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A COMPREHENSIVE STUDY OF DRY-STEAM FLOWMETER ACCURACY AT THE GEYSERS GEOTHERMAL FIELD

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ABSTRACT

Over the last several years, the Bureau of Land Management (BLM) has studied the accuracy of steam flowmeters used for determining federal royalty at The Geysers geothermal field. Accuracy calculation methods described by Miller (1989) were used as the basis for this study. The entire metering system, including primary device, secondary device, and flow calculation methods is considered when determining accuracy. Potential sources of error are identified and classified into three categories. Examples of the main causes of inaccuracy at The Geysers and possible methods to improve accuracy are given.

INTRODUCTION

Even if a steam flowmeter is in good condition and properly calibrated, meter accuracy at The Geysers can range from better than ±1 percent to worse than ± 20 percent. Accurate measurement of steam is important for several reasons. Of primary concern to the BLM is determining royalty from federal leases.

Under the authority of the Geothermal Steam Act of (1970), as amended, the federal government collects a royalty on the value of the geothermal energy produced from federal land. For those situations where value is based on steam quantity, royalty is derived from steam measured by flowmeters. The BLM requires that dry-steam flowmeters used for royalty determination must be accurate to at least ±4 percent of the actual flow (U.S. Department of Interior, 1974).

Aside from sales and royalty, flowmeter accuracy is important for field operation and reservoir engineering. Decline curve analysis, for example, requires a stabilized flowrate history. Inaccurate measurements could alter the results of the analysis and affect a reservoir-engineering decision. Most steam field operations are controlled by computers using flow rate data for input. Accurate flow rate data can result in more precise and efficient operation of the field.

PRIMARY AND SECONDARY DEVICES

Differential flowmeters are used almost exclusively for steam flow rate measurement at The Geysers. Differential flowmeters consist of a primary device and a secondary device. The primary device causes a predictable and measurable pressure drop in the steam pipeline that corresponds to the flow rate being measured. The secondary device receives the pressure and temperature signals from the primary device and converts them into numeric values from which flowrate can be determined.

The types of primary devices used at The Geysers are orifice plates (Figure 1), Annubars (special type of pitot tube, Figure 2), and venturis (Figure 3). Orifice plates and Annubars are generally used for wellhead flow measure-

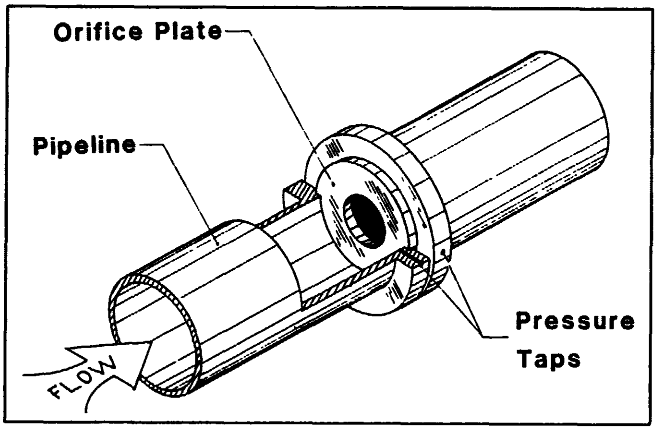

Figure 1. Schematic of orifice plate used for wellhead flow measurement at The Geysers.

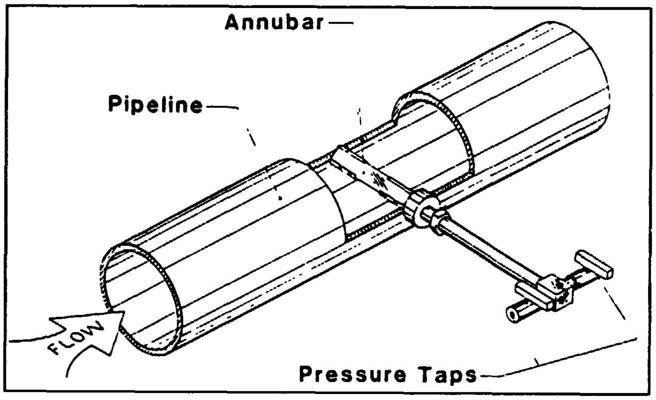

Figure 2. Schematic of Annubar used for wellhead flow measurement at The Geysers.

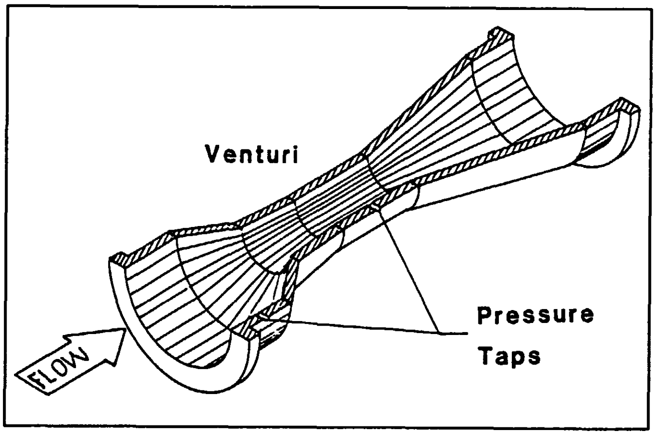

Figure 3. Schematic of venturi used to measure steam flow into a power plant at The Geysers.

ment, whereas venturis are generally used to measure steam flow into a power plant.

All secondary devices used for royalty determination at The Geysers are electronic. They consist of a differential pressure (DP) transmitter, line pressure (LP) transmitter, temperature transmitter (in some cases), and a flow computer and related hardware and software. A transmitter is a transducer that is capable of sending the output signal long distances without loss or distortion.

Also considered part of the secondary device is the impulse tubing that connects the pressure taps on the primary device to the input side of the transmitters. Impulse tubing typically consists of pressure lines, seal pots, and manifold valves. At The Geysers, the impulse tubing also serves to isolate the transmitters from the high temperature steam and is usually filled with liquid.

FLOW EQUATION

The equations used to determine flow rate from LP, DP, and temperature are combinations of theory and correction factors derived from empirical data. Whereas Bernoulli's law is the basis for the flow equations, laboratory data must be used to correct Bernoulli's law for real-world properties such as viscosity, compressibility, and flow profile.

In experiments conducted by various universities and private laboratories, different types of primary devices were set up and methodically tested. Known flow rates were run through each primary device. For each known flow rate LP, DP, and temperature were measured and a theoretical flow rate was calculated. Differences between the known flow rate and the calculated flow rate arose. Causes for these differences were examined, and a correction factor was derived for each cause on the basis of laboratory data.

From Bernoulli's law and laboratory data, the following mass flow equation is derived (Spink, 1978):

$$Q = 358.93 S D^2 F_a F_c Y (h_w d)^{.5}$$

where:

Q = mass flow rate, lb/hr

S = flow index based on primary-device geometry

D = average inside diamter of meter tube, inches

F_a = thermal expansion factor

F_{cf} = Reynolds number correction factor

Y = gas expansion factor

h_w = DP, inches water column (w.c.)

d = fluid density, lb/ft^3

SOURCES OF ERROR

When determining meter accuracy, many sources of error must be considered. Sources of error can be broken down into three major areas: primary device errors, secondary device errors, and flow equation errors.

Primary Device Errors

Laboratory experiments are done to determine the accuracies of different types and sizes of primary devices. By running known flow rates through a device many times, the variation in calculated flow rate for each known flow rate is found. This variation is the accuracy of the device.

When installing a primary device in the field, the laboratory conditions used to determine the correction factors and accuracy values for that device must be duplicated as closely as possible. Differences in the field set up of the primary device will cause errors in the correction factors and alter the accuracy values determined in the laboratory.

The accuracy values for each type and size of primary device given in the literature assume the following conditions:

1. **Installation.** Absence of protrusions such as mis-aligned flanges, gaskets, bolts, or welds, and specific configurations and locations of pressure taps and thermowells are assumed. The primary device is assumed to be installed in accordance with the manufacturer's specifications.

2. **Meter Tube Length.** Minimum lengths of straight and uninterrupted pipeline (meter tubes) are assumed to be present both before and after the primary device. A great deal of work has recently been done to quantify the effects of meter tube length.

3. **Meter Tube Condition.** Certain roughnesses of the inside of the meter tubes are assumed. The meter tube is assumed to be free of pits or pockets.

4. **Reynolds Number.** The Reynolds number of the flow through the primary device is assumed to be in the turbulent region (over 4,000).

5. **Physical Condition.** Literature accuracy values assume that the primary device has certain specific dimensions and characteristics. An orifice plate, for example, is assumed to have a sharp upstream edge, have a certain thickness, have a smooth upstream finish, be flat, be free from chips, nicks, or scale build up, and be free from deposits on either side of the orifice plate.

6. **Pulsation.** Pulsation can effect both the primary and secondary devices. Primary device accuracy values are based on flow rate that does not change with time. To date, there has been no standardization of the frequency or magnitude of acceptable pulsations. Square Root Error (Gegg, 1989) is introduced into the secondary device if the pulsation has a high frequency. Fortunately, the type of pulsation that can cause the most severe errors, such as that caused by a compressor, does not occur at The Geysers.

7. **Dimension Accuracy.** The meter tube and orifice or venturi bore are assumed to be round, within specific tolerances.

8. **Thermal Expansion.** It is assumed that all meter tube and orifice and venturi measurements are taken at 68°F.

Secondary Device Errors

Laboratory determinations of primary device accuracy do not include errors caused by the secondary devices. The LP, DP, and temperature from the primary device must be converted into numeric values before flow can be calculated. Regardless of how carefully a transmitter is built, installed, and calibrated, some error will always be introduced in this conversion.

The transmitter-accuracy specification from the manufacturer must be adjusted to take into consideration changes in ambient temperature, LP, supply voltage, and vibration (Honeywell Inc., 1987). The amount of adjustment required will depend on the specific operating conditions.

1. **Ambient Temperature Effects.** For all transmitters, several of the sensing components are ambient-temperature dependent. As ambient temperature changes from the ambient temperature at the time of field calibration, error will be introduced. The more the ambient temperature changes, the more error will occur. As the span of the transmitter is reduced, the ambient temperature effects are amplified.

The amount of ambient temperature change encountered in the field is dependent on the local climate, exposure of the transmitter to ambient conditions, and how often the transmitter is calibrated. A transmitter located in a room of constant temperature will experience no ambient- temperature change, whereas a transmitter mounted in the open may experience severe ambient-temperature changes.

The amount of ambient temperature fluctuation between calibrations will increase as the time between calibrations increases. For example, the average difference between the high and low temperature over a 24-hour period will always be less than the average difference between the high and low temperature over a month. A transmitter calibrated each day, therefore, will experience less ambient temperature change between calibrations than a transmitter calibrated each month.

2. **LP Effects.** The accuracy of DP transmitters is dependent on LP. As LP increases, the DP diaphram in the transmitter becomes somewhat distorted, causing an increased error. Some or all of this error can be corrected for by using proper calibration techniques.

3. **Vibration.** If the transmitter is subject to vibration, the accuracy of the transmitter will be diminished depending on the frequency and amplitude of the vibration. A severe vibration can knock the transmitter out of calibration as well. In The Geysers, most transmitters are not subject to vibration.

4. **Supply Voltage.** Transmitter accuracy is subject to the variation in the voltage used to power it.

Transmitter accuracy is usually expressed in percent of full scale; therefore, full-scale accuracy must be divided by the percent of full scale at which it is operating to obtain accuracy at that particular pressure or temperature being measured. For example, a certain transmitter has an accuracy of ±0.5 percent full scale and is operating at 40 percent of full scale. The accuracy of the transmitter at the current reading (40 percent full scale) is: ±0.5 percent/0.4 = ±1.25 percent.

A transmitter is also subject to errors that cannot be used to adjust the accuracy because they are not a predictable function of time or operating conditions. These errors should be eliminated or kept to a practical minimum in the field.

5. **Transmitter Drift.** All transmitters lose their ability to accurately convert a physical parameter into an electrical signal over time. For this reason, transmitters must be calibrated against known physical parameters periodically to regain their accuracy.
6. **Calibration Equipment and Techniques.** The equipment used to calibrate the transmitters needs to be more accurate than the rated accuracy of the transmitter, but no consistent standards have been developed as to how much more accurate it should be. In addition, the calibration must be performed to manufacturer specifications.
7. **Linearity.** It is assumed that the transmitter's output varies linearly with the input parameter. This can be checked and corrected for in the field.
8. **Mounting Position.** Some transmitters will experience a shift in output if they are mounted in a nonvertical position. This shift can be calibrated out.
9. **Impulse Tubing.** In calculating transmitter accuracy, it is assumed that the pressure signals going into the transmitter are the same as the pressure signals coming from the pressure taps. Because of the high temperatures associated with geothermal flow measurement, however, the transmitters must be isolated from the geothermal fluid being measured. The isolation technique used must be carefully considered or additional significant errors can result (Netzel, 1989). Typical isolation techniques include seal pots (above or below the pressure taps), capillary tubes, and gas-filled lines.

Flow Equation Errors

When LP, DP, temperature, correction factors, dependent variables, and constants are combined in the flow equation to determine flow rate, the following errors are introduced:

1. **Assuming Correction Factors to be Constant.** Correction factors in the flow equation (F_a, F_c, and Y) are functions of LP, DP, and temperature. For the purpose of simplifying calculation procedures, some of these factors can be assumed to be constant based on average flow conditions. Whenever the actual flow conditions vary from the assumed conditions, errors are introduced.
2. **Approximations of Variables.** Other variables, such as steam density, change drastically with changes in pressure and temperature and must be calculated. Because the equations used to calculate these variables only approximate empirical data, errors are introduced.
3. **Assumption That Steam is Saturated.** In situations where temperature measurement is not practical, the steam is assumed to be saturated. When the steam being measured is actually superheated, the calculated flow rate will be slightly higher than the actual flow rate (about 0.8 percent high per 10°F of superheat).
4. **Gas Expansion Factor.** The pressure drop caused by the primary device causes the steam to expand as it passes from the upstream pressure tap to the downstream pressure tap. The gas expansion factor is a term included in the flow equation to correct for this expansion.

This factor assumes isentropic expansion of the gas. While this is a valid assumption at low DPs, it becomes less valid as the DP increases. At high DPs, therefore, the calculated gas expansion factor does not accurately represent the actual gas expansion, and an increased amount of error is introduced into the flow equation.

5. **Assumption that the Steam is of 100 Percent Quality.** All steam-flow calculations at The Geysers assume that the fluid being measured is 100 percent vapor. While the validity of this assumption is correct when measuring superheated steam, it is not necessarily correct, and will induce an error, when measuring saturated steam. Currently at The Geysers, most steam being measured is superheated.
6. **Sampling Frequency.** The frequency at which LP, DP, and temperature measurements are taken and recorded will affect meter accuracy. For relatively constant flow rates, one reading per hour may be sufficient. For highly fluctuating flow, however, readings may have to be taken every several seconds.

CLASSIFICATION OF ERRORS

To help analyze a particular metering system, the sources of error listed above can be put into three classes: measurable errors, bias errors, and dynamic errors.

Measurable Errors

Measurable errors are those that can be mathematically accounted for if laboratory experiments were able to predict and quantify the effect of the source of error. For example, the effects of ambient temperature on a transmitter are known from the manufacturer's specifications. If the amount of ambient temperature change is known, overall meter accuracy can be calculated, taking ambient temperature changes into account.

Errors that are not measurable are too complex to quantify or did not produce predictable results in the laboratory and cannot be accounted for in the accuracy equation. The effect of pulsating flow on accuracy, for example, is not measurable because conclusive laboratory experiments have not been done to determine the effects.

Because the overall meter accuracy calculation cannot take the unmeasurable sources of error into account, they must be assumed to be nonexistent. In order to make this assumption valid, the unmeasurable sources of error must be eliminated or kept to a practical minimum in the field. From Table 1, the primary device must be in good condition and properly installed, pulsation must be minimized, calibration equipment must be sufficiently accurate, the impulse tubing must be installed to allow an undistorted pressure to reach the transmitters, and sampling frequency must be fast enough to record changes in LP, DP, and flowing temperature. If these conditions are not met, then the calculated accuracy will not represent the true accuracy of the meter.

Bias Errors

While many of the errors found in metering are random, some can cause a predictably high or low reading (see Table 1). As accuracy is considered to be a range of possible error that centers around a true value, bias errors are not included in the accuracy calculation. In order to make the calculated accuracy represent the true accuracy of the meter, flow rate calculations must be corrected to take the bias errors into account or the sources of error that are biased must be minimized. Transmitter drift, for example, is a measurable bias error. To minimize transmitter drift, the transmitters must be calibrated frequently. Bias errors, such as assuming flow-equation correction factors to constant, can be minimized by calculating the correction factors with current average values of DP, LP, and temperature.

Dynamic Errors

Dynamic errors are those which can change with time or operating conditions (see Table 1). The percent of span at which the DP transmitter is operating, for example, will change as flow rate changes. As the percent of span changes, the accuracy of the meter will change.

When calculating meter accuracy, it must be realized that the accuracy value obtained is valid only for the particular operating conditions used for the calculation. Dynamic sources of error must be checked periodically, and the overall accuracy recalculated if a dynamic source of error changes significantly.

OVERALL ACCURACY

After having identified and classified all possible sources of error in a flowmeter, overall accuracy can be calculated from the measurable and unbiased sources of error.

Table 1. Error source classification

	ERROR SOURCE	MEAS	BIAS	DYN
PRIMARY DEVICE	Primary Device Type	X		
	Installation			
	Tube Length	X	X	
	Tube Condition	X	X	X
	Reynolds Number	X		X
	Physical Condition		X	X
	Pulsation		X	
	Dimension Accuracy	X		
	Thermal Expansion	X	X	
SECONDARY DEVICE	Transmitter Model	X		
	Ambient Temperature	X		
	Static Pressure	X	X	X
	Calibration Equipment			
	Linearity	X	X	X
	Mount Position	X	X	
	Lead Lines			
FLOW EQUATION	Assuming Constants	X	X	X
	Approximations of Variables	X	X	
	Assmed Saturated	X	X	X
	Gas Expansion Factor	X		X
	Steam Quality	X	X	X
	Sampling Frequency			

Each source of measurable and unbiased error is related to a variable in the flow equation. Accuracy for each variable is calculated, combined with a sensitivity coefficient, and combined to determine overall flowmeter accuracy.

A sensitivity coefficient takes into account that not all variables have an equal effect on the calculated flow rate. For example, in the flow equation the DP (h_w) is raised to the power of .5 (square root). Therefore, relatively large changes in DP will not greatly affect the calculated flow rate.

CASE STUDIES

Rather than analyze the effects of each source of error on overall accuracy, examples of the two most common causes of poor accuracy (low differential pressure and ambient temperature changes) are given in this section. The following examples are based on typical meters and flowing conditions found at The Geysers. Table 2 shows the actual hardware and data sampling frequencies for the different federal lessees at The Geysers.

All graphs and conclusions in these examples are derived from a computer accuracy model developed by the

Table 2. Data collection/hardware at The Geysers.

LESSEE	LOCATION	SAMPLING FREQUENCY (sec)	TRANSMITTERS: DIFF PRESSURE	TRANSMITTERS: LINE PRESSURE	PRIMARY DEVICE
GGC	wellhead	5	Barton 6001 Honeywell 4110 Honeywell Smart Rosemount 1151	Barton 6005 Honeywell 4122 Honeywell Smart Rosemount 1144	orifice
GGC	SMUD	30	Honeywell Smart	Gould PG3000	venturi
NCPA	wellhead	5	Rosemount 1151	Rosemount 1151	Annubar
NCPA	pwr plnts	.33-.96 *	Rosemount 1151	Rosemount 1151	venturi
Unocal	wellhead	30	Rosemount 1151	Rosemount 1151	orifice
Santa Fe**	wellhead	n/a	n/a	n/a	orifice

* depends on flowrate

** chart recorders - not used for federal royalty purposes

author. The model is based on manufacturer specifications and published laboratory data.

Low Differential Pressure

The BLM routinely calculates the accuracy of over 90 steam flowmeters used for federal royalty determination at The Geysers. In doing these calculations, it has been found that the primary contributor to poor accuracy is DP transmitters operating at a low percentage of their calibrated span. As previously described under "Secondary Device Errors," the accuracy of a transmitter is dependent on the percent of full scale at which it is operating.

It has also been found that one of the main causes of low DP is flow rate decline. When a well is first put into production, the pipeline, primary device, transmitter ranges, and calibrated spans are designed for the initial flow rate. As the flowrate declines, assuming nothing else changes, the DP declines. As the DP declines, the overall accuracy of the meter declines.

Using the example meter described in Table 3, flow rate is varied while everything else is held constant. From Figure 4, the accuracy goes from an initial value of ±1.5 percent at 120,000 lb/hr to a final value of ±23 percent at 20,000 lb/hr. In addition to being well outside the BLM accuracy limit of ±4 percent, the accuracy of this meter at 20,000 lb/hr is unsuitable for any type of precise field operations or reservoir engineering calculations.

The two most common methods of improving poor accuracy caused by a low DP transmitter reading are to install a smaller orifice plate to raise the DP, or to reduce the span of the transmitter.

Table 3. Meter parameters.

PRIMARY DEVICE

Type: Orf. Plate/Flange Taps
Bore Diameter: 8.000 in
Pipe Diameter: 12.000 in
Meter Tube Length: 60.0 ft
Upstream Dist.: 2 elb./2 plns

LP TRANSMITTER[6]

Model: Rosemount 1151GP
Range: 0-1000 psig
Span: 0-400 psig

DP TRANSMITTER[5]

Model: Rosemount 1151DP
Range: 0-750 in w.c.
Span: 0-500 in w.c.

OPERATING CONDITIONS

Flowrate: 40,000 lbs/hr
Line Pressure: 125 psig
Flowing Temp.: 352 deg F (sat.)
Atmospheric Pressure: 13.1 psi
Ambient Temp. Shift: 50 deg F

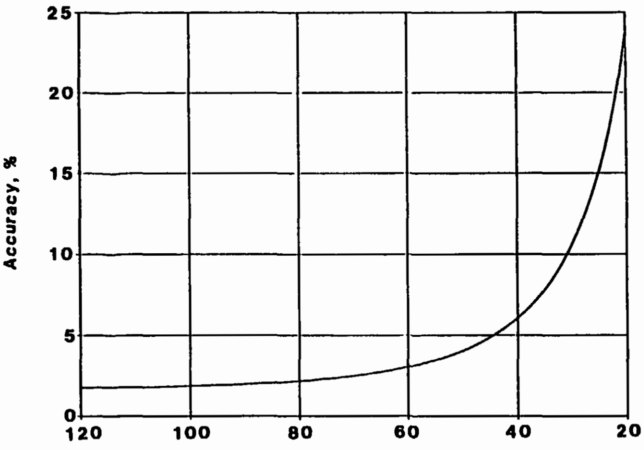

Figure 4. Effect of flow decline on meter accuracy.

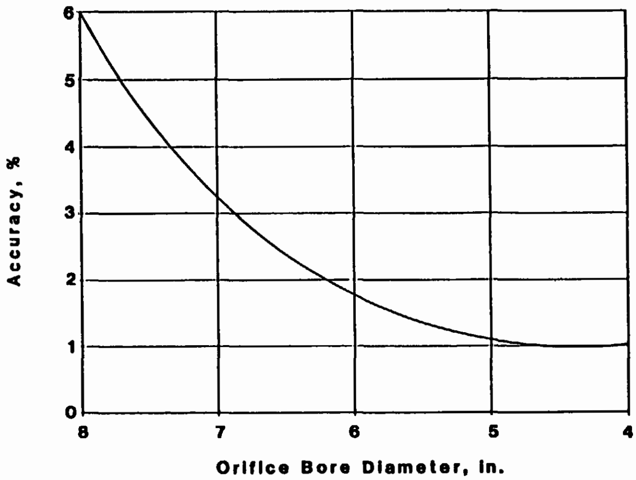

Figure 5. Effect of orifice diameter on accuracy.

1. **Reducing Orifice Plate Diameter.** By installing a smaller orifice plate, the DP is increased for a given flow rate. Because of the higher DP, the transmitter operates at a higher percent of span, and the overall accuracy of the meter improves.

Using the example flowmeter described in Table 3, Figure 5 was developed to illustrate the effect of orifice plate size on accuracy. Initial accuracy of ±6 percent with an 8-inch orifice corresponds to a flow rate of 40,000 pounds per hour from Figure 4. Holding the flow rate at a constant of 40,000 lb/hr, the orifice plate bore is reduced from an intial 8 inches to a final 4 inches. An orifice bore smaller than 4 inches causes the DP to exceed the calibrated span of the DP transmitter (500 inches w.c.).

From Figure 5, two observations can be made. First, for a given flow rate, reducing the orifice bore can cause a significant improvement in meter accuracy. Second, the accuracy reaches an optimum value (±0.9 percent at 4.4 inches) and then begins to get worse with further reductions in orifice diameter. This final worsening of accuracy is caused by errors in the theoretical gas expansion factor at high DPs, as explained under "Flow Equation Errors."

There are limits to the minimum orifice bore size that should be used. Beta ratios less than 0.2, which would correspond to a orifice diameter of 2.4 inches in this example, are beyond the range of Beta ratios for which data are available. Therefore, flow coefficients, factors, and accuracy values given in literature are not valid below a Beta ratio of 0.2.

2. **Reducing Differential Pressure Transmitter Span.** Another method to increase the accuracy of a meter operating at low DP is to reduce the transmitter span. Most transmitters are capable of at least a 6 to 1 span turndown, i.e. the span of a DP transmitter with a maximum range of 0 to 750 inches can be recalibrated anywhere between 750 and 125 inches. The DP transmitter given in Table 3, for example, has been turned down from 0 to 750 inches w.c. to 0 to 500 inches w.c.

The top curve in Figure 6 shows the effects of reducing DP transmitter span for the meter described in Table 3. To calculate this curve, flow rate was held at a constant 40,000 lb/hr as with Figure 5, and an 8 inch orifice plate was used throughout. By reducing the span of the conventional transmitter from 500 inches w.c. to 125 inches w.c., the accuracy went from ±6 percent to ±4.6 percent.

From the top curve in Figure 6, it can be concluded that reducing the DP transmitter span is less effective than reducing orifice size to improve meter accuracy. This is mainly due to the amplified ambient-temperature effects as transmitter span is reduced.

While installing a smaller orifice plate and reducing DP transmitter span are two common methods of improving accuracy, other methods exist as well. These include installing a DP transmitter with a lower range, installing a "smart" DP transmitter (one that is self-correcting for ambient temperature and LP effects), and installing a smaller diameter meter tube.

3. **Low Range DP Transmitter.** By installing a DP transmitter with a lower maximum range, the small DP caused by low flow rate can be measured without reducing transmitter span. Poor accuracy caused by amplified ambient temperature effects is thereby avoided. For example, if the meter described in Table 3 was equipped with a Rosemount range 4 transmitter (0 to 150 inches w.c.), and the span was calibrated at 0 to 150 inches w.c., the accuracy of the meter would be improved from ±6.0 percent to ±2.0 percent.

4. **"Smart" DP Transmitter.** Various manufacturers now make "smart" transmitters that are self compensating for ambient temperature and LP. Span, therefore, can

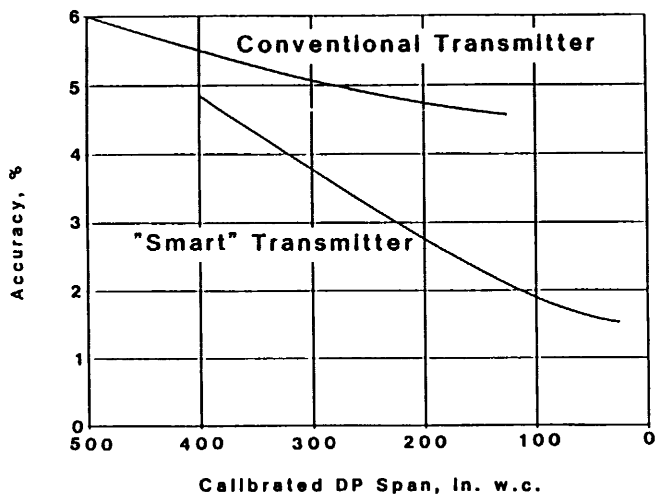

Figure 6. Effect of DP span on meter accuracy.

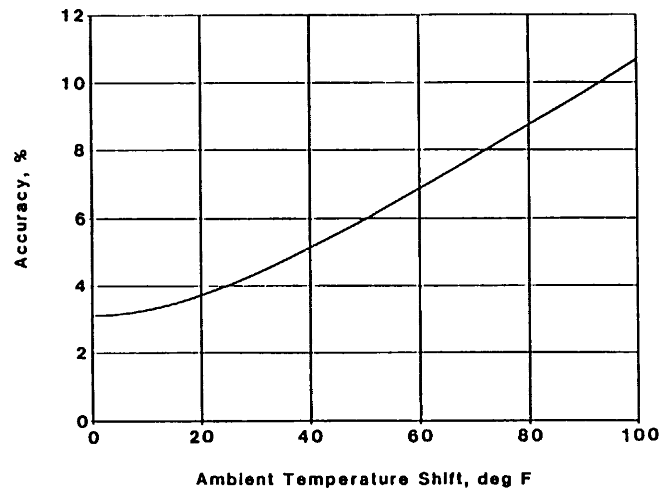

Figure 7. Effect of ambient temperature on accuracy.

be turned down without amplifying the effects of ambient temperature changes. The effects of reducing the span on a "smart" transmitter are shown by the bottom curve in Figure 6. The particular "smart" transmitter used (Honeywell Inc., 1987) has a maximum span of 400 inches w.c. and a minimum span of 25 inches w.c. (16:1 turndown). From Figure 6 it can be seen that reducing the span of a "smart" transmitter does significantly improve meter accuracy.

5. **Small Diameter Meter Tubes.** Probably the least practical method to improve accuracy, from an economic standpoint, is to change the meter tubes to ones of smaller diamter. This would enable smaller orifice plates to be used without exceeding the Beta ratios for which data are available. The smaller orifice plates would keep the DP high and reduce the poor accuracy caused by low DPs.

Meter Tube Length

The effects of meter tubes that are shorter than recommended by the American Petroleum Institute (API, 1985) have been debatable for many years. Recent data (API, 1985), however, suggess flow rate can be adjusted to account for short meter tubes with no significant reduction in primary device accuracy. The recommendation of API to add 0.5 percent to the primary device accuracy for short meter tubes is probably still valid.

If a meter with meter tubes meeting the length recommended by API has an accuracy of ±2 percent, the same meter with shorter meter tubes would have an accuracy of ±2.23 percent based on the API recommendation. According to the work published by Miller, the flow rate should be adjusted to take the short meter tubes into account or a bias error would result.

Ambient Temperature Change

The amount of ambient temperature change the transmitters experience can significantly affect meter accuracy. For the example meter described in Table 3, Figure 7 was developed to illustrate the effects of ambient temperature change. The calculations used to develop Figure 7 hold everything in Table 3 constant while varying the amount of ambient temperature change. For an ambient temperature change of 50°F (±25°F from the ambient temperature during calibration), the accuracy is calculated to be ±6 percent.

As previously described, the amount of ambient temperature change the transmitters experience is affected by three parameters: climate, transmitter location, and calibration frequency. While nothing can be done about the local climate, the amount of ambient-temperature change experienced by the transmitters can be reduced by relocating the transmitters or calibrating the transmitters more often.

1. **Relocating the Transmitters.** By locating the transmitters to a room of constant temperature, the ambient temperature change is effectively reduced to zero. This alone would improve the overall accuracy from ±6 percent to ± 3 percent.

   The room, however, must be large enough to hold the calibration crew and equipment while maintaining a constant temperature. A small temperature-controlled box, for example, is not adequate because the transmitters are exposed to ambient temperature during the calibration.

2. **Calibrating More Often.** Another way to reduce the amount of ambient temperature change is to reduce the time between transmitter calibrations. Figure 8, developed from temperature data obtained from three separate weather stations located in The Geysers, shows the

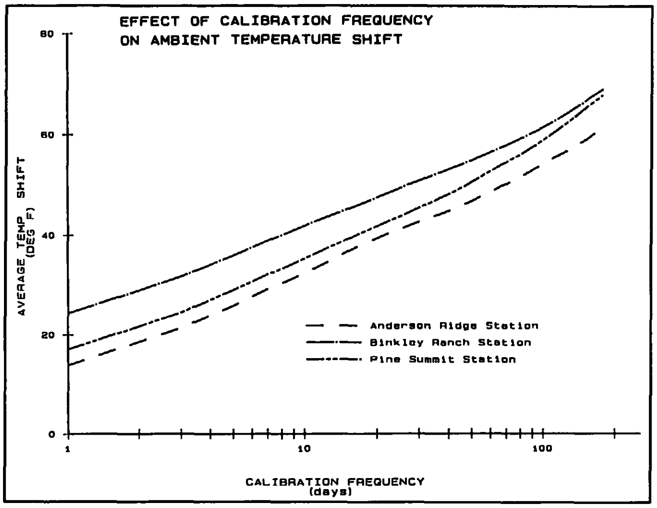

Figure 8. Effect on calibration frequency on ambient temperature shift.

effects of calibration frequency on ambient temperature change experienced by the transmitters.

By decreasing the time between calibrations from 50 days to 10 days, the average temperature change is reduced from 50 to 30°F (see Figure 8). From Figure 7, this results in an improvement in accuracy from ±6 percemt to ±4.5 percent.

CONCLUSIONS

1. In order to calculate a true accuracy value, unmeasurable errors must be minimized and bias errors must be corrected for or minimized.

2. Poor accuracy caused by low flow rates is best improved by increasing the DP. Reducing the span of the DP transmitter is a less effective method.

3. Ambient temperature effects can be reduced by locating the transmitters in a room of constant temperature, by using temperature-compensated ("smart") transmitters, or by minimizing span turndown (lower range DP transmitter).

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