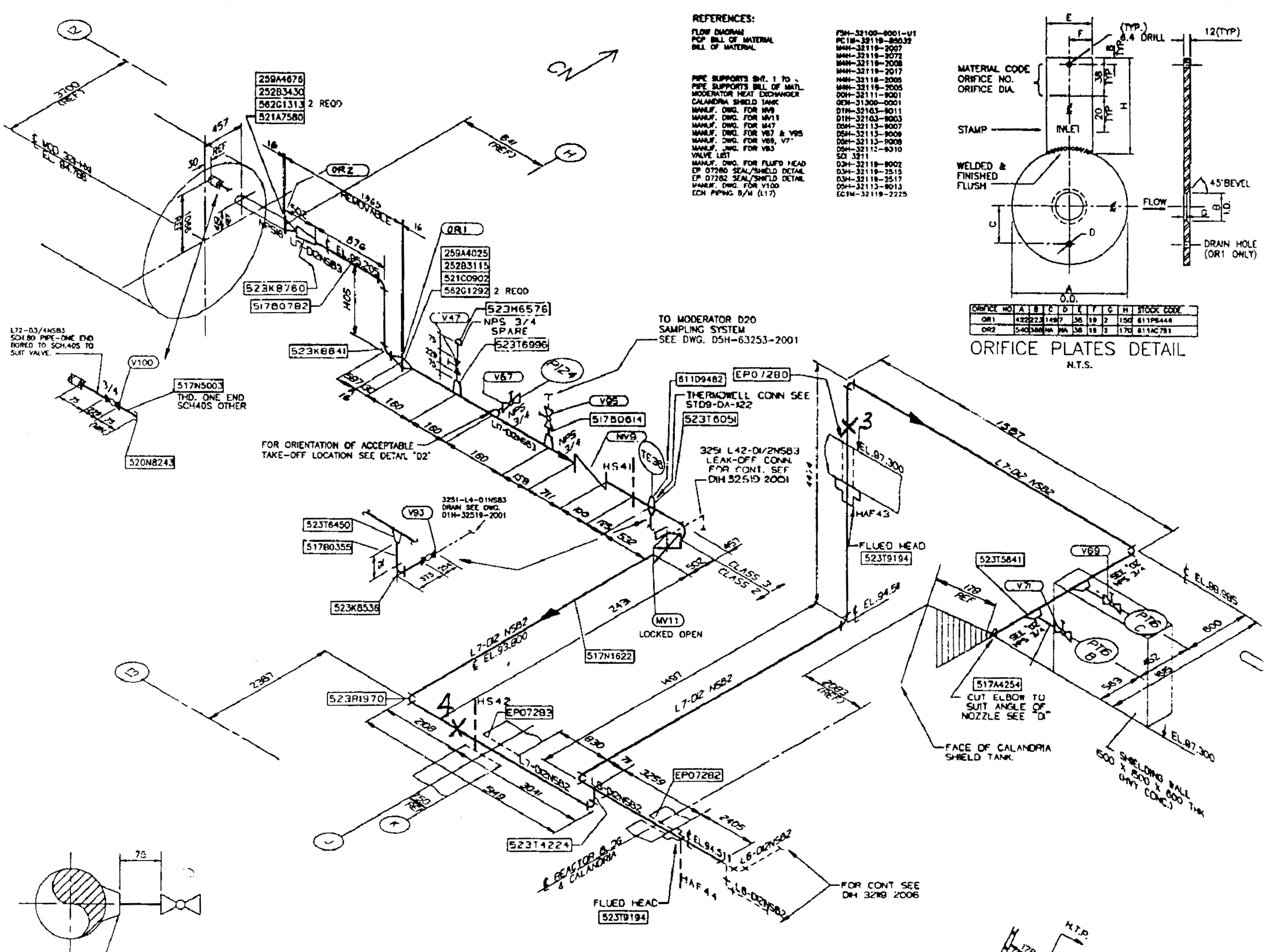

Figure 3.2

BRUCE B MODERATOR SYSTEM PIPING

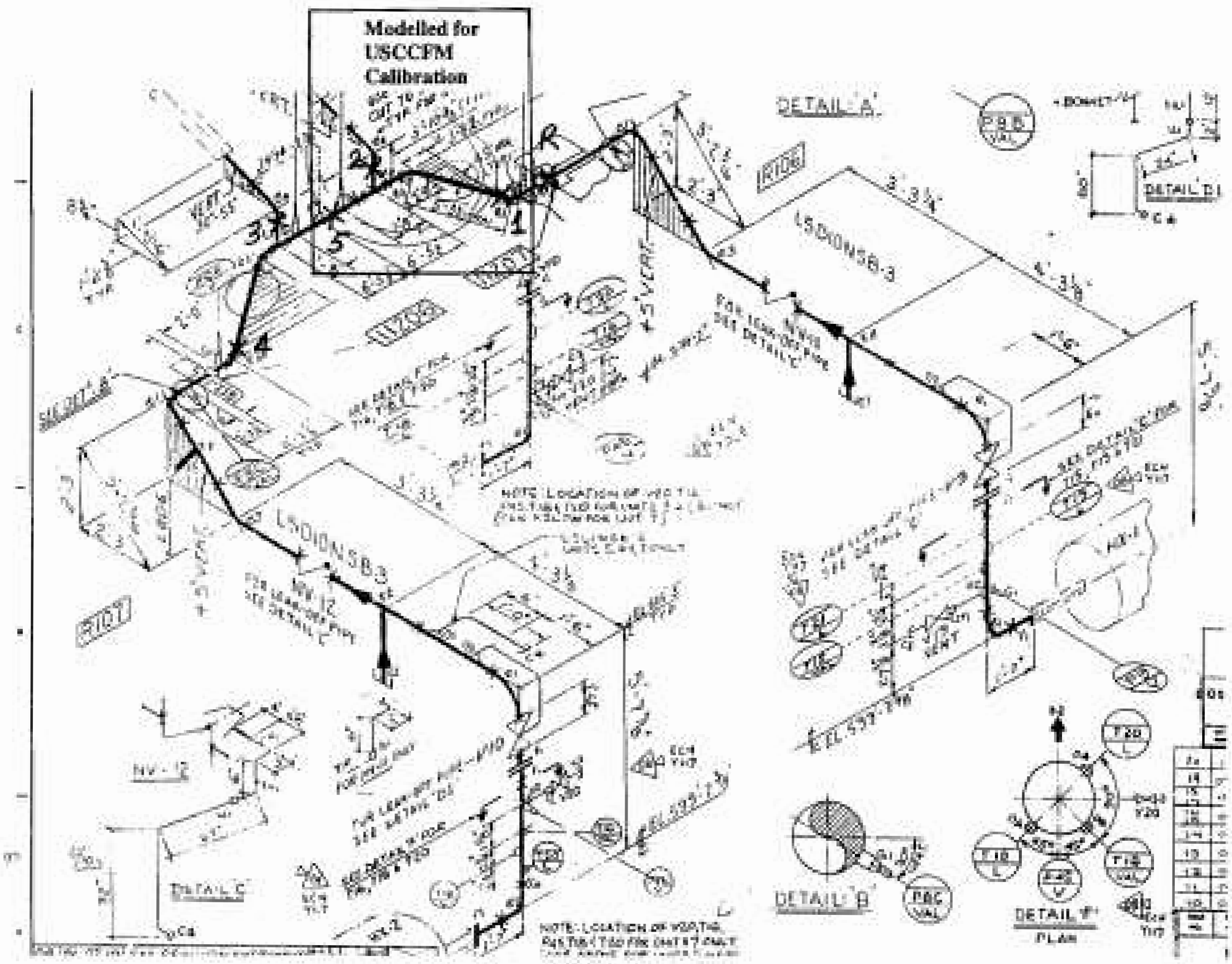

Figure 3.3

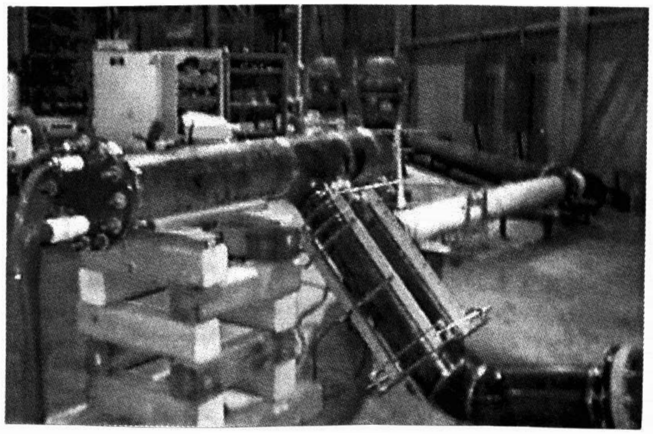

Figure 4.1a

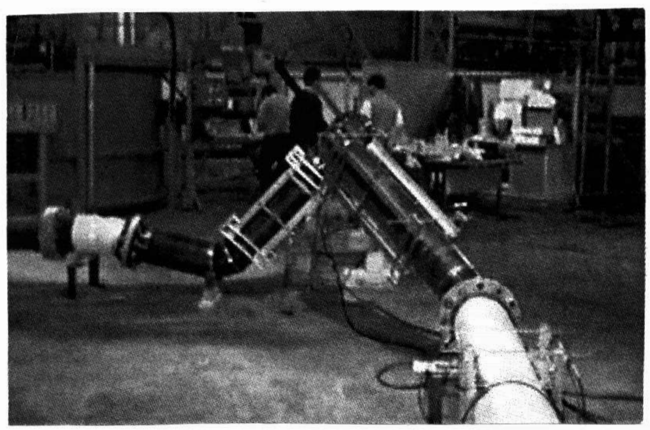

Figure 4.1b

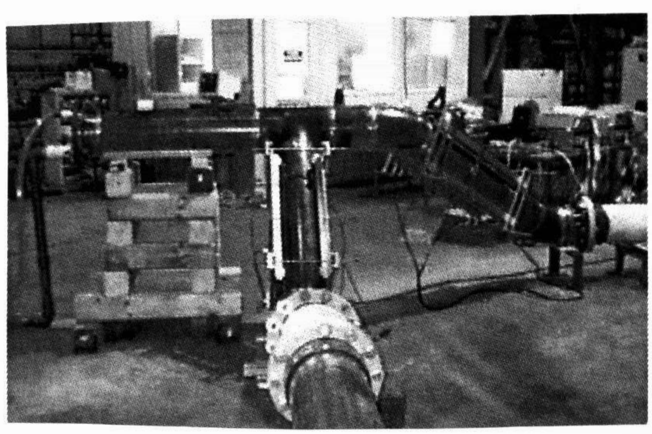

Figure 4.1c

TABLE 4.1

Results of Calibration Measurements Downstream of 135° Elbow

DISTANCE FROM ELBOW		TRANSDUCER ORIENTATION (BEAM ANGLE WITH UPSTREAM PIPE)							
		0°		45°		90°		135°	
(in)	(L/D)	Δt (ms)	FPCF	Δt (ms)	FPCF	Δt (ms)	FPCF	Δt (ms)	FPCF
23.9	2.367					79.06	1.143	64.79	0.938
27.8	2.757							70.03	1.013
								69.95	1.012
29.5	2.953							71.38	1.033
31.5	3.148					76.07	1.100	72.58	1.050
								72.72	1.052
								72.47	1.049
33.7	3.343							73.27	1.060
								72.84	1.054
35.7	3.539	71.19	1.064			74.46	1.076	74.53	1.074
37.6	3.734					74.07	1.071	73.51	1.064
39.6	3.929	70.79	1.058	70.46	1.051	73.73	1.066	73.71	1.062
				70.45	1.050				
41.6	4.124	69.44	1.038	69.44	1.038	71.85	1.039	71.87	1.039
		69.17	1.034	69.43	1.037				
		69.43	1.037	69.22	1.033				
		69.22	1.033	69.25	1.033				
43.5	4.320	70.09	1.048	69.92	1.043	71.82	1.038	71.70	1.033
		69.84	1.044			72.06	1.042	71.36	1.032
						71.86	1.039		
47.5	4.710	68.48	1.024			72.07	1.042	72.04	1.038
								71.89	1.036
								71.83	1.035
								72.00	1.037
								72.09	1.038
2" DRAIN OPEN	4.124			67.96	1.029				
				68.12	1.031				
2"+1" DRAINS OPEN	4.124			68.33	1.037				
				68.16	1.034				
				68.10	1.033				

FPCF $=W_{TANK}/W_{US}$, where W_{US} is calculated according to Eq.(2.1) with $A=0.05148m^2$ and d=0.3m.

TABLE 4.2
Results of Calibration Measurements Downstream of t-Junction

DISTANCE FROM T-JUNCTION		TRANSDUCER ORIENTATION (BEAM ANGLE WITH UPSTREAM PIPE)					
		0°		45°		135°	
(in)	(L/D)	Δt (ms)	FPCF	Δt (ms)	FPCF	Δt (ms)	FPCF
19.0	1.885	79.89	1.149				
		80.11	1.157				
23.0	2.275	75.46	1.085				
		74.50	1.076				
24.9	2.470	72.60	1.048				
		72.68	1.050				
26.9	2.665	71.86	1.033				
		71.82	1.037				
28.0	**2.774**	**69.80**	**1.024**				
		70.02	**1.027**				
		69.83	**1.024**				
		69.89	**1.025**				
28.9	2.860	70.48	1.018	70.16	1.012		
		70.22	1.014				
		70.32	1.016				
30.8	3.055	69.8	1.004				
		69.82	1.008				
		69.72	1.007				
34.8	3.445	68.02	0.978	67.31	0.971	66.99	0.967
		67.87	0.980			67.28	0.971
		65.71	0.979			67.17	0.969
		65.68	0.979			65.31	0.974
		66.03	0.983				
2" DRAIN OPEN	3.445	65.41	0.957				
		65.39	0.957				
2"+1" DRAINS OPEN	3.445	65.73	0.962				
		65.72	0.962				
		65.90	0.964				

(1) FPCF $=W_{TANK}/W_{US}$, where W_{US} is calculated according to Eq. (2.1) with $A=0.05159m^2$ and d=0.3m.

(2) Entries in bold have been obtained in post-test calibration and correspond to the transducer location in the field.

TABLE 5.1
Results of Darlington Unit 2 Moderator Flow Measurements

Pump Running	Total Flow (L/s)	East Calandria			West Calandria			East HX			West HX		
		A=0.072420m^2			A=0.072905m^2			A=0.072456m^2			A=0.072371m^2		
		FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)
P1	**1164**	0.960	37.05	**562.9**	0.960	34.95	**600.8**	0.970	36.29	**581.2**	0.970	36.16	**582.6**
P2	**1167**	0.960	36.63	**569.4**	0.960	35.14	**597.5**	0.968	36.06	**583.5**	0.968	35.99	**583.4**
P3	**127.5**	0.935	114.2	**60.9**	0.935	105.1	**66.6**	0.996	113.5	**63.4**	0.996	112.7	**64.1**
P4	**126.4**	0.935	114.0	**61.0**	0.935	107.0	**65.4**	0.993	114.3	**63.0**	0.993	113.3	**63.4**

TABLE 5.2
Results of Darlington Unit 4 Moderator Flow Measurements

Pump Running	Total Flow (L/s)	East Calandria			West Calandria			East HX			West HX		
		A=0.072383m^2			A=0.073368m^2			A=0.072517m^2			A=0.072723m^2		
		FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)
P1	**1148**	0.960	37.98	**548.9**	0.960	35.26	**599.3**	0.971	37.31	**566.3**	0.971	36.44	**581.4**
P2	**1159**	0.960	37.86	**550.6**	0.960	34.72	**608.6**	0.972	36.18	**584.3**	0.972	36.87	**575.0**
P3	**124.7**	0.935	113.9	**59.4**	0.935	105.0	**65.3**	0.980	113.5	**62.6**	0.980	114.9	**62.10**
P4	**126.1**	0.935	112.6	**60.1**	0.935	104.0	**66.0**	0.977	111.5	**63.5**	0.977	113.4	**62.6**

TABLE 5.3
Results of Bruce B Unit 5 Moderator Flow Measurements

Pump Running	Total Flow (L/s)	East Calandria			West Calandria			East HX			West HX		
		A=0.050991m^2			A=0.050935m^2			A=0.052828m^2			A=0.052843m^2		
		FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)
P1	**1052**	1.035	28.65	**552.6**	1.035	31.68	**499.2**	0.895	17.11	**552.6**	0.873	18.48	**499.2**
P2	**1062**	1.043	27.56	**578.9**	1.043	32.99	**483.1**	0.895	18.67	**506.5**	0.873	16.62	**555.1**
P3	**112.7**	1.010	86.61	**59.5**	1.010	96.64	**53.2**	0.870	75.23	**61.1**	0.848	105.8	**42.4**
P4	**117.7**	1.010	81.78	**63.0**	1.010	94.01	**54.7**	0.870	72.07	**63.8**	0.848	100.0	**44.8**
P3+P4	**162.7**	1.010	63.07	**81.7**	1.010	63.55	**81.0**	0.870	50.77	**90.5**	0.848	76.11	**58.9**

TABLE 5.4
Results of Bruce B Unit 8 Moderator Flow Measurements

Pump Running	Total Flow (L/s)	East Calandria			West Calandria			East HX			West HX		
		A=0.051188m^2			A=0.051334m^2			A=0.051815m^2			A=0.050854m^2		
		FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)	FPCF	Δt(ms)	W(L/s)
P1	**1061**	1.035	27.70	**572.0**	1.035	31.49	**489.1**	1.005	18.02	**572.0**	1.083	19.21	**489.1**
P2	**1077**	1.060	26.99	**603.2**	1.060	34.48	**473.5**	1.005	20.22	**515.1**	1.083	17.41	**561.4**
P3	**122.2**	1.010	80.57	**64.2**	1.010	89.44	**58.0**	0.980	68.08	**74.6**	1.058	114.7	**46.9**
P4	**113.6**	1.010	86.57	**59.7**	1.010	96.12	**53.9**	0.980	74.56	**68.1**	1.058	121.5	**44.3**
P3+P4	**160.6**	1.010	61.36	**84.3**	1.010	67.97	**76.3**	0.980	48.00	**105.8**	1.058	88.52	**60.8**

TABLE 6.1

Individual Components and the Total Flow Measurement Uncertainty for Main Moderator Pumps at Darlington

Component	2σ Uncertainty (%)
FPCF	0.74
Pipe Flow Area	0.31
Transducer Spacing	0.1
Repeatability	0.5
Reproducibility	0.3
Individual Flows	**1.0**
Total Moderator Flow	**0.88**

TABLE 6.2

Individual Components and the Total Flow Measurement Uncertainty for Main Moderator Pumps at Bruce B

Component	2σ Uncertainty (%)
FPCF (P1)	3.27
FPCF (P2)	3.47
Pipe Flow Area	0.58
Transducer Spacing	0.1
Repeatability	0.5
Reproducibility	0.3
Individual Flows (P1)	**3.37**
Individual Flows (P2)	**3.56**
Total Moderator Flow (P1)	**3.32**
Total Moderator Flow (P2)	**3.52**