Reconciliation of Liquid Pipeline Quantities

API STANDARD 2560
FIRST EDITION, DECEMBER 2003

REAFFIRMED, JANUARY 2010

energy **API**®

AMERICAN PETROLEUM INSTITUTE

Reconciliation of Liquid Pipeline Quantities

Measurement Coordination

API STANDARD 2560
FIRST EDITION, DECEMBER 2003

REAFFIRMED, JANUARY 2010

energy **API**®

AMERICAN PETROLEUM INSTITUTE

SPECIAL NOTES

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

API is not undertaking to meet the duties of employers, manufacturers, or suppliers to warn and properly train and equip their employees, and others exposed, concerning health and safety risks and precautions, nor undertaking their obligations under local, state, or federal laws.

Information concerning safety and health risks and proper precautions with respect to particular materials and conditions should be obtained from the employer, the manufacturer or supplier of that material, or the material safety data sheet.

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. Sometimes a one-time extension of up to two years will be added to this review cycle. This publication will no longer be in effect five years after its publication date as an operative API standard or, where an extension has been granted, upon republication. Status of the publication can be ascertained from the API Standards department telephone (202) 682-8000. A catalog of API publications, programs and services is published annually and updated biannually by API, and available through Global Engineering Documents, 15 Inverness Way East, M/S C303B, Englewood, CO 80112-5776.

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this standard or comments and questions concerning the procedures under which this standard was developed should be directed in writing to the Director of the Standards department, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005. Requests for permission to reproduce or translate all or any part of the material published herein should be addressed to the Director, Business Services.

API standards are published to facilitate the broad availability of proven, sound engineering and operating practices. These standards are not intended to obviate the need for applying sound engineering judgment regarding when and where these standards should be utilized. The formulation and publication of API standards is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

FOREWORD

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any federal, state, or municipal regulation with which this publication may conflict.

Suggested revisions are invited and should be submitted to API, Standards department, 1220 L Street, NW, Washington, DC 20005.

CONTENTS

CONTENTS

Reconciliation of Liquid Pipeline Quantities

1   Introduction

1.1   In the ideal world every drop of liquid received into a pipeline system and every drop delivered out of the system, as well as all liquid inventory within the system, would be measured and accounted for precisely, and a comparison of all receipts and all deliveries—adjusted for inventory changes—would be exactly the same. The system would never experience a loss or a gain. Unfortunately, this ideal pipeline balance seldom exists in the real world.

1.2   Most pipeline systems typically experience some degree of loss or gain over time. This represents the normal loss/gain performance for a system. From time to time, losses or gains greater than normal may occur for a variety of reasons. Excessive or unexplained loss/gain often leads to contention between participating parties, sometimes requiring monetary settlements to adjust for abnormal loss/gain. In such cases, it is necessary to be able to (1) identify abnormal loss/gain as quickly as possible, (2) determine the magnitude of abnormal loss/gain, and (3) institute corrective actions.

1.3   Sometimes losses or gains are real, and adjustments must be made to correct shipper batches and/or inventories. Most of the time, though, there are no real physical losses or gains. The loss/gain that occurs in day-to-day operation is usually small (a fraction of a percent) and is caused by small imperfections in a number of measurements in a system.

1.4   In a sense, loss/gain is a measure of the ability to measure within a system. Loss/gain should be monitored for any given system at regular intervals to establish what is normal for that system and to identify any abnormal loss/gain so that corrective action can be taken.

2   Scope

2.1   This publication provides methodologies for monitoring liquid pipeline loss/gain, and for determining the normal loss/gain level for any given pipeline system. Troubleshooting suggestions are also presented.

2.2   This document does not establish industry standards for loss/gain level because each system is an individual and exhibits its own loss/gain level and/or patterns under normal operating conditions.

2.3   The document provides operational and statistically based tools for identifying when a system has deviated from normal, the magnitude of the deviation, and guidelines for identifying the causes of deviation from normal.

3   Field of Application

3.1   The primary application of this publication is in custody transfer liquid pipeline systems in which there is provision for measuring all liquids that enter the system, exit the system and liquid inventory within the system. The application is not intended for non-liquid or mixed phase systems.

3.2   The applications and examples in this document are intended primarily for custody transfer pipeline systems, but the principles may be applied to any system which involves the measurement of liquids into and out of the system and possibly inventory of liquids within the system.

4   Reference Publications

API *Manual of Petroleum Measurement Standards*

Chapter 2	"Tank Calibration"
Chapter 4.8	"Operation of Proving Systems"
Chapter 12.1	"Upright Cylindrical Tanks and Marine Vessels"
Chapter 12.2	"Calculation of Liquid Petroleum Quantities Measured by Turbine or Displacement Meters"
Chapter 12.3	"Calculation of Volumetric Shrinkage From Blending Light Hydrocarbons with Crude Oil"
Chapter 13.1	"Statistical Concepts and Procedures in Measurement"
Chapter 13.2	"Statistical Methods of Evaluating Meter Proving Data"

5   Definitions

For the purposes of this document these specific definitions apply.

5.1   action limits: Control limits applied to a control chart or log to indicate when action is necessary to inspect or calibrate equipment and possibly issue a correction ticket. Action limits are normally based on 95 percent to 99 percent confidence levels for statistical uncertainty analyses of the group of measurements.

5.2   control chart—fixed limit: A control chart whose control limits are based on adopted fixed values. Historically, fixed limits have been used to control the limits on meter factor changes.

5.3   control chart—loss/gain: a graphical method for evaluating whether loss/gain and/or meter proving operations are in or out of a "state of statistical control."

5.4 control chart: A graphical method for evaluating whether meter proving operations are in or out of a state of statistical control.

5.5 control limits: Are limits applied to a control chart or log to indicate the need for action and/or whether or not data is in a state of statistical control. Several control limits can be applied to a single control chart or log to determine when various levels of action are warranted. Terms used to describe various control limits are "warning," "action," and "tolerance" limits.

5.6 mean or central value: The average or standard value of the data being plotted on a control chart, and is the reference value from which control limits are determined.

5.7 standard deviation: The root mean square deviation of the observed value from the average. It is a measure of how much the data differ from the mean value of all the data. Standard deviation can also be a measure of confidence level.

Note: For further information concerning the application of Standard Deviation, reference API *MPMS* Chapters 13.1 and 13.2

5.8 statistical control: The data on a control chart are in a state of statistical control if the data hover in a random fashion about a central mean value, and at least 99% of the data are within the three standard deviation control limits, and the data do not exhibit any trends with time.

5.9 tolerance limits: Control limits that define the extremes or conformance boundaries for variations to indicate when an audit or technical review of the facility design, operating variables and/or computations may need to be conducted to determine sources of errors and changes which may be required to reduce variations. Tolerance limits are normally based on 99% or greater confidence levels, and are used interchangeably with Upper and Lower Control Limits.

5.10 upper and lower control limits: Synonymous with tolerance limits.

5.11 warning limits: Control limits applied to a control chart to indicate when equipment, operating conditions or computations should be checked because one or more data points were outside pre-established limits. Warning limits are normally based on 90 to 95 percent confidence levels.

6 Loss/Gain Analysis

Loss/Gain (L/G) is the difference between deliveries and receipts, adjusted for changes in inventory, experienced by a system over a given time period (e.g., day, week, month). Losses may be real (e.g., leaks, evaporation, theft, etc.). Gains may occur if unmeasured liquid is added to the system - higher than actual receipts or lower than actual deliveries. More often, there is no actual physical loss or gain, just simply small measurement inaccuracies or accounting discrepancies. The combination of these small measurement inaccuracies may result in a system being outside of normal or acceptable limits.

Loss/gain analysis typically involves collecting data, calculating loss/gain, and plotting loss/gain on any of several different types of charts. These charts may include control limits or other analytical guides which are derived from some simple statistical tools. The tools described in this document may be used by anyone and do not require an understanding of statistics.

The terms over/short and imbalance are sometimes used interchangeably with loss/gain.

6.1 LOSS/GAIN EQUATIONS

6.1.1 The two basic Loss/Gain equations are shown below. One expresses a loss as a negative value and the other expresses the loss as a positive value.

6.1.2 It is important to keep in mind which convention is being used in order to correctly decide whether the L/G values represent losses or gains.

Loss expressed as a Negative Number

$$L/G = (CI + D) - (BI + R) \qquad (1)$$

Loss expressed as a Positive Number

$$L/G = (BI + R) - (CI + D) \qquad (2)$$

In which:

CI = Closing inventory in the system at the end of the time period,

D = Deliveries out of the system during the time period,

BI = Beginning inventory in the system at the start of the period,

R = Receipts into the system during the time period,

L/G may be reported in units of volume or mass (e.g., bbls or lbs).

When expressed in percent the actual L/G quantity is divided by the quantity of total receipts for a receipt-based system or by the quantity of total deliveries for a delivery-based system and multiplied by 100.

Note: In the equations above, variables must be expressed in like units of measure. Variables calculated under the same conditions (e.g *GSV/NSV* volumes, standard temperature and pressure) will yield the most meaningful information. (Reference *MPMS* Chapter 12.)

6.2 PRESENTATION OF DATA

6.2.1 Data may be presented in the form of Control Charts, Trending Charts or Cumulative Charts. Guidelines on such charts may include control limits and trending lines.

6.2.2 Charts used for monitoring pipeline systems should be living documents and should be updated whenever new data are available. Accumulating data for some period of time and periodically updating charts (say, semiannually) serves no useful purpose. Charts and monitoring procedures can be effective only if charts are current and used as constructive tools.

6.3 CONTROL CHARTS

6.3.1 Good measurement can be assured by continuously monitoring measurement results to determine if systems, or equipment and procedures, are performing in predictable ways and are operating within acceptable limits. This may be done by the use of Control Charts.

6.3.2 Control charts display a collection of data over some period of time and include control limits shown as horizontal lines on the charts. Control limits help define normal and abnormal system performance, and may indicate when something in the system has changed and/or corrective action(s) may be required.

6.3.3 Control limits are often determined by historical performance of the system. In other cases the control limits are set on an established arbitrary value, e.g., contractual limits. Control charts are the most common method of ascertaining system loss/gain performance. Control charts display a collection of data over some period of time and include the control limits. Control charts help to define normal trends of a system and may indicate when something has changed. Typical loss/gain charts as shown in Figure 1, indicate a system's performance based on a percentage of throughputs over time. Typically, because accounting systems encompass a 30-day period, monthly evaluations of a system are commonly used to evaluate performance. Control charts may be prepared for any time span (e.g., weekly or daily) if adequate data are available.

6.3.4 Control charts may be maintained for entire systems, or for individual segments of a system if adequate measurement and records are available at the junctures of segments.

6.3.5 The data on control charts tend to hover around a central (mean) value, which is the arithmetic average of the data and can be represented by a horizontal line on the chart. The control chart also includes upper and lower control limits (*UCL* and *LCL*) which may be (1) defined as engineering limits which are values based on experience or performance objectives, or (2) defined statistically as three standard deviations (σ) above and below the mean. Standard Deviation is a statistical measure of the spread of a data set with respect to

the mean value of the set. Procedures for calculating statistical quantities are shown in Appendix A.
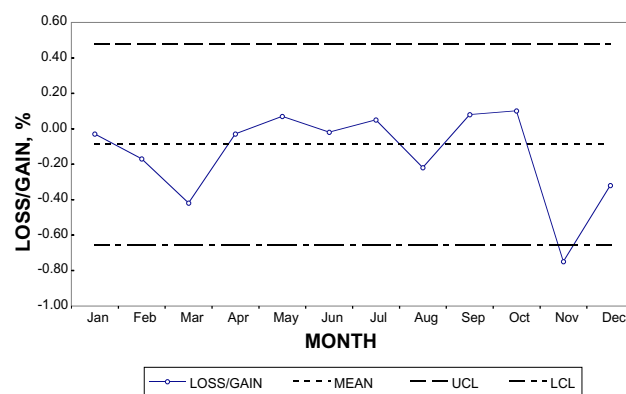
Figure 1 shows a typical control chart.

Figure 1—Sample Control Chart

6.3.6 The data must be representative of the normal performance of the system, as the control limits will be used to predict near future performance. Any data point which is known to be the result of a special cause should be shown on the control chart but should not be included in the calculation of mean, standard deviation or control limits; and the number of data points must be adjusted accordingly. A special cause is an event (e.g., meter failure, late run ticket, line displacement with water for hydrostatic pressure test, etc.) which results in mis-measurement for a given period of time, but is not a part of the normal operation of the system.

6.3.7 Charts can be used to determine system stability, cyclical trends, or step changes in performance. One of the most important benefits of using charts to assess performance is the instant visual representation it provides. The adage, "a picture paints a thousand words," best summarizes the effectiveness of control charting.

6.4 PIPELINE SYSTEM CONTROL CHARTS

6.4.1 A useful tool for monitoring pipeline systems is the control chart which shows loss/gain as percent of throughput over time. Total receipts are used for throughput in receipt-based systems, and total deliveries are used for delivery-based systems.

6.4.2 Strictly speaking, for control limits to be statistically significant, a minimum of 30 data points is required. For practical purposes, control limits for a pipeline system which is monitored monthly will often be based on monthly *L/G* data. For our purposes, the 24 data points are acceptable. It is common practice to set limits at the beginning of each calendar year based on the prior history. These limits are carried

forward for the calendar year unless there is a change in the process that would require new limits.

Figure 2 shows the *L/G* data for 2 years. That data will be used to set control limits for the following year.
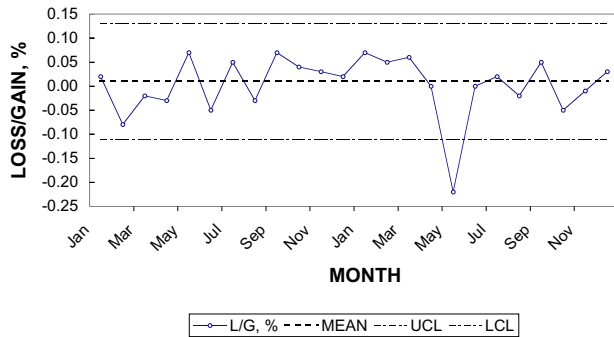

Figure 2—Two Years of Data for Control Limits

Figure 3 shows the first 3 months data compared with the 2-year historical control limits.
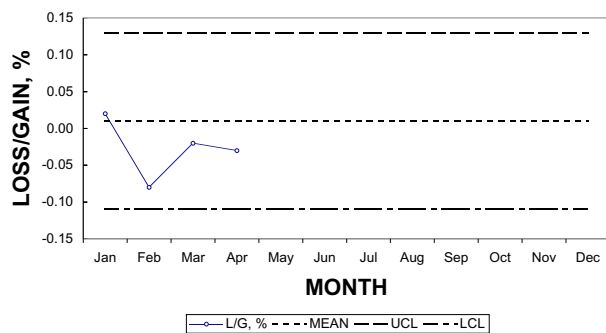

Figure 3—Control Chart for the Following Year

6.4.3   Setting fixed limits for *L/G*, without regard to actual data may provide performance guides which may be required for contractual reasons. Whenever possible, it is more practical to set limits based on historical data. A pipeline system tends to operate at a level of performance which is dictated by physical configuration, equipment, procedures, maintenance practices, environmental conditions, and employee training. All of these factors combine to produce a natural randomness and, sometimes, a natural bias in a system. For systems which have other constraints, such as loss allowance, it may be desirable to include a second set of limits set at the value of the loss allowance. This would indicate how the system is performing with respect to the loss allowance, and if the assigned loss allowance is realistic.

6.4.4   It is good practice to determine whether or not a system is stable and in control. A system is generally considered to be in control if the data are all within control limits which

have been established from the data. Data points outside the control range indicate poor control. A system is said to be stable if the data exhibit only random fluctuations around the mean without trends.

6.4.5   When physical or operational changes are made to a system, the loss/gain pattern for the system will often change. When this happens, the prior two-year's history may not be suitable for setting the control limits. In such cases, a moving range chart may be used until sufficient history is developed to define the system's new pattern. In a moving range chart, the mean and standard deviation are recalculated each time new data are available using all data since the change. The resulting mean and control limit lines on the control chart may exhibit an immediate step change to a new level of control or may change gradually for some period of time until the system stabilizes at a new level of control.

6.4.6   As an example, Figure 4 shows three distinct patterns which may be found on control charts. The points 1 through 7 exhibit random fluctuations around the mean and are well within the control limits. This portion of the data is stable and in control. The points 7 through 12 are within the control limits and appear to fluctuate randomly, but are all above the mean. This is a state of stability but not in control because the data do not hover around the mean. In fact, it would appear that the system has attained a new state of control which is centered about a higher mean value. The points 11 through 16 are neither stable nor in control because they are in a definite downward trend. The data do not center around a mean and appear to be headed off the chart.
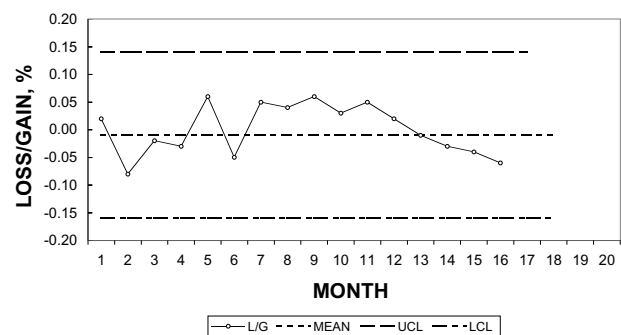
Figure 4—Control Chart With Three Patterns

6.4.7   As a rule, five consecutive points above or below the mean indicate a loss of control or a change to a new level of performance. Five consecutive points trending in one direction (up or down) indicate a loss of control. For some systems, even fewer points in a row may be significant warning. Examples might be leaking tanks (in which case the losses are real) or meters which are wearing badly and are not being proved often enough (which are book losses).

6.4.8 An upward trend is no better than a downward trend. Either condition is out of control. A system gain can be just as bad as a system loss. Losses and gains occur because of some deficiency in measurement.

6.4.9 If the data tend to swing back and forth as shown on Figure 5, the system is cyclic. If the cause of the cycles could be eliminated, the system should be able to achieve a state of better control with narrower control limits.

Figure 5—Control Chart with Cyclic Patterns

6.4.10 A system may be stable and in control, but not acceptable if the mean differs significantly from zero. For example, a system which has a average loss of -0.25% loses 0.25% consistently. Similarly, a wide span between UCL and LCL may indicate instability in the system and may not be acceptable performance.
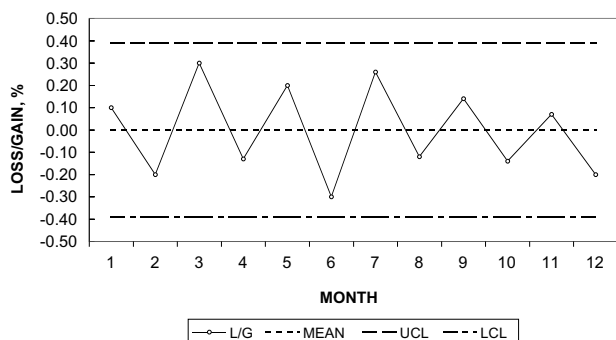
6.4.11 The performance of a system may change due to deliberate process changes, such as better equipment or improved procedures. Sometimes, though, a system will change without any apparent reason. Any process change, be it deliberate or unplanned, will usually show up as a change in performance.

6.4.12 Whenever the data clearly show a change, the mean and control limits should be changed accordingly as shown on Figure 6.
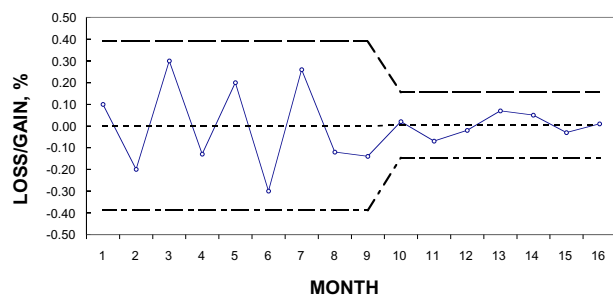

Figure 6—Control Chart with a Change in the Process

6.4.13 Any data point which falls outside the control limits is the result of a special cause (e.g., equipment failure, procedural error, etc.) and should be investigated immediately to determine the cause. Special causes often lead to correction tickets, and should be investigated as soon as possible before the data becomes dated and the investigation becomes difficult.

6.5 METER FACTOR CONTROL CHARTS

6.5.1 Control charts can be used for tracking various things. Meter factors are an example.

6.5.2 Control charts may also be used to monitor meter performance, in which case meter factor is plotted as a function of either time or volume throughput.

6.5.3 It may not be practical to accumulate 24 meter factor data points for meters before setting control limits, because changes in operating conditions (e.g., different grades of crude liquids or products, different flow rates, etc.) or normal meter wear may cause meter factor to change enough to invalidate control limits before achieving 24 provings.

6.5.4 Thus, when plotting meter factor control charts it may be more representative to use a moving range chart in which control limits are reset more often. Typical examples for meter factor control charts include resetting after every five or ten provings. In these cases, the conventional standard deviation calculated by the equation in Appendix A cannot be used. Instead, control limits and an "estimated standard deviation" are based on the ranges (differences) between contiguous meter factors.

6.5.5 Figure 7 is an example of a moving range chart for which control limits are reset after every five meter provings.
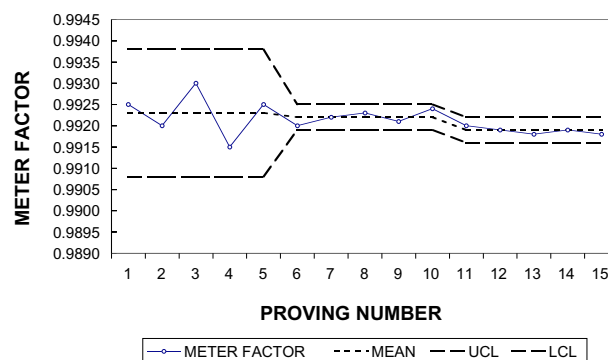

Figure 7—Moving Range Chart

6.5.6   Meter factors usually behave in a predictable way. If operating conditions are essentially constant and wear is not excessive, meter factors may be plotted on conventional control charts with warning, action and tolerance limits. However, if meters are subject to variable operating conditions and/or liquids with different physical properties, their control charts will exhibit enough natural variation to dilute the value of warning and action limits.

6.5.7   Meter factor patterns on control charts should be reviewed to determine if a meter (1) is about to go out of tolerance or (2) is developing an abnormal pattern or trend. If either of these occurs, the meter should be inspected for wear or damage. Some companies set a fixed meter factor tolerance for mandating meter repair.

6.5.8   For multi-functional meters, interpretation of control charts is not straight forward. The patterns on the charts are composites of several sub-patterns which are dictated by flow rate, temperature, pressure and liquid properties. Insofar as possible, the data for such meters should be broken into separate plots of meter factor segregated by one variable, such as liquid type, with other conditions being as nearly constant as possible.

6.5.9   Even when charts are broken out by crude type, conventional control charts may not be adequate, because in order to get enough data with one crude type, it may be necessary to accumulate single meter factors or small groups of meter factors for a given crude which are separated from each other by significant lengths of time. As a result, each subsequent factor or group of factors may be affected by meter use and wear between factors. This leads to a trending situation, and trending charts may be required to depict the data.

6.6   TRENDING CHARTS

6.6.1   Trending charts may be used when data exhibit a definite upward or downward trend and do not hover around a simple horizontal mean value. Such charts may be shown as a trending run chart merely to show a trend in the data, or may resemble a control chart with lines representing average performance (similar to "mean") and control limits that follow the upward or downward trend of the data.

6.6.2   Meter factor charts are often trending charts, as meter factors generally tend to increase in a regular fashion with time due to wear in a meter.

6.6.3   An example of a trending control chart is shown on Figure 8.
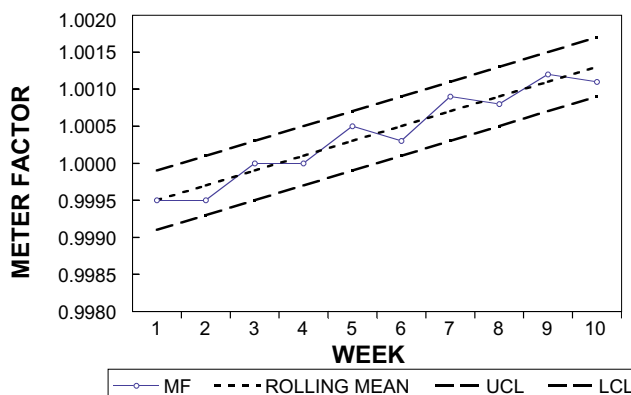
Figure 8—Trending Control Chart

6.6.4   Mean and control limit values cannot be represented by fixed-value horizontal lines on a trending control chart since the normal trend of data would soon move past the control limits. With a normal meter factor control chart, this would signal a need for some sort of action. However, with a trending chart, the system may be quite all right and the data are simply following a normal trend. Hence, mean and control limits must be calculated in a different fashion. This can be done with a mathematical procedure called "linear regression." Many computer spreadsheet programs and some types of hand-held calculators (e.g., "Scientific", "Engineering", "Statistical", etc.) have linear regression programs and can be used simply by keying in the data. A method for hand-calculating a linear regression by the "Least Squares" method is given in the Appendix A.

Linear regression yields an equation of the form:

$$y = a + bx \tag{3}$$

In which y is the dependent variable (e.g., meter factor), "a" is a constant (called the zero intercept), "b" is a constant (called the X coefficient), and x is the independent variable (e.g., month, proving sequence, etc.).

The values of "a" and "b" are derived from the data set and are unique to the particular data set.

The mean and control limits of trending data are represented by equations rather than fixed values.

Note: For linear regression to work, values for x must be numeric. That is, months must be 1, 2, 3, etc., not January, February, March, etc..).

6.7 CROSS PLOTS

6.7.1 A cross plot is a way of illustrating how one variable changes as another variable changes. In particular, cross plots between meter factor and each operating variable can contribute to a better understanding of meters and their reactions to different variables. For example, Figure 9 shows a marked increase in meter factor during the last two months.
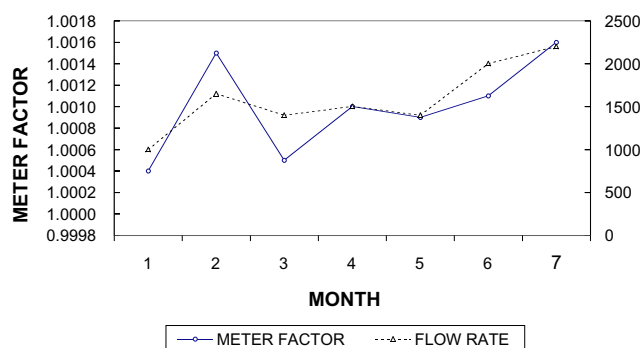

Figure 9—Simultaneous Variations in Meter Factor and Flow Rate

6.7.2 Note that flow rates plotted on the same figure also increased markedly. A cross plot of meter factor vs. flow rate on Figure 10 shows that the meter factor increases are due to flow rate increases. This chart may be inspected to determine if the new meter factor appears to be reasonable based on flow rate.
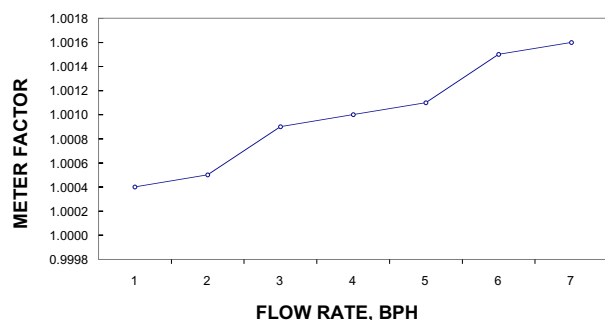

Figure 10—Cross Plot of Meter Factor vs. Flow Rate

6.7.3 A line representing the trending mean of the data can be constructed on a trending control chart by calculating the regression equation from the data, calculating the end points of the trending mean line from the regression equation, plotting those points on the chart and connecting them with a straight line.

6.7.4 Lines representing control limits may be constructed by calculating end points for UCL and LCL as $m \pm 3\sigma$, plotting those points on the chart and connecting the end points with straight lines. However, standard deviation (σ) cannot be

calculated in the conventional way. The term (y-m) in the equation for standard deviation must be calculated point-by-point using the value of m which corresponds to each X value.

6.7.5 Sometimes it is helpful to know how much two variables interact with each other. One variable is the "independent variable" and the other is the "dependent variable". The value of the dependent variable depends on the value of the independent variable. In other words, the dependent variable will change every time the independent variable changes. If the dependent variable is changed by some other influence, the independent variable will not change as a result. For example, a meter factor can be changed by changing flow rate, but flow rate cannot be changed by changing meter factor.

6.7.6 The relationship between two variables is called the "correlation" and may be "strong", in which case the dependent variable changes in a very predictable manner with changes in the independent variable, or may be "weak", in which case the dependent variable tends to change with the independent variable but the amount of change is not predictable.

6.7.7 The strength of the correlation can be measured statistically with the "correlation coefficient": The procedure for calculating the correlation coefficient is shown in Appendix A.

6.7.8 It should be noted that even though a strong correlation exists, if the slope of the associated regression line is very flat the correlation is relatively insignificant.

6.8 CUMULATIVE CHARTS

6.8.1 Cumulative charts are similar to trending charts but plot the cumulative values of some variable such as, L/G vs. time. The cumulative value is obtained by arithmetically (i.e., keeping the plus and minus signs) adding the value of each data point to the sum of all the data points preceding it in a sequence of data.

6.8.2 The data in cumulative charts do not hover around a central mean value. They exhibit an upward or downward trend. The shape of the curve is the main characteristic of cumulative charts, and changes in shape or general trend are very important.

6.8.3 L/G data may be plotted as cumulative barrels or cumulative percent. Examples are shown on Figure 11. In these examples, the quantities are measured in barrels, but other volume or mass quantities may be used as appropriate.

6.8.4 Cumulative L/G charts can be informative to the practiced eye. They often indicate the onset of a trend before it is evident on a conventional control chart. A system which is performing normally will generally exhibit a steady trend. A sudden shift in the pattern or a definite change in the rate of trend (change in general slope of the data) usually indicates that something abnormal happened.
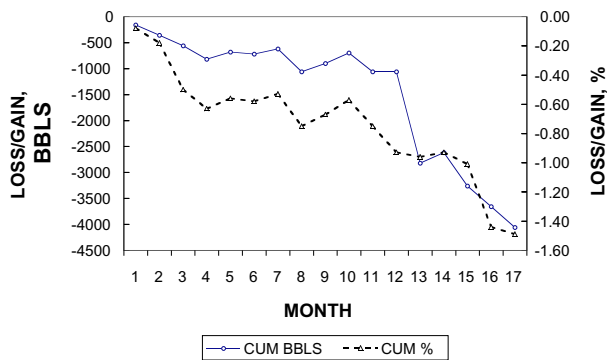
Figure 11—Cumulative Plots

6.8.5 The cumulative chart can also be useful for visually demonstrating the quality of *S&W* (sediment and water) measurement in a crude liquid system by plotting *GSV* (gross standard volume) and *NSV* (net standard volume) on the same chart as shown on Figure 12. On this chart the first eight months are typical of a system with consistent *S&W* measurement. The *NSV* line may be a bit below the *GSV*. However, if the two lines are close together and essentially parallel, *S&W* measurement is consistent and uniform. If, on the other hand, the two lines diverge, as shown during the last eight months on Figure 12, *S&W* measurement is not consistent and/or is not uniform. This could signal an opportunity to improve *S&W* measurement in the system.
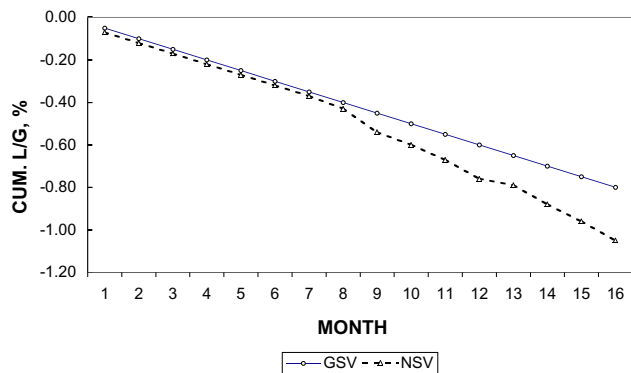

Figure 12—Cumulative *GSV* & *NSV*

6.8.6 If the *NSV* and *GSV* lines on a cumulative chart are parallel and close together the *S&W* measurement is probably about as good as can be achieved. If the two lines are parallel but the spread between them is large the *S&W* measurement is consistent but probably could be improved. *S&W* content is the composite of sampling equipment type and installation, frequency of sampling, stream mixing ahead of the sampler, withdrawing the laboratory portion of sample from the field sample container, maintaining the integrity of the sample between the field and the laboratory, handling and remixing in the laboratory and the *S&W* measurement process. Inexact-

itude in any part of the chain of events will lead to an erroneous answer. Individual companies may set acceptable tolerances based on experience for use in their operations.

6.8.7 The cumulative chart is an easy way to estimate the amount of liquid lost if there is an actual leak, lost to another system, or spill. For this purpose, the cumulative plot of volume is most convenient. An example is shown in Figure 13. The data before the loss, which in this example occurred about the seventh month, are used to develop a regression line which represents the typical behavior of the curve before the leak. The regression line is used to project what the system *L/G* would have been if the leak had not happened. In this example the leak was found and repaired in the eleventh month, and the accumulated loss by that time is 790 barrels. If no liquid had been physically lost, the projected cumulative *L/G* would have been 640 barrels as estimated from the projected regression line. The difference of 150 barrels is the estimated loss due to the leak.
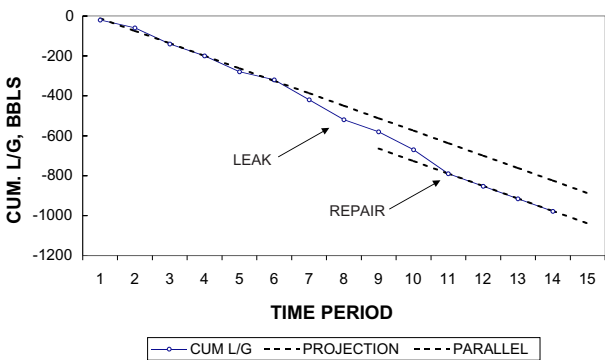
Figure 13—System with a Leak

6.9 TWO TYPES OF CUMULATIVE PERCENT

6.9.1 There are two ways to calculate cumulative percent. One is the cumulative sum. The other is the moving sum, which is often used to report year-to-date (YTD) data.

6.9.2 In the cumulative sum method, each value of *L/G* percent is added to the sum of all the preceding values of *L/G* percent.

For example:

Table 3—Example of Cumulative Sum

Month	Receipts M Bbls	L/G		
		Bbls	%	Cum. %
1	100	100	0.100	0.100
2	120	150	0.125	0.225
3	110	120	0.109	0.334
4	100	110	0.110	0.444

6.9.3 In the moving sum method, for each time period (1) the value of throughput bbls is added to the sum of all the preceding values of throughput bbls, (2) each value of *L/G* bbls is added to the sum of all the preceding values of *L/G* bbls, and (3) each *L/G* bbl sum is divided by the corresponding throughput bbl sum and converted to percent.

For Example:

Table 4—Example of Moving Sum

Month	Receipts M Bbls	Cum. Rcpts. M Bbls	L/G Bbls	Cum. L/G Bbls	Moving Cum. %
1	100	100	100	100	0.100
2	120	220	150	250	0.114
3	110	330	120	370	0.112
4	100	430	110	480	0.112

6.9.4 Examples of cumulative sum and moving sum (YTD) are plotted on Figure 14. Note how the moving sum tends to flatten the curve. This is because the cumulative *L/G* bbls are divided by an ever-increasing cumulative throughput. The moving sum is a useful tool for some purposes (such as comparing YTD *L/G* with prior years *L/G*), but it is not particularly useful for evaluating system performance. Therefore, the cumulative sum is preferred when L/G data are plotted as percent.

Figure 14—Types of Cumulative Percent

7   Troubleshooting

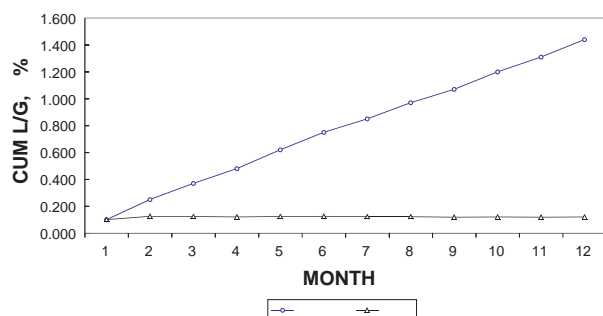One of the challenges of today's pipeline measurement personnel is troubleshooting pipeline losses and gains. Whenever losses or gains exceed established limits, an investigation should be initiated to determine the cause and whether or not adjustments are required to bring a system into balance.

Troubleshooting pipeline losses involves an understanding of the loss/gain process, and may require collecting and analyzing data, interviewing personnel, and visiting facilities to assess equipment performance and witness measurement activities. Ultimately, loss investigations should include a conclusion of the findings along with recommendations for correction and improvements.

7.1   THE TROUBLESHOOTING PROCESS REFERENCE APPENDIX B

Investigating pipeline losses can often be challenging if not frustrating. It is not uncommon for the process to take as long to resolve as it does for losses to appear. With a keen eye for detail some losses can be resolved in minutes, whereas some may take weeks, months, or even longer.

7.1.1   Analyzing measurement data

The first step in identifying losses involves a review of the measurement data. A loss/gain report is usually the red flag that signals that a system is out of control. Start by carefully reviewing the report and insure that input data were accurate and timely. Computer generated reports are only as good as the data entered. It is important to first understand the data entry process and then the integrity of the data used to populate the report.

7.1.2   Looking for the Obvious

Custody measurement records such as tickets, proving reports, and meter performance logs can be obtained and reviewed from the office environment. Reviewing measurement calculations are an easy way to check for measurement error. Often, human error, equipment failure, or software glitches can quickly be identified.

Reviewing records and historical data is of key importance. Look for patterns, often hidden among the noise caused by large month-to-month variations. Are step changes linked to operational changes at the facility? There are many possible operational changes that can affect reported losses. Areas of change to investigate are:

- Personnel
- Procedures
- Facilities
- Equipment
- Calibration of equipment
- Piping
- Computers/Calculations
- Security
- Missing Data (e.g., run tickets)

7.1.3   Interviewing Personnel

The best method of identifying change is by interviewing the personnel responsible for the system(s). This includes the measurement technician, gauger, or operator as well as the electrical and mechanical technicians performing work at the sites. Supervisors who may have information pertinent to the entire process should also be consulted. The key to obtaining

useful information from field personnel is to establish a dialogue which is non-confrontational. Sharing ownership of the problem as well as the credit for the resolution is often the best approach.

7.1.4 Reviewing the facility

Another step in the process involves a visit to the facilities to review the equipment and the measurement procedures. Determine if the proper procedures are being followed in accordance with company and industry guidelines. Observe piping details, equipment placement, and other visual records that may be indicators to or influence the measurement performance. Also, it is very important to be able to discuss the facility and its operation with the measurement personnel who conduct day-to-day activities. They usually know the facility much better than the investigator and can often provide a detailed history of changes for a facility.

7.2 INACCURACIES AND UNCERTAINTIES

Many everyday things can cause inaccuracy or uncertainty in measurement and, thereby, contribute to losses and gains in a system.

7.2.1 Meters

7.2.1.1 Meter factor is sensitive to almost every operating condition. Changes in flow rate, temperature, pressure and density (API gravity) can cause measurable changes in meter factor. Cross plots can be helpful in determining changes in variables that could signal the need for reproving a meter .

7.2.1.2 Meter factor may be very sensitive to changes in flow rate if the meter is operating outside the linear range.

7.2.1.3 The right meter must be used for the right job. For example, using conventional turbine meters in high viscosity liquids usually is not good practice.

7.2.1.4 Wrong meter factors are a common source of error. For example, using a gasoline meter factor on diesel liquid can cause an error on the order of three percent.

7.2.1.5 Start-stop operation of meters with very short run times may introduce errors, because slippage is often greater at start up.

7.2.1.6 Leaking valves in manifolds can permit liquid to bypass a meter, or permit liquid to enter or exit a system without being accounted for.

7.2.2 Meter Proving

7.2.2.1 Good meter proving requires stable conditions. However, it is possible to have five consecutive proving runs which are within 0.05% while the system is still stabilizing. The average of those five runs may not be the true meter fac-

tor. For example, Figure 15 shows five sequential proving runs which are within 0.05% repeatability, but exhibit a slight upward trend. If the data were not plotted, the upward trend may not have been noticed, and the meter factor calculated on the basis of those five runs.
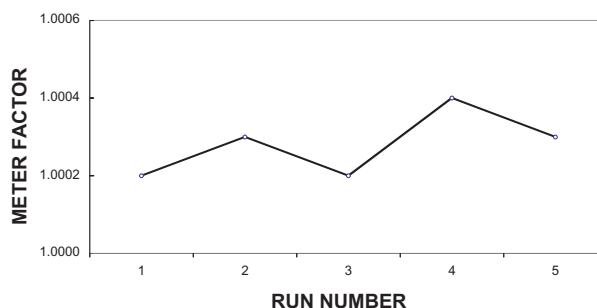
Figure 15—Initial Meter Proving

7.2.2.2 Figure 16 shows what happened when additional proving runs were made. The system finally stabilized, and the meter factor based on the last five stable runs is somewhat higher than the meter factor which would have been calculated based on the first five runs.
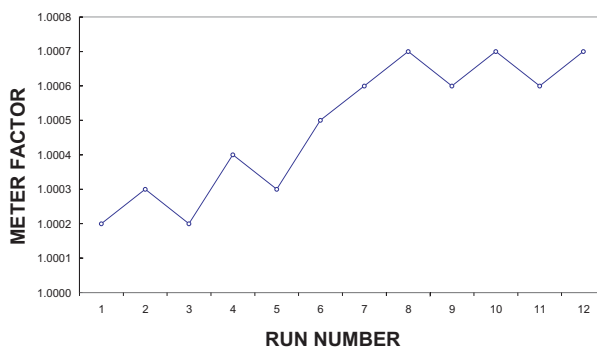
Figure 16—Meter Proving Continued

7.2.2.3 Pipe Provers are typically calibrated using water. When a prover is calibrated, the water must be free of entrained air and must be at a stable temperature. Even with this, the accuracy of the prover calibration can be only as good as the calibration of the certified field test measures (cans) used in the calibration. Based on the current standard NIST procedures used when certifying cans, the uncertainty of can volumes range from about 0.004% to 0.03%, depending on can size and method of calibration. When cans are used in a field environment for calibrating provers, the overall uncertainty of prover volume may be on the order of 0.05% to 0.15%.

7.2.2.4 Sometimes a meter won't exhibit repeatability within 0.05% even when conditions are stable. This may occur for a variety of reasons, such as detector switch repeatability, using a prover that is too small for the meter or small fluctuations in operating conditions.

7.2.2.5 Leaking block valves can cause errors in meter proving.

7.2.2.6 Dirty or dented field measures (water draw cans) will cause errors in prover calibration.

Note: Refer to API *MPMS* Chapter 4.8.

7.2.3 Tanks

7.2.3.1 Tank gauging may be inaccurate if tanks are tilted, have flexing bottoms, or the insides of the walls are coated with sludge and encrustation.

7.2.3.2 Tank capacity tables which are not corrected for bulge due to hydrostatic head will be in error.

7.2.3.3 Temperature measurements in tanks may be wrong if thermometers are not suspended in the liquid long enough to reach thermal equilibrium. Even then, individual temperature measurements may not represent the entire product temperature.

7.2.3.4 An innage gauge may be in error if a free water layer in the bottom of a tank is frozen, thereby stopping the gauge-tape bob above the true bottom.

7.2.3.5 Where tank gauging is used for receipts, free water in the receiving tank should not be drained before the tank is gauged to determine the quantity.

7.2.3.6 Measurements made in tanks with floating roofs in the critical zone are uncertain and may be subject to significant error.

7.2.3.7 Snow, water, ice or other debris on a floating roof will change the buoyant weight of the roof and result in a quantity error.

7.2.3.8 An un-slotted gauge-well (pipe) can result in erroneous liquid depth and temperature measurement in the gauge-well. The depth (height) of the hydrostatic column in the gauge-well will be different from the depth of the hydrostatic column in the tank when there is a difference in liquid densities in the gauge well and in the bulk of the tank. Any water in the tank that extends into the gauge pipe might also be impacted similarly.

7.2.3.9 Outage gauge errors may be caused by reference height markers which are loose or have moved.

7.2.3.10 Reference height markers on gauge-hatches which are affixed to the top of cone-roof tanks without gauging wells may be subject to vertical movement as a tank fills or empties due to flexing of the tank wall; as well as any flexibility of the roof itself -(weight and position of gauger and others). This may introduce a measurable error in level gauging.

7.2.3.11 The accuracy of tank tables is obviously dependent on the accuracy with which the tanks were strapped. Some things that can affect the accuracy of strapping are:

- Strapping Tape Temperature and Tension
- Temperature of Tank Shell
- Tank Filled or Empty
- Accuracy of Strapping Operation

7.2.3.12 Other possible errors relating to tank calibration are discussed in API *MPMS* Chapter 2.

7.2.3.13 Tank volumes do tend to change with time. This may be due to stretching of the shell with continuous use over time, slippage between the plates of bolted or riveted tanks, disassembly and re-erection, being "moved bodily" or sitting idle for a long time.

7.2.3.14 Experience in the industry has shown that tanks of up to 1,000 bbl nominal capacity which have not been moved or disassembled do not show a significant change in volume over a period of ten years. Larger tanks, though, may change volume enough over a ten-year span to warrant recalibration.

7.2.4 System and General

7.2.4.1 The size of a tender (batch, parcel, movement, shipment) is a factor in the overall loss or gain in the tender. By way of illustration, a system loss of 0.1% would be 1 bbl in a tender of 1,000 bbls or 100 bbls in a 100,000 bbl tender. This is based on overall system loss/gain. Yet, the apparent per cent loss/gain in a 100,000 bbl tender may be less than that in a 1,000 bbl tender. This may be due to a lesser effect of end effects (e.g., interface cut point) and more opportunity for operating conditions to stabilize during the longer run time of the larger tender. The measured loss on the 100,000 batch may be only 80 bbls, or 0.08%, and the loss on the 1000 bbl batch may be 20 bbls, or 2%. The overall system is still 0.1

7.2.4.2 A real source of loss is evaporation. The empty space in a tank above a volatile liquid, such as gasoline, is filled with varying concentrations of vapor from the liquid. When the contents of the vapor space are expelled from the tank during filling of the tank or diurnal breathing, the vapors in the expelled air are lost. Refer to *MPMS* Chapter 19 .

7.2.4.3 Evaporation losses can be minimized by using floating roof tanks, which eliminate the air space above the liquid contents of a tank, or by connecting the roof vents of cone-roof tanks to a vapor recovery system. Some states require evaporation loss prevention to reduce air pollution.

7.2.4.4 Equipment that is not calibrated, certified, or verified—such as thermometers, hydrometers, temperature

gauges, gauge tapes and centrifuge tubes - may be inaccurate. If so, this will add a bias to the system L/G.

7.2.4.5 Perhaps the most common errors occurring on manually calculated measurement tickets are arithmetic errors and wrong correction factors pulled from tables.

7.2.4.6 Tickets that don't get into the accounting process on time will cause an apparent loss or gain in the current accounting period and an offsetting gain or loss in the following period.

7.2.4.7 Timing discrepancies, period to period, in closing meter readings and inventory information can be a major factor in properly establishing loss/gain for an accounting period.

7.2.4.8 The closing tank gauge reading from the previous period should match the opening tank gauge reading for the current period.

7.2.4.9 Tanks which are gauged for inventory and which are active at the time of gauging must be gauged at the same time of the same day, or stilled long enough to be gauged without liquid moving in or out.

7.2.4.10 Accurate month-end inventory gauges are very important because they are used to balance and closeout pipeline and/or terminal inventories, and to issue customer reports, and billing. Multiple customers may share the same storage in a commingled tank, and loss-gain offsets from month to month can be difficult to allocate. Month-end gauges are also useful to identify trends that may reveal a bias (e.g., a systematic error).

7.2.4.11 Line fill may contribute significantly to system inventory. If possible, line fill should be corrected for temperature and pressure. Pipelines should be completely empty or completely full at the beginning and end of the accounting period.

7.2.4.12 Sampling in lines and tanks requires good mixing to assure that a representative sample is obtained.

7.2.4.13 Sumps collect drips and drains from a number of sources, and may add a bias to a system L/G if the sumps are emptied by pumping into a pipeline system without being measured. Usually, sump volumes are small enough to be insignificant. However, the volumes may be significant if sumps accumulate large volumes such as frequent drain downs from provers or scraper traps.

7.2.4.14 Apparent losses may result from shrinkage due to mixing stocks with significantly different gravities or chemical composition. Methods for evaluating shrinkage are given in API *MPMS* Chapter 12.3

7.2.4.15 Changes in operating pressure, operating temperature, or fluid characteristics are indicators that an overage or

shortage may be occurring. The following are some examples of sources of over/short inaccuracies:

- A pipeline or valve leak.
- A faulty relief system.
- Improper line up.
- Errors in calculating volumes.
- Not applying a meter factor to the registered volume.
- Applying a meter factor not applicable to the operating flow rate and pressure.
- Comparing a temperature compensated (net) meter volume to a gross volume.
- Meter malfunction.
- Automatic gauge malfunction.

Data from SCADA systems can be very useful in identifying problems and trends.

7.3   EXPLAINABLE LOSS/GAIN

Certain loss/gain inaccuracies can be explained and quantified, while others can be explained but not quantified. Likewise, minor meter imbalances or recurring hourly shortages/overages can be the result of many factors:

- Pipeline pressure change, increase or decrease, will created a false over/short condition due to accumulated volume of pipeline varying with pressure.
- Product interfaces cause a varying meter in/meter out reading as a result of relative density changes.
- Seasonal temperature changes along the pipeline will affect metering via expansion or contraction of produce in line. Imbalances between locations can be caused when pipeline passes under a river and temperature of product is changed.
- Small leak or puncture.
- DRA Laden Product
- Evaporation
- Volumetric Shrinkage (See *MPMS* Chapter 12.3)

7.3.1   Bias

Examples of system bias include, but are not limited to:
- Methods of analysis, i.e. S&W
- Different types of meters
- Meter proving procedures
- Measurement systems – tanks vs. meters
- Fahrenheit vs. Celsius
- Proving frequency
- Liquid Properties
- Volume Correction Factor (VCF) The physical characteristics of given liquid(s) may not be accurately represented by the applicable volume correction table, e.g., API *MPMS* Table 6
- Wax may deposit on pipe walls when a waxy crude liquid is cooled below the cloud point. Wax changes volume by a measurable amount when it changes from the

liquid state to the solid state. This can affect line fill volume and, thereby, affect loss/gain. Even if wax doesn't deposit on the inside of pipe walls, the change from liquid to suspended microcrystalline solids results in a volume change in the overall liquid, and there may be a measurable difference between pipeline receipt volumes and delivery volumes.

- Viscosity
- Line fill
- Tank capacity table error
- Tank bottom flexure
- Tank datum plate movement
- Inadequate meter backpressure
- Pressure – Psia vs Psig.

8 Reporting

8.1 RESOLVING THE LOSS / GAIN

8.1.1 A loss investigation is successful when the cause has been identified and the appropriate actions are taken to resolve or correct the problem. A key role of the loss investigator is to thoroughly document the findings from background to resolution so there is a clear understanding of the problem, how the problem lead to a loss (or gain), and most importantly what is required to resolve the problem. Generally, investigative reports should provide detailed recommendations and responsibility assignments to insure complete resolution.

8.1.2 It is probably true that almost all measurement systems could be improved in one form or another. Unfortunately, improvements usually have associated costs. Justification for these costs are usually decided based on some acceptable level of system performance, or in other words, the costs of the losses. It is important to understand the capabilities of a particular system and what uncertainty to expect in the monthly loss numbers. The uncertainty is difficult to assess and usually depends on the equipment and procedures in-place.

8.1.3 An analysis of the measurement system can be used to define the current capability and the improvement that might be accomplished with upgraded equipment and procedures. Installing more accurate measurement equipment, using improved operational procedures, and instituting an ongoing training program for measurement personnel should decrease pipeline losses.

8.1.4 Pipeline measurement accuracy may take several months, or even years, to reach a performance level acceptable to the pipeline organization. To some extent, better performance may be obtained by improving procedures and practices, and by training personnel in proper procedures and practices. Further improvement in performance may require additional or improved equipment, in which case, the relative economics must be evaluated.

9 Calculating Statistical Uncertainties

9.1 This section summarizes some of the statistical methods discussed in the API *MPMS* Chapter 13.2, "Statistical Evaluation of Meter Proving Data."

9.2 A measurement taken under undefined or variable conditions will not yield meaningful statistics. In order to establish statistical control, great care must be taken to ensure that factors, such as temperature and flow rate, are correctly measured and that all external influences have been identified.

9.3 It is often difficult to establish statistical control quantitatively. It may be possible, however, to examine performance charts and calculate the maximum allowable range for a set of measurements obtained under the given operating conditions. At the very least, it is essential that the measurement procedure is clearly understood and that the equipment is fully operational.

CAUTION: Once a set of "n" repeated measurements is obtained, the set should be examined for outliers. This can be done with Dixon's Test (see *MPMS* Section 13.1). If an outlier is detected, it should be discarded from the data set and further measurements made until a good set of data is obtained.

CAUTION: It should be determined that the extreme value was not due to a change in an uncontrolled variable such as temperature or flow rate.

9.4 If the scatter in data is already known for a given operation, then the uncertainty limits will be known, and any measurement that falls outside the limits corresponding to 95% probability (this will be discussed shortly) may be rejected. When only two measurements are available, and their difference exceeds the repeatability, then both measurements may be suspect. It should be stressed, however, that measurements should never be discarded freely. An attempt should always be made to find a reason for the extreme values, after which, corrective action can be taken.

9.5 *MPMS* Chapter 13.2 points out that "Minimizing systematic and random errors, estimating remaining errors and informing affected parties of errors" is becoming increasingly important to industry. A consistent basis of estimating the size and significance of errors is essential for communications between affected parties. A consistent basis of estimating and controlling errors can help to avoid disputes and dispel delusions on the accuracy of activities and equipment related to meter proving operations.

9.6 A wide range of designs, equipment and service operating conditions are experienced in meter proving operations. Because of these variations, it is impractical to establish fixed

procedures for maintenance, calibration and proving activities for all installations. Meter proving factors (meter factors) should be monitored to detect trends or sudden deviations as an indication of when to perform maintenance and/or calibration of measurement equipment.

9.7 Stable operating conditions are particularly important during meter proving operations, as changes in any operating condition (flow rate, temperature, pressure, API gravity) will cause changes in meter factor. Therefore, operating changes during and between meter proving runs should be minimized so that any variations in meter pulses or meter factors are primarily due to performance of the meter and proving system. Meter factors or meter pulses for each run can be evaluated in sequence to determine if there is a time related trend due to changing operational parameters or malfunctioning equipment

9.8 Throughout the application of statistical controls to pipeline operations, it is essential to remember that the goal is improved operation and understanding of systems. The use of any statistical process must lead to an expected result. There is little to be gained from statistics for the sake of statistics.

9.9 We often have two sets of data available for stock balances.

- "Accounting Month" includes all transactions that entered the books during the month including adjustments, corrections, and late tickets from prior months.
- "Current Month" includes only actual receipts, deliveries and inventory changes during the month. It does not include late tickets or adjustments from prior months.

It is desirable to look at current month data, because that data set tells us the most about the physical operation of a system. It tends to highlight the fundamental accuracy of a system, equipment malfunctions and procedural errors.

Analysis of accounting month data can help to identify problems in ticket preparation and handling, and other accounting type problems. It may not be necessary to be concerned about the occasional bobble, but recurring problems need to be identified and corrected.

APPENDIX A—STATISTICAL CALCULATIONS

A.1 Mean and Standard Deviation

A.1.1 CONVENTIONAL STANDARD DEVIATION

In a data set containing n data points, each of which has a value of y, the mean (m) and standard deviation (σ, i.e., sigma) are defined as:

$$m = \frac{\Sigma y}{n} \qquad (4)$$

$$\sigma = \sqrt{\frac{\Sigma(y-m)^2}{n}} \qquad (5)$$

where

y	=	the value of any data point in the set,
m	=	the mean (arithmetic average) of the data set,
Σ	=	the sum of all Σy or $(y-m)^2$ values,
n	=	the number of data points in the set.

For example:

Table 1—Sample Calculation of Mean and Standard Deviation

Month	L/G, %	y	$y-m$	$(y-m)^2$
1	0.12	0.12	0.00	0.0000
2	0.15	0.15	0.03	0.0009
3	0.11	0.11	−0.01	0.0001
4	0.08	0.08	−0.04	0.0016
5	0.13	0.13	0.01	0.0001
Sum		0.59		0.0027

$m = 0.59/5 = 0.12$

$\sigma = \sqrt{(0.0027/5)} = \pm 0.023$

A.1.2 ESTIMATED STANDARD DEVIATION

For a meter factor data set containing less than 24 data points, control limits and an "estimated standard deviation" are based on the ranges (differences) between contiguous meter factors and are calculated from statistical factors D_4 and d_2 which have the numerical values of 3.268 and 1.128 for this application. These values of D_4 and d_2 are for systems of subgroups of size = 2, since each pair of contiguous data points may be considered as a subgroup containing two points. Each data point—with the exception of the first and last in the series—is used twice.

Control Limits are:

$$(UCL)/(LCL) = m \pm 3s \qquad (6)$$

(m is "mean" and s is "estimated standard deviation")

$$s = (Ra)/d_2 \qquad (7)$$

Ra is the arithmetic average of the individual ranges for the set of meter factors. For example, consider the following set of five sequential meter provings:

Table 2—Sample Calculation of Estimated Standard Deviation

Proving Number	Meter Factor	Range Between Contiguous MFs
1	1.0005	
2	1.0011	0.0006
3	1.0009	0.0002
4	1.0006	0.0003
5	1.0012	0.0006
Totals	5.0043	0.0017

$m = (5.0043)/(5) = 1.00086,$
$Ra = (0.0017)/(4) = 0.00043,$
$s = (0.00043)/(1.128) = 0.00038.$
$UCL = 1.00086 + (3)(0.00038) = 1.0020,$
$LCL = 1.00086 - (3)(0.00038) = 0.99972.$

Note: Only the magnitudes of the ranges are used. Plus or minus signs, which indicate direction of change are ignored.

A.1.2.1 Correlation Coefficient

The strength of the correlation between two variables can be measured statistically with the "correlation coefficient":

$$r = \sqrt{1 - \{\Sigma(Y-Ye)^2/(Y-Ym)^2\}}$$

In which r is the correlation coefficient, Y is a measured value of the dependent variable, Ye is the estimated value for the same independent variable of Y, and Ym is the mean of all the Y values in the data set.

The value of "r" varies from 0 to 1. Numeric values close to unity indicate a strong correlation, and numeric values close to zero indicate a weak or no correlation. Intermediate numeric values indicate moderate correlation.

A.2 Least Squares Method for Calculating Linear Regression Lines

A linear regression line is a straight line that represents the "best fit" of a straight line to the data, and takes the form:

$$Y = a + bX$$

where

Y = the dependent variable, e.g., Loss/Gain,

X = the independent variable, e.g., Time Period (Month, etc.),

"a" and "b" are constants derived form the data by the Least Squares Method and apply only to that data set.

The Least Squares Method is a statistically derived pair of equations for determining the values of the constants "a" and "b". The equations are:

$$b = [\Sigma xy - n(X_b)(Y_b)]/[\Sigma X^2 - n(X_b)^2]$$

$$a = (Y_b) - b(X_b)$$

where

X_b and Y_b are the means (i.e., arithmetic averages) of all the X values and all the Y values in the data set. X_b and Y_b are read as "X bar" and "Y bar" and are commonly written with a small horizontal bar over the "X" and the "Y" instead of the subscript "b". The subscript form is used when the bars could be lost in typing and/or editing.

Use of the Least Squares Method is most easily illustrated with an example. Using the data from the first six data points of Figure 13, the calculations are as shown in the following table.

Note that all values must be numerical. For example, months must be 1, 2, 3, etc., not Jan., Feb., Mar., etc.

X (Month)	Y (Cum. L/G)	X^2	XY
1	– 20	1	– 20
2	– 60	4	– 120
3	– 140	9	– 420
4	– 200	16	– 800
5	– 280	25	– 1400
6	– 320	36	– 1920
$\Sigma X = 21$	$\Sigma Y = -1020$	$\Sigma X^2 = 91$	$\Sigma XY = -4680$

$n = 6$

$(X_b) = \Sigma X/n = 21/6 = 3.5$

$(Y_b) = -1020/6 = -170$

$b = [\Sigma XY - n(X_b)(Y_b)]/[\Sigma X^2 - n(X_b)^2]$
$= [-4680 - (6)(3.5)(-170)]/[91 - (6)(3.5)^2]$
$= -63.4$

$a = (Y_b) - b(X_b) = -170 - (-63.4)(3.5) = 51.9$

Thus: Cum L/G = 51.9 – 63.4*Month. This equation was used to calculate the values for the "Projection Line" plotted on Figure 13.

A.3 The Standard Error of Estimate

The Standard Error of Estimate, s_e, is similar to Standard Deviation and may be used to evaluate the uncertainty of an estimated value calculated by linear regression (i.e., the Least Squares Method). If the data are normally distributed around the regression line, $\pm 1s_e$ represents a 68% confidence level, $\pm 2s_e$ represents a 95.5% confidence level, and $\pm 3s_e$ represents a 99.7% confidence level. The Standard Error of Estimate may be calculated from the following equation:

$$s_e = \sqrt{[\Sigma Y^2 - a\Sigma Y - b\Sigma XY]/[n-2]}$$

Where X, Y, a, b, and n are the same terms and the same values as in the Least Squares Method.

APPENDIX B—TROUBLESHOOTING GUIDE FOR PIPELINE MEASUREMENT OPERATIONS

Symbol, Variable or Statement	Affected Equipment	Conditions or Definition	Measurement Calculation Affected	Resulting Affect	Test	Corrective Action	
TEMPERATURE	Meter	Too high	CTLm too low	Metered volumes understated	Thermometer check	Calibrate transmitter	
		Too low	CTLm too high	Metered volumes overstated	Thermometer check	Calibrate ATG	
	Prover	Too high	CTLp too low	MF decrease	Thermometer check	Calibrate transmitter	
		Too low	CTLp too high	Ticketed volumes understated	Thermometer check	Reprove meter	
				MF increase			
				Ticketed volumes overstated			
	Densitometer	Too high	CTLm too low	Metered volumes understated	Thermometer check	Calibrate transmitter or	2°F causes
		Too low	Gravity/SG is reduced	Metered volumes overstated	Thermometer check	calibrate densitometer	0.10 –0.15% error
			CTLm too high				
PRESSURE	Meter	Too high	CPLm too high	Metered volumes overstated	Certified gauge check	Calibrate Transmitter	
		Too low	CPLm too low	Metered volumes understated		Relocate? Add pump?	
	Prover	Too high	CPLp too high	MF increase	Certified gauge check	Calibrate transmitter	
		Too low	CPLp too low	Ticketed volumes overstated			
				MF decrease			
				Ticketed volumes understated			
	Densitometer	Too high	RD/API too high	Metered volumes overstated	Certified gauge check	Calibrate transmitter	Can be caused by
		Too low	RD/API too high	Metered volumes understated		Relocate? Add pump?	inadequate flow
DIFFERENTIAL PRESSURE	Orifice Meter	Too low	Flow rate, Klbs	Metered volumes understated	Deadweight check	Calibrate transmitter	Flow error increases
		Underranged			Verify clear tubing	Decrease orifice size	when DP < 20" H_2O
			Flow rate, Klbs	Metered volumes overstated			
		Too high			Deadweight check	Calibrate transmitter	Other uncertainties
		Over ranged			Verify clear tubing	Increase orifice size	unknown
API GRAVITY (Operating temperature less than 60°F)	Meter	Too high	CTLm too high	Metered volumes overstated	Hydrometer orpycnometer check	Calibrate densitometer or establish DMF	Fixed gravity should be within 1° API
		Too low	CTLm too low	Metered volumes understated			
	Prover	Too high	CTLp too high	MF increase	Hydrometer or pycnometer check	Calibrate densitometer or establish DMF	
		Too low	CTLp too low	Ticketed volumes overstated			
				MF decrease			
				Ticketed volumes understated			
API GRAVITY (Operating temperature greater than 60°F)	Meter	Too high	CTLm too low	Metered volumes understated	Hydrometer or pycnometer check	Calibrate densitometer or establish DMF	
		Too low	CTLm too high	Metered volumes overstated			
	Prover	Too high	CTLp too low	MF decrease	Hydrometer or pycnometer check	Calibrate densitometer or establish DMF	
		Too low	CTLp too high	Ticketed volumes understated			
				MF increase			
				Ticketed volumes overstated			
PROVER VOLUME (In MF calculations)	Prover	Too high	MF increase	Metered volumes overstated	Verify prover calibration certificate	Perform water-draw	
		Too low	MF decreases	Metered volumes understated	Verify prover calibration certificate		

Symbol, Variable or Statement	Affected Equipment	Conditions or Definition	Measurement Calculation Affected	Resulting Affect	Test	Corrective Action	
POOR PROVING REPEATABILITY		Trapped air/vapor		Unstable counts, aborted meter proving		Vent prover, run, vent Reprove meter	Water-draw required
		B & B valves leaking Bad detector		More pulse, decrease in MF Continuous/intermittent counts	Check block and bleed Check against external signal source	Seat/cycle valve; repair Replace or adjust	
		Temperature variation Damaged sphere Damaged piston Damaged coating Meter bearing wear Gear wear Blocked straightening vanes Electrical interference Cavitation in meter Pulse generator Pre-amp		Unstable pulses More pulses More pulses Bypass More pulses Less pulses	Thermometer Check Oscilloscope check Check backpressure Meter head count check	Calibrate transmitter Inspect/Replace Inspect/Replace Inspect/Recoat Inspect/Replace Inspect/Clean Eliminate interference	
POOR METER LINEARITY		Damaged rotor Gear/bearing wear Upstream turbulence			Linearity test	Repair/replace Inspect/repair Add flow conditioner	Turbines also affected by viscosity and swirl
METER FACTOR							
Increase	Meter	Meter bearing wear Prover temp too low Dragging turbine rotor	Net Volume	Less meter pulses			
Decrease	Meter	Prover temp too high Viscosity change		More meter pulses			
	Piston/Sphere	Piston/Sphere bypass Sphere undersized					
	Prover	Buildup on pipe wall Scarred/scratched wall		Reduces prover volume			
METER FACTOR USED IN NET	Flow computer printout of NET bbls	Automatically applies MF to net bbl volume					
METER FACTOR AUTO IMPLE-MENTED	Flow computer printout of NET bbls and proving report	Automatically stores the MF to implement in the NET bbl volume					
COMPOSITE METER FACTOR (CMF)	REPORTS Ticket	CMF includes an additional CPLm factor which is multiplier to MF		Ticketed volumes overstated when CMF is used on flow computer NET volumes			
OVERSTATED VOLUMES		For system receipts For system deliveries		Causes a system loss Causes a system gain			
UNDERSTATED VOLUMES		For system receipts For system deliveries		Causes a system gain Causes a system loss			

American Petroleum Institute

1220 L Street, Northwest
Washington, D.C. 20005-4070
202-682-8000

Product No. H25601