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A program was conducted to determine repeatability and linearity of the ultrasonic time-delay types of flowmeters, so that their applicability to leak detection on underwater pipelines could be assessed. Field tests using merchantable crude oil were conducted on two off-the-shelf, commercially available flowmeters at a refinery meter proving station. These tests showed a short-term repeatability of 0.2 percent for both meters. Long-term

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20. Abstract (Cont'd)

(7 hours) repeatability was 0.6 percent for one meter and 2.5 percent for the other.

For a leak detection system in which line balance is continually computed and line packing is compensated for, slow drifts in line balance due to drifts of meter factors can be compensated for by periodically adjusting meter factors. For a meter with drift characteristics similar to those measured, a computerized simulation indicates that the probability of detecting a leak greater than 0.6 percent of the total flow in 10 minutes is greater than 99 percent. The probability of a false alarm for the same conditions is about once per week.

FOREWORD

Portions of this paper were published previously in the proceedings of the 54th International School of Hydrocarbon Measurement.

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1. INTRODUCTION

The U.S. Army's Harry Diamond Laboratories (HDL), under technology transfer authorization, has been conducting a flowmeter evaluation program funded by the Conservation Division of the U.S. Geological Survey. The overall objective of the program is to identify measurement techniques that can be applied effectively and efficiently for improving safety and pollution control during operations on the outer continental shelf.

To further this objective, a program was initiated to determine new flowmeter technologies that are potentially applicable to offshore flow measurement problems, particularly the problem of detecting underwater pipeline leaks. The hydrocarbon fluids handled by offshore pipelines typically have had the gas separated, but the liquid phase still contains salt water (up to 50 percent or even greater), some sand, and other sedimentary materials. The flow rate of this raw crude oil historically has been impossible or highly impractical to measure by conventional means. The performance of positive displacement or turbine meters that are used routinely for custody transfer of merchantable crude oil or products would be seriously degraded by these fluids.

A new meter was sought that could withstand the corrosive and erosive action of these fluids and that could meter the fluids reliably for leak detection, even though they may not be as accurate as custody transfer meters on clean crude oil. In addition, to widen the potential applicability of the meter to offshore problems by allowing the free passage of pipeline pigs, a meter was sought that would not intrude into the pipeline or require any pipeline diameter change.

Meters were investigated that operated on the principles of vortex shedding, differential pressure, induced swirl, fluidic oscillators, magnetic flux, and time delay or doppler frequency shift during the transmission of ultrasonic sound. The only meter that met both the criteria of fluid suitability and no intrusion into the pipeline was the ultrasonic, time-delay type of meter. The operation of this meter is discussed in the next section, followed by the results of a field test of two meters of this type conducted at a merchantable crude meter proving station.

Initially, six different meters from four manufacturers were to be included in this program. One manufacturer was to supply two different meters, but defaulted on delivery. Another manufacturer was to supply prototypes of two experimental meters, but was not able to meet the test schedule due to late entry into the program. The meters that were tested were the Clampatron flowmeter, manufactured by the Controlotron Corporation, and the NUSONICS flowmeter, manufactured by MAPCO, Inc. (both shown in fig. 1).

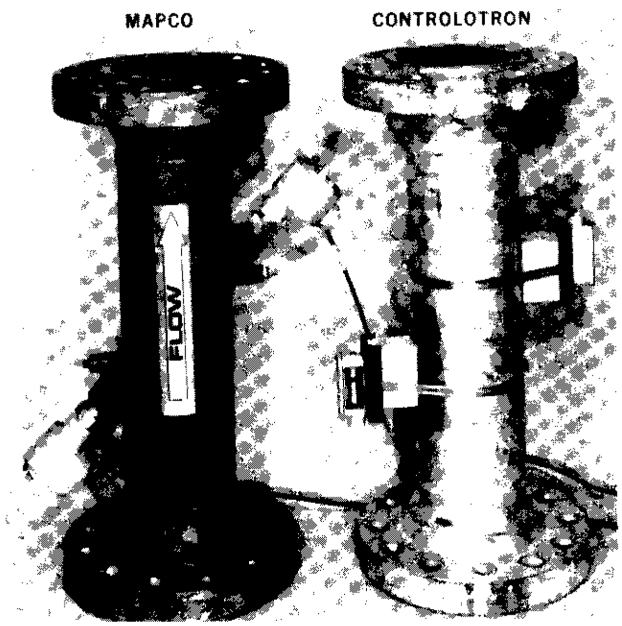


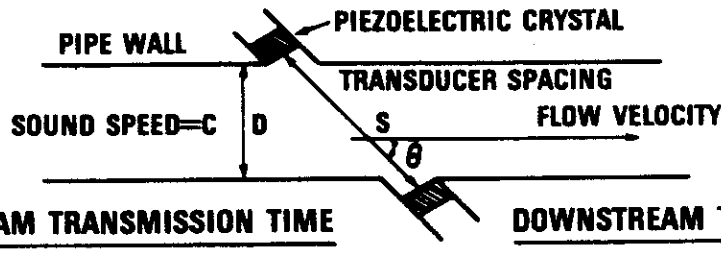
Figure 1. MAPCO and Controlotron meter tubes.

2. ULTRASONIC FLOWMETER OPERATION

Each test meter was mounted on a 30-in.-long, schedule 40-A-106 pipe spool, made of 6-in.-diameter carbon steel (grade B). The Controlotron meter ultrasonic tranducers were clamped to the outside of the pipe so that the sound passed through the wall of the pipe into the fluid being metered. The MAPCO meter transducers were mounted on bosses welded to the pipe so that they were actually wetted by the fluid being metered.

Both meters work on the principle of measuring time delay differences between sound pulses transmitted upstream and downstream in the flowing medium. The speed of sound in the flowing medium is eliminated as a variable because the flow rate calculations are based on the reciprocals of the transmission times, as shown in figure 2.

Although each manufacturer differs on the details in implementing this calculation, the process generally used is to set the frequencies (f_i) of two voltage-controlled oscillators (VCO's), one to be inversely proportional to the upstream and the other to the downstream delay times (T_i) (i.e., $f_i = N/T_i$ where N is the proportionality constant). The frequencies can be set by filling a counter, beginning with the transmission of a pulse and then comparing the fill time with the arrival time of the pulse at the other transducer. If the counter fills early, then the VCO frequency is decreased and vice versa. Each VCO frequency is updated several hundred times per second with the arrival of either a valid upstream or a valid downstream signal. (If a noisy or excessively distorted pulse is received, no update occurs.) The difference between the two VCO frequencies (or the difference between their controlling voltages) is proportional to the flow velocity averaged across the diameter of the pipe.



UPSTREAM TRANSMISSION TIME

$$T_1 = \frac{S}{C - V\cos\theta}$$

DOWNSTREAM TRANSMISSION TIME

$$T_2 = \frac{S}{C + V\cos\theta}$$

TO ELIMINATE SPEED OF SOUND (C) AS A VARIABLE

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{2V\cos\theta}{S} \quad \text{OR} \quad V = \frac{S}{2\cos\theta}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

TO SOLVE FOR SPEED OF SOUND

$$\frac{1}{T_2} + \frac{1}{T_1} = \frac{2C}{S} \quad \text{OR} \quad C = \frac{S}{2}\left(\frac{1}{T_2} + \frac{1}{T_1}\right)$$

Figure 2. Ultrasonic flowmeter operating principle.

The major difference between the flowmeters lies in their method of deciding when a sound pulse has been received. The magnitude of this problem can be understood only when the required timing precision is known. From the equations shown in figure 2, it can be shown that for V (the average flow velocity) much less than C (the speed of sound),

$$T_2 - T_1 = \Delta T = \frac{2S\cos\theta}{C^2} V \quad ,$$

where T_1 and T_2 are the downstream and upstream transmission times, S is the transducer spacing, and θ is the angle between the sound path and the pipe axis. For a 6-in.* pipe filled with a fluid with sound speed

*in. × 25.4 = mm.

3000 ft/s, a velocity resolution of 0.005 ft/s (0.1 percent of 5 ft/s) requires the time difference between upstream and downstream transit times to be known to 0.4×10^{-9} s (0.4 ns). This is about the time required for light to travel 5 in. The sound frequency typically transmitted through the fluid is about 1 MHz (a period of 10^{-6} s), so the received signal must be timed to within 4×10^{-4} cycle.

Circuitry that could accomplish this degree of timing precision was not available until the advent of modern integrated circuit technology. Thus, the most sensitive part of the ultrasonic flowmeter is the circuitry that detects the arrival time of the received sound pulse. Although every meter manufacturer has a different method of detecting the signal, both meters tested have circuitry to maintain a constant received signal amplitude (by adjusting the transmitted signal amplitude) and to discriminate against signals that have been distorted or interfered with while transversing the pipe. Other details of the detection circuitry vary considerably between manufacturers. However, the output of each meter is a pulse rate proportional to flow rate, so each meter has a meter factor similar to any turbine or positive displacement meter. The output of the MAPCO meter was about 1300 pulses/barrel; that of the Controlotron meter was about 2000 pulses/barrel.

The accuracy of ultrasonic flowmeters depends on flow profile. Both of the test meters are single-path meters (i.e., the velocity profile is sampled only along a single line through the center of the pipe). As a result, assumptions must be made about the relationship between the velocity averaged along a diameter and the velocity averaged over a cross section. These relationships are accurate for high Reynolds numbers, but are difficult to obtain for Reynolds numbers near the transition region.

Thus, two major factors can affect the accuracy of ultrasonic flowmeters: (1) the flow profile change as a result of flow velocity and viscosity variations and (2) electronic drift of meter zero due to timing errors. Figure 3 shows the effect of these sources of error on the meter correction factor (i.e., a number that, when multiplied by the flow volume indicated by the meter, yields the correct volume passed by the meter). In figure 3 are shown the variations of the meter factor resulting from two types of crude oil with viscosities differing by a factor of two, a positive and a negative zero shift of about 2 Hz (about 0.001 barrel/s), and flow velocities from 500 to 4500 barrels/hr (a total Reynolds number change from 16,500 to 280,000). The total change in the meter factor over these conditions is about 2 percent. The zero error dominates at low flow rates; the change in viscosity alone causes a shift of about 0.4 percent in the meter factor.

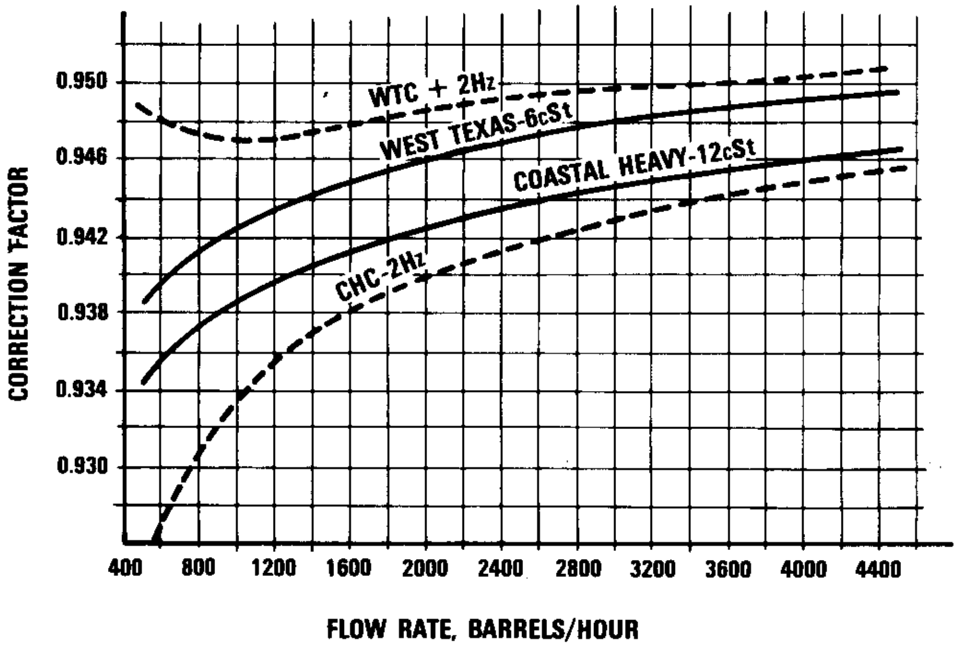


Figure 3. Ultrasonic meter characteristics (WTC = West Texas crude oil, CHC = Coastal Heavy crude oil).

3. MERCHANTABLE CRUDE OIL TEST FACILITY

The meters were tested on a flow loop through which various types of crude oil could be passed (shown in fig. 4). The crude oil was then passed through a mechanical displacement, bidirectional, running start-stop meter prover with a 30-barrel round-trip volume. This device provides a precise measurement of liquid volume between switch closures that are actuated near either end of a straight section of pipe by a displacer that travels back and forth in the pipe for a round trip. This type of prover can repeatedly displace a quantity of liquid with maximum error of 0.02 percent.

The test facility was located at the input to a major refinery where the meter prover is used routinely for proving custody transfer meters. The use of the facility was provided at cost by the pipeline company.

The meters were installed by the pipeline company and operated by Harry Diamond Laboratories (HDL) personnel. A representative of the meter manufacturer was present during the testing of each meter to assure that the meter had been installed and was being operated properly.

During the tests, three types of crude oil were available: Coastal Heavy, West Texas, and Yates. All three were not available at all times, however; so it was possible to test each meter on only two types of crude oil. Yates and Coastal Heavy crude oils were available for the MAPCO meter tests, and West Texas and Coastal Heavy were available for the Controlotron meter tests. Each meter was tested at flow rates ranging from 500 to 4500 barrels/hr, which corresponds to about 4 to 36 ft/s flow velocity in the 6-in. pipe.

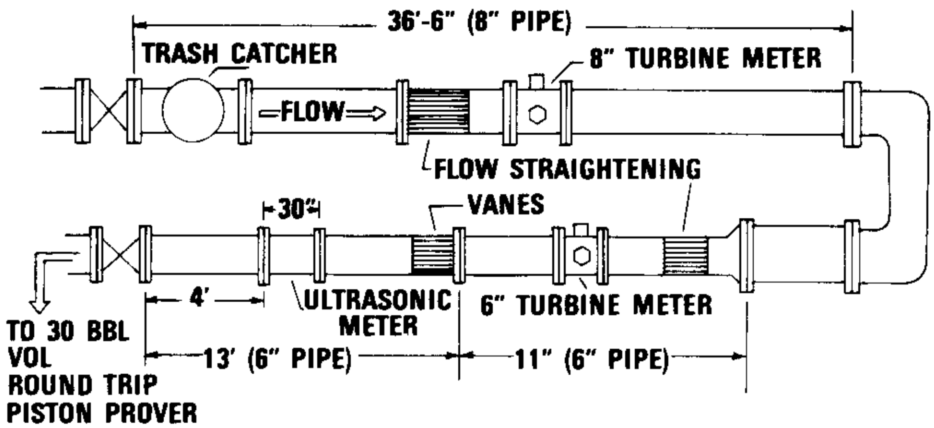


Figure 4. Merchantable crude-oil meter test loop (in. × 25.4 = mm; ft × 0.3048 = m).

4. MERCHANTABLE CRUDE OIL TEST RESULTS

The results of the proving runs for the meters are shown in figures 5 and 6. Each point on the figures represents the average of at least four round-trip proving runs taken in succession at a constant flow rate. The total counts indicated by each meter for successive 30-barrel round trips repeated to within 0.2 percent. (The meter prover reproducibly measures volume to within 0.02-percent accuracy over a wide range of flow rates and crude oil viscosities.) The meter correction factor plotted in the figures was arrived at by dividing a constant by the total counts indicated by the meter for a round-trip proving run. The constant was 40,149 for the MAPCO meter and 62,600 for the Controlotron meter. Thus, for any flow volume indicated by the meter, the true volume is given by the indicated count multiplied by the appropriate correction factor and the true prover volume (31.0174 barrels at 60 F--~15 C-- and 40 psi) divided by the above constant. Normalization of the results in this manner enabled easy computation of the percentage of variation of the meter factor and easy comparison of the results for the two meters.

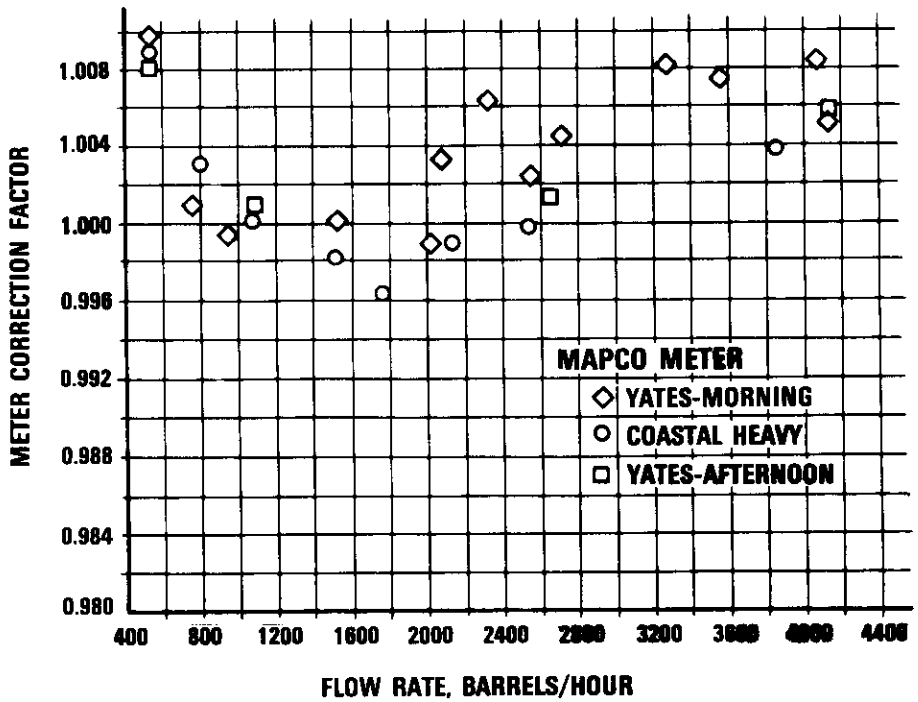


Figure 5. Test results for MAPCO meter.

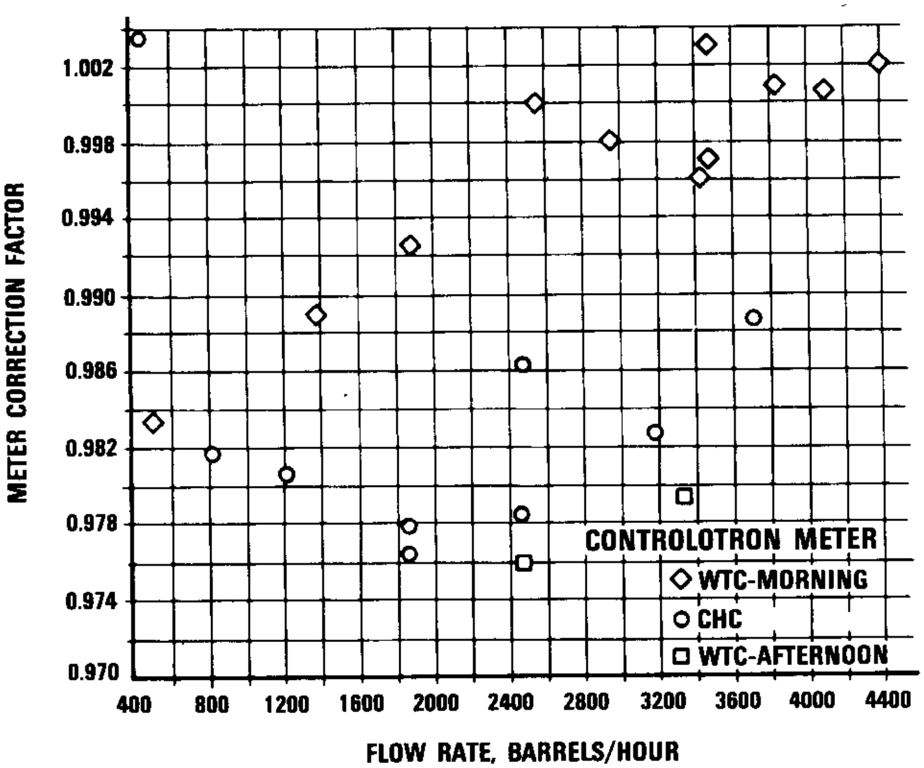


Figure 6. Test results for Controlotron meter (WTC = West Texas crude oil, CHC = Coastal Heavy crude oil).

The results for the MAPCO meter are presented in figure 5. The meter was proved with Yates crude oil in the morning followed by Coastal Heavy in the early afternoon. Later in the afternoon, the meter was again proved with Yates crude oil at several flow rates to check the repeatability of the meter factor after 6 to 8 hr.

Each point on the figure indicates the average of four prover round trips so that each point took about 10 to 20 min to obtain. The MAPCO meter repeated its output count to within 0.2 percent for this time interval. The results for the morning Yates prover run required 2 to 3 hr to obtain; the data of figure 5 show the meter repeatability to be about 0.4 percent over this period. For the 6 to 8 hr between the morning and afternoon Yates runs, the meter repeatability was about 0.6 percent. This scatter in data almost completely obscures the shift in the meter factor due to the change in crude oil. Also, the trend of the data toward higher meter factors at the lower flow rate indicates a positive zero flow offset for the meter, but no significant change in zero was noted during the tests.

The results for the Controlotron meter are presented in figure 6. This meter was proved with a West Texas crude oil in the morning followed by Coastal Heavy oil in the early afternoon. The meter was again proved later in the afternoon with the West Texas crude oil.

For the four prover round trips taken for each point, the Controlotron meter was also repeatable to within 0.2 percent. There is considerably more scatter in the data for longer times between points, however. During the morning run with West Texas crude oil, the repeatability of points was about 0.6 percent for times of 2 to 3 hr between points. Between the morning and afternoon runs with West Texas crude oil, the meter factor shifted 2.5 to 3 percent, obscuring the shift due to changing crude oils. Also, there was a zero shift between the crude oil runs, indicated by the increase in the meter factor for the Coastal Heavy crude oil seen at lower flowrates.* Repeatability data for both meters are summarized in figure 7. However, very few data are associated with the long-term repeatability points, so that extended testing may change these points significantly.

The data shown in figures 5 and 6 indicate linearities for the flowmeters to be about 1.0 percent for the MAPCO meter and about 2.5 percent for the Controlotron meter for flow rates ranging from 500 to 4500 barrels/hr. However, a negative zero shift of the MAPCO meter (instead of the apparent positive shift) could increase the nonlinearity to 1.5 to 2 percent for the same range of flow rates.

**After these tests, Controlotron Corporation acknowledged (by letter) this drift problem. They stated, however, that they had determined the cause of the drift and had introduced corrections into their new flowmeter line.*

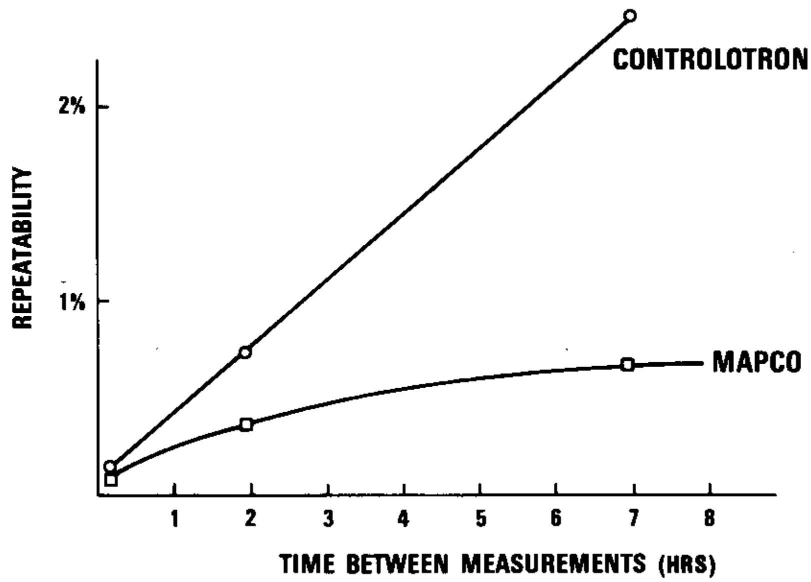


Figure 7. Repeatability of 30-barrel measurements.

5. METER SIMULATON

The data gathered during the merchantable crude oil tests of the two meters provide a limited statistical basis for an estimate of potential meter performance in leak detection systems. Thus, in lieu of expensive and time-consuming long-term testing, meter operation in a simple leak detection configuration was simulated by computer.

The simulation is outlined in figure 8. It consists of a simple gathering system in which the flows from two feeder pipelines are combined to flow through a main pipeline. The flow into the feeder line is assumed to be cycled on and off as shown in figure 8. This type of cyclic operation simulates conditions typically found in off-shore operations. In many such operations, flow from a well is accumulated in a reservoir until it is full. A pump is then turned on to pump the oil into the pipeline until the reservoir is emptied, at which time the pump is turned off.

A simple leak detection system for this model could be implemented by comparing the totalized flow measured at the two metering stations on the feeder lines with that measured on the main line. In actual pipeline operations, the accuracy of such a system would be limited both by flowmetering accuracy and by line-packing effects (the variation of pipeline volume due to variations in pressure and temperature). Because the purpose of the computerized simulation was to evaluate the effect of various levels of meter repeatability on leak detection, no attempt was made to simulate the line-pack phenomenon.

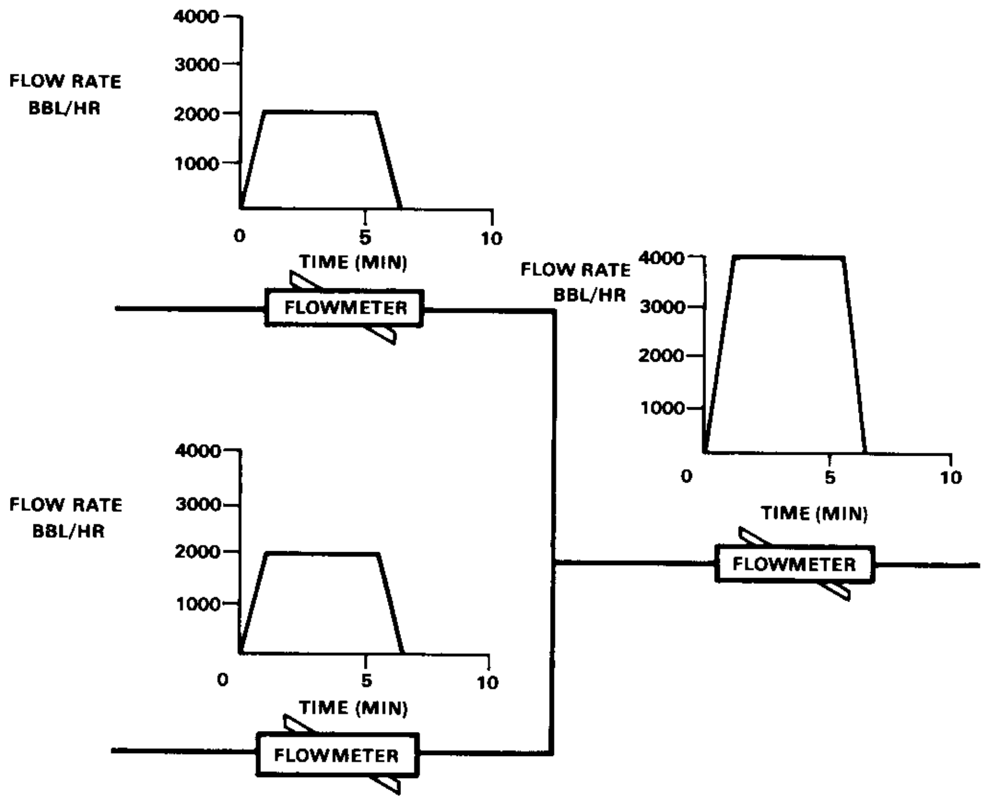


Figure 8. Computer-simulated gathering line (linepack not considered).

Numerical integration of each of the three flow curves shown in figure 8 was used to simulate totalized flow-rate readings from the three flowmeters. The curves for the feeder lines were integrated by dividing the constant, 2000 barrels/hr portion of the curves into five 30-barrel flow increments. The portions of the curves simulating turnon and turnoff of the pumps were divided into seven 1-barrel increments at flow rates of 200, 400, 600, 800, 1000, 1200, and 1500 barrels/hr. The flow through the main pipeline was divided into five 60-barrel increments during the constant, 4000 barrel/hr portion of the cycle, and seven 2-barrel increments at flow rates of 400, 800, 1200, 1600, 2000, 2400, 3000, and 4000 barrels/hr. Total volume for each of the feeder lines was thus 164 barrels for each flow cycle. For the main line, the total volume per cycle was 328 barrels.

The effect of meter nonlinearity, random error, and drift were introduced in the simulation during the numerical integration. Before the flow increments were totalized (1 and 30 barrels for the feeder lines and 2 and 60 barrels for the main line), they were divided by a meter factor, so the exact volumes were converted to volumes as they would be measured by a flowmeter.

The basic meter factor was derived from the curve for 12-cSt* oil in figure 3. The basic meter factor was modified to simulate random drift of the meters by multiplying it by a factor, F_i, which was derived from

$$F_i = F_{i-1} + f_2/12 + f_8/48 \quad ,$$

where f_2 and f_8 are random numbers. A new F_i is calculated for each flow cycle (10 min elapsed time per cycle), with F_i being chosen randomly from a distribution with a mean value of 1.0 and a standard deviation determined by the meter drift to be simulated. The factors f_2 and f_8 are chosen from random distributions with mean values of zero and standard deviations determined by the 2- and 8-hr drift characteristics of the meter. A new f_2 is chosen every 12 flow cycles (2 hr), and a new f_8 is chosen every 48 cycles (8 hr). This procedure causes the meter factor to drift linearly between randomly adjusted values with 2- and 8-hour periods. To simulate the meter drift observed experimentally, values for the standard deviations were derived from the curves of figure 7.

By applying the randomly drifting meter factor to the volume increments in the numerical integration, meter drift and nonlinearity are simulated. To simulate meter short-term repeatability, the volume increments were multipled by a random variable with a mean of 1.0 and a standard deviation determined by the volume. For the 30-barrel increments, the standard deviation was 0.0005 (0.05 percent). This choice results in volumes which repeat to within 0.2 percent (± 2 standard deviations) for 95 percent of the volumes (this was the observed performance of both meters during the field tests). The standard deviation for any other volume, V, was taken to be $0.0005/\sqrt{V/30}$. This value was chosen because, for totalized independent random errors, the error in the total is proportional to the square root of the sample size (recall that a total volume measurement is obtained from the meter by summing individual output pulses, which represent a specific volume).

**Centistokes* × $10^{-6} = m^2/s$.

To simulate the effect of zero drift of the Controlotron meter, random values (zero mean, 1-Hz standard deviation) were chosen for the zero frequency offset. In the calculation of incremental volume, the meter zero was allowed to drift linearly between these values, with a new value being chosen every 8 hr.

A sample of the data calculated by the above technique is shown in figure 9. The ordinate plots the volume calculated to pass through a feeder line for each 10-min pump cycle. The graph shows how a meter with characteristics similar to the MAPCO meter might drift during a day.

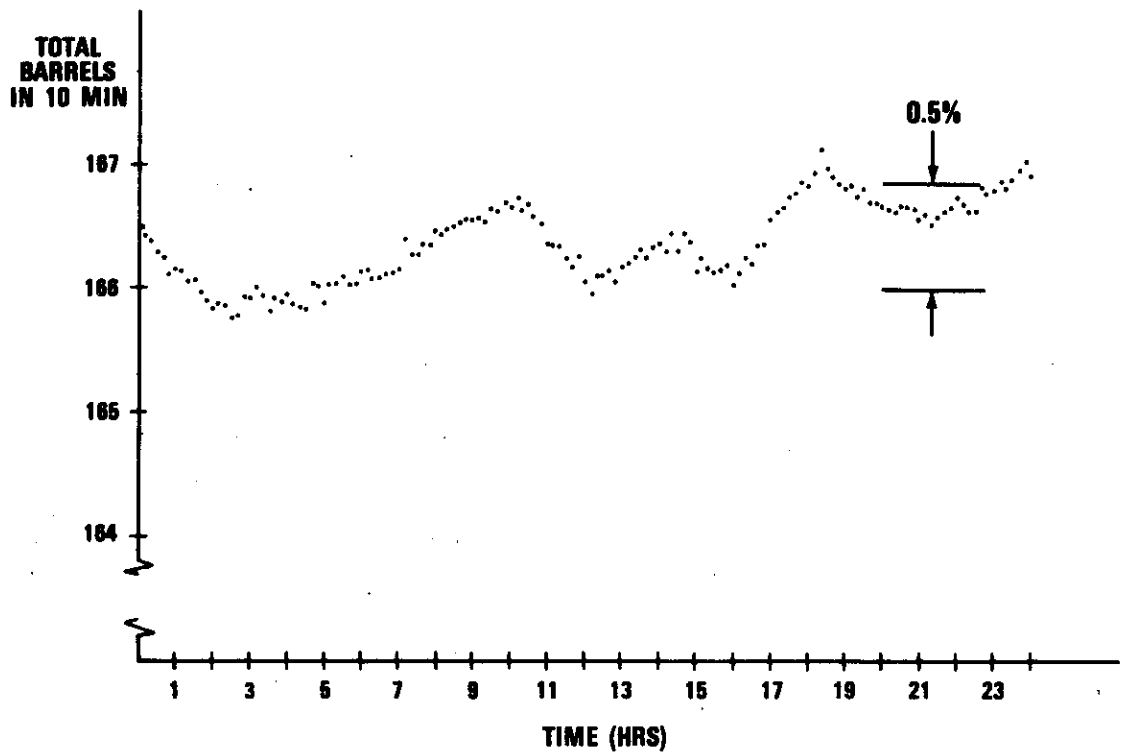


Figure 9. Simulated meter drift (MAPCO meter characteristics).

6. SIMULATION RESULTS

A computer program was written to repetitively perform the calculations outlined above. The drift characteristics derived from the data taken on the MAPCO and Controlotron meters were used to generate leak detection data for 1008 of the 10-min pump cycles (seven days). If, on any given pump cycle, the total flow calculated for the feeder lines exceeded the flow calculated for the main line by more than a certain leak detection level (in percentage of total flow), then a leak was said to occur. The number of apparent leaks was then accumulated as a function of leak detection level. Since all of these indicated leaks were caused by simulated meter error, they would represent false alarms in a real system.

Figures 10 and 11 are plots of the number of false alarms (as a function of detection level) that are calculated to occur during a week for meters having drift characteristics similar to those of the MAPCO and Controlotron meters. Also included in the figures are plots of the false-alarm rate for periodic normalization of the meters in the model. In this case, instead of allowing the meters to drift continually apart, a correction was periodically applied to the total flow calculated for the main line meter, so that the main line flow was the same as the sum of the two feeder lines. Between corrections, the calculations were allowed to drift as before.

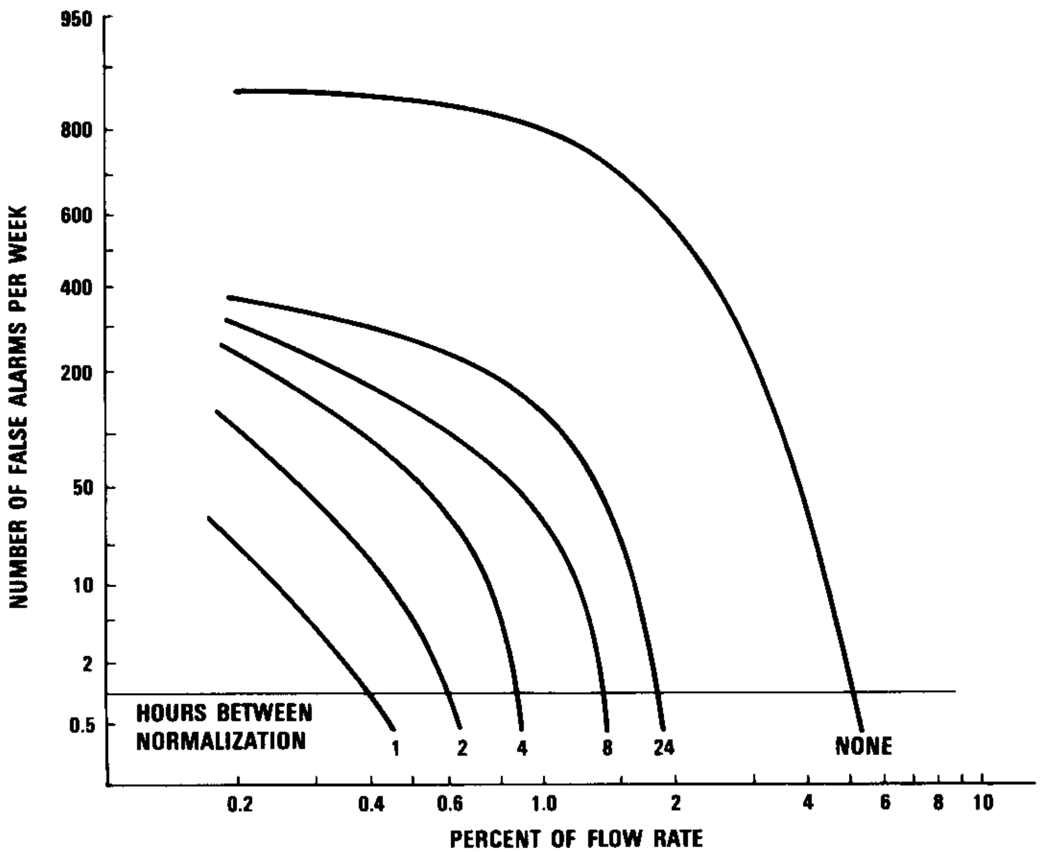


Figure 10. Simulated false-alarm rate (MAPCO meter characteristics).

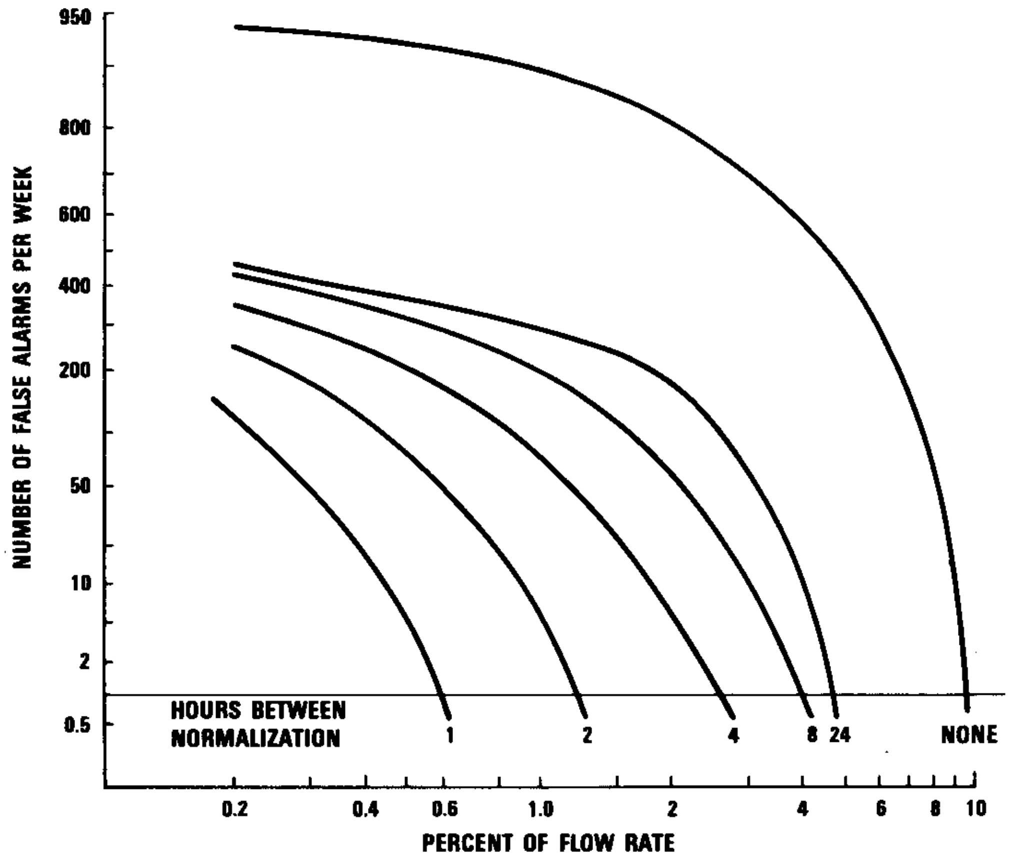


Figure 11. Simulated false-alarm rate (Controlotron meter characteristics).

Each curve in figures 10 and 11 shows the false-alarm rate as a function of detection level for a particular time between normalizations of the calculated flows. The figures show that the false-alarm rate can be significantly reduced by periodically normalizing meter readings to reduce the effect of long-term drift. The disadvantage of this technique is that, if a leak occurs, it must be detected before normalization. If not, there is no way to detect the leak until the leakage rate increases. The significant reduction in the size of a detectable leak and in the false-alarm rate, however, may far outweigh this disadvantage for transient leak detection applications.

The results shown in figures 10 and 11 are summarized in table 1 for a false-alarm rate of one per week. The table shows that, even for detection levels set high enough to insure this low false-alarm rate, a significant degree of leak detection is still possible.

TABLE 1. DETECTION LEVEL (PERCENTAGE OF FLOW RATE) FOR ONE FALSE ALARM PER WEEK

Data Simulated	Hours Between Normalization					
	1	2	4	8	24	None
MAPCO	0.4	0.6	0.9	1.4	1.9	5.5
Controlotron	0.6	1.3	2.6	4	4.7	10

7. DISCUSSION OF LEAK DETECTION APPLICATIONS

As an example, the probability of detecting a leak during the first 10 min (one flow cycle) after its occurrence is plotted in figure 12. This probability curve was plotted for the data simulated from the MAPCO meter characteristics. The simulated readings were normalized every hour. A leak was indicated if the total flow in the feeder lines was greater than that in the main line by more than 0.4 percent. The figure plots the probability of detecting a leak versus the size of the leak. The figure shows that the probability of detecting a leak greater than 0.6 percent of the total flow in 10 min is greater than 99 percent. The probability of a false alarm (leak size equal to zero) for the same conditions is 0.1 percent (once per week).

The preceding discussion is intended only to illustrate the potential of the ultrasonic meters in transient leak detection systems, and is not intended to represent a recommended approach to leak detection. Although a more stable meter than the ultrasonic meters may be desired for many applications, other advantages of the ultrasonic meters may outweigh this disadvantage for certain applications.

For example, as was discussed earlier, line-pack calculations are necessary to implement any flow balance leak detection system on a long pipeline. At best, the accuracy of these calculations has been reported[1] to be 1 to 2 percent (for a pipeline 104 mi or 167.3 km long). In general, line-pack calculation errors increase as the length of the unmetered section of pipe becomes longer. Thus, for long pipelines on which full flow, custody transfer measurements are made only at each end, it may be possible to improve line-pack calculations by making intermediate flow measurements with ultrasonic meters.

[1]*David E. Goldberg, Liquid Pipeline Leak Detection and Line Balance, Stoner Associates, Inc., Proceedings of the 54th International School of Hydrocarbon Measurement, Norman, Oklahoma (April 1979).*

Because the ultrasonic meters measure flow across the full diameter of the pipe without intruding into the flow stream, they allow the free passage of pipeline pigs without the necessity of installing a bypass, as would be required by other metering systems.

Ultrasonic meters also offer the advantage of reliable operation on corrosive and erosive fluids. Because they have no moving parts or seals, contamination in the flow stream causes very little problem in the operation of the meter.

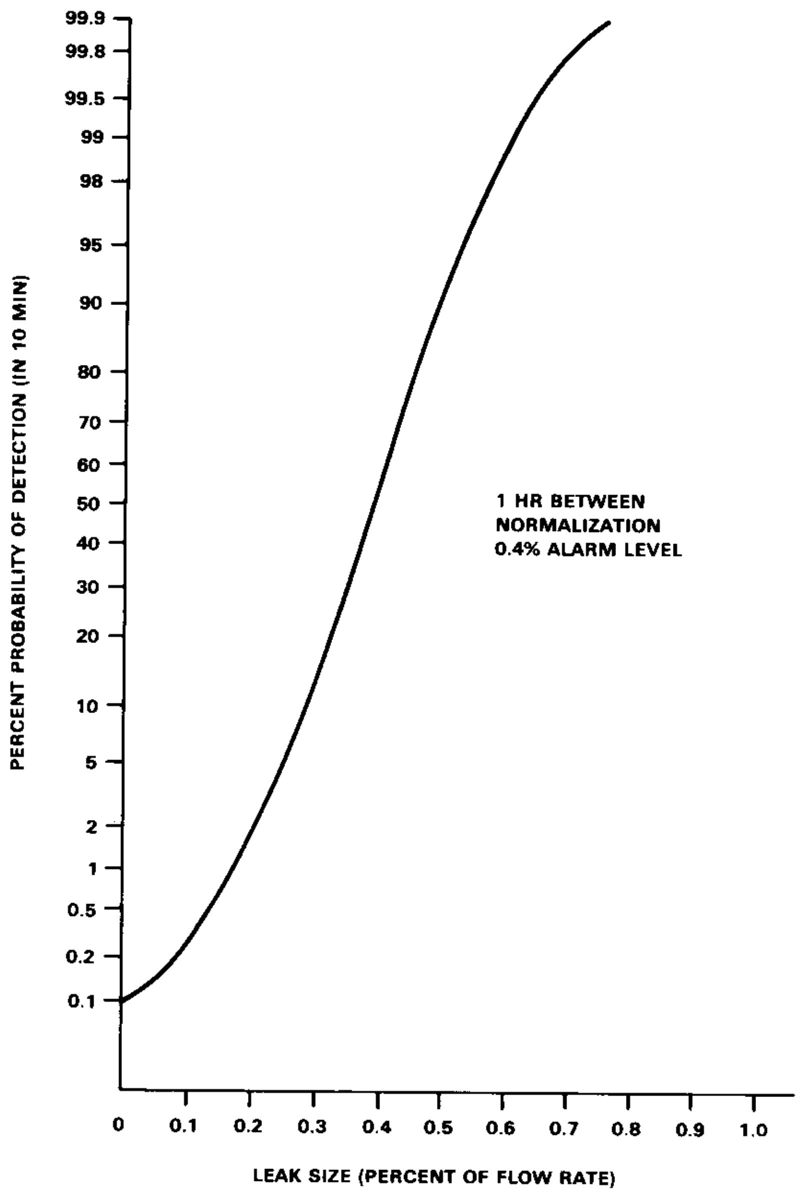


Figure 12. Simulated leak detection probability as a function of leak size (MAPCO meter characteristics).

8. CONCLUSIONS

This program was conducted to determine the repeatability and linearity of the ultrasonic time-delay types of flowmeters, so that their applicability to leak detection on underwater pipelines that carry raw crude oil may be assessed. The flow tests that have been completed used merchantable crude oil, so conclusions may be drawn about the use of the meters under these more favorable conditions. Further tests would be necessary to determine any meter degradation due to the use of raw crude oils. The data from the two meters are summarized for 30-barrel measurements in table 2.

TABLE 2. SUMMARY OF TEST RESULTS

Meter	Repeatability (%)			Linearity (%)
	20 min	2 hr	7 hr	
MAPCO	0.2	0.4	0.6	1.0
Controlotron	0.2	0.6	2.5	2.5

In conventional line-balance leak detection systems, flow measurements are taken at either end of a pipeline, and their difference, when line-packing effects are compensated for, is used to indicate leakage from the pipeline. For a leak detection system in which line balance is continually computed and line packing is compensated for, slow drifts in line balance due to slow drifts of meter factors can be compensated for by periodic adjustment of meter factors. For a meter with drift characteristics similar to the MAPCO meter, a computerized simulation indicates that the probability of detecting a leak greater than 0.6 percent of the total flow in 10 min is greater than 99 percent. The probability of a false alarm for the same conditions is about once per week. Conventional custody transfer meters (turbine or positive displacement) do not offer this capability because contamination in the flow stream can cause rapid changes in meter performance, for instance, if grass-like sediment sticks to a turbine blade or if sand damages a seal in a positive displacement meter.

Although they are not as accurate as custody transfer meters, ultrasonic meters have many advantages that can make them more desirable for particular applications. Because the meters measure full bore on a pipeline with no parts intruding into the flow stream, they offer no obstruction to the flow or to the passage of pipeline pigs. Their simple, no-moving-parts design assures continuous operation on any fluid that can be put through a pipe, provided that the fluid will transmit the sound. In evaluating the results presented here, one should remember that these data were taken on off-the-shelf models.

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