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

Richard M. Estabrook

United States Department of the Interior
Bureau of Land Management
555 Leslie St.
Ukiah, CA 95482

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 R.W. Miller[3] were used as the basis for this study. The entire metering system including primary device, secondary device, and flow calculation methods are considered when determining accuracy. Potential sources of error are identified and classified into three categories. Examples of the main causes of inaccuracy 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% to worse than ±20%. 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[9], as ammended, the federal government collects a royalty on the value of the geothermal resource produced from federal land. For those situations where value is based on steam quantity, royalty is derived from steam flowmeters. The BLM requires that dry-steam flowmeters used for royalty determination must be accurate to at least ±4% of the actual flow[8].

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 flowrate data for input. Accurate flowrate data can result in more precise and efficient operation of the field.

Differential flowmeters are used almost exclusively for flowrate measurement at The Geysers. Differential flowmeters consist of a primary device and a secondary device. The primary device causes a predictable and measureable pressure drop in the steam pipeline that corresponds to the flowrate 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, Annubars (special type of pitot tube), and venturis. Orifice plates and Annubars are generally used for wellhead flow measurement, whereas venturis are used to measure steam flow into a powerplant.

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.

FLOW EQUATIONS

The equations used to determine flowrate 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 laboratory experiments, different types of primary devices were set up and methodically tested. Known flow rates were run through each primary device. For each known flowrate LP, DP, and temperature are measured and a theoretical flowrate is calculated. Differences between the known flowrate and the calculated flowrate arise. Causes for these differences were examined and, based on the laboratory data, a correction factor was derived for each cause.

From Bernoulli's law and laboratory data, the following mass flow equation is derived[7]:

$$Q = 358.93SD^2F_aF_cY(h_wd)^{.5}$$

where:

Q = mass flowrate, lbs/hr
S = flow index based on primary-device geometry
D = average inside diamter of meter tube, inches
F_a = thermal expansion factor
F_c = Reynolds number correction factor
Y = gas expansion factor
h_w = DP, inches water column (w.c.)
d = fluid density, lbs/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 flowrates through a device many times, the range of error between the known and calculated flowrates is found. This range of error 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 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 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 manufacturers 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 round within specific tolerances and to be free of pits or pockets.

4. Reynolds Number. The Reynolds number of the flow through the primary device is assumed to be a minimum value.

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, 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. Primary device accuracy values are based on flowrate that does not change with time. While all flows are subject to some change, there has been no standardization of the frequency or magnitude of acceptable pulsations.

7. Dimension Accuracy. When determining overall accuracy, the degree of accuracy to which primary device dimensions (pipeline and bore diameter) are measured will effect overall accuracy.

8. Thermal Expansion. Because the thermal expansion factor (F_a) is based on measurements at 68°F, measurements taken at temperatures other than 68°F will affect dimension accuracy.

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, or 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, changes in supply voltage, and vibration. 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 effect of ambient temperature change is increased.

   The actual temperature change between calibrations encountered in the field is dependent on the local climate, exposure of the transmitter to ambient conditions, and how often it 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. Also, a transmitter that is calibrated more frequently will experience less ambient temperature change between the calibrations.

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, and the amount of vibration can be measured, the rated transmitter accuracy can be mathematically adjusted to take the vibration into consideration. 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 ±.5% full scale and is operating at 40% of full scale. The accuracy of the transmitter at the current reading (40% full scale) is: ±.5%/.4 = ±1.25%.

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:

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 non-vertical position. This shift can be calibrated out.

9. Pressure Lead Lines. 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[4]. Typical isolation techniques include seal pots (above or below the pressure taps), capillary tubes, and gas-filled lead lines.

Flow Equation Errors

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

1. Assuming Factors to be Constant. Correction factors in the flow equation 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 flowrate will be slightly higher than the actual flowrate (about .8% 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. While this theoretically-derived factor is fairly accurate at low DPs, it becomes less accurate as the DP increases.

5. Assumption that the Steam is of 100% 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 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 flowrates, 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.

Measureable Errors

Measureable errors are those that can be mathematically accounted for if laboratory experiments were able to predict and quantify the effect of the differences. 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 to take ambient temperature changes into account.

Errors that are not measureable 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 measureable because conclusive laboratory experiments have not been done to determine the effects.

Because the overall accuracy calculation of the meter cannot take the unmeasureable errors into account, they must be assumed to be non-existent. In order to make this assumption valid, they must be minimized in the field. Therefore, the primary device must be installed properly, pulsation must be eliminated, calibration equipment must be of sufficient accuracy, etc. (see Table 1). 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, flowrate calculations must be corrected to take the bias errors into account or the sources of error that are biased must be minimized.

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 flowrate 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 re-calculated if a dynamic source of error changes significantly.

	ERROR SOURCE	MEAS	BIAS	DYN
PRIMARY DEVICE	Prim. Dev. Type	X		
	Installation			
	Tube Length	X	X	
	Tube Condition	X	X	X
	Reyn. Number	X		X
	Physical Cond.		X	X
	Pulsation		X	
	Dimension Acc.	X		
	Therm Expansion	X	X	
SECONDARY DEVICE	Xmitter Model	X		
	Ambient Temp.	X		
	Static Pressure	X	X	X
	Vibration	X		
	Power Supply	X		
	Xmitter Drift	X	X	X
	Cal. Equip.			
	Linearity	X	X	X
	Mount Position	X	X	
	Lead Lines			
FLOW EQUATION	Assm. Constants	X	X	X
	Approx. of Var.	X	X	
	Assm. Saturated	X	X	X
	Gas Exp. Factor	X		X
	Steam Quality	X	X	X
	Sampling Freq.			

Table 1 - Error Source Classification

OVERALL ACCURACY

After having identified and classified all possible sources of error in a flowmeter, overall accuracy can be calculated. Sources of error that are biased or unmeasureable are not included in the accuracy calculation.

Each source of measureable 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 most common causes of poor accuracy are given in this section. The following examples are based on typical meters and flowing conditions found at The Geysers.

All graphs and conclusions in these examples are derived from a computer accuracy model developed by the 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 contributer to poor accuracy is DP transmitters operating at a low percentage of their calibrated span. As previously described, 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 flowrate decline. When a well is first put into production, the pipeline, primary device, transmitter ranges, and calibrated spans are designed for the initial flowrate. As the flowrate declines, assuming nothing else changes, the DP declines. As the DP declines, the overall accuracy of the meter declines.

Using the meter described in Table 2, flowrate is varied while everything else is held constant. From Figure 1, the accuracy goes from an initial value of ±1.5% at 120,000 lbs/hr to a final value of ±23% at 20,000 lbs/hr. In addition to being well outside the BLM accuracy limit of ±4%, the accuracy of this meter at 20,000 lbs/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.

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

Table 2

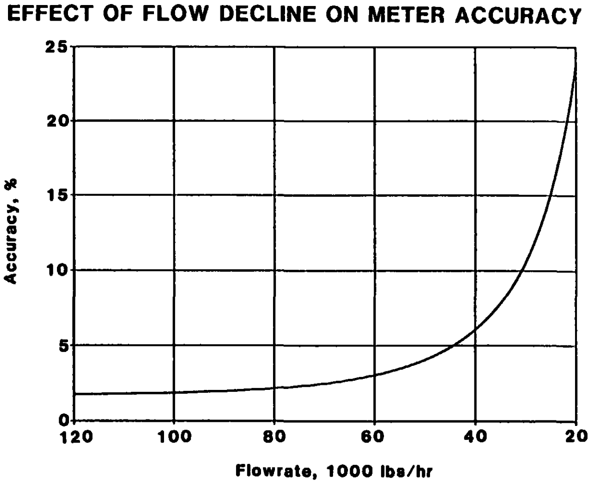
EFFECT OF FLOW DECLINE ON METER ACCURACY

Figure 1

1. Reducing Orifice Plate Diameter. By installing a smaller orifice plate, the DP is increased for a given flowrate. Because of the higher DP, the accuracy of the meter improves.

Using the parameters from Table 2, Figure 2 was developed to illustrate the effect of orifice plate size on accuracy. Initial accuracy of ±6% with an 8-inch orifice

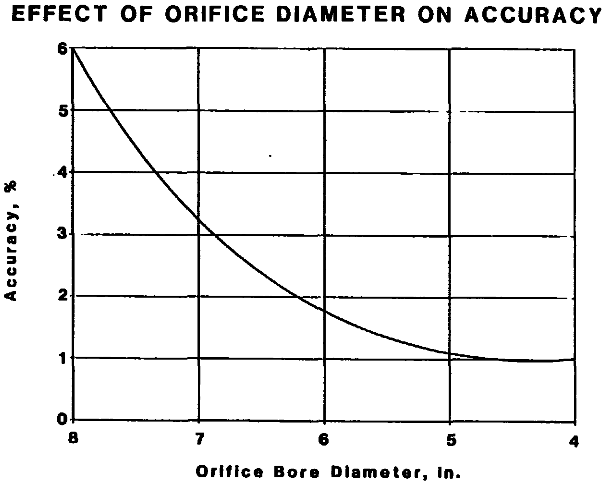

Figure 2

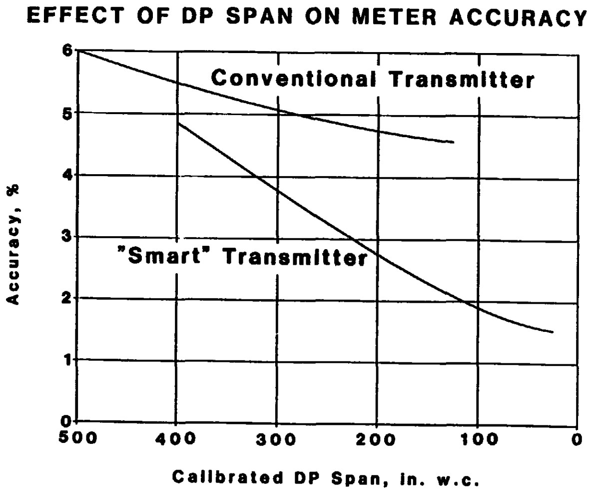

Figure 3

corresponds to a flowrate of 40,000 pounds per hour from Figure 1. Holding the flowrate at a constant of 40,000 lbs/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 2, two observations can be made. First, reducing the orifice bore can cause a significant improvement in meter accuracy. Second, the accuracy reaches an optimum value (±.9% at 4.4 inches) and then begins to get worse with further reductions in orifice diameter.

There are limits to the minimum orifice bore size that should be used. Beta ratios less than .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 is available. Therefore, flow coefficients, factors, and accuracy values given in literature cannot be used to calculate an accurate flowrate.

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 0-750 inches can be re-calibrated anywhere between 750 and 125 inches. The DP transmitter given in Table 2, for example, has been turned down from 0-750 inches w.c. to 0-500 inches w.c.

   The top curve in Figure 3 shows the effects of reducing DP transmitter span for the meter described in Table 2. To calculate this curve, flowrate was held at a constant 40,000 lbs/hr as with Figure 2, 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% to ±4.6%.

   From this curve, 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 increased 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 flowrate can be measured without reducing transmitter span. Ambient temperature effects are thereby reduced. For example, if the meter described in Table 2 was equipped with a Rosemount range 4 transmitter (0-150 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% to ±2.0%.

4. "Smart" DP Transmitter. Various manufacturers now make "smart" transmitters that are self compensating for ambient temperature and LP effects. Span, therefore, can 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 3. The particular "smart" transmitter used[2] has a maximum span of 400 inches w.c. and a minimum span of 25 inches w.c. (16:1 turndown). From Figure 3 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 is available.

Meter Tube Length

The effects of meter tubes that are shorter than recommended by the American Petroleum Institute (API)[1] have been debatable for many years. Recent data[3], however, suggests flowrate can be adjusted to account for short meter tubes with no significant reduction in primary device accuracy. The recommendation of API to add .5% 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%, the same meter with shorter meter tubes would have an accuracy of ±2.23% based on the API recommendation. According to the work published by Miller, the flowrate 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 meter parameters listed in Table 2, Figure 4 was developed to illustrate the effects of ambient temperature change. The calculations used to develop Figure 4 hold everything in Table 2 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 ±6%.

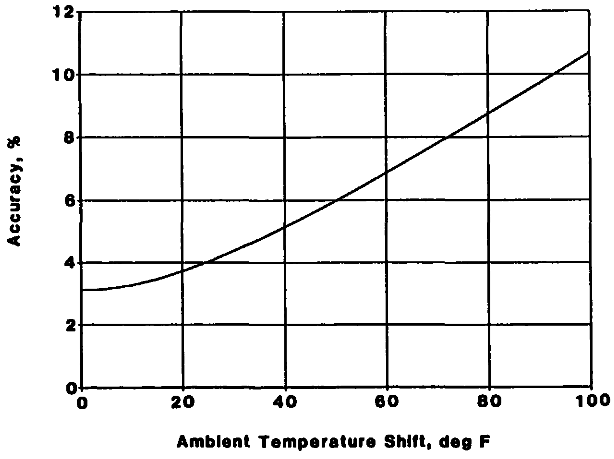
EFFECT OF AMBIENT TEMPERATURE ON ACCURACY

Figure 4

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, ambient-temperature change can be reduced by relocating the transmitters or calibrating the transmitters more often.

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

   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 effects of ambient temperature change is to reduce the time between transmitter calibrations. The average difference between the maximum and minimum ambient temperature increases as the time between calibration increases. Figure 5 was developed from temperature data obtained from three separate weather stations located in The Geysers.

   By decreasing the time between calibrations from 50 days to 10 days, the average temperature shift is reduced from 50°F to 30°F (see Figure 5). From Figure 4, this results in an improvement in accuracy from ±6% to ±4.5%.

CONCLUSIONS

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

2. Poor accuracy caused by low flowrates 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).

4. Accuracy is not greatly affected by meter tube length. For meter tubes shorter than recommended by API, the flowrate should be corrected based on the curves published by Miller.

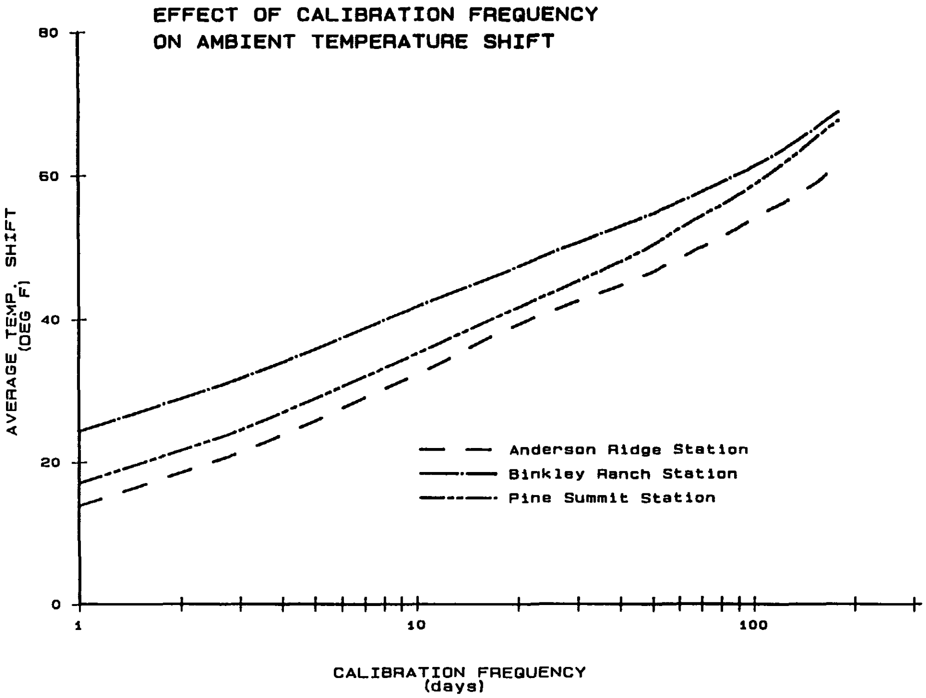

Figure 5

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