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EVALUATION OF THE PERFORMANCE OF AN ULTRASONIC CROSS-CORRELATION FLOWMETER

by

H. BAZERGHI and K.J. SERDULA

Paper presented at the Canadian Nuclear Association Annual
Conference, June 6-8, 1977, Montreal, Quebec

Chalk River Nuclear Laboratories
Chalk River, Ontario
September 1977

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Evaluation de la performance d'un débitmètre ultrasonique à intercorrélation

par

H. Bazerghi (Ecole Polytechnique)
et K.J. Serdula

Résumé

On a évalué à Chalk River un débitmètre ultrasonique à intercorrélation développé par CGE (Canadian General Electric) sous contrat de l'EACL dans le but d'améliorer la performance des usines d'eau lourde. On donne dans ce rapport les résultats du programme d'évaluation.

La performance générale du débitmètre est satisfaisante. Cet appareil est idéal pour les applications industrielles et il a une précision et une reproductibilité comparables à celles de nombreux instruments de laboratoire. Une précision de 3% est facilement obtenue. Avec un choix suffisant d'emplacements de mesure et un fonctionnement soigné du système, un opérateur expérimenté peut obtenir une précision meilleure que 2%.

Ce nouveau débitmètre portatif accrochable devrait s'avérer utile dans les applications suivantes:

- faire des mesures de débit dans des systèmes où la pénétration dans les tuyaux est trop coûteuse ou peu pratique.

- vérifier ou remplacer les débitmètres existants.

- mesurer les débits dans les conduites n'ayant pas été précédemment instrumentées pour donner un meilleur contrôle ou pour vérifier la performance des systèmes.

* Rapport présenté au Congrès annuel de l'Association Nucléaire Canadienne tenu à Montréal, P.Q., du 6 au 8 juin 1977.

L'Energie Atomique du Canada, Limitée
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Chalk River, Ontario

AECL-5848

Septembre 1977

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EVALUATION OF THE PERFORMANCE OF AN ULTRASONIC CROSS-CORRELATION FLOWMETER*

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ABSTRACT

An ultrasonic cross-correlation flowmeter, developed by Canadian General Electric under contract from Atomic Energy of Canada Limited to assist in improving performance of heavy water plants, was evaluated at Chalk River Nuclear Laboratories. Results of this evaluation program are reported.

Overall performance of the flowmeter is satisfactory. The flowmeter is ideally suited to industrial applications and has an accuracy and repeatability comparable to many laboratory instruments. An accuracy of 3% is readily obtainable. With adequate choice of measuring locations and careful operation of the system, an experienced operator can achieve an accuracy of better than 2%.

This new "clamp-on" portable flowmeter should prove useful in the following applications:

- provide flow measurements in systems where pipe penetration is too costly or not practical.
- verify or replace existing flowmeters.
- measure flows in lines not previously instrumented to provide better control or to verify performance of systems.

* Paper presented at the Canadian Nuclear Association Annual Conference, June 6 - 8, 1977, Montreal, Quebec.

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Chalk River, Ontario

September 1977

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by

H. Bazerghi (Ecole Polytechnique)
K.J. Serdula (Atomic Energy of Canada Limited)

INTRODUCTION

A large number of industries rely heavily on the movement of fluids in pipes for their operation. Advancing industrialization has kept a constant pressure on flowmeter designers. New operational requirements (temperatures from absolute zero to molten steel; pressures from high vacuum to hundreds of atmospheres; conduit dimensions from few millimeters to several meters; new liquids, corrosive or radioactive, of low or high viscosity; new flow ranges, etc.) and new applications of flowmeters (like automatic process control, more strict accounting of polluant quantities, etc.) create a continuous demand for new flowmeters, with new characteristics. The nuclear industry, with its reactors and heavy water plants, is no exception.

The Ultrasonic Cross-Correlation Flowmeter was developed by Canadian General Electric (CGE), under contract from Atomic Energy of Canada Limited (AECL), to assist in improving the performance of heavy water plants. The efficiency of the heavy water plants depends on the control and adjustment of several flows. Accurate, repeatable and dependable flow measurements are needed to satisfy both the accountant and the engineer. A non-intrusive form of flowmeter was favoured, because of the corrosive and toxic nature of the liquid, and also because such a flowmeter could be moved from one location to another, to check existing flowmeters, replace defective ones, and measure flow in lines not previously equipped with flowmeters.

2. OPERATING PRINCIPLES

The CGE flowmeter is based on two principles:

i) modulation by the flow of two parallel ultrasonic beams, a distance s apart, which travel across the pipe;

ii) determination of the flow transport time between the two beams by cross-correlation of the downstream and upstream modulation of the signals.

The definition of the cross-correlation function is illustrated in Figure 1. This function is the time average of the product of two signals, one of which is delayed in time with respect to the other.

Suppose we have two random signals, from which we subtract their respective means. We are left with signals that fluctuate around zero, and if they are truly random, then they must have equal probabilities of being positive or negative. If the two signals are completely unrelated, then their product also is of random sign being as frequently positive as negative. The product therefore averages to zero. However, if the two signals are identical, their product is positive, and hence averages to some non-zero value. Therefore, the maximum of the cross-correlation function occurs at the delay time at which the two signals are most similar.

This property of the cross-correlation function is used for flow measurement as illustrated in Fig. 2.

Inherent tracers moving with the flow (imhomogeneities in the fluid, or naturally occurring turbulences) modify the speed of sound of the liquid, imposing phase modulation on the ultrasonic beams going across the pipe.

Provided that the beams' separation is not too large, a cause of modulation in the upstream beam will, after a certain time, cause similar modulation in the downstream one. The maximum of the cross-correlation of the two modulation signals then indicates the transport time of the liquid between the two beams.

The transport time is then used to compute the flow, G,

$$G = k \cdot \frac{s}{\tau} \cdot A$$

k = theoretical correction factor for the velocity profile as explained in Fig. 3.

s = transducer spacing

τ = transport time

A = pipe cross-sectional area.

The above equation illustrates the relationship between time delay and flow. The correlator output is a frequency, proportional to $1/\tau$, and therefore the output is linearly proportional to flow.

3. ADVANTAGES FOR INDUSTRIAL APPLICATIONS

Obvious advantages of such a system of flow measurement are its non-intrusive "clamp-on" feature and its portability. It can be useful in applications where penetration of the pipe is too costly and/or not practical. Experience has shown that the transducers can be removed and installed in a new location in less than 30 minutes. In addition, one instrument is capable of measuring flows in pipes of different diameters, wall thicknesses and materials, without surface preparation. Because of the operating principle, (i.e. timing of inherent traces in the flow), the flowmeter does not require calibration or flow manipulation. The instrument output and electronic oscillator clock frequency is directly proportional to the flow. Extensive use of digital electronics has resulted in an instrument which is not susceptible to "drifts".

4. THEORETICAL EVALUATION

The cross-covariance is a quantitative measure of the quality of a cross-correlation function and is defined as,

$$\rho(\tau) = \frac{R_{xy}(\tau)}{\sqrt{R_{xx}(o)\cdot R_{yy}(o)}}$$

If the two signals to be correlated are identical, then $\rho = 1$. If they are completely unrelated, then $\rho = 0$. The cross-covariance is then a measure of the correlatable content of the analyzed signals.

Theoretical models developed(1) show the relationship between the standard error(+) on delay time measurement (σ_τ) and cross-covariance (ρ) as illustrated in Figure 4; where T is the correlator integration time and B is the bandwidth of the filter which limits the high frequency content of the signal.

Figure 4 shows that for some combinations of B and T the standard error is almost constant for $\rho > 30\%$, and therefore the method used is not very sensitive to the signals' "quality", above a certain minimum. Experimental results confirming this behaviour, are discussed later. The cross-covariance computed by the correlator is displayed on the front panel of the instrument and is used in an automatic mode control circuit(2) to prevent erroneous results by rejecting data whose cross-covariance drops below a preset minimum.

It should also be noted that reduction of the standard error through continuously increasing T is small above a certain T. For these conditions, standard error reduction is more effectively accomplished through use of

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(+) "Standard error" is used to refer to the standard deviation (σ) of the error distribution. σ characterizes this distribution, and is hence used for evaluating the error. (Error being the difference between "observed" value and "true"value). See Section 5 (Page 8) for more definitions.

analogue averaging circuits following the output of the correlator. A mathematical model was also developed to study the action of the averaging circuits.

Results from the theoretical studies yield a standard error of less than 2% for integration periods between 2 and 5 seconds. The computation of standard errors that follows, is based on signal bandwidth of 36 Hz and a correlation integration period of 5 s. The measured ρ and τ are used in a theoretical model to obtain σ_τ.

RUN	τ ms	ρ %	σ_τ ms	σ_τ/τ %	σ_τ/τ After Analogue Averaging in the Instrument %	σ_τ/τ After Taking The Average of 10 read. %	To obtain std. error on flow measurement from the one on time delay add 1% for pipe area & .5% for trans. spac.
72	36.38	75	5.50	15.12	1.97	0.62	2.12
84	296.57	40	6.39	2.15	0.28	0.09	1.59

The above two results are for the two extreme measurement conditions (i.e., the two which give the largest and smallest standard error. The standard error for the average measurement condition is 1.65%.

The above results were obtained from theoretical models, simulated to approximate the physical situation. Although errors predicted by the models may not be correct in absolute magnitude, results should be useful in evaluating the order of the error and its trends with changes in system parameters.

Error in the time delay measurement is also dependent on the type of cross-correlator used in the analysis. Complete amplitude correlation requires many bit-quantization and complicated electronics. The flowmeter used in this work has a process correlator that performs only polarity correlation(3) through "add-only" counters. The two level quantization simplifies the electronics and reduces the cost of the instrument. In Table 1, values of time delays obtained by the instrument polarity coincidence correlator are compared with values computed by a digital signal processor correlator which uses multi-level quantization*. No significant difference between the results of the two methods is seen. Therefore, time delay measurement derived from the polarity coincidence correlator of the flowmeter yield results of sufficient accuracy.

5. FLOW MEASUREMENT

Measurements were conducted on a water loop calibration facility at the Chalk River Nuclear Laboratories to determine the accuracy of the flowmeter as well as optimum installation conditions(4).

The flow calibration facility (Figure 5) is a closed-cycle water loop with a weigh tank and a fast acting diverter valve. A reading from an electronic timer, indicating the duration of time the diverter valve is directing the water in the weigh tank and the weight of the water collected in that tank, are used to obtain the mass flow. Flow measurements were conducted on 15 cm (6 in.) schedule 40 aluminum pipe, with no other surface preparation than wiping off dust. In the performance measurement program flows were varied from 40,000 to 350,000 kg/h, temperatures from 14 to 45°C and transducer spacings from 0.1 to 0.6 m.

Horizontal as well as vertical beams were used at several of the locations, 1 through 6, given in Figure 5. Photographs of some of the installations are shown in Figure 6.

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* The number of the quantization levels is so high, that the processor effectively treats a continuous amplitude signal.

These locations were chosen to study the effects, if any, on flowmeter readings of mounting the transducer after a valve, elbow, flange, blanked T or a long straight length of pipe.

The first series of measurement (at location 3) was designed to study the effect of transducer spacing on error. As can be seen from Table 2, the main effect of increasing the spacing is a decrease in the cross covariance. But, as expected from theoretical models, the standard error is constant for $\rho > 30\%$ and therefore no positive relationship between error and spacing was observed.

Based on observations during the second series of runs at the different locations, the following recommendations can be made:

a) Measuring locations after long straight sections of pipe (more than 20 diameters) result in reduced turbulence and the present form of the instrument cannot measure flows in these locations when Re* < 2×10^5. Above that limit performance is normal. The absence of sufficient turbulence can be compensated by the presence of small amounts of entrained gas or impurities. Entraining small amounts of air in the water enabled measurements below Re < 2×10^5. Another technique used to obtain measurements under these conditions was to filter out the low frequency uncorrelatable content of the signals between the phase demodulator output and the input to the correlator. A high pass filter with cut off between 4 and 6 Hz proved to be helpful in these situations.

b) Errors obtained from measurements after the flange and blanket T, location 6, were comparable to errors obtained from measurements obtained after long straight lengths of pipe, locations 4 and 5.

c) Increased scatter (about 1% more) noted in results from transducers mounted close to a standard elbow could have been influenced by the investigation of modifications to the electronics during these

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* Re = Reynolds number

measurements. However, the recommendation of 5 to 10 diameters downstream from an elbow, as noted in the users manual, should be adhered to where possible.

d) The instrument works equally well with transducers mounted on vertical or horizontal pipes.

e) After a fully opened valve, performance of the instrument was normal. However, partially closing the valve resulted in readings higher than the actual flow, due to a reduction in the effective cross-section of the pipe. Therefore, installations less than 12 diameters downstream of a valve, orifice plate or other piping configuration which changes the effective cross-section of the pipe are not recommended.

f) Small amounts of entrained air in the liquid result in improved performance, since the small bubbles increase the correlatable content of the signal. However, correction for the volume occupied by the air must be applied when computing the flow.

g) Good results are obtained with transducers mounted in vertical or horizontal planes.

Results were not obtained for all runs because some combinations of transducer spacings and flows produced values outside the instrument's range.

The performance of the flowmeter was then evaluated by comparison of its readings with the weigh tank results. It should be noted that the standard deviation ($1\ \sigma$) of the weigh tank error was measured to be 1.72%. Any figures found lower than this value are then insignificant. Table 3 summarizes the results of the runs on the water loop.

Average error is defined as,

$$\text{Average error} = \frac{\sum_{1}^{N} \frac{\text{Flowmeter - Weigh Tank}}{\text{Weigh Tank}}}{N} \times 100\%$$

It is a measure of the absolute accuracy of the system; or how far on the average all the measurements are from their reference flows.

Standard deviation, denoted by σ, is defined as,

$$\text{Standard deviation} = \sqrt{\frac{\sum_{1}^{N} \left(\frac{\text{Flowmeter - Weigh Tank}}{\text{Weigh Tank}}\right)^2}{N - 1}} \times 100\%$$

and this value shows how much spread there is in the ultrasonic flowmeter measurements around the reference flow measurement, i.e. it characterizes the distribution of flowmeter error. This is an important quantity in evaluating a measurement system.

In a normal distribution, 68% of measurements are within 1σ, 95% are within 2σ, and 99.5% are within 3σ. Two standard deviations are usually used in measuring flowmeter performance and is referred to by ASME (PTC 19.5, 4 - 1959) as the "tolerance" of a flowmeter. The tolerance referred to in the Tables is the instrument standard deviation corrected for the weigh tank deviation, and multiplied by <u>two</u> to give the established measure,

$$\text{Tolerance} = 2 \times \sqrt{(\text{Deviation})^2 - (1.72)^2}.$$

Runs 44 to 99 (Table 1) were done to test the effects of transducer spacing and distance from elbow on the flowmeter performance, as well as to verify the range of the instrument (location 3 on Figure 5).

Runs 101 to 124 (Table 5) were done expressly to measure the standard deviation of the instrument. On the same day, in the same conditions and with the same procedures, six different measurements (with different transducer spacing and distance from elbow) were taken for each of four different flows covering a wide range of the water loop (also at location 3). These results obtained for optimum installation conditions illustrate the full capability of the flowmeter.

Runs 175 to 199 (Table 6) were done on five different locations, to test these locations (1, 2, 4, 5, 6, Fig.5,6). A consistent bias of ~2% higher than weigh tank measurements was obtained. (This bias was later thought to be due to investigation of modifications to the electronics during the runs). Subtracting 0.02 from the Birger's coefficient yielded the corrected results, which are shown on the last line of Table 3.

6. CONCLUSIONS

Overall performance of the flowmeter is satisfactory. The flowmeter is ideally suited to industrial applications and has an average error and standard error comparable to many calibrated laboratory instruments.

Table 7 classifies and compares the characteristics of the ultrasonic cross-correlation flowmeter with the still most widely used pressure differential system using the orifice plate.

This new portable flowmeter should prove to be very useful in:

- providing flow measurements in systems where pipe penetration is too costly and/or not practical.
- verifying or replacing existing flowmeters.
- checking flows in lines not previously equipped with flowmeters, for better control and verifying performance of complex systems.

7. ACKNOWLEDGMENTS

The authors wish to thank the personnel of the Advance Engineering Branch at CRNL for the use of their facilities. We gratefully acknowledge the significant contribution of P.J. Smith of CRNL in operating the flowmeter and analyzing the results.

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2. Canadian General Electric, "Principal of Operation and Maintenance Manual - Ultrasonic Cross-Correlation Flowmeter (Preliminary)", CGE, Peterborough, Ontario.

3. Flemons, R.S., "A New Non-intrusive Flowmeter", 1976 Flow Measurement Symposium of the National Bureau of Standards, Gaithersburg, Md.

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TABLE 1

COMPARISON OF DELAY TIMES AS MEASURED BY AMPLITUDE CORRELATION (τ_1) TO THOSE MEASURED BY POLARITY COINCIDENCE CORRELATION (τ_2)

RUN No.	ρ %	τ_1 ms	τ_2 ms	Error $\frac{\tau_2 - \tau_1}{\tau_1} \times 100\%$
63	65	92.7	92.7	0
64	40	183.0	183.0	0
66	45	183.0	185.0	+1.1
67	65	92.7	92.5	-0.2
68	65	92.7	91.9	-0.9
69	55	87.8	89.2	1.6
72	75	36.6	36.4	-0.5
73	80	36.6	38.1	4.1
74	75	39.0	39.1	0.3
75	75	41.4	41.4	0
76	78	48.8	48.6	-0.4
77	70	58.5	58.7	0.3
78	62	68.3	69.7	2.0
79	65	68.3	70.1	2.6
80	65	85.4	86.9	1.8

τ_1 = measured by SD-360 digital signal processor

τ_2 = measured by CGE flowmeter

Average error 0.9%

Standard deviation 1.6%

TABLE 2

MEASUREMENTS TAKEN WITH INCREASING SPACING BETWEEN TRANSDUCER SETS

(At location 3, see Figure 5)

RUN NO.	TRANSDUCER SPACING m	NORMALIZED CROSS-COVARIANCE %	DELAY TIME ms	GRAV. FLOW 1000 kg/h	INST. FLOW 1000 kg/h	ERROR %
50	0.2	60	103.23	116.56	120.48	3.37
123	0.2	60	93.92	135.59	132.71	-2.13
67	0.2	65	92.49	133.93	134.63	0.52
89	0.2	65	48.97	252.53	255.13	1.03
111	0.2	70	40.71	316.75	307.17	-3.02
105	0.2	75	50.00	257.51	249.76	-3.01
117	0.2	65	72.86	173.41	171.22	-1.26
		$\langle\rho\rangle = 66$			$\sigma = 2.48$	
104	0.4	55	98.89	258.78	252.54	-2.41
51	0.4	40	206.85	116.41	120.26	3.30
122	0.4	50	187.13	135.67	133.21	-1.81
90	0.4	50	98.37	252.03	253.99	0.78
116	0.4	60	145.26	173.37	171.76	-0.93
58	0.4	55	143.43	179.96	173.83	-3.41
99	0.4	70	81.84	312.83	305.41	-2.37
66	0.4	45	185.61	133.85	134.16	0.23
110	0.4	45	87.26	286.84	286.45	-0.14
		$\langle\rho\rangle = 52$			$\sigma = 2.20$	
65	0.6	25	270.04	133.86	138.34	3.34
121	0.6	35	274.21	135.77	136.37	0.44
115	0.6	50	215.34	173.90	173.80	-0.06
57	0.6	40	214.05	179.85	174.72	-2.85
87	0.6	40	202.66	185.69	184.63	-0.57
103	0.6	40	151.87	258.58	246.60	-4.63
109	0.6	40	128.77	293.53	291.16	-0.81
98	0.6	40	119.63	313.44	313.44	0.00
		$\langle\rho\rangle = 39$			$\sigma = 2.45$	

TABLE 3

SUMMARY OF PERFORMANCE MEASUREMENT PROGRAM

Run No.	Average Error %	Standard Deviation %	Tolerance (2σ) %
44 to 99	0.27	2.125	2.50
101 to 124	-0.91	1.842	1.32
44 to 124 (combined)	-0.14	2.016	2.10
175 to 199	2.27	3.209	5.42
175 to 199 (corrected)	0.05	2.155	2.60

TABLE 4

COMPARISON OF ULTRASONIC FLOWMETER READINGS TO WEIGH TANK MEASUREMENTS FOR DIFFERENT FLOW MEASUREMENT CONDITIONS

RUN NO.	SPACING m	DDE* m	ρ^+ %	GRAV. FLOWMETER 10^3 kg/h	CGE FLOWMETER 10^3 kg/h	ERROR %
44	0.2	0.97	60	113.16	112.27	-0.79
45	0.4	0.77	45	111.20	111.11	-0.08
47	0.2	0.97	55	116.41	117.66	1.07
48	0.4	0.77	35	115.69	115.99	0.26
50	0.2	0.57	60	116.56	120.48	3.37
51	0.4	0.57	40	116.41	120.26	3.30
53	0.2	0.97	45	116.30	120.75	3.83
55	0.2	0.97	60	178.31	177.74	-0.32
56	0.4	0.77	50	180.44	175.05	-2.99
57	0.6	0.57	40	179.85	174.72	-2.85
58	0.4	0.57	55	179.96	173.83	-3.41
61	0.2	0.77	65	180.40	172.62	-4.32
63	0.2	0.77	65	133.98	134.29	0.23
64	0.4	0.77	40	133.69	135.86	1.63
65	0.6	0.57	25	133.86	138.34	3.34
66	0.4	0.57	45	133.85	134.16	0.23
67	0.2	0.57	65	133.93	134.63	0.52
68	0.2	0.77	65.	133.68	135.58	1.42
69	0.2	0.97	55.	133.72	139.57	4.37
72	0.2	0.77	75.	351.42	343.92	-2.14
73	0.2	0.77	80.	335.29	328.46	-2.04
74	0.2	0.77	75.	324.95	319.96	-1.53
75	0.2	0.77	75.	308.70	302.34	-2.06
76	0.2	0.77	78.	253.58	257.31	1.47
77	0.2	0.77	70.	214.39	212.71	-0.78
78	0.2	0.77	62.	177.31	178.90	0.90
79	0.2	0.77	65.	181.74	177.62	-2.26
80	0.2	0.77	65.	143.82	143.12	-0.49
81	0.2	0.77	55.	106.60	106.48	-0.11
82	0.2	0.77	60.	79.69	78.78	-1.14
84	0.2	0.77	40.	40.46	41.71	3.08
85	0.2	0.77	70.	238.59	245.53	2.91
86	0.4	0.77	60.	200.53	207.77	3.61
87	0.6	0.57	40.	185.69	184.63	-0.51
89	0.2	0.57	65.	252.53	255.13	1.03
90	0.4	0.57	50.	252.03	253.99	0.78
91	0.4	0.77	40.	252.60	253.40	0.32
92	0.2	0.77	60.	246.60	250.26	1.48
93	0.2	0.97	60.	249.67	249.32	-0.14
95	0.2	0.77	75.	312.80	314.33	0.49
96	0.4	0.77	60.	312.80	314.04	0.40
97	0.4	0.77	65.	313.20	320.76	2.41
98	0.6	0.57	40.	313.44	313.44	-0.00
99	0.4	0.57	70.	312.83	305.41	2.37

* DDE = Distance Downstream from Elbow

Average error = 0.27%
Standard Deviation = 2.125%

Tolerance (2 σ) = 2.5%

$^+\rho$ normalized cross-covariance in %.

TABLE 5

COMPARISON OF ULTRASONIC FLOWMETER READINGS TO WEIGH TANK MEASUREMENTS FOR DIFFERENT FLOW MEASUREMENT CONDITIONS

RUN NO.	SPACING m	DDE* m	ρ^+ %	GRAV. FLOWMETER 10^3 kg/h	CGE FLOWMETER 10^3 kg/h	ERROR %
101	0.2	0.97	70	259.00	256.42	-1.00
102	0.4	0.77	65	259.36	256.10	-1.26
103	0.6	0.57	40	258.58	246.60	-4.63
104	0.4	0.57	55	258.78	252.54	-2.41
105	0.2	0.57	75	257.51	249.76	-3.01
106	0.2	0.77	70	257.81	253.13	-1.74
107	0.2	0.97	78	311.28	314.26	0.96
108	0.4	0.77	60	302.19	304.13	0.64
109	0.6	0.57	40	293.53	291.16	-0.81
110	0.4	0.57	45	286.84	286.45	-0.14
111	0.2	0.57	70	316.75	307.17	-3.02
112	0.2	0.77	70	305.47	300.49	-1.63
113	0.2	0.97	70	174.32	175.57	0.71
114	0.4	0.77	60	173.84	172.92	-0.53
115	0.6	0.57	50	173.90	173.80	-0.06
116	0.4	0.57	60	173.37	171.76	-0.93
117	0.2	0.57	65	173.41	171.22	-1.27
118	0.2	0.77	65	173.56	172.80	-0.44
119	0.2	0.97	60	135.68	138.70	2.23
120	0.4	0.77	50	135.91	133.51	-1.77
121	0.6	0.57	35	135.77	136.37	0.44
122	0.4	0.57	50	135.67	133.21	-1.81
123	0.2	0.57	60	135.59	132.71	-2.13
124	0.2	0.77	55	135.39	137.65	1.66

Average Error = -0.91%

Standard Deviation = 1.842%

Tolerance (2 σ) = 1.32%

* DDE = Distance Downstream from Elbow.

$^+\rho$ = normalized cross-covariance in %.

TABLE 6

COMPARISON OF ULTRASONIC FLOWMETER READINGS TO WEIGH TANK MEASUREMENTS FOR DIFFERENT FLOW MEASUREMENT CONDITIONS

RUN NO.	SPACING m	LOCATION*	ρ^+ %	GRAV. FLOWMETER 10^3 kg/h	CGE FLOWMETER 10^3 kg/h	ERROR %
175	0.2	2	60	238.39	242.75	1.83
176	0.2	2	55	238.47	246.71	3.45
179	0.2	2	65	324.45	331.92	2.30
180	0.2	2	65	325.80	336.73	3.35
181	0.2	2	80	330.09	318.92	-3.38
182	0.2	2	72	326.75	325.61	-0.35
183	0.2	1	60	234.13	238.54	1.68
184	0.2	1	60	234.13	245.32	4.78
186	0.2	4	65	250.42	248.60	-0.73
187	0.2	4	65	251.21	257.22	2.39
188	0.2	4	70	251.60	258.03	2.56
189	0.2	4	65	251.50	263.38	4.72
190	0.2	4	40	251.50	258.75	2.88
191	0.2	6	50	161.13	166.65	3.42
193	0.2	6	45	60.84	63.91	5.04
195	0.2	6	50	55.78	58.98	5.75
197	0.2	6	-	309.46	311.37	0.62
930	0.1	5	-	114.61	116.48	1.63
198	0.2	5	55	114.81	118.08	3.03
199	0.1	5	45	114.61	114.92	0.27

Average Error = 2.27%

Standard Deviation = 3.209%

Tolerance (2 σ) = 5.42%

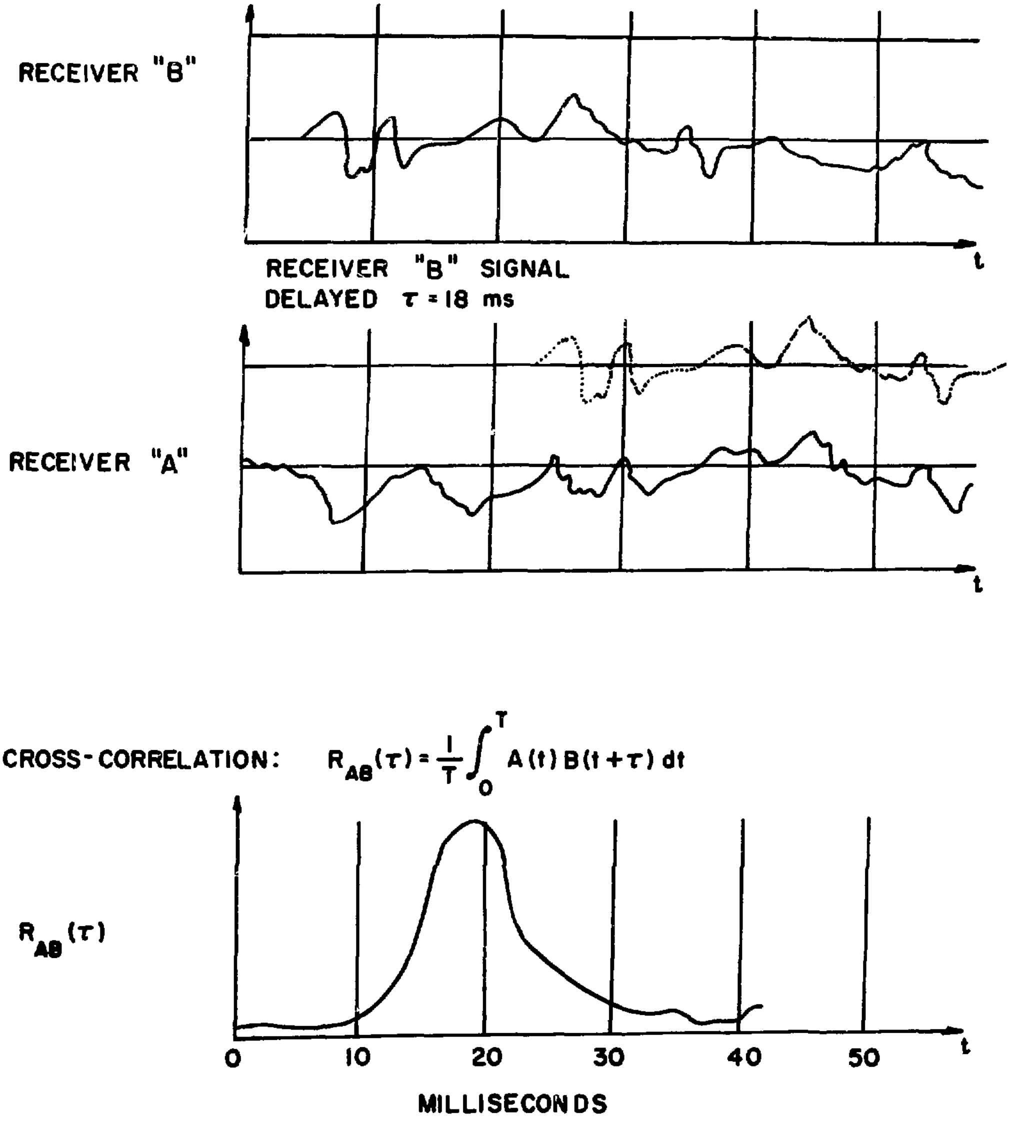
* Locations 1, 2, 4, 5 and 6, Figure 5.

+ρ = Normalized cross-covariance in %.

TABLE 7

PERFORMANCE COMPARISON OF DP TRANSMITTER-ORIFICE PLATE FLOW MEASURING SYSTEM TO ULTRASONIC CROSS-CORRELATION FLOWMETER

	ORIFICE PLATE	ULTRASONIC CROSS-CORRELATION
Calibration	Due to the semi-empirical relation between flow and measured quantity, calibration may be required. It is usually carried out in the manufacturer's labs, and users must comply with his installation instructions. Calibration on site is a must for applications that require accuracy. Calibration factors include pipe size, flow range, temperature, pressure and nature of liquid.	It operates on the timing of inherent tracers in the flow, and therefore requires no calibration and no flow manipulation. The relation between measured flow and average flow is a known, practically constant, flow coefficient.
Accuracy	% of full scale With the square root relationship between pressure and flow, the error becomes quite large at lower flows: e.g. 1% at full scale, 4% at half scale and 9% at 1/3 scale. Maximum accuracy is about 1.5% of full scale if standard specifications and installations instructions are followed carefully. Accuracy of about 3% full scale is considered normal.	Constant % of actual reading Linear relationship between flow and reading. Measurements indicate an accuracy of about 3% of measured flow is readily obtainable. With adequate choice of measuring locations and careful operation of the system, an experienced operator can achieve accuracy of better than 2%.
Range	Maximum 3:1	Greater than 10:1. Present design of the instrument limits the measureable time range from 30 to 300 ms. By changing the transducer's spacings, one can extend the flow range beyond 10:1.
Drift	Occurs during normal operation, and is due to changes in geometry because of corrosion, wear and accumulation of dirt, or changes in system pressure and temperature, or liquid composition. Drift could also arise from analog circuitry in pressure transducer.	Cross-correlator is digital and will not drift. Phase demodulators are synchronised with the transmitters, so drifts in the latter's freauencies is no problem.
Installation	Installation is inside the pipe. It therefore requires system shutdown for installation, maintenance, inspection, or any servicing to the plate or pressure taps. It could reduce the integrity of system containment. It introduces a large pressure drop in the system.	Clamps on outside of pipe without penetration. Does not cause any distrubance to the flow.
Flexibility	None. Installation is permanent, it has no mobility. An orifice plate and pressure taps designed for an application cannot be easily transferred to another location.	Can be easily and quickly moved from one location to another. One flowmeter is used for various types and sizes of pipes, various liouids and wide range of flows. One flowmeter may be used to monitor several sets of transducers mounted at different locations. Can operate with small amounts of entrained solids or gas in the liquid. Can be used as a detector for impurities or voids. Can be easily reversed for measuring flow in opposite direction.



RECEIVED SIGNALS AFTER PHASE DEMODULATION

FIGURE 1: SCHEMATIC ILLUSTRATION OF CROSS-CORRELATION FUNCTION

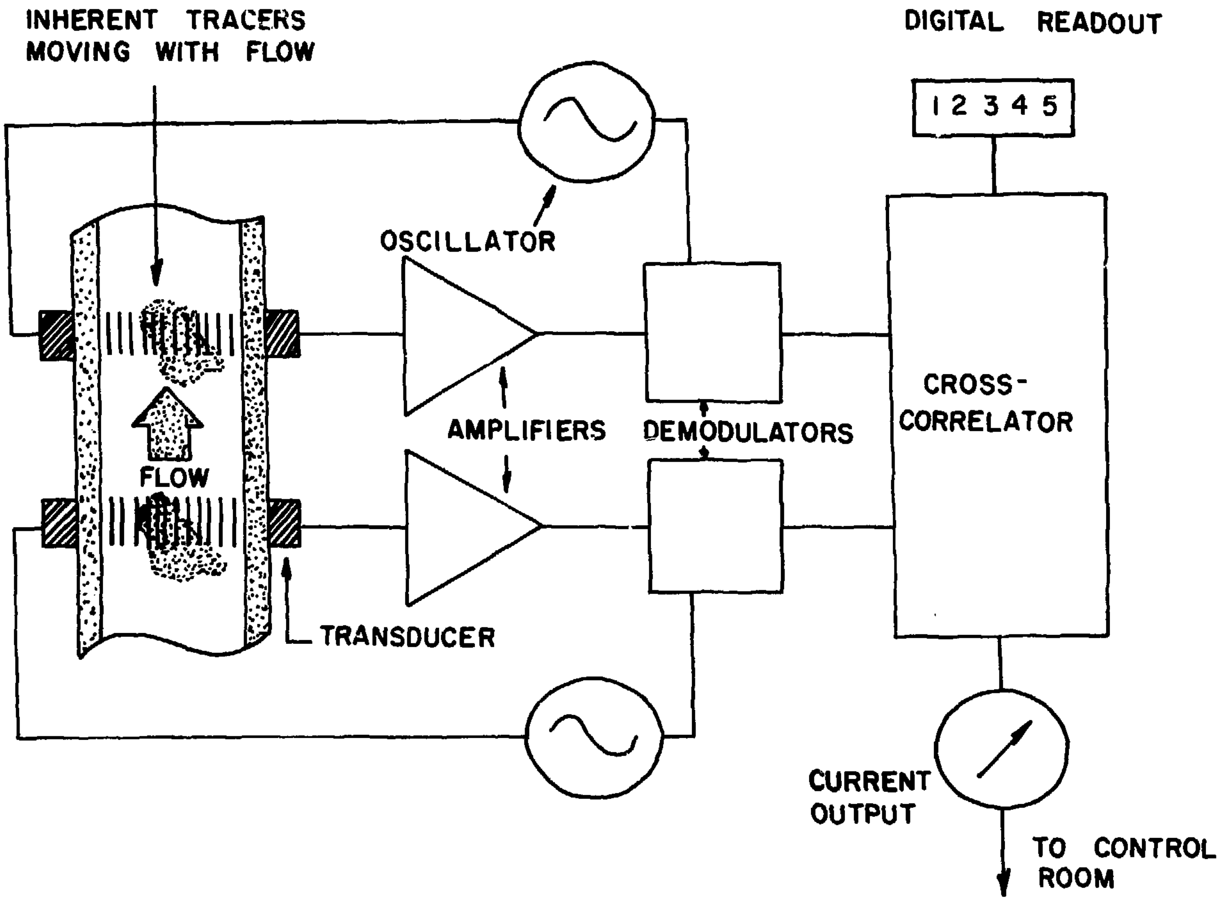
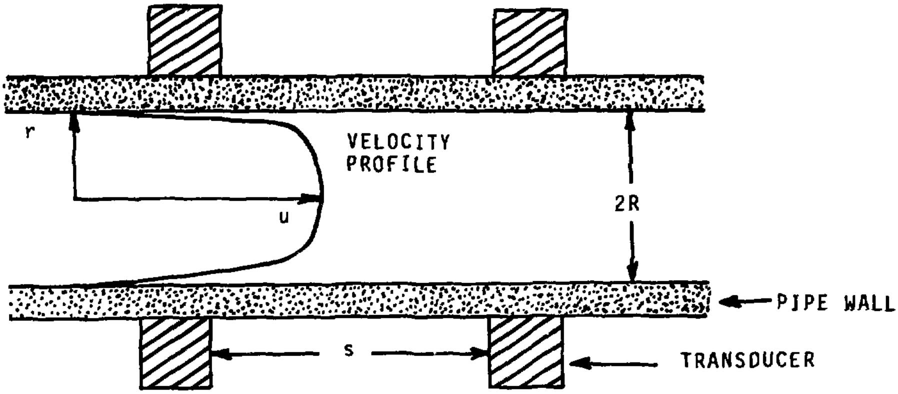


FIGURE 2: ULTRASONIC CROSS-CORRELATION FLOWMETER



MEASURED VELOCITY

$$\bar{V}_d = \frac{2\int_0^R u\,dR}{2R}$$

Velocity averaged over pipe diameter.

TRUE VELOCITY

$$\bar{V}_a = \frac{\int_0^R u 2\pi r\,dr}{\pi R^2}$$

Velocity averaged over pipe area.

BIRGER'S COEFFICIENT

$$k = \frac{\bar{V}_a}{\bar{V}_d} = \frac{1}{1 + 0.19\ \mathrm{Re}^{-0.1}}$$

For $\mathrm{Re} = 10^5 \rightarrow 10^6$, $k = .95 \pm .5\%$

Source: Birger, G.I., "Certain Problems in Calibrating Ultrasonic Flowmeters", Izmeritel naya Technika, No. 10, pp. 53-55, October 1962.

FIGURE 3: VELOCITY PROFILE CORRECTION FACTOR

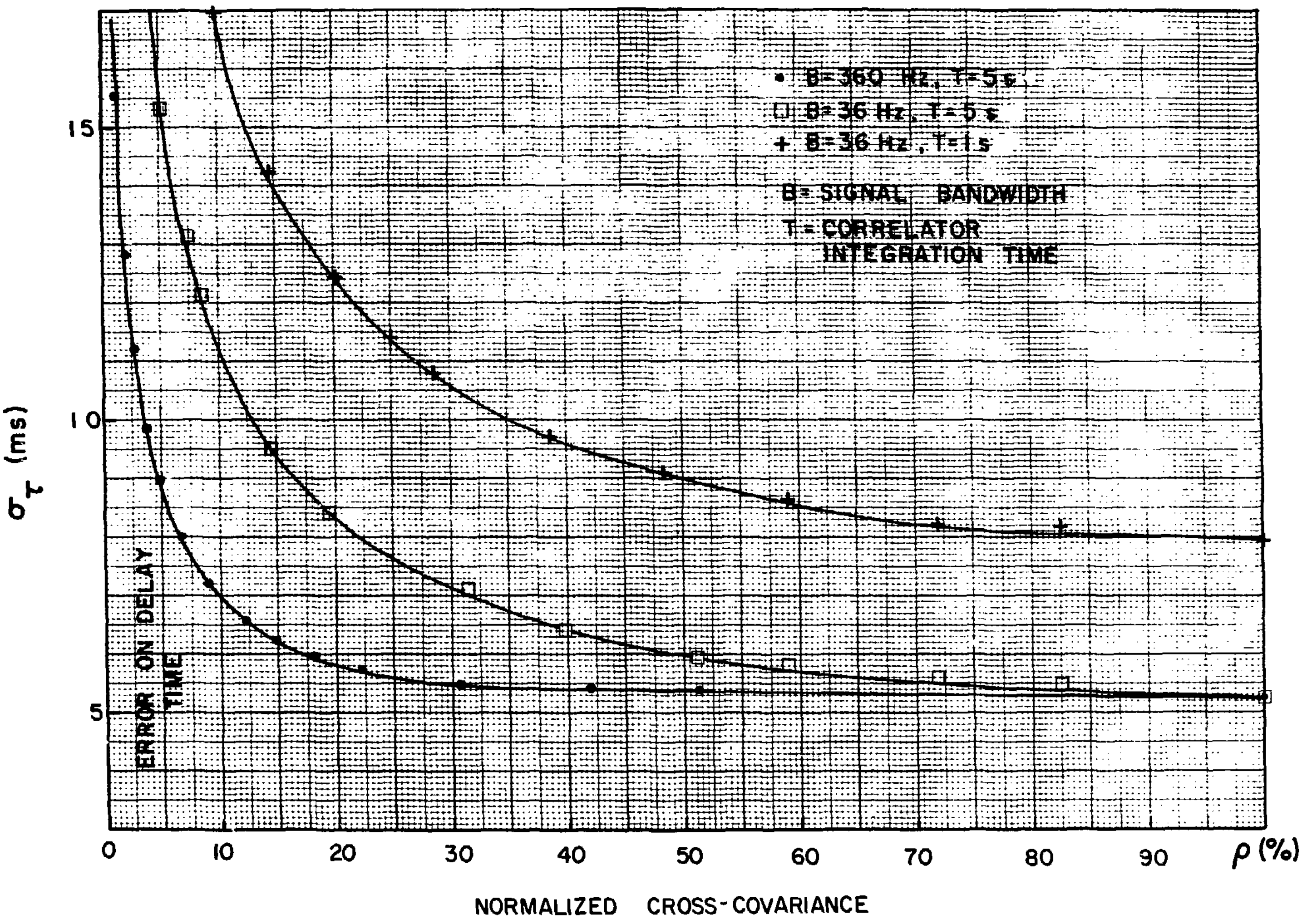


FIGURE 4: STANDARD ERROR ON DELAY TIME VERSUS NORMALIZED CROSS-COVARIANCE

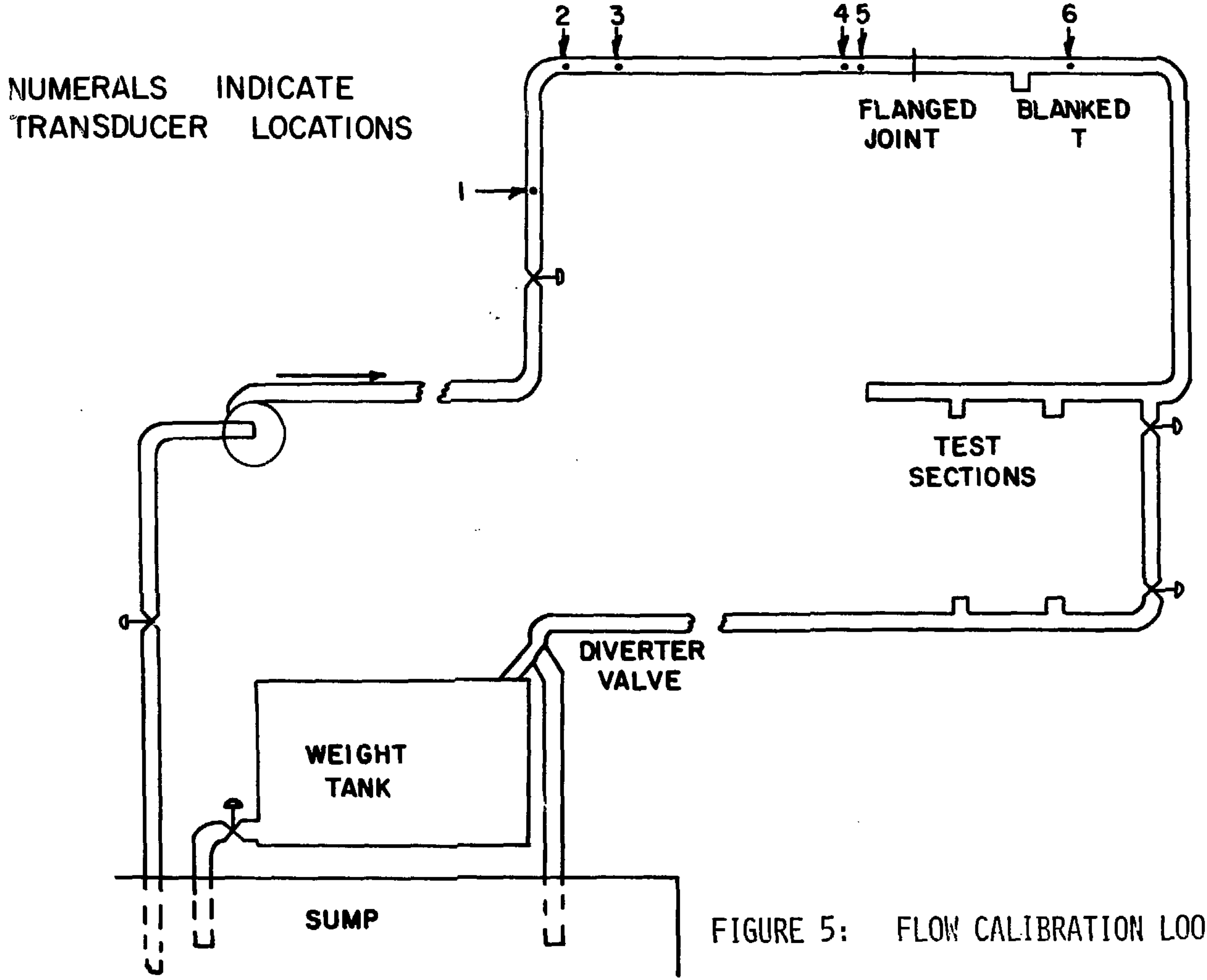
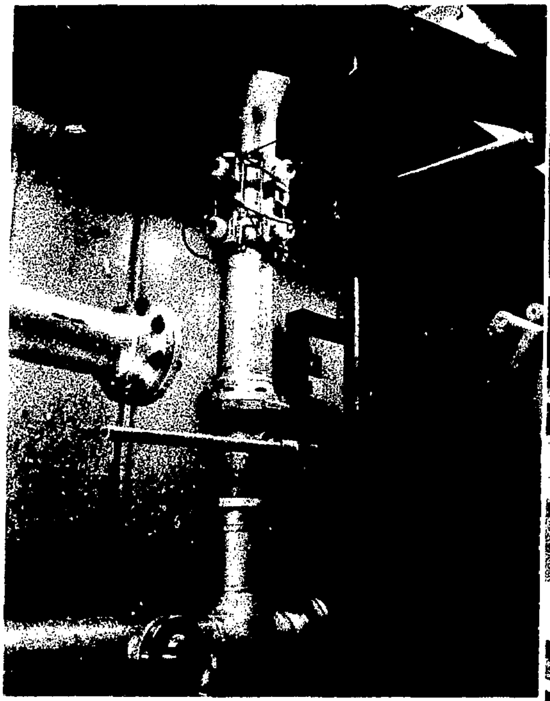
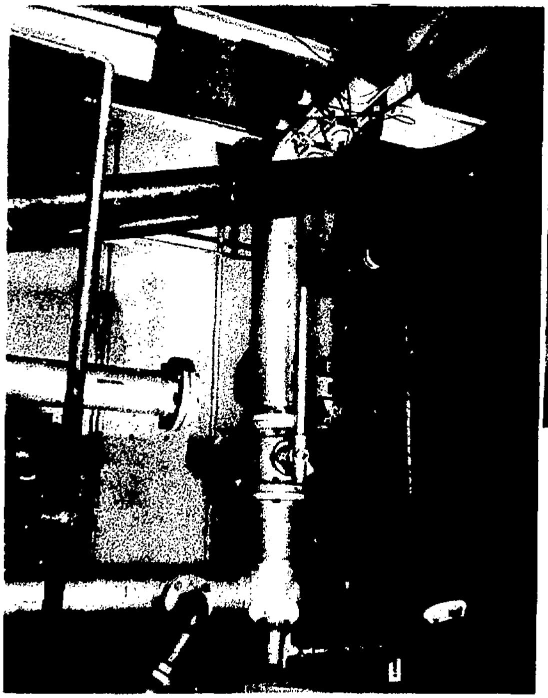


FIGURE 5: FLOW CALIBRATION LOOP

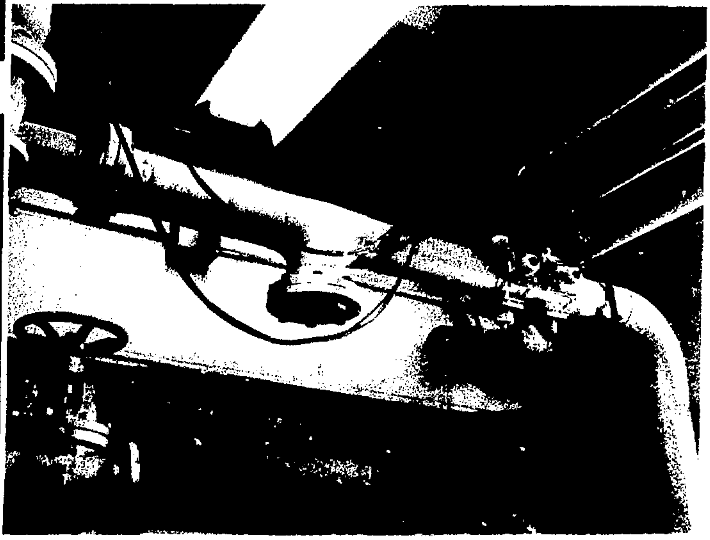


LOCATION 1



LOCATION 2

LOCATION 4



LOCATION 6

FIGURE 6: TRANSDUCER LOCATIONS ON FLOW CALIBRATION LOOP

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ISSN 0067–0367

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