

QUALITY CONTROL PROGRAM OF THE CEESI VENTURA CALIBRATION FACILITY

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Abstract

The CEESI Iowa Quality Control program is made up of three parts. The first part addresses management issues as described in the ISO 9000 series of standards. It consists of the documented procedures and policies that govern the day to day operations. The second part addresses technical issues as described in the ISO 17025 standard. Examples include uncertainty analyses, calibration records and software verification. The Measurement Assurance Program (MAP) is the third part of the CEESI Iowa Quality Control program. This paper discusses the components of the CEESI Iowa MAP.

The main component of the MAP is the use of check standards. Each test section includes an ultrasonic meter check standard that is present during each calibration. Over time historical data have been accumulated on each check standard and typical performance has been quantified. At the conclusion of a customer calibration the consistent performance of the check standard provides assurance that the entire calibration process is also operating consistently. The formal tool used to monitor the check standards is the control chart.

While the check standards monitor the entire calibration, several programs are in place to monitor the individual components. The turbine substitution test identifies the performance of individual turbine meters relative to each other. The critical pressure and temperature measurements are made with redundant instruments. Control charts are used to monitor the transducer pair differences. Finally, the weekly calibration results for the gas chromatograph are monitored using control charts.

There are two overall objectives in the CEESI Iowa MAP, the first is to assure that the measurement process is operating consistently. The resulting benefits have been understood in the manufacturing community for many years, it is only more recently that the measurement community has adopted similar techniques.

The second objective of the MAP is to provide data for the uncertainty analysis, this results in several benefits. The first results from obtaining uncertainty estimates based on data rather than other methods. Data based estimates improve credibility and the likelihood of inadvertently excluding any components is reduced. The second benefit is the general improvement in uncertainty resulting from using historical calibration data instead of manufacturer's specifications. A manufacturer may include operating constraints not present in a particular application. A set of specifications may reflect the performance for an entire production batch, the performance of a single unit may be better. Finally, the use of historical data allows for the continuous maintenance of traceability, an important part of measurement uncertainty.

Facility Description

The Iowa calibration facility has been operational since March 1999¹. It is located adjacent to a custody transfer station on a pipeline operated by the Northern Border Pipeline Company. The basic layout is shown in Figure 1. One 1067 mm (42") pipeline enters the facility at A while three pipelines exit the facility at B, C, and D. The nominal diameters are 762 mm (30") for B and D and 914 mm (36") for the pipeline exiting at C. A flow regulating station (valves V_4 , V_5 , and V_6) is located within the facility on pipeline D. As part of their normal operation, Northern Border controls flow through pipelines B, C, and D.

The gas that bypasses the pipeline is directed through a parallel array of nine 305 mm (12") turbine meters which serve as flow standards. One or more turbine meters are opened to achieve a particular flowrate, double block and bleed valves isolate those turbine meters not in use. Turbine meters are selected such that flowrate is always measured with the lowest possible uncertainty. Operating with all nine turbine meters at full capacity results in a test section flowrate of 38,200 m³/hr (22,500 ft³/min). The gas exits the turbine meter array and flows through one of three test sections. Three test sections allow for the calibration of a range of meter sizes and installation conditions.

With normal pipeline operation the test section pressure is between 6.9 and 7.6 MPa (1000 and 1100 psia).

For ultrasonic meters smaller than 406 mm (16"), part of the gas flowing through pipeline D is directed through the test facility. Valves V_1 , V_2 , and V_{10} are open, valve V_3 is closed. For higher velocities through ultrasonic meters 406 mm (16") or larger, part of the gas flowing through pipelines B, C, and D is directed through the test facility. Valves V_1 and V_2 are closed, valves V_3 and V_{10} are open. For all calibrations primary flow control is achieved using valves V_4 , V_5 , and V_6 . Secondary flow control, if required, is achieved using valves V_7 , V_8 , or V_9 .

Two ultrasonic flowmeters, 508 mm (20") and 610 mm (24") in size, have been permanently installed in two of the three test sections. More recently a 305 mm (12") turbine meter has been installed in the third test section. Data are obtained from one of these meters during every calibration performed on a client meter. The purpose of these meters is to serve as check standards that confirm consistent performance of the calibration facility. In other words, the consistency of a particular set of check standard calibration data is strong evidence for the validity of the corresponding client meter calibration data.

Measurement Uncertainty

The uncertainty of the lowa facility is detailed in Reference 2. That analysis resulted in an estimated uncertainty in test meter K Factor of $\pm 0.23\%$ at a 95% level of confidence. This value is made up of the following components:

1. Turbine array volumetric flowrate:
 $u = \pm 1792 \text{ ppm} = \pm 0.179\%$
2. Test meter K Factor:
 $u = \pm 824 \text{ ppm} = \pm 0.082\%$
3. Temperature measurement:
 $u = \pm 644 \text{ ppm} = \pm 0.064\%$
4. Pressure measurement:
 $u = \pm 556 \text{ ppm} = \pm 0.056\%$
5. State equation (AGA 8):
 $u = \pm 58 \text{ ppm} = \pm 0.006\%$
6. Gas composition:
 $u = \pm 34 \text{ ppm} = \pm 0.003\%$

Each turbine meter was calibrated in the CEESI Colorado facility. Item 1 above includes the uncertainty associated with that process as well as the random effects associated with the use of the turbine meters. Items 3-6 account for the determination of density values at the turbine meter array and test section. The uncertainty components are highly correlated

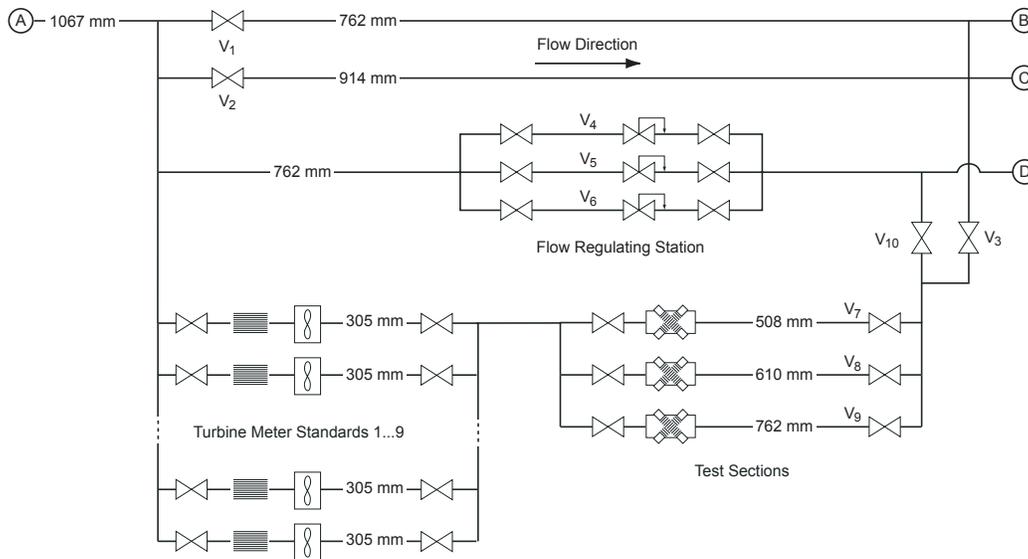


Figure 1: Facility Layout

because the changes in pressure, temperature and composition between turbine array and test section are very small. The result of this correlation is to significantly reduce the uncertainty components identified as Items 3-6 above. Additional details are provided in Ref. 2.

Item 2 in the uncertainty analysis accounts for several effects present in a "typical" ultrasonic meter under test. This component is included in the analysis for two reasons. First, these effects can be readily determined from the control charts, that determination is discussed below. Second, the uncertainty in meter K Factor is more valuable to the customer because it includes the performance of their meter.

Statistical Process Control

The purpose of the check standards is to confirm consistent performance of the calibration facility. The statistical technique applied to quantify the consistency of the check standard meter data is called *statistical process control* (SPC)³. The SPC tool used in the Iowa facility is control charting, the development of that tool is described in this section. As a typical example, the results from the 610 mm (24") ultrasonic meter will be presented. This meter was included in 251 calibrations (4196 data points) between August 2000 and September 2002.

The meter performance is defined by a *K Factor* and *confidence interval*. The K Factor is the difference between meter indications and calibration values for volumetric flowrate. A curve fit relates K Factor and velocity. The 95% confidence interval about the curve

fit is the statistical interval that contains 95% of the data. The interval width is $\pm 2s_{ci}$, where:

$$s_{ci} = (av^b + c)\% \quad [1]$$

and v is velocity [m/s]. Typical data for this meter are shown in Figure 2. The shape of the curve clearly shows two effects that are typical for flowmeter calibration data. The "percent of full scale" effects are represented by av^b while "percent of reading effects" are represented by c .

The process for construction of control charts is now described. A single data point consists of K Factor and velocity values. The residual is the difference between measured K Factor and the *accepted value* which is calculated from the curve fit. The residual, expressed as a percent, is then normalized by s_{ci} . A

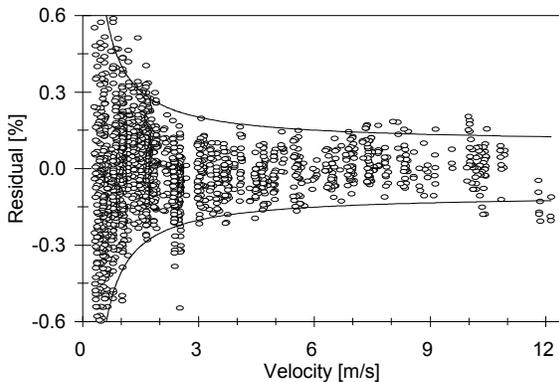


Figure 2: Typical Ultrasonic Meter Data

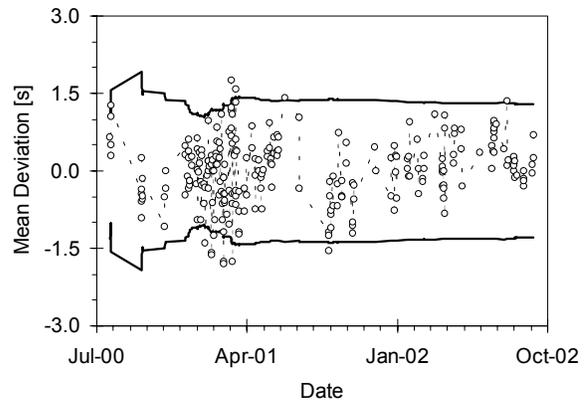


Figure 3: Flowmeter Control Chart

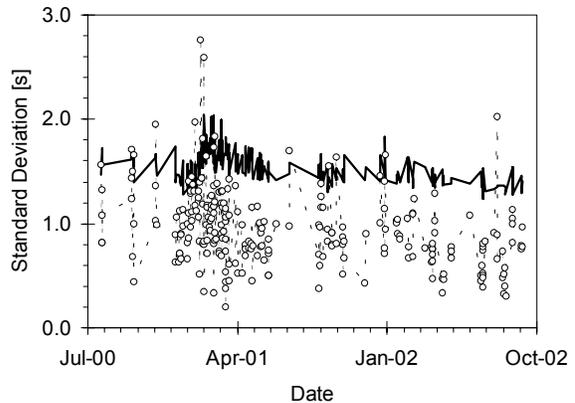


Figure 4: Flowmeter Control Chart

set of data points comprise a single calibration, the exact number varies depending on the calibration objectives. For each calibration the mean (x_i) and standard deviation (s_i) of the data point residuals are calculated, these values are plotted over time to form the two control charts contained in Figures 3 and 4. The circles connected by the dashed lines represent the 251 calibrations.

The solid lines in Fig. 3 represent control limits that lie $\pm L_b$ apart where:

$$L_b = t_{95} s_b \quad [2]$$

and t_{95} is the Student's t statistic for a 95% confidence level. The *between* standard deviation, s_b , is calculated from the accumulated values of x_i . In Fig. 4 the single sided limit is represented by L_w where:

$$L_w = \sqrt{F_{95}} s_w \quad [3]$$

and F_{95} is the F statistic for a 95% confidence level. The *within* standard deviation, s_w , is calculated from:

$$s_w = \sqrt{\frac{\sum n_i s_i^2}{\sum n_i}} \quad [4]$$

where n_i is the number of data points that make up a calibration.

The $\pm L_b$ control limits can be interpreted as representing the confidence interval as it changes over time. At any point in time the interval width contains 95% of the accumulated history of data. Early in the history, the width can change significantly as additional calibrations are obtained. Later in the history the effect of any one calibration is smaller relative to the accumulated data, the interval width changes with time are therefore smaller. The confidence interval allows for monitoring the consistency of the process. If the process remains consistent, data points remain within the confidence interval. A few data points (up to 5%) can lie outside the limits associated with a consistent process because the limits are defined at a 95% level of confidence. If too many data points lie outside the interval some inconsistency may be present.

The single L_w control limit exhibits much of the same behavior as the $\pm L_b$ control limits. The major difference, readily observed in Figs. 3 and 4, is that L_w changes more than L_b . This difference is due in part to F_{95} being a function of n_i while t_{95} is a function of i . It is also a result of the particular measurement process. Many ultrasonic meter calibrations include a six point verification following a 20-30 point calibration. The verification serves to check that the proper curve fit coefficients have been entered into flow meter's control computer. Values for F_{95} range from 2.10 for six points and 1.44 for 32 points, which is responsible for the variations observed in L_w .

The control charts for this meter exhibit very consistent performance for the 25 months of interest. Both charts show a slight trend of process improvement between April 2001 and September 2002 which is highly encouraging. This improvement corresponds to a reduction in uncertainty of approximately 14%. The chart in Fig. 3 shows a trend between September 2001 and May 2002 that seems to have stabilized. If that trend were to continue it would raise concern.

Uncertainty Considerations

The two standard deviations, s_w and s_b , can be interpreted as accounting for short and long term random effects. The *reported* standard deviation, s_r , accounts for both categories of random effects:

$$s_r = \sqrt{s_w^2 + s_b^2} \quad [5]$$

The reported standard deviation represents one component of measurement uncertainty associated with the facility, this interpretation is now described. The control charts of Figs. 3 and 4 account for all of the random effects present during the August 2000 to September 2002 time interval. These effects are contributed by the pressure and temperature instruments and gas chromatograph as well as the turbine meter standards. Also included are the random effects associated with the check standard itself. The traditional approach to uncertainty analysis is to account for the random effects contributed by the various components. The control chart analysis provides independent support to the traditional approach based on a range of historic data to estimate this component of uncertainty.

Control charts for both ultrasonic check meters were initially maintained with values of $a = 0.230$, $b = -0.1$ and $c = 0.7$ in Eq. 1. An analysis performed in April 2001 resulted in $s_b = 0.395$, $s_w = 0.597$, and $s_r = 0.716$ for the 610 mm (24") meter and $s_b = 0.383$, $s_w = 0.615$, and $s_r = 0.725$ for the 508 mm (20") meter. The similarity in s_b and s_w values for the two meters is a good indication of consistent calibration performance. The control charts are intended to operate with control limits at two standard deviations. A value of $s_r = 0.716$ means that the Eq. 1 interval is wider than needed, a value $0.716 \times s_{ci}$ would correspond to one standard deviation. As a result of this analysis the Eq. 1 coefficients were changed to $a = 0.164$, $b = -0.1$ and $c = 0.5$ for both ultrasonic meters. At a velocity of 6.1 m/s (20 ft/s) this corresponds to $s_{ci} = 0.075\%$. This value is assigned to account for the uncertainty due to all random effects present in the calibration process².

Turbine Substitution Testing

A typical control chart involves several flow standards, particularly at the higher flowrates. A slight shift in the performance of one standard can therefore go undetected; the effect of the shift is reduced in proportion to the number of flow standards in use. The turbine substitution test (TST) has been developed to confirm the absence of any turbines meter shifts based on intercomparison testing⁴. The TST data provide a strong complement to the SPC data.

A turbine substitution test is implemented as follows. One of the turbine standards is connected in series with a test artifact and stable flow is established. A minimum of three data points are obtained. Control valves divert the flow through a different turbine standard. Care is taken to avoid changing the flowrate while the meters are switched. After the flow transients have dissipated a second set of data points are obtained. A third turbine meter is substituted for the second and additional data are obtained. This process continues with different standards until a complete set of data have been obtained.

The process of switching standards in and out is the second of two parts of that make up a TST. The first part involves characterizing the performance of a test artifact. Three types of test artifact have been used. The first is the meter under test (MUT) present in nearly all TST. A calibration will have just been completed, these data are used to determine the MUT performance at the flowrate of interest. The second

artifact type is the SPC check standard. These meters have long calibration histories, the performance at the flowrate of interest is determined from the historical data. The third type of meter is a check standard that has a short calibration history. The available calibration data are used to determine the performance. Most of the TST artifacts are turbine or ultrasonic type meters, several TSTs were performed using orifice meters as artifacts. In many cases two artifacts are installed, in some cases there are three.

The TST database currently contains 3834 data points from 43 tests. Tests have been performed on a regular basis since July 1999. The discussion of Ref. 4 includes an analytical technique to determine the uncertainty of the TST process. That technique is based on "Youden plots" created when multiple test artifacts are available. An estimate for the standard uncertainty⁵ of $u = 0.075\%$ has been calculated from 21 Youden plots that have been created thus far.

The results of a TST consist of a series of data points, K Factor and flowrate, that are collected for each turbine standard. The accumulated results for each turbine standard have been used to determine the best possible relationship (curve fit) between K Factor and flowrate. The curve fit residuals, plotted against flowrate, are shown in Figure 5. The plot represents the TST results obtained between January 2000 and October 2001. The solid lines represent an interval that attempts to contain 95% of the data points. The open circles represent 1520 data points that fall within the interval. The plus symbols represent 67 data points that fall outside the interval. The interval width is de-

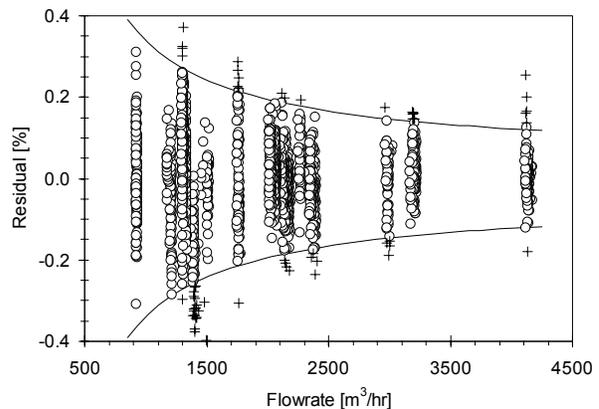


Figure 5: Turbine Substitution Test Results

finned by:

$$\text{width} = \pm(289/Q + 0.04)\% \quad [6]$$

where Q is the flowrate in m³/hr. Equation 6 represents all the random effects present during a typical turbine swap test.

Pressure and Temperature Measurement

Redundant pressure and temperature transducers installed on each turbine meter standard allows for a novel application of SPC. When two transducers are used to measure the same measureand, the random effects associated with the transducers can be determined. If the measureand varies randomly, the transducer output signals will react equally. Varia-

tions in the measureand will cancel out when the difference between the two transducer outputs is calculated, this behavior is called "common mode rejection".

The control charting process begins with the calculation of the difference between transducer outputs. The mean and standard deviation for each calibration are used to form control charts. Typical charts are contained in Figures 6-9. They are based on 1257 calibrations (16,264 data points) obtained between May 2000 and October 2002. The y axes of the charts are expressed as part per million of nominal values. Nominal values are in absolute units (Kelvin, and MPa absolute) as required to calculate density.

The measurement processes charted in Figs. 6-9 are quantified based on standard deviations. For tempera-

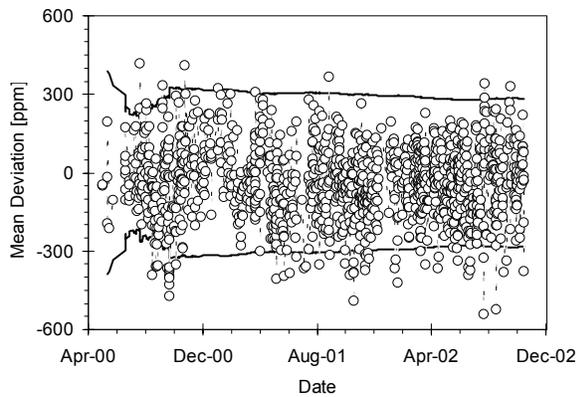


Figure 6: Pressure Control Chart

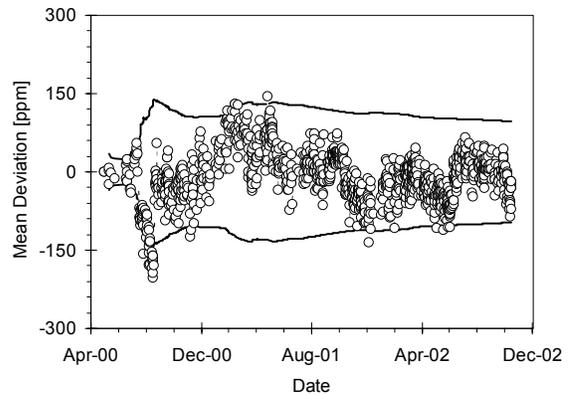


Figure 8: Temperature Control Chart

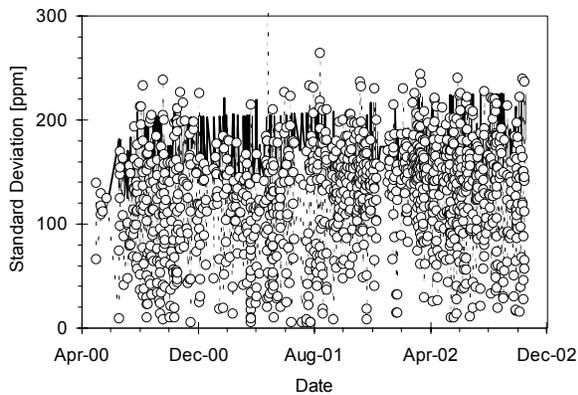


Figure 7: Pressure Control Chart

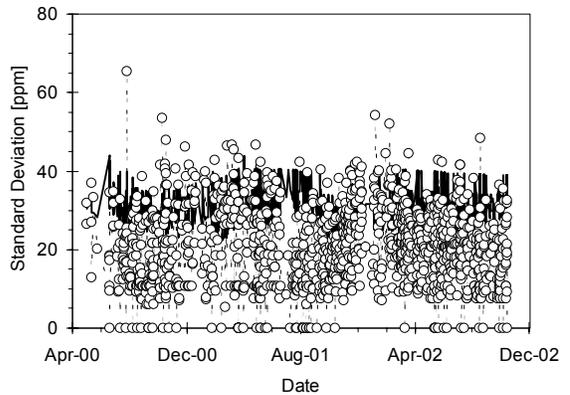


Figure 9: Temperature Control Chart

ture measurement: $s_w = 24.5$ ppm, $s_b = 48.9$ ppm and $s_r = 54.7$ ppm. For pressure measurement: $s_w = 142$ ppm, $s_b = 144$ ppm and $s_r = 202$ ppm. For all of the measurements monitored with control charts the values of s_r range from 121 ppm to 233 ppm for pressure measurements and 52.4 ppm to 72.0 ppm for temperature. In general the control charts indicate that pressure and temperature measurement processes are operating in a state of control. There are some structures present in charts that may have some physical significance, but they are well within the measurement uncertainty.

The pressure transducers are maintained in calibration by an unconventional method. Each morning the transducers that will be used for testing are checked using a pressure calibrator. If a transducer reading differs from the calibrator by more than 1.4 kPa (0.2 psi) then that transducer is adjusted. No adjustments are made if the two instruments agree to within 1.4 kPa (0.2 psi). The temperature transducers are maintained in calibration by conventional means.

There are several comments regarding the pressure transducer calibration process. First, the calibration is "end-to-end" meaning the data acquisition system is included. Second, the long term random effects associated with the transducers and data acquisition system are exchanged for those associated with the calibrator. This likely results in lower uncertainty. The third comment concerns an SPC "rule of thumb" stating that a process operating in a state of statistical control should not be adjusted⁶. Presumably the repeated adjustments will introduce an additional random effect. While the pressure calibration process would seem to violate this rule, the control charts

don't indicate a problem. The data analysis is proceeding with an investigation of this issue.

A final comment concerns correctly interpreting the charts. During a calibration the pressure and temperatures transducers are sampled for 120 seconds. The averaged values from the sampling process make up one data point. Multiple data points make up a calibration. The control charts monitor the consistency of the data points, not the individual samples. The consistency of the individual samples is monitored via a different process. In particular, the samples must be stable within 2 kPa (0.3 psi) and 0.05 °C (0.1 °F).

Gas Chromatograph

A gas chromatograph is located in the 1067 mm (42") pipeline. A calibration is performed once a week that involves comparing the instrument performance to a know standard. The history consists of 52 calibrations, obtained between November 2001 and February 2003.

Some preliminary efforts have been directed towards developing control charts for the chromatograph. The following procedure has been applied to the data. First, the mean and standard deviation of "as found" response factors are calculated for each component. The values are determined from results of the 52 calibrations). Next, normalized residual are calculated for each component of each calibration. Finally, the mean and standard deviations of the normalized residuals are plotted on the control charts. Initial results are contained in Figures 10 and 11.

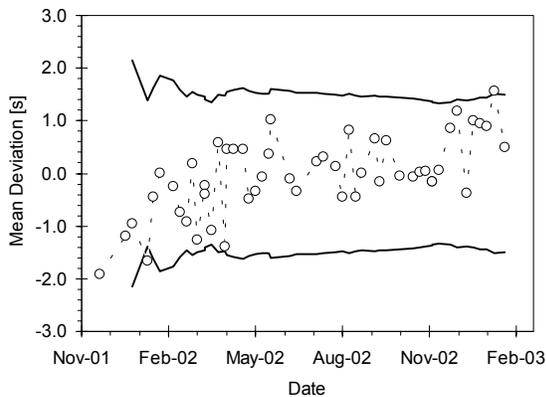


Figure 10: Chromatograph Control Chart

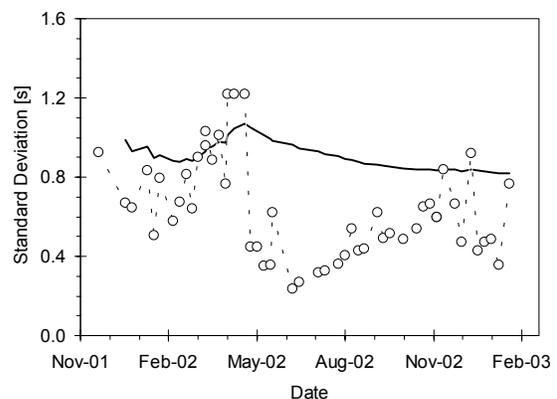


Figure 11: Chromatograph Control Chart

With the exception of the April 2002 data the process is operating in control. A consistent upward trend noted in Fig. 10. The initial slope is attributed to start-up, the chromatograph was installed in November 2001. The cause of final slope is unknown, it may indicate column performance. The post April 2002 Fig. 11 data after also show an upward trend. Such a trend with a flowmeter would indicate an increase in scatter, a random effect. With the chromatograph data it may indicate changes in response between different components, a systematic effects. The response factor for ethane, for example, seems to be changing over time relative to the other components.

The application of SPC to gas chromatography is a new activity at the Iowa facility, as such many questions remain unanswered. Should the results be weighted based on component concentration? What about molecular weight? What is the impact of a 2s shift in C6+ compared to a 2s shift in methane? Or nitrogen? The current analysis only monitors the "as found" results. What is the effect of "as left" results? How much did they change? The relevant issues are similar to those associated with the pressure calibrations. Answering these and other questions remains the objective of ongoing investigation.

Summary

The components of the CEESI Iowa Measurement Assurance Program (MAP) have been described in detail. These components include:

1. A set of flowmeter check standards used to monitor the consistency of the entire calibration process.
2. A turbine substitution test program that confirms the absence of turbine standard shifts.
3. A method to monitor the consistency of pressure and temperature measurements.
4. An initial attempt to develop a method to monitor the consistency of the gas composition measurement.

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