TRACKING THE GAS TEMPERATURE EFFECT IN A DISTRIBUTION SYSTEM

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AGA Operations Conference, Nashville, TN, May 24-27, 2011

1. INTRODUCTION

Most of Questar's domestic gas meters do not compensate for variations in the gas flowing temperature from the assumed 60˚F fixed billing temperature. Because of the climate in Questar's service area, this practice contributes to unaccounted-for gas. This problem could be corrected by installing new temperature compensated (TC) meters or retrofitting existing meters with temperature correctors, but the required capital expenditure is significant, particularly if done in a short period of time. An alternative method would allow Questar to begin adjusting volumes for actual gas temperature, while gradually phasing-in the use of temperature-compensating meters.

A sensitivity analysis was conducted to determine the impact of the constant temperature assumption on flow rate measurement. The results of the sensitivity analysis showed that significant measurement errors occur if the flowing gas temperature differs from the assumed gas temperature of 60˚F. Figure 1 shows the relationship. When the actual gas temperature is 10˚F from the assumed gas temperature, errors in measurement of as much as 2 percent are possible. The error increases significantly as the temperature difference increases. The average slope, based on a linear curve fit is 0.17%/ ˚F.

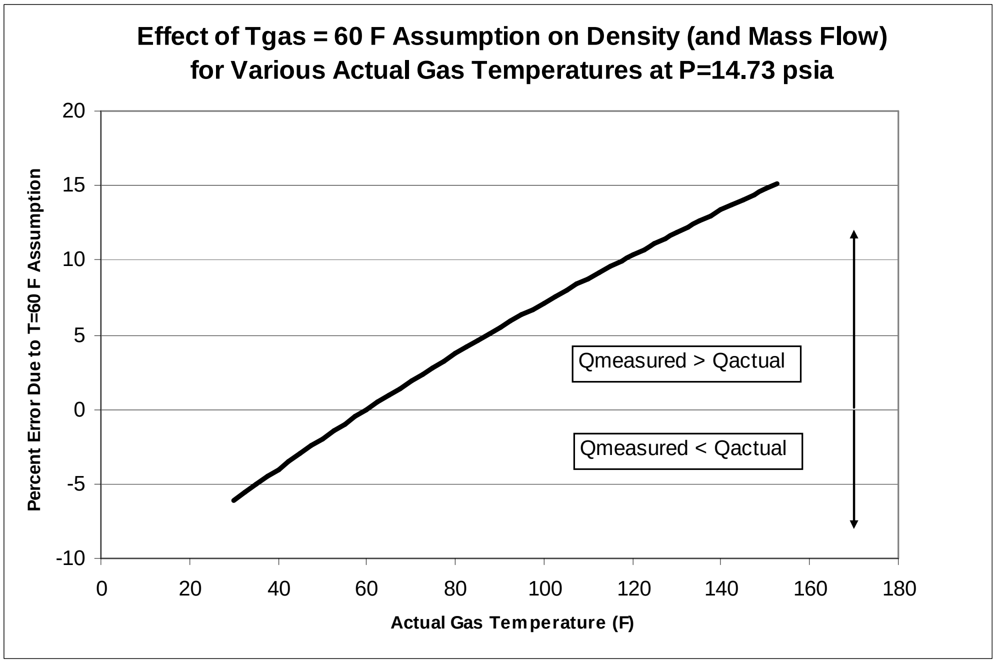

Figure 1. Effect of constant gas temperature assumption on measurement accuracy.

The purpose of this project was to assess the potential to improve meter accuracy by using temperature correction factors based on representative ambient temperature measurements made in zones within the Questar service area. The zone approach would be implemented using a single weather station, providing temperatures representative of the temperatures throughout the zone. The maximum and minimum temperatures during a given period would be used to calculate an "average" temperature, $(T_{high} + T_{low})/2$, for that period. The resulting temperature would be used to adjust the flow rates based on the relationship between the ambient temperature and the flowing gas temperature. The project was organized into three tasks: Task 1 - *Review Current State of Knowledge*, Task 2 – *Temperature Zone Development* and Task 3 – *Experimental Program*. This paper provides an overview of the project and a review of the results, with particular emphasis on the experimental program.

2. TASK 1 - REVIEW CURRENT STATE OF KNOWLEDGE

The objective of the first task was to assess the current state-of-the-art related to temperature compensation. This was accomplished by conducting a literature search and a benchmark survey of local gas distribution companies (LDCs) in the US and Canada. Task 1 concluded that:

- It is common practice among some LDCs to temperature compensate using temperature correction factors that are based on ambient temperature readings
- In general, the literature showed that the flowing gas temperature at outdoor meter installations closely agreed with the local ambient temperature. Better correction factor accuracy can be achieved by using a flow-weighted average temperature rather than a simple temperature average.

Tasks 2 and 3 were intended to develop and test a method for adjusting gas flow measurement, using the ambient temperature in a zone. Tasks 2 and 3 were complementary, in that Task 2 used historical climate data to select temperature zones and Task 3 used experimental measurements within a test zone to confirm that the historical data provided a reliable means for selecting temperature zones. Task 3 was also intended to investigate the dependence of flowing gas temperature on parameters such as ambient temperature and solar radiation flux, and to compare the performance of temperature compensating (TC) meters.

3. TASK 2 - TEMPERATURE ZONE DEVELOPMENT

3.1 Objective

The objective of this task was to provide the basis for the establishment of temperature zones in the Questar Gas service area, to select temperature zones and to select sites for the experimental program.

WeatherBank Inc. of Edmund Oklahoma provided monthly maximum and minimum temperatures covering a thirty-year period (1975-2004) from 179 weather stations in Utah, Colorado, Arizona, Nevada, Idaho and Southwest Wyoming. Monthly "averages" were computed from these data by averaging the minimum and maximum temperatures. WeatherBank also provided plots of isotherms for the Questar service area. Figure 2 is an example of the average temperature isotherm plot for August.

3.2 Temperature Zone Selection

Based on analysis of the historical 30-year average temperature data, nine temperature zones within the state of Utah were defined. A single zone was selected for the Task 3 experimental program. The zone representing Salt Lake City (SLC), Ogden, Provo and other cities along the Wasatch Front region was chosen because (1) it encompassed a relatively large geographical area, (2) there were many residential homes near the weather stations currently being monitored, and (3) the area included a large residential population.

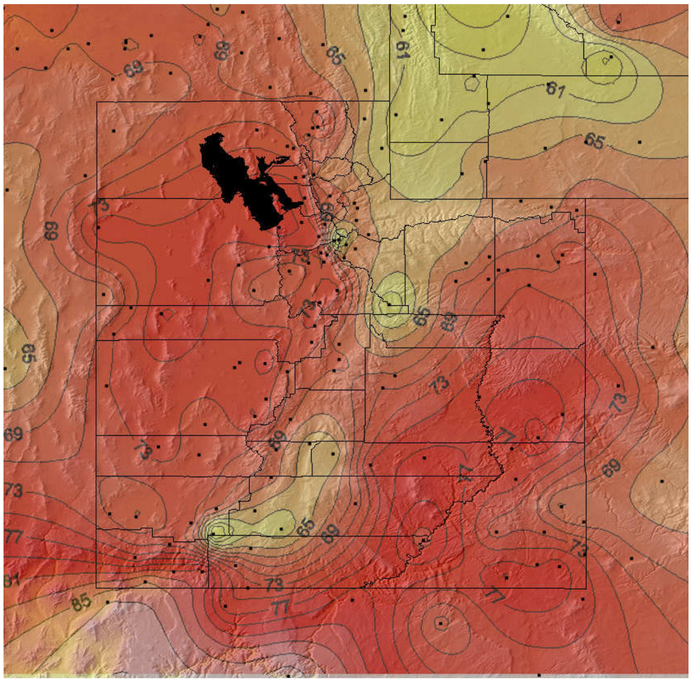

Figure 2. Average August temperature contour map for Questar service area based on a 30-year period.

4. TASK 3 - EXPERIMENTAL PROGRAM

4.1 Objective and Approach

The experimental program had three objectives. The first was to confirm or reject historical temperature profiles for the Wasatch Front zone that was selected in Task 2. The second was to provide data to confirm or reject the relationship between ambient temperature and flowing gas temperature that was suggested in an article by Columbia Gas of Ohio[1]. The third objective was to provide data comparing the accuracy of flow measurements using various flowing gas temperature assumptions and to compare the performance of TC meters. The experimental program kicked-off on April 1, 2006. Data collection was completed on March 31, 2007.

Tests were conducted at sixteen field sites in the SLC/Ogden/Provo area selected during the temperature zone selection task. Sixteen field sites were needed in order to provide an acceptable level of confidence in the statistical comparison of the average monthly temperatures across the field sites within the experimental temperature zone[2] and to provide back-up data in case of equipment failure. In addition, the field tests were positioned throughout the zone to assess the statistical validity of using a single ambient temperature measurement location to represent the ambient temperature throughout the whole zone. Last, the assumption that the zone temperature variation in the historical data was not statistically

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[1] “Outsourcing Meter Repair May Lower Distribution System Costs,” Monte, Dave. Pipeline & Gas Industry, January, 2000, pp. 63-66.

[2] The number of field sites required depends on the standard deviation of the historical temperature data, the statistical acceptance region, the probability of rejecting the hypothesis when it is true (Type I error) and the probability of accepting the hypothesis when it is false (Type II error).

different from the zone temperature variation in the field data was also tested. The measurement sites are shown in Figure 3. Map with locations of the 16 stations (red) and SLC Airport

In addition to the ambient temperature data, ground temperature, flowing gas temperature, meter surface temperature and solar radiation flux were measured in order to understand the variables that impact flowing gas temperature. This is critical for successful implementation of the temperature zone approach, since it relies on ambient temperature as an estimate of flowing gas temperature.

The flow rate comparisons were accomplished using the non-TC meter flow rate, adjusted for flowing gas temperature, as the reference flow measurement. The flowing gas temperature was calculated using the "average" of the non-TC meter's inlet and outlet gas temperatures ($(T_{in} + T_{out})/2$). Certain simplifying assumptions were made because of the lack of gas composition data at each site and because of standard distribution flow measurement practices. The assumptions were:

- Compressibility Factor, $Z = 1$
- Specific Heats, C_p and C_v = Constant
- $P_{std} = P_{flow} = 14.73$ psia (no pressure compensation)[3]
- P = constant through both meters

Since these are relative comparisons and the assumptions are applied equally to all methods under comparison, any biases associated with the first three assumptions will cancel out. The fourth assumption, P = constant through both meters, could have some effect on the results. However, calculations estimated the effect to be no more than 0.16%.

The compressibility factor assumption allowed use of the Ideal Gas relationship to separate the effect of pressure from the effect of temperature. This is a common practice in distribution measurement and allows for the use of factors to correct for temperature and pressure. In Questar's case, the pressure is corrected using elevations and the temperature factor is fixed, using an assumed gas temperature of 60˚F. The net effect due to these assumptions is that the flow rate can be calculated using $Q = Q_{flow} (T_{std}/T_{flow})$, where "std" implies 60˚F and "flow" implies flowing gas temperature. For the experimental program, the flow rate equation was modified to $Q = Q_{NTC} (T_{std}/T_{test})$, where Q_{NTC} was the output of the non-temperature-compensating meter and T_{test} was the temperature associated with the method being tested. Using this convention, the following flow rate equations were used for the flow rate comparisons:

1. Reference flow rate: $Q_{ref} = Q_{NTC} (T_{std}/T_{ref})$, where $T_{ref} = (T_{in}+T_{out})/2$
2. Fixed Factor: $Q_{fixed} = Q_{NTC} (T_{std}/60^{O}F)= Q_{NTC}$
3. Ambient Temperature: $Q_{amb} = Q_{NTC} (T_{std}/T_{ambient})$
4. Meter Surface Temperature: $Q_{surf} = Q_{NTC} (T_{std}/T_{meter\ surface})$
5. Temperature-Compensating Meter: $Q = Q_{TC}$

The net effect of these equations is that if a particular method assumes the gas temperature is lower than the reference temperature, the method will result in a flow rate measurement that is biased high. Likewise, if the gas temperature is assumed higher than the reference temperature, the method will result in a measurement that is biased low.

4.2 Measurement System

The measurement system components were selected for accuracy, stability and suitability for operation in a harsh environment. Onset, a manufacturer of weather monitoring equipment, was selected

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[3] In practice, Questar corrects flow to 12.85 psia. Pressure compensation was not necessary for the relative comparisons of this study.

to provide the dataloggers, the solar radiation sensor, and the thermistors. Weed was selected to provide the resistance temperature devices used to measure gas temperature. Riotronics was selected to provide the meter pulsers. The flowmeters and temperature devices were calibrated to ensure traceability to national standards.

Figure 3. Map with locations of the 16 stations (red) and SLC Airport (blue).

The test sites included a temperature compensated meter installed in series with the existing meter. The data acquisition system included:

- Inlet and outlet gas temperature measurement devices
- Ground, ambient and surface temperature measurement devices
- Flow pulsers
- Solar radiation sensor
- Datalogger
- 12 volt battery

Photos of the system installed on-site are shown in Figure 4 and Figure 5. A protective cover was added to isolate the power supply and wiring from the elements. The non-TC meter was used as the reference. It was located upstream of the TC meter. Temperature measurements were made at the inlet and outlet of the reference meter, to capture any changes in gas temperature as the gas flowed through the meter. The reference meter gas temperature was measured as the average of the inlet and outlet gas temperatures. Since each meter provided an independent measurement, the relative locations of the meters should have had no effect on the results.

Temperature instrumentation was calibrated using a Standard Platinum Resistance Thermometer submerged in a variable temperature water bath, and controlled by a LabView application. After calibration, the uncertainties in the thermistor and RTD measurements were approximately 0.05˚F at the 95% confidence level. The meters were calibrated using Questar Gas' SNAP prover. The estimated uncertainty of the SNAP prover is +/- 0.15%. During data reduction, flow rates were adjusted using the average calibration factor for each meter.

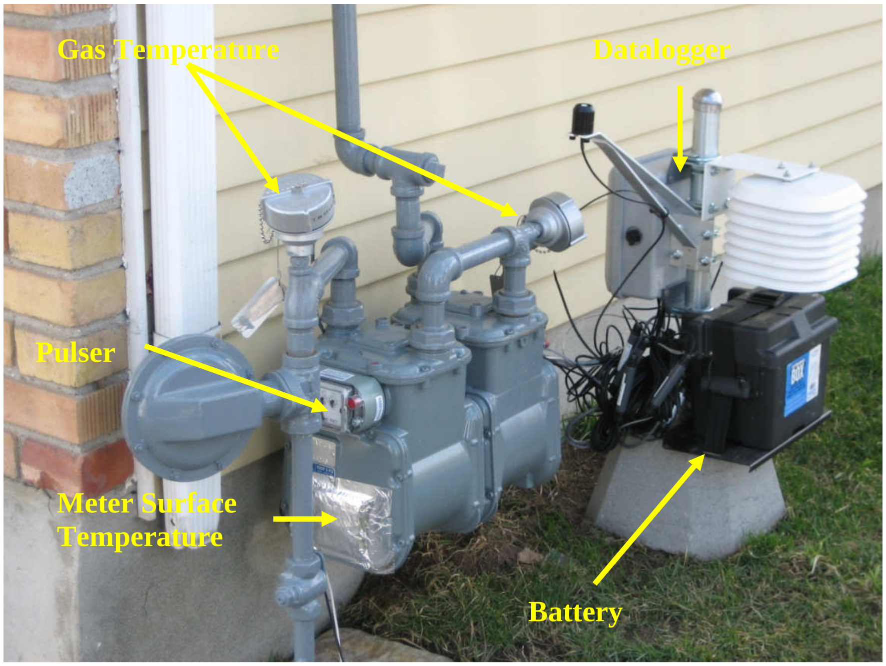

Figure 4. Site measurement setup showing components.

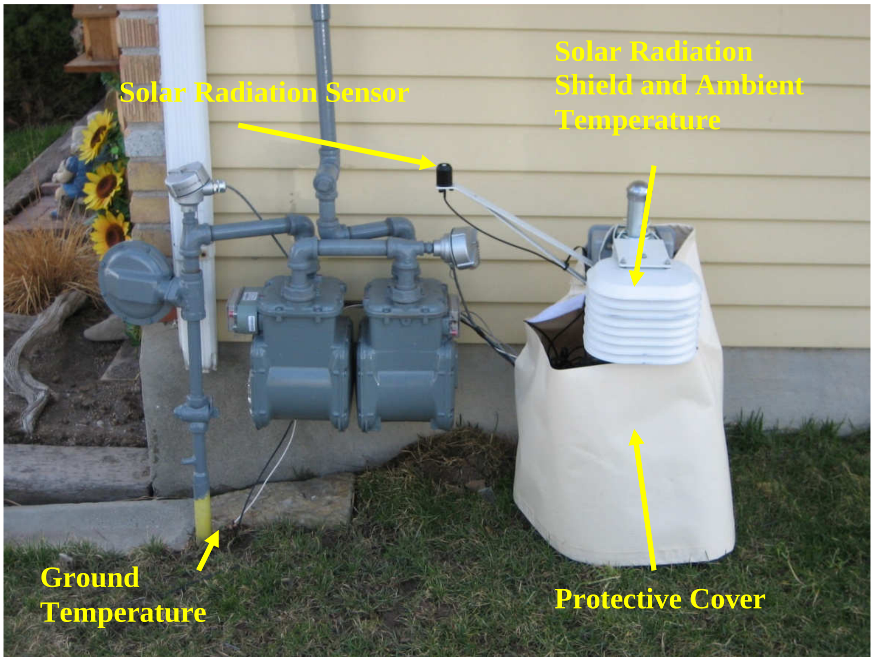

Figure 5. Site measurement setup showing protective cover.

4.3 Results

Objective 1- Confirm or Reject the Historical Temperature Profiles

This project objective included two important comparisons. First, the data collected at the test sites was analyzed in order to determine if it was representative of the historical temperature data from the Wasatch Front zone. Second, the 1-year temperature data from the SLC Airport was compared to the temperatures from the test sites to determine whether a single weather station could represent a larger geographical area.

Table 1 summarizes the monthly temperature average, standard deviation and delta temperature for both the 30-year Wasatch Front zone data and the 1-year experimental data collected from the test sites within the zone. The delta temperature is the difference between the 30-year average temperature and the 1-year test site average temperature. Note that the test year average temperature was within ±5˚F of the historical average temperature for all months except January and September. Both of these months recorded warmer temperatures during the test year.

Month	**30-yr Historical Wasatch Front zone**		**1-yr Test Sites**		**Delta Temperature**
	Avg. Temp ˚F	**Std. Dev. ˚F**	**Avg. Temp ˚F**	**Std. Dev. ˚F**	**Historical Avg. – Test Site Avg.**
Apr	50.36	3.77	51.86	2.78	-1.50
May	58.78	3.31	62.71	2.33	-3.93
Jun	68.51	3.39	71.30	1.87	-2.79
Jul	76.34	3.08	79.06	1.85	-2.72
Aug	74.57	2.74	73.31	2.47	1.25
Sep	65.05	3.14	58.89	1.66	6.16
Oct	52.84	3.22	48.84	1.60	4.00
Nov	39.27	3.82	41.30	1.17	-2.03
Dec	30.71	3.76	30.04	1.42	0.67
Jan	29.08	5.22	21.31	2.53	7.77
Feb	33.88	4.71	35.86	1.06	-1.98
Mar	42.59	3.64	43.38	4.25	-0.79

Table 1. Temperature descriptive statistics for historical data and test year data.

To statistically compare the site temperature data to the historical database from the zone, prediction intervals were computed using the historical data as the sample population. The test site temperatures were then compared to the prediction interval to see if they were contained within the temperature prediction bounds for the zone. In general, the temperature data from the test sites appeared consistent with the temperature profiles of the 30-year historical data within the defined zone. Therefore, historical temperature data may be used to select appropriate temperature zones.

To compare the monthly temperature average across the test sites to the monthly temperature at the SLC Airport, prediction intervals were computed using the test site data as the representative population. In all months except September, the SLC Airport temperature average fell within the 95% prediction interval limits, indicating that the average temperature at the SLC Airport can be used as a representative temperature of the test zone area.

Objective 2 – Investigate the Presumed Correlation between Ambient Temperature and Flowing Gas Temperature

To investigate the possible correlation between ambient temperature and gas inlet temperature, a linear regression was fit independently for each of the test sites by month using the daily temperatures collected during each month. Thus, an R^2 value representing the amount of variation explained by the linear relationship between the ambient temperature and gas inlet temperature was computed for each site by month. R^2 values near 0 indicate no linear relationship while R^2 values near 1.0 signify strong linear associations.

Figure 6 illustrates the comparison of the R^2 values from the ambient temperature and gas inlet temperature correlations with the maximum radiation at each test site and month. Although there is a large spread in the data some general observations can be made:

- There is a significant downward trend in the R^2 values as the maximum radiation increases. This suggests that the correlation is weakened when the solar radiation is above approximately 600 W/m^2.
- The majority of the low radiation (less than 600 W/m^2) corresponds to the winter months and during those months, the correlation between ambient temperature and gas temperature is generally greater than 0.8.
- In general, the correlation is stronger during the winter months than during the summer months.

It appears that radiation impacts the correlation between gas temperature and ambient temperature. However, the extent of the impact depends on the level of radiation. If it is high, such as during the summer months, the effect is considerable, and controls the gas temperature (i.e. weakens the correlation). If it is low, such as during the winter months, the effect is secondary and the ambient temperature/gas temperature correlation is stronger.

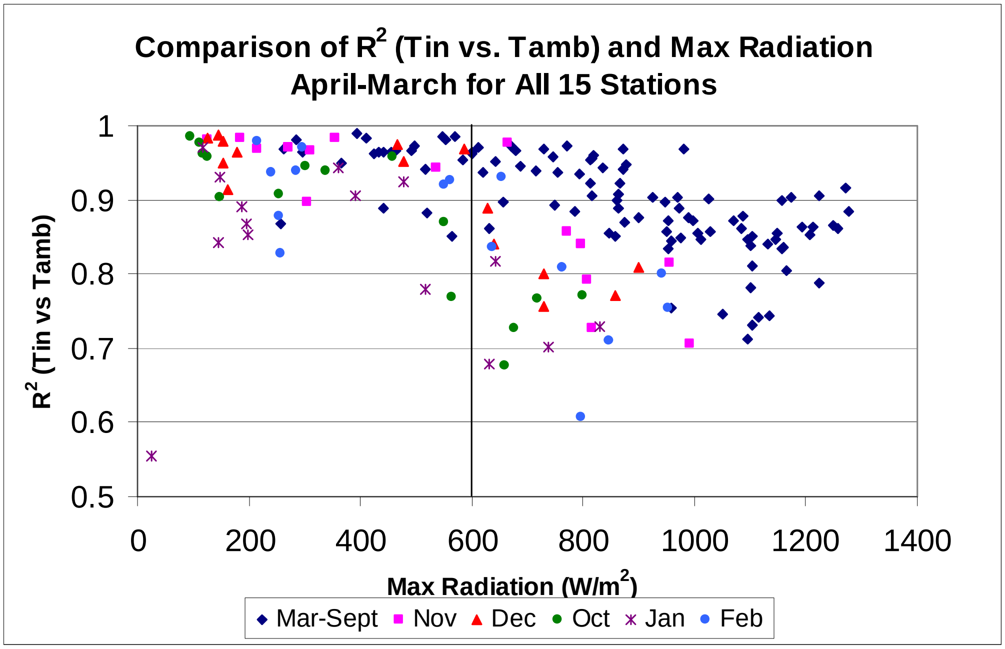

Figure 6. R^2 (Ambient Temperature and Flowing Gas Temperature) as a function of maximum solar radiation for all stations in the test zone.

Objective 3 – Flow Measurement Comparisons

The six flow measurement methods were compared to the reference flow rate on a relative percentage basis (i.e. %Diff = $100(Q_{test}-Q_{ref})/Q_{ref}$). Table 2 shows the results of the comparisons. Flow was calculated every five minutes. The reference flow rate, and Methods 1, 2, 3, and 6 were compared by summing the five minute volumes, after correcting for temperature ($Q_{tot} = \sum(Q_i \cdot Tcorrect_i)$ over a period of approximately one calendar month. This minimized the chance of "masking" ambient or radiation effects that might occur if volumes were corrected based on average temperatures for a given month ($Q_{tot} = Tcorrect_{avg}\sum Q_i$). The total volumes for Methods 4 and 5 were calculated using the "average" shown above. TC meter flow rates were calculated using the total pulses recorded, multiplied by the pulse factor, in cubic feet/pulse. The most accurate approach, in terms of percent difference relative to the reference, was the meter surface temperature approach. The "averaging" methods, from data collected at the airport and at the sites, performed similarly to the TC meter. The least accurate method was the Fixed Factor method.

Method	Mean	Max	Min	Range
1. Fixed Factor	-1.45%	6.28%	-7.67%	13.95%
2. Meter Surface	0.08%	0.46%	-0.46%	0.92%
3. Ambient at Site	0.46%	1.82%	-0.45%	2.27%
4. "Average" Ambient at Site	-0.24%	2.92%	-2.43%	5.35%
5. "Average" Ambient at Airport	-0.16%	2.39%	-2.95%	5.34%
6. Temperature Compensating Meter	0.54%	3.23%	-3.10%	6.33%

Table 2. Summary of flow measurement comparisons showing percent difference, relative to the reference flow rate.

Summary results are plotted in Figure 7 through Figure 12 for all stations, all months and all methods. The fixed factor method (Figure 7) produced the largest errors, relative to the reference. This was due to the wide seasonal variation in ambient temperature in the Questar Gas service area. Actual gas temperatures were near 60˚F during the spring and fall, but significantly above and below 60˚F during summer and winter, respectively. As discussed previously, this introduces significant errors.

Figure 8 shows the percent error when the gas temperature was assumed equal to the meter body surface temperature. This method was the most accurate and indicated that the gas temperature was controlled by the meter body temperature, which was influenced by exposure to solar radiation, as discussed earlier.

Figure 9 shows the percent error when the gas temperature was assumed equal to the ambient temperature at the site. The overall performance was not as good as the Meter Surface method, but was a significant improvement over the Fixed Factor method.

Figure 10 shows the percent error when the gas temperature was assumed equal to the "average" ambient temperature at the site. The method performed differently from late spring to early fall, than during early fall to early spring. The difference was associated with the effect of solar radiation, which rose to a maximum in mid-summer and fell to a minimum in mid-winter. As discussed earlier, the effect of radiation was more pronounced during the summer months, and became a secondary effect during winter months. Despite the influence of solar radiation, the mean, maximum, minimum and range improved, relative to the Fixed Factor method.

Figure 11 shows the percent error when the gas temperature was assumed equal to the “average” ambient temperature at the airport. This is the site that would be used to adjust gas temperature in the implementation of the temperature zone method. The method also performed differently from late spring to early fall, than during early fall to early spring. This was not surprising, since both methods rely on ambient temperature. As with the previous method, despite the influence of solar radiation, the mean, maximum, minimum and range improved, relative to the Fixed Factor method.

Figure 12 shows the performance of the TC meter, relative to the reference meter. Overall, performance of most TC meters was steady over the course of the year, with the bulk of the comparisons showing a difference of about +/- 1 to 2 percent. Stations 1, 5, 11 and 13 showed greater variability over the course of the year, increasing the percent difference for all TC meters to about +/- 3%. Measurement precision worsened during the winter months. In comparison, both of the “average” ambient methods (Figure 10 and Figure 11) showed improved precision during the winter months. A statistical comparison of the standard deviations among the TC meter, “average” ambient at site and the “average” ambient at the airport methods showed that the standard deviation for the TC meter method was significantly greater than the standard deviation for the other two “ambient” methods for the months of October, Novermber, December, and January. This is important because of the increased gas consumption during the winter. For all the remaining months, the precision performance of the TC meters was not statistically different from the precision performance of the two “average” ambient methods. The ambient temperature methods performed better, in terms of precision during the cold months because of the improved correlation between ambient temperature and gas temperature observed during the colder months, when solar radiation is relatively low. The cause of the higher variations for Stations 1, 6, 11, and 13 is unknown, but may be associated with manufacturing variability.

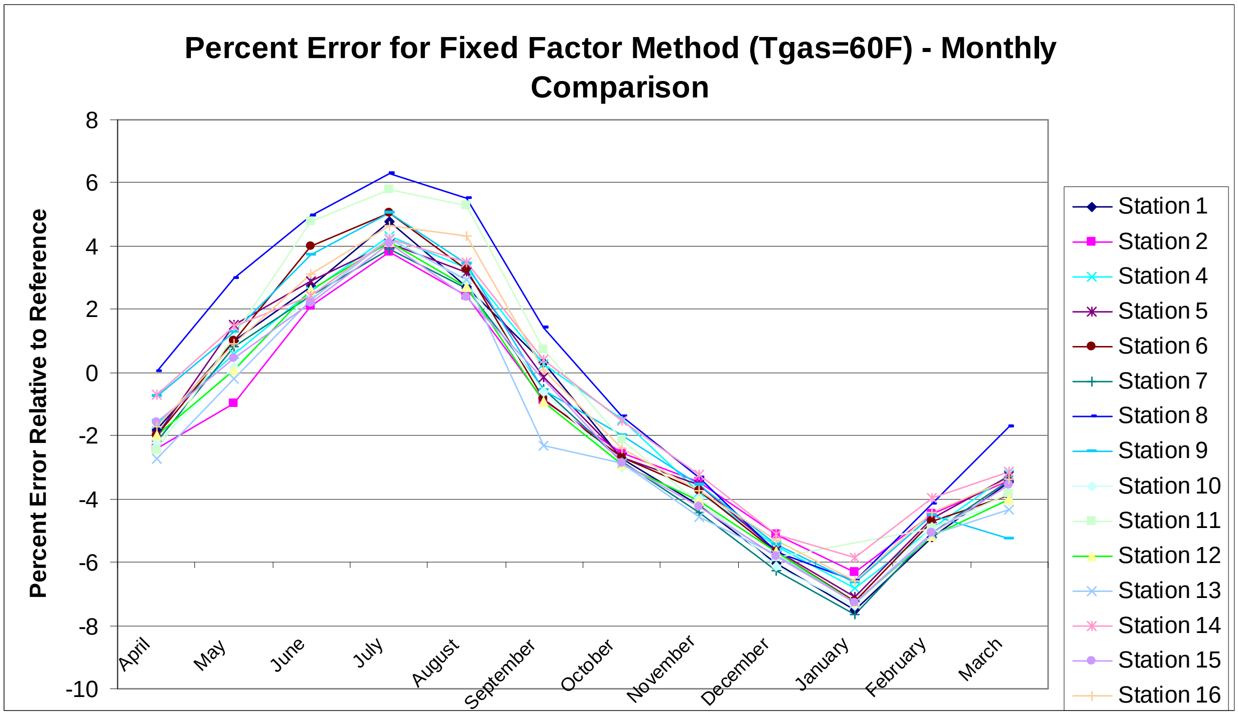

Figure 7. Flow measurement comparison for Fixed Factor method, all stations and all months.

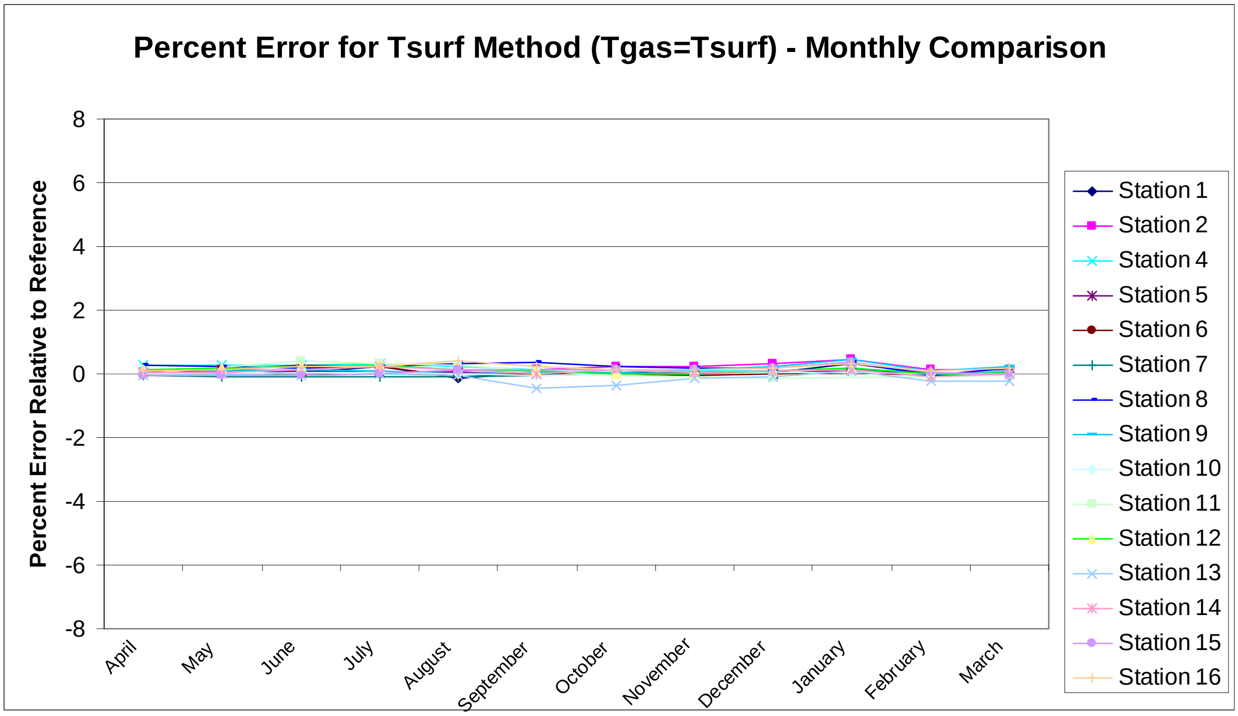

Figure 8. Flow measurement comparison for Meter Surface method, all stations and all months.

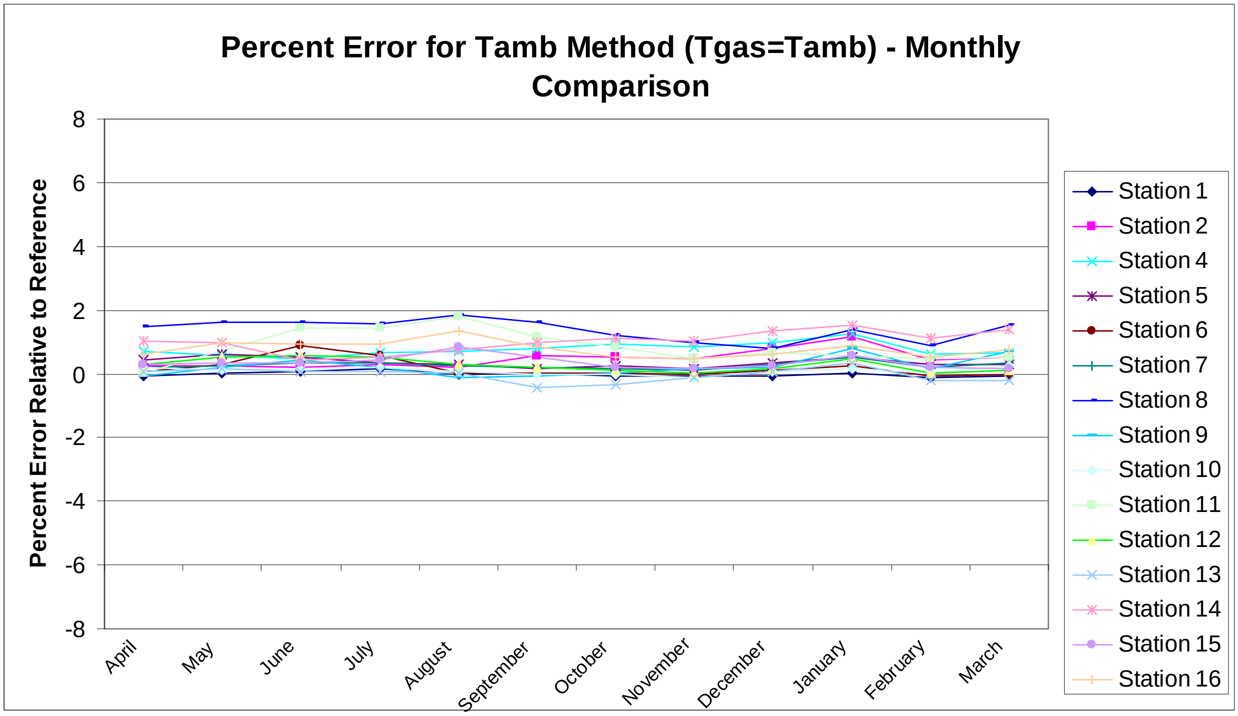

Figure 9. Flow measurement comparison for Ambient at Site method, all stations and all months.

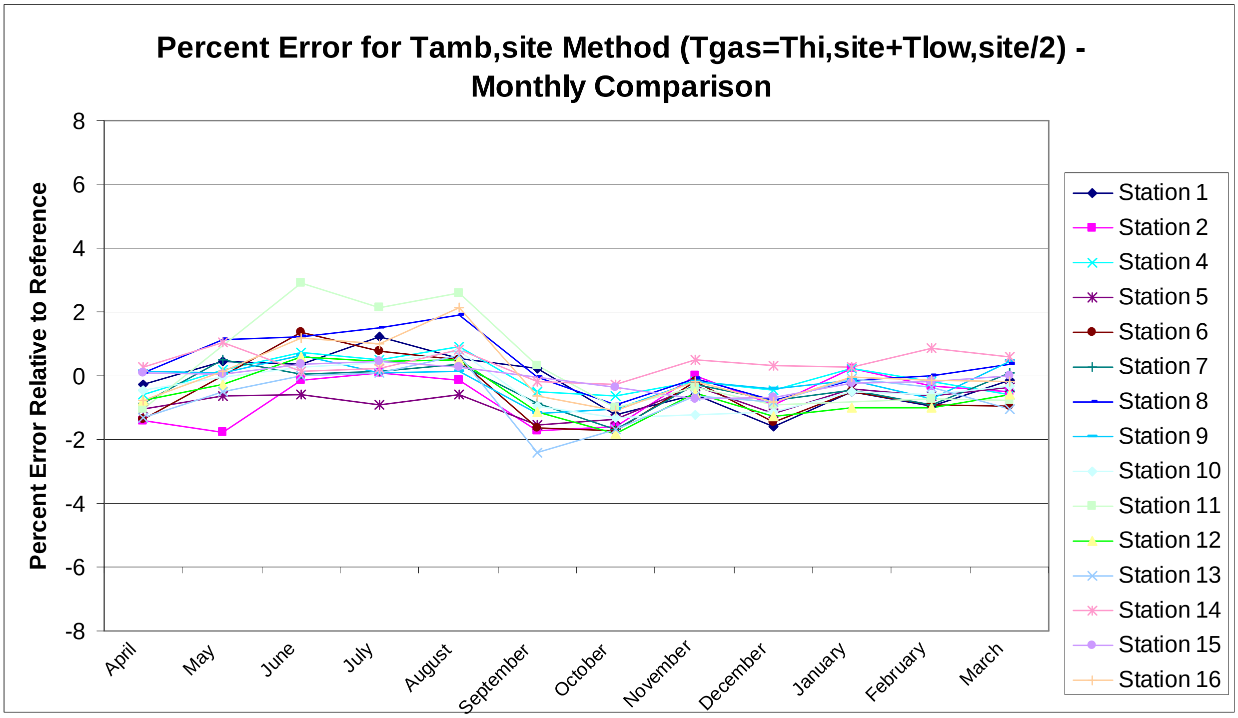

Figure 10. Flow measurement comparison for "Average" Ambient at Site method, all stations and all months.

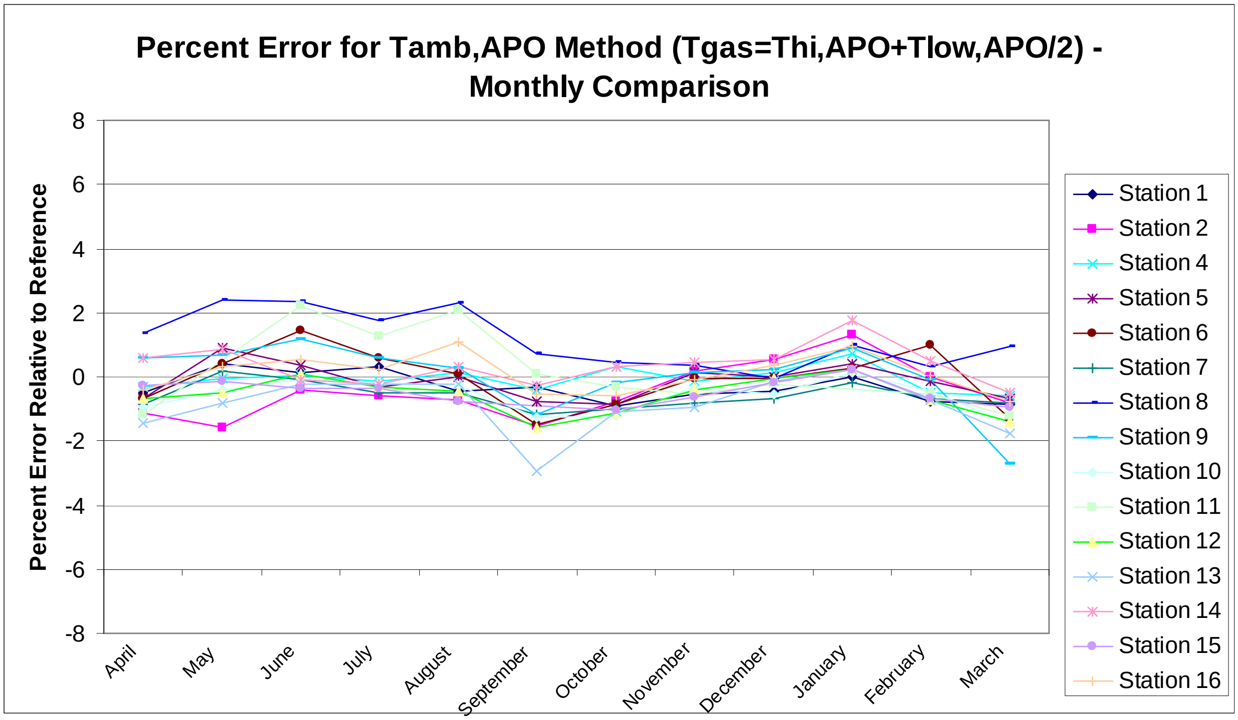

Figure 11. Flow measurement comparison for "Average" Ambient at Airport method, all stations and all months.

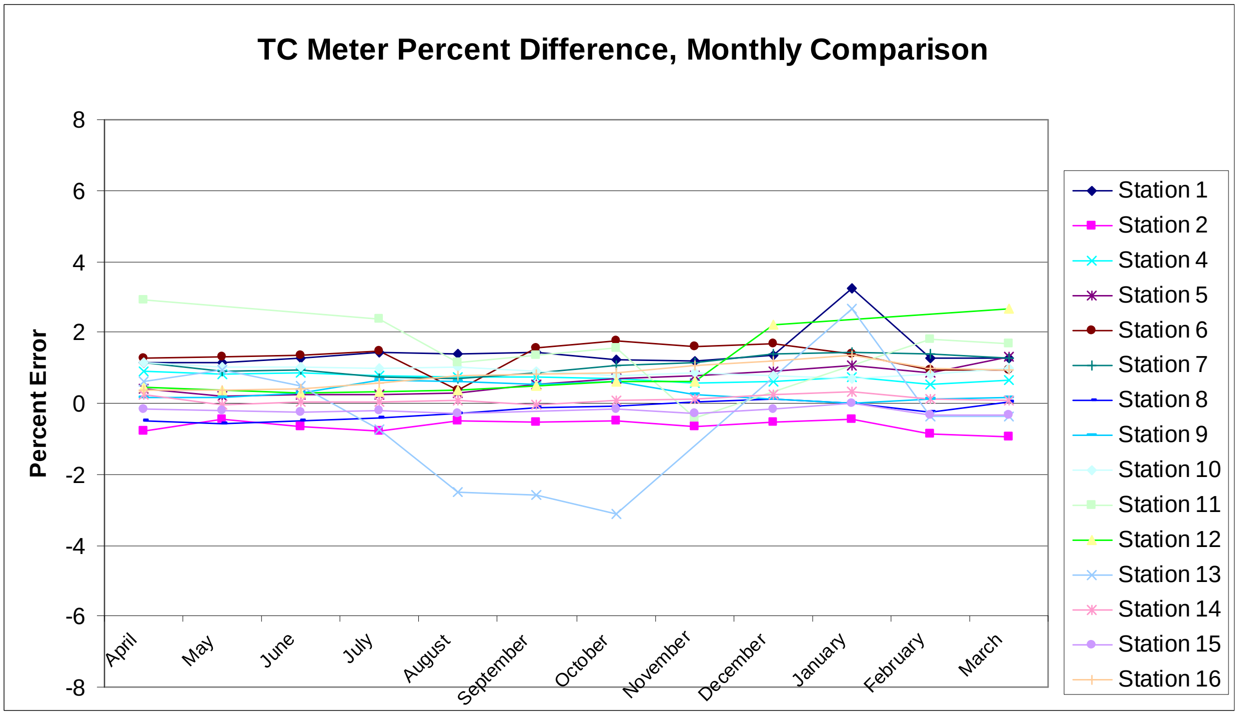

Figure 12. Flow measurement comparison for the Temperature Compensating meter, all stations and all months.

5. CONCLUSIONS

- Ambient temperature data can be used to select zone boundaries and to predict intra-zone temperature variability. "Average" ambient temperature data at a single location (the SLC airport in this study) can be used to represent the temperature throughout a zone. The temperature zone approach can be used to provide improved flow measurement.
- The accuracy of the "average" ambient temperature methods improved during the winter months, relative to the summer months. This is because 1) solar radiation exposure is greater during the summer months and 2) the effect of solar radiation on the correlation between ambient temperature and gas temperature is more pronounced during the summer months, when solar radiation tends to be high, and becomes secondary during the winter months, when solar radiation tends to be low. This is significant because more gas is consumed during the winter months.
- The Fixed Factor method performed poorly. The error, relative to the reference measurement, ranged from +6 to -7 %. Errors were greater during mid-summer (July through August) and mid-winter (December through January). Errors were lowest during spring and fall. The effect of the percent error on total volume for a given site was impacted by seasonal load variations. Over the course of the year, the Fixed Factor method produced a net undermeasurement.
- Temperature-compensating meters performed significantly better than the fixed factor method. The percent difference in flow rate, relative to the reference, of the temperature-compensating meters, was approximately in the middle of the group of methods tested

(excluding the fixed-factor method). The results of the temperature-compensating meter tests were comparable to the accuracy produced by the “average” ambient temperature methods.

- Overall, performance of the TC meters was steady over the course of the year, with the bulk of the comparisons showing a difference of about +/- 1 to 2 percent. Measurement precision worsened during the winter months. In comparison, both of the “average” ambient methods (Figure 10 and Figure 11) showed improved precision during the winter months (see **Error! Reference source not found.**).
- In contrast to the “average” ambient temperature methods, the precision of temperature-compensating meters worsened during October, November, December, and January. For all the remaining months, the precision performance of the TC meter was not statistically different from the precision performance of the two “average” ambient methods. The cause of the worsening precision was not studied because it was outside the scope of the project.
- The use of meter surface temperature stood out as the most accurate indicator of flowing gas temperature, producing differences in flow rate of +/- 1%. This is because of the “plenum” effect of the meter, which facilitates heat transfer to/from the meter body to/from the gas.
- The effect of solar radiation on the correlation between ambient temperature and gas temperature is greater during the summer months, when solar radiation and ambient temperatures are higher and the effect is lower during the winter months, when solar radiation and ambient temperatures are lower. This observation may help explain the difference in the performance of the “average” ambient temperature methods during summer versus winter.
- The use of the statistical average ambient temperature, or daily high and low temperatures, at the SLC airport may improve the accuracy of the zone method.