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Profile Factor Calculations

ER No.	Date	Description	Description
	Date of Test	Check and CheckPlus Meters	Alden Report Number
ER-265 R0	12/20/01	ASCO 1&2	ARL NO.356-01/C730
ER-175 R0	9/11/00	Beaver Valley	ARL NO.279-00/C730
ER-254 R0	10/19/01	Cofrentes	ARL NO.340-01/C730
ER-227 R1	10/08/01	Davis Besse	ARL NO.310-01/C730
ER-287 R1	4/22/02	DC Cook 1	ARL NO.121-02/C730
ER-320 R0	1/20/03	DC Cook 2	ARL NO.23-03/C730
ER-182 R0	12/13/00	Grand Gulf	ARL NO.388-00/C730
ER-295 R2	06/10/02	H5	ARL NO.170-02/C730
ER-406 R0	12/10/03	Ikata 1	ARL NO.324-03/C730
ER-407 R0	12/17/03	Ikata 2	ARL NO.325-03/C730
ER-416 R0	02/11/04	Ikata 3	ARL NO. 35-04/C730
ER-394 R0	10/09/03	Millstone 3	ARL NO.248-03/C702
ER-292 R0	5/21/02	Peach Bottom 2	ARL NO. 148-02/C730
ER-441 R0	6/30/04	Peach Bottom 2	ARL NO. 147-04/C730
ER-375 R0	6/23/03	Peach Bottom 3	ARL NO.141-03/C730
ER-327 R1	1/23/03	River Bend	ARL NO.29-03/C730
ER-300 R0	7/08/02	Robinson	ARL NO. 212-02/C730
ER-426 R1	2/25/04	Robinson	ARL NO. 44-02/C730
ER-223 R2	09/05/01	Sequoyah 1	ARL NO. 262-01/C730
ER-277 R0	09/19/01	Sequoyah 2	ARL NO.284-01/C730
ER-219 R0	7/30/01	Susquehanna 1	ARL NO. 241-01/C730
ER-199 R0	1/05/01	Susquehanna 2	ARL NO. 01-01/C730
ER-264 R2	12/14/01	Vandellos 2	ARL NO.355-01/C730

Profile Factor Calculations

ER No.	Date	Description	Description
	Date of Test	Check and CheckPlus Meters	Alden Report Number
ER-214 R0	06/19/01	Waterford	ARL NO.195-01/C730
ER-168 R2	8/15/00	Watts Bar	ARL NO.252-00/C730

Traceability of Thermal Power Measurements

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Part 2
Modified Venturi Tubes

ABSTRACT

This is the second of two papers describing the traceability of nuclear feedwater flow measurements. The first considered the challenges and methodology for establishing the traceability of chordal ultrasonic flow meters. This paper considers the challenges of establishing the traceability in a measurement using a flow element of the modified venturi tube type. It specifically considers the assumptions and uncertainties associated with the extrapolation, for use in the field, of tube calibration factors measured in the laboratory. To quantify these uncertainties, the in-situ performance of four modified venturi tubes is compared with the performance of four 8-path chordal ultrasonic flowmeters. The data analyzed were collected in the feeds of four steam generators in a large pressurized water reactor plant, each feed containing one meter of each type. The meters were initially calibrated in this series arrangement in a NIST traceable calibration lab and then operated in the same arrangement in the field.

1. INTRODUCTION

A continuous, accurate determination of thermal power is essential in the operation of a nuclear power plant. Errors in the power determination can cause lost revenue or reduced safety margin—both serious consequences. It is therefore appropriate that the rigor of traceability be applied to each component of the thermal power determination. The key element in the determination of thermal power is the measurement of the mass rate of feedwater flow. The desirability of applying rigorous traceability requirements to the feedwater flow measurement is underlined by recent problems with flow instrumentation in nuclear applications.

Traceability is defined as a process whereby a measurement can be related to a standard via a chain of comparisons (International Standards Organization, (1)). The companion to this paper (Augenstein, et al, 2)) listed the following key elements of traceability:

- The standard must be acceptable to all parties with an interest in the measurement and is usually a standard maintained by a national laboratory such as the National Institute of Standards and Technology.
- The chain of comparisons must be unbroken—the field measurement must be connected, by one or more links directly to the standard.
- Every link in the chain involves a comparison that necessarily carries with it an uncertainty. Hence the total uncertainty of the measurement must reflect the aggregate uncertainties of each link of the comparison chain.
- There can be no unverified assumptions in the chain of comparisons; it is clearly not possible rationally to assign an uncertainty to an assumption with no quantitative basis.

This paper analyzes the traceability chains for flow elements of the modified venturi tube type+, from their basic measurements—the differential pressure between the upstream and throat taps of the modified venturi and the fluid temperature and pressure--to the process variable, feedwater mass flow. Much of the discussion applies qualitatively to nozzle-type flow elements. The paper covers explicitly the calibration uncertainties of the flow element(s), including the application of the flow element calibration data taken in a hydraulics facility operating at 100 F and 50 psig to the 430 to 450 F, 1000 to 1200 psig conditions in a nuclear feedwater system at full power.

2. DISCUSSION

The Algorithm for a Nozzle or Venturi -Based Mass Flow Measurement

The algorithm for the determination of mass flow of water for a differential producer (nozzle, Venturi, orifice, etc) is as follows (refer to the *Fluid Meters,* (4)):

$$q_{lbm/s} = 0.0997019C\frac{d^2}{\sqrt{1-(d/D)^4}}\sqrt{h_w \cdot \rho} \qquad (1)$$

Where $q_{lbm/s}$ is the mass flow rate in lbs/s

C discharge coefficient (dimensionless)

d throat diameter (inches at the flowing temperature)

$d = 1 + \alpha_{Throat}(T_{flowing} - 68^0 F)d_{68^0 F}$

Where $d_{68^0 F}$ is the throat diameter at $68^0 F$

+ The modified Venturies whose calibrations are described in this paper are similar to the "Universal Tube" (trademark, General Signal Corp.) described by Halmi, (3)

D Diameter of inlet (inches at the flowing temperature)

$D = 1 + \alpha_{Inlet}(T_{flowing} - 68^0 F)D_{68^0 F}$

$D_{68^0 F}$ Inlet Venturi diameter at $68^0 F$

$h_{w,68^0 F}$ Differential pressure in inches of water at $68^0 F$

ρ Fluid density in lbm/cubic ft

α_{Inlet} Thermal expansion factor of inlet Venturi section

α_{Throat} Thermal expansion factor of throat material

The fluid density is a function of both pressure and temperature

$\rho = f_\rho\,(T, p)$

Here T is the temperature of the feedwater.

The function f_ρ can be defined with high accuracy using the equations for water in an appropriate table (e.g., the ASME Steam Tables, (5))

Note: In many older installations the thermal expansion factor is incorrect by 0.1 to 0.2 % if the upstream meter section is of another material than the throat.

Elements of the Traceability and Accuracy of a Nozzle or Venturi Tube Based Flow Measurement

Fundamentally, the traceability of the mass flow algorithm for a venturi or nozzle type meter requires that a chain of comparisons be constructed for the following elements of the algorithm described above:

- The Discharge Coefficient, C
- The Fluid Temperature Measurement, T
- The Differential Pressure Measurement h
- The Fluid Pressure Measurement p

This listing presumes that the nozzle or venturi tube has been calibrated in a certified facility, to establish a discharge coefficient, C. The calibration embeds any errors in the measurement of the throat diameter, d or the upstream diameter D. It also presumes that the uncertainties in the function f_ρ are established on a one-time basis by reference to appropriate standards and are small relative to other uncertainties in the flow measurement.

The principal challenges and uncertainties in the flow measurement are associated with the discharge coefficient and differential pressure instrument. The density of compressed water is very insensitive to fluid pressure. Reasonable care in the installation, calibration and maintenance of a Resistance Temperature Detector (an RTD), typically employed for feedwater temperature measurements can yield a traceable accuracy in the ±1°F range, which translates to an uncertainty in the mass flow measurement of less than ±0.05%.

Modern instrumentation and digital signal processing removes many of the uncertainties associated with the computation of flow from a differential pressure measurement, particularly in the performance of the multiplications and the square root function. If care is taken in the selection of the instrument range, high quality transmitters are used, attention is paid to the arrangement of impulse lines, and calibrations are performed with high quality, traceable test equipment on a periodic basis, the differential pressure measurement can contribute an uncertainty of no more than ±0.5% to ±0.75% of rated flow.

The key determinant in the accuracy in feedwater flow measurements with venturis or nozzles is the first of the list of traceable elements above—the determination of the discharge coefficient in an appropriate calibration facility and the extrapolation of the coefficient thus determined to the field, where fluid conditions—specifically viscosity—will be very different from those of the facility. Quantifying the uncertainties of the facility measurements is straightforward; there are the uncertainties of the facility standards—the weigh tank, the time measurements, the fluid temperature and pressure measurements, and the secondary standard used for the differential pressure measurement—and the calibration technique itself—the repeatability of the diverter mechanism, etc. It is the extrapolation of the discharge coefficient thus determined for use in the field that presents the challenges, particularly, assumptions that are difficult to verify in quantitative terms. Specifically:

- The discharge coefficient is sensitive to global fluid velocity fields. Both the axial and transverse fluid velocities will differ in some degree from lab to field. The sensitivity of nozzles and s to axial velocity profile is usually small but not negligible (Halmi, (6), Ferron, (7)); differences in transverse velocity—in particular swirl—can produce large biases (*Fluid Meters,* previously cited).
- The discharge coefficient is sensitive to Reynolds Number. The boundary layer thins as the Reynolds Number increases from lab conditions (1 to 3 × 10^6) to field conditions (1 to 3 × 10^7). For some specific nozzle designs there have been theoretical treatments of the impact of the thinning on Discharge Coefficient (e.g., Benedict, (8)) but experimental proof of these analyses in Reynolds Number regime for 450 F feedwater has been very limited.
- The sensitivity of discharge coefficient to Reynolds Number is not limited to the thinning of the boundary layer. Separation and reattachment effects are also sensitive to Reynolds Number (Miller, (9)). Separation "bubbles" (i.e., vortices) can change the form of the velocity field in the throat of a nozzle or venturi and, depending on their location, can cause biases of 1% or more in *either* direction.
- The deposition of corrosion deposits in the throat of nozzles and venturis ("fouling") can cause a change in the effective internal diameter of the throat (d), thereby changing the discharge coefficient from the extrapolated value determined at the time of calibration. The deposition is electrochemical in nature and preferentially occurs at the reduced pH attending high power operation*.

* In Pressurized Water Reactor plants feedwater is usually treated with a volatile agent such that its pH at room temperature is in the 9.5 range. However, the solubility of the H^+ and OH^- ions is such that, at operating temperature, the pH is reduced to the 7 range. (Estrada, (10)). The change in pH can change the

Hence it may not be possible to ensure the cleanliness of a nozzle during the full power run following a shutdown, even when the nozzle is cleaned during that shutdown. The deposition often occurs as full power is approached.

- The discharge coefficients of nozzles and venturis are sensitive to the local flow field in the vicinity of the pressure taps, particularly the throat tap. Small upsets in the surface at or near the taps can cause stagnation of the local velocity upstream of the upset. Depending on its location, an upset can cause a high or low bias in the indication of the instrument. The presence of an upset can often be detected in the calibration process, allowing for its correction (by careful smoothing of the surface in the vicinity of the taps). However, the deposition of corrosion products can also create local upsets in the throat surface, as can the cleaning of nozzles with high-energy water jets.

Each of the effects described above requires an assumption regarding the performance of the nozzle or venturi at full power feedwater conditions. The bounding of the uncertainties associated with these assumptions represents the greatest difficulty in establishing an accurate discharge coefficient for venturis and nozzles in feedwater service.

Laboratory Calibration of the Modified Venturi Tubes and the 8-path Chordal UFMs

Both the 8 path chordal ultrasonic flowmeters and the modified venturi tubes whose performance is described in this paper were calibrated in a hydraulic model that simulated the field application of the instruments. With respect to nozzles and venturis, this process is unusual—normally, these devices are calibrated in straight pipe with a flow conditioner at a distance of about 20 diameters to eliminate any transverse velocity components in the calibration flow field. Field installations are typically 10 to 20 diameters downstream of the closest bend, based on the (unverified) assumption that this distance is sufficient to eliminate flow field disturbances produced by this feature and features further upstream. The approach taken for the modified venturis of this paper reduces the uncertainties in discharge coefficient due to the global flow field in the plant by modeling the features that produce that flow field.

Figure 1 is an artist's sketch of the actual plant installation. Note that the modified venturis are roughly 30 diameters downstream of the header, while the 8-path chordal UFMs are at distances ranging from about 15 to 22 diameters. The varying locations for the UFMs provide access for removal of transducers from individual flow elements.

Figure 2 is a photograph of the hydraulic model used in the calibration tests. The UFM is in the foreground of the photo; the modified venturi, downstream of the UFM, is not visible. As can be seen from the photo, a single steam generator feed was used in the calibration laboratory model. The varying distances of the UFMs were however explicitly modeled in the tests for each instrument package. The effect of installation hydraulics on the flow fields of the individual steam generator feeds was investigated by varying the fraction of the total flow from the individual feeds to the header. Variations in the

sign of the electrostatic forces between the throat surface and colloidal corrosion products in the flowing feed such that colloids that were repelled at room temperature are attracted at operating temperature.

fractions of total feed to the header from the individual supplies were also used to test the sensitivity of meter calibrations to variations in velocity fields. Additionally, straight pipe calibration tests were run for two of the UFM-modified venturi tube packages, as benchmarks.

Figure 1
Arrangement of Chordal UFMs and Modified Venturi Tubes in Plant

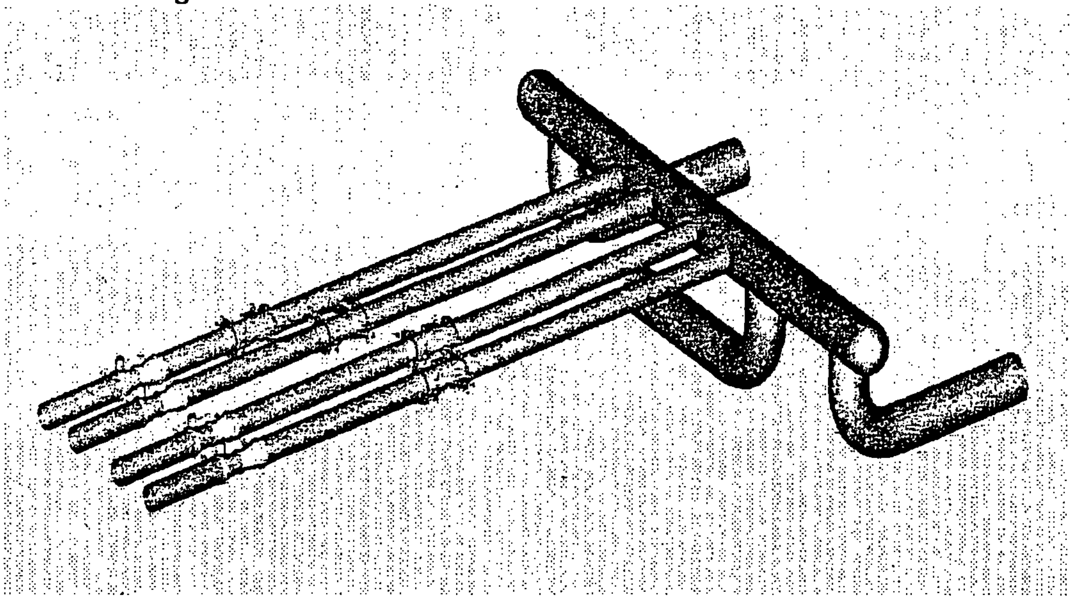
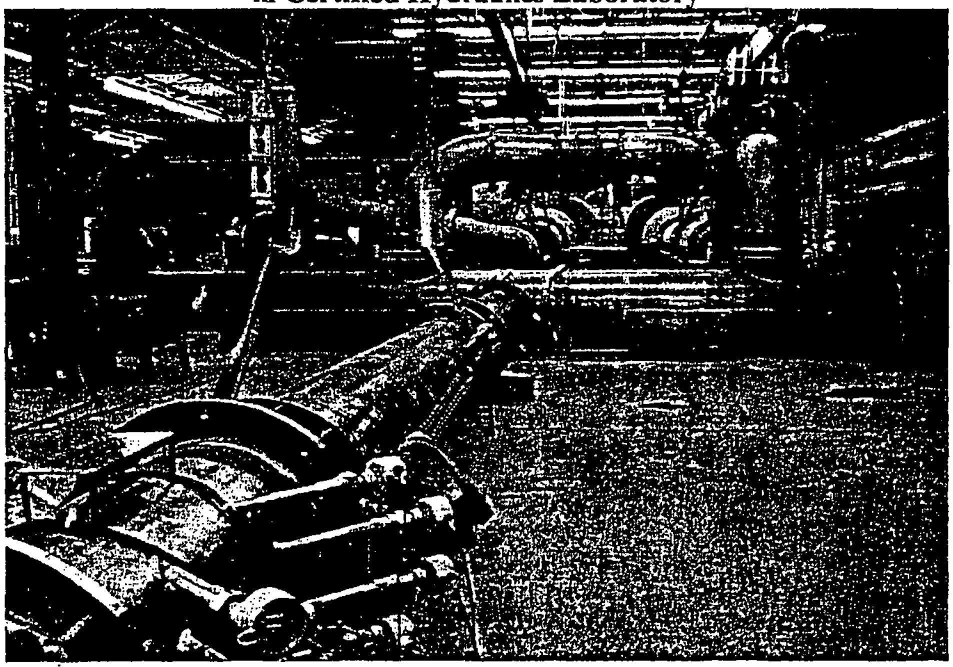


Figure 2
Calibration Arrangement for Modified Venturi Tubes and Chordal UFMs in Certified Hydraulics Laboratory



Calibration of the Chordal Ultrasonic Meters and Extrapolation of the Results to Plant Conditions

The companion to this paper (Augenstein, et al, cited previously) describes the methodology whereby the calibration factor of chordal UFMs can be extrapolated from the calibration lab to field conditions with bounded and modest uncertainty. The methodology involves characterizing the meter factor of the chordal system using the "flatness" of the axial velocity profile as measured in a model simulating the hydraulics of the field installation. The model is also varied parametrically to determine the sensitivity of the calibration to changes in flatness. Flatness is defined as the ratio of the axial fluid velocity averaged along the outer (short) chords of the UFM to the axial fluid velocity averaged along the inner (long) chords of the UFM.

Figures 3A, 3B, 3C, and 3D show the meter factors (also called the profile factor, PF) for the UFM flow elements for Loops A, B, C, and D. (In the plant the loops are actually numbered 1, 2, 3 and 4). The meter factors are plotted against the flatness. Also shown on each figure is the theoretical sensitivity of the meter factor to flatness. It will be noted that the calibration data for all UFMs lie within ±0.15% or less of the theoretical sensitivity over the range of flatness ratios produced by parametrically varying the flow model, with the modest exception of one set of data for Loop D, Figure 3D (the 0- 50 -50 flow splits from the first, second and third feeds), where the difference approaches 0.2%.

Comparison of the figures also shows that the profiles for Loops A and B are rounder than those for Loops C and D (that is, the flatness ratios for A and B tend to be lower than those for C or D), because, as Figure 1 shows, the latter instruments are closer to the header. Downstream of a sudden contraction a profile is flat, becoming rounder as the profile develops (Schlichting, (11)).

Figures 3A through 3D also show the meter factors implemented on the basis of the calibration data. These are plotted (in green) for the flatness ratios measured in the plant during power escalation from roughly 30% to 100% of rating. It will be noted that the extrapolations of the meter factor for Loops B and D are relatively modest in terms of flatness —a change of 0.02 or less. The extrapolations for Loops A and C are slightly larger (0.02 to 0.04). The flatter-than-predicted profiles are due to the presence of larger swirl in the plant than was present in the lab (swirl is measured from the differences in the measured velocities of outer acoustic paths at the same chordal location). Nevertheless, the difference in flatness does not lead to a significant extrapolation uncertainty. Specifically the uncertainty in meter factor due to the uncertainty in the hydraulics of the model and the extrapolation fit is accounted at ±0.14%. This figure—the differential uncertainty of the UFM—also accounts the time measurement uncertainty of the instruments used in the calibration tests and the observational uncertainty—turbulence and other effects cause statistical variation in measured results. It does *not* include the uncertainty of the facility, which for this test was bounded at ±0.15%. The reason it does not is that any facility bias that is present in the calibration of a UFM will also be present, with exactly the same magnitude and sign, in the meter factors for the modified venturi tubes. Since the objective of this paper is to investigate the extrapolation of modified venturi tube meter factors to plant conditions by comparing their indications with the UFMs, the uncertainty associated with the facility itself need not and should be included in the analysis.

Figure 3A

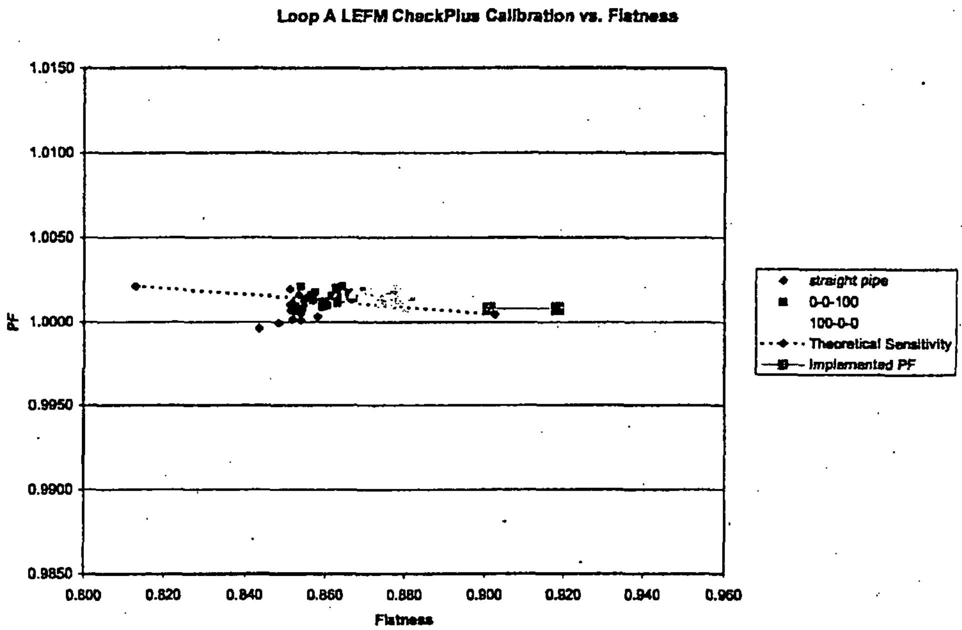


Figure 3B

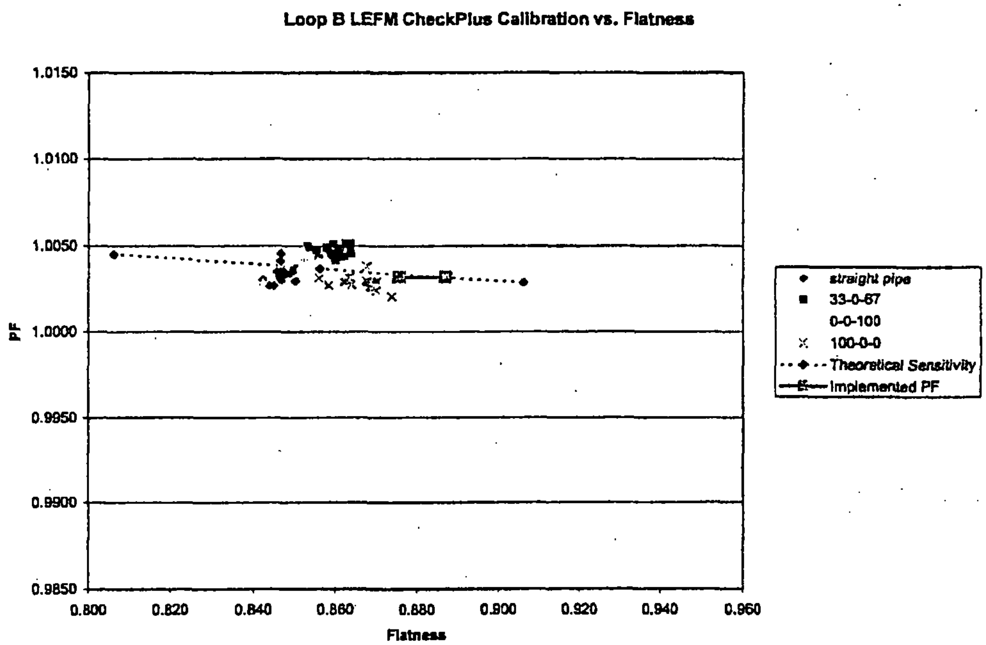


Figure 3C

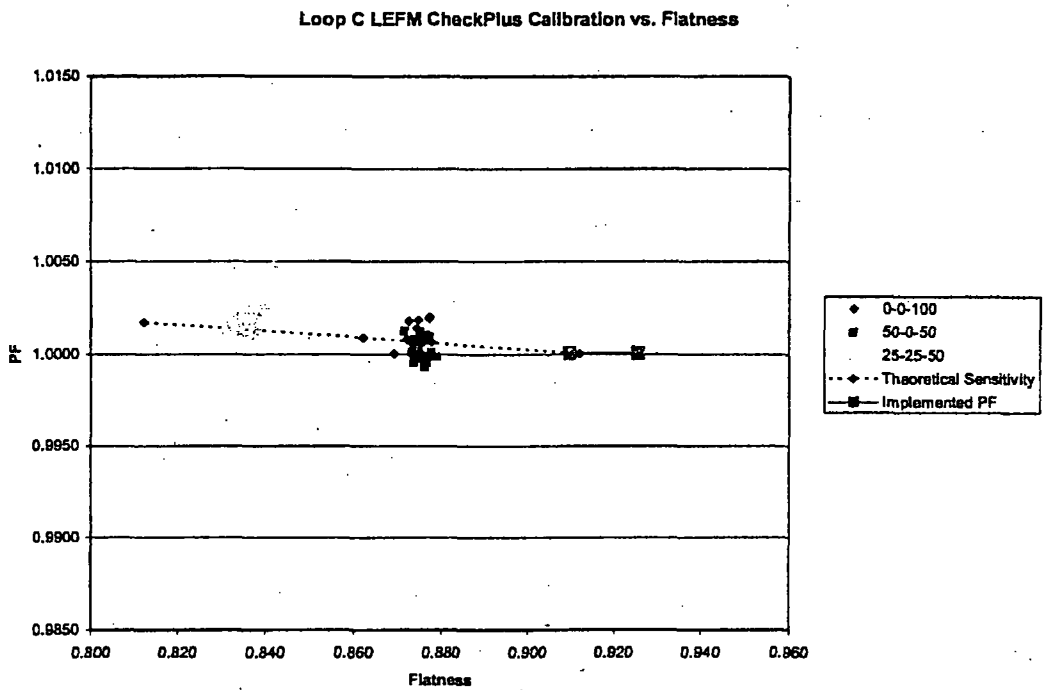
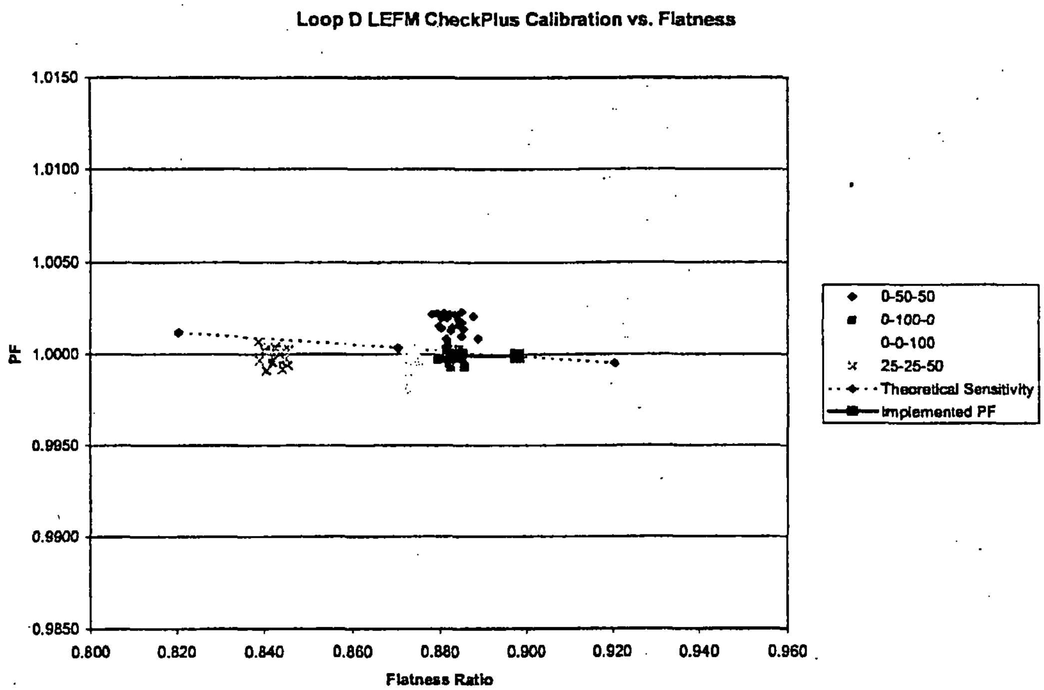


Figure 3D



As noted in the introductory discussion, Reynolds Number is a key descriptor for the behavior of venturis and nozzles, since it is a significant factor in the thickness of the boundary layer in the throat of the nozzle. It is therefore appropriate to characterize the response of the meter factors of the chordal UFMs to Reynolds Number, so that a comparison in response can be readily carried out. Figures 4A, 4B, 4C, and 4D plot the meter factor data from the calibration tests against Reynolds Number (based on pipe diameter).

The figures also show the theoretical sensitivity of meter factor to Reynolds Number. The sensitivity arises because increasing Reynolds Number thins the boundary layer and flattens the profile, slightly changing the bias associated with the numerical integration of the four chordal velocity measurements. It will be noted that the data for all UFMs closely follow the theoretical sensitivity (within about ±0.1% to ±0.2%).

The figures also show the meter factors implemented in the field (shown in green) plotted against the range of Reynolds Numbers actually experienced during power escalation from 30% to 100%. Note that there is overlap between lab Reynolds Numbers and plant Reynolds Numbers for all meters, giving high confidence in the use of the UFMs as comparative standards for the modified venturi tubes in the plant Reynolds Number regime.

Figure 4A

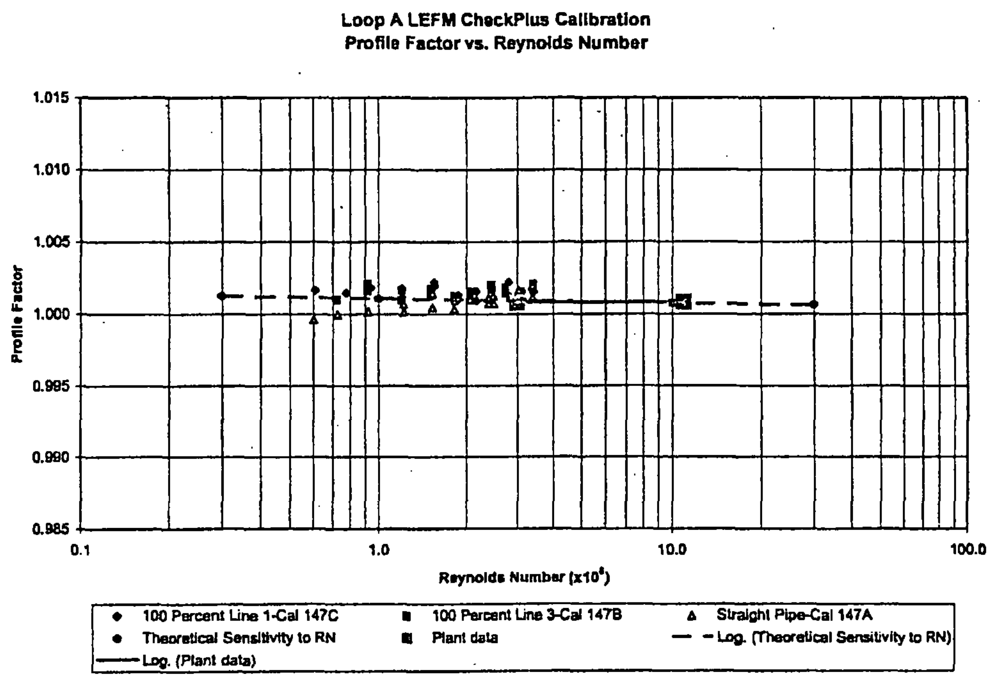


Figure 4B

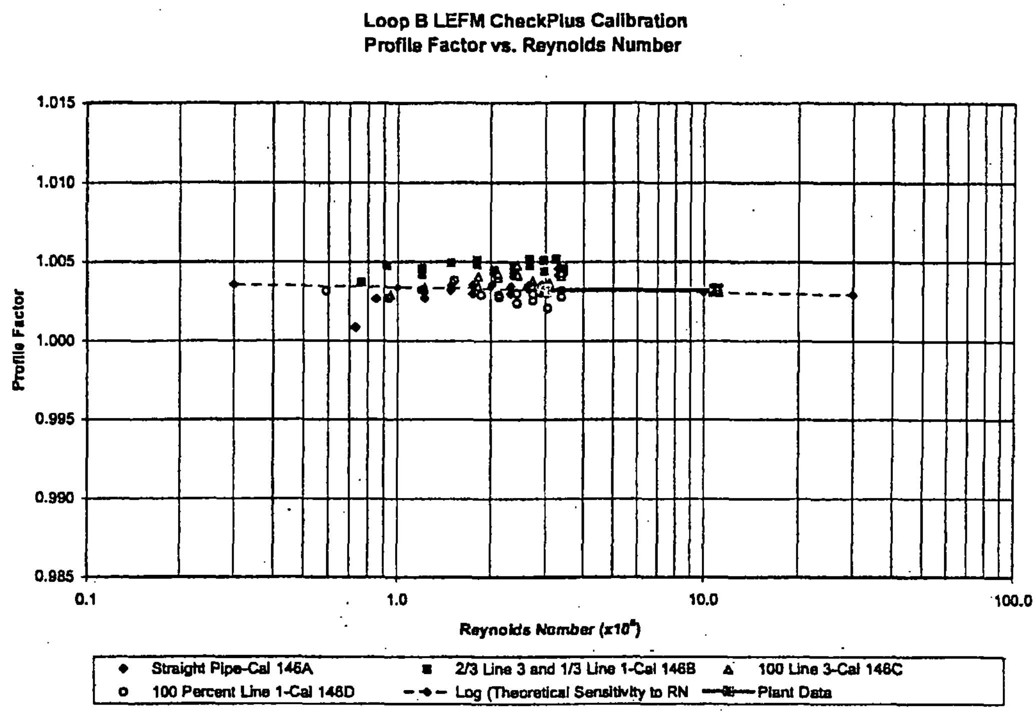


Figure 4C

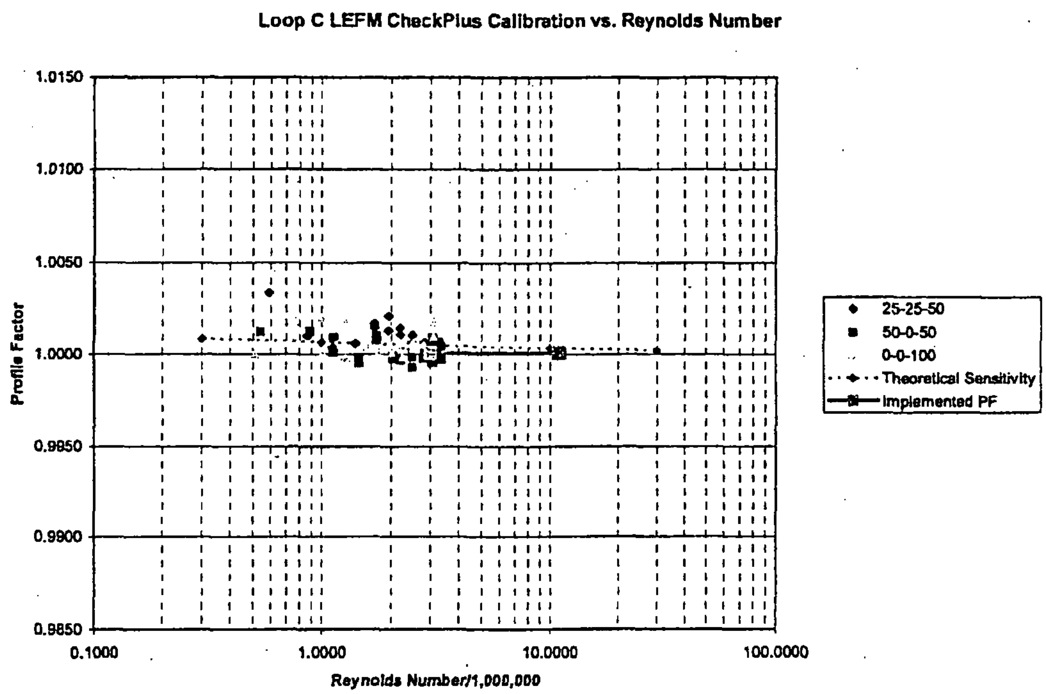
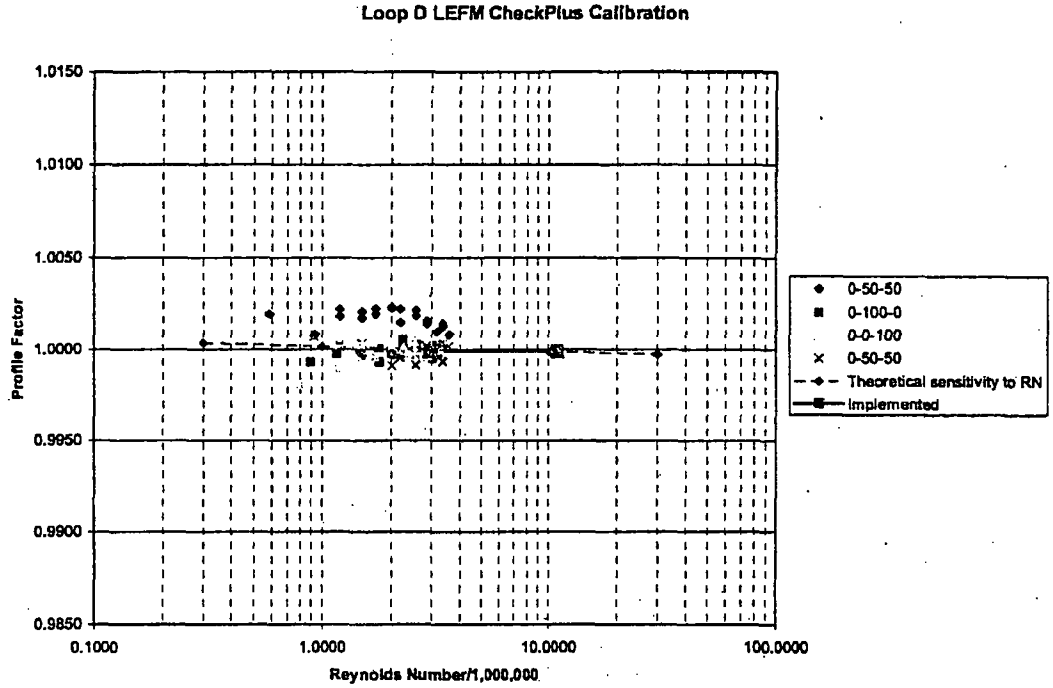


Figure 4D



Calibration of the Modified Venturi Tubes and Extrapolation of Results to Plant Conditions; Comparison with Chordal UFMs as Standards

Calibration data for the modified venturi tubes are plotted against pipe Reynolds Number in Figures 5A, B, C, and D, for loops A, B, C, and D. [The throat Reynolds Number is normally used to characterize venturis and nozzles but, for ease of comparison with Figures 4, pipe Reynolds Number is used here. For these modified venturis the difference in the two Reynolds Numbers is a constant factor of about 2, throat higher.] It should be pointed out that the highest calibration Reynolds Numbers for the modified venturis is somewhat lower than that for the UFMs. The reason is that, in the calibration facility, cavitation in the throats of the venturis occurred as the Reynolds Number approached 3 million, whereas cavitation does not begin in the UFMs until a Reynolds Number above 3.6 million is reached. [At high flow rates in the calibration facility, the pressure at the UFM, just upstream of the modified venturi tubes, was in the 12 to 15 psig range. In the throat of the venturi, where the fluid velocity is increased by a factor of roughly 4, the attendant reduction in static pressure causes cavitation.]

Also shown in the figures are two empirical bases commonly used to extrapolate the discharge coefficient from the lab to operational Reynolds Numbers. The first (higher) basis for extrapolation is a simple log linear fit of the data; the meter factor is assumed to correlate linearly with the logarithm of the Reynolds Number. There is no theoretical basis for the use of the log linear fit but it seems generally to correlate data for some nozzles well and it appears to do so here. The second basis for extrapolation is the so-called reciprocal square root fit. Here the correlation for discharge coefficient is assumed to be of the form:

$C_D = a - m/SQRT\,(RN)$, where RN is Reynolds Number.

This form has some theoretical basis in that it assumes that, as the boundary layer in the throat diminishes in thickness with increasing Reynolds Number, the discharge coefficient approaches an asymptote. For some applications, the asymptote, a, is assumed to be 1, which implies that the discharge coefficient approaches that for a reversible gradual contraction with increasing Reynolds Number. This form is not used here, however, because the residual error for this form is quite large. Instead the asymptote, a, and the slope, m, are selected to minimize the root mean square error of the data relative to the fit. It will be observed that there is a significant difference in the predictions of the two approaches to extrapolation (1/2 to 1% in C_D) as the plant Reynolds Number regime (10 to 20 million) is approached.

The figures also show the discharge coefficients implemented for each modified venturi plotted against the range of Reynolds Numbers they see in the escalation of plant power from 30 to 100%. The coefficients were chosen on the basis of the reciprocal square root fit of the data.

The aggregate differential uncertainty in the discharge coefficients for the individual venturis averages ±0.72%. Again this figure excludes the uncertainty of the calibration facility (±0.15%) which is not pertinent to the comparison of the UFM and the venturi data. It also does not include explicit allowances for calibration biases due to changes in throat diameter or tap geometry caused by the deposition of corrosion products. Neither does it include an explicit allowance for separation effects that may occur at Reynolds Numbers above those at which the modified venturi is calibrated. The uncertainty quoted *does* include allowances the secondary standard used to measure differential pressure during calibration, the modeling uncertainty as evidenced by the spread in data for various flow feed fractions in the test model, the uncertainty of the data fit, the random uncertainty in the Reynolds Number Extrapolation, and the systematic uncertainty in Reynolds Number Extrapolation (the latter is a measure of the spread in the two approaches to the extrapolation process). For the comparison with the UFM, this last uncertainty component will be removed, since one of the purposes of the comparison is to establish an appropriate extrapolation basis for these devices. When the systematic uncertainty in Reynolds Number extrapolation is removed, the differential uncertainty of the modified venturi discharge coefficient is diminished to ±0.24%. If then the UFMs are used to calibrate the modified venturis at power the aggregate uncertainty of a calibration point is the root sum square of the reduced venturi differential uncertainty (±0.24%), the UFM differential uncertainty(±0.14%), and an allowance for the transmitters used to read out the differential pressure in the plant. A figure of ±0.25% will be used for this last element. A larger figure is appropriate for long term use, to account for drift and other effects, but the transmitters were calibrated just prior to plant startup and the 0.25% figure is considered reasonable for this purpose. The aggregate uncertainty in each calibration point is thus $[(0.24)^2 + (0.14)^2 + (0.25)^2] = \pm 0.37\%$.

Figures 5A through 5D show what the respective UFM measurements in the plant indicate the discharge coefficients should have been; these data are the red squares shown on each figure. Despite the uncertainty in these points, the data of Figures 5A, 5B and 5C indicate that a log linear fit is a far better extrapolation basis that the reciprocal square root fit. This conclusion is supported not only by data at full power (Reynolds Number 11 million) but also, for Loops A and B, at 50% power (Reynolds Number 4 million). [No data were obtained for loop C at reduced power.] It should be pointed out that the reciprocal square root fit, which is somewhat more commonly used for extrapolation is non conservative with respect to the determination of power. The data of Figures 5A, 5B and 5C indicate the non conservatism is in the order of 0.5%

The data for the Loop D modified venturi, Figure 5 D, differ significantly from the other three flow tubes. Here a significant, non conservative bias is present—roughly 1% *above* the log linear fit at full power. There is nothing in the laboratory calibration data for this flow tube that would suggest the imminent departure from the log linear fit. The difference cannot be explained by the differential accuracy of the UFM or the modified venturi. The deposition of corrosion products is not a likely cause since normally this phenomenon causes a shift in the other direction, and no shifts are seen in the other three flow tubes, which are exposed to the same feedwater chemistry. What the data suggest (but do not prove) is that a separation "bubble" abruptly occurs in the D modified venturi at a Reynolds Number in the 3 to 4 million range which causes a 1% shift in the C_D characteristic. As noted previously, such shifts have been seen elsewhere in similar flow measuring devices.

Figure 5A

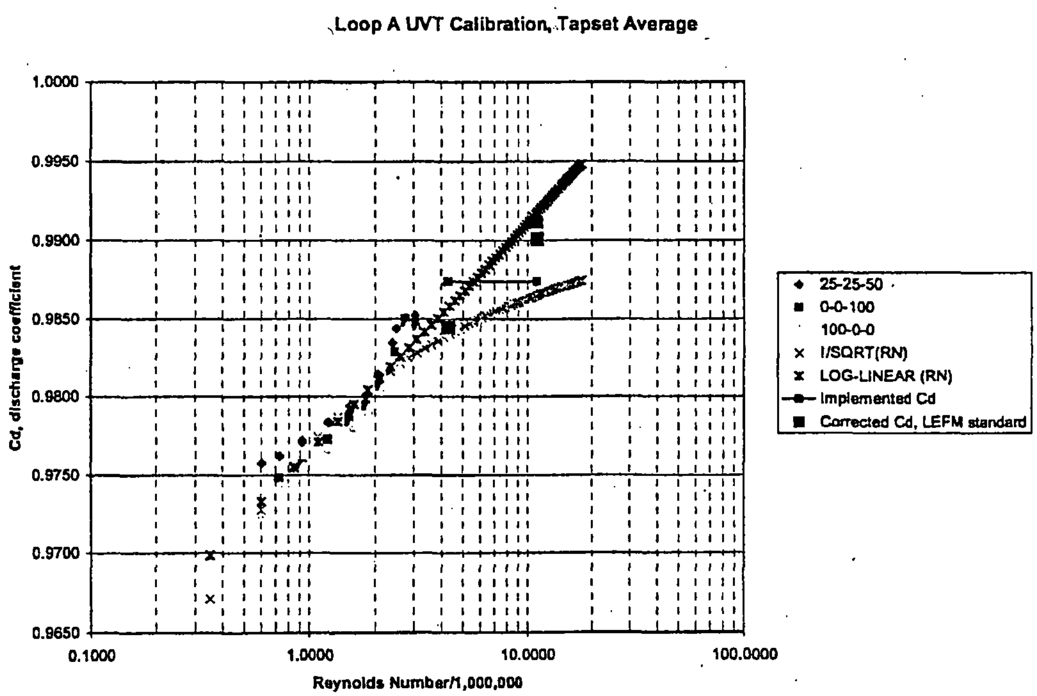


Figure 5B

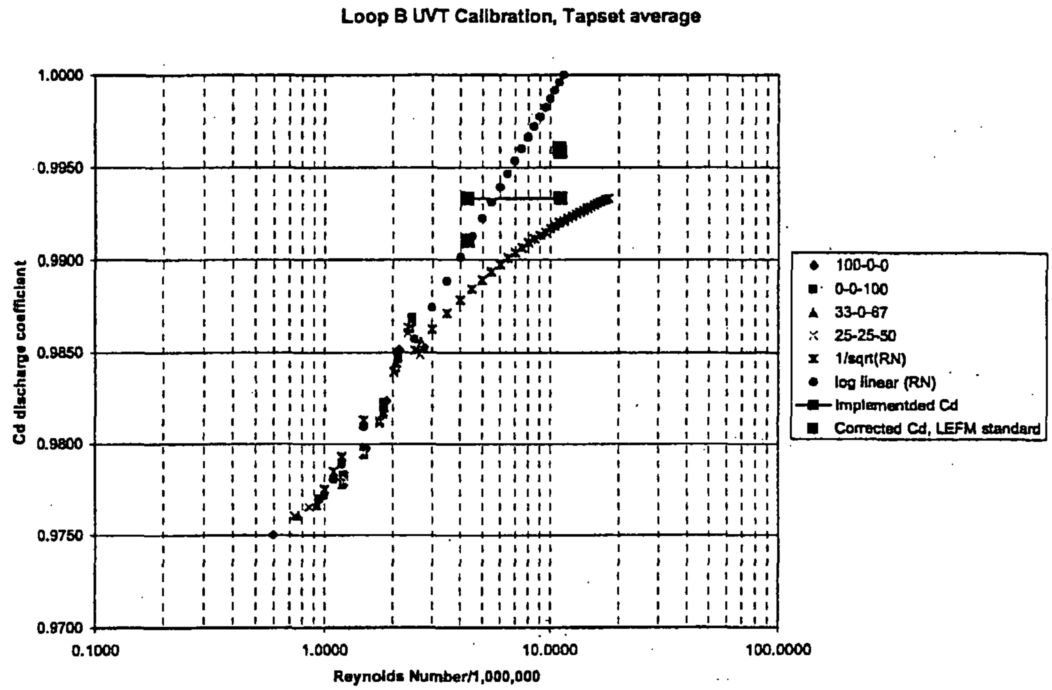


Figure 5C

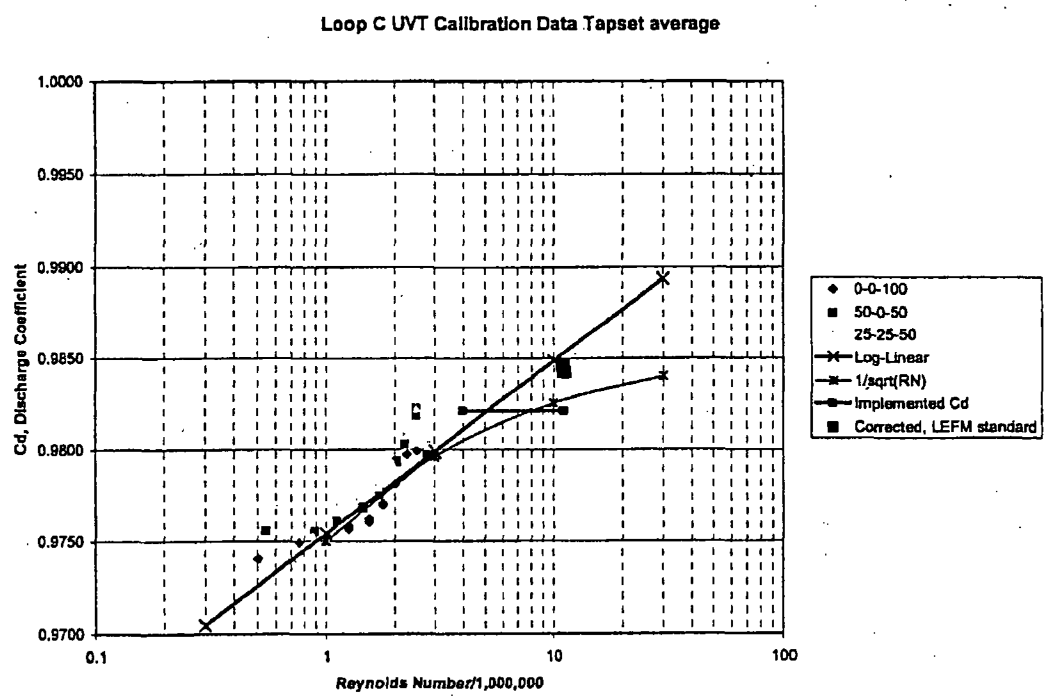
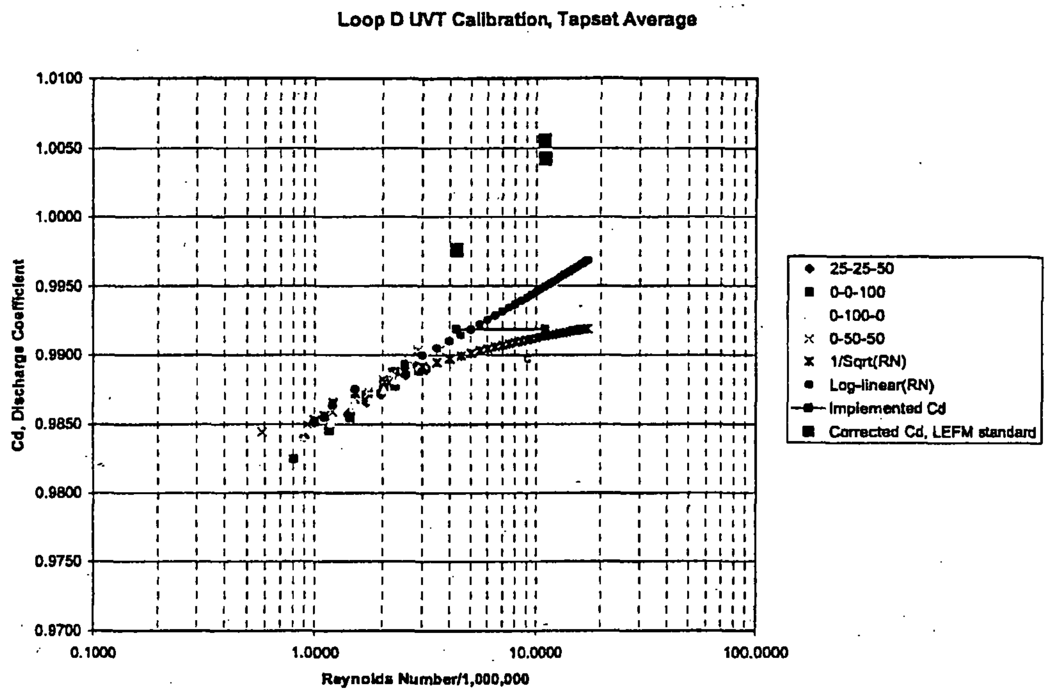


Figure 5D

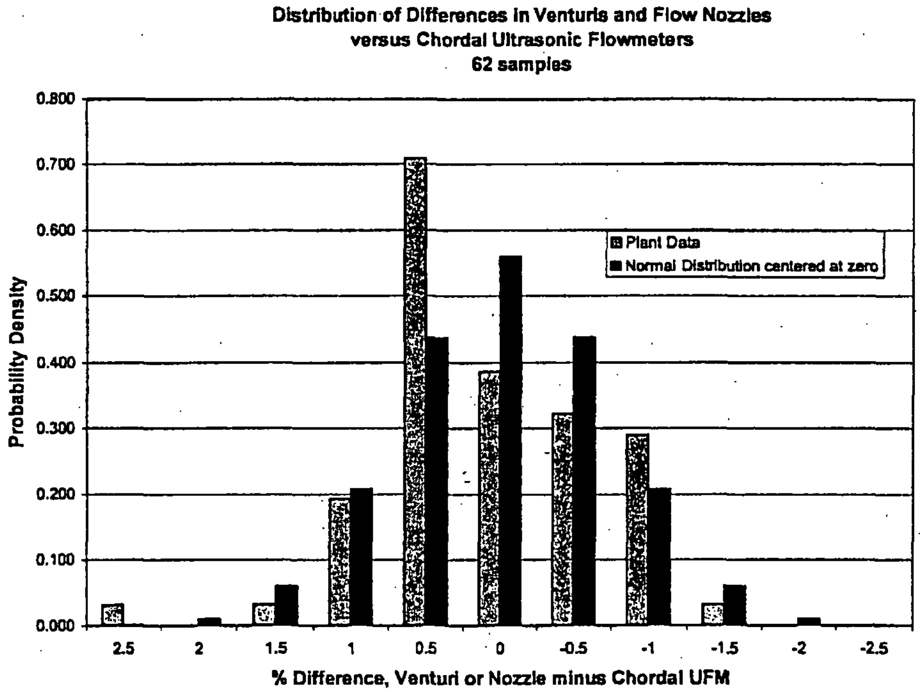


Comparison of Other Venturi Tubes and Flow Nozzles with Chordal UFMs

Over the years Caldon has collected data comparing the indications of the venturi tubes and flow nozzles used for the measurement of feedwater flow in nuclear power plants against the measurements of 4- and 8-path chordal meters. Such comparisons are not generally as accurate as the comparisons of this paper; they nevertheless provide a statistical insight into the potential uncertainties of nozzles and venturis in service. Sixty two such comparisons have been made. The results are plotted in Figure 6. The figure shows an approximately normal distribution whose mean is 0.08% above zero (nozzles greater than UFMs), with 2 standard deviations about the mean of about ±1.4%. This figure characterizes the root sum square of the aggregate venturi/flow nozzle uncertainties and the chordal UFM uncertainties.

The chordal meters are a mix of 4 and 8- path meters. The 4 path meters have mass flow uncertainties in the range of ±0.5%; the 8-path meters have uncertainties in the ±0.3% range. These figures include the uncertainty of the calibration facility, as is appropriate since the UFMs were not calibrated at the same time as the flow nozzles and venturi tubes. The aggregate uncertainty of the chordal ultrasonic flowmeters in the figure is estimated at about ±0.4% (2 standard deviations). If the 0.4 % figure is used for the UFM uncertainty, the distribution of Figure 6 implies a typical nozzle or venturi uncertainty of $[1.4^2 - 0.4^2]^{1/2} \cong 1.3\%$. The uncertainty of the flow nozzle/venturi tube indication is made up of two principal components: (1) the differential pressure transmitter and the associated signal processing loop and (2) the discharge coefficient. If an uncertainty of, say, ±0.8% is assigned to the transmitter and signal processing (most of the installations of the figure did not employ digital signal processing), the ±1.3% residual uncertainty for the nozzle/ measurements implies an uncertainty for the discharge coefficient of slightly greater than ±1% (2 standard deviations). This result is entirely consistent with the performance of the modified venturis described in this paper.

Figure 6



3. CONCLUSIONS:

1. For the modified venturi tubes analyzed in this paper, a log linear fit of the laboratory calibration data is superior to a reciprocal square root fit in predicting the discharge coefficient at plant Reynolds Numbers. The reciprocal square root fit leads to a systematic non conservative bias in the discharge coefficient of about ½%.

2. The data of this paper, as well as comparative data between chordal UFMs and nozzles and venturis in other nuclear installations support an allowance of at least ± 1% for the uncertainty in extrapolating discharge coefficient of nozzles and venturis from laboratory to nuclear feedwater conditions. This allowance is over and above any allowance for differences between lab and field hydraulics, which were explicitly modeled for the venturis analyzed in this paper.

Acknowledgement

The authors wish to acknowledge the contribution of Richard W. Miller, P. E., who reviewed and commented on this paper.

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EFFECTS OF VARYING HYDRAULICS ON THE CALIBRATION OF EIGHT PATH CHORDAL ULTRASONIC METERS

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Keywords: flow measurement, ultrasonic, measurement uncertainty, calibration.

INTRODUCTION

Eight path transit time ultrasonic meters are being used in the US, Europe and Japan to support measurement uncertainty uprates of nuclear power plants. Four path meters are also being used for more limited uprates; the focus of this paper is on the performance of the eight path meters. The power uprates rely on the demonstration of improved power accuracy to justify a reduction in the traditional 2% margin between operating power and the power at which loss of coolant accidents and other transients have been analyzed. The flow, density and enthalpy of the feedwater are key elements in the power calculation, and the eight path ultrasonic meters measure the flow and temperature from which these elements are derived.

Caldon's uncertainty analyses for uprates that employ these meters are rigorous carrying multiple elements in several categories (e.g., time measurements, length measurements, hydraulics). A key element in the uncertainty analysis is an allowance for the uncertainties that the feedwater flow profiles introduce in the meters' flow calibrations. To minimize and bound this uncertainty calibration tests are performed on each eight path element to be used in an uprate application.

Calibration coefficients are defined as the ratio of flow indication by the calibration facility to the flow indication by the ultrasonic meter. The calibration coefficients of eight path flow meters differ from one another, regardless of installation geometry, over a range of about 1%. Power uprate applications that use eight path meters require an accuracy in the range of ± 0.3%. To obtain this accuracy, it is necessary to calibrate eight path flow meters against a traceable standard of high accuracy. Accordingly, Caldon calibrates their flow elements at a certified laboratory. Calibrations are performed in straight pipe, and, in addition, in full scale models of the plant piping configuration in which they will be used, to establish the value of any bias that the flow profile specific to the application may introduce.

For a power uprate, it is also necessary and appropriate to establish bounds for, and to limit the uncertainty introduced by plausible flow profile effects that may not be present in the laboratory model test. Such effects can arise because of the physical limitations of the laboratory or because of unforeseen perturbations in plant hydraulics versus those of the lab. During calibration tests, therefore, the model configuration is varied parametrically, to establish the bounds for and to limit the uncertainty that hydraulic variability may introduce in a calibration.

This paper describes extensive testing of a prototype eight path meter, results of which have be used to define the sensitivity of 8 path meters to broad variations in flow profiles, both axial and transverse and to establish a methodology whereby the impact of these changes on the uncertainty of the meters can be minimized.

The test data include axial profiles varying from the rounded characteristic of developed flow in rough pipe to the nearly flat characteristic downstream of non-planar bends. Swirl, a globally rotating transverse flow pattern, ranges from near zero to 40% of the axial velocity in one configuration, the latter . The prototype test results have been compared with hydraulic variations that have been measured by production eight path meters in a wide range of specific nuclear applications, to establish the bounding nature of the prototype testing.

CHARACTERIZATION OF FLOW PROFILES USING EIGHT PATH METERS

Caldon's eight path ultrasonic meters are arranged in two planes of four chords each, at right angles to each other and at a nominal 45^0 with respect to the axis of the flow element. The eight path meter prototype is shown in Figure 1. Because orthogonal paths are paired in four chordal planes, transverse velocities projected onto each path pair offset, when the velocity measurements of a pair of paths are averaged. Hence the path arrangement makes the 8 path flow meter insensitive to variations in transverse velocity.

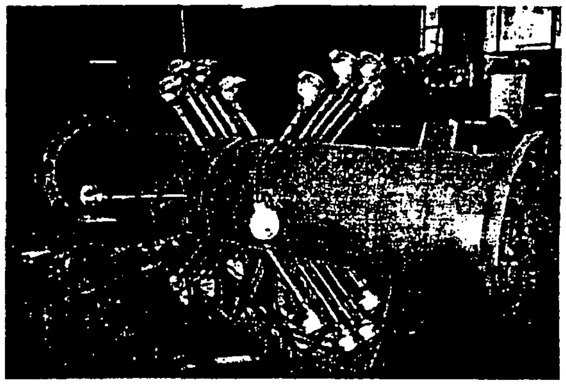

Figure 1. Caldon's Eight Path Meter Prototype

The chordal arrangement of the paired paths provides axial velocity measurements for each chordal location. As will be seen these data can be used to characterize the axial velocity profile. Transverse fluid velocities in the field of the measurement can also be established, using the *differences* in the fluid velocities measured in each chordal plane.

The chordal arrangement of Caldon's eight path ultrasonic flow meter permits the shape of the axial velocity profile to be characterized using the ratio of the average of the velocities measured along the outside (short) chords to the average of the velocities measured along the inside chords. This ratio, called the flatness, can be used to predict the performance of ultrasonic meters in both eight path and single diametral path configurations. This flatness ratio defines how flat a flow profile is as compared to other measured profiles. The flatter the velocity profile, the higher the flatness ratio. A perfectly flat profile has a flatness of 1.0. Developed turbulent flow profiles in straight pipe with high relative roughness or low Reynolds number will have a flatness in the 0.75 to 0.8 range. Developed profiles at high Reynolds number in smooth pipe can produce a flatness of up to 0.9.. Downstream of nonplanar bends and similar features, flatness can approach 0.95. For the feedwater flow measurements associated with power uprates, the flatness for actual profiles measured in service have ranged from 0.81 to 0.95.

As has been noted, an eight path meter can also be used to quantify the transverse velocities present at a specific hydraulic location. Swirl, a globally rotating transverse flow pattern depicted schematically in Figure 2, is measured with an eight path meter using one half of the difference in the velocities measured along the outside chords. It may be shown that the mean tangential velocity at the location of the outside chords is equal to this difference. As with flatness, swirl can affect the calibration of flow measurement systems (e.g., flow nozzles).

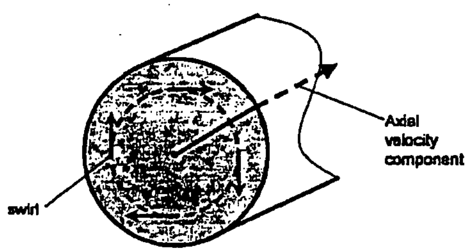

Figure 2. Depiction of Swirl In Pipe Flow

CALIBRATION DATA FOR THE PROTOTYPE METER

Extensive tests of the Caldon eight path prototype meter show that the calibration of this flow element is not very sensitive to the shape of the axial profile. Figure 3 shows a linear best fit of calibration coefficients for this meter versus flatness of the flow profile. These data were obtained in a broad range of hydraulic configurations. The low flatness data were obtained in straight pipe with a variety of upstream flow conditions at varying distances from the flow element. The high flatness data were obtained in hydraulic configurations dominated by inertial forces, at varying distances downstream of single and compound bends, planar and non planar.

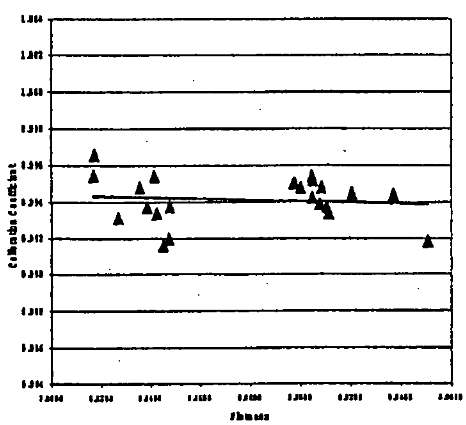

Figure 3. Calibration Coefficients Versus Flatness

Over the extreme flatness range of the tests (flatness ratios of 0.81 to 0.95), the nominal change in the prototype meter calibration is less than 0.05%. A difference in calibration test flatness versus a measured flatness after installation in the plant of 0.04—relatively large based on present experience—would, according to the best fit of the data produce a calibration bias of less than 0.02%. The downward trend of the calibration coefficient with increasing flatness is generally in accordance with theory, reference (1). The slope in this case is somewhat lower than that calculated in the reference.

Likewise the eight path calibration is insensitive to swirl. Figure 4 plots calibration factor against swirl, as measured by the tangential velocity (normalized to the average axial velocity) at the outside paths. The linear fit of the data indicates that an extreme swirl of 40% produces only a 0.18% reduction in meter factor. This reduction is almost certainly due to the flatness of the profile in the maximum swirl configuration. The slope of the linear fit is negative because of the increasing flatness that generally accompanies swirling flow. Suppose a difference of 10% in the swirl present at calibration versus the swirl present at the installed location in the plant. With the prototype 8 path meter, the resultant bias in-plant would be less than 0.05%. Additionally, the differences in the profiles can be characterized by their flatness and, as will be discussed in the next section, the measurement of flatness in situ allows a small correction to be made to the calibration coefficient.

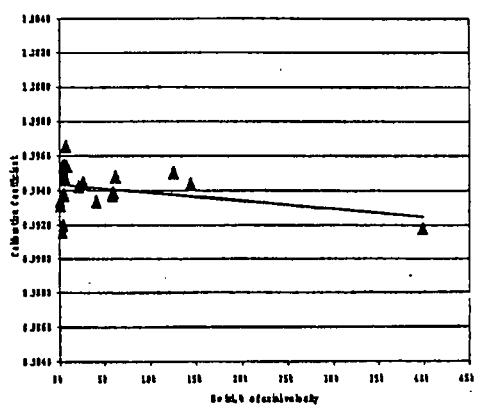

Figure 4. Calibration Coefficients Versus Swirl

The insensitivity of the 8 path prototype flow element to velocity profile is confirmed by calibration experience for flow elements other than the prototype. Calibration data for Caldon CheckPlus flow elements produced for nuclear customers show that the calibration factors for a meter are generally insensitive to the profile flatness and that the flatness range measured for parametric variations in hydraulic configuration in the calibration lab bounds any difference between the nominal plant configuration in the lab and the plant. Furthermore, as will be discussed in the next section calibration test data, in combination with in-plant measurements can be used to limit uncertainties due to differences between calibration and plant profiles still further.

USE OF PLANT DATA TO ENHANCE THE ACCURACY OF THE CALIBRATION COEFFICIENT

When a Caldon eight path meter is installed in a nuclear plant feedwater system, the in situ flatness is calculated from the individual path velocities, and compared to the flatness measured during calibration tests. The purpose of this measurement is to ensure that the calibration factor chosen based on the testing is appropriate for the installed conditions in the plant. This process is illustrated using the data for an eight path LEFM CheckPlus system recently commissioned at a large Pressurized Water Reactor plant.

The eight path flow meter for this unit was calibrated in a model of the hydraulic configuration of the unit's feedwater system. The feedwater model configuration was varied parametrically to provide reasonable assurance that the actual plant flow profiles would be bounded by the calibration data. The parametric test data showed only a small variation in calibration coefficient with flatness—over a range from 0.84 to 0.90, the variation in was ± 0.1% about the mean. The mean calibration coefficient for all of the parametric data, 1.0022, was chosen as the value to be used in the plant.

Data from the plant, taken following commissioning, showed that the plant profile was flatter than the mean flatness for the parametric tests. Specifically the flatness in the plant is 0.90, at the upper end of the range for the calibration tests. The average flatness of the five calibration tests used to determine the profile factor was 0.88. The increased flatness in the plant is almost certainly due to increased swirl, which tends to flatten the velocity profile. The swirl in the plant, as measured by the tangential velocity at the 0.86 of the interior radius is 5% of the mean axial velocity. The mean swirl for the calibration tests was 2.6%, with a range from 0 to 5% depending on the piping configuration tested.

As has been noted, the theoretical relationship between the shape of an axial velocity profile and the flow measurement of a 4 or 8 path chordal meter, reference (1), predicts that, as the velocity profile becomes flatter, the profile (meter) factor becomes slightly lower. This trend was seen in the prototype flow element discussed in the preceding section. Calibration data for this PWR flow element, including data for tests in straight pipe and for parametric variations of the plant model configuration, confirm the trend of reducing profile factor with increasing flatness. These data are plotted in Figure 5.

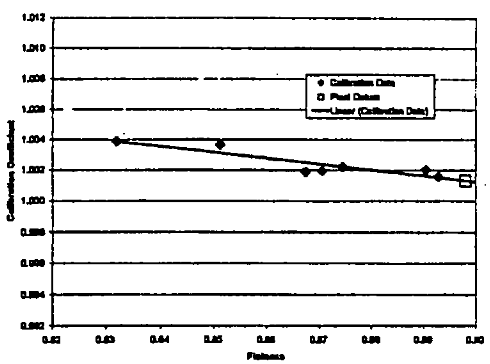

Figure 5. Large PWR, Calibration Coefficient Versus Flatness

Since the actual flatness of the profile at the plant was established by measurement in-plant, the least squares fit of the calibration data could be used to establish the calibration coefficient for the flatness in the plant. This point is plotted on Figure 5 (the "Plant datum"). Based on the fit and the measured flatness, the profile factor appropriate to this PWR is 1.0015--about 0.07% less than the factor implemented at the time of installation and commissioning. It should be noted that the calibration coefficients for the two calibration test configurations that produced a flatness comparable to the plant's (about 0.90) are also close to this figure. However, the use of the fit is considered more appropriate, since the fit utilizes all of the calibration data. Accordingly, the calibration coefficient input to the LEFM CheckPlus at the plant was revised to 1.0015.

The uncertainty in this profile factor (that is, the uncertainty in the fit of the data) is ± 0.04% (2σ). The use of the calibration coefficient based on the in situ flatness does not increase the uncertainty in the calibration coefficient and may, in fact, decrease it. This follows because the uncertainty in the mean of the parametric tests (which was used as a basis for the commissioning calibration) is essentially the same as the uncertainty of the least square fit used to determine the calibration coefficient appropriate to the in situ flatness. Furthermore, the bounding analysis used to support the uprate carries an allowance for the uncertainty in the calibration due to the extrapolation from calibration laboratory conditions to plant conditions (the Reynolds number in the plant may be a factor of 6 to 10 greater than that in the lab). But the use of the in situ profile to correct the calibration coefficient arguably involves no extrapolation.

CONCLUSIONS

1. Extensive testing of an 8 path prototype meter in a broad spectrum of hydraulic configurations confirms the general insensitivity of 8 path chordal systems to axial and transverse fluid velocity profiles.

2. An 8 path chordal system provides a quantitative measurement of the axial profile, specifically, the flatness—the ratio of the axial velocities measured by the short (outside) chords to the axial velocities measured by the long (inside) chords. This information allows a quantitative assessment of the differences in hydraulic profile seen by a meter in a plant versus the hydraulic profile seen by that same meter in the calibration lab.

3. Data for a prototype 8 path meter and for a typical 8 path meter now installed in a large PWR show small downward trends in calibration coefficient with increasing flatness. The trends are generally in accordance with theory, reference (1).

4. The sensitivity of an 8 path meter's calibration to flatness can be established quantitatively by parametric variations of the hydraulic configuration during calibration testing. When this meter is installed in the field, the flatness measured in the field can be used with the calibration coefficient versus flatness relationship established in the lab to determine a calibration coefficient precisely adapted to the field application.

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THEORY OF ULTRASONIC FLOW MEASUREMENT—GASES AND LIQUIDS

Class 3190

Herb Estrada, Chief Engineer, Caldon, Inc.

Introduction

Ultrasonic flow measurement systems (UFMs) are being applied with increasing frequency to hydrocarbon flow measurements. Most of these UFM s are transit time (also called time-of-flight) systems—they measure the transit time of ultrasonic energy pulses traveling with and against the direction of flow. This paper will outline the principles of three kinds of transit time UFMs:

- Externally mounted ("strap on") transit time meters measuring liquid flow. In meters of this kind, the ultrasonic pulses travel through the liquid on a path at an angle determined by the physical properties of the liquid, the pipe on which transducer assemblies are mounted, and the mounting hardware.
- "Chordal" transit time meters measuring liquid flow. In meters of this kind, the transducers are installed in wells, similar to the thermowells that are sometimes used to house RTDs or thermocouples. The angles of the acoustic paths in these meters are determined by the mechanical design of the transducer wells and the spool piece in which the wells are mounted. The term "chordal" is used here because, in Caldon's designs of meters of this type, the acoustic paths are arranged in parallel chords across the spool. Other manufacturers arrange paths differently, but unless otherwise noted, the discussion will generally apply to their meters as well.
- Chordal meters measuring gas flow. Mechanically, these meters resemble chordal meters that measure liquid flow. But different factors affect the performance of UFMs for gas, and they merit separate discussion.

It will be noted that there will be no coverage of externally mounted UFMs measuring gas flow. The technological challenges confronting the design of such meters are formidable (as will be evident from the discussion that follows). A few manufacturers provide external meters for a limited range of gas applications, but they have not found wide use.

Discussion

Transit Time Measurement Fundamentals

A transit time ultrasonic flow measurement system transmits acoustic energy along one or more diagonal paths through the pipe in which flow is to be measured. Such an acoustic path is illustrated in Figure 1. In the configuration shown, a pair of transducers are mounted to form a diametral diagonal path through flowing liquid, but the fundamental principles described in the following paragraphs apply to gas and liquid, internal or external.

If the upstream (A) transducer is excited by a burst of electrical energy, it will transmit a packet or pulse of mechanical (acoustic) energy into the adjacent medium. In Caldon's LEFMs, the electrical excitation of the transducer also initiates a time measurement by causing counts from a precision electronic clock to be accumulated in a counter. The pulse of ultrasound will consist of several cycles having a frequency typically in the 0.5 to 3 megahertz range for liquid flows, and in the 50 to 500kilohertz range for gas flows. The transducer is usually designed to be directional, so, in the configuration illustrated in the figure, a significant fraction of the acoustic energy will travel in a straight line from transducer A to transducer B, where it will produce a small burst of electrical energy. If the arrival of the energy at transducer B is detected with suitable electronics and this detection causes the accumulation of clock pulses in the time counter to stop, the elapsed time t_{AB}, from the time of transmission to the time of detection, has been measured (by the number of clock pulses accumulated).

If, now, the downstream or B transducer is excited and the arrival of acoustic energy at transducer A is detected, the transit time t_{BA} can be measured in like manner. The measured times are related to the dimensions, properties and velocity of the fluid as follows:

1) $t_{AB} = [\, L_{path} / (c_{path} + v_{path})] + \tau_{non\ fluid\ delay}$

2) $t_{BA} = [\, L_{path} / (c_{path} - v_{path})] + \tau_{non\ fluid\ delay}$,

Where

L_{path} is the length of the acoustic path,

c_{path} is the mean ultrasound propagation velocity along the acoustic path with the fluid at rest,

v_{path} is the mean fluid velocity projected onto the acoustic path, and

$\tau_{non\ fluid\ delay}$ is the total of the electronic and acoustic delays exterior to the fluid.

Each energy pulse traverses exactly the same path in the non fluid media and, in Caldon's LEFMs, the same transmitter produces each pulse and the same electronic detector detects each pulse. Consequently, the difference in the transit times, Δt, is given by:

3A) $\Delta t = t_{BA} - t_{AB}$

$= [\, L_{path} / (\, c_{path} - v_{path})\,] - [\, L_{path} / (c_{path} + v_{path})\,]$

Putting both terms over a common denominator and performing the algebra:

3B) $\Delta t = 2\, L_{path}\, v_{path} / (c_{path}^{\ 2} - v_{path}^{\ 2})$

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In most liquids the sound velocity is two orders of magnitude larger than the fluid velocity, c ranging from 2500 ft/sec to 5500 ft/sec versus v of 2 to 30 ft/sec. Hence equation 3B can be approximated

3C) $\Delta t \cong 2\, L_{path}\, v_{path} / c_{path}{}^{2}$

Or

3D) $v_{path} \cong \Delta t\, c_{path}{}^{2} / (2\, L_{path})$

Some early UFMs had the user input sound velocity from a look-up table in equation (3D) to find path velocity. This procedure is not consistent with good accuracy. In most liquids, sound velocity varies strongly with temperature and weakly with pressure. Hence varying liquid product temperature renders the meter calibration invalid.

If sound velocity is determined from transit time by one of the methods described in a later paragraph, equation (3D) is an acceptable approximation to determine path velocity in liquids. Even with a relatively compressible hydrocarbon like liquefied natural gas (with, therefore, a relatively low sound velocity) the error due to v^2 is unlikely to exceed 0.01%. However, the approximation of equations (3C) and (3D) is usually unacceptable for gas flow. Here neglecting the v^2 term can introduce velocity-dependent errors of 1% or more.

For precision, therefore, a gas UFM must use its transit time measurements to determine $(c^2 - v^2)$ as well as Δt. The transit times in the fluid, t_{fAB} and t_{fBA} are found by subtracting the non fluid delay from the measured transit times. For a given application, the non fluid delay $\tau_{non\ fluid\ delay}$ may be calculated or measured (or both).

4A) $t_{fAB} = t_{AB} - \tau_{non\ fluid\ delay}$

4B) $t_{fBA} = t_{BA} - \tau_{non\ fluid\ delay}$

The product of these fluid transit times yields the following:

5) $t_{fAB}\, t_{fBA} = [L_{path} / (c_{path} + v_{path})] \times [L_{path} / (c_{path} - v_{path})]$

$$= L_{path}{}^{2} / (c_{path}{}^{2} - v_{path}{}^{2})$$

Combining equations 3B and 5, the following expression is obtained for the product of the acoustic path length and the fluid velocity projected onto the path.

6) $L_{path}\, v_{path} = (\frac{1}{2}) L_{path}{}^{2}\, \Delta t / (t_{fAB}\, t_{fBA})$

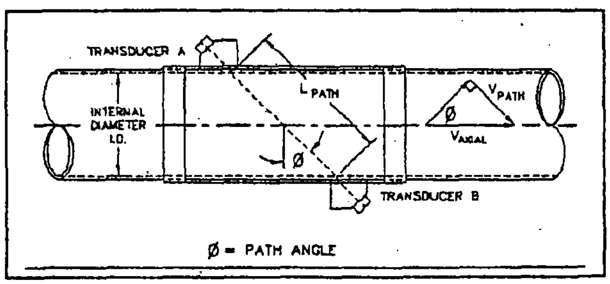
This relationship is fundamental to the operation of all transit time flowmeters. Essentially it says that the product of the path length and the mean velocity along that path can be determined by transit time measurements with an absolute accuracy limited only by

- The accuracy of the transit time measurements
- The accuracy of the measurement (or calculation) of the non fluid time delay
- The accuracy of the path length measurement

This is of course only a statement about the accuracy of a path velocity measurement—not volumetric flow. The accuracy with which one or more of these path velocity measurements gets translated into volumetric flow is affected by other factors, both acoustic and hydraulic. These factors will be covered in later discussion.

Note that the sound velocity can also be determined from the measurements of the transit times by substituting the fluid transit times in equation 5. [The v^2 term can be calculated using equation 6 or, if it is small compared to c^2, neglected.] The sound velocity of a product is a state variable like temperature and pressure and in a pipeline carrying a single product can be used with pressure to determine temperature. Alternatively, in multiproduct pipelines, sound velocity can be used alone, or with a temperature measurement, to detect product interfaces.

Figure I
Geometry of a Transit Time Acoustic Path



How accurately can the fluid velocity projected along the acoustic path be measured using equation (6)? Essentially, with an accuracy determined entirely by the accuracy of the measurements of the transit times and the separation distance, and the accuracy of the measurement or calculation of the non fluid delays.

THEORY OF ULTRASONIC FLOW MEASUREMENT—GASES AND LIQUIDS
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Some Numbers

How big are the times and time differences that UFMs measure? Suppose a 2-path chordal UFM with a path angle ϕ of 45° is measuring crude oil flow in a 12 inch pipeline. Petroleum product sound velocities usually lie in the range of 2700 ft/sec to 5000 ft/sec. If a sound velocity of 4500 ft/sec is assumed (typical of a medium crude), the transit times will be about 280 μsec. The time difference, Δt, at rated flow will equal 430 nanoseconds (1 nanosecond = 10^{-9} seconds), for a pipeline velocity of 5 ft/sec. If a 10:1 turndown is specified for this meter, the Δt at the low end of the flow range will be 43 nanoseconds.

The transit time of an external UFM, like that in Figure 2, may be slightly smaller than the chordal example because physical properties of the pipe and fluid dictate a shallower path angle. With typical petroleum product properties and steel pipe, the angle will be about 20°. [How the path angle of an externally mounted UFM is determined will be described later.] The transit times for an external meter mounted on the same 12 inch pipe will lie in the 250 μsec range. The Δt at rated flow of 180 nanoseconds. [To increase the magnitude of the Δt many externally mounted UFMs are configured in a "bounce" or V mode, wherein the two transducers are mounted on the same side of the pipe and the acoustic path length is doubled. This arrangement doubles both the t and Δt.]

Clearly, one of the challenges of a UFM measuring liquid flow is the accurate measurement of very small times and particularly time differences (Δt). For a 10:1 turndown and a linearity of 0.2%, the chordal UFM described above must measure time differences with an accuracy of ± 90 picoseconds (1 picosecond = 1 × 10^{-12} seconds). The externally mounted UFM must do even better—it must measure time differences with an accuracy of ± 35 picoseconds if it is configured in the direct mode (as in Figure 2 below) and ± 70 picoseconds if it is configured in the bounce mode.

Some UFMs achieve these accuracies and better. To do so, their designers must pay particular attention to what is called the reciprocity of the signal processing that they use—the non fluid delays must be *exactly* the same in the upstream and downstream direction. Signal quality is also essential—here, elimination of noise is the key.

There are different challenges for the designers of UFMs that measure gas flow. Here the transit times and Δt's are several orders larger than for meters measuring liquid flow. For example, the transit times for a two path chordal meter measuring the flow of natural gas in a 24 inch pipeline would be around 1.75 milliseconds. At rated flow, the time difference (Δt) would lie in the 100 to 200 μsecond range, depending on pipeline velocity. A major challenge in gas flow measurement lies in reliably detecting a relatively small ultrasonic pulse, possibly in the presence of noise. Dealing with wide variations in transit times due to turbulence and other factors is also more difficult in gas versus liquid meters.

The small size of received pulses in ultrasonic gas flow measurements is the inherent result of what is called the acoustic impedance mismatch between the transducers and the flowing medium. Because the pulse-producing transducer is relatively dense and stiff and the flowing medium is relatively light and compressible, most of the acoustic energy reaching an interface between the two stays where it started. That is, a large fraction of the energy is reflected rather than transmitted. There are at least two such interfaces in every acoustic path. Pulses traveling liquid paths also are attenuated at interfaces, but the degree of attenuation is several orders less challenging in the liquid case.

Translating Path Velocities into Axial Velocities and Volumetric Flow

All of the preceding describes a methodology for measuring a fluid velocity projected onto an acoustic path. To determine volumetric flow rate from one or more sets of path measurements requires that

(1) the path velocity (or velocities if more than one measurement is made) be related to the axial fluid velocity which produced it, and

(2) the axial fluid velocity for the acoustic path (or paths, if there is more than one) be related to the mean axial velocity for the pipe cross section.

The first of these conditions requires a knowledge of the angle ϕ between the acoustic path and the pipe axis, illustrated in Figure 1. It also requires a knowledge of the fluid velocity component *normal* to the pipe axis, if there is any (i.e., the transverse fluid velocity). The projection of the axial fluid velocity onto the acoustic path is shown in Figure I. No transverse velocity component is shown in the figure; its impact will be discussed later. From the trigonometry:

5) $$v_{path} = v_{axial} \sin \phi$$

Where v_{axial} is the mean axial fluid velocity projected along the acoustic path, and ϕ is the angle of the acoustic path through the fluid, measured from the normal to the pipe axis.

Equation 4 can be rewritten in terms of the axial fluid velocity in the way of the acoustic path:

6A) $v_{path} = V_{axial} \sin\phi = \Delta t\, c_{path}^2 / (2 L_{path})$

6B) $V_{axial} = \Delta t\, c_{path}^2 / (2 L_{path} \sin\phi)$

The specifics of how the path angle is determined and how one or more axial velocity measurements along the path(s) are translated into volumetric flow depends on whether the meter is external or chordal, and if chordal, the arrangement of the chords. The external meter will be covered first.

Principles of Externally Mounted Transit time Systems

In an externally mounted UFM, Snell's Law of Refraction constrains the geometry of the path traveled by acoustic pulses through the flowing fluid. Essentially these pulses must travel in a diametral plane. Such a configuration is shown in Figure 2. Here the path length is related to the internal diameter of the pipe, ID, by

7) $L_{path} = ID / \cos\phi$.

For this configuration, from equations (6B) and (7), the axial velocity averaged over the diametral acoustic path is given by

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This is the governing equation for externally mounted transit time ultrasonic flowmeters, in the absence of transverse flow. As has been noted, the acoustics of the pipe wall and fluid require placement of the transducers for such meters on diametral diagonals; hence, externally mounted ultrasonic flowmeters are essentially velocimeters. From the velocity measured in accordance with equation 8, the flow must be determined.

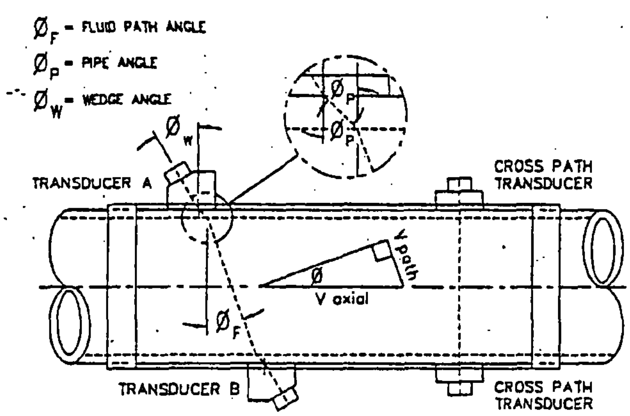
It should be pointed out that for externally mounted transit times ultrasonic systems, the path angle ϕ is not simply determined by transducer placement. Figure 2 provides a picture of external system acoustics. Piezoceramic transducer elements are mounted on wedges which, in turn, are mounted on the exterior of the pipe. The wedge optimizes the acoustic interfaces between the transducer-wedge assembly and the pipe wall and between the pipewall and the fluid. The three angles of the ray path in Figure 2, ϕ_F, ϕ_P and ϕ_W are the path angles followed by the pulses in the fluid, pipe, and wedge respectively. The angle ϕ_F is equivalent to ϕ, the angle through the fluid, that has been used in the discussion of Figure 1. The wedge, the pipe, and the fluid angles are all governed by Snell's law of refraction. They are also affected by the size, placement, and configuration of the wedges. Snell's law stipulates that

9) $\sin\phi_F / c_F = \sin\phi_P / c_P = \sin\phi_w / c_w$

Where c_F, c_P and c_w are the respective sound velocities of fluid, pipe, and wedge.

If the three sound velocities are measured or otherwise determined, it remains only to establish one of the three angles. The angle ϕ_W would seem to be the obvious choice to determine the others, and thus the acoustic path through the fluid, since the wedge can be manufactured with a precise geometry.

Figure 2
Acoustics of an Externally Mounted Transit time UFM



But determining the exact angle of the path in the fluid from the wedge angle is not always straightforward. If the transducers are acoustically distant from one another, ϕ_w can be determined by assuming the path connects the centers of the piezoceramic elements (refer again to Figure 2). Note that in this case, the ray path is not necessarily perpendicular to the transducer face; hence the wedge angle is not necessarily equal to the mechanical angle of the sloping face.

On the other hand, if the transducers are acoustically close to one another, ϕ_w *is* determined by the mechanical configuration of the wedge; it is the angle between a normal to the transducer transmitting surface and a normal to the axis of the pipe. Often, the acoustics are such that neither assumption is exactly valid, and both wedge configuration and transducer placement affect the path angle through the fluid.

Returning to equation 8, it can be seen that the accuracy of the velocity measurement of an externally mounted transit time system is a function not only of the accuracy of the time, distance and non fluid delay measurements, but also of the accuracy with which their acoustics can be characterized. The answer one obtains from equation 8 is very sensitive to the tangent of the angle ϕ_f.

An accurate fluid sound velocity measurement is crucial to establishing the path angle ϕ. To enhance the accuracy with which fluid sound velocity is determined in its external meters, Caldon employs a second pair of transducers, mounted so as to form an acoustic path normal to the pipe axis (the "cross path" in Figure 2). This arrangement is inherently less susceptible to variations in the physical properties and dimensions of the pipe than is the diagonal path. Data from this path can also be used to compensate for transverse flow, as noted below.

The variable of interest is volumetric flow—not velocity. Volumetric flow Q is given by

10A) $Q = \text{(pipe cross sectional area)}\ v_{mean,\ axial}$

where $v_{mean\ axial}$ is the mean or average fluid axial velocity over the internal pipe cross sectional area.

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For the determination of volumetric flow from an acoustic system with transducers on a diametral diagonal as they are in an externally mounted UFM, it thus remains to relate the diametral axial velocity to the axial velocity averaged over the pipe cross section.

The two velocities are rarely the same. In a long straight section of feedwater pipe at Reynolds numbers in the 10^6 range, the velocity measured along a diametral diagonal will typically be greater than the true mean velocity by 5 or 6%. The exact number depends not only on kinematic viscosity, diameter and velocity (that is, the Reynolds Number) but also on relative roughness of the pipe wall. At a Reynolds number of 10^4, the measured velocity may be 10% or 12% greater than the true mean. In the laminar flow regime it is 33% greater. On the other hand, a short distance downstream of a header the measured velocity and mean velocity may be within 1 or 2% of each other. Summing up, in a specific application, meter calibration may vary with:

- product (because viscosity and hence Reynolds Number varies),
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The differences between diametral axial velocity and mean axial velocity arise because of the differences in the shapes of the velocity profiles. The diametral diagonal paths of externally mounted ultrasonic meters undersample the region near the pipewall relative to its area, and oversample the region near the middle of the pipe relative to its area.

Caldon ultrasonic systems use a profile factor, PF, to relate the axial fluid velocity measured along one or more acoustic paths to mean axial fluid velocity. Specifically

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Hence,

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Equation 11B is used by Caldon for externally mounted systems operated in the direct mode, as in Figure 2. These meters can produce excellent linearity and repeatability, providing the range of Reynolds number coverage is not too broad.

As has been noted, the inference of axial velocity from diagonal path Δt (implicit in equation (11B)) is only valid in the absence of significant transverse velocity.

Unfortunately, transverse velocity is sometimes present in locations where it is practical to install an externally mounted ultrasonic system. Caldon LEFMs deal with transverse velocity in one of two ways:

(1) The time differential from a path normal to the pipe axis (which path is also used to determine fluid sound velocity) is used to calculate transverse velocity and the result is subtracted from or added to the path velocity as appropriate, or

(2) The diagonal path is configured in the 'bounce' mode. That is, both diagonal path transducers are mounted on the same side of the pipe so as to form a V-shaped acoustic path through the fluid. In this configuration, the transverse velocity projection on one leg of the V (relative to the axial component) is offset by the approximately equal and opposite projection on the other leg. For this mode, the divisor of equation 11B is doubled (because the acoustic path in the fluid is twice as long).

THEORY OF ULTRASONIC FLOW MEASUREMENT—GASES AND LIQUIDS

Class 3190

Herb Estrada, Chief Engineer, Caldon, Inc.

Some Numbers

How big are the times and time differences that UFMs measure? Suppose a 2-path chordal UFM with a path angle ϕ of 45° is measuring crude oil flow in a 12 inch pipeline. Petroleum product sound velocities usually lie in the range of 2700 ft/sec to 5000 ft/sec. If a sound velocity of 4500 ft/sec is assumed (typical of a medium crude), the transit times will be about 280 μsec. The time difference, Δt, at rated flow will equal 430 nanoseconds (1 nanosecond = 10^{-9} seconds), for a pipeline velocity of 5 ft/sec. If a 10:1 turndown is specified for this meter, the Δt at the low end of the flow range will be 43 nanoseconds.

The transit time of an external UFM, like that in Figure 2, may be slightly smaller than the chordal example because physical properties of the pipe and fluid dictate a shallower path angle. With typical petroleum product properties and steel pipe, the angle will be about 20°. [How the path angle of an externally mounted UFM is determined will be described later.] The transit times for an external meter mounted on the same 12 inch pipe will lie in the 250 μsec range. The Δt at rated flow of 180 nanoseconds. [To increase the magnitude of the Δt many externally mounted UFMs are configured in a "bounce" or V mode, wherein the two transducers are mounted on the same side of the pipe and the acoustic path length is doubled. This arrangement doubles both the t and Δt.]

Clearly, one of the challenges of a UFM measuring liquid flow is the accurate measurement of very small times and particularly time differences (Δt). For a 10:1 turndown and a linearity of 0.2%, the chordal UFM described above must measure time differences with an accuracy of ± 90 picoseconds (1 picosecond = 1 × 10^{-12} seconds). The externally mounted UFM must do even better—it must measure time differences with an accuracy of ± 35 picoseconds if it is configured in the direct mode (as in Figure 2 below) and ± 70 picoseconds if it is configured in the bounce mode.

Some UFMs achieve these accuracies and better. To do so, their designers must pay particular attention to what is called the reciprocity of the signal processing that they use—the non fluid delays must be *exactly* the same in the upstream and downstream direction. Signal quality is also essential—here, elimination of noise is the key.

There are different challenges for the designers of UFMs that measure gas flow. Here the transit times and Δt's are several orders larger than for meters measuring liquid flow. For example, the transit times for a two path chordal meter measuring the flow of natural gas in a 24 inch pipeline would be around 1.75 milliseconds. At rated flow, the time difference (Δt) would lie in the 100 to 200 μsecond range, depending on pipeline velocity. A major challenge in gas flow measurement lies in reliably detecting a relatively small ultrasonic pulse, possibly in the presence of noise. Dealing with wide variations in transit times due to turbulence and other factors is also more difficult in gas versus liquid meters.

The small size of received pulses in ultrasonic gas flow measurements is the inherent result of what is called the acoustic impedance mismatch between the transducers and the flowing medium. Because the pulse-producing transducer is relatively dense and stiff and the flowing medium is relatively light and compressible, most of the acoustic energy reaching an interface between the two stays where it started. That is, a large fraction of the energy is reflected rather than transmitted. There are at least two such interfaces in every acoustic path. Pulses traveling liquid paths also are attenuated at interfaces, but the degree of attenuation is several orders less challenging in the liquid case.

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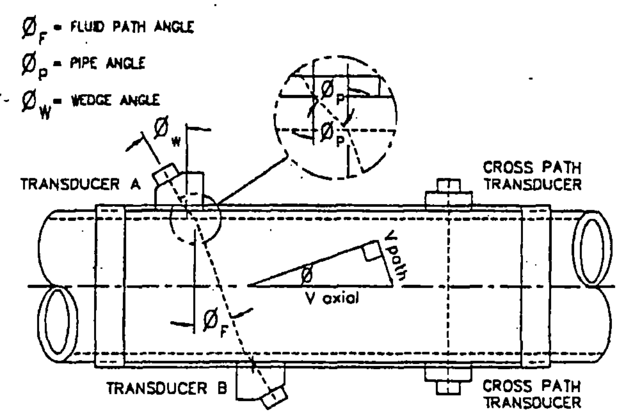

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As has been noted, the inference of axial velocity from diagonal path Δt (implicit in equation (11B)) is only valid in the absence of significant transverse velocity.

Unfortunately, transverse velocity is sometimes present in locations where it is practical to install an externally mounted ultrasonic system. Caldon LEFMs deal with transverse velocity in one of two ways:

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To determine the profile factor PF of equation 11, the hydraulics at the location of the measurement must be characterized. Caldon draws on an extensive library of hydraulic model testing for external systems for this purpose. For readers interested in more detail on Caldon's experience in profile factor measurements for external systems, Mazzola and Augenstein[1] is suggested.

Principles of Chordal (internal) Transit time Systems

The discussion in the preceding section has focused on externally mounted LEFMs, where the acoustic paths are diametral and the acoustics themselves are determined by the properties and placement of transducer wedges and the dimensions and properties of pipe and fluid. It is now appropriate to consider the operative equations for a chordal or internal system. In these systems, transducers are inserted in wells that are, as noted before, somewhat similar to thermowells. The ultrasound generated by a transducer passes through the "face" or "window" of the well in a direction normal to the face. Opposing transducer wells are located so that the centerlines normal to their faces coincide and form the nominal acoustic path.

This is the first of two important distinctions between external and chordal systems: the angle of the acoustic path in a chordal system is established mechanically by the angle formed by the centerline connecting the two transducer wells and the axis of the spool piece. As a consequence, the path angle for a chordal system (or the angles for systems with multiple chords) can be established with an accuracy determined by dimensional control of the spool piece as opposed to the acoustics of wedges, pipe and fluid. Path angle is crucial to determining the axial velocity subtended by the acoustic path (as was shown in equation 6B). Since dimensions are typically controllable with much greater precision than acoustics, chordal systems possess an inherent accuracy advantage on this score.

In order directly to measure volumetric flow, one must integrate the axial fluid velocity over a cross section normal to the pipe axis, as illustrated in Figure 3. That is,

13) $Q = \iint_{cross\ section} v_{axial}(x, y)\, dx\, dy$

A four path chordal system approximates this double integration. To understand how, recall equation 6:

6) $L_{path} v_{path} = (½) L_{path}^2 \Delta t / (t_{fAB}\, t_{fBA})$

Also recall, from equation (5)

5) $v_{path} = v_{axial} \sin \phi$

Refer now to the illustration of the four path chordal system in Figure 4. It will be seen that, for chord 1,

14) $L_{path1} = L_{chord1} / \cos \phi_1$

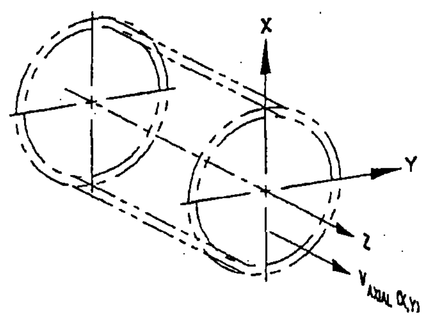
Substituting for v_{path} and L_{path} in equation (6), the following expression is obtained for chord 1:

15A) $(v_{axial\,1} L_{chord\,1})(\sin \phi / \cos \phi) = (½) L_{path}^2 \Delta t / (t_{fAB}\, t_{fBA})$

15B) $v_{axial\,1} L_{chord\,1} = (½)(L_{path1}^2 / \tan \phi_1)(\Delta t / (t_{fAB}\, t_{fBA}))$

The LV product of equation 15B is exactly the line integral of V_{axial} dx at the location of chord 1. The chordal instrument illustrated in figure 4 performs four such integrations at locations y_1, y_2, y_3, and y_4, effectively dividing the pipe cross-section into four segments. The effective width of each segment is a fraction, w, of the internal diameter, ID, measured along the y axis.

Figure 3
Integration of Axial Velocity over a Pipe Cross Section



Treating the four chordal measurements as four elements of a numerical integration, the volumetric flow can be calculated as follows:

16) $Q = ID\, [w_1 L_{chord1} v_{axial\,1} + w_2 L_{chord2} v_{axial\,2} + w_3 L_{chord3} v_{axial3} + w_4 L_{chord4} v_{axial4}]$

Or, substituting the lengths and times measured by the UFM in a more general expression:

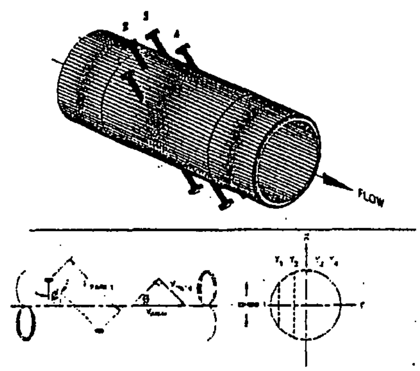
17) $Q = (ID/2) \{\sum_{i=1}^{N} (w_i L_{pathi}^2 / \tan \phi_i)(\Delta t_i / (t_{fABi}\, t_{fBAi}))\}$

where, in the four path system, the subscript can take on values from I through 4. Note that the times t_{fABi} and t_{fBAi} in the above are transit times in the fluid;

[1] D.E. Mazzola and D.R. Augenstein, *Hydraulic Testing of External Mount Ultrasonic Flow Meters*, July 1995

non fluid delays must be determined and subtracted from the measured transit times to obtain the times used in this expression.

Figure 4
A 4 Path Chordal LEFM



For Caldon chordal systems, the path locations, y, and weighting factors w are not chosen arbitrarily but comply with numerical integration rules specified by the mathematician Gauss[2].

This integration technique will integrate polynomials up to the seventh order without error. Caldon has collected extensive calibration data for four path systems operating in a wide variety of hydraulic configurations. These data were obtained at a certified facility, for the most part at high Reynolds Numbers. The data show that a meter factor in the 0.994 to 1.004 range is necessary, primarily to account for the difference between the circular geometry and the rectilinear geometry for which the Gauss procedure was developed. The data also demonstrate that the meter factor for four path Gaussian integration will handle a broad range of hydraulic geometries, with departures from nominal usually less than 0.2%.

The preceding discussion illustrates the second significant distinction between chordal and external systems: the chordal system is an actual, if approximate, volumetric flowmeter whereas the external system is a diametral velocimeter, which places a greater burden on knowledge of the hydraulics at the location in which it is installed.

Incorporating a profile factor PF, in equation 17, the algorithm used by Caldon for chordal systems is obtained:

18) $Q = (PF)(ID/2) \{\sum_{i=1}^{N} (w_i L_{path\,i}^2 / \tan \phi_i)(\Delta t_i / (t_{fABi}\, t_{fBAi})\}$

Where $\Delta t_i = t_{BAi} - t_{ABi}$
$t_{fABi} = t_{ABi} - \tau_{non\ fluid\ delay}$ and
$t_{fBAi} = t_{BAi} - \tau_{non\ fluid\ delay}$.

Transverse velocity components can affect chordal systems as they do external systems, but usually to a lesser degree. The vortices produced by a single bend 5 diameters upstream of a chordal UFM may affect the calibration by 0.1 or 0.2% (versus several percent for an external system without transverse velocity compensation). The swirl produced by nonplanar bends can significantly alter the calibration of both chordal and external systems unless the distance between the UFM and the second bend is enough to center the swirl. Generally speaking, UFMs are more forgiving of upstream and downstream hydraulics than turbine meters. By following a few rules, the use of flow conditioners can be avoided.

In chordal LEFMs, there is a pocket formed on the internal spool piece diameter by the aperture through which the acoustic beam passes as it makes its way from the transducer well into the flow stream. If the transducer aperture is large with respect to the pipe internal diameter, the hydraulics and acoustics of the pockets can influence the velocities measured. The profile factor for such installations, in addition to its other functions, must account for the influence of the pockets.

Summary of LEFM Principles
The velocity measurements of Caldon's transit time ultrasonic systems rest on first principles. The accuracy with which one can measure velocity does not rest on an empirical relationship, but on the accuracy with which one can measure the transit time, the dimensions, and, in the case of external systems, the acoustics of the installation.

Translating the velocity measured by an external UFM into a volumetric flow is essentially an empirical process. The calibration of external meters is sensitive to pipe condition and Reynolds Number, limiting their flow range in some applications.

The velocity measurements of Caldon's chordal UFMs lie along four mathematically specified, parallel chords. Because these four measurements are combined in accordance with the rules of a predictable numerical integration method the volumetric flow determination of a Caldon chordal system rests on first principles.

[2] *Handbook of Mathematical Functions*, page 887, National Bureau of Standards, Applied Mathematics Series.

A. Enclosure to letter, Susquehanna Benchmark Alarm Evaluation and Recommendations, *Evaluation of Velocity Profile Change at SSES Unit 2*, dated October 16, 2001

Evaluation of Velocity Profile Change at SSES Unit 2

Summary

On October 6, 2001, a Profile Test (Benchmark Velocity) alarm occurred for the Loop A subsystem of the LEFM Check installed at Susquehanna Unit 2. This alarm occurs when the velocity measured on any one of the 4 paths, normalized to the average velocity and weighted according to its contribution to the total flow result, differs from a reference value by more than a preset amount (± 0.5% was the allowable deviation in weighted path velocity at the time of the alarm). A reference value for the velocity in each path was established at commissioning. The purpose of the alarm is to alert the user of the LEFM that the velocity profile may have changed from that which prevailed when the instrument's calibration was established.

When the alarm occurred, there was concern that the meter may have been malfunctioning. A review of the data shows, however, that the meter was performing exactly in accordance with its specifications and that, in fact, a significant profile change had occurred in Loop A. An evaluation of the profile data shows:

(1) The profile change was transient in nature, and
(2) The (temporary) potential calibration error introduced by the profile change was no greater than about 0.1% and was in fact conservative. That is, the true flow was probably slightly lower than the indicated flow (by no more than 0.1% of reading) during the period when the profile was altered. [It should be noted that, because of the alarm, the plant was not using the LEFM to determine power, but, in accordance with its procedures, was using the venturi nozzles.]

In summary, this evaluation shows that the LEFM was operating within its design basis during the period when the Loop A profile differed from the reference. Because it appears possible that similar profile changes may occur again (see the discussion below), revised alarm settings will be implemented, to prevent these anticipated profile changes from causing the alarm in the future. The revised settings will still ensure that profile changes that could cause calibration errors larger than the design basis will be alerted.

Discussion

The change in the velocity profile seen by the LEFM in the A Loop at SSES was probably produced by a decrease in the relative roughness of the upstream piping system. This decrease in roughness resulted in an increase in the swirl velocity seen by the Loop A LEFM. Swirl is typically produced by non planar changes in flow direction. The hydraulic geometries of loops A, B, and C in Susquehanna Unit 2 are very similar, but a swirl is present at the Loop A LEFM location, while none is present in Loop B or C. When the Loop A LEFM was commissioned, the tangential velocity of the swirl was modest—a tangential velocity of about ± 4% of the axial velocity at the outside (short) paths (an 8% difference in path velocities) and less than ± 1% at the inside (long) paths. This pattern persisted for the months following commissioning.

The change in profile that initiated the velocity alarm occurred on October 6, 2001. On this date, a reduction in power to about 75% power appears to have brought about plant chemistry and/or flow changes that reduced the roughness in the feedwater piping upstream of the loop A LEFM. A reduction in roughness causes a flattening of the profile in and of itself, but for a plausible roughness change—say, a factor of 2—the amount of flattening would not be as great as the data show[+]. However, a reduction in roughness also increases the velocity of the swirl at the LEFM location (because the rate of dissipation of the swirl in the straight pipe upstream of the LEFM is diminished). The centripetal force produced by the high tangential velocity causes fluid traveling at high axial velocity to migrate to the outside of the pipe, further flattening the profile.

These changes can be seen in Figures 1A, 1B, and 1C. The change in axial velocity profile is characterized by the data plotted in Figure 1A. The figure shows the ratio of the average short (outside) path velocity to the average long (inside) path velocity. A swirling (tangential) velocity component tends to add to the axial velocity component on paths on one side of the pipe centerline and subtract from the axial component on the other side. Hence the ratio of the *average* short path velocity to the *average* long path velocity measures what the axial profile would have been in the absence of swirl. It will be seen in Figure 1A that the axial profile flattens abruptly between 132 and 133 hours[•] --the ratio increases from roughly 0.87 to 0.89. This change is coincident with a reduction in power and feedwater flow to about 75% of rating (the velocity profile alarm occurred somewhat later, because of the long term averaging used in its implementation).

Simultaneously with the flattening of the profile, the swirl velocities on the short and long paths increase abruptly, as seen in Figures 1B and 1C. These figures look at the normalized *difference* in the velocities measured by the outside paths and the inside paths. They indicate that the angular velocity of the swirl roughly doubled coincident with the down power. The swirl velocity is one half of the difference; Figure 1B indicates a swirl of about ± 4% increasing to over ± 7% in the outside paths

The velocity profiles seen by the LEFMs in loops B and C show little or no change with the reduction in flow and power at 133 hours. This can be seen from the data of Figures 2A and 3A. These profiles are more "round shouldered" than the profiles of loop A—their short-to-long path velocity ratios are about 0.83 versus 0.87 on loop A before the down power. This is probably because there is very little swirl present at these locations, as can be seen in Figures 2B and 3B. It is therefore not surprising that there is little change evident on these figures with the down power. [The velocity differences of the inside paths for loops B and C have not been plotted; they show smaller transverse velocity components than do the outside paths.]

Figures 1A, 1B and 1C show the change in A loop profile brought about by the down power gradually disappearing in the hours following the return to full flow. This response suggests that the change in profile was caused by a change in wall roughness brought about by a water chemistry transient coincident with the down power. A change in feedwater chemistry is inherent with the

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[+] A reduction in relative roughness from 0.0002 to 0.0001 would cause about half as much flattening as occurred on October 6.

[•] 132 hours corresponds to 11:37 AM on October 6. The down power appears to begin an hour earlier.

change in final feed temperature that accompanies a power reduction#. Additionally, heater drains, which can alter the dissolved and undissolved content of the feed, may be redirected during such transients**. Changes in profile of the kind observed at Susquehanna have been seen in several other plants, and will be the subject of a Caldon Bulletin, to be issued in the near future.

It may be demonstrated that the (temporary) and limited flattening of the profile, as occurred during the transient of Figure 1, causes a 4 path LEFM to read conservatively by about 0.1%*** The uncertainty analysis for the LEFM includes an allowance for profile factor (calibration) uncertainty that encompasses changes of this kind. Hence, the LEFM in Loop A at SSES was at all times operating within its design basis.

Changes to the velocity profile alarm settings for loop A should be implemented to prevent unnecessary alarms should such profile changes occur in the future. To select a revised profile test setpoint while retaining assurance that path velocity changes which could represent a profile outside the LEFM design basis would be alarmed, path velocities measured during calibration testing of the SSES spool pieces at Alden Research Labs were examined. These tests encompassed a several hydraulic geometries, including several orientations of the spools with respect to the upstream bend, and straight pipe. For each hydraulic geometry, the profile factor (calibration coefficient) for the spool was measured, as well as the path velocities, over a range of flows. The data for the Loop A spool show that, over all hydraulic geometries, the span in the calibration coefficient was about 0.2% (i.e., ±0.1%). Although the calibration remained nearly constant, the changes in geometry caused path velocity changes of as much as 3% on the inside (long) paths and 9 to 10% on the outside (short) paths. In computing the velocity change needed to initiate a profile alarm path velocities are weighted according to their contribution to the flow calculation. The weighting factors are, approximately, 0.11 for the short paths and 0.39 for the long paths. When the weighting factors are applied to the changes measured during calibration testing, a Profile Test alarm setting of at least 1.2% (more than twice the setting on October 6) is justified. This setting for the Profile Test alarm will provide the necessary protection without false actuations (the maximum weighted path velocity change seen in the transient of October 6 was only slightly above the setting at the time, 0.5%). To ensure that the profile protection is effective at or near plant rating, a setting for the profile alarm-enabling threshold of 90% full flow is recommended. At lower flows, the LEFM will deliver a flow measurement accuracy of ± 0.4% of rating or better, even if weighted velocity changes greater than 1.2% occur. SSES calibration data, as well as other spool calibration data show that even extreme changes in profile are

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Examination of the LEFM data through October 12 (beyond the range of the Figures) shows the gradual return continuing until a down power on October 12. When this occurred, the Loop A profile, which was still slightly flatter than originally, abruptly returned to its original shape. The response shows that down powers can lead to both smoothing and roughening of the loop A piping.

** Plant personnel have suggested the following, plausible explanation: Reactor water level at SSES is controlled by changing the speed of the feed pumps in Loops A, B, and C. Different settings are employed for each of the feed pump governors—Loop A pump is the "lead" pump, while the pumps for Loops B and C are "followers". All small adjustments to flow are made by the A pump. This response was seen in the data of the October 6 transient; the change in flow in the A Loop was larger and more "busy" than either of the other loops. This control arrangement has prevailed since startup. The constantly changing flow in A loop may be responsible for a corrosion layer having a different and smoother character than the other loops.

*** Calculation and experimental verification on file at Caldon. The theoretical maximum change for a fully developed profile at a Reynolds number of 3×10^7 is about 0.2%. That is, if the full developed profile suddenly became flat, the LEFM would read high by 0.2%.

unlikely to cause calibration changes of more than 0.3 to 0.4% *of reading.* Hence, calorimetrics can be performed at all power levels below 90% with excellent accuracy, without the profile alarm.

Figure 1A

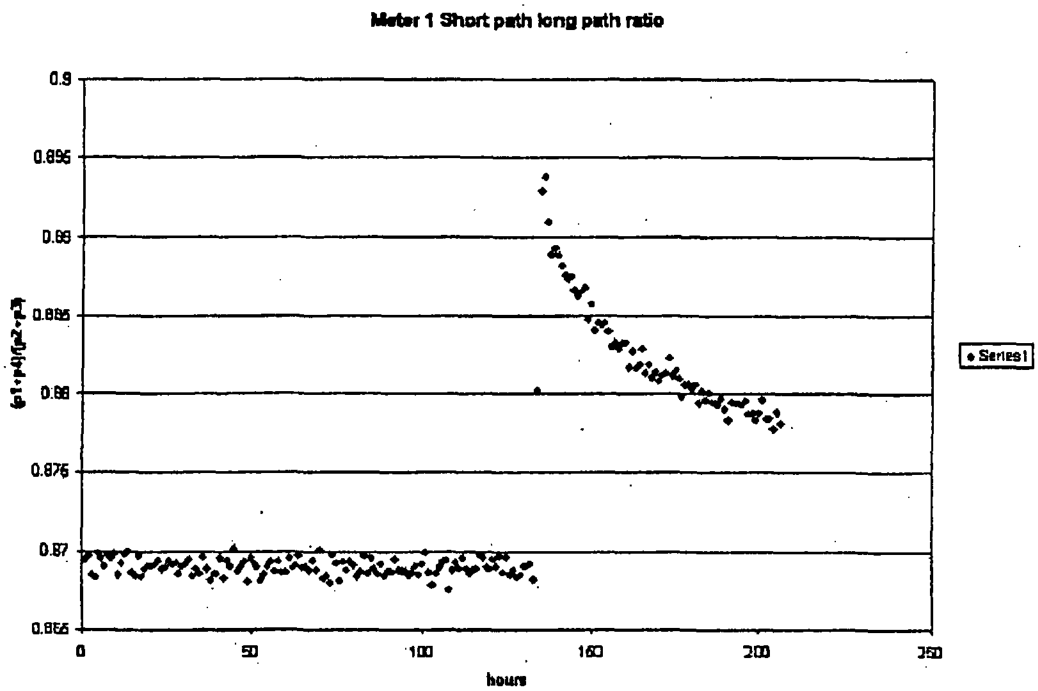


Figure 1B

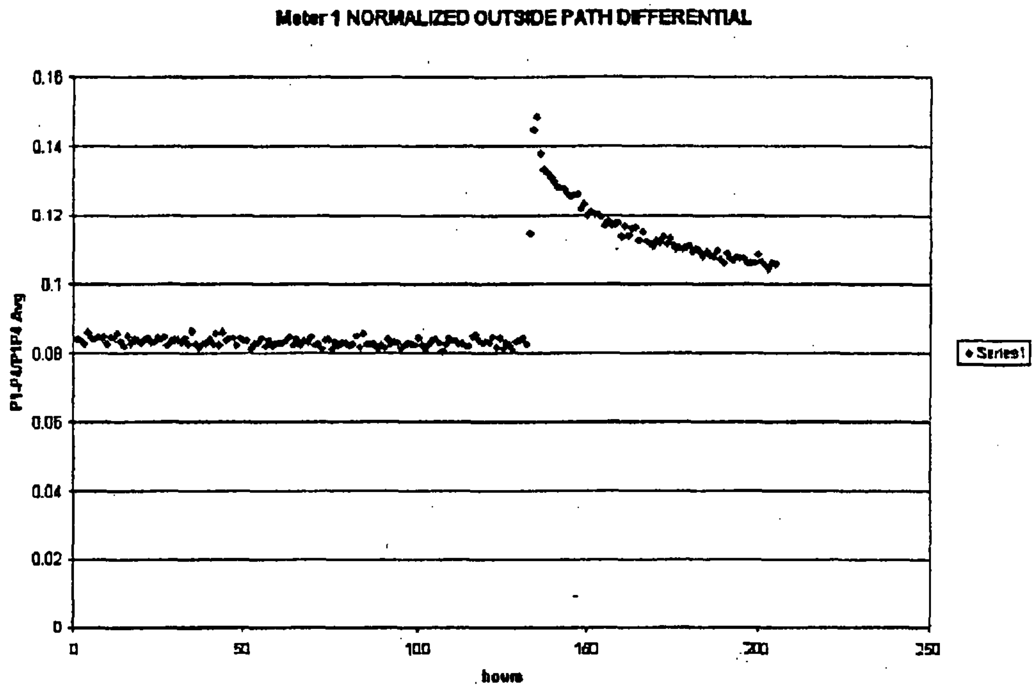
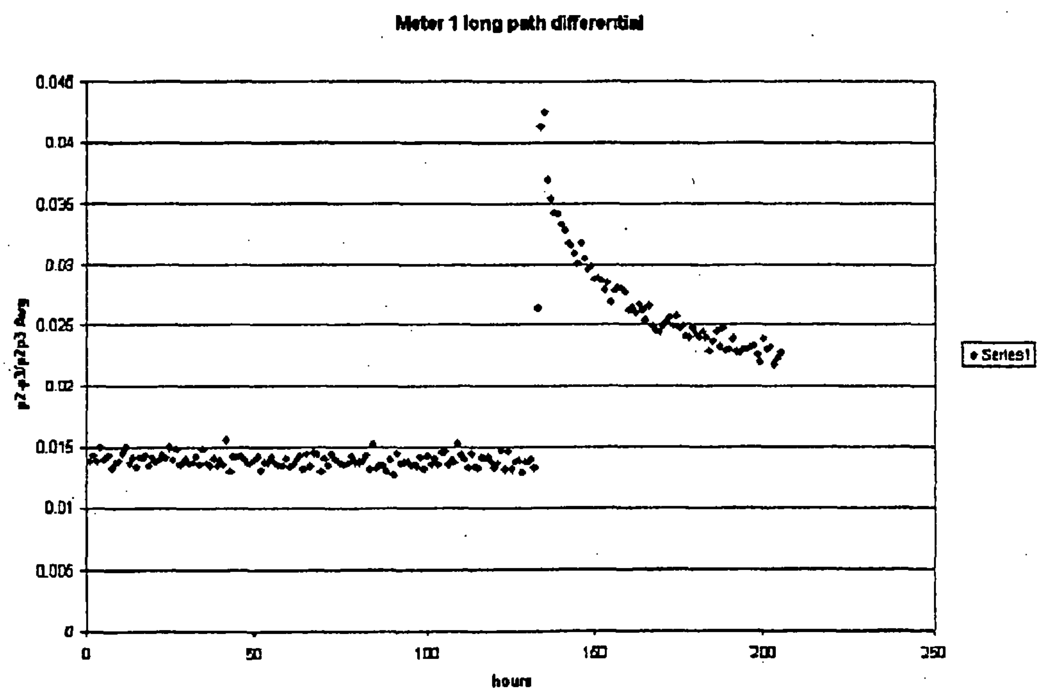
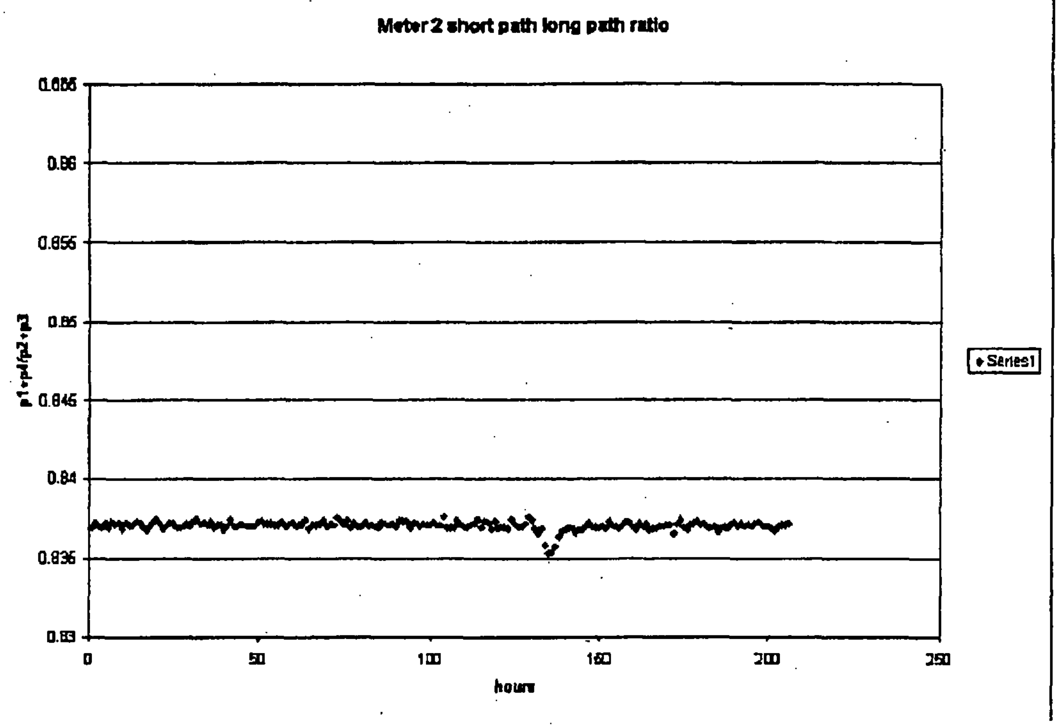
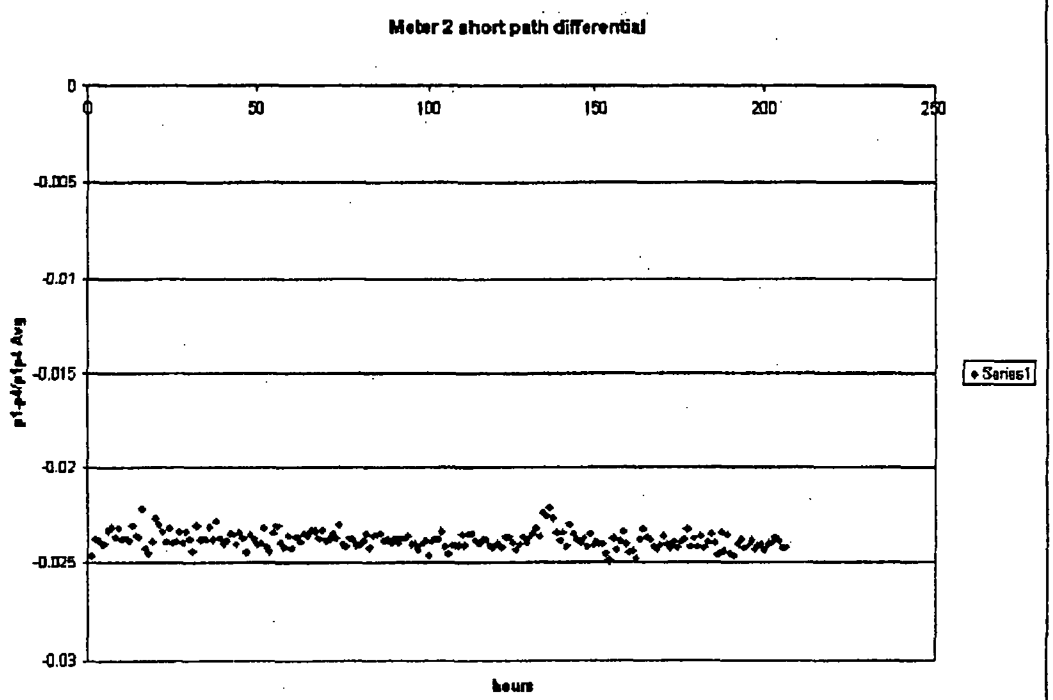


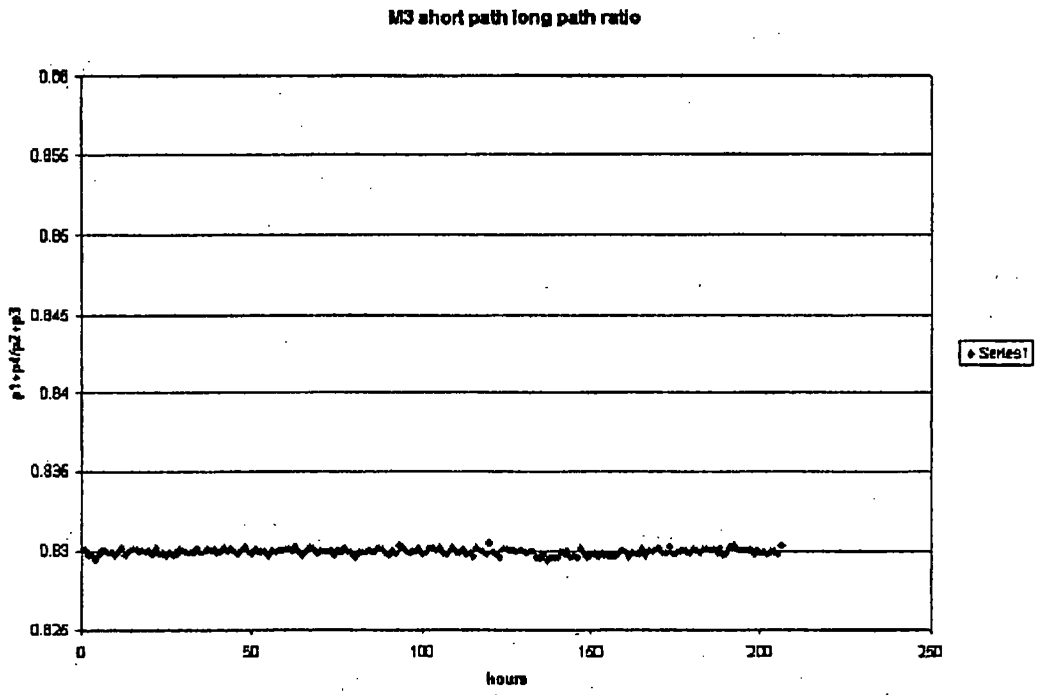
Figure 1C



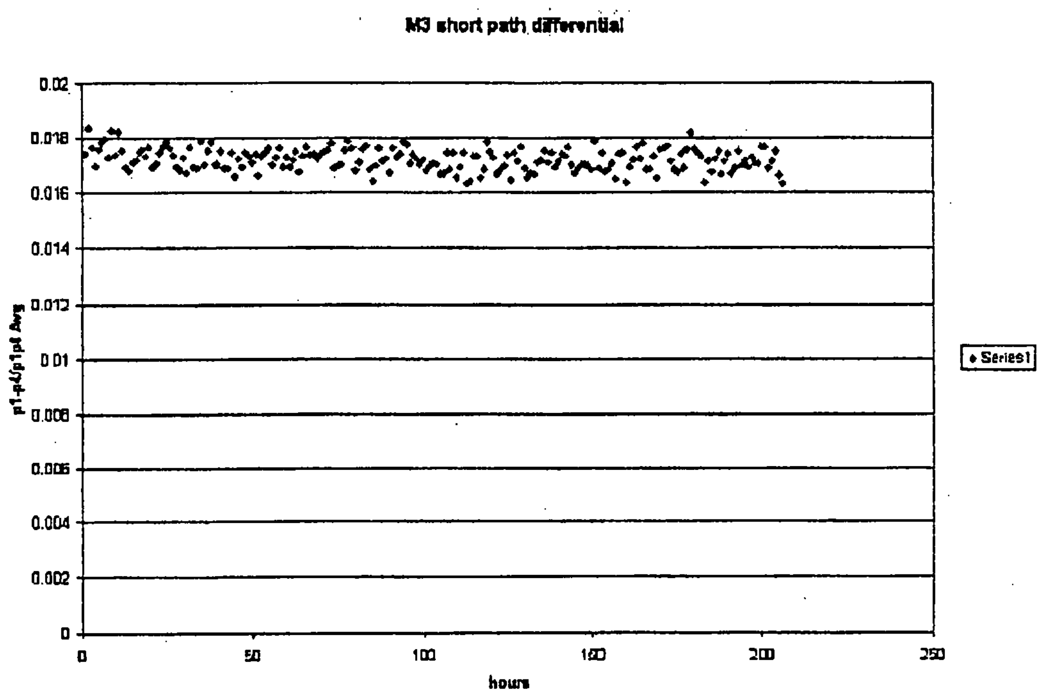


Figures 2A and 2B





Figures 3A and 3B



B. Letter, H. Estrada, Caldon to Ms. Debra Echols, Tennessee Valley Authority, dated September 7, 2001,"Change in Velocity Profile Measured by the WBN LEFM [Check]"

Caldon, Inc.

September 7, 2001

Ms. Debra Echols (for distribution)
Tennessee Valley Authority
Watts Bar Nuclear Power Station

Subject: Change in Velocity Profile Measured by the WBN LEFM Check

Dear Ms. Echols:

This letter provides Caldon's evaluation of the effect, on the accuracy of the LEFM Check, due to the change in the fluid velocity profile recently seen by this instrument. The change in profile was observed following restart after a plant trip, and was sufficient to trigger the LEFM Check velocity profile alarm. The alarm is intended to alert users of the LEFM Check that the velocity profile has changed significantly from that measured at the instrument's commissioning. The profile measured at commissioning is, in turn, compared with that measured during calibration testing of the LEFM Check, to ensure applicability of the calibration in the field. It is Caldon's practice, when a user reports a profile alarm, to evaluate the specifics of the change, to ensure that the calibration for the meter still applies and that its uncertainty is within its design basis. It should be noted that profile alarms are unusual, but have occurred in 2 or 3 chordal systems currently in service.

The LEFM Check at Watts Bar is installed in a 32 inch header about 45 diameters downstream of a single 90^0 bend. High pressure feedwater heaters feed the header upstream of the bend. The velocity profile data for Watts Bar, recorded before the plant trip and following the profile alarm are given in the table below. Velocities are normalized to the velocity averaged over the pipe cross section. V1 and V4 are the velocities measured along the two outside (short) chords of the LEFM Check; V2 and V3 are measured along the two inside (long) chords.

	V1	V2	V3	V4	V_{SHORT}/V_{LONG} (average)
Profile before plant trip	0.86	1.03	1.04	0.90	0.85
Profile with alarm	0.82	1.00	1.05	1.01	0.89

The profile before the trip is typical of developed flow in a straight pipe. The slight asymmetry in the profile before the trip (V3 and V4 are slightly larger than V2 and V1) is believed to be due to a very small swirl residual from the interaction of the velocity profile distortion produced by the heater discharge lines and the bend upstream of the LEFM Check.

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The swirl has increased following the trip, based on the increased asymmetry of V3 and V4 versus V1 and V2, though it is still small (about 9% of the axial velocity near the outer pipe wall). The swirl is centered in both cases and produces no error in the LEFM Check reading.

The overall shape of the profile following the trip is flatter than it was before the trip. This is the reason that the ratio of the average short path velocities to the average long path velocities increases from 0.85 to 0.89. A profile of this short path/long path ratio is not unusual, but is characteristic of developed flow at high Reynolds Number in *very smooth pipe*. It appears that the trip, and the subsequent operation of the feedwater system removed some or most of the rough corrosion film from the 45 diameters of pipe upstream of the LEFM Check, thereby producing a flatter profile and reducing the rate at which the swirl produced by the bend is dissipated. It is understood that condenser vacuum was maintained during the shutdown and the feedwater system was operated in a "long recycle" configuration throughout the period. This operating history, coupled by the sudden temperature change inherent in the shutdown, is consistent with the scale removal hypothesis.

The flatter profile does not significantly change the calibration of the LEFM Check, nor does it change the uncertainties associated with the calibration. In fact, the present meter factor is likely to be slightly conservative (less than 0.1%). Accordingly, we recommend that operation using the LEFM Check for thermal power computations be resumed. Because the change in profile is likely to persist for a long period—the rough film will likely take months or years to reform, if it reforms at all—we recommend that the settings of the velocity profile alarm be revised. Data for these revised settings will be provided under separate cover.

Sincerely

Herb Estrada

Herb Estrada
Chief Engineer

Cc: Ernie Hauser
Cal Hastings
Don Augenstein
Ed Madera
Ryan Hannas

C. Calculation: ***Determination of Axial Velocity Profiles from Chordal Velocity Measurements*****, dated October 31, 2001.**

ER-262
APPENDIX C
JANUARY 2002
REV 0

CALDON, INC.
ENGINEERING REPORT: ER-262
APPENDIX C

CALCULATION
DETERMINATION OF AXIAL VELOCITY PROFILES FROM CHORDAL VELOCITY MEASUREMENTS

Prepared By: Herb Estrada
Reviewed By: Ernie Hauser

Calculation
Determination of Axial Velocity Profiles from Chordal Velocity Measurements

A. Purpose

The purpose of this calculation is to describe the methodology whereby the velocity measurements of 4 path chordal transit time flowmeters in a specific hydraulic geometry can be used to determine the mean velocity along a diametral path in that same hydraulic geometry. The calculation also describes how these data can be used to compute calibration coefficients for 4 path chordal systems and for external (diametral path) systems.

B. Assumptions

1. Any swirl that may be present is centered. The 4 paths of a chordal system (two long, inside paths and two short, outside paths) are parallel to each other and are symmetrical with respect to the pipe centerline. When the swirl is centered, the swirl (tangential) velocity projections on each of the two acoustic paths on one side of the centerline are equal and opposite to the components projected onto the two acoustic paths on the other side of the centerline. The contribution to the path velocity readings can be determined from the difference in path velocities, and the axial profile shape can be determined by averaging the velocities measured on inner chords and the velocities measured on outer chords. Experimental data indicate that the centripetal forces associated with swirling flow tend to center the swirl in about 15 diameters of straight pipe.[1] Furthermore, Caldon practice is to orient the acoustic paths normal to the plane of the last bend, which orientation leads to a symmetrical profile in even shorter lengths (about 5 diameters).[2]
2. Axial velocity profiles at chordal flowmeter locations can be characterized by the ratio of the measured axial short path (outside chord) velocity to the average long path (inside chord) velocity (i.e., the swirl contribution has been removed). From these data the velocity as a function of local radius over the pipe cross section can be fitted using the inverse power law by varying the exponent. The justification for this procedure is based on the work of Nikuradse and others on flow in smooth and rough pipe[3].

C. Summary

Figure 1 presents the relationship between the profile factor for a 4 chord (4 path) ultrasonic transit time system, calculated using an inverse power law fit of short and long path velocities, and the ratio of average short path velocity to average long path velocity (SP/LP VR).

Figure 2 presents the relationship between the profile factor for a single (diametral) path ultrasonic system, also calculated using an inverse power law fit of short and long path velocities, and the ratio of average short path velocity to average long path velocity (SP/LP VR).

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[1] Murakami et al, *Studies on Fluid Flow in Three Dimensional Bend Conduits,* JSME Bulletin, Vol. 12, No. 54, December 1969

[2] Westinghouse Oceanic Division Report OEM 78-40, February 1979, G.P. Erickson and P.G. Spink

[3] *Boundary Layer Theory*, Dr. H. Schlichting, McGraw Hill, Sixth Edition, Chapters XIX and XX

Table 1 provides average short path velocity to average long path velocity ratios (SP/LP VRs) characterizing the variations in chordal path data measured at 18 chordal installations. The Table also includes the calculated variations in calibration (Profile Factor) for 4 chord systems and diametral path systems experiencing the profile variations tabulated. The calculated calibration variations are based on linear fits of the curves of Figures 1 and 2.

D. Calculation

1. Symmetrical axial profiles can be described using the so called inverse power law which represents the spatial axial velocity distribution in a pipe of circular cross section as follows:

$$u / U = (y / R)^{1/n}$$

Where u is local fluid velocity,
U is the fluid velocity at the centerline,
y is the distance from the pipe wall,
R is the internal radius of the pipe, and
n is an empirically determined exponent.

The inverse power law was used extensively by Nikuradse and others to fit flow profiles over a wide range of Reynolds Numbers in rough and smooth pipe, in the development of the methodology for calculating friction losses in turbulent flow[4].

2. The mean axial velocity through the pipe (i.e., the local axial velocity averaged over the pipe cross section) is given by:

$$u_{AVG} = \int u\,(r)\, dA / \int dA$$

Here the local radius, $r = R - y$, and
The incremental area, $dA = 2\pi r\, dr$

Using the relationship of paragraph 1 and writing the integral in terms of y

$$u_{AVG} = -\,(U/\,\pi R^2) \int (y/\,R)^{1/n} \times 2\pi\,(R - y)\, dy$$

Where the integration is performed from R to zero.

This integration yields the following relationship between the mean axial velocity u_{AVG} and the centerline velocity U:

$$U = u_{AVG}\,[1 + 1.5 / n + 0.5 / n^2]$$

For a given n, then, the centerline velocity can be computed from the expression above.

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[4] *Boundary Layer Theory*, op. cit.

A selection of n also allows the computation of the mean velocity along any chordal path within the pipe. Rectilinear coordinates will be employed. The x axis will be defined as parallel to the chord and passing through the pipe centerline. The y axis will be defined as perpendicular to the chord and passing through the pipe centerline. [NOTE: The coordinate y does not correspond to the variable of integration in paragraphs 1 and 2.] The y coordinate defines the specific chordal location relative to a centerplane defined by the x axis and the axial centerline of the pipe. Three specific y coordinates are of interest:

- For the short (outside) chords in Gaussian quadrature integration using Legendre spacing, $y_1 = 0.861R$
- For the long (inside) chords in Gaussian quadrature integration using Legendre spacing, $y_2 = 0.340R$
- For the diametral chord inherent in any externally mounted ultrasonic meter, $y_3 = 0.000R$

At any location, x, along the chord at y_i a local radius, r can be computed:

$$r = [\, x^2 + y_i^2 \,]^{1/2}$$

For the selected n, the local velocity u (r) at this location can then be computed using the relation of paragraph 1

$$u(r) = U\,(1 - r / R)^{1/n}$$

The mean velocity measured at any chord is:

$$u_{CHORD} = \int u(x, y_i)\, dx \,/ \int dx$$

This integration is performed numerically by dividing the chord length into increments Δx. Increments of 0.001 of the chord length X were used. Here

$$X = [\, R^2 - y_i^2 \,]^{1/2}$$

Note that the integration process is carried out over only half of the total chordal length. That is, it is performed from 0 to X; the chord extends from –X to + X. However, because the profile is symmetrical about 0, the integration as performed gets the correct result.

3. The calculation described in the preceding paragraph has been performed using an Excel spreadsheet[5]. The process is as follows:

- An exponent n is assumed. (Profiles for values of n ranging from 6 to 30 were calculated).
- The centerline velocity is computed relative to a mean velocity of 1.00.
- For chords located at each of the three y coordinates of interest, the mean axial velocity for the chord is calculated. In each case the procedure is:

[5] The spreadsheet is on file at Caldon.

- Starting at $x = 0$, $u(x, y_i)$ is calculated.
- x is incremented by an amount $\Delta x = X_i / 1000$)
- The value of $u(x, y_i)\, \Delta x$ is computed
- The cumulative sum of $u(x, y_i)\, \Delta x$ is computed.
- The process is continued until $x = X$.
- The mean velocity along the chord is obtained by dividing the cumulative sum of $u(x, y_i)\, \Delta x$ by X

- The ratio of the mean long path to mean short path velocity that would be measured by a 4 path chordal system, with a profile as defined by the assumed exponent n, is calculated.
- The theoretical profile factors (calibration coefficients) for a 4 path chordal system and a diametral (external) system, operating in the velocity profile characterized by the exponent n, are computed. The procedures for these calculations are described below.

4. A Profile Factor (PF) as used in Caldon instruments is defined as the quotient of the true flow to the flow as measured by the instrument prior to any correction. Hence,

$$PF = (u_{TRUE}\, A_{TRUE}) / (u_{MEAS}\, A_{MEAS})$$

Here u_{TRUE} is the true mean axial velocity over the pipe cross section,
A_{TRUE} is the exact area of the pipe cross section,
u_{MEAS} is the axial velocity measured by the instrument, and
A_{MEAS} is the cross sectional area embedded in the measurement of the instrument.

This analysis will assume no errors in the area measurements.

5. Accordingly, the Profile Factor, PF_1 for a diametral path (external) system is given by

$$PF_1 = (u_{TRUE}) / (u_{MEAS}) = 1 / u_{MEAS} = 1 / [\int u(x, 0.0)\, dx / R]$$

Where the integration is performed from 0 to R

6. For a 4 path chordal system, the measured mean short chord velocity, u_{SHORT}, is multiplied by a factor k_{SHORT} that reflects the weighting specified for this chord by the quadrature integration method and the chord length. Likewise the mean long chord velocity u_{LONG} is weighted by a factor k_{LONG} that reflects the weighting specified for this chord by the quadrature integration method and the chord length. Thus, the Profile Factor for a 4 path chordal system, PF_4, is given by

$$PF_4 = 1 / [\, 2 \times k_{SHORT}\, u_{SHORT} + 2 \times k_{LONG}\, u_{LONG}\,]$$

Where $k_{SHORT} = 0.112$,
$k_{LONG} = 0.388$,
$u_{SHORT} = \int u(x, 0.86R)\, dx / X_{SHORT}$, and
$u_{LONG} = \int u(x, 0.34R)\, dx / X_{LONG}$

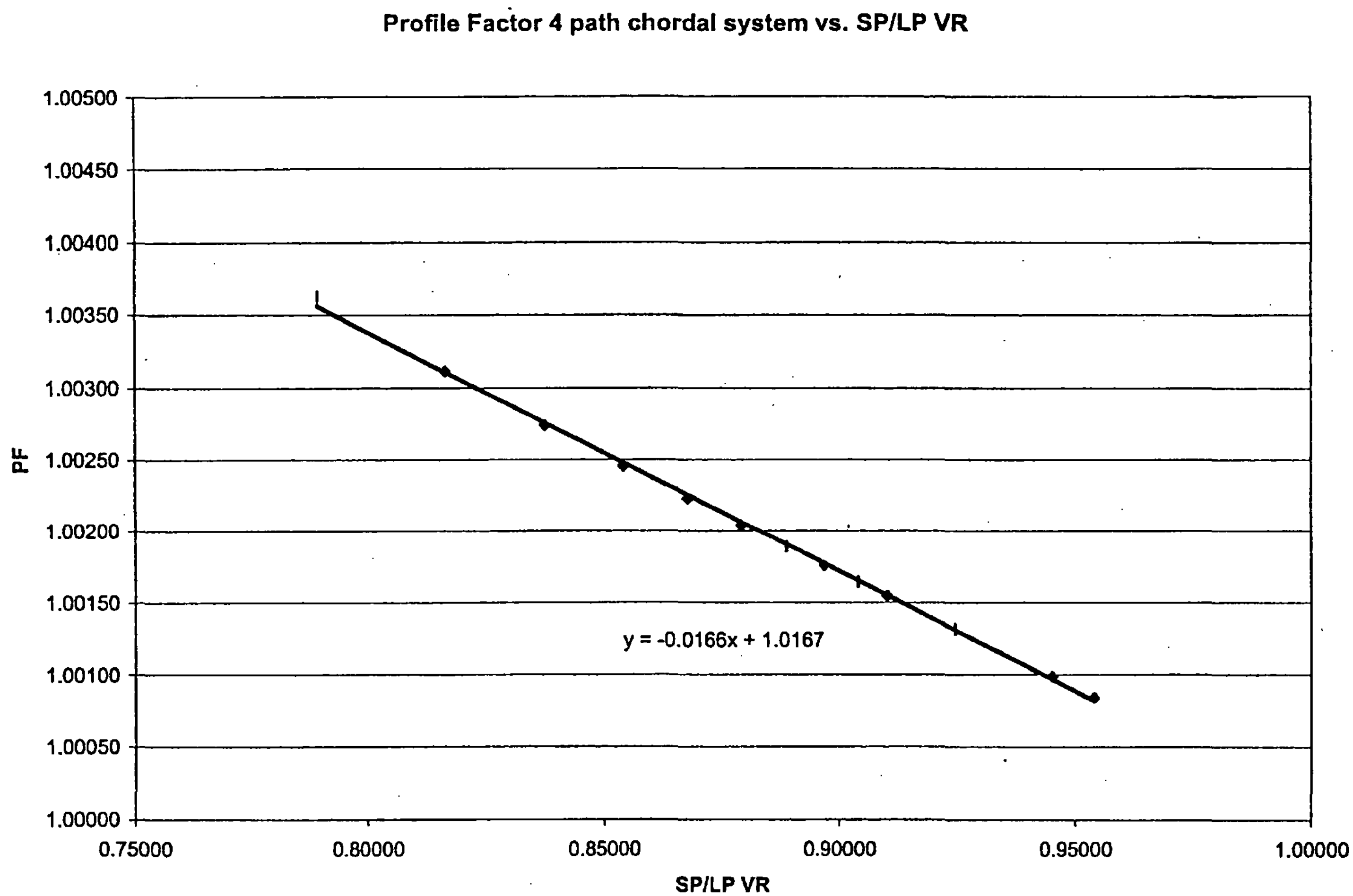
7. As previously noted, mean velocities for the short chords, the long chords, and the diameter were calculated for profiles whose inverse exponent n ranged from 6 to 30. Profile factors for the 4 chord and diametral systems were also calculated. For each selected exponent, the profile factors for both systems were then plotted against the ratio of the short path velocity to the long path velocity (SP/LP VR) for that exponent. The Profile Factor (calibration coefficient) for a 4 chord system is graphed against SP/LP VR in Figure 1. A linear fit (shown in the figure) has been used to characterize the relationship. The Profile Factor (calibration coefficient) for a diametral (external) system is graphed against SP/LP VR in Figure 2. Again, a linear fit (shown in the figure) has been used to characterize this relationship. For comparative purposes Figure 2 also shows the 4 chord system Profile Factor (the flatter curve near the top).

   The linear fits of the Profile Factor relations are as follows:

   - $PF_1 = 0.368\ (SP/LP\ VR) + 0.6331$
   - $PF_4 = -\ 0.0167\ (SP/LP\ VR) + 1.0167$

   These relations have been used to calculate the calibration changes that variations in the short and long path velocities measured in 18 Caldon chordal systems would produce in diametral and 4 chord systems. Results are tabulated in Table 1.

Figure 1



Profile Factor 4 path chordal system vs. SP/LP VR
1.00500
1.00450
1.00400
1.00350
1.00300
1.00250
1.00200
1.00150
1.00100
1.00050
1.00000
PF
y = -0.0166x + 1.0167
0.75000
0.80000
0.85000
0.90000
0.95000
1.00000
SP/LP VR

Figure 2

Calibration Coefficient (PF) versus short chord/long chord velocity ratio

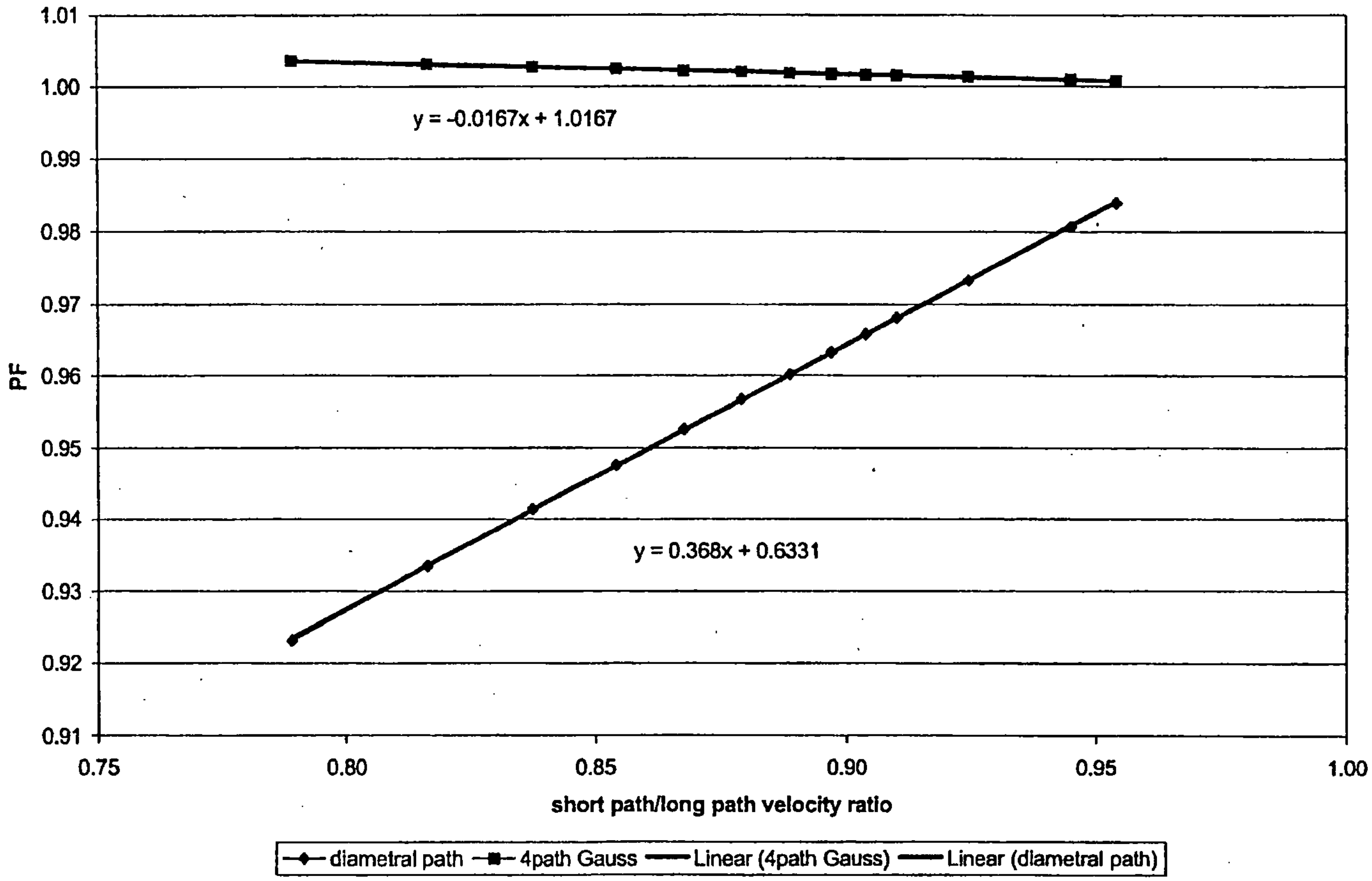


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Table 1
Calculated 4 Path and Single Path Profile Factors* versus Measured Chordal Velocity Ratios
Based on a random sample of logged data over periods of operation ranging from 2 months to several years

Plant/Unit		Hydraulic Geometry	Max SP/LP VR+	Min SP/LP VR+	4Path Chordal PF			Diametral Path PF		
					Max	Min	Δ	Max	Min	Δ
WBN 1		LEFM Check 45D downstream of single 90 ° bend. 3 HP heater feeds upstream of bend include non planar reverse bend	0.892	0.854	1.0024	1.0018	0.0006	0.961	0.947 **	0.014 ***
SSES 2	Loop A Loop B Loop C	Three loops similar. LEFM Check ~13D downstream of single 90 ° bend. Non planar 90 ° bend 11 to 12 diameters upstream.	0.894 0.837 0.830	0.864 0.827 0.822	1.0023 1.0029 1.0030	1.0018 1.0027 1.0028	0.0005 0.0002 0.0001	0.962 0.941 0.939	0.951 0.937 0.936	0.011 0.004 0.003
IP 2	Loop 21 Loop 22 Loop 23 Loop 24	LEFM in each loop between 10 and 15D downstream of 90 ° bend with nonplanar 90 ° bend 10D upstream	0.894 0.931 0.916 0.939	0.884 0.883 0.874 0.917	1.0019 1.0020 1.0021 1.0014	1.0018 1.0012 1.0014 1.0010	0.0002 0.0008 0.0007 0.0004	0.962 0.976 0.970 0.979	0.958 0.958 0.955 0.971	0.004 0.018 0.015 0.008
IP 3	Loop 31 Loop 32 Loop 33 Loop 34	LEFM in each loop 6D downstream of 90 ° bend with nonplanar 90 ° bend 10D upstream	0.940 0.925 0.952 0.976	0.921 0.916 0.932 0.952	1.0013 1.0014 1.0011 1.0008	1.0010 1.0012 1.0008 1.0004	0.0003 0.0002 0.0003 0.0004	0.979 0.974 0.983 0.992	0.972 0.970 0.976 0.983	0.007 0.004 0.007 0.009
CP 1 CP2		~LEFM in each unit 11 D downstream of 90 ° bend Non planar feed ~ 18 diameters upstream.	0.918 0.909	0.914 0.908	1.0014 1.0015	1.0014 1.0015	0.0000 0.0000	0.971 0.967	0.969 0.967	0.002 0.000

Continued, next page

Table 1, continued

Plant/Unit	Hydraulic Geometry	Max SP/LP VR	Min SP/LP VR	4Path Chordal PF			Diametral Path PF		
				Max	Min	Δ	Max	Min	Δ
PI 2 Loop 31 Loop 32	LEFM in each loop~20D downstream of 90 ^{0} bend. Each loop is fed from the branches of a non planar symmetrical lateral ~ 4 diameters upstream of bends.	0.867 0.881	0.851 0.868	1.0023 1.0022	1.0020 1.0020	0.0003 0.0002	0.957 0.957	0.951 0.953	0.006 0.004
BV 1 BV 2	U1 LEFM ~6 D downstream of header, 2 non planar feeds upstream (U1) U2 LEFM ~10 D downstream of header, 2 non planar feeds upstream (U1)	0.922 0.920	0.913 0.915	1.0015 1.0014	1.0013 1.0013	0.0002 0.0001	0.972 0.972	0.969 0.970	0.003 0.002
Mean High – Low PF (Δ), ± 1 σ (standard deviation)						**0.0003 ±0.0002**			**0.007 ±0.005**

Average Diametral Path PF: 0.964

Notes

* A Profile Factor is the calibration coefficient for an ultrasonic meter. It is sometimes referred to as a "velocity profile correction factor" and is equivalent to the discharge coefficient of a flow nozzle.

$^{+}$ SP/LP VR is the ratio of the average velocity projected onto the short chords (or paths) to the average velocity projected onto the long chords.

** A Profile Factor of 0.953, based on model tests, was employed on an external (Diametral Path) ultrasonic meter installed 20D upstream of the LEFM Check (i.e., 25D downstream of the bend).

*** The indication of the external meter installed at 25 diameters downstream of the bend shifted about 1.6% relative to the indication of the 4 path chordal instrument during an operational sequence when the chordal velocity ratio changed from its minimum to its maximum value. Allowing for a change in the calibration of the 4 path meter of 0.06%, the net calibration change measured for the external meter at 25D was about 1.5%, a figure entirely consistent with the 1.4% calculated from the change in the measured chordal velocities.

D. Summary Table: *Evaluation of Hydraulic Configurations and Uncertainties for Operating External LEFMs*

ER-262 APPENDIX D:

SUMMARY TABLE:
EVALUATION OF HYDRAULIC CONFIGURATIONS AND UNCERTAINTIES FOR OPERATING EXTERNAL LEFMS

Summary Table: Evaluation of Hydraulic Configurations and Uncertainties for Operating External LEFMs

Results of Caldon's analysis indicate that current external meter applications in the industry fall into one of four categories:

A. **No measurable effect.** The LEFM 8300 external meter is installed downstream of and in close proximity to a flow straightener designed to dominate the local velocity profile. This effectively isolates the LEFM from effects of changing upstream velocity profiles.

B. **Possible effect modeled and bounded.** Potential velocity profile changes at the installation location were modeled and are bounded by calibration testing.

C. **Possible effect bounded.** The calibration testing did not specifically address the profile changes that have since been observed. However, their effect on meter accuracy is bounded by the existing uncertainty allowance.

D. **Uncertainty bounds affected.** The calibration testing did not specifically address the profile changes since observed. Furthermore, their effect on meter accuracy is not bounded by the existing uncertainty allowance.

No action is necessary for any of these categories except category D.

All LEFM 8300 installations were evaluated. As shown by the following table, only one of the 55 feedwater pipes with LEFM 8300 external meters falls in category D.

Plant	Category	Report
Cofrentes	A	ER-236
Fitz Patrick	A	ER-238
Kashiwazaki Unit 1	A	ER-239
Kashiwazaki Unit 5	A	ER-241
Perry	A	ER-242
River Bend	A	ER-244
Doel Units 3 and 4	B	ER-228
Grand Gulf	B	ER-229
Millstone Unit 3	B	ER-230
Nine Mile Point 1	B	ER-231
Nine Mile Point 2	B	ER-232
Palo Verde Units 1, 2, and 3	B	ER-233
Trillo Unit 1	B	ER-234
Vandellos Unit 2	B	ER-235
Doel Units 1 and 2	B	ER-237
Kashiwazaki Unit 4	B	ER-240
VC Summer	B	ER-247
St. Lucie Unit 2	Loop A = B Loop B = C	ER-246
Quad Cities Units 1 and 2	C	ER-243
Sequoyah Units 1 and 2	C	ER-245
Watts Bar	D	ER-250

E. Scoping Calculation: *Errors in Flow Nozzles with Swirl Velocity of 10% Axial Velocity*

ER-262 APPENDIX E:

**SCOPING CALCULATION:
ERRORS IN FLOW NOZZLES WITH SWIRL VELOCITY
OF 10% AXIAL VELOCITY**

Scoping Calculation:
Errors in Flow Nozzles with Swirl Velocity of 10% Axial Velocity

Purpose:

The purpose of this calculation is to provide an approximate estimate of the error in the flow measurement of a nozzle, produced by swirl having a tangential velocity of 10% of the axial velocity. Errors will be calculated for nozzles having beta (diameter) ratios of 0.5 and 0.7.

Assumptions:

1. The hydraulic losses between the upstream (pipe) tap of the nozzle based flow measurement and the throat tap are negligible. That is, the total pressure at these two stations is the same.
2. The flow is incompressible. That is, the product of the mean axial velocity and the cross sectional area at the upstream tap location equals the product of the mean axial velocity and the cross sectional area at the throat tap location.
3. The swirl can be characterized as a rotating disk of fluid, having a tangential velocity at the pipe wall equal to the product of the radius and the angular velocity.
4. Rotational momentum is conserved between the upstream pipe tap and the throat tap. That is, the products of the rotational moment of inertia and the angular velocity of the fluid at each of these stations are equal.

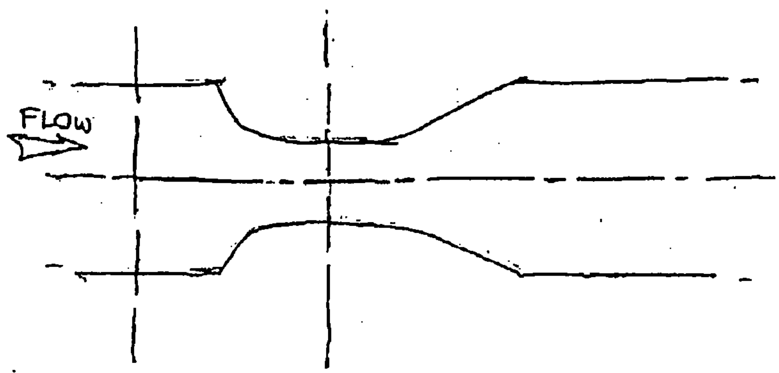
Summary:

With a tangential velocity due to swirl of 10% of the axial velocity, a flow nozzle with a beta ratio of 0.5 will read in error by 2%. The actual flow will be less than the indicated flow.

This same tangential velocity will produce an error of 0.65% in a flow nozzle having a beta ratio of 0.7. Again the actual flow will be less than the indicated flow.

Calculation:

1. The nozzle configuration and nomenclature are shown in the sketch below



Station	1	2
Total pressure	p_{T1}	p_{T2}
Static pressure	p_{S1}	p_{S2}
Axial Velocity	V_1	V_2
Area	A_1	A_2
Internal Radius	R_1	R_2
Moment of Inertia	I_1	I_2
Angular Velocity	ω_1	ω_2

2. The fluid energy per unit volume at each station is given by the total pressure. In accordance with Assumption 1:

   p_{T1} = (potential energy/ unit volume + kinetic energy/ unit volume)$_1$ =
   p_{T2} = (potential energy/ unit volume + kinetic energy/ unit volume)$_2$

3. The static pressure defines the potential energy/ unit volume at each station. Rearranging terms in the above equations and noting the difference in total pressure is zero, the difference in static pressures is given by

   p_{S1} - p_{S2} = (kinetic energy/ unit volume)$_2$ – (kinetic energy/ unit volume)$_1$

4. In the base case no swirl is present. In this case, the difference in kinetic energy per unit volume is given by:

   $$p_{S1} - p_{S2} = \frac{1}{2} \rho V_2^2 / g - \frac{1}{2} \rho V_1^2 / g$$

   where g is the gravitational constant.

5. The velocity at station 2 is determined in terms of the velocity at station 1 using Assumption 2.

   $$V_1 A_1 = V_2 A_2$$

   $$V_2 = V_1 A_1 / A_2 = V_1 R_1^2 / R_2^2 = V_1 / \beta^2$$

The term β is defined as the ratio of the throat diameter to the pipe diameter. Hence β equals the ratio of the throat radius to the pipe radius.

6. Substituting for V_2 in the equation of paragraph 4, the differential pressure for the nozzle is given by

   $$p_{S1} - p_{S2} = \Delta p = \frac{1}{2} (\rho / g) (V_1 / \beta^2)^2 - \frac{1}{2} (\rho / g) V_1^2 = \frac{1}{2} (\rho / g) V_1^2 [(1/ \beta^4) - 1]$$

7. For the case where swirl is present, rotational kinetic energy per unit volume must be added to the kinetic energy per unit volume term. Using Assumption 3, the rotational kinetic energy per unit volume, KER/V at any station is given by

   $$KER/V = \frac{1}{2} (I\, \omega^2) / A\Delta L$$

   Where ΔL is a unit of axial length

   The rotational moment of inertia of a rotating disc of thickness ΔL is given by[1]

   $$I = (\rho / g) (\pi R^4 / 4) \Delta L$$

   The term $A\Delta L$ is given by

   $$A\Delta L = \pi R^2 \Delta L$$

   Hence

   $$KER/V = \frac{1}{2} (\rho / g) (R^2 \omega^2 / 4)$$

8. Assumption 4 implies that

   $$(I\, \omega)_1 = (I\, \omega)_2$$

   Using the equation for moment of inertia from paragraph 7 in this equation, and canceling common terms

   $$R_1^4 \omega_1 = R_2^4 \omega_2$$

   Thus

   $$\omega_2 = \omega_1 (R_1 / R_2)^4 = \omega_1 (1/ \beta^4)$$

9. At each station, the rotational kinetic energy per unit volume adds to the kinetic energy due to the axial velocity. It therefore increases the difference in static pressures by an amount equal to the difference between the rotational kinetic energy per unit volume terms at stations 1 and 2. The net error in the pressure differential $\delta\Delta p$ is

   $$\delta\Delta p = (KER/V)_2 - (KER/V)_1 = \frac{1}{2} (\rho / g) (R_1^2 \omega_1^2 / 4) [(1/ \beta^8) - 1]$$

---

[1] Eshbach, Handbook of Engineering Fundamentals First Edition Chapter 4

In the absence of swirl, the differential pressure for the nozzle was derived in paragraph 6:

$\Delta p = ½ (\rho / g) V_1^2 [(1/\beta^4) - 1]$

Hence the per unit error in differential pressure, $E_{\Delta p}$ is the quotient of these expressions.

$E_{\Delta p} = \{(R_1^2 \omega_1^2 / 4) [(1/\beta^8) - 1]\} / \{V_1^2 [(1/\beta^4) - 1]\}$

Noting that $R_1 \omega_1$ is the tangential velocity at station 1, V_{T1}, the per unit pressure error is

$E_{\Delta p} = ¼ (V_{T1} / V_1)^2 [(1/\beta^8) - 1]\} / [(1/\beta^4) - 1]$

10. Since volumetric flow is proportional to velocity, and differential pressure is proportional to the square of velocity, the per unit error in flow, $\delta Q/Q$ is one-half the per unit error in pressure. Accordingly, for a tangential velocity of 10% of the mean axial velocity

$\delta Q/Q = ½ E_{\Delta p} = 1/8 (0.1)^2 [(1/\beta^8) - 1]\} / [(1/\beta^4) - 1]$

For $\beta = 0.5$,

$\delta Q/Q = 2.0\%$

For $\beta = 0.7$,

$\delta Q/Q = 0.65\%$

Note that in both cases the swirl causes the nozzle's flow indication to be high, since the rotational kinetic energy increases the differential pressure for a given axial velocity.

F. Plant Data, 4 and 8 Path Chordal Installations

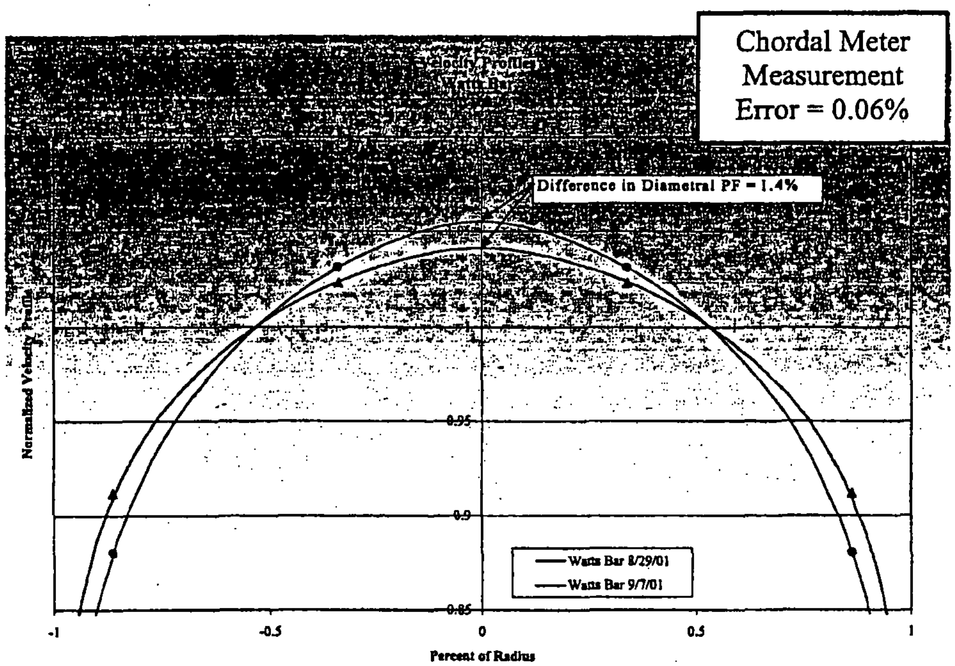
TABLE OF CONTENTS

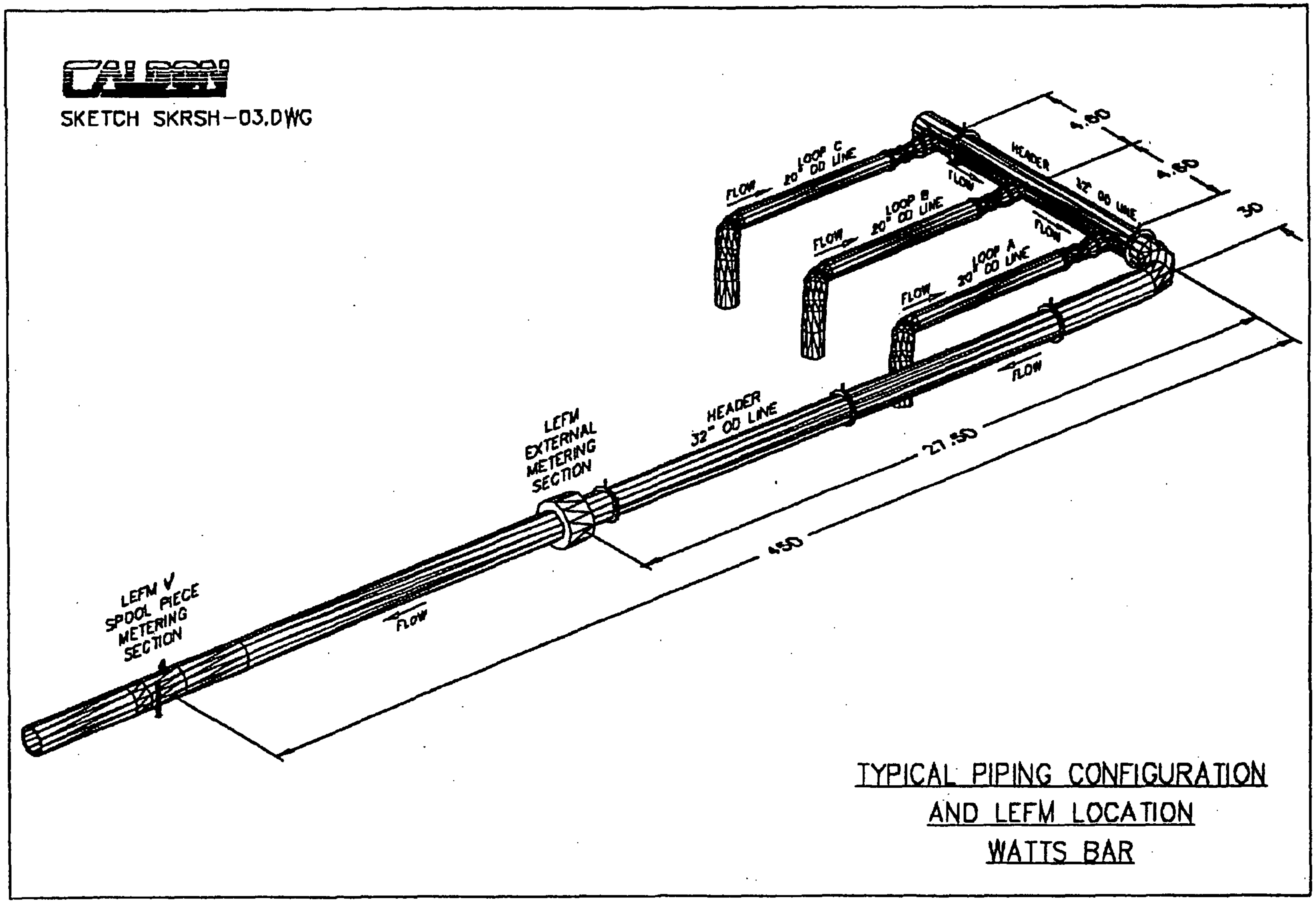
1. Plant Data Watts Bar Unit 1
2. Plant Data Susquehanna Unit 2 Loops A, B, and C
3. Plant Data Indian Point Unit 2 Loops 21, 22, 23, and 24
4. Plant Data Indian Point Unit 3 Loops 31, 32, 33, and 34
5. Plant Data Comanche Peak Unit 1 and Comanche Peak Unit 2
6. Plant Data Prairie Island Unit 2 Loop A and B
7. Plant Data Beaver Valley Unit 1 and Beaver Valley Unit 2

Plant Name: Watts Bar Unit 1

Feedwater Measurement System: LEFM✓

Installation Geometry: 45 L/D Downstream of Single 90° Elbow




SKETCH SKRSH-03.DWG
LOOP C 20" OD LINE
FLOW
LOOP B 20" OD LINE
LOOP A 20" OD LINE
HEADER 32" OD LINE
4.50
4.50
30
27.50
450
LEFM EXTERNAL METERING SECTION
LEFM ✓ SPOOL PIECE METERING SECTION
TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
WATTS BAR

Unit 1 02:46:21 2001/08/29

Configuration Files

ALARM.INI	2000/12/12	18:15:40	FFFED282
FAT.INI	2000/12/12	18:15:40	FFFFEB2F
HYDRAULI.INI	2000/12/12	18:15:40	FFFF4541
METER.INI	2000/12/12	18:15:40	FFFD66BF
PARAMETR.INI	2000/12/12	18:15:40	FFFB8AE0
P_CONFIG.INI	2000/12/12	18:15:40	FFFF82DC
PROPERTY.INI	2000/12/12	18:15:40	FFFF6C54
SETUP.INI	2000/12/12	18:15:40	FFFF9D29

Setup Files

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Setapu2.txt	2000/12/12	18:15:40	FFF899D5
Setapu3.txt	2000/12/12	18:15:40	FFF899D5
Setapu4.txt	2000/12/12	18:15:40	FFF899D5
Setapu5.txt	2000/12/12	18:15:40	FFF899D5
Setapu6.txt	2000/12/12	18:15:40	FFF899D5
Setapu7.txt	2000/12/12	18:15:40	FFF899D5
Setapu8.txt	2000/12/12	18:15:40	FFF899D5

Unit 1 Current Flow:	82.50
Unit 1 Average Flow:	82.39
Unit 1 Maximum Flow:	82.88
Unit 1 Minimum Flow:	81.91
Unit 1 Deviation Flow:	0.18
Unit 1 Current Temp:	443.7
Unit 1 Average Temp:	443.7
Unit 1 Maximum Temp:	443.9
Unit 1 Minimum Temp:	443.6
Unit 1 Deviation Temp:	0.0
Unit 1 Current System Status:	ALERT
Unit 1 Minimum System Status:	ALERT
Unit 1 Current Mass Flow:	15463.292
Unit 1 Average Mass Flow:	15442.563
Unit 1 Maximum Mass Flow:	15532.904
Unit 1 Minimum Mass Flow:	15350.739
Unit 1 Deviation Mass Flow:	34.223
Unit 1 Uncertainty:	0.11
Meter 1 Current Flow:	82.50
Meter 1 Average Flow:	82.39
Meter 1 Maximum Flow:	82.88
Meter 1 Minimum Flow:	81.91
Meter 1 Deviation Flow:	0.18
Meter 1 Current Temp:	443.7
Meter 1 Average Temp:	443.7
Meter 1 Maximum Temp:	443.9
Meter 1 Minimum Temp:	443.6
Meter 1 Deviation Temp:	0.0

Meter 1 Current Press:	1159.77
Meter 1 Average Press:	1158.10
Meter 1 Maximum Press:	1160.50
Meter 1 Minimum Press:	1155.75
Meter 1 Deviation Press:	0.04

Meter 1 Current Meter Status:	ALERT
Meter 1 Minimum Meter Status:	ALERT

Meter 1 Current Mass Flow:	15463.292
Meter 1 Average Mass Flow:	15442.563
Meter 1 Maximum Mass Flow:	15532.904
Meter 1 Minimum Mass Flow:	15350.739
Meter 1 Deviation Mass Flow:	34.223

Meter 1 Uncertainty:	0.11

	Path 1	Path 2	Path 3	Path 4
Meter 1 Current Variance:	10167.92	19972.27	14771.31	8568.18
Meter 1 Average Vnorm:	0.8648	1.0277	1.0402	0.8996
Meter 1 Current Vnorm:	0.8679	1.0281	1.0408	0.8933
Meter 1 Maximum Vnorm:	0.8831	1.0395	1.0528	0.9166
Meter 1 Minimum Vnorm:	0.8484	1.0151	1.0288	0.8772
Meter 1 Deviation Vnorm:	0.006	0.004	0.004	0.006
Meter 1 Benchmark Vnorm:	0.8648	1.0277	1.0402	0.8995
Meter 1 Limit % Vnorm:	0.50	0.50	0.50	0.50
Meter 1 Average Gain:	66.01	70.39	76.07	66.04
Meter 1 Current Gain:	66.01	70.41	76.13	65.97
Meter 1 Maximum Gain:	66.33	70.68	76.37	66.25
Meter 1 Minimum Gain:	65.66	70.17	75.78	65.82
Meter 1 Deviation Gain:	0.09	0.08	0.09	0.07
Meter 1 Limit Gain:	76.00	76.00	76.00	76.00
Meter 1 Current Gain Up:	65.54	70.09	76.21	65.39
Meter 1 Current Gain Down:	66.33	70.56	75.90	66.48
Meter 1 Current TPGain Up:	70.72	70.72	70.56	70.56
Meter 1 Current TPGain Down:	70.56	70.56	70.56	70.56
Meter 1 Average S/N Ratio:	38.50	26.71	15.31	38.33
Meter 1 Current S/N Ratio:	39.73	27.35	15.27	39.49
Meter 1 Maximum S/N Ratio:	40.66	29.16	17.02	40.97
Meter 1 Minimum S/N Ratio:	35.50	23.83	13.54	35.28
Meter 1 Deviation S/N Ratio:	1.47	1.28	0.70	1.60
Meter 1 Average TDown:	478419	823170	823193	478446
Meter 1 Current TDown:	478373	823095	823121	478413
Meter 1 Maximum TDown:	478533	823378	823398	478567
Meter 1 Minimum TDown:	478325	823008	823010	478339
Meter 1 Deviation TDown:	35	60	61	36
Meter 1 Current TPTDown:	4000747	4000748	4000746	4000747
Meter 1 Average DeltaT:	2158.4	4812.0	4861.4	2209.0
Meter 1 Current DeltaT:	2168.5	4819.0	4869.7	2196.0
Meter 1 Maximum DeltaT:	2207.3	4876.3	4919.1	2254.9
Meter 1 Minimum DeltaT:	2107.8	4746.0	4794.5	2160.4
Meter 1 Deviation DeltaT:	15.7	22.8	23.5	15.4

Meter 1 Current TPDeltaT:	-2.3	-0.6	-0.6	-1.4
Meter 1 Current Path Status:	NORMAL	NORMAL	ALERT	NORMAL
Meter 1 Minimum Path Status:	NORMAL	NORMAL	ALERT	NORMAL
Meter 1 Average Reject %:	0.1	0.1	2.0	0.0
Meter 1 Current Reject %:	0.0	0.0	3.5	0.0
Meter 1 Maximum Reject %:	2.8	1.2	6.5	1.5
Meter 1 Minimum Reject %:	0.0	0.0	0.0	0.0
Meter 1 Deviation Reject %:	0.3	0.2	1.0	0.2
Meter 1 Incoming Samples:	719	719	719	719
Meter 1 Number Failed Rejects:	0	0	0	0

Alarm Log Events

```
2001/08/29 01:46:18  Meter 1 ALERT
2001/08/29 01:46:18  Unit 1 ALERT
2001/08/29 01:46:19  Meter 1 Path 3 Alert -- Gain
2001/08/29 01:46:19  Meter 1 Path 3 ALERT
2001/08/29 01:46:33  Meter 1 NORMAL
2001/08/29 01:46:33  Unit 1 NORMAL
2001/08/29 01:46:34  Meter 1 Path 3 Pass -- Gain
2001/08/29 01:46:34  Meter 1 Path 3 NORMAL
2001/08/29 01:47:08  Meter 1 ALERT
2001/08/29 01:47:08  Unit 1 ALERT
2001/08/29 01:47:09  Meter 1 Path 3 Alert -- Gain
2001/08/29 01:47:09  Meter 1 Path 3 ALERT
2001/08/29 01:47:28  Meter 1 NORMAL
2001/08/29 01:47:28  Unit 1 NORMAL
2001/08/29 01:47:29  Meter 1 Path 3 Pass -- Gain
2001/08/29 01:47:29  Meter 1 Path 3 NORMAL
2001/08/29 01:47:48  Meter 1 ALERT
2001/08/29 01:47:48  Unit 1 ALERT
2001/08/29 01:47:49  Meter 1 Path 3 Alert -- Gain
2001/08/29 01:47:49  Meter 1 Path 3 ALERT
2001/08/29 01:47:53  Meter 1 NORMAL
2001/08/29 01:47:53  Unit 1 NORMAL
2001/08/29 01:47:54  Meter 1 Path 3 Pass -- Gain
2001/08/29 01:47:54  Meter 1 Path 3 NORMAL
2001/08/29 01:48:03  Meter 1 ALERT
2001/08/29 01:48:03  Unit 1 ALERT
2001/08/29 01:48:04  Meter 1 Path 3 Alert -- Gain
2001/08/29 01:48:04  Meter 1 Path 3 ALERT
2001/08/29 01:48:08  Meter 1 NORMAL
2001/08/29 01:48:08  Unit 1 NORMAL
2001/08/29 01:48:09  Meter 1 Path 3 Pass -- Gain
2001/08/29 01:48:09  Meter 1 Path 3 NORMAL
2001/08/29 01:48:13  Meter 1 ALERT
2001/08/29 01:48:13  Unit 1 ALERT
2001/08/29 01:48:14  Meter 1 Path 3 Alert -- Gain
2001/08/29 01:48:14  Meter 1 Path 3 ALERT
2001/08/29 01:48:23  Meter 1 NORMAL
2001/08/29 01:48:23  Unit 1 NORMAL
2001/08/29 01:48:24  Meter 1 Path 3 Pass -- Gain
2001/08/29 01:48:24  Meter 1 Path 3 NORMAL
2001/08/29 01:48:28  Meter 1 ALERT
2001/08/29 01:48:28  Unit 1 ALERT
```

Unit 1 19:01:03 2001/09/07

Configuration Files

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PARAMETR.INI	2000/12/12	18:15:40	FFFB8AE0
P_CONFIG.INI	2000/12/12	18:15:40	FFFF82DC
PROPERTY.INI	2000/12/12	18:15:40	FFFF6C54
SETUP.INI	2000/12/12	18:15:40	FFFF9D29

Setup Files

Setapu1.txt	2000/12/12	18:15:40	FFF89717
Setapu2.txt	2000/12/12	18:15:40	FFF899D5
Setapu3.txt	2000/12/12	18:15:40	FFF899D5
Setapu4.txt	2000/12/12	18:15:40	FFF899D5
Setapu5.txt	2000/12/12	18:15:40	FFF899D5
Setapu6.txt	2000/12/12	18:15:40	FFF899D5
Setapu7.txt	2000/12/12	18:15:40	FFF899D5
Setapu8.txt	2000/12/12	18:15:40	FFF899D5

Unit 1 Current Flow:	81.49
Unit 1 Average Flow:	81.59
Unit 1 Maximum Flow:	82.37
Unit 1 Minimum Flow:	80.99
Unit 1 Deviation Flow:	0.22
Unit 1 Current Temp:	442.5
Unit 1 Average Temp:	442.7
Unit 1 Maximum Temp:	442.9
Unit 1 Minimum Temp:	435.7
Unit 1 Deviation Temp:	0.3
Unit 1 Current System Status:	NORMAL
Unit 1 Minimum System Status:	FAIL
Unit 1 Current Mass Flow:	15290.738
Unit 1 Average Mass Flow:	15307.514
Unit 1 Maximum Mass Flow:	15454.595
Unit 1 Minimum Mass Flow:	15194.176
Unit 1 Deviation Mass Flow:	41.940
Unit 1 Uncertainty:	0.12
Meter 1 Current Flow:	81.49
Meter 1 Average Flow:	81.59
Meter 1 Maximum Flow:	82.37
Meter 1 Minimum Flow:	80.99
Meter 1 Deviation Flow:	0.22
Meter 1 Current Temp:	442.5
Meter 1 Average Temp:	442.7
Meter 1 Maximum Temp:	442.9
Meter 1 Minimum Temp:	435.7
Meter 1 Deviation Temp:	0.3

Meter 1 Current Press:	1161.97
Meter 1 Average Press:	1155.12
Meter 1 Maximum Press:	1170.75
Meter 1 Minimum Press:	200.00
Meter 1 Deviation Press:	0.33

Meter 1 Current Meter Status:	NORMAL
Meter 1 Minimum Meter Status:	FAIL

Meter 1 Current Mass Flow:	15290.738
Meter 1 Average Mass Flow:	15307.514
Meter 1 Maximum Mass Flow:	15454.595
Meter 1 Minimum Mass Flow:	15194.176
Meter 1 Deviation Mass Flow:	41.940

Meter 1 Uncertainty:	0.12

	Path 1	Path 2	Path 3	Path 4
Meter 1 Current Variance:	11232.52	15020.36	27588.72	16844.19
Meter 1 Average Vnorm:	0.8186	0.9972	1.0523	1.0098
Meter 1 Current Vnorm:	0.8302	1.0023	1.0448	1.0064
Meter 1 Maximum Vnorm:	0.8439	1.0134	1.0768	1.0456
Meter 1 Minimum Vnorm:	0.7865	0.9806	1.0323	0.9736
Meter 1 Deviation Vnorm:	0.009	0.005	0.008	0.012
Meter 1 Benchmark Vnorm:	0.8187	0.9971	1.0519	1.0109
Meter 1 Limit % Vnorm:	0.50	0.50	0.50	0.50
Meter 1 Average Gain:	54.60	60.57	68.16	56.02
Meter 1 Current Gain:	54.68	60.60	68.17	55.97
Meter 1 Maximum Gain:	54.80	60.88	68.44	56.21
Meter 1 Minimum Gain:	54.33	60.25	67.74	55.82
Meter 1 Deviation Gain:	0.08	0.11	0.11	0.08
Meter 1 Limit Gain:	76.00	76.00	76.00	76.00
Meter 1 Current Gain Up:	54.09	60.37	67.90	55.35
Meter 1 Current Gain Down:	55.03	60.68	68.37	56.44
Meter 1 Current TPGain Up:	58.95	58.95	58.80	58.64
Meter 1 Current TPGain Down:	58.64	58.64	58.80	58.80
Meter 1 Average S/N Ratio:	36.63	21.75	11.16	31.41
Meter 1 Current S/N Ratio:	37.58	22.46	11.24	33.03
Meter 1 Maximum S/N Ratio:	38.83	24.15	12.71	33.55
Meter 1 Minimum S/N Ratio:	32.71	18.72	9.49	28.04
Meter 1 Deviation S/N Ratio:	0.72	0.57	0.56	0.61
Meter 1 Average TDown:	477614	821752	821689	477469
Meter 1 Current TDown:	477447	821476	821445	477324
Meter 1 Maximum TDown:	477801	822098	822059	477663
Meter 1 Minimum TDown:	477432	821443	821364	477289
Meter 1 Deviation TDown:	71	122	124	71
Meter 1 Current TPTDown:	4000754	4000755	4000754	4000756
Meter 1 Average DeltaT:	2015.9	4606.8	4852.1	2446.8
Meter 1 Current DeltaT:	2040.5	4621.4	4808.8	2433.8
Meter 1 Maximum DeltaT:	2082.0	4677.9	4974.6	2541.1
Meter 1 Minimum DeltaT:	1940.4	4532.2	4740.5	2353.5
Meter 1 Deviation DeltaT:	21.3	24.8	40.5	30.8

Meter 1 Current TPDeltaT:	0.6	-1.2	-0.4	-2.0
Meter 1 Current Path Status:	NORMAL	NORMAL	NORMAL	NORMAL
Meter 1 Minimum Path Status:	FAIL	FAIL	FAIL	FAIL
Meter 1 Average Reject %:	0.4	0.5	8.0	0.8
Meter 1 Current Reject %:	1.0	0.8	8.5	0.0
Meter 1 Maximum Reject %:	25.0	25.5	31.5	26.0
Meter 1 Minimum Reject %:	0.0	0.0	0.0	0.0
Meter 1 Deviation Reject %:	1.9	1.8	2.5	1.9
Meter 1 Incoming Samples:	599	599	599	599
Meter 1 Number Failed Rejects:	0	0	0	0

Alarm Log Events

```
2001/09/07 18:11:11  Meter 1 Fail -- Path Failure
2001/09/07 18:11:11  Unit 1 FAIL
2001/09/07 18:11:27  Meter 1 Path 1 Fail (APU) -- Not Responding
2001/09/07 18:11:27  Meter 1 Path 1 Pass -- Transit Time
2001/09/07 18:11:27  Meter 1 Path 2 Fail (APU) -- Not Responding
2001/09/07 18:11:27  Meter 1 Path 2 Pass -- Transit Time
2001/09/07 18:11:27  Meter 1 Path 3 Fail (APU) -- Not Responding
2001/09/07 18:11:27  Meter 1 Path 3 Pass -- Transit Time
2001/09/07 18:11:27  Meter 1 Path 4 Fail (APU) -- Not Responding
2001/09/07 18:11:27  Meter 1 Path 4 Pass -- Transit Time
2001/09/07 18:11:32  Meter 1 NORMAL
2001/09/07 18:11:32  Unit 1 NORMAL
2001/09/07 18:11:32  Meter 1 Path 1 Pass (APU) -- Responding
2001/09/07 18:11:32  Meter 1 Path 1 NORMAL
2001/09/07 18:11:32  Meter 1 Path 2 Pass (APU) -- Responding
2001/09/07 18:11:32  Meter 1 Path 2 NORMAL
2001/09/07 18:11:32  Meter 1 Path 3 Pass (APU) -- Responding
2001/09/07 18:11:32  Meter 1 Path 3 NORMAL
2001/09/07 18:11:32  Meter 1 Path 4 Pass (APU) -- Responding
2001/09/07 18:11:32  Meter 1 Path 4 NORMAL
2001/09/07 18:21:16  Verification Test Performed
```

Watts Bar Data taken from commissioning and from plant personnel during the velocity profile alarm

Unit 1

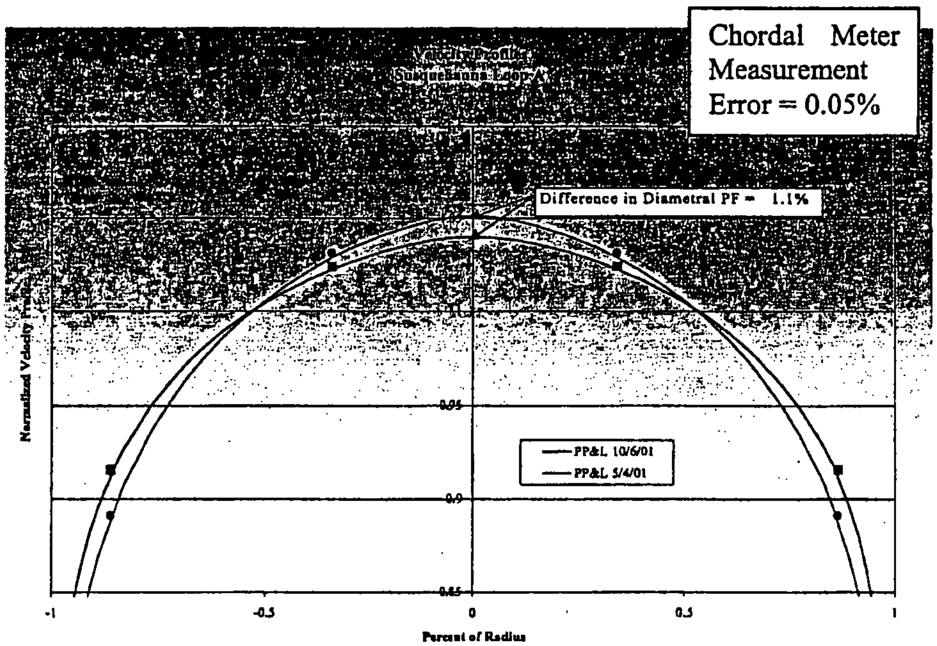
	8/29/01	9/7/01
-0.861136	0.8648	0.8186
-0.339981	1.0277	0.9972
0.33998	1.0402	1.0523
0.86114	0.8996	1.0098
S/L	0.853	0.892

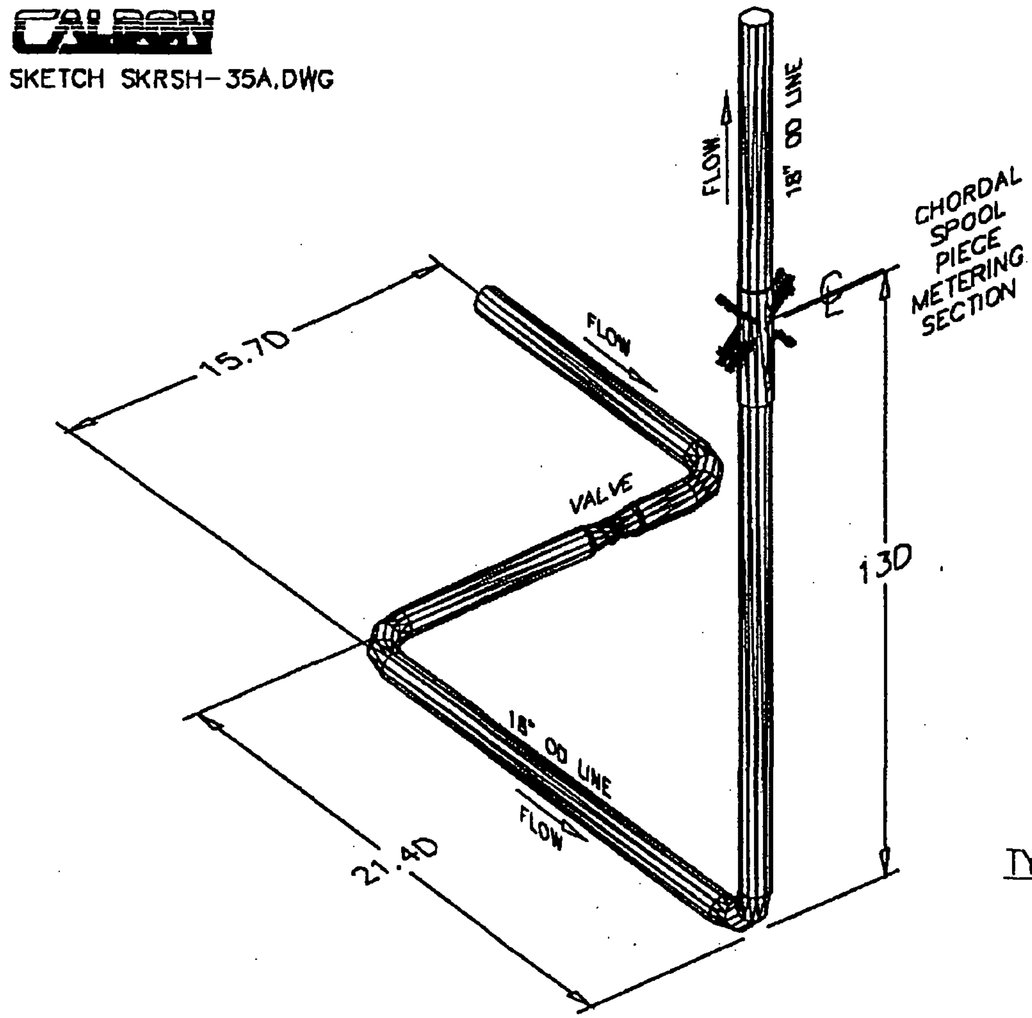
Plant Name: Susquehanna Unit 2 Loop A

Feedwater Measurement System: LEFM✓

Installation Geometry: 10 Diameters Downstream from a 90° Bend

Non-planar bend 21 Diameters Upstream





TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
PP&L SUSQUEHANNA
LOOP A

Data Received by Plant Personnel

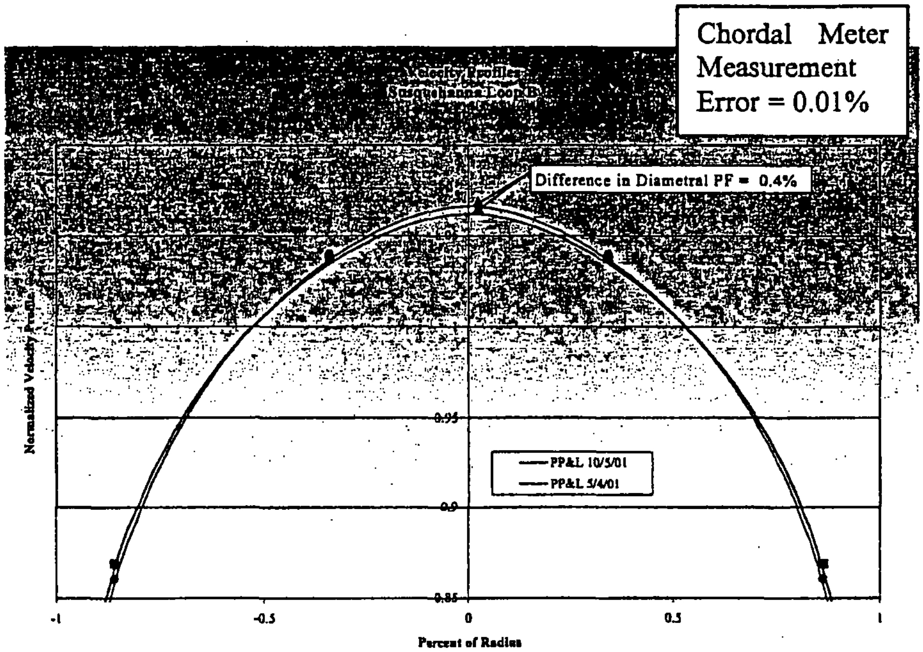
	DATE	TIME	VNORM M1, P1	VNORM M1, P2	VNORM M1, P3	VNORM M1, P4	Short Avg.	Long Avg.	S/L
133	10/6/01	12:37:04	0.931569	1.037217	1.023558	0.857652	0.894611	1.030387	0.868
134	10/6/01	13:37:09	0.95617	1.041084	1.014009	0.85275	0.90446	1.027547	0.880
135	10/6/01	14:37:14	0.981016	1.04572	1.003372	0.848733	0.914874	1.024546	0.893
136	10/6/01	15:37:19	0.983483	1.046115	1.002563	0.847688	0.915586	1.024339	0.894
137	10/6/01	16:37:24	0.976356	1.043928	1.006061	0.850263	0.91331	1.024995	0.891
138	10/6/01	17:37:30	0.972266	1.043657	1.007316	0.85096	0.911613	1.025486	0.889
139	10/6/01	19:05:03	0.939903	1.008246	0.974203	0.823093	0.881498	0.991224	0.889
140	10/6/01	20:05:09	0.971267	1.04306	1.00795	0.851826	0.911546	1.025505	0.889
141	10/6/01	21:05:14	0.970075	1.042778	1.008554	0.851899	0.910987	1.025666	0.888
142	10/6/01	22:05:19	0.968781	1.042657	1.008944	0.852263	0.910522	1.0258	0.888
143	10/6/01	23:05:24	0.968545	1.042203	1.009547	0.85198	0.910263	1.025875	0.887
144	10/7/01	0:05:29	0.968619	1.042056	1.009591	0.852257	0.910438	1.025824	0.888
145	10/7/01	1:05:35	0.967196	1.041938	1.010146	0.85217	0.909683	1.026042	0.887
146	10/7/01	2:05:40	0.966325	1.041626	1.010619	0.852474	0.9094	1.026123	0.886
147	10/7/01	3:05:45	0.966818	1.042383	1.009713	0.852497	0.909657	1.026048	0.887
148	10/7/01	4:05:50	0.967062	1.041676	1.010334	0.852551	0.909806	1.026005	0.887
149	10/7/01	5:05:55	0.963437	1.041647	1.011288	0.852982	0.908209	1.026468	0.885

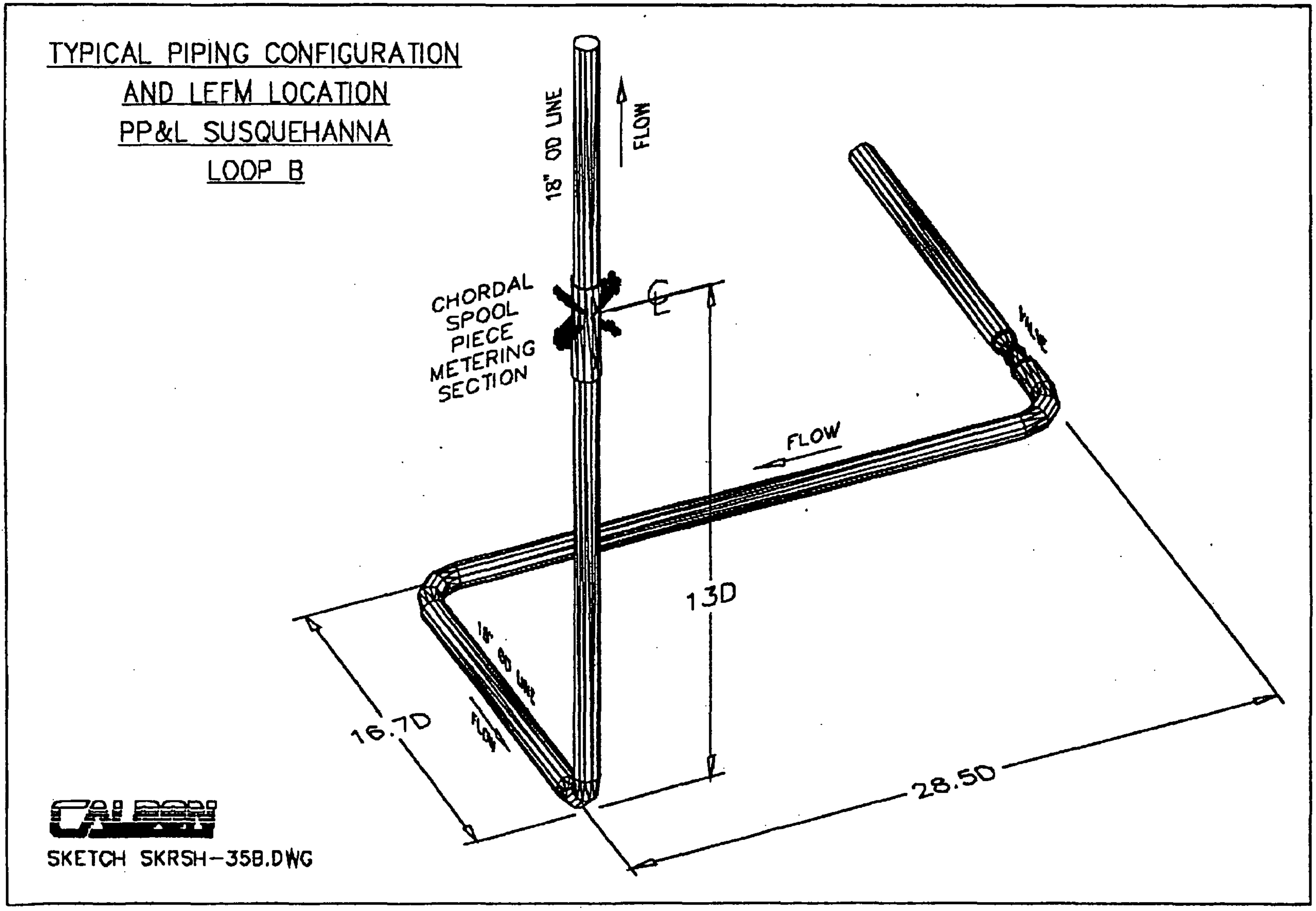
Plant Name: Susquehanna Unit 2 Loop B

Feedwater Measurement System: LEFM✓

Installation Geometry: 10 Diameters Downstream from a 90° Bend

Non-planar bend 17 Diameters Upstream




TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
PP&L SUSQUEHANNA
LOOP B
18" OD LINE
FLOW
CHORDAL
SPOOL
PIECE
METERING
SECTION
FLOW
13D
16.7D
28.5D
SKETCH SKRSH-35B.DWG

Data Received by Plant Personnel

	DATE	TIME	VNORM M2, P1	VNORM M2, P2	VNORM M2, P3	VNORM M2, P4	Short Avg.	Long Avg.	S/L
95	10/4/01	22:34:47	0.8584	1.029299	1.046331	0.87931	0.868855	1.037815	0.837
96	10/4/01	23:34:52	0.858327	1.029064	1.046604	0.879243	0.868785	1.037834	0.837
97	10/5/01	0:34:57	0.858075	1.029354	1.046389	0.879237	0.868656	1.037872	0.837
98	10/5/01	1:35:02	0.858352	1.029276	1.046372	0.879282	0.868817	1.037824	0.837
99	10/5/01	2:35:07	0.85833	1.029248	1.046464	0.879096	0.868713	1.037856	0.837
100	10/5/01	3:35:13	0.857994	1.02937	1.046337	0.879438	0.868716	1.037854	0.837
101	10/5/01	4:35:18	0.858446	1.029274	1.046358	0.879252	0.868849	1.037816	0.837
102	10/5/01	5:35:23	0.858421	1.029451	1.046229	0.879113	0.868767	1.03784	0.837
103	10/5/01	6:35:28	0.858379	1.029293	1.046403	0.879103	0.868741	1.037848	0.837
104	10/5/01	7:35:33	0.858999	1.029274	1.046164	0.879361	0.86918	1.037719	0.838
105	10/5/01	8:35:38	0.858118	1.029351	1.046412	0.879134	0.868626	1.037881	0.837
106	10/5/01	9:34:44	0.857948	1.029428	1.046339	0.879293	0.868621	1.037883	0.837
107	10/5/01	10:34:49	0.858131	1.029239	1.046535	0.87908	0.868606	1.037887	0.837
108	10/5/01	11:34:54	0.858522	1.029101	1.046441	0.879489	0.869005	1.037771	0.837
109	10/5/01	12:34:59	0.85829	1.029324	1.04635	0.879256	0.868773	1.037837	0.837
110	10/5/01	13:35:04	0.858456	1.029479	1.046244	0.878926	0.868691	1.037861	0.837

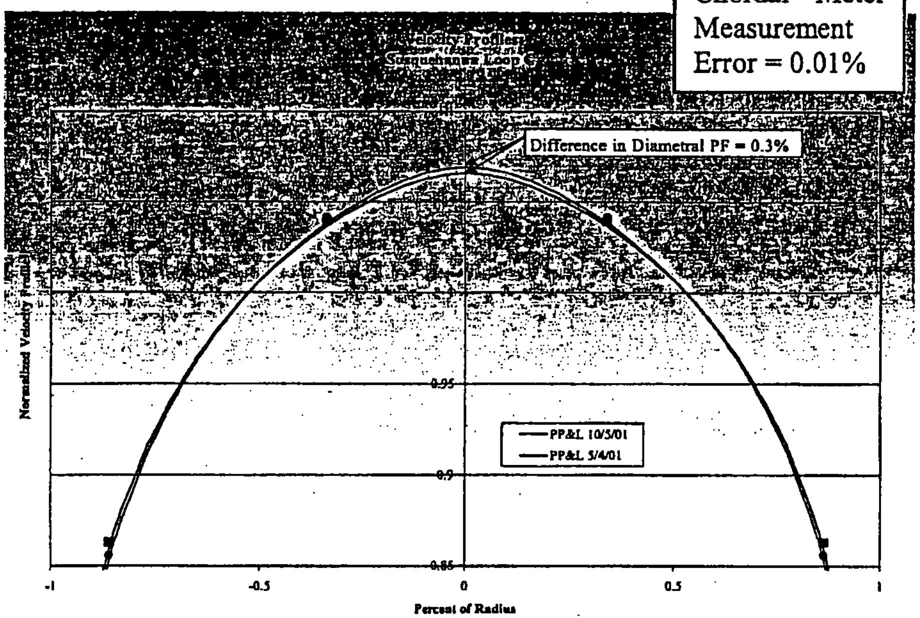
Plant Name: Susquehanna Unit 2 Loop C

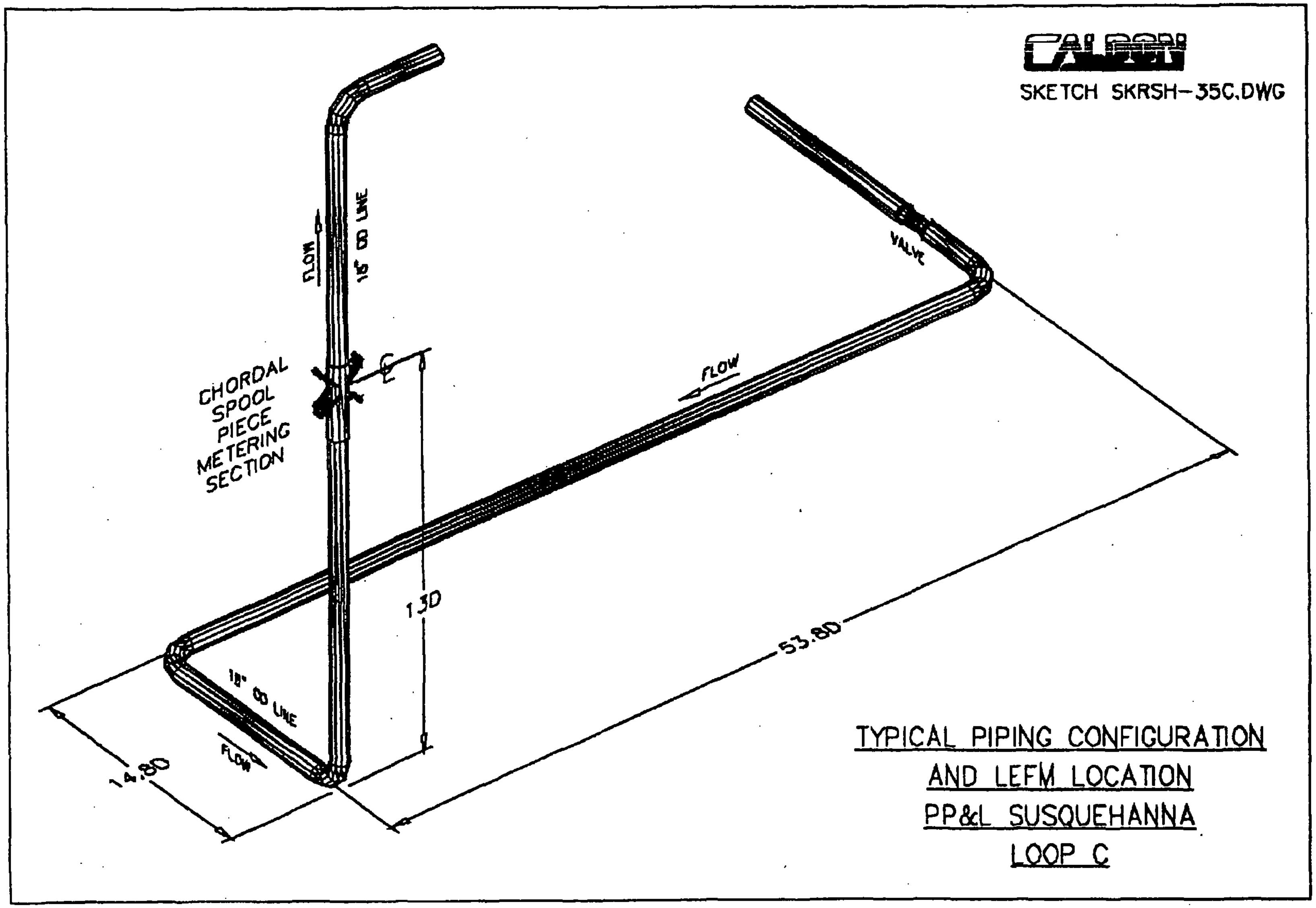
Feedwater Measurement System: LEFM✓

Installation Geometry: 10 Diameters Downstream from a 90° Bend

Non-planar bend 17 Diameters Upstream

Chordal Meter Measurement Error = 0.01%




SKETCH SKRSH-35C.DWG
FLOW
18" OD LINE
VALVE
FLOW
CHORDAL SPOOL PIECE METERING SECTION
13D
53.8D
18" OD LINE
FLOW
14.8D
TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
PP&L SUSQUEHANNA
LOOP C

Data Received by Plant Personnel

	DATE	TIME	VNORM M3, P1	VNORM M3, P2	VNORM M3, P3	VNORM M3, P4	Short Avg.	Long Avg.	S/L
109	10/5/01	12:34:59	0.870465	1.030248	1.0488	0.855393	0.862929	1.039524	0.830
110	10/5/01	13:35:04	0.869863	1.030256	1.048903	0.855594	0.862729	1.039579	0.830
111	10/5/01	14:35:10	0.869964	1.030384	1.048817	0.855356	0.86266	1.039601	0.830
112	10/5/01	15:35:15	0.870409	1.030193	1.048877	0.855363	0.862886	1.039535	0.830
113	10/5/01	16:35:20	0.869652	1.030225	1.049009	0.855552	0.862602	1.039617	0.830
114	10/5/01	17:35:25	0.86979	1.030176	1.048998	0.855629	0.86271	1.039587	0.830
115	10/5/01	18:35:30	0.869946	1.03033	1.048979	0.855002	0.862474	1.039654	0.830
116	10/5/01	19:35:35	0.870376	1.030603	1.048459	0.855435	0.862905	1.039531	0.830
117	10/5/01	20:35:41	0.869924	1.030366	1.048768	0.855638	0.862781	1.039567	0.830
118	10/5/01	21:35:46	0.870015	1.030551	1.048605	0.855456	0.862735	1.039578	0.830
119	10/5/01	22:35:51	0.870349	1.03016	1.049047	0.854947	0.862648	1.039603	0.830
120	10/5/01	23:35:56	0.87075	1.030298	1.048586	0.855666	0.863208	1.039442	0.830
121	10/6/01	0:36:01	0.870223	1.030536	1.0486	0.855323	0.862773	1.039568	0.830
122	10/6/01	1:36:07	0.869851	1.030667	1.048538	0.855451	0.862651	1.039603	0.830
123	10/6/01	2:36:12	0.869714	1.030353	1.048966	0.855188	0.862451	1.039659	0.830
124	10/6/01	3:36:17	0.870174	1.030264	1.048833	0.85551	0.862842	1.039548	0.830
125	10/6/01	4:36:22	0.870365	1.030263	1.048813	0.855385	0.862875	1.039538	0.830

Susquehanna Unit 2 12:09:22 2001/05/04

Configuration Files

ALARM.INI	2001/05/04	11:46:46	FFFF5F6D
FAT.INI	2001/04/16	20:54:32	FFFF04A7
HYDRAULI.INI	2001/05/04	11:45:52	FFFF94D7
METER.INI	2001/05/03	16:47:26	FFFD2091
PARAMETR.INI	2001/04/24	15:06:08	FFFC6D3D
P_CONFIG.INI	2001/05/03	16:01:44	FFFEA975
PROPERTY.INI	2001/04/16	21:17:40	FFFFEC75
SETUP.INI	2001/05/04	11:41:54	FFFEE167

Setup Files

Setapu1.txt	2001/05/03	08:40:10	FFFE17FD
Setapu2.txt	2001/05/03	10:13:30	FFFE17FD
Setapu3.txt	2001/05/03	08:40:48	FFFE17F7
Setapu4.txt	2001/04/16	21:46:14	FFFE18E7

Susquehanna Unit 2 Current Flow:	71.18
Susquehanna Unit 2 Average Flow:	71.17
Susquehanna Unit 2 Maximum Flow:	71.24
Susquehanna Unit 2 Minimum Flow:	71.08
Susquehanna Unit 2 Deviation Flow:	0.04

Susquehanna Unit 2 Current Temp:	385.8
Susquehanna Unit 2 Average Temp:	385.7
Susquehanna Unit 2 Maximum Temp:	385.8
Susquehanna Unit 2 Minimum Temp:	370.0
Susquehanna Unit 2 Deviation Temp:	1.0

Susquehanna Unit 2 Current System Status:	NORMAL
Susquehanna Unit 2 Minimum System Status:	FAIL

Susquehanna Unit 2 Current Mass Flow:	13.970
Susquehanna Unit 2 Average Mass Flow:	13.968
Susquehanna Unit 2 Maximum Mass Flow:	14.111
Susquehanna Unit 2 Minimum Mass Flow:	13.950
Susquehanna Unit 2 Deviation Mass Flow:	0.012

Susquehanna Unit 2 Uncertainty: 0.03

Meter 1 Current Flow:	23.66
Meter 1 Average Flow:	23.68
Meter 1 Maximum Flow:	23.77
Meter 1 Minimum Flow:	23.61
Meter 1 Deviation Flow:	0.04

Meter 2 Current Flow:	23.81
Meter 2 Average Flow:	23.84
Meter 2 Maximum Flow:	23.94
Meter 2 Minimum Flow:	23.75
Meter 2 Deviation Flow:	0.05

Meter 3 Current Flow:	23.71
Meter 3 Average Flow:	23.65
Meter 3 Maximum Flow:	23.82
Meter 3 Minimum Flow:	23.47

Meter 3 Deviation Flow:	0.09
Meter 1 Current Temp:	387.1
Meter 1 Average Temp:	387.0
Meter 1 Maximum Temp:	387.1
Meter 1 Minimum Temp:	371.3
Meter 1 Deviation Temp:	1.0
Meter 2 Current Temp:	385.4
Meter 2 Average Temp:	385.4
Meter 2 Maximum Temp:	385.5
Meter 2 Minimum Temp:	369.6
Meter 2 Deviation Temp:	1.0
Meter 3 Current Temp:	384.8
Meter 3 Average Temp:	384.8
Meter 3 Maximum Temp:	384.9
Meter 3 Minimum Temp:	369.0
Meter 3 Deviation Temp:	1.0
Meter 1 Current Press:	1105.00
Meter 1 Average Press:	1002.21
Meter 1 Maximum Press:	1105.00
Meter 1 Minimum Press:	0.00
Meter 1 Deviation Press:	1.03
Meter 2 Current Press:	1106.10
Meter 2 Average Press:	1003.21
Meter 2 Maximum Press:	1106.10
Meter 2 Minimum Press:	0.00
Meter 2 Deviation Press:	1.03
Meter 3 Current Press:	1104.40
Meter 3 Average Press:	1001.67
Meter 3 Maximum Press:	1104.40
Meter 3 Minimum Press:	0.00
Meter 3 Deviation Press:	1.03
Meter 1 Current Meter Status:	NORMAL
Meter 1 Minimum Meter Status:	FAIL
Meter 2 Current Meter Status:	NORMAL
Meter 2 Minimum Meter Status:	FAIL
Meter 3 Current Meter Status:	NORMAL
Meter 3 Minimum Meter Status:	FAIL
Meter 1 Current Mass Flow:	4.639
Meter 1 Average Mass Flow:	4.643
Meter 1 Maximum Mass Flow:	4.693
Meter 1 Minimum Mass Flow:	4.629
Meter 1 Deviation Mass Flow:	0.009
Meter 2 Current Mass Flow:	4.675
Meter 2 Average Mass Flow:	4.679
Meter 2 Maximum Mass Flow:	4.729
Meter 2 Minimum Mass Flow:	4.662

Meter 2 Deviation Mass Flow:	0.010			
Meter 3 Current Mass Flow:	4.656			
Meter 3 Average Mass Flow:	4.645			
Meter 3 Maximum Mass Flow:	4.689			
Meter 3 Minimum Mass Flow:	4.609			
Meter 3 Deviation Mass Flow:	0.018			
Meter 1 Uncertainty:	0.06			
Meter 2 Uncertainty:	0.04			
Meter 3 Uncertainty:	0.04			
	Path 1	Path 2	Path 3	Path 4
Meter 1 Current Variance:	10611.80	9480.00	6556.76	2452.37
Meter 2 Current Variance:	2306.92	3502.04	3445.44	2121.49
Meter 3 Current Variance:	2339.39	3411.16	3430.44	2677.44
Meter 1 Average Vnorm:	0.9309	1.0403	1.0224	0.8519
Meter 1 Current Vnorm:	0.9300	1.0380	1.0243	0.8541
Meter 1 Maximum Vnorm:	0.9395	1.0425	1.0251	0.8547
Meter 1 Minimum Vnorm:	0.9220	1.0380	1.0197	0.8487
Meter 1 Deviation Vnorm:	0.003	0.001	0.001	0.002
Meter 1 Benchmark Vnorm:	0.9301	1.0399	1.0229	0.8520
Meter 1 Limit % Vnorm:	0.50	0.50	0.50	0.50
Meter 2 Average Vnorm:	0.8524	1.0315	1.0490	0.8685
Meter 2 Current Vnorm:	0.8543	1.0315	1.0479	0.8703
Meter 2 Maximum Vnorm:	0.8551	1.0328	1.0500	0.8712
Meter 2 Minimum Vnorm:	0.8503	1.0300	1.0477	0.8663
Meter 2 Deviation Vnorm:	0.001	0.001	0.000	0.001
Meter 2 Benchmark Vnorm:	0.8522	1.0316	1.0490	0.8684
Meter 2 Limit % Vnorm:	0.50	0.50	0.50	0.50
Meter 3 Average Vnorm:	0.8616	1.0324	1.0507	0.8500
Meter 3 Current Vnorm:	0.8602	1.0330	1.0505	0.8504
Meter 3 Maximum Vnorm:	0.8651	1.0342	1.0520	0.8533
Meter 3 Minimum Vnorm:	0.8580	1.0311	1.0495	0.8468
Meter 3 Deviation Vnorm:	0.002	0.001	0.001	0.002
Meter 3 Benchmark Vnorm:	0.8616	1.0326	1.0506	0.8500
Meter 3 Limit % Vnorm:	0.50	0.50	0.50	0.50
Meter 1 Average Gain:	46.85	50.73	51.38	46.50
Meter 1 Current Gain:	46.89	50.72	51.34	46.61
Meter 1 Maximum Gain:	46.94	50.79	51.46	46.62
Meter 1 Minimum Gain:	46.77	50.67	51.32	46.43
Meter 1 Deviation Gain:	0.04	0.03	0.03	0.03
Meter 1 Limit Gain:	76.00	76.00	76.00	76.00
Meter 1 Current Gain Up:	45.85	50.70	51.49	45.69
Meter 1 Current Gain Down:	47.79	50.55	51.02	47.48
Meter 1 Current TPGain Up:	64.13	63.82	63.97	64.13
Meter 1 Current TPGain Down:	63.82	63.82	63.82	63.97
Meter 2 Average Gain:	44.93	48.41	47.81	48.25

Meter 2 Current Gain:	44.93	48.43	47.79	48.29
Meter 2 Maximum Gain:	44.98	48.46	47.86	48.32
Meter 2 Minimum Gain:	44.88	48.37	47.77	48.19
Meter 2 Deviation Gain:	0.02	0.02	0.02	0.03
Meter 2 Limit Gain:	76.00	76.00	76.00	76.00
Meter 2 Current Gain Up:	44.28	48.58	48.10	47.95
Meter 2 Current Gain Down:	45.38	48.10	47.32	48.42
Meter 2 Current TPGain Up:	63.97	63.97	63.82	63.97
Meter 2 Current TPGain Down:	63.82	63.82	63.66	63.66
Meter 3 Average Gain:	44.20	48.55	47.08	43.29
Meter 3 Current Gain:	44.28	48.56	47.09	43.23
Meter 3 Maximum Gain:	44.28	48.63	47.16	43.40
Meter 3 Minimum Gain:	44.08	48.46	46.93	43.21
Meter 3 Deviation Gain:	0.04	0.03	0.06	0.05
Meter 3 Limit Gain:	76.00	76.00	76.00	76.00
Meter 3 Current Gain Up:	43.50	48.73	47.48	42.87
Meter 3 Current Gain Down:	44.91	48.26	46.54	43.50
Meter 3 Current TPGain Up:	63.66	63.82	63.50	63.66
Meter 3 Current TPGain Down:	63.66	63.66	63.50	63.82
Meter 1 Average S/N Ratio:	97.20	97.09	96.51	96.22
Meter 1 Current S/N Ratio:	97.52	97.26	96.48	95.99
Meter 1 Maximum S/N Ratio:	97.70	97.38	96.84	96.75
Meter 1 Minimum S/N Ratio:	95.13	94.84	94.47	94.85
Meter 1 Deviation S/N Ratio:	0.33	0.32	0.30	0.28
Meter 2 Average S/N Ratio:	87.80	90.28	88.97	86.87
Meter 2 Current S/N Ratio:	87.98	88.75	87.07	86.46
Meter 2 Maximum S/N Ratio:	92.00	95.06	93.49	92.23
Meter 2 Minimum S/N Ratio:	84.45	88.25	86.37	84.25
Meter 2 Deviation S/N Ratio:	1.44	1.48	1.30	1.41
Meter 3 Average S/N Ratio:	18.97	56.05	41.71	15.81
Meter 3 Current S/N Ratio:	19.28	57.13	43.11	15.80
Meter 3 Maximum S/N Ratio:	19.69	57.34	43.59	16.24
Meter 3 Minimum S/N Ratio:	18.18	53.56	39.98	15.39
Meter 3 Deviation S/N Ratio:	0.30	0.63	0.88	0.16
Meter 1 Average TDown:	244697	395163	395068	244698
Meter 1 Current TDown:	244696	395164	395064	244696
Meter 1 Maximum TDown:	244713	395189	395094	244713
Meter 1 Minimum TDown:	244683	395142	395049	244687
Meter 1 Deviation TDown:	6	10	10	5
Meter 1 Current TPTDown:	4500555	4500554	4500554	4500556
Meter 2 Average TDown:	244412	394581	394223	244057
Meter 2 Current TDown:	244411	394583	394227	244057
Meter 2 Maximum TDown:	244427	394605	394247	244071
Meter 2 Minimum TDown:	244398	394556	394201	244044
Meter 2 Deviation TDown:	7	11	11	6
Meter 2 Current TPTDown:	4500594	4500596	4500599	4500595
Meter 3 Average TDown:	243956	393939	394092	243980
Meter 3 Current TDown:	243952	393929	394083	243975
Meter 3 Maximum TDown:	243967	393962	394113	243993
Meter 3 Minimum TDown:	243944	393920	394074	243968

Meter 3 Deviation TDown:	7	12	11	7
Meter 3 Current TPTDown:	4500464	4500468	4500464	4500462
Meter 1 Average DeltaT:	1135.4	2346.7	2307.8	1043.4
Meter 1 Current DeltaT:	1133.2	2339.3	2310.0	1045.0
Meter 1 Maximum DeltaT:	1146.3	2355.9	2321.6	1049.8
Meter 1 Minimum DeltaT:	1126.9	2338.6	2299.8	1039.2
Meter 1 Deviation DeltaT:	4.3	5.0	4.7	2.7
Meter 1 Current TPDeltaT:	-0.6	2.2	2.2	-0.6
Meter 2 Average DeltaT:	1043.2	2315.6	2352.7	1047.8
Meter 2 Current DeltaT:	1044.5	2313.6	2348.0	1048.9
Meter 2 Maximum DeltaT:	1048.5	2324.6	2363.7	1053.5
Meter 2 Minimum DeltaT:	1038.3	2308.0	2343.4	1043.6
Meter 2 Deviation DeltaT:	2.2	4.4	5.2	2.5
Meter 2 Current TPDeltaT:	-2.9	-0.9	-3.8	-1.1
Meter 3 Average DeltaT:	1041.0	2306.7	2349.4	1031.1
Meter 3 Current DeltaT:	1041.8	2313.5	2354.8	1034.1
Meter 3 Maximum DeltaT:	1052.6	2322.7	2367.0	1039.6
Meter 3 Minimum DeltaT:	1034.5	2287.3	2332.7	1021.2
Meter 3 Deviation DeltaT:	4.2	9.4	8.7	4.9
Meter 3 Current TPDeltaT:	0.4	-4.2	2.2	-2.2
Meter 1 Current Path Status:	NORMAL	NORMAL	NORMAL	NORMAL
Meter 1 Minimum Path Status:	FAIL	FAIL	FAIL	FAIL
Meter 2 Current Path Status:	NORMAL	NORMAL	NORMAL	NORMAL
Meter 2 Minimum Path Status:	FAIL	FAIL	FAIL	FAIL
Meter 3 Current Path Status:	NORMAL	NORMAL	NORMAL	NORMAL
Meter 3 Minimum Path Status:	FAIL	FAIL	FAIL	FAIL
Meter 1 Average Reject %:	0.1	0.1	0.1	0.1
Meter 1 Current Reject %:	0.0	0.0	0.0	0.0
Meter 1 Maximum Reject %:	4.2	4.2	4.2	4.2
Meter 1 Minimum Reject %:	0.0	0.0	0.0	0.0
Meter 1 Deviation Reject %:	0.5	0.5	0.5	0.5
Meter 1 Incoming Samples:	258	258	258	258
Meter 1 Number Failed Rejects:	0	0	0	0
Meter 2 Average Reject %:	0.0	0.0	0.0	0.0
Meter 2 Current Reject %:	0.0	0.0	0.0	0.0
Meter 2 Maximum Reject %:	0.0	0.0	0.0	0.0
Meter 2 Minimum Reject %:	0.0	0.0	0.0	0.0
Meter 2 Deviation Reject %:	0.0	0.0	0.0	0.0
Meter 2 Incoming Samples:	258	258	258	258
Meter 2 Number Failed Rejects:	0	0	0	0
Meter 3 Average Reject %:	0.0	0.0	0.0	0.1
Meter 3 Current Reject %:	0.0	0.0	0.0	0.0
Meter 3 Maximum Reject %:	0.0	0.0	0.0	0.3
Meter 3 Minimum Reject %:	0.0	0.0	0.0	0.0
Meter 3 Deviation Reject %:	0.0	0.0	0.0	0.1
Meter 3 Incoming Samples:	258	258	258	258
Meter 3 Number Failed Rejects:	0	0	0	0

```
DEFAULTCFRATIO1:,1.0000,0.9999,1.0003,0.9998
DEFAULTCFRATIO2:,1.0003,1.0000,0.9999,0.9999
DEFAULTCFRATIO3:,1.0002,1.0000,1.0000,0.9999

DEFAULTVELOCITY1:,0.9328,1.0400,1.0217,0.8531
DEFAULTVELOCITY2:,0.8533,1.0311,1.0489,0.8690
DEFAULTVELOCITY3:,0.8632,1.0323,1.0502,0.8507

SOUNDVELOCITYNOM1:,50300
SOUNDVELOCITYNOM2:,50300
SOUNDVELOCITYNOM3:,50300

PROFILEFACTORCOEFA01:,1.0038E+000
PROFILEFACTORCOEFA02:,1.0101E+000
PROFILEFACTORCOEFA03:,1.0068E+000

MAXN:,720
```

PP&L Unit 2 Data taken from commissioning and from plant personnel during the velocity profile alarm

Meter 1	5/4/01	10/6/01
-0.861136	0.9310	0.9510
-0.339981	1.0403	1.0391
0.33998	1.0223	1.0167
0.86114	0.8519	0.8555
S/L	0.864	0.879

Meter 2	5/4/01	10/5/01
-0.861136	0.8524	0.8581
-0.339981	1.0315	1.0295
0.33998	1.0490	1.0463
0.86114	0.8685	0.8793
S/L	0.827	0.837

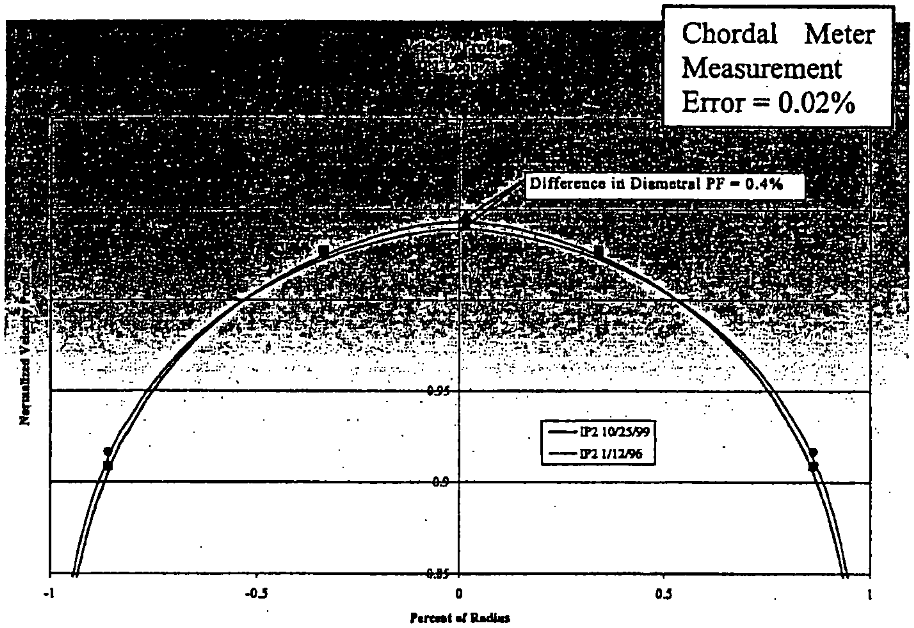
Meter 3	5/4/01	10/5/01
-0.861136	0.8617	0.8703
-0.339981	1.0324	1.0304
0.33998	1.0507	1.0488
0.86114	0.8500	0.8551
S/L	0.822	0.830

Plant Name: Indian Point Unit 2 Loop 21

Feedwater Measurement System: LEFM✓

Installation Geometry: 10 Diameters Downstream from a 90° Elbow

Non-planar bend 10 Diameters Upstream

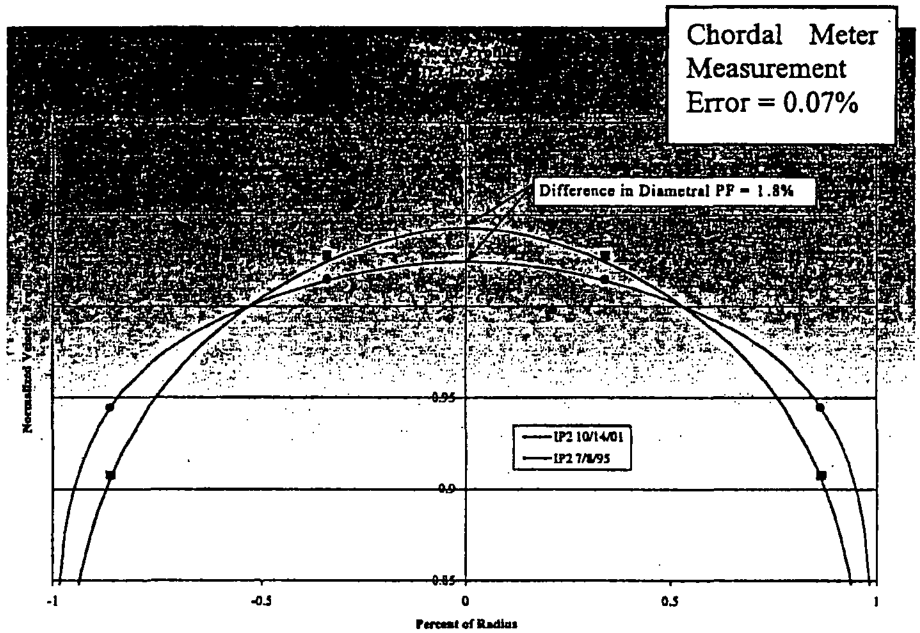


Plant Name: Indian Point Unit 2 Loop 22

Feedwater Measurement System: LEFM✓

Installation Geometry: 12 Diameters Downstream from a 90° Elbow

Non-planar bend 10 Diameters Upstream

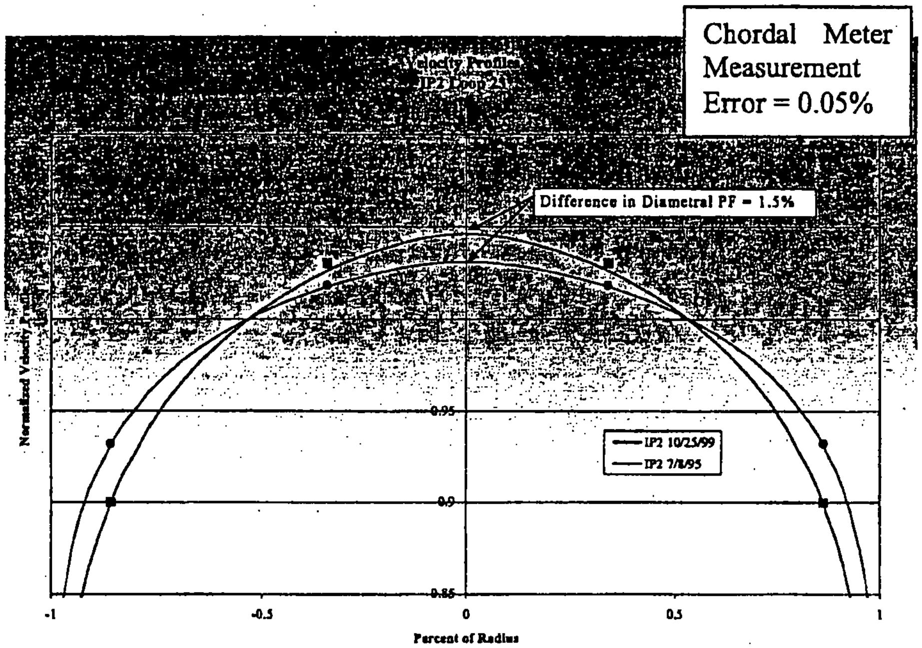


Plant Name: Indian Point Unit 2 Loop 23

Feedwater Measurement System: LEFM✓

Installation Geometry: 15 Diameters Downstream from a 90° Elbow

Non-planar bend 10 Diameters Upstream

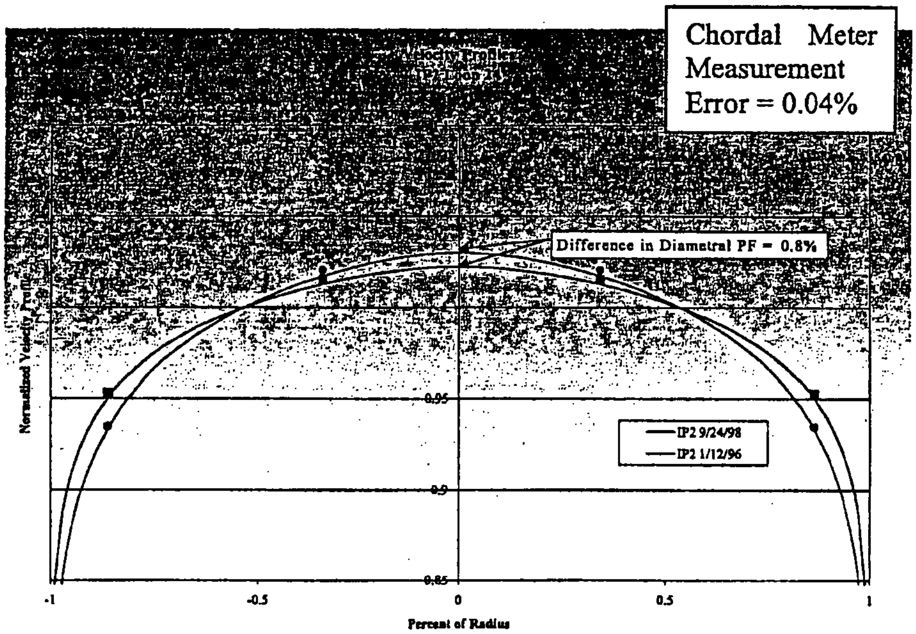


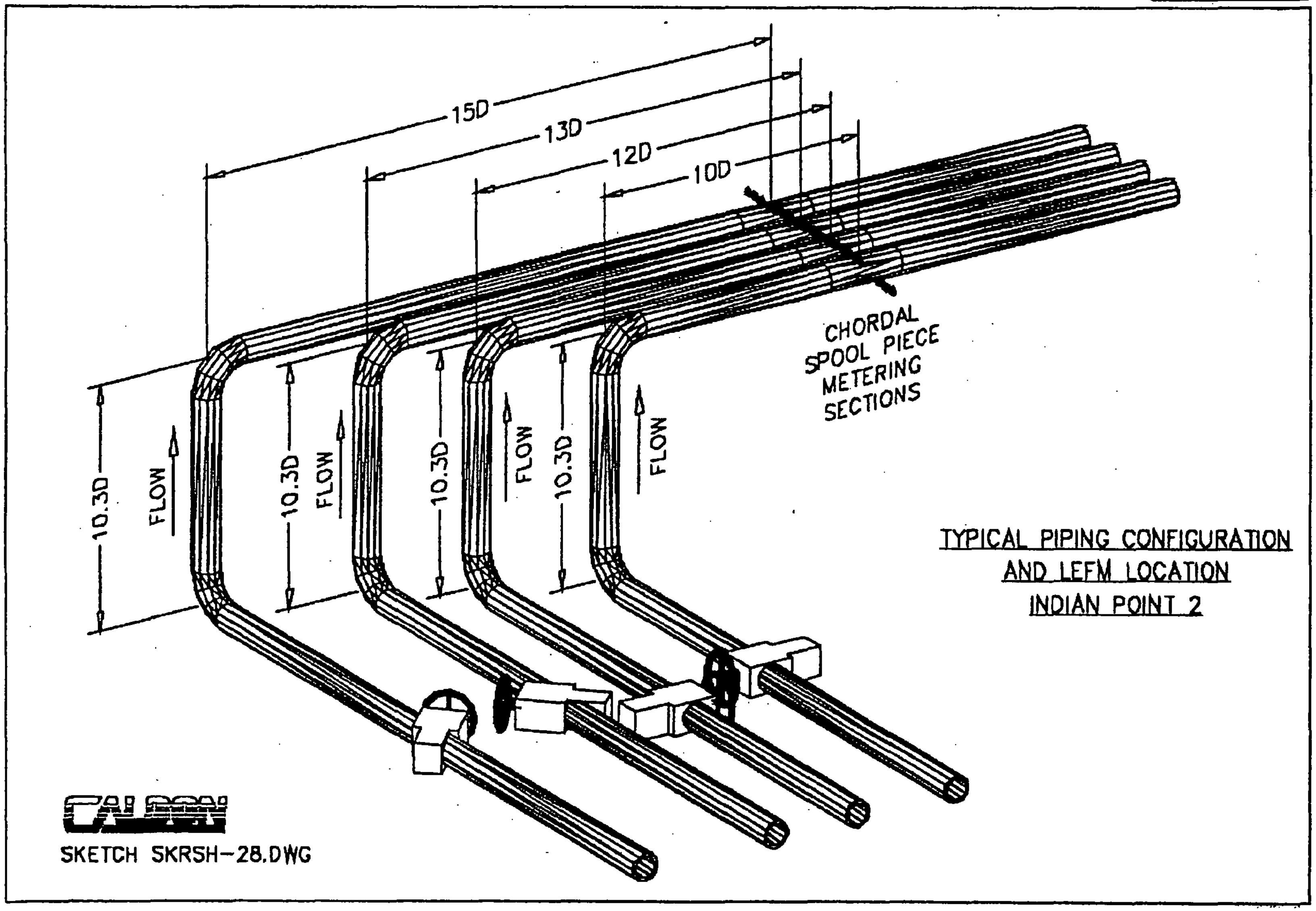
Plant Name: Indian Point Unit 2 Loop 24

Feedwater Measurement System: LEFM✓

Installation Geometry: 13 Diameters Downstream from a 90° Elbow

Non-planar bend 10 Diameters Upstream




15D
13D
12D
10D
CHORDAL
SPOOL PIECE
METERING
SECTIONS
10.3D
FLOW
10.3D
FLOW
10.3D
FLOW
10.3D
FLOW
TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
INDIAN POINT 2
SKETCH SKRSH-28.DWG

Indian Point 2 Data taken from trip reports and commissioning data

Loop 21	7/8/95	1/12/96	9/24/98	10/25/99	10/14/01
-0.861136	0.9834	1.0372	0.9099	0.8412	0.8763
-0.339981	1.0534	1.0837	1.0229	0.9868	1.0070
0.33998	0.9937	0.9671	1.0323	1.0684	1.0503
0.86114	0.8445	0.7954	0.9077	0.9762	0.9468
S/L	0.893	0.894	0.884	0.884	0.886

Loop 22	7/8/95	1/12/96	9/24/98	10/25/99	10/14/01
-0.861136	0.8920	0.8805	0.8943	0.8822	0.8744
-0.339981	0.9978	0.9933	1.0065	1.0053	1.0144
0.33998	1.0315	1.0535	1.0359	1.0460	1.0411
0.86114	0.9974	0.9661	0.9675	0.9489	0.9411
S/L	0.931	0.902	0.912	0.893	0.883

Loop 23	7/8/95	1/12/96	9/24/98	10/25/99	10/14/01
-0.861136	0.8783	0.8845	0.8122	0.7453	0.7813
-0.339981	1.0019	1.0058	0.9925	0.9696	0.9711
0.33998	1.0345	1.0379	1.0496	1.0907	1.0847
0.86114	0.9865	0.9727	1.0508	1.0543	1.0328
S/L	0.916	0.909	0.912	0.873	0.882

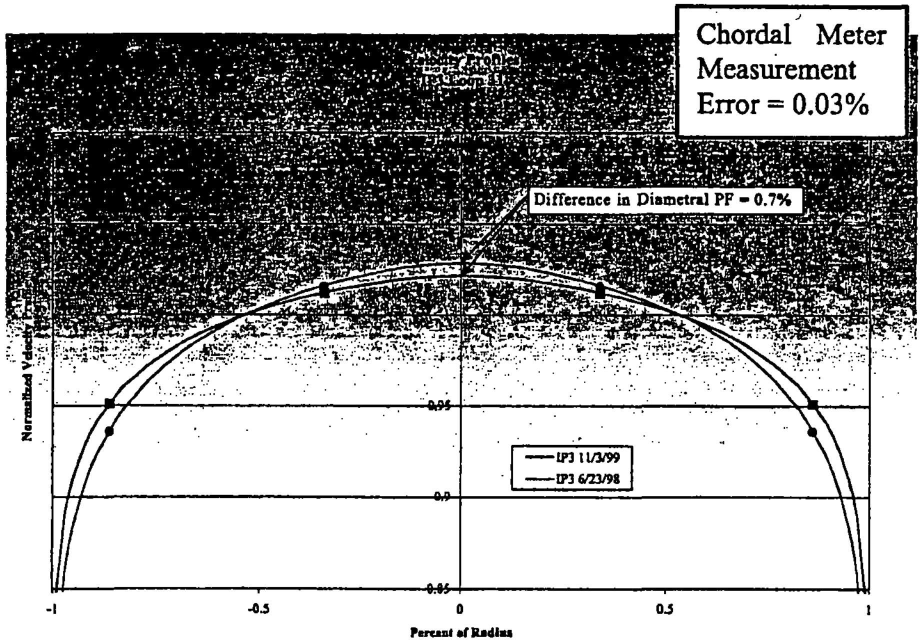
Loop 24	7/8/95	1/12/96	9/24/98	10/25/99	10/14/01
-0.861136	0.8257	0.8087	0.8679	0.8840	0.8822
-0.339981	0.9733	0.9726	0.9801	0.9972	1.0042
0.33998	1.0594	1.0675	1.0498	1.0390	1.0285
0.86114	1.0520	1.0611	1.0375	0.9997	0.9964
S/L	0.924	0.917	0.939	0.925	0.924

Plant Name: Indian Point Unit 3 Loop 31

Feedwater Measurement System: LEFM✓

Installation Geometry: 5.8 Diameters Downstream from a 90° Elbow

Non-planar bend 10 Diameters Upstream

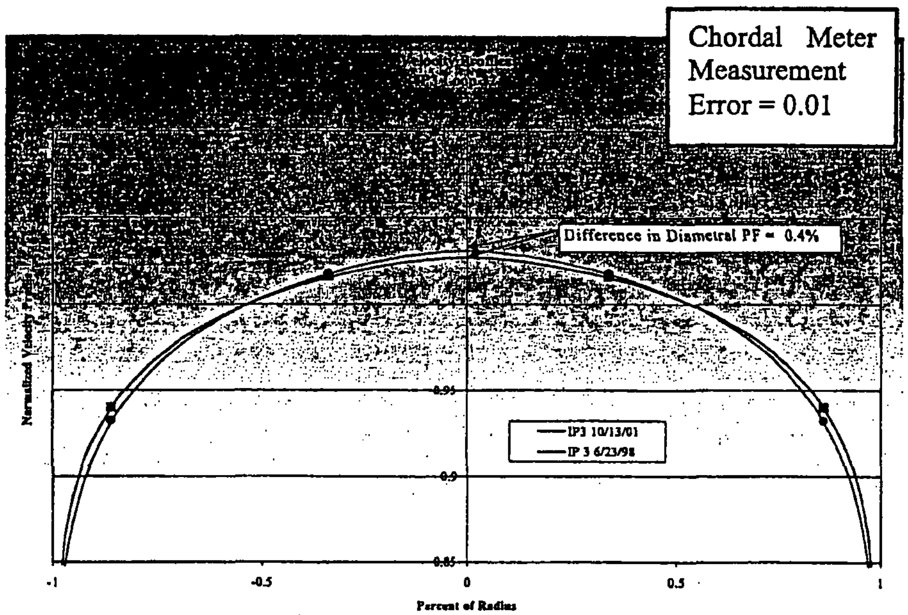


Plant Name: Indian Point Unit 3 Loop 32

Feedwater Measurement System: LEFM✓

Installation Geometry: 5.8 Diameters Downstream from a 90° Elbow

Non-planar bend 10 Diameters Upstream

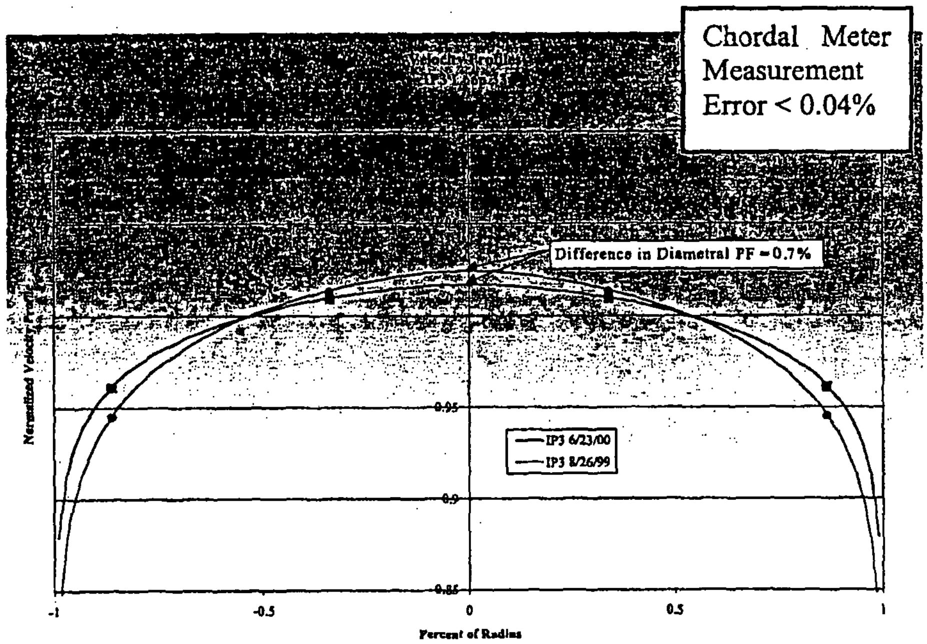


Plant Name: Indian Point Unit 3 Loop 33

Feedwater Measurement System: LEFM✓

Installation Geometry: 5.8 Diameters Downstream from a 90° Elbow

Non-planar bend 10 Diameters Upstream

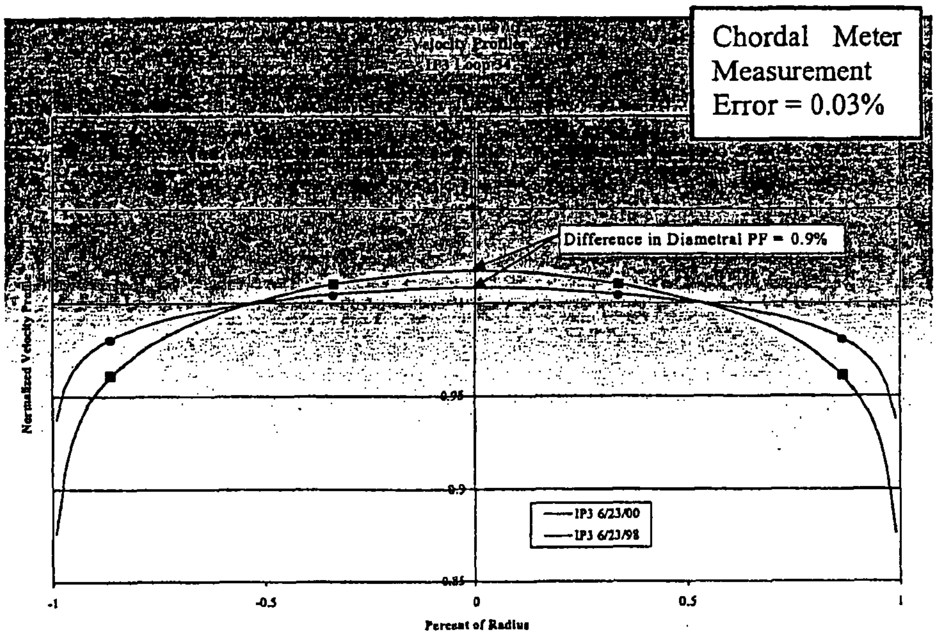


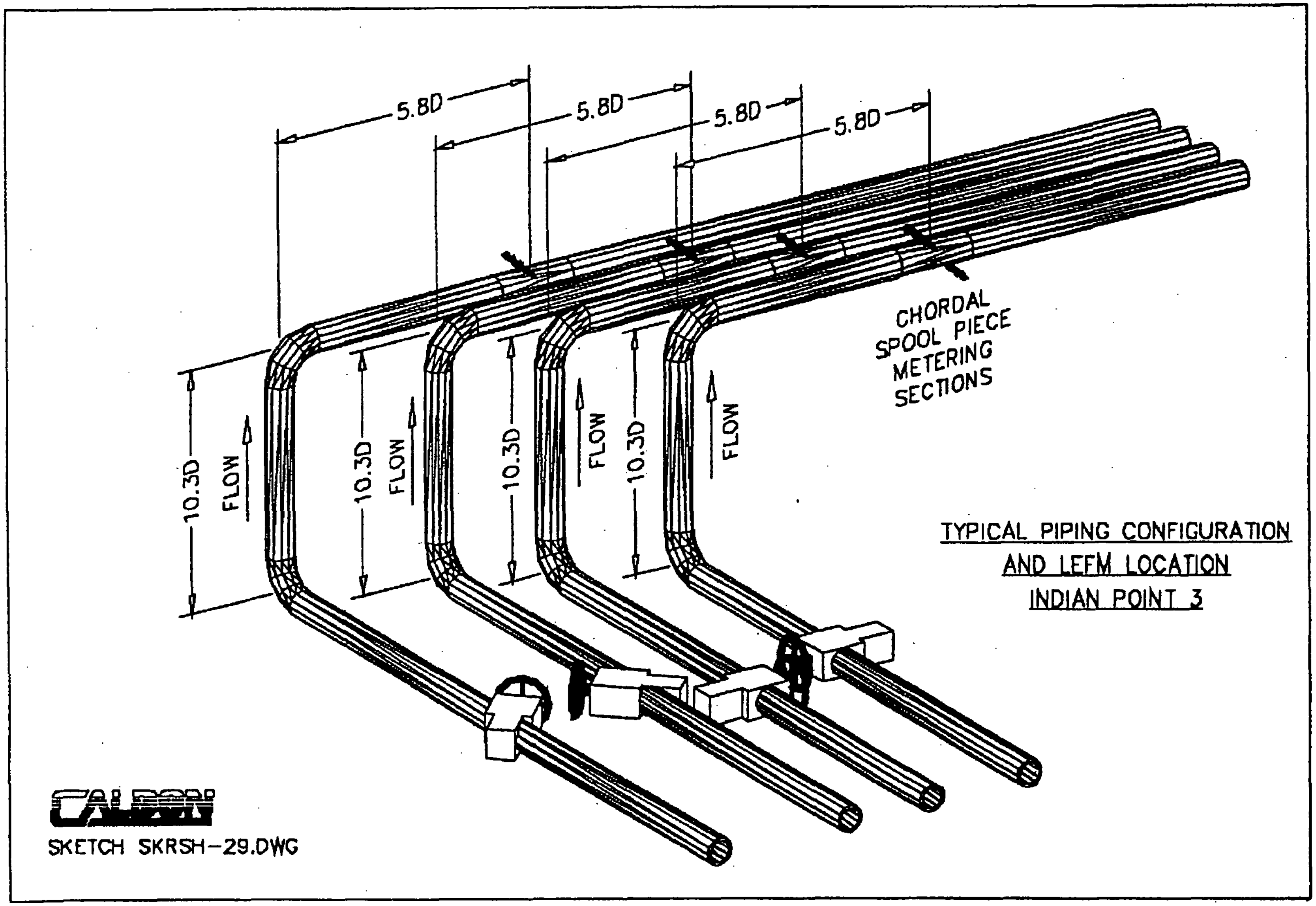
Plant Name: Indian Point Unit 3 Loop 34

Feedwater Measurement System: LEFM✓

Installation Geometry: 5.8 Diameters Downstream from a 90° Elbow

Non-planar bend 10 Diameters Upstream




5.8D
5.8D
5.8D
5.8D
10.3D
10.3D
10.3D
10.3D
FLOW
FLOW
FLOW
FLOW
CHORDAL
SPOOL PIECE
METERING
SECTIONS
TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
INDIAN POINT 3
CALDON
SKETCH SKRSH-29.DWG

Indian Point 3 Data from remote monitoring program - found under LEFMLOGS

Loop 31	6/23/98	8/26/99	11/3/99	6/23/00	12/10/00	6/21/01	10/13/01
-0.861136	0.906	0.898	0.942	0.895	0.898	0.894	0.891
-0.339981	0.999	0.991	0.990	0.995	0.988	1.003	0.999
0.33998	1.034	1.037	1.034	1.032	1.039	1.030	1.034
0.86114	0.966	0.990	0.960	0.990	0.993	0.979	0.981
S/L	0.921	0.931	0.940	0.930	0.933	0.921	0.921

Loop 32	6/23/98	8/26/99	11/3/99	6/23/00	12/10/00	6/21/01	10/13/01
-0.861136	0.846	0.849	0.845	0.838	0.847	0.845	0.851
-0.339981	0.978	0.979	0.983	0.976	0.978	0.980	0.982
0.33998	1.057	1.054	1.050	1.058	1.055	1.053	1.049
0.86114	1.018	1.028	1.028	1.031	1.023	1.025	1.028
S/L	0.916	0.923	0.921	0.919	0.920	0.920	0.925

Loop 33	6/23/98	8/26/99	11/3/99	6/23/00	12/10/00	6/21/01	10/13/01
-0.861136	0.992	0.982	1.024	0.996	0.981	0.968	1.000
-0.339981	1.028	1.030	1.049	1.018	1.012	1.019	1.036
0.33998	0.998	0.996	0.979	1.000	1.009	1.006	0.991
0.86114	0.902	0.907	0.868	0.925	0.931	0.932	0.891
S/L	0.935	0.932	0.933	0.952	0.946	0.938	0.933

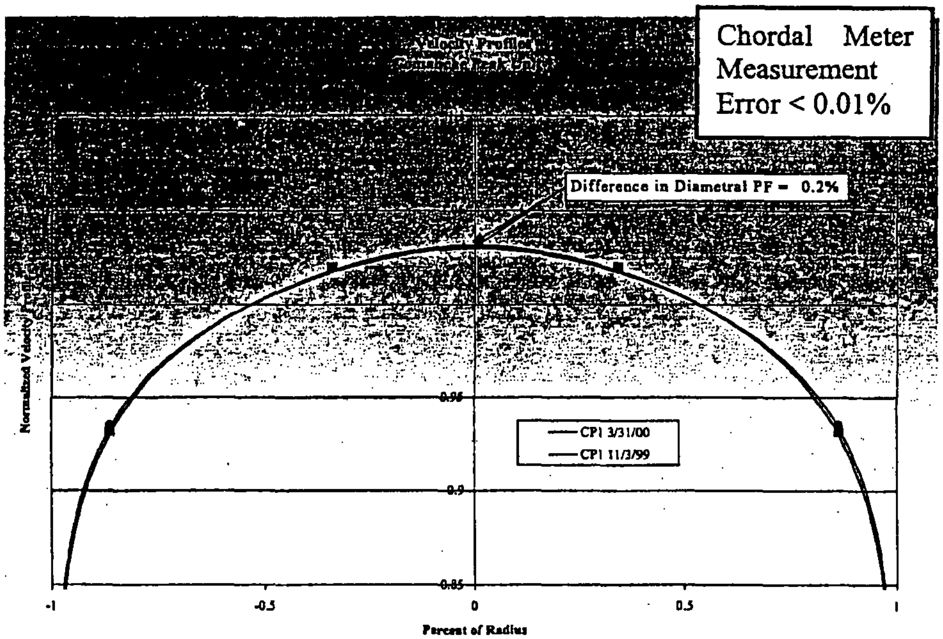
Loop 34	6/23/98	8/26/99	11/3/99	6/23/00	12/10/00	6/21/01	10/13/01
-0.861136	0.996	0.961	0.953	0.964	0.950	0.967	0.956
-0.339981	1.000	0.993	0.995	1.000	0.994	1.002	1.001
0.33998	1.008	1.019	1.018	1.019	1.020	1.013	1.015
0.86114	0.963	0.984	0.991	0.957	0.988	0.969	0.974
S/L	0.976	0.967	0.966	0.951	0.962	0.961	0.957

Plant Name: Comanche Peak Unit 1

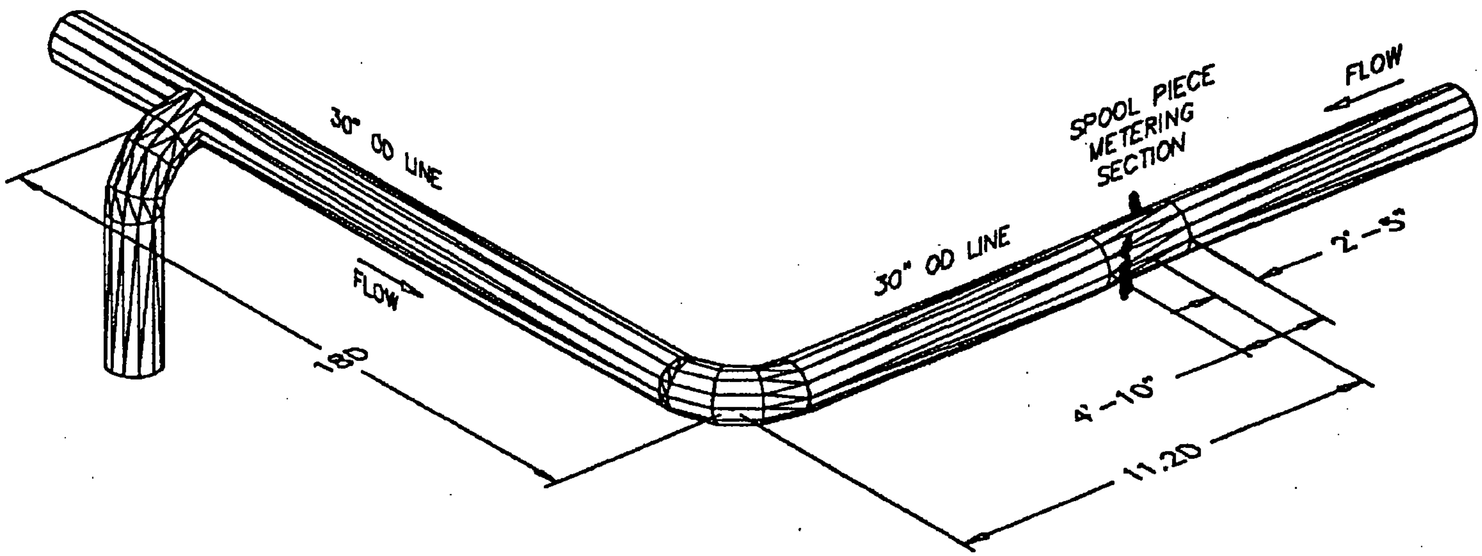
Feedwater Measurement System: LEFM✓

Installation Geometry: 11.2 Diameters Downstream of a 90° Elbow

Non-planar feeds 18 Diameters Upstream



SKETCH SKRSH-30.DWG



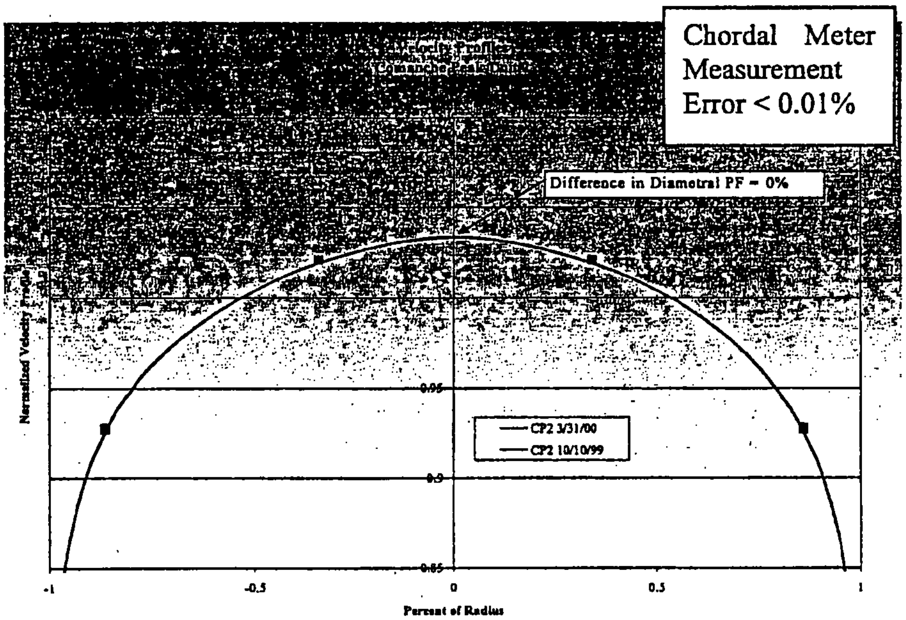
TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
COMANCHE PEAK 1

Plant Name: Comanche Peak Unit 2

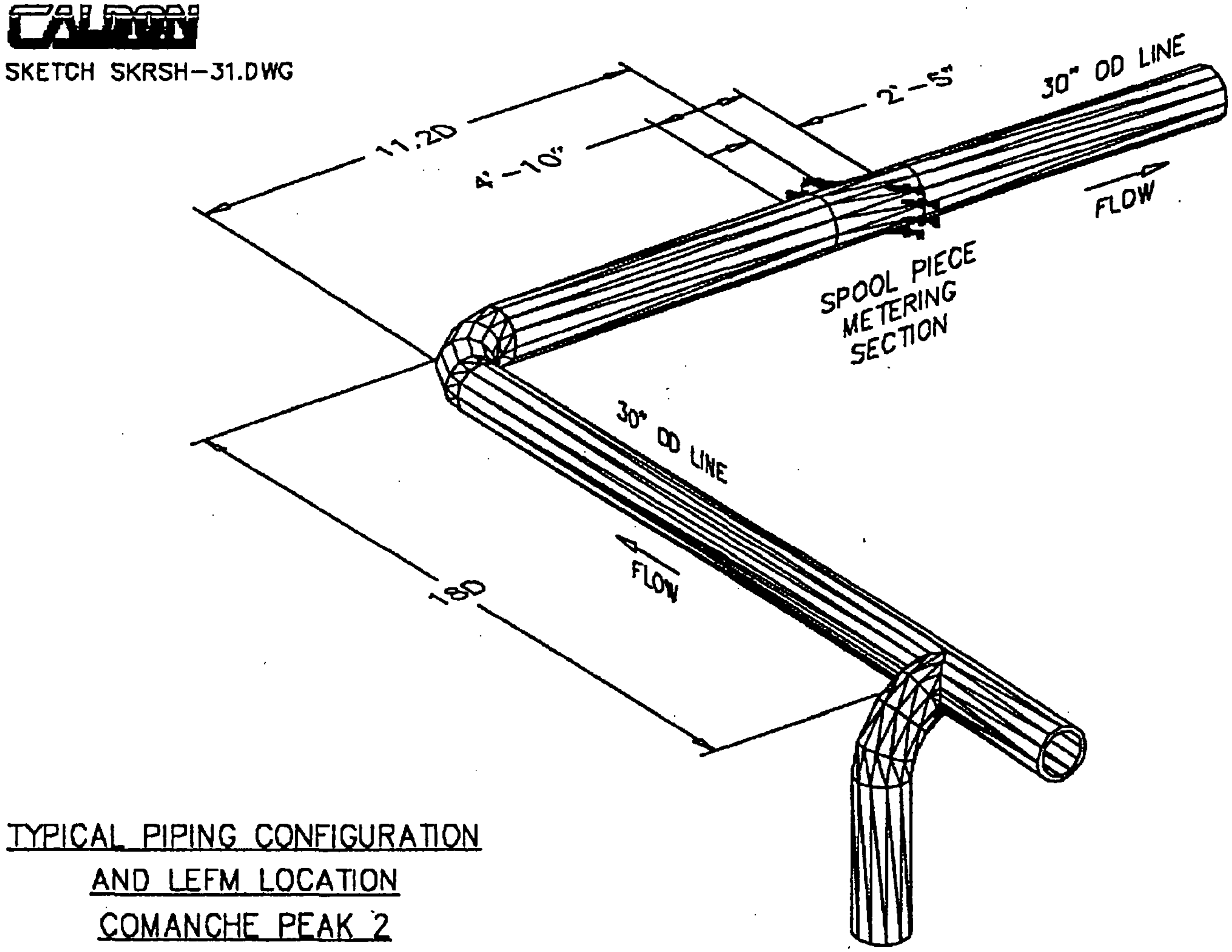
Feedwater Measurement System: LEFM✓

Installation Geometry: 11.2 Diameters Downstream of a 90° Elbow

Non-planar feeds 18 Diameters Upstream



CALDON



TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
COMANCHE PEAK 2

Comanche Peak Data taken from commissioning and from plant personnel

Unit 1	11/3/99	3/31/00
-0.861136	1.0071	1.0069
-0.339981	1.0515	1.0513
0.33998	0.9858	0.9882
0.86114	0.8635	0.8565
S/L	0.918	0.914

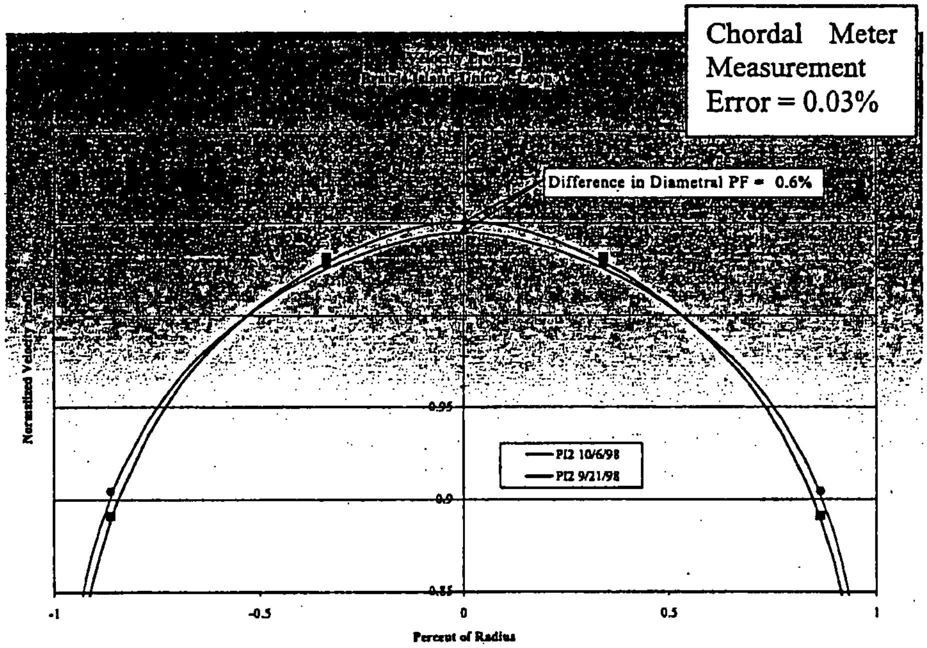
Unit 2	10/10/99	3/31/00
-0.861136	0.9262	0.9265
-0.339981	1.0177	1.0173
0.33998	1.0237	1.0245
0.86114	0.9304	0.9283
S/L	0.909	0.908

Plant Name: Prairie Island Unit 2 Loop A

Feedwater Measurement System: LEFM✓

Installation Geometry: 20 Diameters Downstream from a 90° Bend

Non-planar bend 4 Diameters Upstream

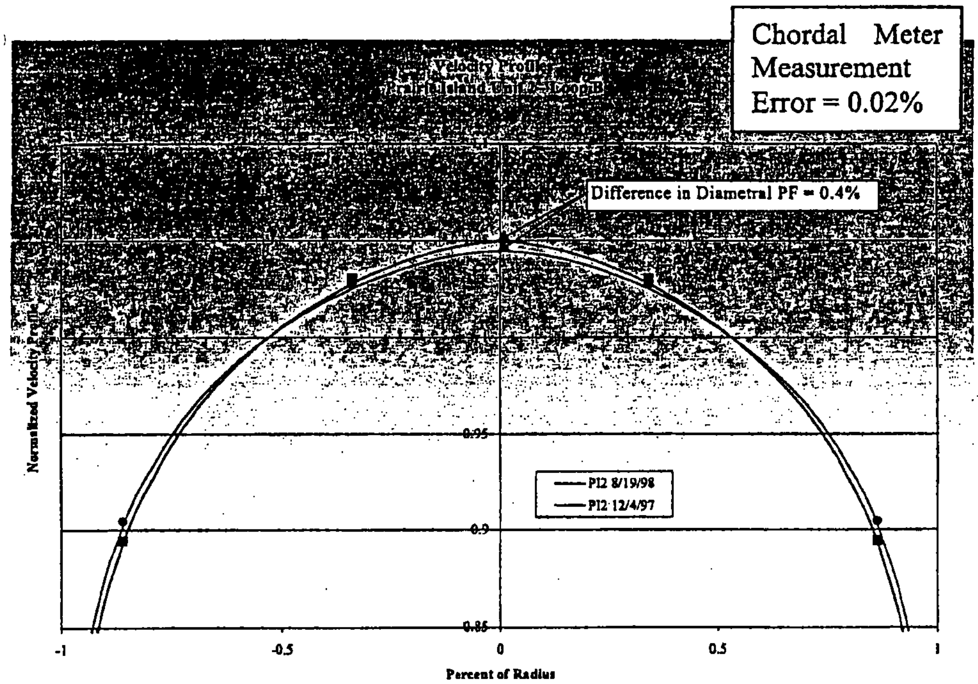


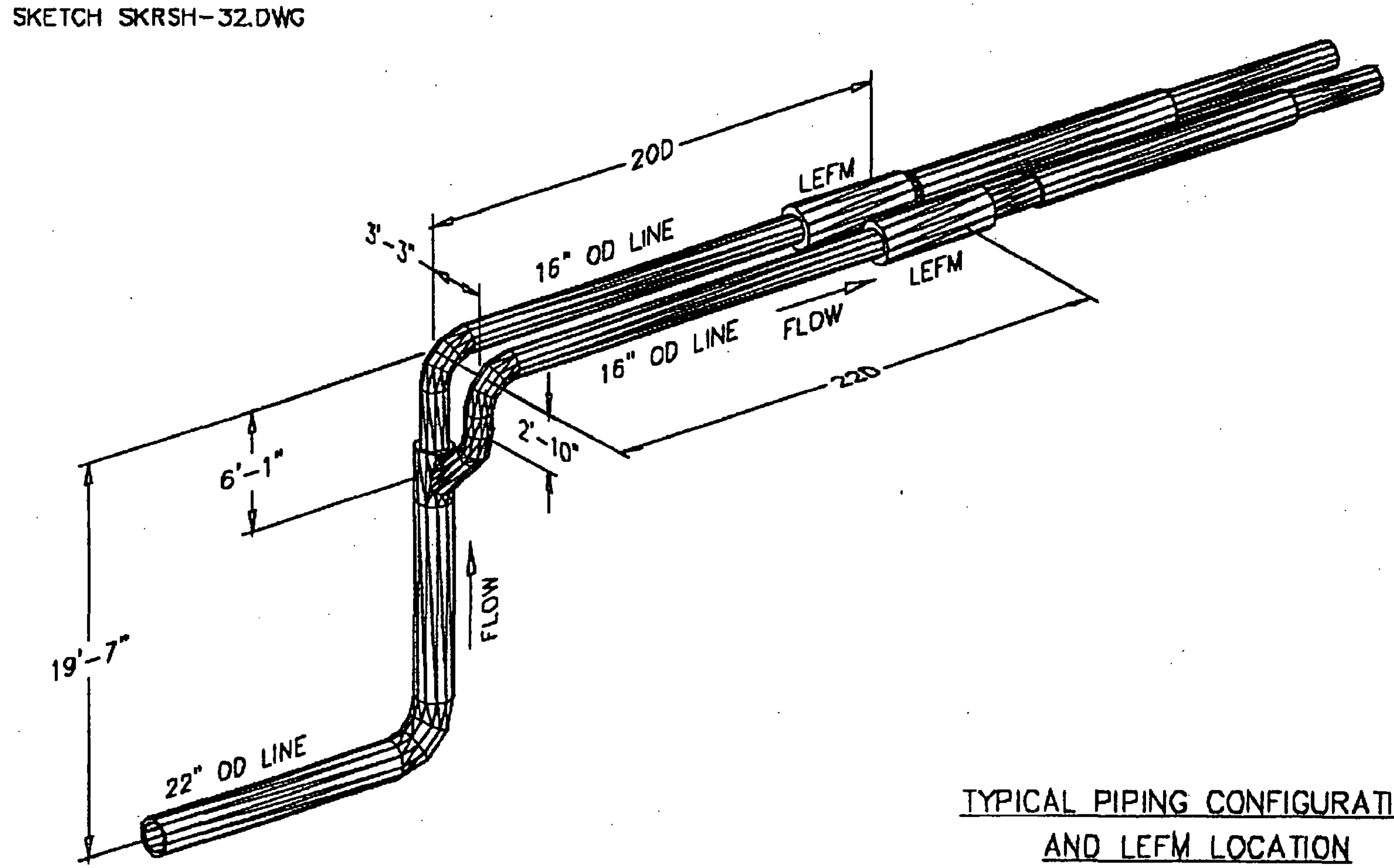
Plant Name: Prairie Island Unit 2 Loop B

Feedwater Measurement System: LEFM✓

Installation Geometry: 20 Diameters Downstream from a 90° Bend

Non-planar bend 4 Diameters Upstream





TYPICAL PIPING CONFIGURATION AND LEFM LOCATION PRAIRIE ISLAND

5/17/98	0.870755	1.015193	1.043678	0.925072	0.897914	1.029436	0.872
5/22/98	0.871222	1.014476	1.042591	0.930922	0.901072	1.028534	0.876
5/26/98	0.871755	1.015432	1.042008	0.929041	0.900398	1.02872	0.875
5/29/98	0.870902	1.015041	1.042119	0.930853	0.900877	1.02858	0.876
6/1/98	0.87008	1.014307	1.043693	0.928702	0.899391	1.029	0.874
6/4/98	0.872683	1.016676	1.039385	0.932975	0.902829	1.028031	0.878
6/6/98	0.869605	1.014675	1.042761	0.931202	0.900404	1.028718	0.875
6/9/98	0.872216	1.015321	1.043119	0.925113	0.898665	1.02922	0.873
6/12/98	0.870692	1.014145	1.043359	0.929805	0.900249	1.028752	0.875
6/15/98	0.871853	1.015781	1.041277	0.930322	0.901087	1.028529	0.876
6/18/98	0.8715	1.015434	1.043109	0.925388	0.898444	1.029272	0.873
6/24/98	0.873052	1.016014	1.042197	0.925216	0.899134	1.029106	0.874
6/27/98	0.871426	1.012633	1.043414	0.934219	0.902822	1.028024	0.878
6/30/98	0.870716	1.016565	1.04245	0.924561	0.897638	1.029508	0.872
7/3/98	0.869836	1.014878	1.042936	0.929472	0.899654	1.028907	0.874
7/7/98	0.870063	1.014531	1.042797	0.931189	0.900626	1.028664	0.876
7/10/98	0.872366	1.016237	1.042103	0.925272	0.898819	1.02917	0.873
7/14/98	0.8711	1.015548	1.041975	0.929519	0.90031	1.028762	0.875
7/17/98	0.871768	1.016207	1.043938	0.919757	0.895763	1.030073	0.870
7/18/98	0.87218	1.015789	1.042993	0.923961	0.89807	1.029391	0.872
7/20/98	0.870761	1.014915	1.043325	0.927327	0.899044	1.02912	0.874
7/23/98	0.870269	1.014806	1.04286	0.929668	0.899969	1.028833	0.875
7/30/98	0.870636	1.01571	1.042882	0.926208	0.898422	1.029296	0.873
8/2/98	0.871142	1.014613	1.042983	0.928955	0.900049	1.028798	0.875
8/4/98	0.87158	1.015787	1.0444	0.919716	0.895648	1.030094	0.869
8/7/98	0.871319	1.01559	1.043088	0.92525	0.898285	1.029339	0.873
8/7/98	0.871319	1.01559	1.043088	0.92525	0.898285	1.029339	0.873
8/10/98	0.871261	1.015809	1.042036	0.928128	0.899695	1.028923	0.874
8/13/98	0.871016	1.014967	1.042444	0.929883	0.90045	1.028706	0.875
8/16/98	0.87071	1.015656	1.0437	0.923476	0.897093	1.029678	0.871
8/19/98	0.871419	1.0159	1.042314	0.926708	0.899064	1.029107	0.874
8/25/98	0.871231	1.01602	1.043287	0.923017	0.897124	1.029654	0.871
8/27/98	0.872619	1.015624	1.041902	0.927836	0.900227	1.028763	0.875
8/30/98	0.872191	1.017478	1.039844	0.929028	0.90061	1.028661	0.876
9/2/98	0.87168	1.015657	1.043692	0.922428	0.897054	1.029675	0.871
9/5/98	0.870872	1.014593	1.043703	0.92696	0.898916	1.029148	0.873
9/8/98	0.870322	1.015253	1.042978	0.927705	0.899013	1.029116	0.874
9/12/98	0.869388	1.016051	1.044317	0.921317	0.895353	1.030184	0.869
9/15/98	0.870605	1.015736	1.043186	0.925086	0.897846	1.029461	0.872
9/18/98	0.86963	1.015043	1.043667	0.926674	0.898152	1.029355	0.873
9/21/98	0.879767	1.018073	1.036881	0.929628	0.904697	1.027477	0.881
9/24/98	0.872419	1.017812	1.0422	0.919366	0.895893	1.030006	0.870
9/27/98	0.869978	1.015507	1.043576	0.925059	0.897518	1.029542	0.872
9/30/98	0.870497	1.015837	1.043162	0.924942	0.897719	1.0295	0.872
10/3/98	0.87028	1.015459	1.043248	0.92613	0.898205	1.029354	0.873
10/6/98	0.870836	1.016599	1.046326	0.910981	0.890908	1.031463	0.864
10/9/98	0.870322	1.015834	1.044506	0.920366	0.895344	1.03017	0.869
10/12/98	0.871669	1.015933	1.043209	0.923216	0.897443	1.029571	0.872
10/15/98	0.872225	1.016998	1.043822	0.91683	0.894528	1.03041	0.868

10/18/98	0.873035	1.017446	1.042911	0.917664	0.89535	1.030179	0.869
10/21/98	0.870439	1.015696	1.043728	0.923475	0.896957	1.029712	0.871
10/24/98	0.870113	1.015195	1.043844	0.925127	0.89762	1.02952	0.872
10/27/98	0.870246	1.015832	1.043589	0.923603	0.896925	1.029711	0.871
10/30/98	0.87015	1.015226	1.043695	0.925691	0.897921	1.029461	0.872
11/2/98	0.870786	1.015424	1.042805	0.927208	0.898997	1.029115	0.874
11/5/98	0.871564	1.015532	1.042504	0.927166	0.899365	1.029018	0.874
11/8/98	0.871828	1.017437	1.044747	0.912569	0.892199	1.031092	0.865

Loop 31		
	Min	0.864
	Max	0.881

10/20/97	0.911422	1.030964	1.0258	0.891634	0.901528	1.028382	0.877
10/23/97	0.911288	1.030804	1.026233	0.890882	0.901085	1.028519	0.876
10/26/97	0.910823	1.031504	1.026489	0.888056	0.899439	1.028997	0.874
10/29/97	0.91067	1.03072	1.025297	0.895056	0.902863	1.028009	0.878
11/1/97	0.911033	1.030843	1.025133	0.894803	0.902918	1.027988	0.878
11/4/97	0.910283	1.031318	1.0246	0.895811	0.903047	1.027959	0.878
11/7/97	0.911725	1.030979	1.025017	0.894061	0.902893	1.027998	0.878
11/12/97	0.911467	1.031886	1.027275	0.883359	0.897413	1.029581	0.872
11/15/97	0.909684	1.030567	1.025617	0.895483	0.902583	1.028092	0.878
11/18/97	0.90965	1.031071	1.024977	0.89582	0.902735	1.028024	0.878
11/21/97	0.911011	1.031691	1.026167	0.888367	0.899689	1.028929	0.874
11/22/97	0.911955	1.030923	1.025257	0.893318	0.902637	1.02809	0.878
11/25/97	0.910925	1.030846	1.025175	0.894706	0.902815	1.028011	0.878
12/1/97	0.911709	1.030873	1.024621	0.89573	0.90372	1.027747	0.879
12/4/97	0.911567	1.030754	1.024402	0.897075	0.904321	1.027578	0.880
12/7/97	0.912488	1.032515	1.025866	0.884905	0.898697	1.029191	0.873
12/11/97	0.910597	1.030948	1.02488	0.895936	0.903266	1.027914	0.879
12/13/97	0.9117	1.03124	1.024343	0.895503	0.903602	1.027792	0.879
12/17/97	0.910822	1.031321	1.024885	0.894197	0.90251	1.028103	0.878
12/22/97	0.910759	1.031114	1.024749	0.89547	0.903114	1.027932	0.879
12/25/97	0.910494	1.031079	1.025811	0.892239	0.901367	1.028445	0.876
12/30/97	0.912247	1.031204	1.024402	0.894903	0.903575	1.027803	0.879
1/3/98	0.910127	1.030744	1.025146	0.896021	0.903074	1.027945	0.879
1/4/98	0.910641	1.031027	1.024928	0.895336	0.902989	1.027978	0.878
1/5/98	0.912216	1.031251	1.026291	0.888186	0.900201	1.028771	0.875
1/8/98	0.909723	1.030582	1.025653	0.895203	0.902463	1.028118	0.878
1/11/98	0.911636	1.031042	1.024733	0.894914	0.903275	1.027888	0.879
1/14/98	0.912836	1.031876	1.025988	0.886628	0.899732	1.028932	0.874
3/10/98	0.91232	1.030635	1.026682	0.888901	0.90061	1.028659	0.876
3/13/98	0.911975	1.030465	1.02719	0.887959	0.899967	1.028828	0.875
3/16/98	0.913333	1.030545	1.02697	0.887136	0.900235	1.028758	0.875
3/19/98	0.912547	1.031612	1.02756	0.882411	0.897479	1.029586	0.872
3/23/98	0.913395	1.030638	1.027459	0.885189	0.899292	1.029049	0.874
3/26/98	0.912127	1.030668	1.027582	0.885984	0.899055	1.029125	0.874
3/29/98	0.912964	1.031743	1.026811	0.88395	0.898457	1.029277	0.873
4/1/98	0.912778	1.030843	1.027709	0.884239	0.898508	1.029276	0.873
4/5/98	0.91228	1.030837	1.02802	0.88365	0.897965	1.029429	0.872
4/10/98	0.911908	1.030738	1.027673	0.885594	0.898751	1.029206	0.873
4/13/98	0.912256	1.031035	1.026883	0.886837	0.899546	1.028959	0.874
4/16/98	0.912156	1.031139	1.027283	0.885285	0.89872	1.029211	0.873
4/19/98	0.911492	1.031101	1.028304	0.882511	0.897001	1.029703	0.871
4/22/98	0.91145	1.03124	1.027254	0.885683	0.898566	1.029247	0.873
4/25/98	0.910739	1.031131	1.027384	0.886211	0.898475	1.029258	0.873
4/29/98	0.911322	1.03117	1.027112	0.886475	0.898899	1.029141	0.873
5/3/98	0.911391	1.031085	1.027426	0.885647	0.898519	1.029256	0.873
5/7/98	0.910847	1.030593	1.028301	0.884961	0.897904	1.029447	0.872
5/10/98	0.91009	1.030934	1.026926	0.889184	0.899637	1.02893	0.874
5/11/98	0.910342	1.030826	1.027685	0.886653	0.898498	1.029256	0.873
5/14/98	0.910952	1.031115	1.028837	0.881017	0.895985	1.029976	0.870

5/17/98	0.910364	1.030179	1.027799	0.888651	0.899507	1.028989	0.874
5/22/98	0.910347	1.030757	1.026973	0.889342	0.899845	1.028865	0.875
5/26/98	0.91137	1.03147	1.027937	0.882531	0.89695	1.029704	0.871
5/29/98	0.910369	1.030909	1.026817	0.889384	0.899876	1.028863	0.875
6/1/98	0.909453	1.03012	1.026942	0.892609	0.901031	1.028531	0.876
6/4/98	0.909902	1.030756	1.027982	0.886519	0.898211	1.029369	0.873
6/6/98	0.90989	1.029693	1.02796	0.890151	0.90002	1.028827	0.875
6/9/98	0.910039	1.030587	1.028685	0.884417	0.897228	1.029636	0.871
6/12/98	0.910494	1.030035	1.027076	0.891387	0.900941	1.028556	0.876
6/15/98	0.910162	1.03138	1.028188	0.883086	0.896624	1.029784	0.871
6/18/98	0.909025	1.029335	1.027693	0.893209	0.901117	1.028514	0.876
6/24/98	0.909612	1.029654	1.027488	0.892298	0.900955	1.028571	0.876
6/27/98	0.907627	1.028976	1.027696	0.895759	0.901693	1.028336	0.877
6/30/98	0.91223	1.03034	1.027903	0.885675	0.898952	1.029122	0.874
7/3/98	0.910986	1.029965	1.027286	0.890401	0.900693	1.028626	0.876
7/7/98	0.909958	1.030337	1.026929	0.891442	0.9007	1.028633	0.876
7/10/98	0.910928	1.0305	1.027306	0.888453	0.89969	1.028903	0.874
7/14/98	0.909859	1.030626	1.026899	0.890714	0.900287	1.028763	0.875
7/17/98	0.911722	1.031477	1.027491	0.883862	0.897792	1.029484	0.872
7/18/98	0.910188	1.030573	1.028039	0.886537	0.898362	1.029306	0.873
7/20/98	0.910138	1.030657	1.027247	0.889126	0.899632	1.028952	0.874
7/23/98	0.909694	1.02988	1.027618	0.890872	0.900283	1.028749	0.875
7/30/98	0.910609	1.030209	1.02726	0.890093	0.900351	1.028735	0.875
8/2/98	0.910362	1.030421	1.027226	0.889794	0.900078	1.028823	0.875
8/4/98	0.908998	1.030784	1.028193	0.88642	0.897709	1.029489	0.872
8/7/98	0.908611	1.030201	1.027824	0.890059	0.899335	1.029013	0.874
8/7/98	0.908611	1.030201	1.027824	0.890059	0.899335	1.029013	0.874
8/10/98	0.908501	1.030065	1.027945	0.890342	0.899421	1.029005	0.874
8/13/98	0.910428	1.030512	1.027503	0.888361	0.899394	1.029008	0.874
8/16/98	0.908901	1.029982	1.027667	0.891162	0.900031	1.028825	0.875
8/19/98	0.91012	1.032095	1.028763	0.878812	0.894466	1.030429	0.868
8/25/98	0.910642	1.029834	1.026611	0.893428	0.902035	1.028223	0.877
8/27/98	0.909814	1.029745	1.027177	0.89287	0.901342	1.028461	0.876
8/30/98	0.911269	1.029857	1.027198	0.890812	0.90104	1.028528	0.876
9/2/98	0.909108	1.029626	1.0272	0.893678	0.901393	1.028413	0.876
9/5/98	0.910936	1.030629	1.028486	0.884064	0.8975	1.029558	0.872
9/8/98	0.910035	1.030021	1.027304	0.89099	0.900513	1.028663	0.875
9/12/98	0.909498	1.030026	1.027056	0.892428	0.900963	1.028541	0.876
9/15/98	0.910383	1.031121	1.026021	0.891484	0.900933	1.028571	0.876
9/18/98	0.910642	1.032304	1.027159	0.882942	0.896792	1.029732	0.871
9/21/98	0.907328	1.030548	1.02774	0.890578	0.898953	1.029144	0.873
9/24/98	0.910292	1.030834	1.026976	0.889101	0.899696	1.028905	0.874
9/27/98	0.909814	1.03012	1.026514	0.893595	0.901705	1.028317	0.877
9/30/98	0.909489	1.030057	1.026447	0.894559	0.902024	1.028252	0.877
10/3/98	0.909553	1.030168	1.026399	0.894256	0.901904	1.028284	0.877
10/6/98	0.910625	1.030907	1.027518	0.886734	0.898679	1.029213	0.873
10/9/98	0.909117	1.030115	1.027228	0.892079	0.900598	1.028672	0.875
10/12/98	0.909706	1.030192	1.026512	0.89352	0.901613	1.028352	0.877
10/15/98	0.909517	1.030408	1.026452	0.893342	0.90143	1.02843	0.877

10/18/98	0.909917	1.030926	1.027442	0.887539	0.898728	1.029184	0.873
10/21/98	0.910431	1.030917	1.026481	0.890514	0.900472	1.028699	0.875
10/24/98	0.909686	1.030992	1.026521	0.8909	0.900293	1.028757	0.875
10/27/98	0.909844	1.031127	1.026245	0.891103	0.900474	1.028686	0.875
10/30/98	0.909936	1.030813	1.02803	0.885908	0.897922	1.029422	0.872
11/2/98	0.91047	1.030654	1.026923	0.889753	0.900111	1.029789	0.875
11/5/98	0.909503	1.030226	1.027067	0.891864	0.900684	1.023647	0.876
11/8/98	0.908368	1.029756	1.027234	0.89397	0.901169	1.023495	0.876

Loop 32

Min	0.868
Max	0.880

Prairie Island 2 Data from remote monitoring program - found under LEFMLOGS

Loop A

					S	L	S/L	
9/21/98	0.8798	1.0181	1.0369	0.9296	0.9047	1.0275		0.881
10/6/98	0.8708	1.0166	1.0463	0.9110	0.8909	1.0315		0.864

Loop B

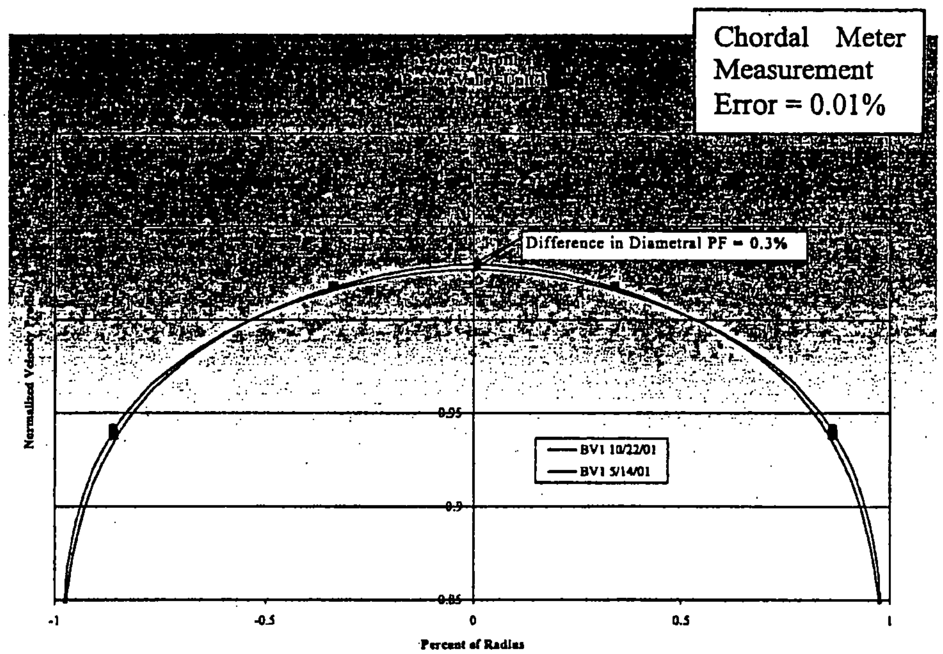
					S	L	S/L	
12/4/97	0.9116	1.0308	1.0244	0.8971	0.9043	1.0276		0.880
8/19/98	0.9101	1.0321	1.0288	0.8788	0.8945	1.0304		0.868

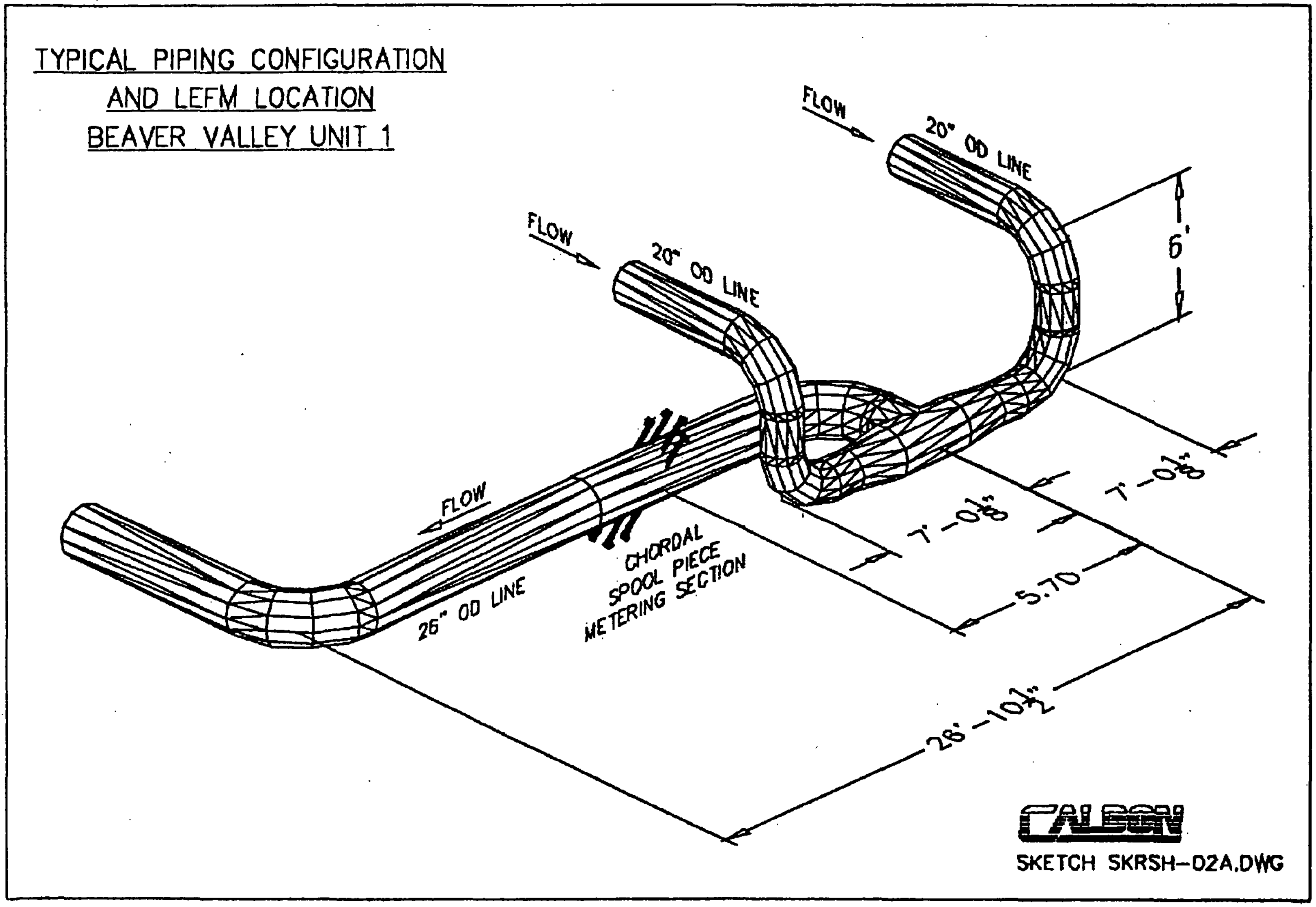
Plant Name: Beaver Valley Unit 1

Feedwater Measurement System: LEFM✓

Installation Geometry: 10 Diameters Downstream from a Header

Non-planar bend 4 Diameters Upstream




TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
BEAVER VALLEY UNIT 1
FLOW
20" OD LINE
FLOW
20" OD LINE
6'
FLOW
26" OD LINE
CHORDAL
SPOOL PIECE
METERING SECTION
7'-0 1/8"
7'-0 1/8"
5.70
28'-10 1/2"
SKETCH SKRSH-02A.DWG

Beaver Valley 1 09:49:40 2001/10/22

Configuration Files

ALARM.INI	2001/10/12	19:31:40	FFFF909D
FAT.INI	2001/03/22	15:07:12	FFFFF185
HYDRAULI.INI	2001/05/08	06:40:22	FFFF820A
METER.INI	2001/07/13	17:35:22	FFFF0EFF
PARAMETR.INI	2001/05/08	17:26:30	FFFC946F
P_CONFIG.INI	2001/04/17	13:30:02	FFFF6881
PROPERTY.INI	2001/03/22	15:20:40	FFFFF97A
SETUP.INI	2001/05/08	06:19:42	FFFFAA6B

Setup Files

Setapu1.txt	2001/04/17	16:21:00	FFFE0F61
Setapu2.txt	2001/02/21	13:44:14	FFF89974

Beaver Valley 1 Current Flow:	62.30
Beaver Valley 1 Average Flow:	62.36
Beaver Valley 1 Maximum Flow:	62.52
Beaver Valley 1 Minimum Flow:	62.16
Beaver Valley 1 Deviation Flow:	0.07
Beaver Valley 1 Current Temp:	434.0
Beaver Valley 1 Average Temp:	434.0
Beaver Valley 1 Maximum Temp:	434.0
Beaver Valley 1 Minimum Temp:	433.9
Beaver Valley 1 Deviation Temp:	0.0
Beaver Valley 1 Current System Status:	NORMAL
Beaver Valley 1 Minimum System Status:	NORMAL
Beaver Valley 1 Current Mass Flow:	11.771
Beaver Valley 1 Average Mass Flow:	11.782
Beaver Valley 1 Maximum Mass Flow:	11.814
Beaver Valley 1 Minimum Mass Flow:	11.744
Beaver Valley 1 Deviation Mass Flow:	0.013
Beaver Valley 1 Uncertainty:	0.12

Meter 1 Current Flow:	62.30
Meter 1 Average Flow:	62.36
Meter 1 Maximum Flow:	62.52
Meter 1 Minimum Flow:	62.16
Meter 1 Deviation Flow:	0.07
Meter 1 Current Temp:	434.0
Meter 1 Average Temp:	434.0
Meter 1 Maximum Temp:	434.0
Meter 1 Minimum Temp:	433.9
Meter 1 Deviation Temp:	0.0
Meter 1 Current Press:	1090.60
Meter 1 Average Press:	1091.02
Meter 1 Maximum Press:	1093.03
Meter 1 Minimum Press:	1089.55
Meter 1 Deviation Press:	0.02

Meter 1 Current Meter Status:	NORMAL			
Meter 1 Minimum Meter Status:	NORMAL			
Meter 1 Current Mass Flow:	11.771			
Meter 1 Average Mass Flow:	11.782			
Meter 1 Maximum Mass Flow:	11.814			
Meter 1 Minimum Mass Flow:	11.744			
Meter 1 Deviation Mass Flow:	0.013			
Meter 1 Uncertainty:	0.12			
	Path 1	Path 2	Path 3	Path 4
Meter 1 Current Variance:	122656.34	86921.20	101972.74	77350.00
Meter 1 Average Vnorm:	1.0594	1.0682	0.9673	0.8175
Meter 1 Current Vnorm:	1.0569	1.0638	0.9704	0.8246
Meter 1 Maximum Vnorm:	1.1004	1.0852	0.9852	0.8428
Meter 1 Minimum Vnorm:	1.0179	1.0547	0.9483	0.7852
Meter 1 Deviation Vnorm:	0.015	0.005	0.006	0.011
Meter 1 Benchmark Vnorm:	1.0585	1.0679	0.9678	0.8179
Meter 1 Limit % Vnorm:	3.00	3.00	3.00	3.00
Meter 1 Average Gain:	63.08	62.65	64.56	66.38
Meter 1 Current Gain:	63.07	62.59	64.68	66.56
Meter 1 Maximum Gain:	63.42	63.09	64.73	66.76
Meter 1 Minimum Gain:	62.68	62.33	64.38	65.99
Meter 1 Deviation Gain:	0.12	0.12	0.06	0.13
Meter 1 Limit Gain:	75.00	75.00	75.00	75.00
Meter 1 Current Gain Up:	60.99	62.41	63.97	65.07
Meter 1 Current Gain Down:	65.07	62.88	65.23	68.05
Meter 1 Current TPGain Up:	63.97	64.13	64.13	64.13
Meter 1 Current TPGain Down:	64.13	64.29	63.97	64.29
Meter 1 Average S/N Ratio:	48.94	50.00	34.90	30.33
Meter 1 Current S/N Ratio:	49.13	50.02	34.75	29.80
Meter 1 Maximum S/N Ratio:	49.85	50.82	35.37	30.85
Meter 1 Minimum S/N Ratio:	48.25	49.06	34.52	29.66
Meter 1 Deviation S/N Ratio:	0.29	0.33	0.14	0.25
Meter 1 Average TDown:	417993	661915	662417	419235
Meter 1 Current TDown:	418011	661957	662429	419240
Meter 1 Maximum TDown:	418066	661993	662487	419294
Meter 1 Minimum TDown:	417930	661823	662339	419177
Meter 1 Deviation TDown:	22	26	26	18
Meter 1 Current TPTDown:	4000452	4000454	4000452	4000449
Meter 1 Average DeltaT:	2542.9	4760.7	4311.6	1962.6
Meter 1 Current DeltaT:	2534.9	4737.2	4321.8	1978.1
Meter 1 Maximum DeltaT:	2643.3	4839.5	4384.9	2019.7
Meter 1 Minimum DeltaT:	2444.8	4691.2	4230.4	1883.9
Meter 1 Deviation DeltaT:	36.3	24.3	27.8	27.0
Meter 1 Current TPDeltaT:	2.0	-2.9	1.7	4.4
Meter 1 Current Path Status:	NORMAL	NORMAL	NORMAL	NORMAL
Meter 1 Minimum Path Status:	NORMAL	NORMAL	NORMAL	NORMAL
Meter 1 Average Reject %:	0.9	0.3	0.3	0.6

Meter 1 Current Reject %:	1.2	0.0	0.1	0.4
Meter 1 Maximum Reject %:	2.2	1.2	1.2	1.8
Meter 1 Minimum Reject %:	0.0	0.0	0.0	0.0
Meter 1 Deviation Reject %:	0.5	0.2	0.2	0.4
Meter 1 Incoming Samples:	719	719	719	719
Meter 1 Number Failed Rejects:	0	0	0	0

Alarm Log Events

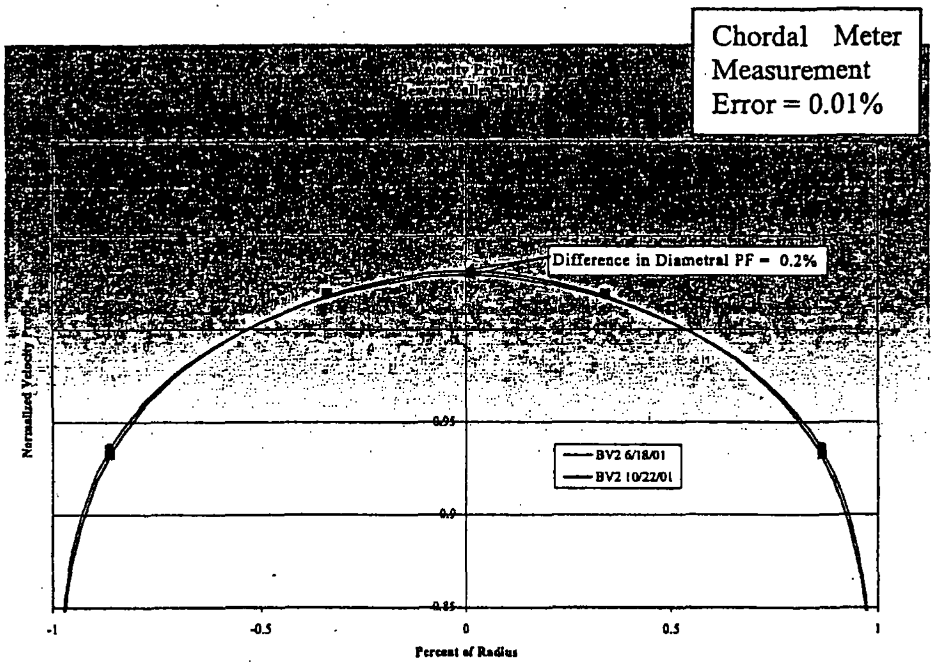
```
REM Sound Velocity Ratio to Nominal
DEFAULTCFRATIO1:,0.9998,1.0002,1.0004,1.0000

REM Nominal Sound Velocity for the Speed of Sound Tests
SOUNDVELOCITYNOM1:,50300

REM Averaging period for the Velocity Profile Benchmark Calculation
*
MAXN:,720

REM Velocity Profiles used to evaluate the profile test
DEFAULTVELOCITY1:,1.1080,1.0894,0.9448,0.7765

REM Profile Factor Coefficients
PROFILEFACTORCOEFA01:,1.0039E+000
```

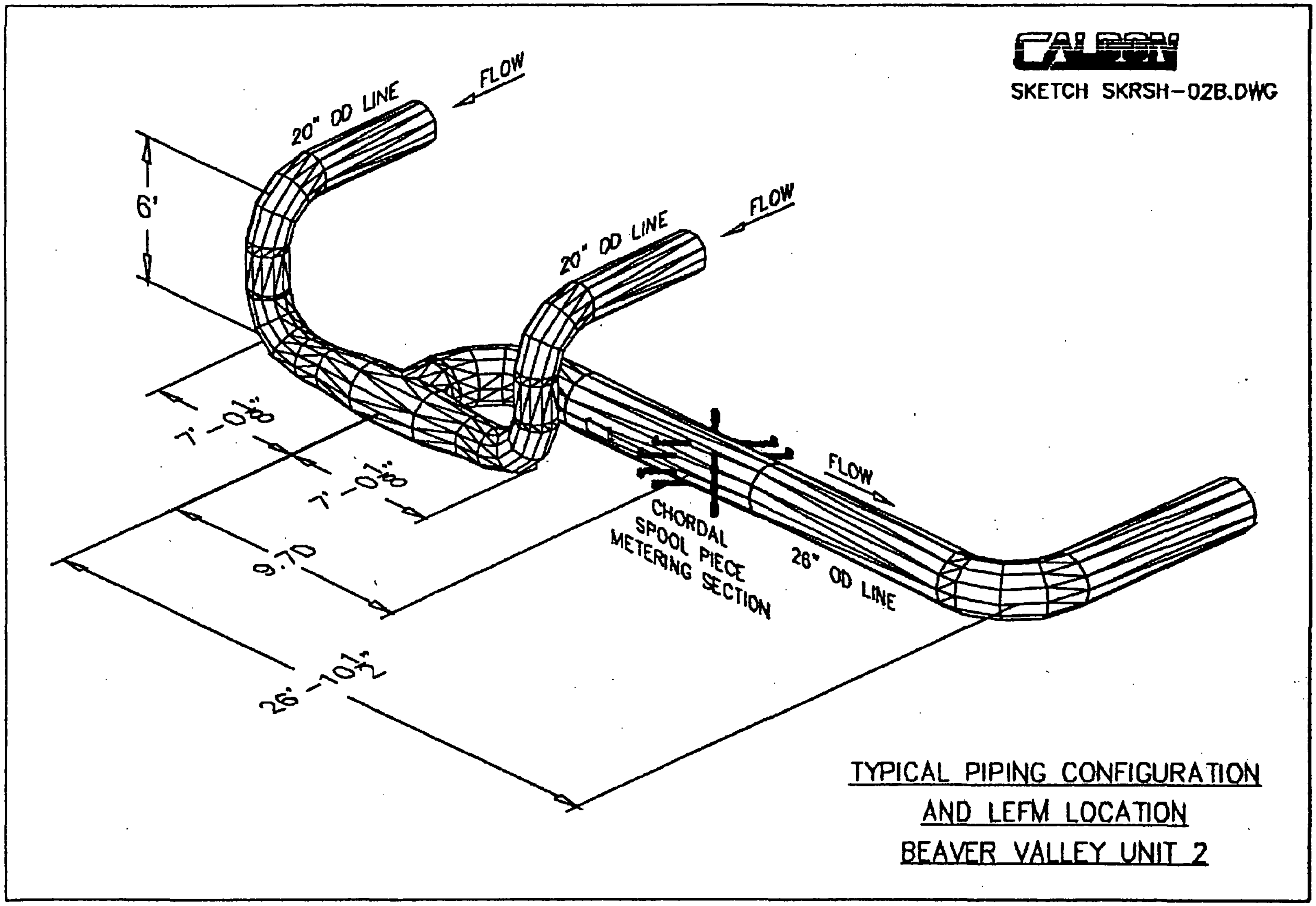
Plant Name: Beaver Valley Unit 2

Feedwater Measurement System: LEFM✓

Installation Geometry: 6 Diameters Downstream from a Header

Two Non-planar Feeds Upstream





SKETCH SKRSH-02B.DWG
FLOW
20" OD LINE
FLOW
20" OD LINE
6'
7'-0 1/8"
7'-0 1/8"
9.7D
26'-10 1/2"
FLOW
CHORDAL
SPOOL PIECE
METERING SECTION
26" OD LINE
TYPICAL PIPING CONFIGURATION
AND LEFM LOCATION
BEAVER VALLEY UNIT 2

Beaver Valley Unit 2 09:37:29 2001/10/22

Configuration Files

ALARM.INI	2001/06/18	09:52:56	FFFF04DE
FAT.INI	2001/03/23	15:40:46	FFFFAA26
HYDRAULI.INI	2001/06/18	12:13:02	FFFF49AE
METER.INI	2001/07/13	17:35:50	FFFC458F
PARAMETR.INI	2001/06/18	12:15:56	FFFC7630
P_CONFIG.INI	2001/05/02	10:02:04	FFFD81CB
PROPERTY.INI	2001/03/23	15:55:34	FFFFD6AC
SETUP.INI	2001/07/05	15:21:36	FFFE7200

Setup Files

Setapu1.txt	2001/06/18	15:00:40	FFFDFB04
Setapu2.txt	2001/05/08	13:56:36	FFFE1903
Setapu3.txt	2001/03/23	15:25:32	FFFE1904
Setapu4.txt	2001/03/23	15:25:32	FFFE1904
Setapu5.txt	2001/06/18	15:01:34	FFFDFAE5
Setapu6.txt	2001/03/23	15:25:32	FFFE1904
Setapu7.txt	2001/03/23	15:25:32	FFFE1904
Setapu8.txt	2001/03/23	15:25:32	FFFE1904

Beaver Valley Unit 2 Current Flow:	61.31
Beaver Valley Unit 2 Average Flow:	61.33
Beaver Valley Unit 2 Maximum Flow:	61.40
Beaver Valley Unit 2 Minimum Flow:	61.23
Beaver Valley Unit 2 Deviation Flow:	0.03
Beaver Valley Unit 2 Current Temp:	432.9
Beaver Valley Unit 2 Average Temp:	432.9
Beaver Valley Unit 2 Maximum Temp:	432.9
Beaver Valley Unit 2 Minimum Temp:	432.9
Beaver Valley Unit 2 Deviation Temp:	0.0
Beaver Valley Unit 2 Current System Status:	NORMAL
Beaver Valley Unit 2 Minimum System Status:	NORMAL
Beaver Valley Unit 2 Current Mass Flow:	11.593
Beaver Valley Unit 2 Average Mass Flow:	11.597
Beaver Valley Unit 2 Maximum Mass Flow:	11.610
Beaver Valley Unit 2 Minimum Mass Flow:	11.578
Beaver Valley Unit 2 Deviation Mass Flow:	0.006
Beaver Valley Unit 2 Uncertainty:	0.10
Meter 1 Current Flow:	61.31
Meter 1 Average Flow:	61.33
Meter 1 Maximum Flow:	61.40
Meter 1 Minimum Flow:	61.23
Meter 1 Deviation Flow:	0.03
Meter 1 Current Temp:	432.9
Meter 1 Average Temp:	432.9
Meter 1 Maximum Temp:	432.9
Meter 1 Minimum Temp:	432.9
Meter 1 Deviation Temp:	0.0

Meter 1 Current Press:	1087.95
Meter 1 Average Press:	1087.57
Meter 1 Maximum Press:	1088.36
Meter 1 Minimum Press:	1086.85
Meter 1 Deviation Press:	0.01
Meter 1 Current Meter Status:	NORMAL
Meter 1 Minimum Meter Status:	NORMAL
Meter 1 Current Mass Flow:	11.593
Meter 1 Average Mass Flow:	11.597
Meter 1 Maximum Mass Flow:	11.610
Meter 1 Minimum Mass Flow:	11.578
Meter 1 Deviation Mass Flow:	0.006
Meter 1 Uncertainty:	0.10

	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8
Meter 1 Current Variance:	109352.58	119133.39	125851.56	102142.39	112477.57	135183.91	125798.45	128769.61
Meter 1 Average Vnorm:	0.7408	0.9327	1.0980	1.1240	1.1506	1.1063	0.9360	0.7313
Meter 1 Current Vnorm:	0.7395	0.9335	1.0987	1.1161	1.1490	1.1014	0.9410	0.7369
Meter 1 Maximum Vnorm:	0.7828	0.9511	1.1167	1.1549	1.1839	1.1236	0.9588	0.7808
Meter 1 Minimum Vnorm:	0.7124	0.9191	1.0813	1.0757	1.0892	1.0869	0.9177	0.6994
Meter 1 Deviation Vnorm:	0.012	0.006	0.006	0.014	0.014	0.007	0.007	0.014
Meter 1 Benchmark Vnorm:	0.7404	0.9322	1.0983	1.1246	1.1522	1.1068	0.9353	0.7307
Meter 1 Limit % Vnorm:	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Meter 1 Average Gain:	69.89	63.03	61.14	66.59	60.13	59.16	69.79	56.50
Meter 1 Current Gain:	69.95	63.10	61.11	66.56	60.25	59.22	69.73	56.52
Meter 1 Maximum Gain:	70.12	63.20	61.25	66.80	60.30	59.31	69.96	56.64
Meter 1 Minimum Gain:	69.75	62.89	60.99	66.39	59.93	58.99	69.67	56.38
Meter 1 Deviation Gain:	0.06	0.05	0.06	0.07	0.07	0.06	0.06	0.05
Meter 1 Limit Gain:	76.00	76.00	76.00	76.00	76.00	76.00	76.00	76.00
Meter 1 Current Gain Up:	69.62	63.03	61.46	65.86	60.37	59.42	69.78	55.66
Meter 1 Current Gain Down:	70.09	63.03	60.68	67.11	60.05	58.95	69.62	57.23
Meter 1 Current TPGain Up:	64.60	64.76	64.76	64.60	64.60	64.60	64.76	64.44
Meter 1 Current TPGain Down:	64.44	64.44	64.44	64.60	64.76	64.44	64.60	64.92

Meter 1 Average S/N Ratio:	25.63	55.07	57.63	31.86	75.85	82.27	22.36	92.80
Meter 1 Current S/N Ratio:	25.66	55.15	58.06	31.97	75.77	82.67	22.38	92.72
Meter 1 Maximum S/N Ratio:	25.86	55.53	58.26	32.25	77.14	83.15	22.54	93.74
Meter 1 Minimum S/N Ratio:	25.44	54.69	57.13	31.56	74.80	81.50	22.17	91.74
Meter 1 Deviation S/N Ratio:	0.07	0.15	0.23	0.13	0.35	0.33	0.06	0.31
Meter 1 Average TDown:	378926	635665	634623	378186	383409	634129	634513	378401
Meter 1 Current TDown:	378930	635663	634624	378194	383410	634138	634499	378394
Meter 1 Maximum TDown:	378970	635710	634670	378237	383479	634184	634563	378450
Meter 1 Minimum TDown:	378874	635618	634573	378147	383366	634081	634459	378343
Meter 1 Deviation TDown:	17	19	17	16	18	19	19	18
Meter 1 Current TPTDown:	4500402	4500402	4500402	4500402	4500508	4500507	4500508	4500507
Meter 1 Average DeltaT:	1733.5	4044.1	4761.3	2634.8	2689.9	4790.6	4052.9	1713.3
Meter 1 Current DeltaT:	1729.9	4046.1	4762.8	2615.4	2685.5	4767.7	4073.1	1725.8
Meter 1 Maximum DeltaT:	1832.5	4125.9	4840.1	2709.1	2768.7	4867.7	4153.0	1829.6
Meter 1 Minimum DeltaT:	1666.1	3986.5	4690.9	2522.6	2547.1	4707.4	3975.7	1638.9
Meter 1 Deviation DeltaT:	28.2	27.1	26.6	32.8	32.7	32.2	29.2	33.2
Meter 1 Current TPDeltaT:	0.1	0.7	-0.0	-0.1	2.2	-0.2	0.2	4.5
Meter 1 Current Path Status:	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL
Meter 1 Minimum Path Status:	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL
Meter 1 Average Reject %:	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.1
Meter 1 Current Reject %:	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
Meter 1 Maximum Reject %:	1.2	0.7	0.8	1.0	1.2	0.8	0.8	1.1
Meter 1 Minimum Reject %:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meter 1 Deviation Reject %:	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2
Meter 1 Incoming Samples:	719	719	719	719	719	719	719	719
Meter 1 Number Failed Rejects:	0	0	0	0	0	0	0	0

Meter 1 Deviation Flow:	0.03
Meter 1 Current Temp:	434.2
Meter 1 Average Temp:	434.2
Meter 1 Maximum Temp:	434.3
Meter 1 Minimum Temp:	434.2
Meter 1 Deviation Temp:	0.0
Meter 1 Current Press:	1075.01
Meter 1 Average Press:	1074.61
Meter 1 Maximum Press:	1075.73
Meter 1 Minimum Press:	1073.57
Meter 1 Deviation Press:	0.01
Meter 1 Current Meter Status:	NORMAL
Meter 1 Minimum Meter Status:	NORMAL
Meter 1 Current Mass Flow:	11.760
Meter 1 Average Mass Flow:	11.779
Meter 1 Maximum Mass Flow:	11.794
Meter 1 Minimum Mass Flow:	11.760
Meter 1 Deviation Mass Flow:	0.005
Meter 1 Uncertainty:	0.10

	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8
Meter 1 Current Variance:	101724.19	128352.37	119280.98	120135.55	127986.56	159406.06	142563.78	137988.53
Meter 1 Average Vnorm:	0.7338	0.9276	1.1020	1.1252	1.1518	1.1157	0.9326	0.7188
Meter 1 Current Vnorm:	0.7440	0.9336	1.0970	1.1115	1.1473	1.1037	0.9414	0.7349
Meter 1 Maximum Vnorm:	0.7734	0.9514	1.1208	1.1620	1.1909	1.1363	0.9505	0.7563
Meter 1 Minimum Vnorm:	0.6977	0.9080	1.0792	1.0767	1.1162	1.0987	0.9136	0.6771
Meter 1 Deviation Vnorm:	0.012	0.007	0.007	0.015	0.014	0.007	0.007	0.015
Meter 1 Benchmark Vnorm:	0.7348	0.9282	1.1014	1.1244	1.1507	1.1154	0.9330	0.7200
Meter 1 Limit % Vnorm:	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Meter 1 Average Gain:	66.98	64.51	62.39	64.05	62.38	60.25	67.51	57.07
Meter 1 Current Gain:	67.02	64.41	62.47	64.03	62.48	60.24	67.52	57.01
Meter 1 Maximum Gain:	67.14	64.68	62.52	64.22	62.63	60.39	67.70	57.22
Meter 1 Minimum Gain:	66.81	64.38	62.24	63.83	62.14	60.01	67.31	56.93
Meter 1 Deviation Gain:	0.06	0.05	0.05	0.06	0.08	0.07	0.06	0.05
Meter 1 Limit Gain:	76.00	76.00	76.00	76.00	76.00	76.00	76.00	76.00
Meter 1 Current Gain Up:	66.48	63.97	62.72	62.88	63.50	60.21	67.90	56.13
Meter 1 Current Gain Down:	67.42	64.60	62.09	65.07	61.31	60.05	66.95	57.86
Meter 1 Current TPGain Up:	64.60	64.76	64.76	64.76	64.44	64.44	64.60	64.44
Meter 1 Current TPGain Down:	64.60	64.60	64.60	64.60	64.60	64.44	64.60	64.76
Meter 1 Average S/N Ratio:	37.21	48.21	50.49	41.69	54.93	74.50	28.73	85.88
Meter 1 Current S/N Ratio:	37.33	48.04	50.44	41.75	54.91	75.05	28.81	84.86

Beaver Valley Data taken from commissioning and from plant personnel during the velocity profile alarm

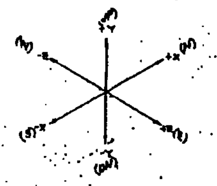
Unit 1

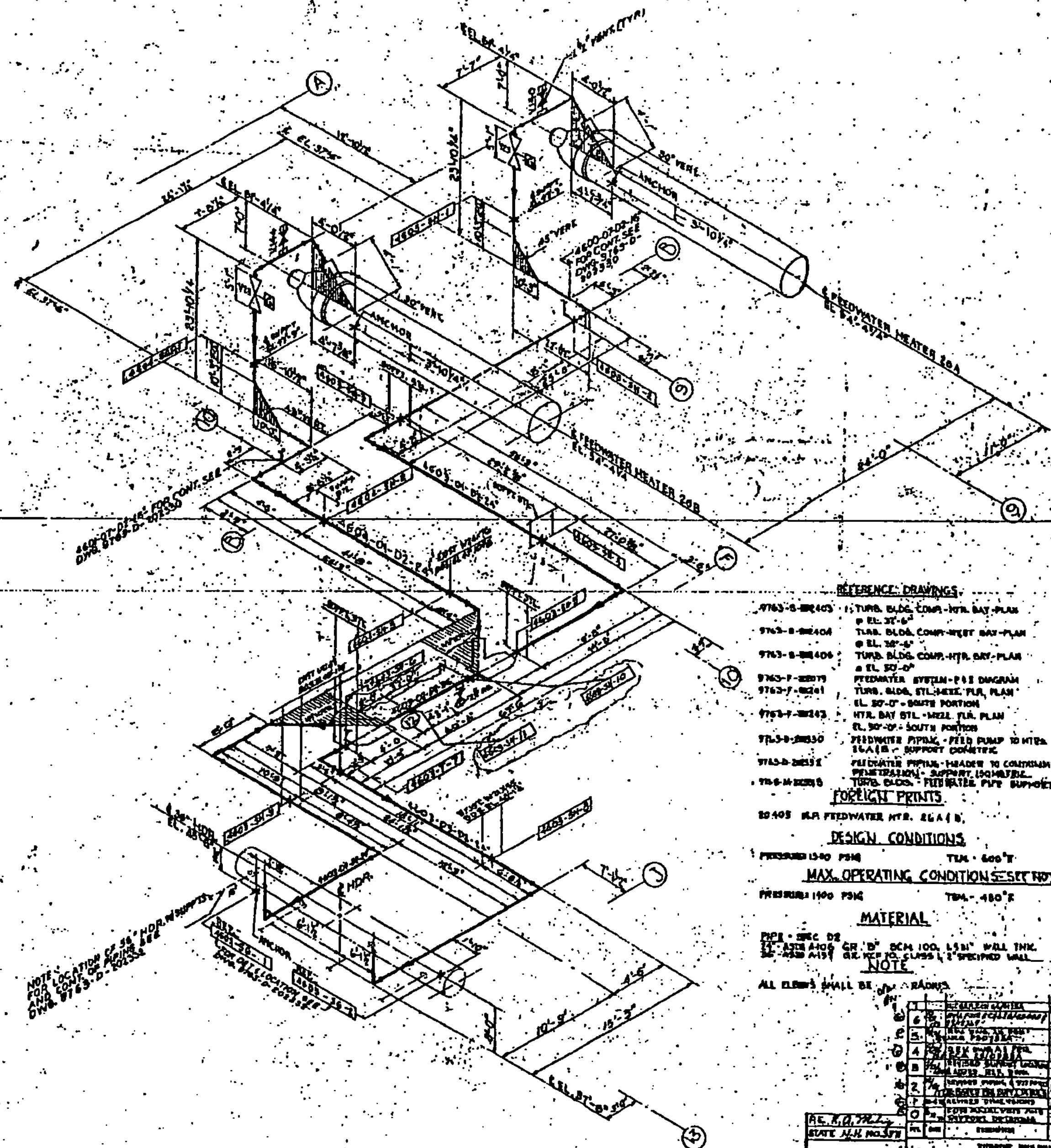
	5/14/01	10/22/01
-0.861136	1.1080	1.0594
-0.339981	1.0894	1.0682
0.33998	0.9448	0.9673
0.86114	0.7765	0.8175
S/L	0.926	0.922

Unit 2

	6/18/01	10/22/01
-0.861136	0.7263	0.7361
-0.339981	0.9301	0.9344
0.33998	1.1089	1.1022
0.86114	1.1385	1.1373
S/L	0.915	0.920

	6/18/01	10/22/01
Path 1	0.7338	0.7408
Path 2	0.9276	0.9327
Path 3	1.1020	1.0980
Path 4	1.1252	1.1240
Path 5	1.1518	1.1506
Path 6	1.1157	1.1063
Path 7	0.9326	0.9360
Path 8	0.7188	0.7313





Ⓐ NORMAL CONDITIONS, ALL LINES 450°F
Ⓑ WHEN BY PASSING HTR 26 A – LINE 4603-1 IS 380° F, LINE 4604-1 IS 450 F, OTHER LINES 415° F APPROX.
Ⓒ WHEN BY PASSING HTR 26 B, LINE 4604-1 IS 380° F, LINE 4604-1 IS 380° F, 4603-1 IS 450° F, OTHER LINES 415° F APPROX.

REFERENCE DRAWINGS

9763-S-202403	TURB. BLDG. COMP.-HTR. BAY-PLAN @ EL. 37'-6"
9763-S-202404	TURB. BLDG. COMP.-WEST BAY-PLAN @ EL. 38'-6"
9763-S-202406	TURB. BLDG. COMP.-HTR. BAY-PLAN @ EL. 50'-0"
9763-F-202079	FEEDWATER SYSTEM-P&I DIAGRAM
9763-F-202241	TURB. BLDG. STL.-MEZZ. FLR. PLAN EL. 50'-0" - SOUTH PORTION
9763-F-202243	HTR. BAY STL.-MEZZ. FLR. PLAN EL. 50'-0" - SOUTH PORTION
9763-D-202330	FEEDWATER PIPING - FEED PUMP TO HTRS. 26A & B - SUPPORT ISOMETRIC
9763-D-202332	FEEDWATER PIPING - HEADER TO CONTAINMENT PENETRATION - SUPPORT ISOMETRIC
9763-M-202515	TURB. BLDG. - FEEDWATER PIPE SUPPORT DETAILS

FOREIGN PRINTS

20405 H.P. FEEDWATER HTR. 26A & B.

DESIGN CONDITIONS

PRESSURE 1540 PSIG TEM. - 600°F

MAX. OPERATING CONDITIONS - SEE NOTES A, B & C

PRESSURE 1400 PSIG TEM. - 450°F

MATERIAL

PIPE - SPEC D2
24" - A106 GR. "B" SCH 100, 1.531" WALL THK.
36" - A155 GR. KCF 70, CLASS 1, 2" SPECIFIED WALL

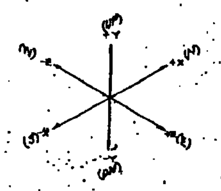
NOTE

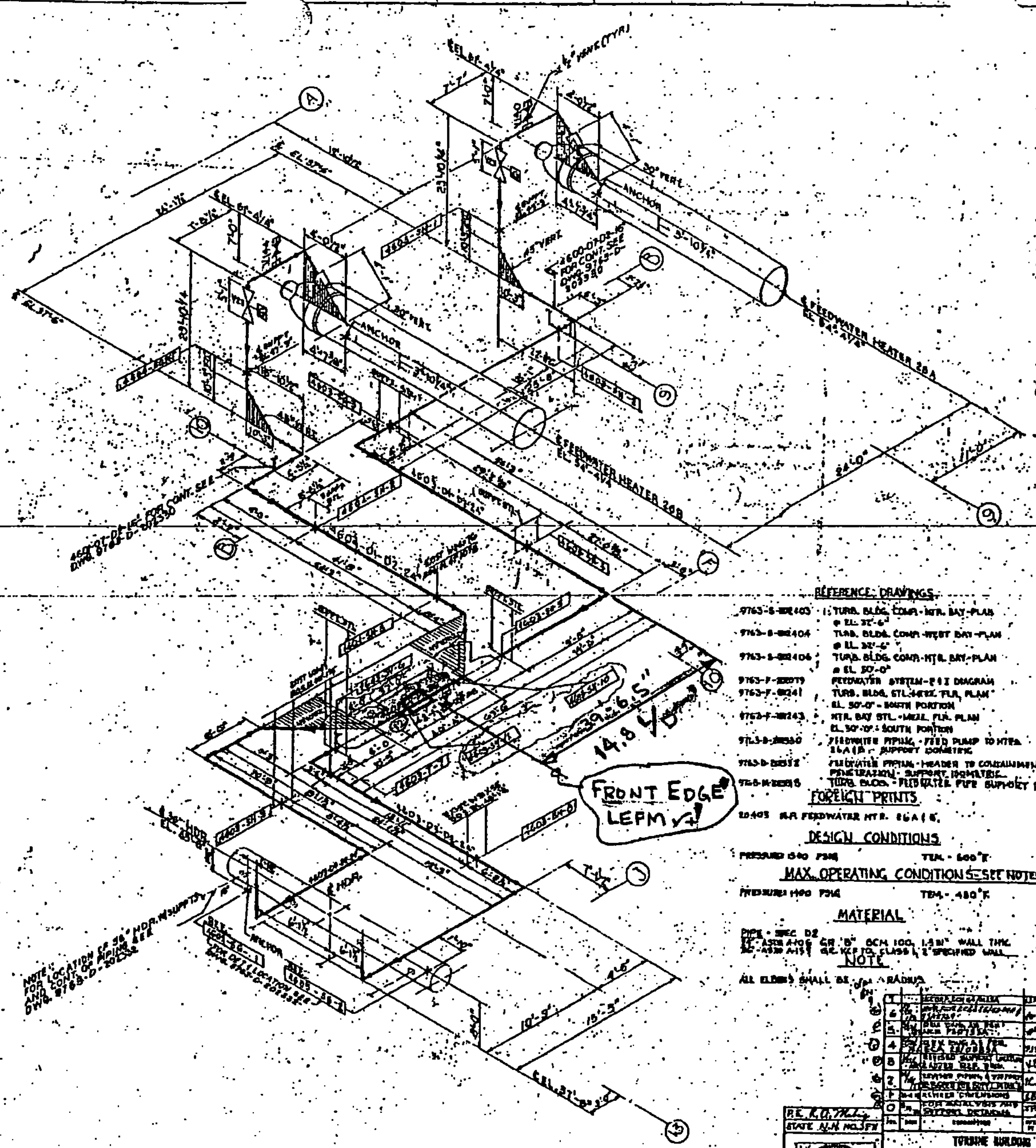
ALL ELBOWS SHALL BE ... RADIUS.

P.E. R.O. [illegible]
STATE N.H. NO. 379

TURBINE BUILDING
FEEDWATER SYSTEM - HEATERS 26A & B
SUPPORT ISOMETRIC
PUBLIC SERVICE CO. OF NEW HAMPSHIRE
SEABROOK STATION
united engineers
UNITS 1 AND 2
9763-D-202331

3 2 1





Ⓐ NORMAL CONDITIONS, ALL LINES 450°F
Ⓑ WHEN BY PASSING HTR 26 A - LINE 4603-1 IS 580°F, LINE 4604-1 IS 450°F, OTHER LINES 415°F APPROX.
Ⓒ WHEN BY PASSING HTR 26 B, LINE 4604-1 IS 580°F, LINE 4604-1 IS 580°F, 4603-1 IS 450°F, OTHER LINES 415°F APPROX.

REFERENCE DRAWINGS

9763-S-202403	TURB. BLDG. COMP.-HTR. BAY-PLAN @ EL. 32'-6"
9763-S-202404	TURB. BLDG. COMP.-WEST BAY-PLAN @ EL. 32'-6"
9763-S-202406	TURB. BLDG. COMP.-HTR. BAY-PLAN @ EL. 50'-0"
9763-F-200079	FEEDWATER SYSTEM-P & I DIAGRAM
9763-F-202241	TURB. BLDG. STL.-HORZ. FLR. PLAN EL. 50'-0" - SOUTH PORTION
9763-F-202243	HTR. BAY STL.-HORZ. FLR. PLAN EL. 50'-0" - SOUTH PORTION
9763-D-202330	FEEDWATER PIPING - FEED PUMP TO HTRS. 26A & B - SUPPORT ISOMETRIC
9763-D-202332	FEEDWATER PIPING - HEADER TO CONTAINMENT PENETRATION - SUPPORT ISOMETRIC
9763-M-202515	TURB. BLDG. - FEEDWATER PIPE SUPPORT DETAILS

FOREIGN PRINTS

20405 H.P. FEEDWATER HTR. 26 A & B.

DESIGN CONDITIONS

PRESSURE 1540 PSIG TEM. - 600°F

MAX. OPERATING CONDITIONS - SEE NOTES A, B & C

PRESSURE 1400 PSIG TEM. - 450°F

MATERIAL

PIPE - SPEC D2
14" - ASTM A106 GR "B" SCH 100, 1.531" WALL THK.
36" - ASTM A155 GR. KCF70, CLASS 1, 2" SPECIFIED WALL

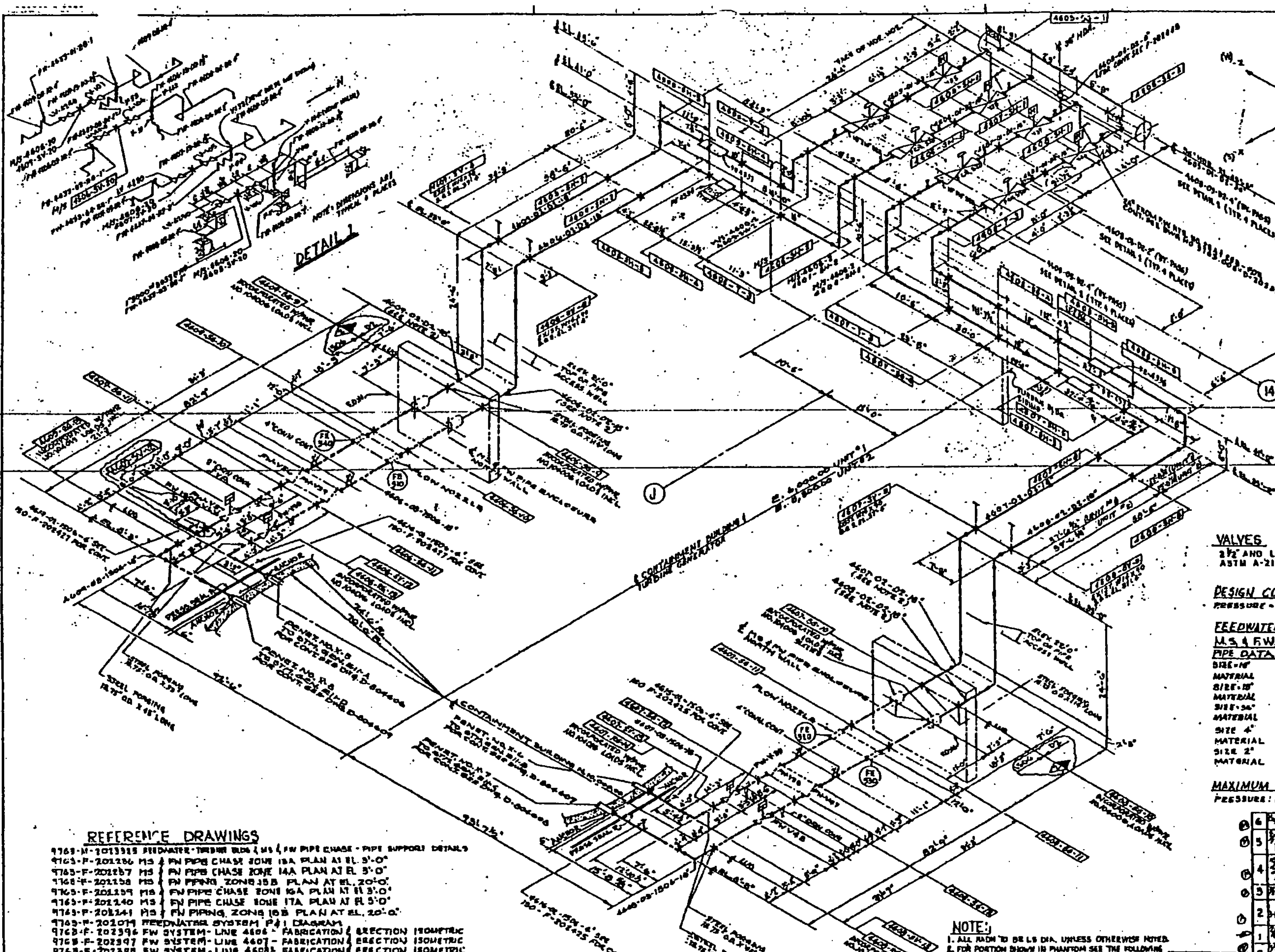
NOTE

ALL ELBOWS SHALL BE ... RADIUS

P.E. R.O. [illegible]
STATE N.H. NO. 3F9

TURBINE BUILDING
FEEDWATER SYSTEM - HEATERS 26A & B
SUPPORT ISOMETRIC
PUBLIC SERVICE CO. OF NEW HAMPSHIRE
SEABROOK STATION
united engineers
UNITS 1 AND 2 9763-D-202331

3 2 1



VALVES

2½" AND LARGER SHALL BE PER ASTM A-216 WCB 900# BW

DESIGN CONDITIONS

PRESSURE = 1350 PSIG   TEMP 600°F

FEEDWATER FROM 36" HEADER TO M.S. & F.W. PIPE CHASE

PIPE DATA

SIZE = 16"	WALL THK.-NOM. 1.031
MATERIAL	ASTM A106 GR. B.
SIZE = 18"	WALL THK. NOM. 1.156"
MATERIAL	ASTM A-106 GR. B
SIZE = 36"	WALL THK. NOM. 2.00"
MATERIAL	ASTM A-155 GR KCF70 CL
SIZE 4"	WALL THK. NOM. .337"
MATERIAL	ASTM A106 GR "B"
SIZE 2"	WALL THK NOM .218"
MATERIAL	ASTM A106 GR "B"

MAXIMUM OPERATING CONDITIONS

PRESSURE: 1400 PSIG. TEMP 450°F

REFERENCE DRAWINGS

9763-M-2013325 FEEDWATER-TURBINE BLDG & MS & FW PIPE CHASE - PIPE SUPPORT DETAILS
9763-F-202236 MS & FW PIPE CHASE ZONE 15A PLAN AT EL. 3'-0"
9763-F-202237 MS & FW PIPE CHASE ZONE 14A PLAN AT EL. 3'-0"
9763-F-202238 MS & FW PIPING ZONE 15B PLAN AT EL. 20'-0"
9763-F-202239 MS & FW PIPE CHASE ZONE 16A PLAN AT EL 3'-0"
9763-F-202240 MS & FW PIPE CHASE ZONE 17A PLAN AT EL 3'-0"
9763-F-202241 MS & FW PIPING ZONE 16B PLAN AT EL. 20'-0"
9763-F-202079 FEEDWATER SYSTEM P&I DIAGRAM
9763-F-202396 FW SYSTEM - LINE 4606 - FABRICATION & ERECTION ISOMETRIC
9763-F-202397 FW SYSTEM - LINE 4607 - FABRICATION & ERECTION ISOMETRIC
9763-F-202398 FW SYSTEM - LINE 4608 - FABRICATION & ERECTION ISOMETRIC
9763-F-202399 FW SYSTEM - LINE 4609 - FABRICATION & ERECTION ISOMETRIC

FOREIGN PRINTS

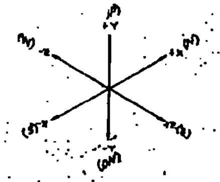
9763-20085 COPES VULCAN 16" CONTROL VALVE (FCV-510, 520, 530 & 540)
9763-20915 BORG WARNER 18" FEEDWATER ISOLATION VALVE (V-30, V-39, V-48 & V-57)
9763-90590 VELAN 16" MOTOR OPERATED GATE VALVE.
9763-52858 FLOW NOZZLE - GENERAL ARRANGEMENT.
9763-70698 LCV 4210, 4220, 4230, 4240.
9763-91372 18" CHECK VALVE - FW-V29, FW-V38, FW-V47 & FW-V56
9763-71560 FE-4134 THRU FE-4331

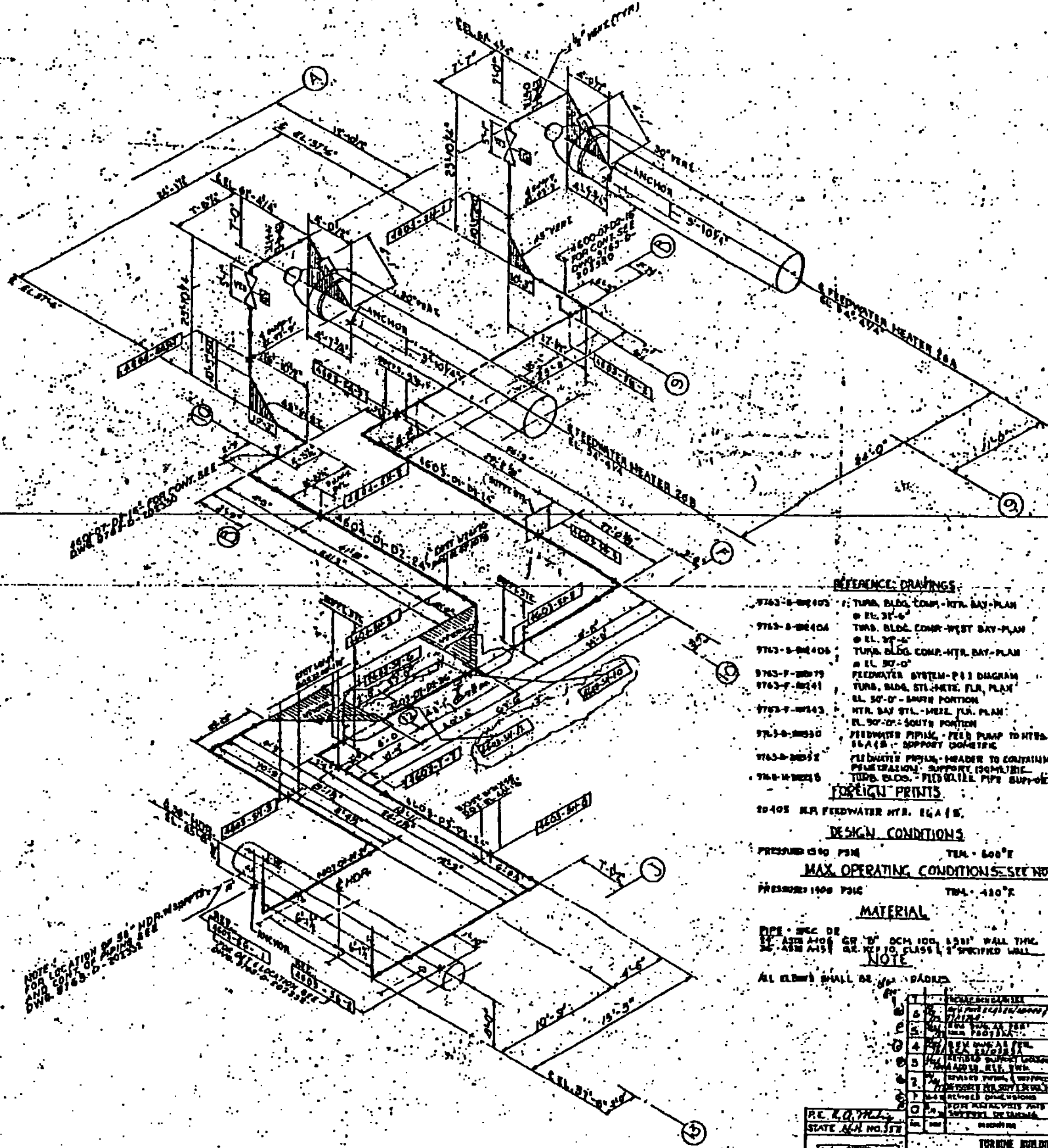
NOTE:

1. ALL RADII TO BE 1.5 DIA. UNLESS OTHERWISE NOTED.
2. FOR PORTION SHOWN IN PHANTOM SEE THE FOLLOWING DRAWINGS:
   LINE NO 4606 SEE DWG. 9763-F-202396
   LINE NO 4607 SEE DWG. 9763-F-202397
   LINE NO 4608 SEE DWG. 9763-F-202398
   LINE NO 4609 SEE DWG. 9763-F-202399

P.E. STATE N.H. NO. 371

TURBINE BUILDING
FEEDWATER SYSTEM
SUPPORT ISOMETRIC
PUBLIC SERVICE CO. OF NEW HAMPSHIRE
SEABROOK STATION
United Engineers
UNITS 1 AND 2   9763-D-202332





Ⓐ NORMAL CONDITIONS; ALL LINES 450°F
Ⓑ WHEN BY PASSING HTR. 26A — LINE 4603-1 IS 380°F, LINE 4604-1 IS 450°F, OTHER LINES 415°F APPROX.
Ⓒ WHEN BY PASSING HTR 26B; LINE 4604-1 IS 380°F, LINE 4604-1 IS 380°F, 4603-1 IS 450°F, OTHER LINES 415°F APPROX.

REFERENCE DRAWINGS

9763-[illegible]403	TURB. BLDG. COMP.-HTR. BAY-PLAN @ EL. 31'-6"
9763-[illegible]404	TURB. BLDG. COMP.-WEST BAY-PLAN @ EL. 31'-6"
9763-[illegible]406	TURB. BLDG. COMP.-HTR. BAY-PLAN @ EL. 50'-0"
9763-F-[illegible]79	FEEDWATER SYSTEM-P & I DIAGRAM
9763-F-[illegible]41	TURB. BLDG. STL.-MEZZ. FLR. PLAN EL. 50'-0" - SOUTH PORTION
9763-F-[illegible]43	HTR. BAY STL.-MEZZ. FLR. PLAN EL. 50'-0" - SOUTH PORTION
9763-D-[illegible]30	FEEDWATER PIPING - FEED PUMP TO HTRS. 26A & B - SUPPORT ISOMETRIC
9763-D-[illegible]32	FEEDWATER PIPING - HEADER TO CONTAINMENT PENETRATION - SUPPORT ISOMETRIC
9763-[illegible]6	TURB. BLDG. - FEEDWATER PIPE SUPPORT DETAILS

FOREIGN PRINTS

20405 H.P. FEEDWATER HTR. 26A & B.

DESIGN CONDITIONS

PRESSURE 1500 PSIG — TEM. - 600°F

MAX. OPERATING CONDITIONS - SEE NOTES A, B & C

PRESSURE 1400 PSIG — TEM. - 450°F

MATERIAL

PIPE - SPEC. DE
18" ASTM A106 GR. "B" SCH. 100, 1.531" WALL THK.
36" ASTM A155 GR. KCF 70 CLASS 1, 2" SPECIFIED WALL

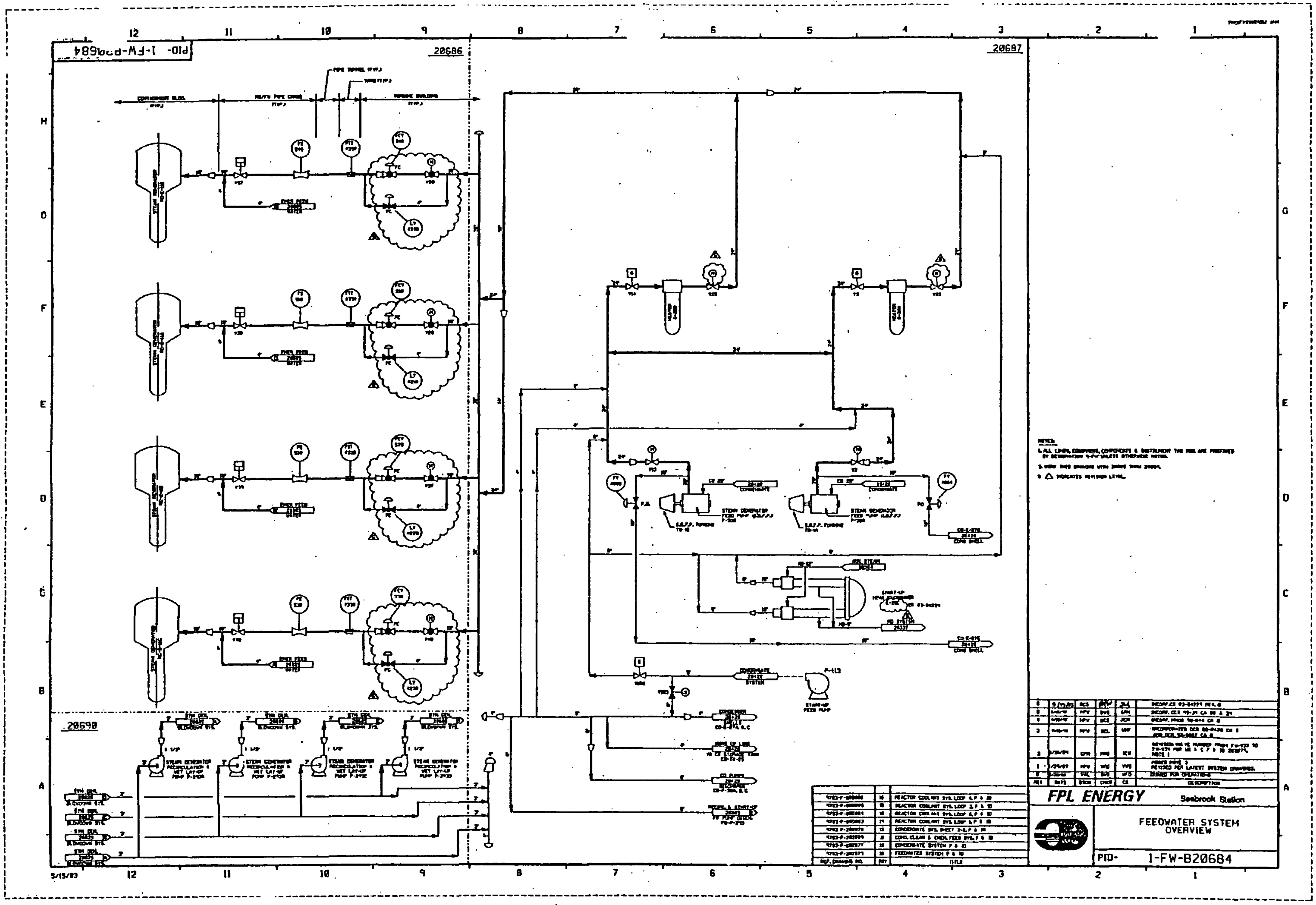
NOTE

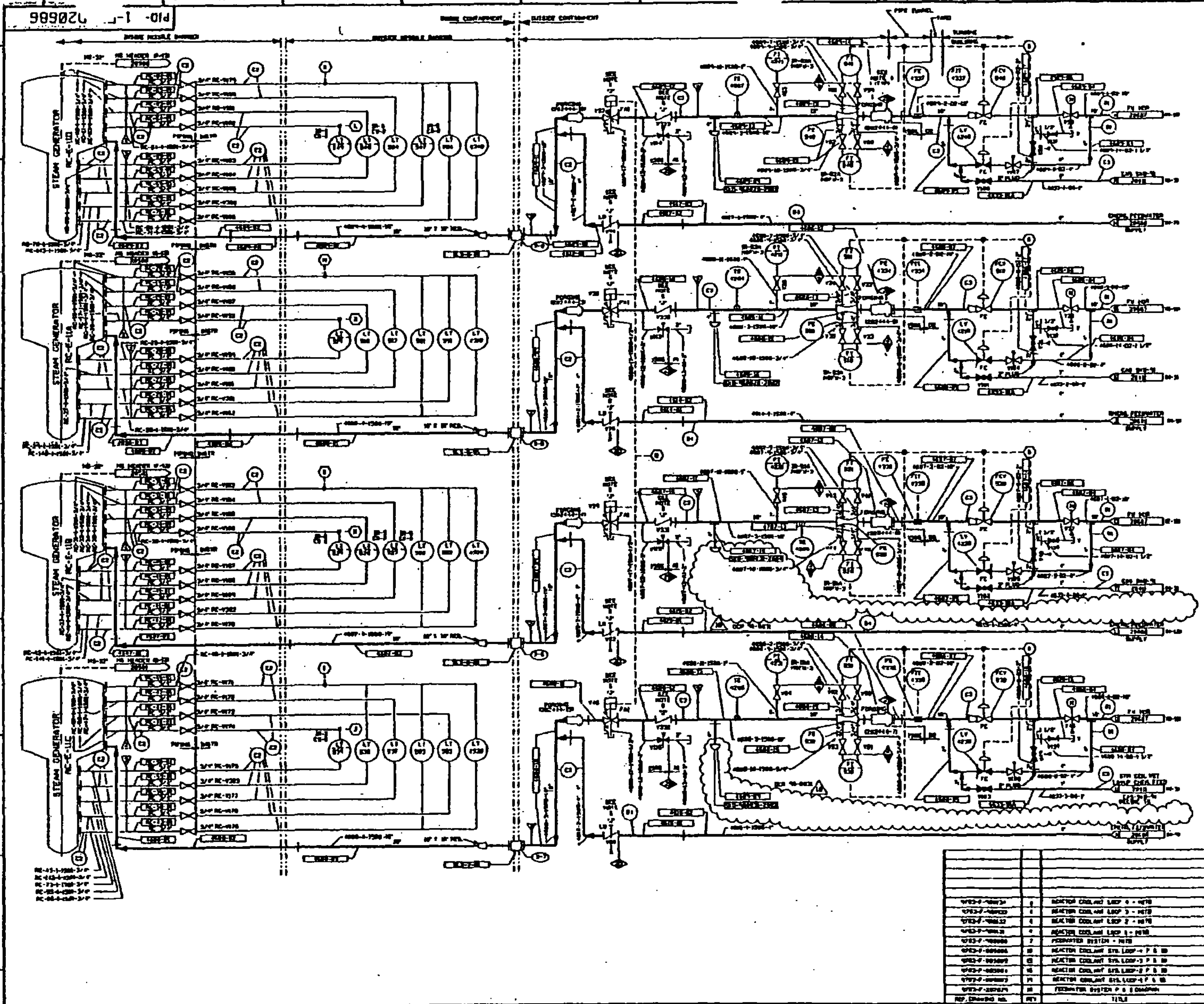
ALL ELBOWS SHALL BE [illegible] RADIUS

P.E. [illegible]
STATE N.H. NO. 378

TURBINE BUILDING
FEEDWATER SYSTEM - HEATERS 26A & B
SUPPORT ISOMETRIC.
PUBLIC SERVICE CO. OF NEW HAMPSHIRE
Seabrook Station
united engineers
UNITS 1 AND 2 — 9763-D-202331

3 — 2 — 1


20686
20687
20690
START-UP FEED PUMP
P-113
FPL ENERGY
Seabrook Station
FEEDWATER SYSTEM OVERVIEW
PID- 1-FW-B20684



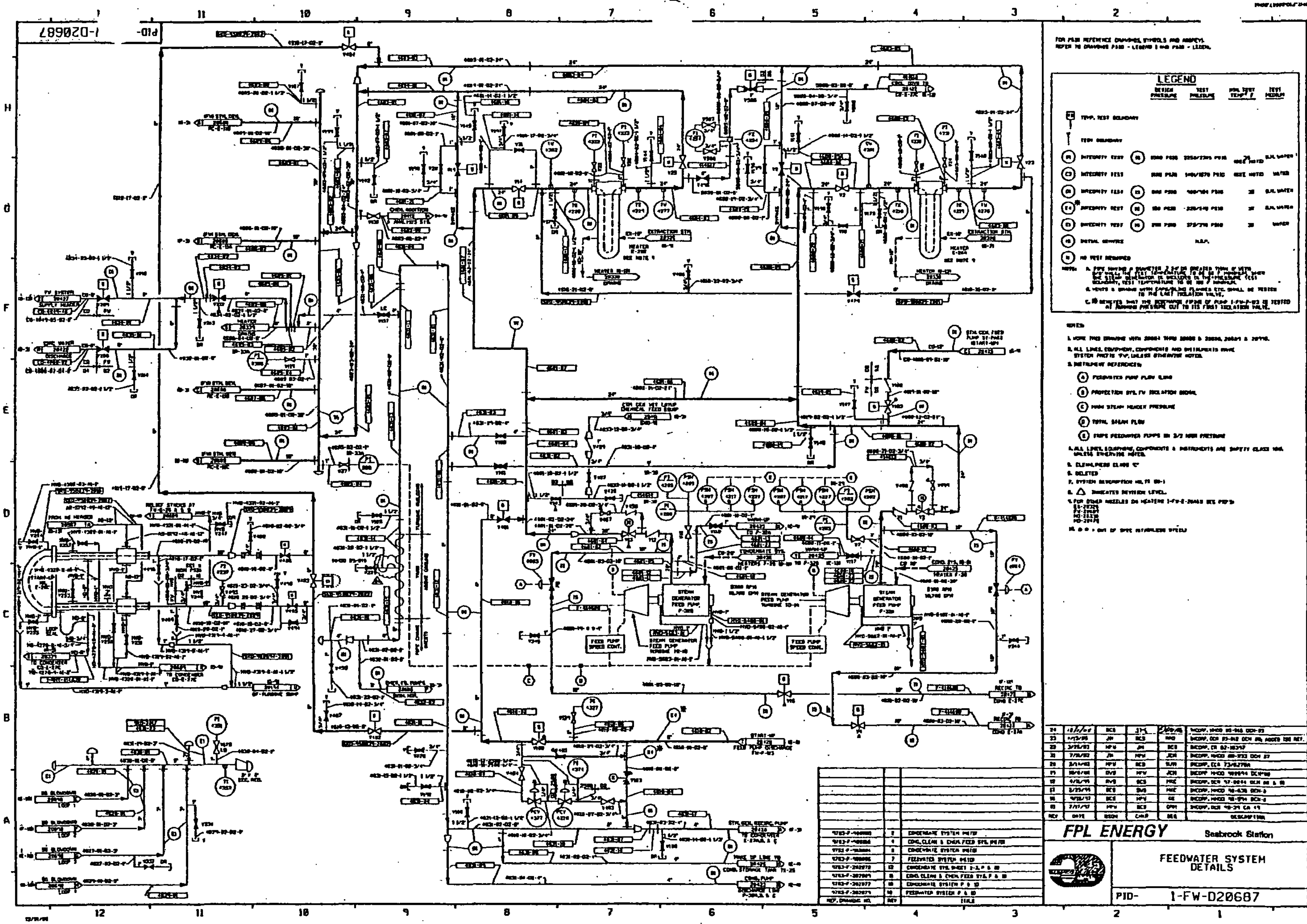
PORTIONS OF THIS DRAWING ARE

NUCLEAR SAFETY RELATED

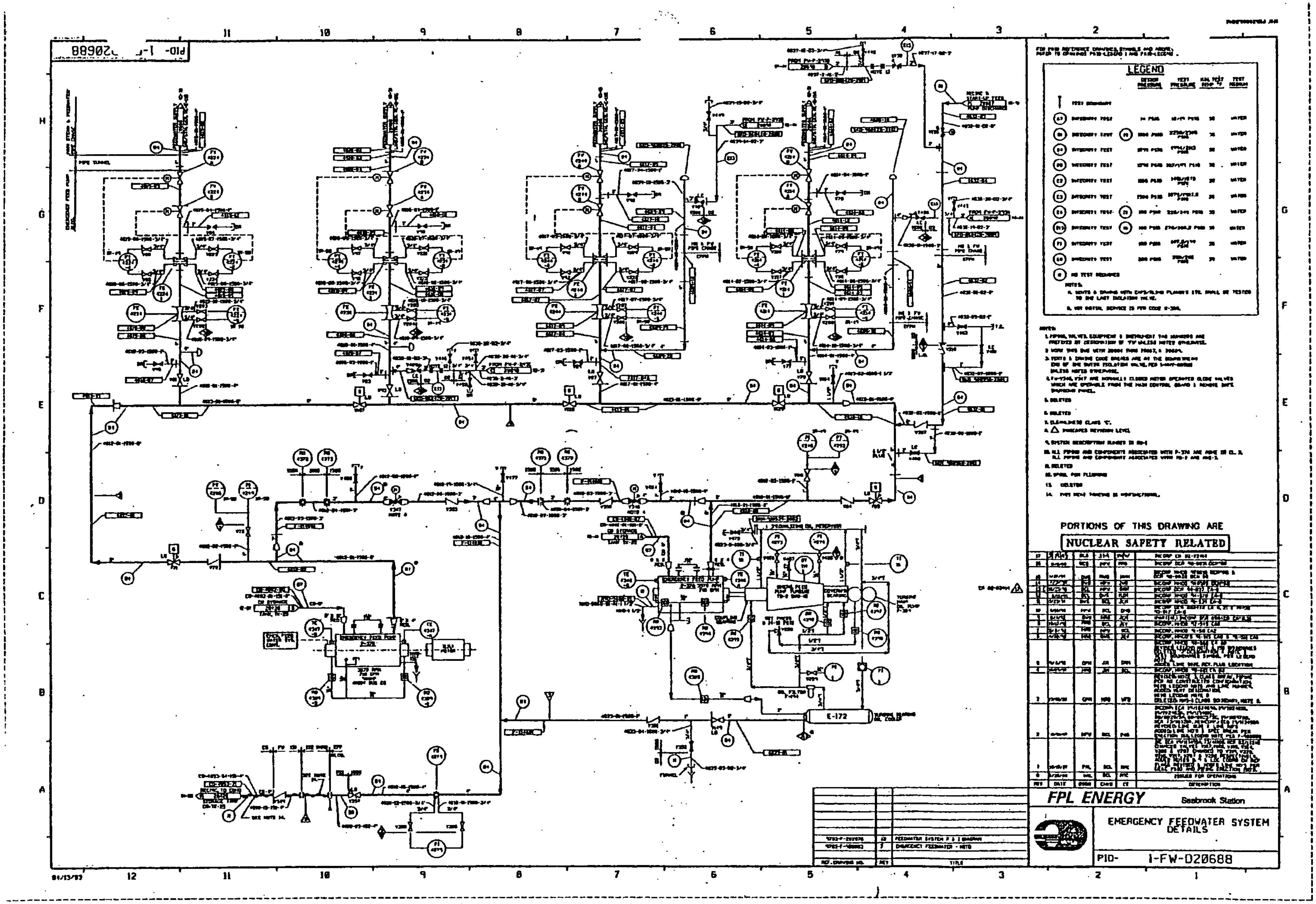
North Atlantic Energy Service Corporation

FEEDWATER SYSTEM
DETAILS

PID- 1-FW-D20686



P10-
1-D20687
LEGEND
DESIGN PRESSURE
TEST PRESSURE
FEED PUMP SPEED CONT.
FPL ENERGY
Seabrook Station
FEEDWATER SYSTEM DETAILS
PID-
1-FW-D20687


LEGEND
PORTIONS OF THIS DRAWING ARE
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Seabrook Station
EMERGENCY FEEDWATER SYSTEM DETAILS
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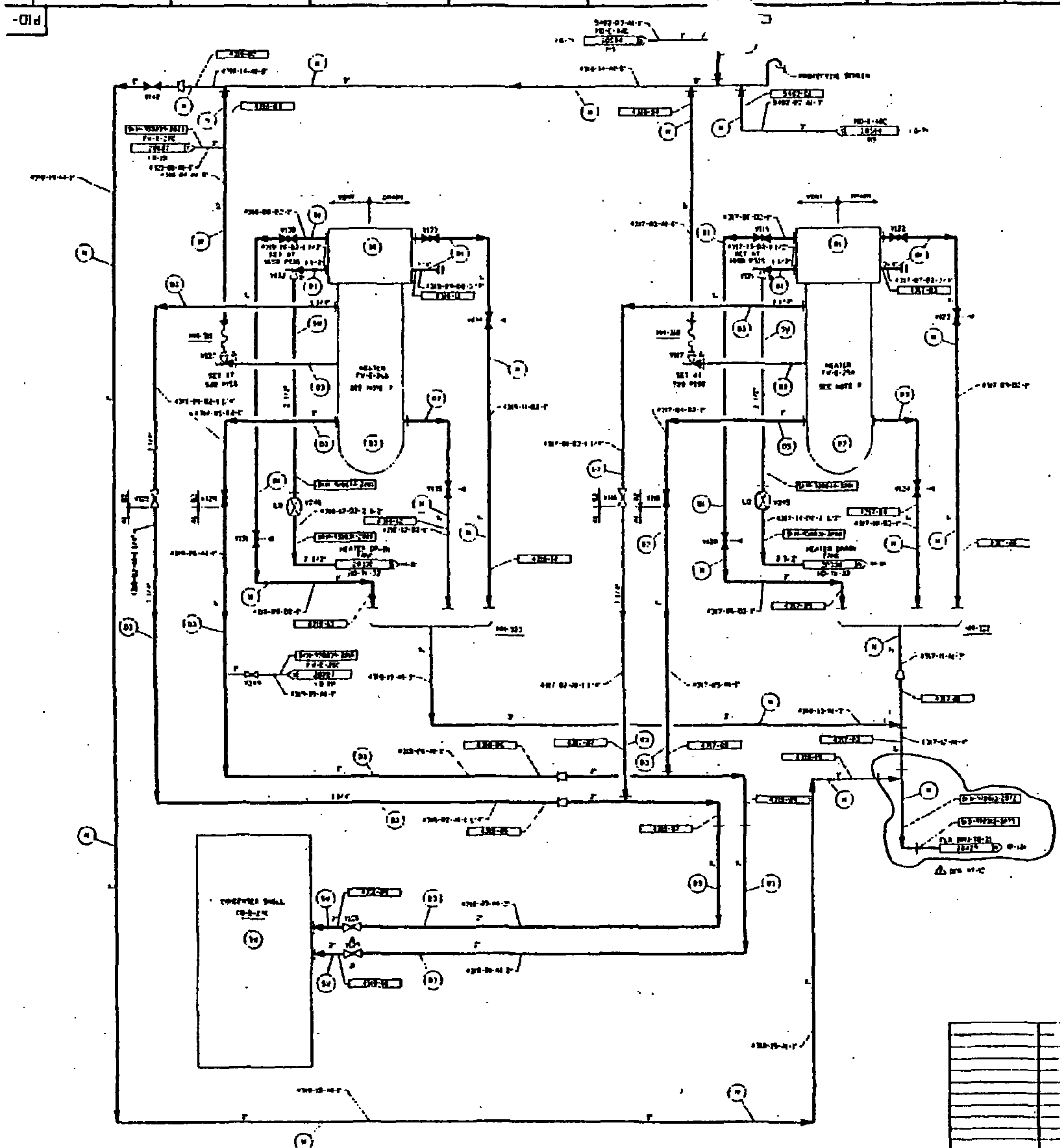
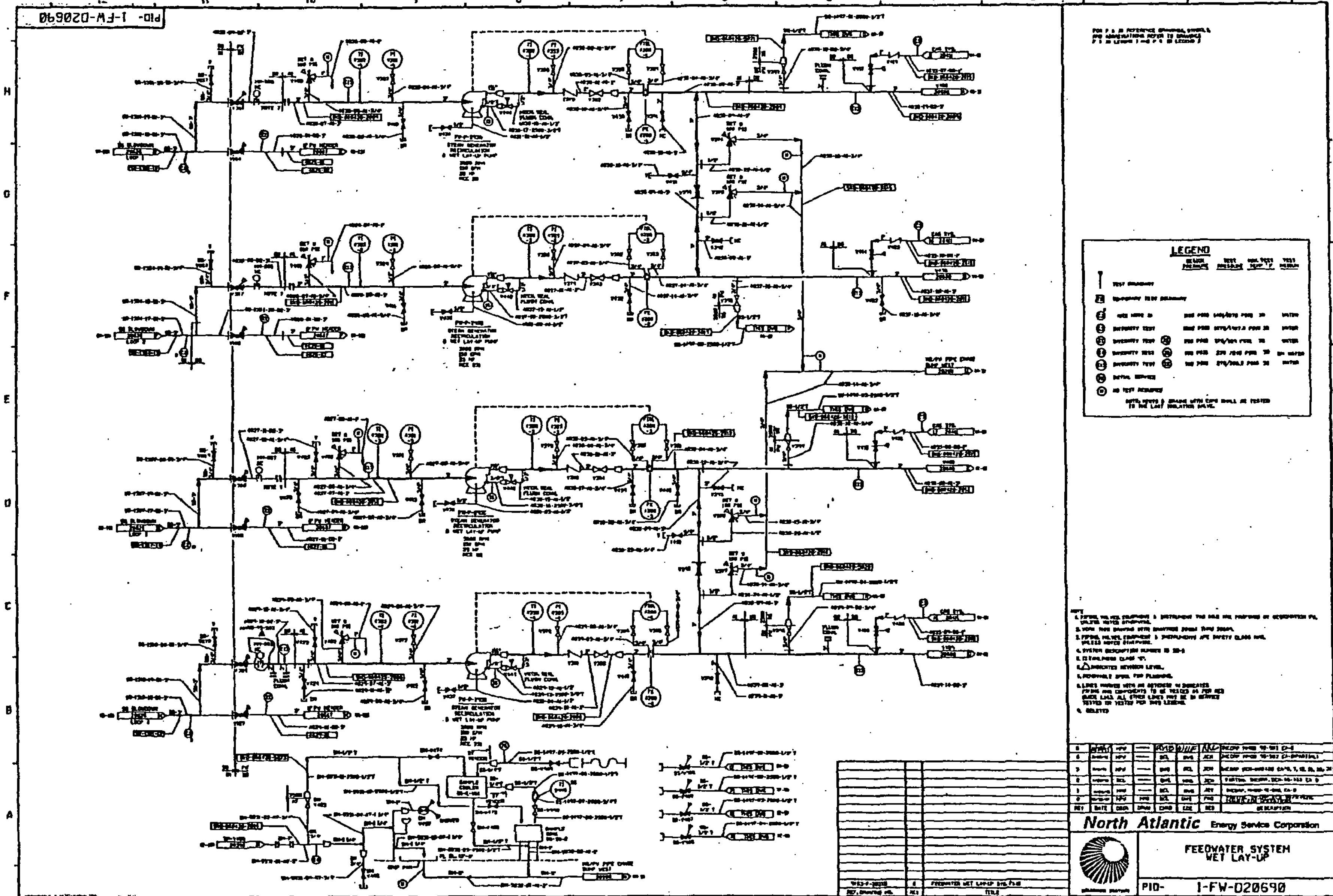


LEGEND

North Atlantic Energy Service Corporation

FEEDWATER SYSTEM
MISCELLANEOUS VENTS & DRAINS
DETAIL

PID- 1-FW-D20689



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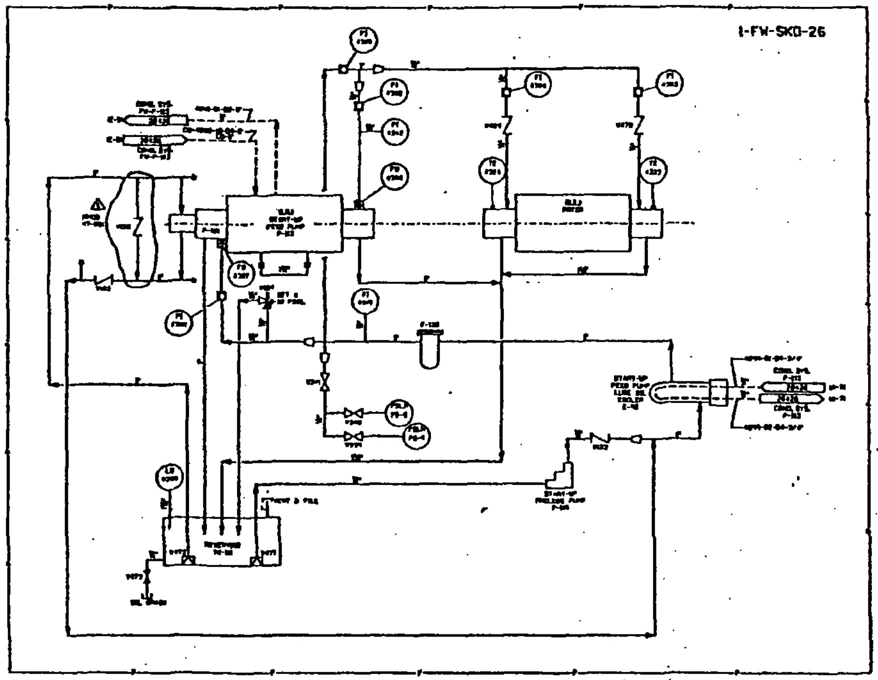
LEGEND
North Atlantic Energy Service Corporation
FEEDWATER SYSTEM
WET LAY-UP
PID- 1-FW-020690

PID- 1-FW-D20691



REV	DATE	DSGN	DRWN	CHKD	CKE	RES	DESCRIPTION
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0	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]	ISSUED FOR OPERATIONS

North Atlantic Energy Service Corporation

LUBE OIL PIPING
FOR SKD-26

PID- 1-FW-D20691

Forth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies (NPIC&HMIT 2004), Columbus, Ohio, September, 2004

Traceability of Thermal Power Measurements

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Part 1
Chordal Ultrasonic Flow Measurements

ABSTRACT

The traceability of a measurement of nuclear feedwater mass flow by a chordal ultrasonic meter is described, with particular emphasis on the methodology whereby transit time measurements and calibration factors used in the field can be traced to an appropriate standard. This paper is a companion to a paper considering the challenges of traceability of feedwater flow measurements by flow nozzles and venturi tubes.

1. INTRODUCTION

A continuous, accurate determination of thermal power is an essential requirement in the operation of a nuclear power plant. Errors in the power determination can cause lost revenue or reduced safety margin—both serious consequences. It is therefore appropriate that the rigor of traceability be applied to each component of the thermal power determination. The desirability to apply rigorous traceability requirements to thermal power determinations is underlined by recent problems with flow instrumentation in nuclear applications.

Traceability is defined as a process whereby a measurement can be related to a standard via a chain of comparisons (International Standards Organization, Reference (1)). Certain requirements apply:

- The standard must be acceptable to all parties with an interest in the measurement and is usually a standard maintained by a national laboratory such as the National Institute of Standards and Technology.
- The chain of comparisons must be unbroken—the field measurement must be connected, by one or more links directly to the standard.
- Every link in the chain involves a comparison that necessarily carries with it an uncertainty. Hence the total uncertainty of the measurement must reflect the aggregate uncertainties of each link of the comparison chain.
- There can be no unverified assumptions in the chain of comparisons; it is clearly not possible rationally to assign an uncertainty to an assumption with no quantitative basis.

In virtually all light water nuclear power plants, thermal power is determined by a power balance around the steam supply. The process involves measuring or otherwise determining the following principal process variables:

(1) The total mass flow into the steam supply, W_{FW}, the total feedwater flow, and the blowdown flow removed from the steam supply (if any), W_{BD}. W_{BD} is returned, purified, via the feedwater system. The third mass flow component of a steam supply mass balance, the steam flow, necessarily equals the difference between the feedwater flow and the blowdown flow in the steady state.[+]
(2) The specific enthalpy of the water fed to the steam supply, h_{FW}
(3) The specific enthalpies of the steam, h_S, and the blowdown, h_f, exiting the steam supply, (it is generally assumed that the blowdown flow exits the steam supply as saturated liquid)

The blowdown energy flow is typically in the order of ½% of the total power. This term does not appear in the power balance for BWRs where the blowdown function is carried out by the reactor water cleanup system, or on PWRs that employ once-through steam generators.

Since the objective of the steam supply power balance is to determine the thermal power generated by the reactor core, there are other gains and losses, such as the power added by reactor coolant pumps, that must be accounted. Although the net of these terms rarely aggregates to more than a fraction of 1% of the reactor power rating, diligence requires that they be measured or otherwise determined and that the uncertainties in these measurements be accounted. This paper, however, will focus on the steam supply power balance and more specifically on the traceability of the measurement that affects the thermal power determination most substantially: the mass rate of feedwater flow, W_{FW}.

No instrument measures this variable directly. Two diverse types of instruments are analyzed in this paper and its companion paper:

[+] In Boiling Water Reactors, a fourth component, the Control Rod Drive Mechanism flow, delivered to the steam supply, is also accounted. This flow is a very small fraction of the feedwater flow and need not be determined with great precision for a thermal power determination.

(1) A chordal ultrasonic flowmeter, an instrument that measures the transit times of ultrasonic pulses traveling along chordal paths in a flow element and from these measurements and a measurement of fluid pressure calculates the mass rate of feedwater flow and the feedwater temperature.

(2) A flow nozzle, an instrument that measures difference in static pressures between a tap upstream of the nozzle and a tap in the throat of the nozzle and from this differential pressure measurement and a determination of feedwater density, determines the mass rate of feedwater flow. The density determination is made using a final feedwater temperature measurement, usually from a resistance temperature detector or RTD.

This paper analyzes the traceability chains for the first of these instruments: from its basic measurements--transit times and fluid pressure--to the process variable W_{FW}. It covers explicitly the calibration uncertainties of the flow element(s), including the application of the flow element calibration data taken in a hydraulics facility operating at 100 F and 50 psig to the 430 to 450 F, 1000 to 1200 psig conditions in a nuclear feedwater system at full power. From the analyses of this paper, the reader will obtain an understanding of the factors affecting the traceability and accuracy of a chordal ultrasonic feedwater flow instrument.

2. DISCUSSION

The algorithms, and traceability chains for a chordal ultrasonic flow measuring instrument are outlined below. For the principles underlying this type of measurement, the reader is referred to the technical literature (Estrada, Reference (2)).

The discussion is based on an ultrasonic meter having eight paths arranged in two planes of four chords each, at right angles to each other and at a nominal 45° with respect to the axis of the flow element. Because orthogonal paths are paired in four planes parallel to the major axis of the flow element, transverse velocities projected onto each path pair cancel when the velocity measurements of a pair of paths are averaged. Hence the path arrangement makes this eight path flow meter insensitive to variations in transverse velocity. The chordal arrangement of the paired paths provides axial velocity measurements for each of the four chordal locations. As will be seen, these data can be used to characterize the axial velocity profile.

As derived in Reference (2), the mass flow rate, as determined by a chordal ultrasonic flow meter manufactured by Caldon, Inc. is calculated by (1) the numerical integration of the axial fluid velocity over the pipe cross section to determine the volumetric flow rate, and (2) by multiplying the result by the spatial average of the fluid density. The axial fluid velocity at each of the four chordal locations is determined from the transit times of ultrasonic pulses traveling with and against the direction of flow along the path. Specifically, the mass flow algorithm is:

$$W_f = \rho \cdot PF \cdot F_{a3}(T) \cdot (ID/2) \sum_{i=1}^{4} \frac{w_i L_{fi}^2 (\Delta t_i)}{\tan(\varphi_i)(t_i + \Delta t_i / 2 - \tau_i)^2} \qquad (1)$$

Where W_f = the mass flow rate through the chordal ultrasonic meter, (lbs/sec)

ρ	=	the mean feedwater density, (lbs/cu. in.)
PF	=	the profile (or meter) factor, dimensionless
F_{a3} (T)	=	the thermal expansion factor. This factor accounts for the difference in internal diameter and transducer face-to-face distance (Lffi) at operating temperature T versus the temperature at which dimensions were measured T_0. $F_{a3}(T) = 1 + 3\alpha(T-T_0)$, where α is the coefficient of thermal expansion of the flow element material in (in./in./°F)
ID	=	the internal diameter of the spool piece, (in.)
w_i	=	the Gaussian quadrature integration weighting factor for path i, (dimensionless)
φ_i	=	the angle between path i and a normal to the spool piece axis (deg)
L_{ffi}	=	the face-to-face distance between transducer housings of path i, (in.)
t_i	=	the total time of flight of pulse along path i in the direction of flow,(sec.)
t_{upi}	=	the total time of flight along path i against the direction of flow, (sec.)
Δt_i	=	the difference in the total transit times of pulses traveling against the flow and with the flow along path i, (sec.); $\Delta t_i = t_i - t_{upi}$, (sec.)
τ_i	=	the total of the non-fluid delays of pulses traveling along path i, (sec.)
T	=	the mean fluid temperature, (°F)

Note that the numerical integration above is carried out for four area segments, although the number of chordal paths is eight. This is because the average of the two velocities measured at each chordal location is, in effect, used to establish the *axial* fluid velocity at that location, which is the variable to be integrated over the pipe cross section.

To determine the thermal expansion, the fluid temperature is needed. To determine the density, the fluid temperature and its pressure are needed. For a measurement of feedwater flow with a Caldon chordal system, the fluid pressure is measured by a conventional pressure transmitter. The temperature is determined from a measurement of the sound velocity, averaged over the pipe cross section and the fluid pressure. The square of the velocity c of pressure wave propagation through a fluid (the sound velocity) is related to the other state variables for the fluid by the partial derivative of fluid pressure p with respect to density ρ along a line of constant entropy, s.

$$c^2 = \partial p/\partial\rho|_s \tag{2}$$

The precision of property tables for steam and water (For example, Reference (3)) is, however, insufficient for an accurate determination of fluid temperature from its sound velocity. Caldon measurement systems therefore rely on a proprietary algorithm, derived from experimental data and confirmed by a large number of comparisons with RTD data (Estrada, Reference (4)).

Expressing the methods employed for determining density and temperature algebraically:

$$\rho = f_\rho\ (T, p) \tag{3}$$

$$T = f_T\ (c_{mean}, p) \tag{4}$$

$$c_{mean} = F_{a1}\ (T) \sum_{i=1}^{4} [w_i\ L_{ffi}]/[t_i + (\Delta t_i/2) - \tau_i] \tag{5}$$

Here $F_{a1}(T) = 1 + \alpha\ (T - T_0)$

The function f_ρ for the determination of density is extracted from the ASME steam tables (previously referenced). The function f_T is Caldon's proprietary algorithm. Note that for each set of time and pressure measurements, the procedure for determining temperature and sound velocity is iterative. This is necessary because the determination of sound velocity is itself sensitive to temperature as evidenced by the F_{a1} (T) term in the equation for the mean sound velocity, c_{mean}. This term accounts for the thermal expansion of the path lengths L_{ffi} from the temperature at which they are measured to the temperature at which the sound velocity is measured.

Fundamentally, the traceability of the mass flow algorithm for a chordal ultrasonic meter requires that a chain of comparisons be constructed for the following elements of that algorithm:

1. The Profile Factor, PF
   This term essentially characterizes the response of the meter to the axial velocity profile it will see in the field (the numerical integration performed by the meter does not integrate the profile perfectly). For Caldon ultrasonic meters, PF is measured in a hydraulic model of the field application at a certified and traceable hydraulic test facility. Because the flow element to be installed in the field is calibrated, measurement errors in the internal diameter, ID, the path angles, φ_i, and, to the extent that they affect the volumetric flow measurement, the path lengths, L_{ffi} are embedded in the Profile Factor and do not affect the accuracy of the field measurement.
2. The time measurements, t_i and t_{upi}
   Clearly, the flow measurement accuracy is affected by the accuracy with which the pulse transit times are measured. Furthermore, errors in the measurement of time may small enough not to affect the accuracy of the t measurements, but if they are not reciprocal, can affect the accuracy of the Δt measurement, which can be seen in the algorithm to be critical to overall measurement accuracy
3. The total non-fluid delays in each path, τ_i
   The non fluid delays consist of the energy transit delays from the transmitter through the transducer cables, the transducers themselves, the acoustic "windows" which serve as interfaces between the transducers and the flowing fluid, the receiving electronics, to the pulse detection logic. Values for the non fluid delays are, like the internal diameter and path angles, embedded in the calibration factor. However, the non fluid delays in the field may differ from those in the lab due to different conditions (e.g., different temperatures of the acoustic window) or different components (e.g., cables of longer length); hence

traceability of the field values of the non fluid delays is required. Although mechanisms whereby non fluid delays might change in service are few, some assurance that any change over time is within the uncertainty bounds of the comparison chain is required for measurements in the field.

4. The fluid pressure, p
A measurement of fluid pressure is necessary to the determination of temperature and density. [The dimensions of the flow element also change with pressure, but the design is such that the effect on the mass flow measurement is negligible.] The chain of comparisons for the verification of the pressure indications is fairly commonplace, involving allowances for uncertainties in the secondary standards used for calibration, allowances for drift in the transmitter due to environmental and other effects while in service, hysteresis and other non-linear properties of the transmitter, and uncertainties due to the length, configuration and density of the fluid in the transmitter impulse line.
5. The individual path lengths L_{fi}
As noted above, errors in path length as regards the volumetric flow determination are imbedded in the calibration factor (PF). However, knowledge of the absolute value of the path lengths is needed for the iterative computation of sound velocity and fluid temperature (see equations (4) and (5) above). The comparison chain for path length is straightforward, involving, primarily, the secondary standard used for its measurement and observational uncertainties. However, assurance must be provided that the path length does not change in service, due for example to the deposition of corrosion products.

It is also necessary to verify, by a chain of comparisons, the correlation functions f_p, f_T, and the thermal expansion terms F_{a1} and F_{a3} (the latter terms involve the coefficient of thermal expansion for the flow element material). However, these verifications can be performed on a one-time basis. Once accomplished, it is not necessary to reverify the functions to confirm their correctness in a specific measurement.

The weighting factors, w_i, and the transverse path locations, which do not appear explicitly in the algorithm but are implicit in the weighting factors, are standard factors for four path Gaussian Quadrature integration (Legendre spacing). Any departure of the spacing from nominal is embedded in the meter calibration factor, that is, the profile factor PF.

Of the five measurements whose traceability is required for the verification of the accuracy of a feedwater flow measurement, the most critical are the Profile Factor, and the time measurements. The balance of this paper will therefore focus on the chain of comparisons used to ensure that the uncertainties in these components of the flow computation remain within the design allowances for their respective chains of comparisons.[++]

Figure 1 is a diagram of the chain of comparisons used to verify the measurements of ultrasonic pulse transit times. The need to establish traceability for the

++ The traceability chains for the remaining three variables—non fluid delay, pressure, and path lengths—will be made available on the Caldon Website.

transit time measurement clock (the first link of the chain) is obvious. Additional assurance that environmental or other mechanisms do not degrade this secondary standard in the field is provided by an additional automatic check of the clock against and independent and diverse time standard (the second link of the chain).

The chain of comparisons for the verification of pulse transit time measurements requires more than a check of the clocks, however. The pulse timing starts with the initiation of transmission, a precisely defined event. But the detection of a pulse after its transit and a precise, repeatable measurement of its time of arrival present several challenges. The remaining checks of the comparison chain of Figure 1 are for the purpose of ensuring that the pulse detection and arrival time measurement comply with the assumptions of the meter's uncertainty analysis.

A detailed description of the means for pulse detection in Caldon's ultrasonic meters is beyond the scope of this paper. Briefly, however, following pulse detection, the zero crossing of a half cycle near the leading edge of the received pulse is used to define the end point of the transit time (from which process the Caldon Trade Name Leading Edge Flow Meter derives). The zero crossing is used rather than an amplitude threshold because it is insensitive to fluctuations in pulse amplitude due to turbulent refraction and other effects. The accuracy of this measurement can be affected by several factors, the most important of which are the magnitude of noise that may be imbedded in the signal and, particularly with respect to the measurement of the time difference Δt, non-reciprocal delays in the upstream and downstream pulse transits (the latter effects are brought about by non linearities in the transmission process and by differences in the delays in receiving electronics). As can be seen from the figure, checks are performed to confirm that actual meter performance complies with the assumptions of the analysis that establishes its uncertainty. Specifically, the magnitude of the noise relative to the signal is measured and the reciprocity of signals received by upstream and downstream transducers is confirmed. Several other checks are performed to ensure that statistical assumptions of the uncertainty analysis remain valid.

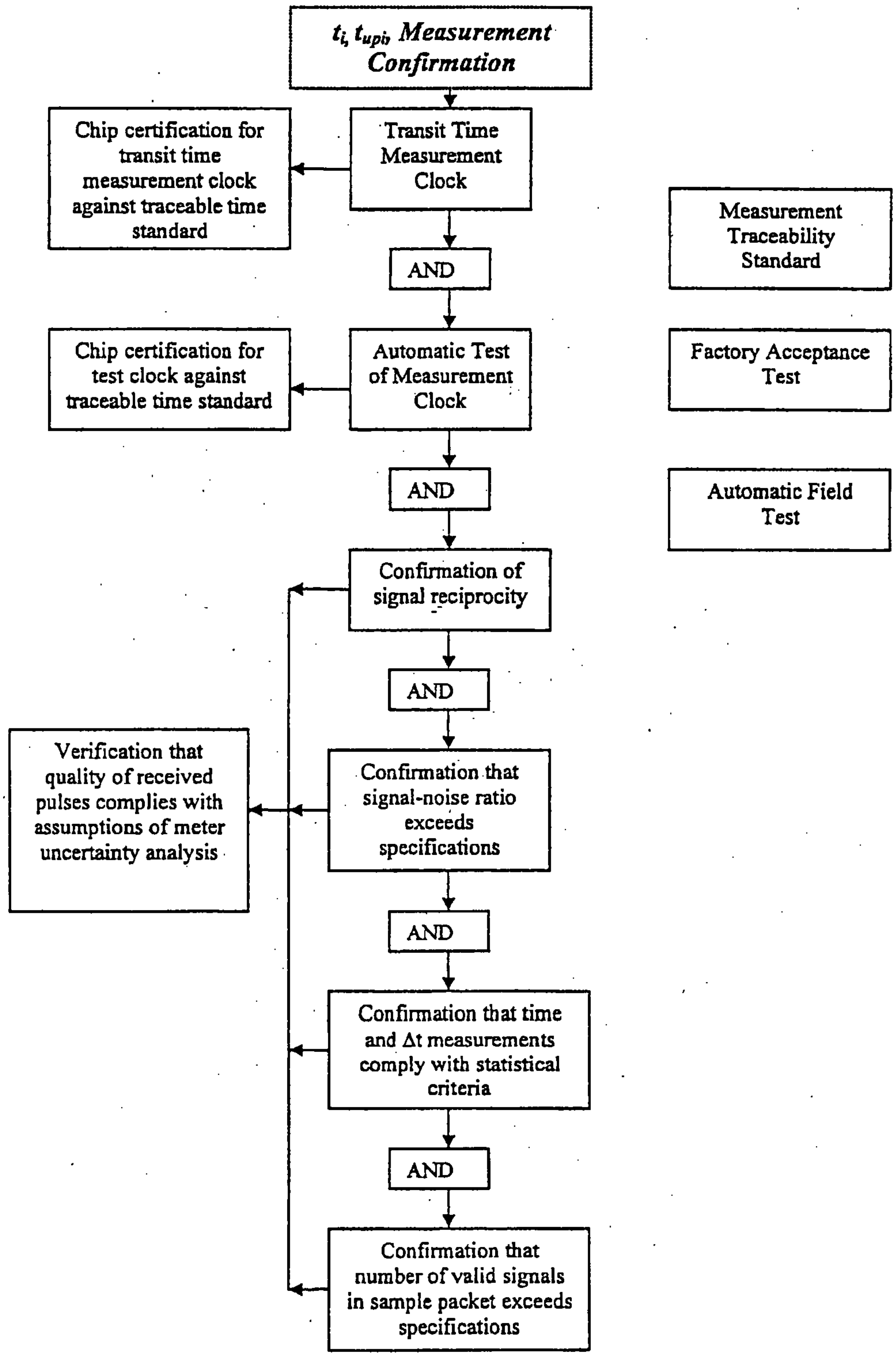


Fig. 1: Comparison Chain

The appropriate procedures for establishing the calibrations—meter factors—of instruments used to measure feedwater flow in nuclear and fossil power plants has long been the subject of debate among measurement specialists. The problem is that fluid conditions in the laboratory do not and cannot duplicate fluid conditions in the field--the maximum Reynolds Number achievable in a certified facility is about 3 or 4 million; the Reynolds Number at full power in the feedwater system of a typical nuclear or fossil steam plant is in the order of 10 to 30 million. A chordal ultrasonic meter performs a numerical integration of the axial velocity profile; the axial velocity profile is, in some circumstances, sensitive to Reynolds Number. From the perspective of traceability, one question that must be addressed is how does one verify whatever assumption one has made relative to the behavior of axial profile with increasing Reynolds Number?

Axial profiles are not a function of Reynolds Number only, however. In many applications including some feedwater systems, the thickness of the boundary layer is dominated not by fluid viscosity, but by the roughness of the pipe wall. In these applications the profile is insensitive to Reynolds Number, but is affected by the relative roughness. Furthermore, in nuclear and fossil feedwater applications, the flow profile is rarely, if ever, "fully developed"; its shape instead reflects the inertial forces exerted on the fluid by upstream hydraulic features. The specific nature of these features is a third (and in many cases dominant) determinate of profile.

The shape of reasonably symmetrical axial velocity profiles of fluid flowing in the turbulent regime can be numerically described using the inverse power law (Schlichting, Reference (5)). This mathematical representation also allows a profile to be related to the chordal velocity measurements of an ultrasonic transit time meter. (Estrada, Reference (6)). Specifically, the chordal arrangement of Caldon's eight path ultrasonic flow meter, permits the shape of the axial velocity profile to be characterized using the ratio of the average of the velocities measured along the outside (short) chords to the average of the velocities measured along the inside chords. This ratio, called the flatness, can be used to predict the response of ultrasonic meters in both eight path and four path configurations to changes in velocity profile. The flatness ratio defines how flat a flow profile is as compared to other measured profiles. The flatter the velocity profile, the higher the flatness ratio. A perfectly flat profile has a flatness of 1.0. Developed turbulent flow profiles in straight pipe with high relative roughness or low (~10,000) Reynolds number will have a flatness in the 0.75 to 0.8 range. Developed profiles at high (10 million) Reynolds number in pipe of nominal roughness will produce a flatness of about 0.86; if the pipe is hydraulically smooth a flatness of up to 0.9 is obtained. Downstream of non-planar bends and similar features, flatness can approach 0.98 or more. For nuclear feedwater flow measurements, the flatness for actual profiles measured in service have ranged from 0.81 to 1.01 (in the latter case, the profile was "dished"). About half of them have a flatness of greater than 0.9, which as noted above is the flatness of a fully developed profile in hydraulically smooth pipe. In these cases clearly (and in many of the others), inertial features such as bends and header exits have had a greater influence on profile than either the Reynolds Number or the relative roughness. It should also be noted that many of the inertially dominated profiles are present in locations where conventional wisdom would assert that profiles are fully developed (that is, 10 to 15 diameters downstream of the nearest bend).

By calibrating chordal ultrasonic meters in a variety of hydraulic configurations of varying flatness, a calibration factor for a high Reynolds Number field application can be determined with very little calibration uncertainty. The calibration process is illustrated in Figure 2 by data for an eight path flow meter for a large nuclear unit. This meter was calibrated in a model of the hydraulic configuration of the unit's feedwater system. Profile flatness was used to characterize the profile "seen" in this model. The feedwater model configuration was then varied parametrically (e.g., by changing the velocity profile upstream of the most distant hydraulic feature of the model) to provide reasonable assurance that the actual plant flow profiles would be bounded by the calibration data.

The Profile Factor for the field application was selected from the flatness measured in the field and a linear fit of the Profile Factor versus Flatness data collected in the lab. The uncertainty in the fit of the data (in this case ± 0.04%, 2 standard deviations) is carried as an uncertainty in the meter calibration (Profile Factor). This uncertainty is of course in addition to the other uncertainties of the calibration process (for example, the uncertainties of the hydraulic standard used to perform the calibration).

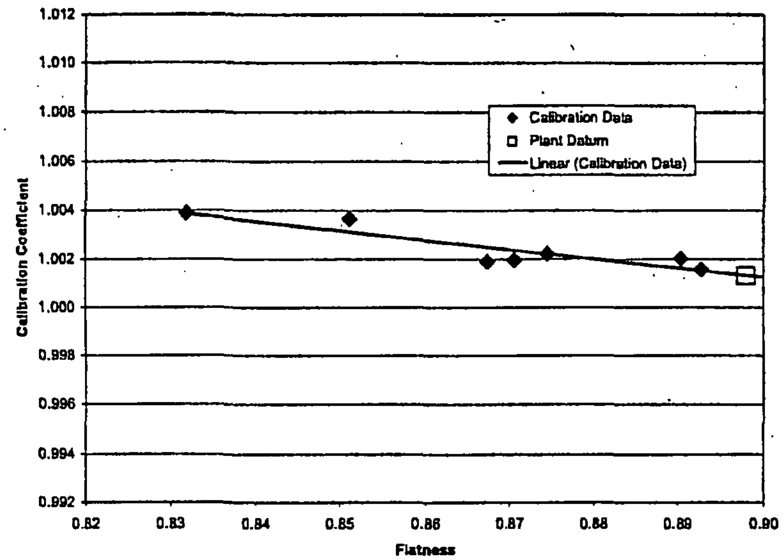


Fig. 2: Dependence of Calibration (Profile Factor) of an Eight Chord Ultrasonic Meter on Profile Flatness; Feedwater Measurement in a Large Nuclear Power Plant

The chain of comparisons required for the traceability of the chordal meter calibration—its Profile Factor—is shown in Figure 3. The chain reflects the calibration process described in the preceding paragraphs. It also accounts for the uncertainties of the calibration laboratory itself and for the uncertainties of the time measurements of the electronics used for the calibration test. [Effectively, time measurement uncertainties must be accounted twice, once for their effect on establishing the Profile Factor and once for each measurement made in the field.]

Figure 3 also accounts for another uncertainty. Using data from chordal ultrasonic instruments, it has been observed that axial velocity profiles in nuclear feedwater systems vary in time, sometimes significantly (Reference (6), previously cited). Such variations could potentially alter the flatness enough to call into question the validity of the Profile Factor and its assigned uncertainty. To ensure that this does not occur, Caldon chordal meters are equipped with a "velocity profile deviation" alarm. The alarm alerts the plant operator if the change in flatness has the potential to produce a bias in the profile factor exceeding the allowance for such changes.

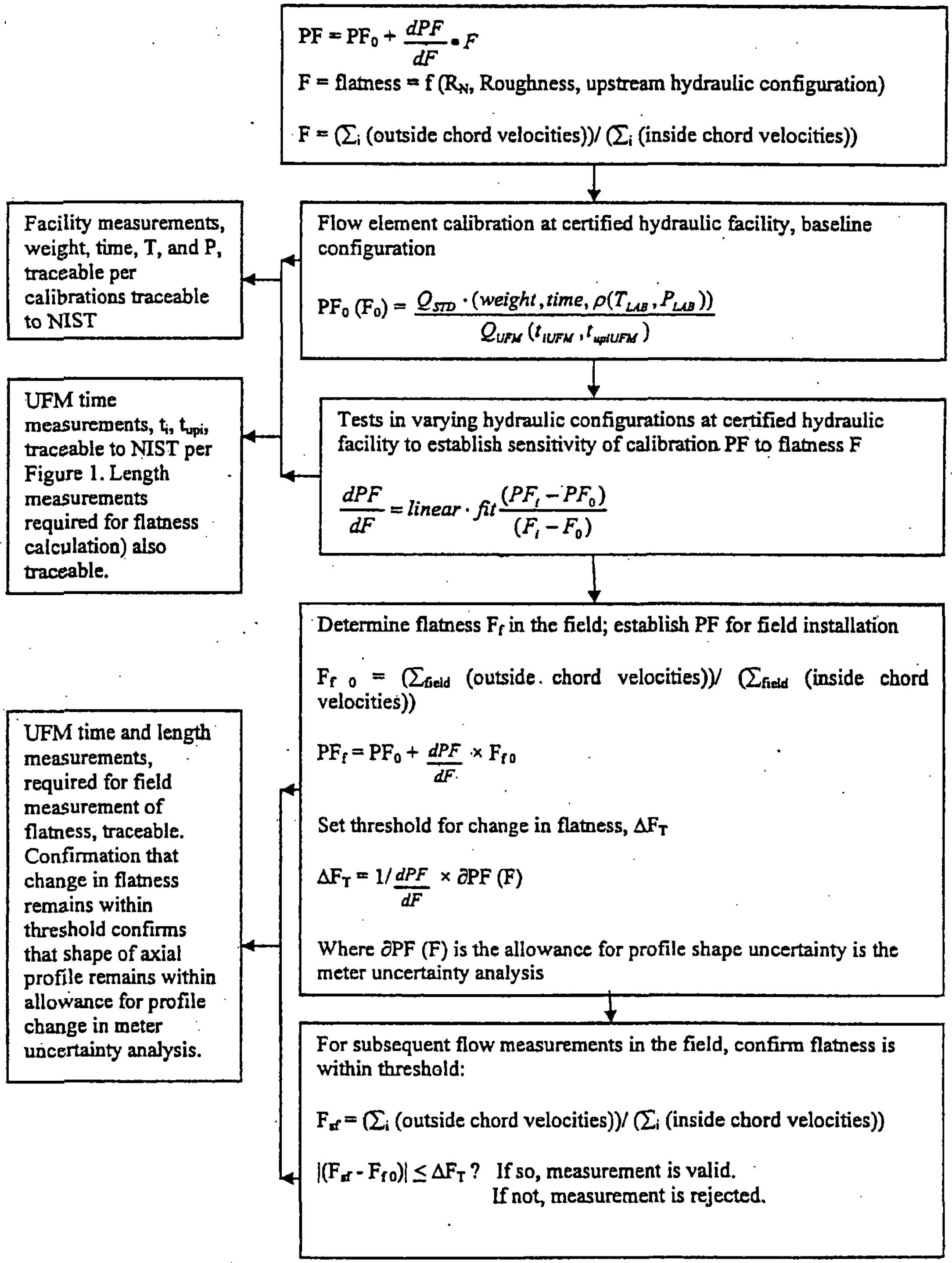


Fig. 3: Traceability of Calibration;
Assurance of Applicability of Calibration Data to Field Installation

3. CONCLUSIONS:

Means for establishing the traceability of key variables in the measurement of nuclear feedwater flow using a chordal ultrasonic meter have been described. These means include a quantitative basis for establishing the uncertainty in meter calibration due differences between the calibration established in a certified hydraulic facility at low temperature and the calibration in an operating nuclear feedwater system. Such differences are due not only to the difference in Reynolds Number but to differences in pipe wall roughness and, most importantly, to differences between the hydraulics of the plant and the calibration facility.

4. REFERENCES:

(1) *International Vocabulary of Basic and General Terms in Metrology (VIM)*, International Organization for Standardization (ISO).
(2) H. Estrada, "Theory of Ultrasonic Flow Measurement, Gases and Liquids", Caldon Technical Paper TP-44, available on the Caldon Website. The principles of ultrasonic flow measurement and the derivation of the algorithm for a chordal instrument are described in this paper.
(3) For instance, the 1967 ASME Steam Tables.
(4) H. Estrada, "An Assessment of the Integrity and Accuracy of Feedwater Flow and Temperature Instruments" EPRI Plant Performance Improvement Seminar, September, 1996.
(5) Hermann Schlichting, *Boundary Layer Theory,* Chapter XX, McGraw Hill
(6) H. Estrada, "Effects of Velocity Profiles Measured In-Plant on Feedwater Flow Measurement Systems", Caldon Engineering Report ER-262, available on the Caldon Website.

TUESDAY, FEBRUARY 5, 2002

Tab	Time	Description	Speaker
1	7:45 – 8:00	Registration and Continental Breakfast	N/A
2	8:00 – 8:15	Welcome & Mission	E. Hauser Caldon, Inc.
3	8:15 – 8:45	Update NRC Approvals *Current Climate* *Review Times* *Review Schedules*	E. Hauser Caldon, Inc.
4	8:45 – 9:45	NRC Guidance on MUR Power Uprate Applications	B. Horin Winston & Strawn
5	9:45 – 10:15	Lessons Learned 1: Entergy Thermal Power Optimization (Appendix K Uprates)	J. Burford Entergy Operations, Inc.
6	10:15 – 10:30	Morning Break	N/A
7	10:30 – 11:00	Lessons Learned 2: Comanche Peak Steam Electric Station	M. Winkelblech TXU
8	11:00 – 11:30	Lessons Learned 3: Beaver Valley Power Station	B. Kline FENOC
9	11:30 – 12:00	Lessons Learned 4: History of the LEFM Applications in Japan	T. Yudate Hitachi
10	12:00 – 1:00	Lunch	N/A
11	1:00 – 2:30	Data Analysis Profile Changes In Situ and Their Effects on LEFM Systems	H. Estrada Caldon, Inc.
12	2:30 – 2:45	Afternoon Break	N/A
13	2:45 – 3:15	LEFM✓ and LEFM✓+ Product Innovations	D. Augenstein Caldon, Inc.
14	3:15 – 4:15	Other Applications for LEFM Technology: RCMS, Blowdown, Steam Flow	E. Hauser Caldon, Inc.
15	4:15 – 5:45	Field Trip to Caldon	N/A

6:30 Boarding Time
Dinner & Entertainment on Gateway Clipper "River Belle"

WEDNESDAY, FEBRUARY 6, 2002

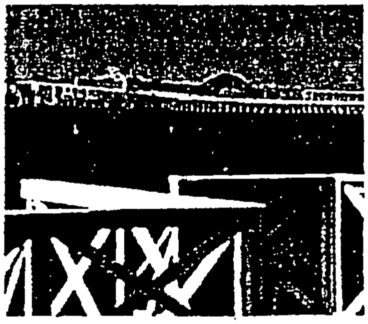
Tab	Time	Description	Speaker
16	7:45 – 8:00	Registration and Continental Breakfast Hand Out Questionnaires	N/A
17	8:00 – 10:15	LEFM Experience Forum Chordal and External A – Quality Assurance B - Maintenance and Reliability C - User Group Info Sharing D - Data Monitoring Demonstration E – Discussion F – Questionnaire	 J. Whitehead, Caldon J. Regan, Key Tech. M. Ventura, Caldon D. Augenstein, Caldon E. Hauser, Caldon E. Hauser, Caldon
18	10:15 - 10:30	Morning Break Collect Questionnaires	N/A
19	10:30 – 12:00	LEFM Session A – NRC Commitments B – LEFM Out of Service C – Remote Monitoring – The value of Remote Monitoring; Case histories (external and chordal)	 J. Regan, Key Tech. J. Regan, Key Tech. S. Corey, Key Tech.
20	12:00 – 1:00	Lunch	N/A
21	1:00 – 2:30	Brainstorming Session on User Group Activities	E. Hauser Caldon, Inc.
22	2:30 – 3:00	Closing Remarks	E. Hauser Caldon, Inc.
23	Appendices	NRC Regulatory Issue Summary 2002-03: Guidance on the Content of Measurement Uncertainty Recapture Power Uprate Applications	N/A
24	Appendices	Paper Capture of Brainstorming Session/Flip Charts	To be supplied later

CALDON LEFM NUCLEAR USER'S GROUP AGENDA

SUNDAY, MAY 4, 2003 – REGISTRATION 5:30 – 7:30
WELCOME RECEPTION – HEAVY HORS D'OEUVRES 7:30 – 9:30
Being held in the Windjammer adjacent to the Atrium

MONDAY, MAY 5, 2003 – GENERAL SESSION 8:00 – 5:00
Being held in Thomas Point of the Powerhouse – 1st Floor

Tab	Time	Description
1	*7:30 – 8:00*	*Continental Breakfast – Windjammer – Users and Spouses*
2	**8:00 – 8:15**	**Welcome CNUG 2003 Members**
3	**8:15 – 9:15**	**Caldon – Ernie Hauser** *Weld Integrity*
4	**9:15 – 10:15**	**Caldon – Herb Estrada** *Update of Velocity Profiles (I)*
5	*10:15 – 10:30*	*Morning Break – in room*
6	**11:00 – 11:30**	**Utility Speaker – Waterford – Ray Conigliaro** *Ultrasonic Flowmeter Caldon LEFM CheckPlus*
7	**11:30 – 12:00**	**Utility Speaker – Hitachi– Tadahiro Yudate** *Recent Status of the LEFM Applications in Japan*
8	*12:00 – 1:00*	*Lunch – Windjammer*
9	**1:00 – 1:30**	**Utility Speaker – Peach Bottom – Jason McDaniel** *Peach Bottom Atomic Power Station – LEFM Performance Monitoring*
10	*1:30 – 3:00*	**Caldon – Don Augenstein** *Reliability Update*
11	*3:00 – 3:15*	*Afternoon Break – in room*
12	**3:15 – 5:00**	**Closing Remarks and Q&A's**
	6:15	*Dinner at Chesapeake Bay Beach Club – Meet in the Lobby at 6:00*

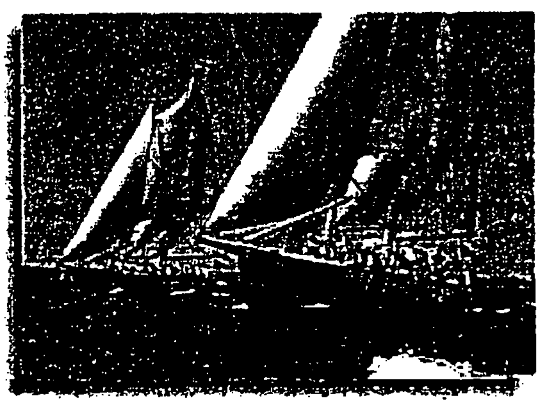


CALDON LEFM NUCLEAR USER'S GROUP AGENDA

TUESDAY, MAY 6, 2003 – GENERAL SESSION 8:00 – 5:00
Being held in Thomas Point of the Powerhouse – 1st Floor

Tab	Time	Description
13	*7:30 – 8:00*	*Continental Breakfast – Windjammer - Users and Spouses*
14	8:00 – 9:15	**Key Technologies – Jenny Regan** *Measurement Uncertainty & Calorimetric Power Uncertainty*
15	9:15 – 10:15	**Caldon – Herb Estrada** *Traceability*
16	*10:15 – 10:30*	*Morning Break – in room*
17	10:30 – 12:00	**Caldon – Don Augenstein** *LEFM Check and LEFM CheckPlus Product Development*
18	*12:00 – 1:00*	*Lunch – Atrium A*
19	1:00 – 2:30	**Caldon – Herb Estrada** *Application Topics*
20	*2:30 –2:45*	*Afternoon Break – in room*
21	2:45 – 4:00	**Caldon – Don Augenstein** *LEFM Check (Plus) Software Development Rev. K & Beyond*
22	4:00 – 5:00	**Closing Remarks and Q&A's**
		Free Time to Explore the City

WEDNESDAY, MAY 7, 2003 – Continental Breakfast Windjammer 7:30 – 8:00
Sailing or Golfing

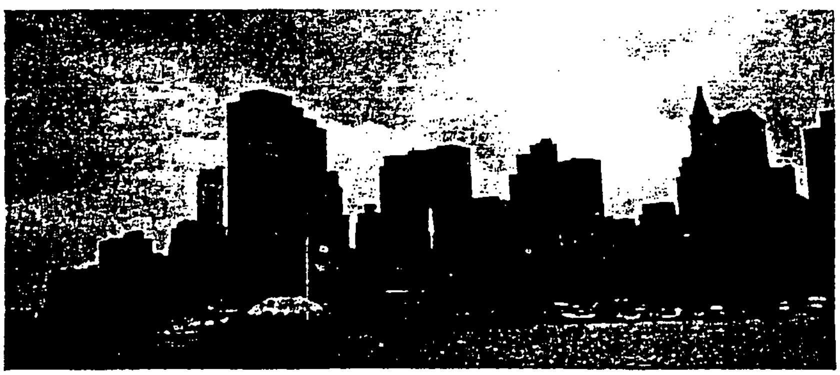


CALDON LEFM NUCLEAR USER'S GROUP AGENDA

SUNDAY, MAY 23, 2004 – REGISTRATION 6:30
WELCOME RECEPTION – HEAVY HORS D'OEUVRES 7:00 – 10:00
Being held in the Kennedy Room adjacent to the Lobby

MONDAY, MAY 24, 2004 – GENERAL SESSION 8:00 – 5:00
Being held in the Press Room

Tab	Time	Description
1	8:00 – 8:30	**Ernie Hauser** *Welcome CNUG 2004 Members*
2	8:30 –10:00	**Ernie Hauser** *Anticipated NRC Action and Response*
3	10:00 – 10:30	**Don Augenstein** *Update of Reliability Review*
4	10:45 – 11:30	**Ryan Hannas** *OE Report - Review since last CNUG*
5	11:30 – 12:00	**Ernie Hauser** *NUPIC Audit Review*
6	1:00 – 2:00	**Matt Mihalcin** *New APU Design:* ***Short Circuit Detection***
7	2:00 – 3:30	**Herb Estrada** *Backup Modes of Operation (with break halfway)*
8	3:30 – 5:00	*Open Discussion*



CNUG 2004 Agenda

CALDON LEFM NUCLEAR USER'S GROUP AGENDA

TUESDAY, MAY 25, 2004 – GENERAL SESSION 8:00 – 12:00
FIELD TRIP TO ALDEN LABS 12:00 – 4:30

Tab	Time	Description
9	8:00 – 8:45	**Tadahiro Yudate - Hitachi** *Recent Status of the LEFM Applications (Part 1 - Uprating with External Units in Japan*
10	8:45 – 9:30	**Don Asay - Dominion** *Millstone Case Study*
11	9:45 – 10:15	**Tom Hokemeyer – CP&L** *Brunswick Case Study* ***FW Venturi Investigation Using LEFM 2000FE***
12	10:15 – 10:45	**Herb Estrada** ***Uncertainties In Nozzle-Based Feedwater Flow Measurements***
13	10:45 – 11:15	**Tadahiro Yudate - Hitachi** ***Recent Status of the LEFM Applications (Part 2*** *NMIJ Testing Report*
	11:45 –4:30	**Dr. Jim Nystrom –Alden Labs** *Hydraulic Accuracy*
	5:00 – 11:00	**Dinner at Boston Billiards and Fenway Park Outing** *Boston Red Sox vs. Oakland Athletics*

WEDNESDAY, MAY 26, 2004

Tab	Time	Description
14	8:00 – 9:00	**Herb Estrada** ***Measuring Flow on Advanced Gas-Cooled Reactors, the Pebble Bed Modular Reactor (PBMR)***
15	9:00 – 9:30	**User's Survey**
16	9:30 – 10:30	**"Predict the Profile" Winners Announced**
17	10:30 – 11:30	**Open Ideas and Topics for CNUG 2005**
	12:00 – 1:00	***Farewell Luncheon***

CNUG 2005 Final Meeting Agenda

MONDAY 5/23/05

<table>
<tr><th colspan="3">Meeting Description</th><th colspan="2">Author/Company - Speaker</th><th>Time</th><th>Tab</th></tr>
<tr><td colspan="3">Welcome to CNUG 2005</td><td colspan="2">Ernie Hauser</td><td>8:00-8:30</td><td>1</td></tr>
<tr><td colspan="3">President's Welcome</td><td colspan="2">Cal Hastings</td><td>8:30-8:45</td><td>2</td></tr>
<tr><td colspan="3">LEFM 101</td><td colspan="2">Herb Estrada</td><td>8:45 - 9:30</td><td>3</td></tr>
<tr><td colspan="7">Group Photo 9:30 - 9:45</td></tr>
<tr><td colspan="7">Morning Break 9:45 - 10:00</td></tr>
<tr><td colspan="3">Licensing Process Update -
Measurement Uncertainty Recapture
Power Uprate License Amendments</td><td colspan="2">Bill Horin/Winston & Strawn</td><td>10:00 - 11:00</td><td>4</td></tr>
<tr><td colspan="3">Summary of June 18 NRC Report on LEFMs</td><td colspan="2">Ernie Hauser</td><td>11:00 - 12:00</td><td>5</td></tr>
<tr><td colspan="7">Lunch 12:00 - 1:00</td></tr>
<tr><td colspan="3">INPO Perspective on Ultrasonic Flowmeter (UFM) Operations Verification and Peer/Self-Assessment</td><td colspan="2">Bob Gambrill/INPO</td><td>1:00 - 2:00</td><td>6</td></tr>
<tr><td colspan="3">LEFM EXTERNAL Users Breakout</td><td colspan="4">LEFM CHORDAL Users Breakout</td></tr>
<tr><td>Verifying External LEFM Systems</td><td>Ernie Hauser</td><td>2:00 - 3:00</td><td>Verifying Chordal LEFM Check and CheckPlus Systems</td><td>Herb Estrada</td><td>2:00 - 3:00</td><td>7E
7C</td></tr>
<tr><td colspan="7">Afternoon Break 3:00 - 3:15</td></tr>
<tr><td>Free Discussion</td><td>External</td><td>3:15 - 4:00</td><td>Free Discussion</td><td>Chordal</td><td colspan="2">3:15 - 4:00</td></tr>
<tr><td colspan="7">Wrap Up - Q/A Session</td></tr>
</table>

CALDON

CNUG 2005 Final Meeting Agenda

TUESDAY 5/24/05

Meeting Description	Author/Company - Speaker	Time	Tab
Palo Verde - Ultrasonic Feedwater Flowmeters - Return to Service	Ken Porter/APS	8:00-8:45	8
Vandellos Report - AND Supplemental Root Cause Investigation Source of Error Corrective Actions	Manel Cambra/ASCO - Herb Estrada	8:45 - 9:30	9
Transducer Update	Don Augenstein	9:30 - 10:15	10
Morning Break 10:15 - 10:30			
APU Updates	Don Augenstein	10:30 - 11:15	11
Ensuring That Ultrasonic Flowmeters Live Up To Their Accuracy Requirements	Ernie Hauser	11:15 - 12:00	12
Lunch 12:00 - 1:00			
Monitoring LEFMs Constructing A Best Estimate Of Feedwater Flow	Herb Estrada	1:00 - 2:00	13
Comparisons of Steam Plant Measurements with Chordal LEFMs (Seabrook & River Bend)	Herb Estrada	2:00 - 2:45	14
Afternoon Break 2:45 - 3:00			
MUR BOP Evaluations	Robert Field/Sargent & Lundy	3:00 - 3:45	15
MUR NSSS Scope	Fred Maass/Framatome	3:45 - 4:30	16
Wrap Up - Q/A Session			

CNUG 2005 Final Meeting Agenda

WEDNESDAY 5/25/05

Meeting Description	Author/Company - Speaker	Time	Tab
Reliability Update	Leeanne Jozwiak	8:00-8:45	17
History & Future of Japanese Nuclear Industry	Tetsuya Takahara/Marubeni	8:45 - 9:30	18
Innovative Practices for the Installation of Caldon Leading Edge Flow Meters	Vic Ferraro & Marion Freeland/WSI	9:30 - 10:15	19
Morning Break 10:15 - 10:30			
New Developments Japanese Architecture	Ryan Hannas	10:30 - 11:15	20
User Survey	All attendees	11:15 - 11:30	21
Open Forum Free Discussion	All attendees	11:30 - 12:30	
Farewell Luncheon 12:30 - 1:30			

Company	Site	First Name	Last Name	Phone	E-Mail
APS	Palo Verde	Carl	Landstrom	623-393-5129	clandstr@apsc.com
Constellation Nuclear	Nine Mile 1	Bill	Stathis	315-349-4601	william.stathis@constellation.com
CP&L	Corporate	Tom	Hokemeyer	919-546-2692	tom.hokemeyer@pgnmail.com
Dominion Generation	Millstone 3	Don	Asay	860-444-5303	Don_F_Asay@dom.com
Dominion Generation	Surry & North Anna	Ron	Thomas	804-273-2205	Ron_Thomas@dom.com
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Entergy Nuclear	Waterford	Ray	Conigliaro	504-739-6229	rconigl@entergy.com
Entergy Operations	Waterford	Tim	Boehm		tboehm@entergy.com
Entergy Operations	Waterford	Lonnie	Weber	504-464-3468	lweber@entergy.com
Exelon Generation	Quad Cities 1 & 2	Jim	Foster	309-227-2703	james.foster@exeloncorp.com
FirstEnergy	Davis-Besse	Bob	Wharry	419-321-7564	rkwharry@firstenergycorp.com
FirstEnergy	Perry	Mike	Yeager	440-280-7517	mjyeager@firstenergycorp.com
Fluids Control Instrument		Kevin	Liu	886-227093389	kevinliu@fluids.com.tw
FP&L	Seabrook	Steve	Hale	603-773-7206	steve_hale@fpl.com
FP&L	Seabrook	Ian	Watters	603-773-7534	ian_watters@fpl.com
Framatome Technologies		Bret	Boman	434-835-2677	bret.boman@framatome_anp.com
Hitachi, Ltd.		Tadahiro	Yudate	011-0294-23-5395	tadahiro_yudate@pis.hitachi.co.jp
Institute of Nuclear Energy		Chin-Jang	Chang	886-2-813177717 X6092	cjchang@iner.gov.tw
Marubeni	All Japan Installations	Tetsuya	Takahara	011-81-3-3214-9020	takahara@mus.co.jp
MPR Associates		Bob	Coward	703-519-0418	rcoward@mpr.com
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NMIJ	Fluid Flow Division	Hiroshi	Sato	011-81-29-861-4242	sato-hiroshi@aist.go.jp
NMIJ	Fluid Flow Division	Yoshiya	Terao	011-81-29-861-4242	terao@ni.aist.go.jp
NMIJ		Masaki	Takamoto	011 81 29 861 4228	m-takamoto@aist.go.jp
PP&L, Inc.	Susquehanna 1 & 2	Bob	Magnotta	570-542-3947	rtmagnotta@pplweb.com
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Sargent & Lundy		Tunglu	Wang	302-622-7270	tunglu.wang@sargentlundy.com
SCE&G	Summer	Bill	Bell	803-345-4389	whbell@scana.com
SNOC	Farley, Hutch,Vogtle	Ray	Herb	205-992-6448	rlherb@southernco.com
TVA	Watts Bar	Jack	Bryant	423-365-3076	jkbryant@tva.gov
TXU	Comanche Peak 1 & 2	Mark	Winkelblech	254-897-6277	mwinkel1@TXU.com
Winston & Strawn		Bill	Horin	202-371-5950	whorin@winston.com

Attendance List CNUG 2005 May 22-25, 2005

Company	Site	First Name	Last Name	E-Mail
ANAV	ASCO/Vandellos	Ignasi	Balazote	ibalazote@anacnv.com
APS	Palo Verde	Dan	Fisher	dfishe01@apsc.com
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Duke Energy	Catawba	Ralph	Neigenfind	rgneigen@duke-energy.com
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Duke Energy	Oconee	Bluford	Jones	gbjones@duke-energy.com
Entergy	Grand Gulf	Jon	Byrnes	jbyrnes@entergy.com
Exelon	Peach Bottom	Jim	Zardus	jim.zardus@exeloncorp.com
FirstEnergy	Davis-Besse	Brian	Young	bdyoung@firstenergycorp.com
Fluids Control	Fluids Control	Kevin	Liu	Kevinliu@fluids.com.tw
Framatome	Framatome	Fred	Maass	Fred.Maass@framatome-anp.com
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INER	INER	Chin-Jang	Chang	cjchang@iner.gov.tw
INPO	INPO	Bob	Gambrill	gambrillra@inpo.org
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NMIJ	Liquid Flow Standard	Hiroshi	Sato	sato-hiroshi@aist.go.jp
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PP&L, Inc.	Susquehanna	Bob	Magnotta	rtmagnotta@pplweb.com
Progress Energy	H.B. Robinson	Rick	Harrold	rick.harrold@pgnmail.com
Progress Energy	H.B. Robinson	Rich	Supler	richard.supler@pgnmail.com
Sargent & Lundy	Sargent & Lundy	Tunglu	Wang	tunglu.wang@sargentlundy.com
Sargent & Lundy	Sargent & Lundy	Robert	Field	robert.m.field@sargentlundy.com
SCE&G	VC Summer	Bill	Bell	whbell@scana.com
Southern Nuclear	Corporate	Michael	Eidson	mgeidson@southernco.com
TEPCO	Corporate	Takashi	Sato	satoh.takashi@tepco.co.jp
TVA Nuclear	Watts Bar	Jack	Bryant	jkbryant@tva.gov
TXU	Comanche Peak	Mark	Winkelblech	mwinkel1@TXU.com
Welding Services, Inc.	WSI	Victor	Ferraro	vferraro@wsi.aquilex.com
Welding Services, Inc.	WSI	Marion	Freeland	mfreeland@wsi.aquilex.com
Winston & Strawn	W&S	Bill	Horin	whorin@winston.com

first_n.	last_name	company	email	phone	Atter. .tg
Greg	Hill	AEP, DC Cook	gjhill@aep.com	616-697-5134	Yes
Kenneth	Riches	AEP, DC Cook	kwriches@aep.com	616-697-5146	Yes
Mark	Williams	AEP, DC Cook	mgwilliams@aep.com	616-697-5129	Yes
John	Simpkins	APS, Palo Verde	jsimpkin@apsc.com	623-393-5325	Yes
Chris	Mills	CP&L, Brunswick	chris.mills@pgnmail.com	910-457-2567	Yes
Chuck	Baucom	CP&L, Robinson	chuck.baucom@pgnmail.com	843-857-1253	Yes
Tom	Hokemeyer	CP&L/Corporate	tom.hokemeyer@pgnmail.com	919-546-2692	Yes
Jim	Snelson	CP&L/Robinson	james.snelson@pgnmail.com	843-857-1129	No
Ron	Thomas	Dominion	ron_thomas@dom.com	804-273-2205	Yes
John	Gibson	Dominion, Millstone	john_j_gibson@dom.com	860-447-1791	Yes
Mike	Withrow	Entergy	mwithro@entergy.com	601-437-6247	Yes
George	Thomas	Entergy, Vermont Yankee Transition Tear	gthomas@entergy.com	802-451-3072	Yes
Jerry	Burford	Entergy, River Bend	fburfor@entergy.com	601-368-5755	Yes
Tom	Fleischer	Entergy, Waterford 3	tfleisc@entergy.com	504-739-6262	No
Mike	Baker	Exelon, Peach Bottom	michael.baker@exeloncorp.com	717-456-4094	No
Jason	McDaniel	Exelon, Peach Bottom	william.mcdaniel@exeloncorp.com	717-456-4015	Yes
Jim	Foster	Exelon, Quad Cities	james.foster@exeloncorp.com	309-227-2000 ext 2703	No
Bill	Kline	FENOC, Beaver Valley	klinew@firstenergycorp.com	724-682-5620	Yes
Curt	Ciocca	FENOC, Consultant	cioccahouse@worldnet.att.net	724-682-1872	Yes
Mark	Musulin	FENOC, Beaver Valley	musulinm@firstenergycorp.com	724-682-5625	No
Craig	Hengge	FirstEnergy, Davis Besse	cahengge@firstenergycorp.com	419-321-7898	Yes
Mike	Yeager	FirstEnergy, Perry	mjyeager@firstenergycorp.com	440-280-8035	No
Mike	Rubano	FP&L, St. Lucie	mike_rubano@fpl.com	561-467-7298	Yes

first_n[illegible]	last_name	company	email	phone	Atten[illegible]tg
Bret	Boman	Framatome	bboman@framatech.com	804-832-2677	No
Martin	Parece	Framatome	mparece@framatech.com	804-832-2474	Yes
Tadahiro	Yudate	Hitachi	tadahiro_yudate@pis.hitachi.co.jp	0294-23-5395	Yes
Scott	Corey	Key Technologies Inc.	scorey@keytechinc.com	410-385-0200	Yes
Jenny	Regan	Key Technologies Inc.	jregan@keytechinc.com	610-274-8258	Yes
Tetsuya	Takahara	Marubeni	takahara@mus.co.jp	81-3-3214-9020	Yes
Tom	McMahon	Niagara Mowhawk, Nine Mile	mcmahont1@niagaramohawk.com	315-349-4045	No
Harv	Hanneman	NMCCO, Point Beach	harv.hanneman@nmcco.com	920-755-7317	Yes
Tom	Behringer	Sargent & Lundy	thomas.j.behringer@sargentlundy.com	312-269-7218	Yes
Frank	Calabrese	Sargent & Lundy	frank.j.calabrese@sargentlundy.com	302-622-7369	Yes
Bill	Bell	SCE&G, VC Summer	whbell@scana.com	803-345-4389	Yes
Mike	Eidson	Southern Nuclear Op Co	mgeidson@southernco.com	205-992-5978	No
Shinichi	Kawamura	TEPCO	kawamura@tepco.com	202-457-0970	Yes
Fumihiko	Ishibashi	Toshiba	fumihiko.ishibashi@toshiba.co.jp	650-875-3464	Yes
Atsushi	Tanaka	Toshiba	atsushi5.tanaka@toshiba.co.jp	212-596-0614	Yes
Stan	Nelson	TVA Watts Bar Unit 1	sbnelson@tva.gov	423-365-3554	No
Jim	Swearingen	TVA, Sequoyah	jdswearingen@tva.gov	423-843-7628	Yes
Mark	Winkelblech	TXU Electric, CP	mwinkel1@TXU.com	254-897-6277	Yes
Bill	Horin	Winston & Strawn	whorin@winston.com	202-371-5950	Yes

last_name	first_name	Nickname	Spouse	company	email	phone	Attending 2003
Stathis	William	Bill	N/A	Constellation Nuclear, 9 Mile	william.stathis@nmp.cn.com	315-349-4601	Yes
Hokemeyer	Thomas	Tom	Carol	CP&L/Corporate - Progress Energy	tom.hokemeyer@pgnmail.com	919-546-2692	Yes
Snelson	James	Jim		CP&L/Robinson	james.snelson@pgnmail.com	843-857-1129	Yes
Thomas	Ronald	Ron	Anne	Dominion	ron_thomas@dom.com	804-273-2205	Yes
Waddill	John			Dominion			Yes
Zumbo	Wendy	Wendy		Dominion, Millstone	Wendy_E_Zumbo@dom.com	860-447-1791	Yes
Wyspianski	Leslaw	Les		Dominion, Millstone	leslaw_wyspianski@dom.com	860-447-1791 x6800	Yes
Thomas	Walter	Ed		Dominion North Anna Power Station	Ed_Thomas@dom.com	540-894-2784	Yes
Gibson	John		Jill	Dominion, Millstone	john_j_gibson@dom.com	860-447-1791	Yes
Byrnes	Jonathon	Jon		Entergy, Grand Gulf	jbyrnes@entergy.com	601-436-2493	Yes
Conigliaro	Raymond	Ray		Entergy, Waterford 3	RCONIGL@entergy.com	504.739.6229	Yes
Dowhy	Thomas	Tom	Nadine	FENOC, Beaver Valley	dowhyt@firstenergycorp.com	724-682-7935	Yes
Beese	Larry		Ginger Torres	FirstEnergy, Davis Besse	lwbeese@firstenergycorp.com	419-321-7543	Yes
Yudate	Tadahiro			Hitachi	tadahiro_yudate@pis.hitachi.co.jp	0294-23-5395	Yes
Regan	Jennifer	Jenny	Tim	Key Technologies Inc.	jregan@keytechinc.com	610-274-8258	Yes
Takahara	Tetsuya	Tetsu		Marubeni	takahara@mus.co.jp	81-3-3214-9020	Yes
Magnotta	Robert	Bob	Lynn	PPL Susquehanna LLC	rtmagnotta@pplweb.com	570-542-3947	Yes
Bieter	Walter	Walt		Sargent & Lundy	WALTER.J.BIETER@sargentlundy.com	302-622-7278	Yes
Bartoski	Thomas	Tom		Sargent & Lundy	Thomas.bartoski@sargentlundy.com	302-622-7275	Yes
Eidson	Michael	Mike		Southern Company	MGEIDSON@southernco.com	205 992-5978	Yes
Horiguchi	Masahiro			Toshiba International Corp.	masahiro1.horiguchi@toshiba.co.jp	212-596-0669	Yes
Sakamoto	Hiroshi	Hiroshi		Toshiba International Corp.	hiroshi6.sakamoto@toshiba.co.jp	212-596-0614	Yes
Bryant	Jack		Tracy	TVA, Watts Bar Unit 1	jkbryant2@tva.gov	423-365-3076	Yes
Winkelblech	Mark			TXU Electric, CP	mwinkel1@TXU.com	254-897-6277	Yes
Horin	William	Bill		Winston & Strawn	whorin@winston.com	202-371-5950	Yes

October 17, 2003

Michael Baker
Program Manager
Exelon Nuclear
Peach Bottom Atomic Power Station
1848 Lay Road
Delta, Pa. 17314-9032

Phone: 717-456-4094

Reference: Exelon Nuclear P.O. No. 01038929
Caldon, Inc CO-22862

Subject: Caldon, Inc. Peach Bottom Unit 3 LEFM✓ + System Commissioning Certificate of Compliance Letter

Dear Mr. Baker:

Caldon has reviewed the commissioning results, i.e., Fluid Velocity ratios, Sound Velocity ratios, Non Fluid Tau's, Spool Dimensions, Alarm Settings, etc. at the plant operating condition of ~98% power and has concluded that the LEFM✓ + System is operating within its bounding uncertainty of +/- 0.30 % of its rated flow rate. The LEFM✓ + System can be used for flow measurement.

Caldon will send a copy of the Field Commissioning Data Package, FCDP-125, by the end of October, 2003.

If you should have any questions and/or comments, please call or email me at emadera@caldon.net.

Sincerely Yours,

Ed Madera
Caldon Senior Project Engineer

CC: Ernie Hauser, President of Nuclear Division, Caldon, Inc.
Garry Ventura, V.P. of Operations, Caldon, Inc.
Don Augenstein, V.P. of Engineering, Caldon, Inc.