Manual of Petroleum Measurement Standards Chapter 12—Calculation of Petroleum Quantities

Section 2—Calculation of Liquid Petroleum Quantities Measured by Turbine or Displacement Meters

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American
Petroleum
Institute

Helping You Get The Job Done Right.℠

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FOREWORD

This publication consolidates and presents standard calculations for metering petroleum liquids using turbine or displacement meters. All units of measure in this publication are U.S. customary units. A parallel document in metric units will be available in the future.

In addition to this publication a field manual, designated F12.2, is being published simultaneously. The field manual provides instructions to individuals charged with calculating metered petroleum quantities without detailed explanations of why a particular course of action is necessary. This publication provides the explanations and serves as a backup to the field manual.

Suggested revisions to this publication are invited and should be submitted to the director of the Measurement Coordination Department, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005.

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Chapter 12—Calculation of Petroleum Quantities

SECTION 2—CALCULATION OF LIQUID PETROLEUM QUANTITIES MEASURED BY TURBINE OR DISPLACEMENT METERS

12.2.0 Introduction and Purpose

Before the compilation of this publication, which is part of the API *Manual of Petroleum Measurement Standards*, calculation procedures and examples of calculations were mixed in with former API measurement standards dealing with provers, meters, tank gaging, and so forth. The writing of the former standards was spread over a period of 25 years or more: each standard was written by a different group of persons; and each group was faced with slightly different requirements. As a result, the calculation procedures lacked coherence and the interpretations of words and expressions varied. Because the data was spread over so many standards comparisons of the finer points of calculations were difficult.

Moreover, when most of the former standards were written, mechanical desk calculators were widely used for calculating measurement tickets, and tabulated values were used more widely than is the case today. Rules for rounding and the choice of how many significant figures to enter in each calculation were often made up on the spot. With the advent of computers and of solid state scientific desk calculators, it soon became apparent, to discerning practitioners, that a × b × c was not necessarily identical with c × a × b or with b × c × a. For different operators to obtain identical results from the same data, the rules for sequence, rounding, and significant figures have to be spelled out. This publication aims, among other things, at spelling out just such a set of minimum rules for the whole industry. Nothing in this publication precludes the use of more precise determinations of temperature, pressure, and density (gravity) or the use of more significant digits, by mutual agreement among the parties involved.

The present publication consolidates and standardizes calculations pertaining to metering petroleum liquids using turbine or displacement meters and clarifies terms and expressions by eliminating local variations of such terms. The compilation of this publication would not have been possible even 5 years ago because the methods and equipment used in dynamic measurement of petroleum liquids have greatly advanced in the recent past. It is therefore timely, perhaps overdue; but it is not a denial of former methods so much as a refinement and clarification of them. The purpose of standardizing calculations is to produce the same answer from the same data regardless of who or what does the computing.

12.2.1 Scope

This publication defines the various terms (be they words or symbols) employed in the calculation of metered petroleum quantities. Where two or more terms are customarily employed in the oil industry for the same thing, this publication selects what should become the new standard term, for example, "run tickets," "receipt and delivery tickets," and the like are herein simply "measurement tickets."

The publication also specifies the equations which allow the values of correction factors to be computed. Rules for sequence, rounding, and significant figures to be employed in a calculation are given. In addition, some tables, convenient for manual as well as computer calculations, are provided.

12.2.2 Referenced Publications

The following publications are referenced throughout this publication.

API

Manual of Petroleum Measurement Standards

	Chapter 1, "Vocabulary"
	Chapter 4, "Proving Systems"
	Chapter 11.1, "Volume Correction Factors" (Standard 2540)
	Chapter 11.2 (Standard 1101, Table II)
	Chapter 11.4.2, (Standard 1101, Table I)
Std 1101	*Measurement of Petroleum Liquid Hydrocarbons by Positive Displacement Meter*

NBS[1]

Handbook 105-3	*Specifications and Tolerances for Reference Standards and Field Standards*
Monograph 62	*Testing of Metal Volumetric Standards*
Handbook 91	*Experimental Statistics*

[1]National Bureau of Standards, Washington, D.C. 20234.

12.2.3 Field of Application

The field of application of this publication is limited to liquid hydrocarbons having a density greater than 0.500, measured by a turbine or displacement meter and prover, including those hydrocarbons that by suitable adjustments of temperature and pressure are liquids while being measured. Two-phase fluids are not included (though it may be found useful in such situations) except insofar as sediment and water may be mixed in with crude oil (see the definition of sediment and water in Chapter 1, "Vocabulary").

12.2.4 Hierarchy of Accuracies

There is an inevitable or natural hierarchy of accuracies in petroleum measurement. At the top are test measures which are usually calibrated by the National Bureau of Standards or a certified laboratory. From this level downwards any uncertainty in a higher level must be reflected in all the lower levels as a bias (that is, as a systematic error). Whether such bias will be positive or negative is unknown; uncertainty carries either possibility.

To expect equal or less uncertainty in a lower level of the hierarchy than exists in a higher level is unrealistic. The only way to decrease the random component of uncertainty in a given measurement system or method is to increase the number of determinations and then find their mean value. The number of digits in intermediate calculations of a value can be larger in the upper levels of the hierarchy than in the lower levels; but the temptation to move towards imaginary significance must be tempered or resisted by a wholesome respect for realism.

The hierarchy of accuracies in this publication is structured, in general, as shown in Table 1.

Rules for rounding, truncating, and reporting final values are given for each level of the hierarchy in 12.2.6, 12.2.7, and 12.2.8. Rounding in this manual conforms to National Bureau of Standards Handbook 91, Chapter 22, as reprinted in Appendix D.

12.2.5 Principal Correction Factors

Designation of correction factors by symbols rather than by words is recommended because, first, expressions are abbreviated; second, algebraic manipulations are facilitated; third, the similarities of expressions are pointed out subject only to the particular liquid or metal involved; and fourth, confusion is reduced as, for example, the difference between compressibility (F) of a liquid and the correction factor (C_{pl}), which is a function of F. There are six principal correction factors employed in calculations of liquid quantities; all of them are multipliers. The first correction factor, commonly called the meter factor, is defined as:

MF = a non-dimensional value which corrects a volume as indicated on a meter to the "true" volume (see 12.2.7).

The next four correction factors are employed in calculations of liquid quantities. They are needed because changes in volume from the effects of temperature and pressure upon both the containing vessel (usually made of mild steel) and upon the liquid involved must be accounted for. These four correction factors are:

C_{ts} (or CTS) = the correction factor for the effect of temperature on steel (12.2.5.1).
C_{ps} (or CPS) = the correction factor for the effect of pressure on steel (12.2.5.2).
C_{tl} (or CTL) = the correction factor for the effect of temperature on a liquid (12.2.5.3).
C_{pl} (or CPL) = the correction factor for the effect of pressure on a liquid (12.2.5.4).

While the customary subscripted notation is used in this publication, the allowed upper case notation is needed for computer programming and is convenient in typing.

Finally, there is a correction factor C_{sw} (which is never greater than 1.000) for accounting for the presence of sediment and water in crude oil (see 12.2.8.4).

Additional subscripts may be added to the symbolic notations above to make it clear to what part of the measuring apparatus it applies, namely "p" for prover, "m" for meter, and "M" for measure.

In the worked examples given in this publication, and in the standard calculating procedures recommended, the above six correction factors are applied in a set sequence:

$$MF,\ C_{ts},\ C_{ps},\ C_{tl},\ C_{pl},\ C_{sw}$$

All multiplication within a single operation must be completed before the dividing is started.

12.2.5.1 CORRECTION FOR THE EFFECT OF TEMPERATURE ON STEEL, C_{ts}

Any metal container, be it a pipe prover, a tank prover, or a portable test measure, when subjected to a change in temperature will change its volume accordingly. The volume change, regardless of prover shape, is proportional to the cubical coefficient of thermal expansion of the material of which the container is made. The correction factor for the effect of temperature on steel is called C_{ts}, and it may be calculated from:

$$C_{ts} = 1 + (T - 60)\gamma \tag{1}$$

Where:

T = temperature in °F of the container walls.
γ = coefficient of cubical expansion per °F of the material of which the container is made.

Table 1—Hierarchy of Accuracies

Paragraph	Level	Correction Factors and Intermediate Calculations to	Volumes, Significant Digits	Temperature Discrimination, to at least, °F
12.2.6	Prover calibration	6 decimal places[a]	5	0.1
12.2.7	Meter proving	4 decimal places	5	0.5
12.2.8	Measurement tickets	4 decimal places	5	1.0

[a] Values are not valid beyond four decimal places for the purpose of correcting volumes to 60°F. However, for correcting for small temperature differences between a meter and a prover, linear interpolation to more decimal places is acceptable.

Thus C_{ts} will be greater than 1 when temperature T is greater than 60°F and less than 1 when temperature T is less than 60°F.

The value of γ (gamma) per °F is 1.86×10^{-5} (or 0.0000186 per °F) for mild or low carbon steels and falls in a range of values from 2.40 to 2.90×10^{-5} per °F for Series 300 stainless steels. The value used in calculation should be that found on the report from the calibrating agency for a test measure or from the manufacturer of a prover. Tables of C_{ts} values against observed temperature will be found in Appendix A of this publication. Values for Series 300 stainless steels are based on the mean value of 2.65×10^{-5} for gamma.

When the volume of the container at standard temperature (60°F) is known, the volume (V) at any other temperature (T) can be calculated from:

$$V_T = V_{60} \times C_{ts} \quad (2)$$

Conversely, when the volume of the container at any temperature (T) is known, the volume at standard temperature (60°F) can be calculated from:

$$V_{60} = V_T / C_{ts} \quad (3)$$

12.2.5.2 CORRECTION FOR THE EFFECT OF PRESSURE ON STEEL, C_{ps}

If a metal container such as a tank prover, a pipe prover, or a test measure is subjected to an internal pressure, the walls of the container will stretch elastically and the volume of the container will change accordingly. While it is recognized that simplifying assumptions enter the equations below, for practical purposes the correction factor for the effect of internal pressure on the volume of a cylindrical container, called C_{ps}, may be calculated from:

$$C_{ps} = 1 + (PD/Et) \quad (4)$$

Where:

P = internal pressure, in pounds per square inch gage.
D = internal diameter, in inches (outside diameter minus twice the wall thickness).
E = modulus of elasticity for container material, 3.0×10^7 pounds per square inch for mild steel or 2.8 to 2.9×10^7 for stainless steel.
t = wall thickness of container, in inches.

A table of C_{ps} values for specific sizes and wall thicknesses of mild steel pipe provers and pressures may be found in Appendix A of this publication. When the volume of the container at atmospheric pressure is known, the volume at any other pressure (P) can be calculated from:

$$V_p = V_{atmos} \times C_{ps} \quad (5)$$

When the volume at any pressure P is known, the equivalent volume at atmospheric pressure can be calculated from:

$$V_{atmos} = V_p / C_{ps} \quad (6)$$

12.2.5.3 CORRECTION FOR THE EFFECT OF TEMPERATURE ON A LIQUID, C_{tl}

If a quantity of petroleum liquid is subjected to a change in temperature, its volume will expand as the temperature rises or contract as the temperature falls. The volume change is proportional to the thermal coefficient of expansion of the liquid, which varies with density (API gravity) and temperature. The correction factor for the effect of temperature on a volume of liquid is called C_{tl}. Its values are given in Tables 6A, 6B, and 6C, which may be found in 11.1 of this manual. Tables 6A, 6B, and 6C are used when the API gravity is known and lies between 0°API and 100°API; 100°API corresponds to a relative density of 0.6112. If the relative density is known Tables 24A, 24B, and 24C should be used, or Table 24 (API Standard 2540) for lower relative densities.

When the volume of a petroleum liquid is known at any temperature (T), the equivalent volume at standard temperature (60°F) can be calculated from:

$$V_{60} = V_T \times C_{tl} \quad (7)$$

When the volume of a petroleum liquid is known at 60°F, the equivalent volume at any temperature T can be calculated from:

$$V_T = V_{60} / C_{tl} \quad (8)$$

12.2.5.4 CORRECTION FOR THE EFFECT OF PRESSURE ON A LIQUID, C_{pl}

If a volume of petroleum liquid is subjected to a change in pressure, it will decrease as the pressure increases and increase as the pressure decreases. The volume change is proportional to the liquid's compressibility factor F, which depends upon both its relative density (API gravity) and the temperature. Values of the compressibility factor F for hydrocarbons will be found in Chapter 11.2 of this manual. The correction factor for the effect of pressure on a volume of petroleum liquid is called C_{pl} and can be calculated from:

$$C_{pl} = \frac{1}{1 - (P - P_e)F} \quad (9)$$

Where:

P = pressure, in pounds per square inch gage.

P_e = equilibrium vapor pressure at the measurement temperature of the liquid being measured, in pounds per square inch gage. P_e is considered to be 0 for liquids which have an equilibrium vapor pressure less than atmospheric pressure (14.73 pounds per square inch absolute) at measurement temperature.

F = compressibility factor for hydrocarbons from Chapter 11.2 of this manual. The value of F for water is 3.2×10^{-6} per pound per square inch.

When P_e is 0, Equation 9 becomes:

$$C_{pl} = \frac{1}{(1 - PF)} \quad (10)$$

When P_e is greater than 0, Equation 9 must be used. Values of P_e for densities between 0.500 and 0.512 are found in Chapter 11.2.

NOTE: A convenient way of determining P_e while proving a meter against a pipe prover is to proceed as follows:
1. Upon conclusion of the last proving run, stop flow through the pipe prover and isolate it from the flowing lines by shutting the appropriate valves.
2. Reduce pressure on the pipe prover by bleeding off liquid until the gage pressure stops falling. This will imply that a vapor space has been created and that the liquid has reached its equilibrium pressure. Shut the bleed valve, and read P_e on the gage, making a record of the temperature at the time.
This procedure may be used for determining P_e for liquid mixtures that do not conform with published charts showing P_e values plotted against the temperature or as a routine procedure.

When the volume of a low vapor pressure liquid is known at any pressure P, the equivalent volume at standard pressure (0 pounds per square inch gage) can be calculated from:

$$V_0 = V_P \times C_{pl} \quad (11)$$

When the volume of a low vapor pressure liquid is known at 0 pounds per square inch gage, the equivalent volume at any pressure P can be calculated from:

$$V_P = V_0/C_{pl} \quad (12)$$

When the volume of high vapor pressure liquid is known at any measurement temperature T and pressure P, the pressure correction is done in two steps. The equivalent volume at such liquid's equilibrium pressure P_e at measurement temperature can be calculated from:

$$V_{pe}@T = V_p \times C_{pl} \quad (13)$$

In this equation C_{pl} is calculated from Equation 9. When this volume is in turn temperature corrected to 60°F using Equation 7, the value of C_{tl} taken from the appropriate table also corrects the volume for the change in pressure from P_e at measurement temperature, to equilibrium pressure at the standard temperature of 60°F. It should be noted that while P_e at measurement temperature T may be higher than standard atmospheric pressure (14.73 pounds per square inch absolute), equilibrium pressure at 60°F may have fallen to atmospheric pressure or less. As noted under Equation 9, the distinction between a low vapor pressure liquid and a high vapor pressure liquid depends on whether its equilibrium pressure is less or greater than atmospheric pressure at measurement temperature.

12.2.5.5 COMBINED CORRECTION FACTOR (CCF)

The recommended method for correcting volumes by two or more correction factors is to first obtain a *CCF* (combined correction factor) by multiplying the individual correction factors together in a set sequence, rounding at each step. Only then multiply the volume by the *CCF*. The set sequence is *MF*, C_{ts}, C_{ps}, C_{tl}, C_{pl}, and C_{sw}, omitting any unused factors.

12.2.6 Calculation of the Volume of Provers

12.2.6.1 PURPOSE AND IMPLICATIONS

The purpose of calibrating a prover is to determine its base volume. The procedures to be used are described in Chapter 4, Sections 2 and 3, of this manual.

Base volume is expressed in barrels or gallons, both of which are multiples of the cubic inch. Whereas the cubic inch does not vary with temperature or pressure, the volume of a metal prover does vary. Therefore, the statement of the base volume of a prover or volumetric standard has to specify standard conditions, namely 60°F and atmospheric pressure.

12.2.6.2 FIELD STANDARDS

Field reference standards, which are described and discussed in Chapter 4, Section 1, are usually calibrated by the National Bureau of Standards or by an approved laboratory. Their reported volumes are expressed either in customary or metric (SI) units at standard conditions. The lastest edition of National Bureau of Standards Handbook 105-3 may be consulted for details of construction, calibration, and so forth.

12.2.6.3 RULE FOR ROUNDING—PROVERS

In calculating a prover volume, determine individual correction factors to six decimal places by using the appropriate formula; interpolation will be required for C_{tl}. Record the combined correction factor (*CCF*) rounded to six decimal places. Multiply the sum of the measured volumes, each of which has been individually adjusted to starting temperature, by the *CCF*, and report the base volume so determined to five significant digits. Round the corrected individual withdrawal volumes to the same number of significant digits as the uncorrected volumes.

12.2.6.4 CALCULATION OF BASE VOLUMES

The procedure for calibrating pipe provers will be found in Chapter 4, Section 2. The following subsections, 12.2.6.4.1 through 12.2.6.4.4, specify the calculation of the base volume of a pipe prover calibrated by the water draw method.

12.2.6.4.1 Initial Step

During the calibration of a pipe prover, the temperature and pressure of the water in the prover at the start of calibration are observed and recorded. Likewise, the temperatures of the individual withdrawals into field standards are observed and recorded.

NOTE: At this point attention is drawn to a long established practice detailed in API Standard 1101, Paragraphs 2123 to 2125, that no correction for C_{tsM} need be applied in calculating base volume by the water draw method. Such practice is valid only when the prover and the field standard test measures are made of the same material and then only if the temperature in the prover differs by less than 3°F from the temperature in the test measures. Appendix B of this chapter details the corrections required under other conditions and gives an example to illustrate the type of error which can result if these corrections are neglected.

12.2.6.4.2 Corrections Applied to Measured Volumes

In the water draw calibration procedure, the volume observed in the field standards must be subjected to certain corrections in order to determine the base volume of the prover (see Equation B1, Appendix B). The final subscripts mean "p" for prover and "M" for measure.

Thus, the following steps are performed:

1. The volume of water in a field standard must be corrected for the effect of temperature and pressure on the liquid to determine what volume the water occupied when it was in the prover; this is done by multiplying the volume by C_{tdw},[2] the value for which can be found in Chapter 11.4.2, and dividing by C_{plp}, the value of which can be computed from Equation 10 using F for water.
2. The volume so determined must then be corrected for thermal expansion of the field standard shell at the measuring temperature by multiplying the certified volume by C_{tsM} (see Equation 3).
3. Finally, the measured volume of the prover so calculated must be corrected for both temperature and pressure effects on the prover pipe in order to obtain the base volume, which is the equivalent volume at standard conditions. These corrections require dividing by C_{psp} and C_{tsp}, respectively. In calculating the values of C_{tsp} and C_{psp} the physical characteristics of the prover metal must be known. Because an accuracy greater than 1 part in 10,000 is desirable in prover base volumes, determine all correction factor values to six decimal places. In practice, when several test measures are filled, the calculation is performed according to Equation B6 in Appendix B in the manner specified in the following example (12.2.6.4.3).

12.2.6.4.3 Example Calculation for a Pipe Prover

The form or record used for a water draw calibration of a pipe prover must make provision for at least the information shown in Figure 1. The values shown are for example only,

[2] C_{tdw} is defined as the correction for the temperature difference of the water in the test measure and in the prover; this is not the same as C_{tl} which corrects to 60°F rather than to prover temperature.

A. GENERAL INFORMATION

Calibration report no. ________	Prover serial no. ________
Prover dimensions *10" pipe, 0.365" wall*	Prover type *unidirectional*
Metal *mild steel*	Prover location ________
Date ________	Calibrator's name ________

B. FIELD STANDARDS (TEST MEASURES)

1. Nominal sizes, gallons	*25*	*50*

Figure 1–Example Calculation for a Pipe Prover (Continued on Page 6)

2. Volume, cubic inches	*5775.81*	*11551.80*
3. Serial number	*m*	*n*

C. OBSERVED VALUES

4. Starting average pressure in prover, psig	*41*
5. Starting average temperature in prover, °F	*82.0*

Fill number	*1*	*2*	*3*	*4*
Field standard used	*m*	*n*	*n*	*n*
6. Reported volume	*5775.81*	*11551.80*	*11551.80*	*11551.80*
7. Scale reading				
above zero	—	*+37.5*	*+32.5*	*+3.0*
below zero	*−1.0*	—	—	—
8. Measured volumes (Line 6 + Line 7)	*5774.81*	*11589.30*	*11584.30*	*11554.80*
9. Withdrawal temperature, °F	*82.0*	*82.0*	*82.8*	*84.0*
10. Change from starting temperature (Line 9 − Line 5)	*0*	*0*	*+0.8*	*+2.0*
11. Volume adjustment for temperature difference of water (Chap. 11.4.2)	*1.000000*	*1.000000*	*0.999864*	*0.999670*
12. Volume adjusted to starting temperature (Line 8 × Line 11)	*5774.81*	*11589.30*	*11582.72*	*11550.99*

13. Sum of adjusted volumes, cubic inches *40.497.82*

D. CORRECTIONS NEEDED TO CALCULATE BASE VOLUME

14. C_{tsM} for test measures at mean weighted temperature of 82.8°F (see 12.2.5)	*1.000424*
15. C_{tsP} for prover at 82°F	*1.000409*
16. C_{psP} for metal of prover at 41 psig (see 12.2.5.2)	*1.000038*
17. C_{plP} for water in prover at 41 psig (see 12.2.5.4, Equation 10)	*1.000131*

E. BASE VOLUME

If the change from starting temperature (Line 10) weighted for all runs is 3°F or greater or if the metals of the prover and the test measure(s) are not the same, include C_{ts} for both test measures (C_{tsM}) and prover (C_{tsP}).

$$\text{Base volume} = \text{Sum of adjusted volumes (Line 13)} \times \left[\frac{C_{tsM}(14)}{C_{tsP}(15) \times C_{psP}(16) \times C_{plP}(17)}\right]$$

$$= \textit{40.491.58 cubic inches} \text{ at 60°F and O psig} = \textit{175.2882 gallons}$$

$$= \textit{4.17353 barrels}$$

If the change from starting temperature (Line 10) weighted for all runs is 3°F or less and the metal of the test measure(s) is the same as that of the prover use the following equation:

$$\text{Base volume} = \text{Sum of adjusted volumes (Line 13)} \times \frac{1}{C_{psP}(16) \times C_{plP}(17)}$$

NOTE: In this worked example, even though the weighted average withdrawal temperature (82.8°F) is less than 3°F different from the starting temperature (82.0°F), corrections for C_{ts} to both test measures and prover have been made in order to show how they are applied to calculate the base volume regardless of what starting and withdrawal temperature may have been (see 12.2.6.4.2). In this example, correcting for C_{ts} alters the result by one part in one hundred thousand. Leaving it out would have the same insignificant effect.

Figure 1—Example Calculation for a Pipe Prover (Continued)

and because the difference between starting prover temperature and field standards temperature is small (less than 3°F) use of the simplified method (see 12.2.6.4.1) is warranted. C_{ts} corrections can be neglected, but they are included in the example for illustration purposes. The word "measure" means the field standard(s) used. The example is limited to one determination, although at least two are required.

12.2.6.4.4 Rounding of Reported Values

The base volume of a prover as computed cannot be more accurate than the volumes of the field standards employed in its calibration, and because of accumulated experimental uncertainties in the calibration process, it will be somewhat less accurate. Experience shows that five significant figures in a computed value, such as the base volume of a prover, is the best that can be expected. Thus, the calculated base volume in the example in Figure 1 should be rounded to five significant figures showing 4.17353 as 4.1735 barrels; 175.2882 gallons as 175.29 gallons; or 40,491.58 cubic inches as 40,492 cubic inches.

12.2.6.4.5 Example Calculation for a Tank Prover

The form or record used for a water draw calibration of a tank prover must make provision for at least the information shown in the example in Figure 2.

It is assumed that this is a field recalibration; that the top and bottom necks do not need recalibration; that any small adjustments to the top or bottom zero marks will be made by sliding the reading scales up or down as needed, and that both scales will then be resealed.

It is further assumed that the difference between starting temperatures and withdrawal temperature is kept small (less than 3°F) so that the C_{ts} for the measures and tank correction can be omitted (see note in 12.2.6.4.1). Since the tank prover is at atmospheric pressure, no pressure correction for either liquid or prover tank shell is required.

The calibration run must be repeated, and if the two runs after correction for temperature agree within 0.02 percent (in this example within 0.200 gallon) the mean value of the two runs becomes the calibrated volume of the prover at 60°F.

The total of the values in Column 6 of Figure 2 is 1001.561 gallons, which is at 80.7°F. Each withdrawal has been corrected to 80.7°F by the correction factor shown in Column 5. Since the field standards and the prover being calibrated are made of the same material (mild steel) and the weighted temperature difference is not greater than 3°F, no further correction is needed to bring the calibrated volume of the prover to 60°F, as the certified volumes of field standards were adjusted to 60°F at the time of their calibration. If the reading on the top neck was, for example, 1001.000 gallons at the start of calibration and as the true volume is now known to be 1001.561 gallons, the top scale will have to be moved downwards 0.561 gallons. If the neck contains 1 gallon per inch (which is usually the case) the top scale will be moved downwards 9/16 or 0.563 inch.[3] An alternative would be to move the zero mark on the bottom neck scale upwards by 9/16 inch. Both scales should be resealed afterwards.

12.2.6.4.6 Rounding of Reported Values

The volume of a tank prover between top reading marks and bottom zero mark in this example was adjusted to 1001 gallons. Applying the five significant figures rule explained in 12.2.6.4.4 requires that the calibrated volume be reported as either 1001.0 gallons after adjustment or 23.833 barrels.

[3] Using a conventionally scaled foot rule, and knowing that 17/32 inch = 0.5313 inch and 9/16 inch = 0.5625 inch, the latter is as close as scale and meniscus reading will allow to be achieved.

A. GENERAL INFORMATION

Calibration report no. ____	Prover serial no. ____
Prover type *Open stationary tank (top & bottom gage glasses)*	Prover location ____
Metal *mild steel*	Nominal capacity ____
Date ____	Calibrator's name ____

B.	**FIELD STANDARDS**		
1.	Nominal sizes, gallons	*50*	*1*
2.	Delivered volume, gallons	*49.985*	*0.997*
3.	Serial number	*m*	*n*
C.	**OBSERVED VALUES**		
4.	Prover starting temperature, top, °F	*80.8*	
5.	Prover starting temperature, middle, °F	*80.6*	
6.	Prover starting temperature, bottom, °F	*80.6*	
7.	Prover starting temperature, average, °F	*80.7*	

Figure 2 Example Calculation for a Tank Prover (Continued on Page 8)

D. CORRECTIONS

1	2	3	4	5	6
Withdrawal	Volume	Temperature °F	t°	Volumetric Correction Factor C_{tm}	Field Standard Volume at Prover Temperature
1	*49.985*	*80.6*	*−0.1*	*1.000015*	*49.986*
2	*49.985*	*80.6*	*−0.1*	*1.000015*	*49.986*
3	*49.985*	*80.6*	*−0.1*	*1.000015*	*49.986*
4	*49.985*	*80.7*	—	*1.000000*	*49.985*
5	*49.985*	*80.7*	—	*1.000000*	*49.985*
6	*49.985*	*80.8*	*0.1*	*0.999984*	*49.984*
7	*49.985*	*81.0*	*0.3*	*0.999952*	*49.983*
8	*49.985*	*81.1*	*0.4*	*0.999936*	*49.982*
9	*49.985*	*81.1*	*0.4*	*0.999936*	*49.982*
10	*49.985*	*81.2*	*0.5*	*0.999920*	*49.981*
11	*49.985*	*81.3*	*0.6*	*0.999904*	*49.980*
12	*49.985*	*81.4*	*0.7*	*0.999888*	*49.979*
13	*49.985*	*81.5*	*0.8*	*0.999872*	*49.979*
14	*49.985*	*81.7*	*1.0*	*0.999840*	*49.977*
15	*49.985*	*82.0*	*1.3*	*0.999793*	*49.975*
16	*49.985*	*82.4*	*1.7*	*0.999730*	*49.972*
17	*49.985*	*82.5*	*1.8*	*0.999714*	*49.971*
18	*49.985*	*83.0*	*2.3*	*0.999635*	*49.967*
19	*49.985*	*83.1*	*2.4*	*0.999619*	*49.966*
20	*49.985*	*83.5*	*2.8*	*0.999555*	*49.963*
21	*0.997*	*84.0*	*3.3*	*0.999473*	*0.996*
22	*0.997*	*84.0*	*3.3*	*0.999473*	*0.996*
					1001.561

8. Sum of temperature adjusted field standard volumes *1001.561*
9. Final lower gage reading *0*
10. Weighted mean withdrawal temperature, °F *81.6*
11. Change from starting temperature (Line 10 − Line 7) .... *<3°F*

E. CALIBRATED VOLUME

13. The general formula for calibrated volume is:

$$\text{Calibrated volume} = \text{Sum of adjusted volumes} \times \frac{C_{tsm}}{C_{tsp} \times C_{psp} \times C_{plp}}$$

12. Calibrated volume = *1001.561* × *1*

NOTE: Calculations for C_{tsm} and C_{tsp} are shown even though it makes no difference in the calibrated volume to five significant digits. It does demonstrate to the user what he must do if he has temperature differences greater than 3°F or dissimilar metals.

Figure 2—Example Calculation for a Tank Prover (Continued)

12.2.6.4.7 Example Calculation Using the Master Meter Method

The procedure for calibrating a pipe prover using the master meter method will be found in Chapter 4 of this manual.

The first step is to prove the master meter in the liquid selected for the prover calibration. In this example a displacement meter is used, proved against a tank prover. A turbine meter calibrated against a pipe prover may be employed equally well, provided it is not removed from the manifolding of which it is a part at the time of its proving. The flow rate through a master meter, while it is being used to calibrate a prover, should be held within about 2.5 percent of the rate at the time of its proving. An alternative method is to develop an accuracy curve and read off the meter factor for the rate observed during the calibration.

The form or work sheet used to record data and calculations should provide for at least the information shown in Figure 3. Only one worked example of a master meter calibration run is shown in Figure 3 although five runs are desirable in such a calibration.

STEP 1 Proving of the Master Meter

A. GENERAL INFORMATION

Proving report no. ______ Date ______ Time ______

Liquid *motor gasoline at 60.8°API* Rate *715 barrels per hour*

Operator's name ______ Witness ______

B. MASTER PROVER INFORMATION

1.	Calibrated volume, barrels	*20.427*
2.	Prover starting temperature, top, °F	*73.6*
3.	Prover starting temperature, middle, °F	*73.6*
4.	Prover starting temperature, bottom, °F	*73.4*
5.	Prover starting temperature, average, °F	*73.5*

NOTE 1: For a gravity of 61° API (that is, 60.8° rounded) Table 6B of Chapter 11.1 gives values for 70°F and 80°F of 0.9931 and 0.9862. Thus the average increment per °F for this span is 0.00069, so for 73.5°F the six digit value will be 0.990685 as shown in Line 9. (See Note 2.)

6.	Pressure, pounds per square inch gage	*0*
7.	C_{tsp} for prover (see 12.2.5.1)	*1:000251*
8.	C_{psp} for prover (see 12.2.5.2)	*1.000000*
9.	C_{tlp} for prover (see 12.2.5.3)	*0.990685*
10.	C_{plp} for prover (see 12.2.5.4)	*1.000000*
11.	CCF_p for master prover (Line 7 × Line 8 × Line 9 × Line 10) (see 12.2.5.5)	*0.990934*
12.	Corrected master prover volume, barrels	*20.241809*

C. MASTER METER INFORMATION

13.	Closing reading, barrels	*14683.492*
14.	Opening reading, barrels	*14663.155*
15.	Indicated meter volume	*20.337*
16.	Temperature of metered stream, °F	*73.4*
17.	Pressure in meter, pounds per square inch	*40*
18.	C_{tlm} for meter (see 12.2.5.3)	*0.990754*
19.	C_{plm} for meter (see 12.2.5.4)	*1.000328*
20.	CCF_m (Line 18 × Line 19) for master meter (see 12.2.5.5)	*0.991079*
21.	Corrected master meter volume, barrels (Line 15 × Line 20)	*20.155574*

D. METER FACTOR

Meter factor = Line 12 ÷ Line 21

= *1.004278 for this run*

NOTES:

2. As this example is for an open tank prover, the pressure is 0 pounds per square inch gage so C_{plp} and C_{psp} are unity. If a pipe prover is employed, these factors would have other values.

3. Six decimal places in a C_{tl} value are not valid for correcting a volume to 60°F. But six decimal places for correction factors may be employed for correction within a small temperature range such as exists between a prover and a meter. The six decimal places are determined by linear interpolation within a 10°F span, selected from Table 6B, that includes both C_{tlp} and C_{tlm}.

4. The meter factor to be used in the calibration should be the average for all runs made that meet the repeatability requirements in Chapter 4.

STEP 2 Calibrate the Pipe Prover

A. GENERAL INFORMATION

Nominal or expected prover volume, barrels *40*

Figure 3—Example Calculation Using the Master Meter Method (Continued on page 10)

	Pipe size, inches	*16*
	Wall thickness, inches	*0.375*
	Gravity of liquid used, °API	*60.8*
	Flow rate when master meter was proved, barrels per hour	*715*
	Tolerable ± 2½ percent flow rate range	*697 to 733*
B.	PIPE PROVER INFORMATION Data from five runs may be averaged for Lines 22 and 23 and the base volume in Part D.	
22.	Temperature, °F	*75.1*
23.	Pressure, pounds per square inch gage	*100*
24.	C_{tsp} for pipe prover (see 12.2.5.1)	*1.000281*
25.	C_{psp} (see 12.2.5.2)	*1.000136*
26.	C_{tlp} (see 12.2.5.3)	*0.989581*
27.	C_{plp} (see 12.2.5.4)	*1.000821*
28.	*CCF* for pipe prover (Line 24 × Line 25 × Line 26 × Line 27)	*0.990807*
C.	MASTER METER INFORMATION	
29.	Rate, barrels/hour	*705*
30.	Temperature, °F	*75.6*
31.	Pressure, pounds per square inch gage	*75*
32.	Closing reading	*15226.727*
33.	Opening reading	*15186.254*
34.	Indicated meter volume, barrels (Line 32 − Line 33)	*40.473*
35.	Master meter factor (see Note 5)	*1.004284*
36.	C_{tlm} for meter (see 12.2.5.3)	*0.989236*
37.	C_{plm} for meter (see 12.2.5.4)	*1.000623*
38.	CCF_m (Line 35 × Line 36 × Line 37)	*0.994093*
39.	Corrected master meter volume, barrels (Line 34 × Line 38)	*40.233926*
40.	Volume of prover, this run, barrels (Line 39 ÷ Line 28)	*40.607228*
D.	BASE VOLUME	
	Base volume of pipe prover, barrels, at standard conditions (see Note 6)	*40.609*

NOTES:
5. Master meter factor (Line 35) does not agree with the value shown for one run in Step 1 Section D as it is assumed that the value used (Line 35) is an average of more than one run.
6. Base volume of pipe prover (D) does not agree with value for one run (Line 36) as it is assumed that at least five runs have been made and averaged. Also base volume to be reported should be realistic; that is, it should be rounded to five significant figures (see 12.2.6.4.2). Any theoretical sacrifice of accuracy that this may entail is largely imaginary and is offset by the advantage of having a standard method of calculating and reporting values.

Figure 3—Example Calculation Using the Master Meter Method (Continued)

12.2.7 Calculation of the Meter Factor

12.2.7.1 PURPOSE AND IMPLICATIONS

Some custody transfers of liquid petroleum measured by meter are sufficiently small in volume or value, or are performed at essentially uniform conditions, so that the meter can be mechanically adjusted to read within a predetermined accuracy. Examples would be retail measurements and some bulk plant measurements into and/or out of tank wagons. However, in most large scale custody transfers when a single meter is used to measure several different liquids or to measure at several different flow rates, meter adjustment for each change is impracticable. In such service, accuracy can be achieved by leaving the calibrator setting undisturbed and sealed, using a dummy calibrator, or dispensing with the calibrator entirely and determining within narrow limits a meter factor for each operating condition. Thus the purpose of determining a meter factor is to ensure accuracy of measurement by batch, regardless of how operating conditions change with respect to density (gravity), viscosity, rate, temperature, pressure, or lubricating properties, by always proving the meter under the specific operating conditions encountered. If any one of the specific operating conditions changes significantly, a new meter factor should be obtained by re-proving the meter.

The definition of meter factor as given in Chapter 1 of this manual is:

> *Meter factor*—A number obtained by dividing the actual volume of liquid passed through a meter during proving by the volume registered by that meter.

From the definition it is clear that:

$$\left.\begin{array}{l}\text{Actual meter}\\ \text{throughput at}\\ \text{operating conditions}\end{array}\right\} = \text{Indicated volume} \times MF \quad (14)$$

During proving, the temperature and pressure existing in the prover and in the meter are significant in calculating a meter factor. This is so because the actual volume of liquid passed through the meter during proving must be determined indirectly from a knowledge of the exact volume measured in the prover. This calculation involves pressure and temperature differences between the prover and the meter. As a result, standard measurement practice is first to correct the volume of the liquid in the prover to standard conditions (60°F and equilibrium pressure) and then also to correct the indicated volume during proving to what it would have been if the meter had operated at standard conditions.

Thus, in practical terms:

$$MF = \frac{\text{Volume of liquid in the prover corrected to standard conditions}}{\text{Change in meter reading corrected to standard conditions}} \quad (15)$$

It must be emphasized that a meter factor thus calculated is valid over a range of operating temperatures and pressures limited only by the consideration that the temperature and pressure during metering should not differ from the temperature and pressure during proving sufficiently to cause a significant change in the mechanical dimensions of the meter or in the viscosity of the metered liquid. Whether the differences are significant for a specific application can be determined by re-proving. In the application of meter factors to measurement tickets (see 12.2.8), the concept of a "volume at standard conditions" arises only because bulk custody transfers are measured in volumes which must be converted to a quantity represented by an equivalent volume-at-standard-conditions.

Thus:

$$\text{Actual metered volume} = \text{Indicated volume} \times MF \quad (16)$$

and

$$\text{Actual metered quantity} = \text{Indicated volume} \times (MF \times C_{tlm} \times C_{plm}) \quad (17)$$

C_{tlm} and C_{plm} are the appropriate correction factors for determining the equivalent volume at standard conditions from a measured volume at metering conditions.

In some metering applications, the variables MF and C_{plm} in Equation 17 are combined into a "composite meter factor." When such a composite meter factor is applied to the indicated volume of a temperature compensated meter (which automatically applies C_{tlm}), the metered quantity in barrels at standard conditions can be obtained by multiplying indicated volume by the composite MF alone.

It is important not to confuse a standard meter factor (Equation 15) with a composite meter factor. They are not interchangeable.

12.2.7.2 HIERARCHY OF ACCURACIES

Meter factors fit into the hierarchy of accuracies between calibrated prover volumes (12.2.6) and calculation of measurement tickets (12.2.8). Thus temperature readings for proving should be averaged and then rounded to the nearest 0.5°F. Pressure readings for proving should be averaged and then rounded to the nearest scale division, a pressure gage with its appropriate range having previously been selected.

12.2.7.3 RULE FOR ROUNDING—METER FACTORS

In calculating a meter factor, determine the numerator and denominator values separately, with each rounded to at least five significant digits. In intermediate calculations determine individual correction factors to four decimal places. Multiply individual correction factors together, rounding to four decimal places at each step (for each numerator and denominator), and record the combined correction factor (*CCF*) rounded to four decimal places. Divide corrected prover volume by corrected meter volume, and round the resulting meter factor to four decimal places.

12.2.7.4 CALCULATION OF THE METER FACTOR USING A TANK PROVER AND A DISPLACEMENT METER

In calculating a standard meter factor use Equation 15.

Determine the numerator by reading the upper gage glass of the tank; the indicated volume should be recorded to the nearest thousandth of a barrel. If the bottom gage glass was not at zero before the proving run was started, its reading must be added to or subtracted from (as the case may be) the upper gage glass reading, and the algebraic sum recorded as the indicated volume.

To calculate a meter factor, both prover and meter volumes must be in the same units. If the meter registers in barrels, record to 0.001 barrels, or if in gallons to the nearest 0.01 gallon, or to five significant digits. Read all prover

A. GENERAL INFORMATION

Proving report no.	Batch
API gravity 60.8	Rate, barrels/hour
Meter no.	Liquid motor gasoline
Prover location	Station
Date and time	Operator (signature)

B. DATA FROM PROVER TANK	Run 1	Run 2
1. Indicated volume, barrels	20.445	20.427
2. Prover starting temperature, top, °F	73.6	73.6
3. Prover starting temperature, middle, °F	73.6	73.6
4. Prover starting temperature, bottom, °F	73.4	73.4
5. Prover starting temperature, average (rounded), °F	73.5	73.5
6. C_{tsp} for prover (see Table A-1)	1.0003	1.0003
7. C_{tlp} for prover (see 11.1, Table 6)	0.9907	0.9907
8. CCF_p (Line 6 × Line 7)	0.9910	0.9910
9. Corrected prover volume, barrels (Line 1 × Line 8)	20.261	20.243

C. DATA FROM METER	Run 1	Run 2
10. Closing reading, barrels	14556.595	14683.494
11. Opening reading, barrels	14536.214	14663.155
12. Indicated volume, barrels	20.354	20.339
13. Temperature, °F	73.5	73.5
14. Pressure, pounds per square inch gage	40	40
15. C_{tlm} for meter (see 11.1, Table 6 or use 1.0000 if meter is temperature compensated)	0.9907	0.9907
16. C_{plm} for meter	1.0003	1.0003
17. CCF_m for meter (Line 15 × Line 16)	0.9910	0.9910
18. Corrected meter volume (Line 12 × Line 17)	20.171	20.156
19. *Meter factor (Line 9 ÷ Line 18)*	1.0045	1.0043

D. METER FACTOR

The meter factor to be used is the mean of the two runs 1.0044

Figure 4—Example Calculation for a Tank Prover and Displacement Meter

thermometers to 0.1°F, average them, round, and record to 0.5°F. Calculate the correction factors C_{ts} (see 12.2.5.1) and C_{tl} for the prover (see 12.2.5.3) and round them to four decimal places (that is, 0.9962). Multiply C_{ts} by C_{tl} to obtain *CCF* (see 12.2.5.5) and round to four decimal places. Multiply indicated volume by the *CCF* for the prover to obtain the corrected prover volume to 0.001 barrels.

Determine the denominator by subtracting the opening meter reading from the closing meter reading, both read or estimated to 0.001 of a barrel or 0.01 of a gallon. Record this reading as indicated meter volume. Calculate correction factors C_{tl} and C_{pl} for the meter and record to four decimal places. Multiply indicated meter volume by *CCF* for the meter to obtain the corrected meter reading to 0.001 barrel.

Calculate the meter factor by dividing the numerator by the denominator and round the meter factor to four decimal places.

The purpose of the above conventions is to establish standard procedures which will ensure the same results from the same data regardless of who or what does the computing. Any seeming sacrifice of hypothetical maximum accuracy is insignificant and must take second place to consistency. The standard procedures and conventions are based on the use of a simple desk calculator (not a scientific calculator) such as has traditionally been employed in the field, as well as by accounting personnel who may wish to check meter factor calculations. Accordingly, if meter proving reports calculated in the field are subsequently checked by a computer, the computer must be programmed in such a way as to reproduce the conventions described here. Remainders should not be held in memory; roundings should occur as described above.

12.2.7.5 EXAMPLE CALCULATION FOR A TANK PROVER AND DISPLACEMENT METER

A meter factor report form used for a nontemperature compensated displacement meter proved against a tank prover should allow for at least the information shown in Figure 4. Two runs are shown in the example, for each of which a run meter factor calculation is made separately; the two results are then averaged, the result obtained sometimes being called the "meter factor to be used." Note that this procedure differs from that employed with a pipe prover in which pulses, temperature, and pressure are averaged, and the meter factor is calculated from the average values of pulses, temperature, and pressure (see 12.2.7).

12.2.7.6 CALCULATION OF THE METER FACTOR USING PIPE PROVERS

12.2.7.6.1 General

Turbine meters and pipe provers were developed after displacement meters and tank provers; therefore, the procedure for calculating a meter factor for a turbine meter proved against a pipe prover was generally modeled on older procedure, but some changes were made.

Because a pipe prover is subject to the effects of both temperature and pressure on the steel, its base volume (which is at standard conditions) has to be corrected to obtain its volume at proving conditions. The volume of the displaced liquid must then be corrected to the equivalent volume at standard temperature and pressure. This latter value becomes the numerator in Equation 15 and the corrected meter volume becomes the denominator. For this procedure to be applied, the displacement meter must have a high resolution electrical output, that is, a large number of pulses per barrel so that at least 10,000 pulses or their equivalent are obtained.

The other rules and conventions discussed in 12.2.7.4 apply to calculation of a meter factor using a pipe prover and a turbine meter.

NOTE: The proper pulses-per-unit-volume figure for proving calculations.—It is important to bear in mind that when proving a turbine meter, or a displacement meter equipped with a high resolution electrical pulser, the change in the meter reading is rarely determined from the meter's normal totalizer register. Instead, the high speed pulses generated by the meter during the proving run are usually counted and displayed by a separate electronic proving counter. In some cases the pulses generated by the meter are multiplied by a totalizer scaling factor and/or a temperature compensating factor before being counted by the proving counter. In either case, it is critical that the "change in meter reading" required to calculate the meter factor be determined by dividing the number of counts from the counter by exactly the number of proving counts required by the meter's totalizer to register one unit of volume. For a displacement meter this is determined by the pulse per revolution rate of the electrical pulser and the gear ratio driving the mechanical register. For an electronic totalizer, the number of pulses at the meter required to register one unit of volume is generally the inverse of the product of the totalizer's scaler factor and its divider factor. Thus, a meter with its totalizer scaler set to multiply by 0.2500 and its divider set to divide by 100 (or multiply by 0.01) has a counts per unit volume of—

$$\frac{1}{0.2500 \times 0.01} = 400$$

If the pulses from the meter are passed through the scaler before being directed to the prover counter, then the appropriate counts or pulses-per-unit volume would be 100, as only 100 counts would be required at that point to register one unit of volume.

In any case, where the pulses at the point where the prover counter is connected have been corrected by a mechanical or electronic temperature compensator, the meter factor is calculated as for a temperature compensated meter; that is, without applying an additional C_{tl} factor in the denominator. When proving a turbine meter equipped with a temperature compensated totalizer, the meter factor is calculated as for a noncompensated meter if the prover counter is connected directly at the meter. In such a case, C_{tl} is applied in the denominator because the proving pulses are not temperature compensated.

The key distinction is that the pulses or counts-per-unit-volume figure used in the proving report form calculation is determined by the settings and arrangement of the totalizer used with the meter rather than by the particular pulse-per-unit-volume characteristic of the meter itself.

12.2.7.6.2 Example Calculation for a Pipe Prover, Turbine Meter, and Liquid of Low Vapor Pressure

Figure 5 provides an example calculation for a pipe prover with a turbine meter on a liquid of low vapor pressure.

A. GENERAL INFORMATION

Proving report no. ____	Batch ____
API gravity *63.7*	Prover dimensions *14" pipe, 0.312" wall*
Rate, barrels/hour *1570*	Liquid ____
Meter no. ____	Station ____
Totalizer pulses per barrel *1000*	
Date and time ____	Operator ____ (signature)

B. DATA FROM PROVING RUNS

	Temperature, °F		Pressure, psig		
Run no.	Prover	Meter	Prover	Meter	Pulse Count
1	*63.0*	*64.5*	*80*	*62*	*17743*
2	*63.0*	*64.5*	*80*	*62*	*17744*
3	*63.5*	*64.5*	*80*	*62*	*17746*

Figure 5 Example Calculation of a Pipe Prover, Turbine Meter, and a Liquid of Low Vapor Pressure (Continued on Page 14)

4	*64.0*	*65.5*	*80*	*62*	*17746*
5	*64.0*	*65.5*	*80*	*62*	*17747*
Averages	*63.5*	*64.9*	*80*	*62*	*17745.2*
1. Averages (rounded)	*63.5*	*65.0*	*80*	*62*	*17745*

2. Meter volume

Metered volume = *17745* ÷ *1000* = *17.745 barrels*

NOTES:
1. Average temperatures are rounded to the nearest half degree Fahrenheit.
2. Pressures are read to the nearest scale division, which in this case is assumed to be in 2 pound per square inch increments.
3. Pulse count is divided by the totalizer pulses per barrel (in this case 1000) and reported as barrels, rounded to three places.

C.	**DATA FOR PROVER**	
3.	Base volume of prover, barrels	*17.654*
4.	C_{tsp} (see 12.2.5.1)	*1.0001*
5.	C_{psp} (see 12.2.5.2)	*1.0001*
6.	C_{tlp} (see 12.2.5.3) (see 11.1, Table 6)	*0.9975*
7.	C_{plp} (see 12.2.5.4)	*1.0007*
8.	CCF_p (see 12.2.5.5) (Lines 4 × 5 × 6 × 7) (rounded to four decimal places at each step)	*0.9984*
9.	Corrected prover volume, barrels (Line 3 × Line 8)	*17.626*
D.	**DATA FOR METER**	
10.	C_{tlm} (see 12.2.5.3) (see 11.1, Table 6)	*0.9965*
11.	C_{plm} (see 12.2.5.4)	*1.0005*
12.	CCF_m (Line 10 × Line 11)	*0.9970*
13.	Corrected meter volume (Line 9 × Line 12)	*17.692*
E.	**METER FACTOR**	
14.	Meter factor (Line 9 ÷ Line 13)	*0.9963*

Figure 5—Example Calculation for a Pipe Prover, Turbine Meter, and a Liquid of Low Vapor Pressure (Continued)

12.2.7.6.3 Example Calculation for a Turbine Meter, Pipe Prover, and Liquid of Vapor Pressure Above Atmospheric

It is assumed for this example, see Figure 6, that the liquid measured is a propane mix of a specific gravity at 60°F of 0.554 and that a nontemperature compensated turbine meter and bidirectional pipe prover are used.

In this example, the equilibrium pressure P_e is given as 115 pounds per square inch gage determined by the method explained in the note to 12.2.5.4.

The value of F for the meter can be read from the table of compressibilities vs. relative density (see Chapter 11.2) in this case by entering the temperature at 76.5°F and by reading against the column for 0.554 specific gravity, a value of 0.0000285. The value of C_{pl} (Line 11) using Equation 9 works out to 1.0080 rounded to four decimal places.

The value of F for the prover is calculated likewise except that the pressure P is 385 pounds per square inch gage and the temperature t is 77.0°F, giving a value for C_{pl} (Line 6) of 1.0078 rounded.

For C_{tl} values see 12.2.5.3, for C_{ts} see 12.2.5.1, and for C_{ps} see 12.2.5.2, for which references to are also shown in the example.

For both meter and prover a combined correction factor (CCF) is calculated according to instructions in 12.2.5.5.

12.2.8 Calculation of Measurement Tickets

12.2.8.1 PURPOSE AND IMPLICATIONS

The purpose of standardizing the terms and arithmetical procedures employed in calculating the amounts of petroleum liquid on a measurement ticket is to avoid disagreement between the parties involved. The standardized procedures for calculation aim at obtaining the same answer from the same measurement data, regardless of who or what does the computing.

A *measurement ticket* is a written acknowledgment of a receipt for delivery of crude oil or petroleum product. If a change in ownership or custody occurs during the transfer, the measurement ticket serves as an agreement between the authorized representatives of the parties concerned as to the measured quantities and tested qualities of the liquids transferred.

Care must be taken to ensure that all copies of a measurement ticket are legible. Standard procedure forbids making corrections or erasures on a measurement ticket unless the interested parties agree to do so and initial the ticket to that effect. Should a mistake be made, the ticket should be marked VOID and a new ticket prepared. If the voided ticket has mechanically printed numbers on it which cannot be reprinted on the new ticket, the voided ticket should be clipped to the new one to support the validity of such printed numbers.

12.2.8.2 TERMS

Standard conditions mean 60°F and atmospheric pressure

A. GENERAL INFORMATION

Proving report no. ______

Batch ______

Specific gravity *0.554*

Meter size *1½*

Totalizer pulses per barrel *13188*

Prover dimensions *12" pipe, 0.375" wall*

Date and time ______

Company ______

Prover type ______

Vapor pressure (at operating temperature) *115*

Meter manufacturer ______

Liquid *propane mix*

Base prover volume, barrels *2.0734*

Station ______

Operator's name ______

______ (signature)

B. DATA FROM PROVING RUNS

	Temperature, °F		Pressure, psig		Pulse Count/
Run No.	Prover	Meter	Prover	Meter	Round Trip
1	*76.6*	*76.0*	*385*	*395*	*28629*
2	*76.8*	*76.8*	*385*	*395*	*28626*
3	*76.8*	*76.0*	*385*	*395*	*28635*
4	*77.6*	*77.0*	*385*	*395*	*28634*
5	*77.0*	*77.2*	*385*	*395*	*28633*
6	*77.0*	*76.6*	*385*	*395*	*28631*
Averages	*77.0*	*76.6*	*385*	*395*	*28631.3*
1. Averages (rounded)	*77.0*	*76.5*	*385*	*395*	*28631*

NOTES:
1. Average temperatures are rounded to the nearest half degree Fahrenheit.
2. Pressures are read to the nearest scale division.
3. Pulse count is rounded to the nearest count.

2. Base volume of prover, barrels	*2.0734*
3. C_{tsp} (see 12.2.5.1)	*1.0003*
4. C_{psp} (see 12.2.5.2)	*1.0004*
5. C_{tlp} (see 12.2.5.3) (see 11.1, Table 6)	*0.9780*
6. C_{plp} (see 12.2.5.4)	*1.0078*
7. CCF_p (Lines 3 × 4 × 5 × 6)	*0.9863*
8. Corrected prover volume, barrels (Line 2 × Line 8)	*2.0450*

C. DATA FOR METER

9. Metered volume (Line 2 ÷ pulses/barrel)

28631 ÷ *13188* = *2.1710*

10. C_{tlm} (see 12.2.5.3) (see 11.1, Table 6)	*0.9789*
11. C_{plm} (see 12.2.5.4)	*1.0080*
12. CCF_m (Line 10 × Line 11)	*0.9867*
13. Corrected metered volume, barrels	*2.1421*

D. METER FACTOR

14. Meter factor (Line 8 ÷ Line 13)	*0.9547*

Figure 6—Example Calculation for a Turbine Meter and Pipe Prover with a Liquid of a Vapor Pressure Above Atmospheric

(0 pounds per square inch gage). In the case of liquids having an equilibrium pressure above 0 gage at 60°F, the standard conditions are 60°F and the equilibrium pressure of the liquid at 60°F.

A *barrel* is a unit volume equal to 9702.0 cubic inches, and a *gallon* is a unit volume equal to 231.0 cubic inches.

Volumes are expressed in barrels or gallons with the several terms incorporating the word volume having the meanings described below.

Indicated volume is the change in meter reading that occurs during a receipt or delivery. The word *registration*, though not preferred, often has the same meaning.

Gross volume is the indicated volume multiplied by the meter factor for the particular liquid and flow rate under which the meter was proved. This is a volume measurement.

Gross volume at standard temperature is the gross volume multiplied by C_{tl} (see 12.2.5.3), the values of which may be found in Tables 6 or Tables 24 (see Chapter 11.1). If a meter is equipped with a temperature compensator, the change in meter reading during a receipt or delivery will be an indicated volume at standard temperature, which when multiplied by the meter factor becomes a gross volume at standard temperature.

Gross standard volume is the gross volume at standard temperature, corrected also to standard pressure, and is therefore a quantity measurement. The factor for correcting a volume to standard pressure is called C_{pl} (see 12.2.5.4).

In summary (for a nontemperature compensated meter):

$$\begin{array}{l}\text{Gross}\\ \text{standard}\\ \text{volume}\end{array} = \left[\begin{pmatrix}\text{Closing}\\ \text{meter}\\ \text{reading}\end{pmatrix} - \begin{pmatrix}\text{Opening}\\ \text{meter}\\ \text{reading}\end{pmatrix}\right] \times [MF \times C_{tl} \times C_{pl}]$$

Net standard volume is the same as gross standard volume for refined products. When referred to crude oil, it means that the determined percentage of sediment and water has been deducted. It is sometimes called "standard barrels of net clean oil." The correction factor for sediment and water (S&W) is:

$$C_{sw} = 1 - \%\ \text{S\&W}/100$$

Therefore:

$$\begin{array}{l}\text{Net}\\ \text{standard}\\ \text{volume}\end{array} = \left[\begin{pmatrix}\text{Closing}\\ \text{meter}\\ \text{reading}\end{pmatrix} - \begin{pmatrix}\text{Opening}\\ \text{meter}\\ \text{reading}\end{pmatrix}\right] \times [MF \times C_{tl} \times C_{pl} \times C_{sw}]$$

A *reading* or meter reading is the instantaneous display on a meter head. When the difference between a closing and an opening reading is being discussed, such difference should be called an indicated volume.

Measurement ticket is the generalized term used in this publication to embrace and supersede expressions of long standing such as "run ticket," "receipt and delivery ticket," and other terms. It is also used to mean whatever the supporting pieces of paper or readout happen to be in a meter station that is automated, remotely controlled, and/or computerized.

12.2.8.3 RULE FOR ROUNDING—MEASUREMENT TICKETS

In calculating a net standard volume, record temperatures to the nearest whole degree Farenheit and pressures to the nearest scale reading line. Tables of correction factors should be used, with values expressed to four decimal places.

Multiply the meter factor to be used by the correction factors, rounding to four decimal places at each step in this intermediate calculation. Round the combined correction factor (*CCF*, which in this situation includes a meter factor value and C_{sw}) to four decimal places. Round the resulting net standard volume to the nearest whole barrel or whole gallon, as the case may be.

12.2.8.4 CORRECTION FACTORS

The correction factors that apply to measurement tickets, and their notation, are explained in 12.2.5. In measurement tickets for crude oil another correction factor is introduced to allow for known volumes of sediment and water (S&W). The value of this correction factor (C_{sw}) is 1 − [%S&W/100]. Like the corrections for temperature and pressure, it too should be combined into the *CCF* (see 12.2.5.5) when calculating measurement tickets.

12.2.8.5 HIERARCHY OF ACCURACIES

The hierarchy of accuracies assigns measurement ticket values to a level below meter factor calculations because the accumulated uncertainties entering the calibration of provers, and then entering the calculation of meter factors, makes it unrealistic to assign a higher position. Thus, only four decimal places in the correction factors are warranted, and the conventions for rounding and truncating are necessary in order to obtain the same value from the same data regardless of who or what does the computing.

12.2.8.6 STANDARD PROCEDURES

Meter readings shall be truncated so that fractions of a standard unit (barrels or gallons) are eliminated (not rounded) and the indicated volume determined therefrom shall enter the calculation for net standard volume. (Should it be agreed between the interested parties to employ a unit larger than a barrel, such as a unit of 10 barrels, the truncation will eliminate anything less than such a unit.)

For example:.

	Displayed Value	Truncated Value
Closing reading	3.867.455.2	3.867.455
Opening reading	3.814.326.9	3.814.326
Volume by difference	53.128.3	53.129

Non-resettable counters should be employed.

Temperature shall be read and rounded to the nearest whole degree Farenheit.

Pressures shall be read and rounded to the nearest scale reading.

12.2.8.7 CONVENTIONS

In order to avoid multiplying a large number (for example. an indicated volume) by a small number (for example. a correction factor) over and over again. and possibly losing significance in the process. obtain the combined correction factor (*CCF*) first and only then. multiply the indicated volume by the *CCF* (see 12.2.5.5). Multiply each correction factor by the next one. and round to four decimal places at each step. Report all correction factors to four decimal places. including the *CCF*.

12.2.8.8 EXAMPLE MEASUREMENT TICKET FOR A LOW VAPOR PRESSURE LIQUID

A measurement ticket form should allow for the recording of at least the data shown in Figure 7 and the calculated values. The example applies to a nontemperature compensated meter.

A. GENERAL INFORMATION

Ticket no. ______	Month/day/year ______
Time started ______	Time finished ______
Measuring station ______	Delivered to ______
Liquid *crude oil*	Batch ______
Sediment and water *0.15%*	API gravity at 60°F (see Note 1) *39.6°API*
Remarks ______	Witness name ______ (signature)
	Operator's name ______ (signature)

B. MEASUREMENT INFORMATION

1.	Closing meter reading (truncated), barrels	*3.867.455*
2.	Opening meter reading (truncated), barrels	*3.814.326*
3.	Indicated volume, barrels	*53.129*
4.	Meter factor *1.0016* from Report No. ______	
5.	Average stream temperature, °F	*88*
6.	C_{tlm} (see 11.1, Table 6)	*0.9860*
7.	Average meter pressure, psig	*370*
8.	C_{plm}	*1.0022*
9.	Sediment and water (if applicable), percent	*0.15*
10.	C_{sw} (For dry, clean products, use 1.0000)	*0.9985*
11.	Combined correction factor, CCF_m (Lines 4 × 6 × 8 × 10)	*0.9983*
12.	Net standard volume, barrels (Line 3 × 11)	*52.507*

NOTE 1: Gravity is assumed to be rounded to .5 degrees API.

Figure 7—Example Measurement Ticket for a Low Vapor Pressure Liquid

APPENDIX A

CORRECTION FACTORS FOR STEEL

Table A-1—Temperature Correction Factors for Mild Steel, C_{ts}
Table A-2—Temperature Correction Factors for Stainless Steel, C_{ts}
Table A-3—Pressure Correction Factors for Steel, C_{ps}

Table A-1—Temperature Correction Factors for Mild Steel

C_{ts} for mild steel having a cubical coefficient of expansion of 1.86×10^{-5} per °F

Observed Temperature, °F	C_{ts} Value	Observed Temperature, °F	C_{ts} Value
−7.2– −1.9	0.9988	73.5– 78.8	1.0003
−1.8– 3.5	0.9989	78.9– 84.1	1.0004
3.6– 8.9	0.9990	84.2– 89.5	1.0005
9.0– 14.3	0.9991	89.6– 94.9	1.0006
14.4– 19.6	0.9992	95.0–100.3	1.0007
19.7– 25.0	0.9993	100.4–105.6	1.0008
25.1– 30.4	0.9994	105.7–111.0	1.0009
30.5– 35.8	0.9995	111.1–116.4	1.0010
35.9– 41.1	0.9996	116.5–121.8	1.0011
41.2– 46.5	0.9997	121.9–127.2	1.0012
46.6– 51.9	0.9998	127.3–132.5	1.0013
52.0– 57.3	0.9999	132.6–137.9	1.0014
57.4– 62.6	1.0000	138.0–143.3	1.0015
62.7– 68.0	1.0001	143.4–148.7	1.0016
68.1– 73.4	1.0002	148.8–154.0	1.0017

NOTE: This table is suitable for application in meter proving; in prover calibration use the formulas. For the formula used to derive the tabulated values and to calculate values, see 12.2.5.1.

Table A-2—Temperature Correction Factors for Stainless Steel

C_{ts} for stainless steel having a cubical coefficient of expansion of 2.65×10^{-5} per °F

Observed Temperature, °F	C_{ts} Value	Observed Temperature, °F	C_{ts} Value
−9.8– −6.1	0.9982	73.3– 76.9	1.0004
−6.0– −2.3	0.9983	77.0– 80.7	1.0005
−2.2– 1.5	0.9984	80.8– 84.5	1.0006
1.6– 5.2	0.9985	84.6– 88.3	1.0007
5.3– 9.0	0.9986	88.4– 92.0	1.0008
9.1– 12.8	0.9987	92.1– 95.8	1.0009
12.9– 16.6	0.9988	95.9– 99.6	1.0010
16.7– 20.3	0.9989	99.7–103.3	1.0011
20.4– 24.1	0.9990	103.4–107.1	1.0012
24.2– 27.9	0.9991	107.2–110.9	1.0013
28.0– 31.6	0.9992	111.0–114.7	1.0014
31.7– 35.4	0.9993	114.8–118.4	1.0015
35.5– 39.2	0.9994	118.5–122.2	1.0016
39.3– 43.0	0.9995	122.3–126.0	1.0017
43.1– 46.7	0.9996	126.1–129.8	1.0018
46.8– 50.5	0.9997	129.9–133.5	1.0019
50.6– 54.3	0.9998	133.6–137.3	1.0020
54.4– 58.1	0.9999	137.4–141.1	1.0021
58.2– 61.8	1.0000	141.2–144.9	1.0022
61.9– 65.6	1.0001	145.0–148.6	1.0023
65.7– 69.4	1.0002	148.7–152.4	1.0024
69.5– 73.2	1.0003	152.5–156.2	1.0025

NOTE: This table is suitable for application in meter proving; in prover calibration use the formulas. For the formula used to derive the tabulated values and to calculate the values, see 12.2.5.1.

Table A-3—Pressure Correction Factors for Steel, C_{ps}

(All measurements are in pounds per square inch gage.)

Factor C_{ps}	Prover Dimensions									Factor C_{ps}
	6-In. Pipe 0.25-In. Wall	6-In. Pipe 0.280-In. Wall	8-In. Pipe 0.322-In. Wall	8-In. Pipe 0.375-In. Wall	10-In. Pipe 0.365-In. Wall	10-In. Pipe 0.375-In. Wall	12-In. Pipe 0.375-In. Wall	14-In. Pipe 0.312-In. Wall	14-In. Pipe 0.375-In Wall	
1.0000	0- 61	0- 69	0- 60	0- 71	0 - 54	0- 56	0- 46	0- 34	0- 42	1.0000
1.0001	62-183	70-207	61-181	72-214	55 -163	57-168	47-140	35-104	43-127	1.0001
1.0002	184-306	208-346	182-302	215-357	164 -273	169-281	141-234	105-174	128-212	1.0002
1.0003	307-428	347-484	303-423	358-499	274 -382	282-393	235-328	175-244	213-297	1.0003
1.0004	429-551	485-623	424-544	500-642	383 -491	394-506	329-421	245-314	298-382	1.0004
1.0005	552-673	624-761	545-665	643-785	492 -601	507-618	422-515	315-384	383-466	1.0005
1.0006	674-795	762-900	666-786	786-928	602 -701	619-731	516-609	385-454	467-551	1.0006
1.0007	796-918	901-1038	787-907	929-1071	711 -819	732-843	610-703	455-524	552-636	1.0007
1.0008	919-1040		908-1028		820 -928	844-956	704-796	525-594	637-721	1.0008
1.0009					929 -1038	957-1068	797-890	595-664	722-806	1.0009
1.0010							891-984	665-734	807-891	1.0010
1.0011							985-1078	735-804	892-976	1.0011
1.0012								805-874	977-1061	1.0012
1.0013								875-944		1.0013
1.0014								945-1014		1.0014
1.0015										1.0015
1.0016										1.0016
1.0017										1.0017
1.0018										1.0018
1.0019										1.0019
1.0020										1.0020
1.0021										1.0021
1.0022										1.0022
1.0023										1.0023
1.0024										1.0024

Table A-3—Pressure Correction Factors for Steel, C_{ps} (Continued)

(All measurements are in pounds per square inch gage.)

Factor C_{ps}	Prover Dimensions: 16-in. Pipe 0.375-in. Wall	18-in. Pipe 0.375-in. Wall	20-in. Pipe 0.375-in. Wall	24-in. Pipe 0.375-in. Wall	26-in. Pipe 0.375-in. Wall	26-in. Pipe 0.500-in. Wall	30-in. Pipe 0.500-in. Wall	30-in. Pipe 0.500-in. Wall	Factor C_{ps}
1.0000	0- 36	0- 32	0- 29	0- 24	0- 22	0- 30	0- 25	0- 21	1.0000
1.0001	37-110	33- 97	30-087	25- 72	23- 66	31- 89	26- 77	22- 64	1.0001
1.0002	111-184	98-163	88-146	73-120	67-111	90-150	78-129	65-107	1.0002
1.0003	185-258	164-228	147-204	121-169	112-155	151-209	130-181	108-149	1.0003
1.0004	259-331	229-293	205-262	170-217	156-200	210-270	182-232	150-192	1.0004
1.0005	332-405	294-358	263-321	218-266	201-245	271-329	233-284	193-235	1.0005
1.0006	406-479	359-423	322-379	267-314	246-289	330-390	285-336	236-278	1.0006
1.0007	480-553	424-489	380-438	315-362	290-334	391-449	337-387	279-321	1.0007
1.0008	554-627	490-554	439-496	363-411	335-378	450-510	388-439	322-364	1.0008
1.0009	628-700	555-619	497-555	412-459	379-423	511-569	440-491	365-407	1.0009
1.0010	701-774	620-684	556-613	460-508	424-467	570-630	492-543	408-450	1.0010
1.0011	775-848	685-749	614-672	509-556	468-512	631-689	544-594	451-492	1.0011
1.0012	849-922	750-815	673-730	557-604	513-556	690-750	595-646	493-535	1.0012
1.0013	923-995	816-880	731-788	605-653	557-601	751-809	647-698	536-578	1.0013
1.0014	996-1069	881-945	789-847	654-701	602-646	810-870	699-750	579-621	1.0014
1.0015		946-1010	848-905	702-749	647-690	871-929	751-801	622-664	1.0015
1.0016			906-964	750-798	691-735	930-990	802-853	665-707	1.0016
1.0017			965-1022	799-846	736-779	991-1049	854-905	708-749	1.0017
1.0018				847-895	780-824		906-956	750-792	1.0018
1.0019				896-943	825-868		957-1008	793-835	1.0019
1.0020				944-991	869-913			836-878	1.0020
1.0021				992-1040	914-957			879-921	1.0021
1.0021					958-1002			922-964	1.0022
1.0022								965-1007	1.0023
1.0023									1.0024
1.0024									

NOTES:

1. This table is based on the following equation:

$$C_{ps} = 1 + \frac{P_p - P_b D}{E t}$$

Where:

C_{ps} = steel correction factor for pressure to account for the change in volume with the change in pressure.
P_p = operating or observed pressure, in pounds per square inch gage.
P_b = Pressure, in pounds per square inch gage, at which the base volume of the prover was determined (usually, 0 pounds per square inch gage).
D = internal diameter of the pipe in the prover section, in inches.
E = modulus of elasticity for steel equals (30)(10^6).
t = wall thickness of the pipe in the prover section, in inches.

2. This table is suitable for application in meter proving; in prover calibrations, use the formula (see F12.2.5.2).

APPENDIX B

CORRECTIONS TO OFFSET THE EFFECTS OF TEMPERATURE ON METAL SHELLS

This appendix presents the derivations of the corrections necessary to offset the effects of temperature on the metal shells of both the field standard test measures and the prover they are used to calibrate.

The general equation for determining the base volume of a prover by water drawing it with field standard test measures is:

$$PBV = [V_M \times C_{tdw}] \times \left[\frac{C_{tsM}}{C_{tsp} \times C_{psp} \times C_{plp}}\right] \quad \text{(B1)}$$

Where:

PBV = the prover base volume at 60°F and 0 pounds per square inch gage.

V_M = the indicated volume in the test measure.

C_{tsM} = the correction for the temperature of the steel shell of the test measure (see 12.2.5.1).

C_{tdw} = the correction for the temperature difference between the water when in the individual test measures and the water when in the prover. (This factor must be used out of sequence.) It can be obtained from tabulated values in Chapter 11.4.2.

C_{plp} = the correction for pressure on the water in the prover (see 12.2.5.4).

C_{tsp} = the correction for the temperature of the steel shell of the prover (see 12.2.5.1).

C_{psp} = the correction for the pressure on the steel shell of the prover (see 12.2.5.2).

For the purpose of discussion, or even of calculation, the two corrections for the temperature of the steel shell can be combined as follows:

$$CC_{ts} = \left(\frac{C_{tsM}}{C_{tsp}}\right) = \left(\frac{1 + (T_M - 60)\gamma_M}{1 + (T_p - 60)\gamma_p}\right) \quad \text{(B2)}$$

Where:

CC_{ts} = the combined correction factor for the effect of temperature on the steel of both the prover and the measure.

T_M and T_p = the temperatures of the steel shells of the measure and the prover, respectively, generally taken as equal to the temperature of the water contained therein.

γ_M and γ_p = the coefficients of cubical expansion of the materials of the measure and the prover, respectively.

Multiplying both the numerator and denominator of Equation B2 by $1 - (T_p - 60)\gamma_p$ and dropping the second order infinitesimals as negligible gives:

$$CC_{ts} = 1 + (T_M - 60)\gamma_M - (T_p - 60)\gamma_p \quad \text{(B3)}$$

Equation B3 is the general case.

For the special case when the prover and the test measures are made of the same material—

$$\gamma_M = \gamma_p = \gamma$$

and

$$CC_{ts} = 1 + (T_M - T_p)\gamma \quad \text{(B4)}$$

For the other special case when the prover and the test measure are at the same temperature but are made of different materials—

$$T_M = T_p = T$$

and

$$CC_{ts} = 1 + (T - 60)(\gamma_M - \gamma_p) \quad \text{(B5)}$$

Equations B4 and B5 are the corrections discussed in Section 7.2 and Section 7.3 of the National Bureau of Standards Monograph 62, *Testing of Metal Volumetric Standards*. The general case value for all combinations of temperatures and materials, however, is covered by Equation B2 and is used in B1.

With respect to Equation B1 it should be noted that in practice the value of C_{tdw} is determined for each test measure withdrawn and applied to the volume in that test measure. These corrected volumes are then summed and the remaining corrections are applied to the sum. In that case T_M is taken as the volume-weighted average temperature of all the measures withdrawn. This practice is acceptable for the normal range of temperature experienced because the cubical coefficient of thermal expansion of the usual metals is only about one-tenth that of water. Equation B1 then becomes:

$$PBV = \Sigma[V_n \times C_{tdw}]i \times \left[\frac{C_{tsM}}{C_{tsp} \times C_{psp} \times C_{plp}}\right] \quad \text{(B6)}$$

It should be noted that while the coefficient of cubical expansion of mild steel is usually 1.86×10^{-5}, the coefficient for stainless steel and other metals generally varies with the composition of the metal, and only those values given by the manufacturer of the test measures or prover should be used.

As an example of the extent to which the failure to apply the steel temperature corrections affects the prover base volume, consider the case where both the measures and the prover are made of mild steel but the temperature in the test measures is 87°F while the temperature in the prover at the beginning of the water draw is 78°F. Then:

$$\frac{C_{tsM}}{C_{tsp}} = \frac{1 + [(87 - 60) \times 1.86 \times 10^{-5}]}{1 + [(78 - 60) \times 1.86 \times 10^{-5}]} = 1.000167$$

Failure to apply these corrections in Equation B6 would therefore result in understating the prover base volume by 0.0167 percent.

Thus it can be seen that the statement in Paragraph 2125 of API Standard 1101, "If the test measure and the prover are made of the same material, no correction of the volume of the prover to 60°F need be made," is true only if the temperature in the prover differs from the temperature in the test measure by 3°F or less.

APPENDIX C

SAMPLE METER PROVING REPORT FORMS

General Purpose Meter Proving Report for Use with Pipe Provers
Meter Proving Report for Tank Prover Method
Meter Proving Report for Master Meter Method

GENERAL PURPOSE METER PROVING REPORT
FOR USE WITH PIPE PROVERS

LOCATION	DATE	AMBIENT TEMP.	REPORT NO.

PROVER DATA

BASE VOLUME AT 60°F AND "0" psi.	SIZE	WALL
bbl.		

PREVIOUS REPORT

FLOW RATE	FACTOR	DATE
bbl/hr.		

METER DATA

SERIAL NO.	METER NO.	PULSES/bbl.	TEMP. COMP.	MANUF.	SIZE	MODEL

FLOW RATE	NON-RESET TOTALIZER
bbl/hr.	

RUN DATA

TEMPERATURE		PRESSURE		TOTAL PULSES	RUN NO.
PROVER AVG.	METER	PROVER	METER		
					1
					2
					3
					4
					5
					6
					7
					8
					9
					10
					AVG.

C_{ts} = CORRECTION FOR TEMPERATURE ON STEEL

C_{ps} = CORRECTION FOR PRESSURE ON STEEL

C_{tl} = CORRECTION FOR TEMPERATURE ON LIQUID TABLE 6 OR TABLE 24 FOR LPGs

C_{pl} = CORRECTION FOR PRESSURE ON LIQUID

LIQUID DATA

TYPE	API GRAVITY	SPECIFIC GRAVITY	R.V. PRESS	BATCH/TENDER NO.
	AT 60°F	AT 60°F		

FIELD CALCULATIONS

PROVER VOLUME X [C_{ts} X C_{ps} X C_{tl} X C_{pl}] = CORRECTED PROVER VOLUME

AVERAGE PULSES ÷ PULSES/bbl. = GROSS METER VOL. X [C_{tl} USE ONLY FOR NONTEMP. COMP. METER X C_{pl}] = CORRECTED METER VOLUME

CORRECTED PROVER VOLUME ÷ CORRECTED METER VOLUME = METER FACTOR

X C_{pl} LIQUID CORR. FOR PRESS. AT METERING COND. = COMPOSITE FACTOR USE FOR CONSTANT PRESSURE APPLICATIONS

REMARKS, REPAIRS, ADJUSTMENTS, ETC., ______

SIGNATURE	DATE	COMPANY REPRESENTED

METER PROVING REPORT FOR TANK PROVER METHOD

LOCATION	TENDER	LIQUID	°API	DATE	AMBIENT TEMP.	REPORT NO.

PROVER DATA		PREVIOUS REPORT NO. ______		
NOMINAL VOLUME AT 60°F AND "0" psig.	SERIAL NO.	FLOW RATE	FACTOR	DATE
gal/bbl		bbl/hr		

METER DATA					
SERIAL NO.	METER NO.	TEMP. COMPENSATED	MANUFACTURER	SIZE	MODEL
		☐ YES ☐ NO			

FLOW RATE	NON RESET COUNTER
bbl/hr	

REMARKS, REPAIRS, ADJUSTMENTS, ETC.

	PROVER TANK VOLUME DATA	RUN NO. 1	RUN NO. 2	RUN NO. 3	RUN NO. 4
1	DELIVERY TO TANK, gal/bbls				
2	TANK TEMPERATURE (AVERAGE) °F				
3	C_{ts}				
4	C_{tl}				
5	COMBINED CORRECTION FACTOR (LINE 3 × LINE 4)				
6	CORRECTED PROVER VOLUME (LINE 1 × LINE 5)				

	PROVED METER DATA				
7	FINAL METER READING				
8	INITIAL METER READING				
9	INDICATED VOLUME BY METER, bbls (LINE 7 − LINE 8)				
10	INDICATED VOLUME BY METER, gals (LINE 7 − LINE 8) OR (42 × LINE 9)				
11	TEMPERATURE AT METER, °F				
12	PRESSURE AT METER, psig				
13	C_{tl} USE 1.000 IF TEMP. COMPENSATED				
14	C_{pl}				
15	CCF (LINE 13 × LINE 14)				
16	CORRECTED METER VOLUME (LINE 10 × LINE 13)				
17	METER FACTOR (LINE 6 ÷ LINE 16)				

METER FACTOR (AVERAGE VALUE)	X	C_{pl} LIQUID CORRECTION FOR PRESSURE AT METERING CONDITIONS	=	COMPOSITE FACTOR USE FOR CONSTANT PRESSURE APPLICATION

SIGNATURE	DATE	COMPANY REPRESENTATIVE

METER PROVING REPORT FOR MASTER METER METHOD

LOCATION	TENDER	LIQUID	°API	DATE	AMBIENT TEMP.	REPORT NO.

METER DATA						
SERIAL NO.	METER NO.	PULSES/bbl	TEMP. COMPENSATED	MANUFACTURER	SIZE	MODEL

FLOW RATE	NON RESET COUNTER

PREVIOUS REPORT NO. __________

FLOW RATE	FACTOR	DATE
bbl/hr.		

MASTER METER DATA MAKE: ________ SIZE ______ MODEL ______ SERIAL NO. ______

1	CLOSING READING, bbls/gals					
2	OPENING READING, bbls/gals					
3	INDICATED VOLUME (LINE 1 − LINE 2)					
4	TEMPERATURE AT METER, °F					
5	PRESSURE AT METER, psig					
6	MASTER METER FACTOR					
7	C_{tl}					
8	C_{pl}					
9	CCF (LINE 6 × LINE 7 × LINE 8)					
10	CORRECTED PROVER VOLUME (LINE 3 × LINE 9)					

PROVED METER DATA

11	CLOSING METER READING, bbls/gals					
12	OPENING METER READING, bbls/gals					
13	INDICATED VOLUME (LINE 11 − LINE 12)					
14	TEMPERATURE AT METER, °F					
15	PRESSURE AT METER, psig					
16	C_{tl}					
17	C_{pl}					
18	CCF (LINE 16 × LINE 17)					
19	CORRECTED METER VOLUME (LINE 13 × LINE 18)					
20	METER FACTOR (LINE 10 ÷ LINE 19)					

METER FACTOR (AVERAGE VALUE)	×	C_{pl} LIQUID CORRECTION FOR PRESSURE AT METERING CONDITIONS	=	COMPOSITE FACTOR USE FOR CONSTANT PRESSURE APPLICATION

SIGNATURE	DATE	COMPANY REPRESENTATIVE

APPENDIX D

CHAPTERS 22 AND 23 FROM NBS HANDBOOK 91[1]

CHAPTER 22—NOTES ON STATISTICAL COMPUTATIONS

22-1 Coding in Statistical Computations

Coding is the term used when arithmetical operations are applied to the original data in order to make the numbers easier to handle in computation. The possible coding operations are:

(a) Multiplication (or its inverse, division) to change the order of magnitude of the recorded numbers for computing purposes.

(b) Addition (or its inverse, subtraction) of a constant—applied to recorded numbers which are nearly equal, to reduce the number of figures which need be carried in computation.

When the recorded results contain non-significant zeros, (e.g., numbers like .000121 or like 11,100), coding is clearly desirable. There obviously is no point in copying these zeros a large number of times, or in adding additional useless zeros when squaring, etc. Of course, these results could have been given as 121×10^{-6} or 11.1×10^{3}, in which case coding for order of magnitude would not be necessary.

The purpose of coding is to save labor in computation. On the other hand, the process of coding and decoding the results introduces more opportunities for error in computation. The decision of whether to code or not must be considered carefully, weighing the advantage of saved labor against the disadvantage of more likely mistakes. With this in mind, the following five rules are given for coding and decoding.

1. The whole set of observed results must be treated alike.

2. The possible coding operations are the two general types of arithmetic operations:

   (a) addition (or subtraction); and,

   (b) multiplication (or division). Either (a) or (b), or both together, may be used as necessary to make the original numbers more tractable.

3. Careful note must be kept of how the data have been coded.

4. The desired computation is performed on the coded data.

5. The process of decoding a computed result depends on the computation that has been performed, and is indicated separately for several common computations, in the following Paragraphs (a) through (d).

(a) *The mean* is affected by every coding operation. Therefore, we must apply the inverse operation and reverse the order of operations used in coding, to put the coded mean back into original units. For example, if the data have been coded by first multiplying by 10,000 and then subtracting 120, decode the mean by adding 120 and then dividing by 10,000.

	Observed Results		Coded Results
	.0121		1
	.0130		10
	.0125		5
Mean	.0125	Coded mean	5

Decoding:

$$\text{Mean} = \frac{\text{Coded mean} \div 120}{10{,}000} = \frac{25}{10{,}000} = .0125$$

(b) *A standard deviation* computed on coded data is affected by multiplication or division only. The standard deviation is a measure of dispersion, like the range, and is not affected by adding or subtracting a constant to the whole set of data. Therefore, if the data have been coded by addition or subtraction only, no adjustment is needed in the computed standard deviation. If the coding has involved multiplication (or division), the inverse operation must be applied to the computed standard deviation to bring it back to original units.

(c) *A variance* computed on coded data must be: multiplied by the square of the coding factor, if division has been used in coding; or divided by the square of the coding factor, if multiplication was used in coding.

(d) *Coding which involves loss of significant figures:* The kind of coding thus far discussed has involved no loss in significant figures. There is another method of handling data, however, that involves both *coding* and *rounding*, and is also called "coding". This operation is sometimes used when the original data are considered to be too finely-recorded for the purpose.

[1] Extracted from National Bureau of Standards Handbook 91, Natrella, M. G., *Experimental Statics*. U.S. Government Printing Office, Washington, D.C. 1963.

For example, suppose that the data consist of weights (in pounds) of shipments of some bulk material. If average weight is the characteristic of interest, and if the range of the data is large, we might decide to work with weights coded to the nearest hundred pounds, as follows:

Observed Weights Units: lbs.	Coded Data Units: 100 lbs.
7,123	71
10,056	101
100,310	1003
5,097	51
543	5
.	.
.	.
.	.
etc.	etc.

Whether or not the resulting average of the coded data gives us sufficient information will depend on the range of the data and the intended use of the result. It should be noted that this "coding" requires a higher order of judgment than the strictly arithmetical coding discussed in previous examples, because some loss of information does occur. The decision to "code" in this way should be made by someone who understands the source of the data and the intended use of the computations. The grouping of data in a frequency distribution is coding of this kind.

22-2 Rounding in Statistical Computations

22-2.1 ROUNDING OF NUMBERS

Rounded numbers are inherent in the process of reading and recording data. The readings of an experimenter are rounded numbers to start with, because all measuring equipment is of limited accuracy. Often he records results to even less accuracy than is attainable with the available equipment, simply because such results are completely adequate for his immediate purpose. Computers often are required to round numbers—either to simplify the arithmetic calculations, or because it cannot be avoided, as when 3.1416 is used for π or 1.414 is used for $\sqrt{2}$.

When a number is to be rounded to a specific number of significant figures, the rounding procedure should be carried out in accordance with the following three rules.

1. When the figure next beyond the last place to be retained is less than 5, the figure in the last place retained should be kept unchanged.

For example, .044 is rounded to .04.

2. When the figure next beyond the last figure or place to be retained is greater than 5, the figure in the last place retained should be increased by 1.

For example, .046 is rounded to .05.

3. When the figure next beyond the last figure to be retained is 5, and,

(a) there are no figures or are only zeros beyond this 5, an odd figure in the last place to be retained should be increased by 1, an even figure should be kept unchanged.

For example, .045 or .0450 is rounded to .04; .055 or .0550 is rounded to .06.

(b) if the 5 is followed by any figures other than zero, the figure in the last place to be retained should be increased by 1, whether odd or even.

For example, in rounding to two decimals, .0451 is rounded to .05.

A number should always be rounded off in one step to the number of figures that are to be recorded, and should not be rounded in two or more steps of successive roundings.

22-2.2 ROUNDING THE RESULTS OF SINGLE ARITHMETIC OPERATIONS

Nearly all numerical calculations arising in the problems of everyday life are in some way approximate. The aim of the computer should be to obtain results consistent with the data, with a minimum of labor. We can be guided in the various arithmetical operations by some basic rules regarding significant figures and the rounding of data:

1. *Addition*. When several approximate numbers are to be added, the sum should be rounded to the number of decimal places (not significant figures) no greater than in the addend which has the smallest number of decimal places.

Although the result is determined by the least accurate of the numbers entering the operation, one more decimal place in the more-accurate numbers should be retained, thus eliminating inherent errors in the numbers.

For example:

$$\begin{array}{r} 4.01 \\ .002 \\ \underline{.623} \\ 4.635 \end{array}$$

The sum should be rounded to and recorded as 4.64.

2. *Subtraction*. When one approximate number is to be subtracted from another, they must both be rounded off to the same place before subtracting.

Errors arising from the subtraction of nearly-equal approximate numbers are frequent and troublesome, often making the computation practically worthless. Such errors can be avoided when the two nearly-equal numbers can be approximated to more significant digits.

3. *Multiplication*. If the less-accurate of two approximate numbers contains n significant digits, their product can be relied upon for n digits at most, and should not be written with more.

As a practical working plan, carry intermediate computations out in full, and round off the final result in accordance with this rule.

4. *Division*. If the less-accurate of either the dividend or the divisor contains n significant digits, their quotient can be relied upon for n digits at most, and should not be written with more.

Carry intermediate computations out in full, and round off the final result in accordance with this rule.

5. *Powers and Roots*. If an approximate number contains n significant digits, its power can be relied upon for n digits at most; its root can be relied upon for at least n digits.

6. *Logarithms*. If the mantissa of the logarithm in an n-place log table is not in error by more than two units in the last significant figure, the antilog is correct to $n - 1$ sigificant figures.

The foregoing statements are working rules only. More complete explanations of the rules, together with procedures for determining explicit bounds to the accuracy of particular computations, are given in Scarborough[1], and the effects of rounding on statistical analyses of large numbers of observations are discussed in Eisenhart[2].

22-2.3 ROUNDING THE RESULTS OF A SERIES OF ARITHMETIC OPERATIONS

Most engineers and physical scientists are well acquainted with the rules for reporting a result to the proper number of significant figures. From a computational point of view, they know these rules too well. It is perfectly true, for example, that a product of two numbers should be reported to the same number of significant figures as the least-accurate of the two numbers. It is not so true that the two numbers should be rounded to the same numbers of significant figures before multiplication. A better rule is to round the more-accurate number to one more figure than the less-accurate number, and then to round the product to the same number of figures as the less-accurate one. The great emphasis against reporting more figures than are reliable has led to a prejudice against carrying enough figures in computation.

Assuming that the reader is familiar with the rules of the preceding Paragraph 22-2.2, regarding significant figures in a single arithmetical operation, the following paragraphs will stress the less well-known difficulties which arise in a computation consisting of a long series of different arithmetic operations. In such a computation, strict adherence to the rules at each stage can wipe out all meaning from the final results.

For example, in computing the slope of a straight line fitted to observations containing three significant figures, we would not report the slope to seven significant figures; but, if we round to three significant figures after each necessary step in the computation, we might end up with no significant figures in the value of the slope.

It is easily demonstrated by carrying out a few computations of this nature that there is real danger of losing all significance by too-strict adherence to rules devised for use at the final stage. The greatest trouble of this kind comes where we must subtract two nearly-equal numbers, and many statistical computations involve such subtractions.

The rules generally given for rounding-off were given in a period when the average was the only property of interest in a set of data. Reasonable rounding does little damage to the average. Now, however, we almost always calculate the standard deviation, and this statistic does suffer from too-strict rounding. Suppose we have a set of numbers:

$$\begin{array}{c} 3.1 \\ 3.2 \\ \underline{3.3} \\ \text{Avg.} = 3.2 \end{array}$$

If the three numbers are rounded off to one significant figure, they are all identical. The average of the rounded figures is the same as the rounded average of the original figures, but all information about the variation in the original number is lost by such rounding.

The generally recommended procedure is to carry two or three extra figures thorughout the computation, and then to round off the final reported answer (e.g., standard deviation, slope of a line, etc.) to a number of significant figures consistent with the original data. However, in some special computations such as the fitting of equations by least squares methods given in ORDP 20-110, Chapters 5 and 6, one should carry extra decimals in the intermediate steps—decimals sufficiently in excess of the number considered significant to insure that the computational errors in the final solutions are negligible in relation to their statistical imprecision as measured by their standard errors. For example, on a hand-operated computing machine, use its total capacity and trim the figures off as required in the final results. (See Chapter 23.)

REFERENCES

1. J. B. Scarborough, *Numerical Mathematical Analysis*, Chapter 1, (3d edition), The Johns Hopkins Press, Baltimore, Md., 1955.

2. C. Eisenhart, *Techniques of Statistical Analysis*, Chapter 4, McGraw-Hill Book Co., New York, N.Y., 1947.

CHAPTER 23—EXPRESSION OF THE UNCERTAINTIES OF FINAL RESULTS

23-1 Introduction

Measurement of some property of a thing in practice always takes the form of a sequence of steps or operations that yield as an end result a number that serves to represent the amount or quantity of some particular property of a thing—a number that indicates how much of this property the thing has, for someone to use for a specific purpose. The end result may be the outcome of a single reading of an instrument; with or without corrections for departures from prescribed conditions. More often, it is some kind of average: e.g., the arithmetic mean of a number of independent determinations of the same magnitude, or the final result of a least squares "reduction" of measurements of a number of different magnitudes that bear known relations with each other in accordance with a definite experimental plan. In general, the purpose for which the answer is needed determines the precision or accuracy of measurement required, and ordinarily also determines the method of measurement employed.

Although the accuracy required of a reported value depends primarily on the use, or uses, for which it is intended, we should not ignore the requirements of other uses to which the reported value is likely to be put. A certified or reported value whose accuracy is entirely unknown is worthless.

Strictly speaking, the actual *error* of a reported value, that is, the magnitude and sign of its deviation from the truth, is usually unknowable. Limits to this error, however, can usually be inferred—with some risk of being incorrect—from the *precision* of the measurement process by which the reported value was obtained, and from reasonable limits to the possible *bias* of the measurement process. The *bias*, or *systematic error*, of a measurement process is the magnitude and direction of its tendency to measure something other than what was intended; its *precision* refers to the typical *closeness together* of successive independent measurements of a single magnitude generated by repeated applications of the process under specified conditions; and, its *accuracy* is determined by the *closeness of the true value* characteristic of such measurements.

Precision and *accuracy* are inherent characteristics of the measurement process employed, and not of the particular end result obtained. From experience with a particular measurement process and knowledge of its sensitivity to uncontrolled factors, we can often place reasonable bounds on its likely systematic error (bias). It also is necessary to know how well the particular value in hand is likely to agree with other values that the same measurement process might have provided in this instance, or might yield on remeasurement of the same magnitude on another occasion. Such information is provided by the *standard error* of the reported value, which measures the characteristic disagreement of repeated determinations of the same quantity by the same method, and thus serves to indicate the precision (strictly, the *imprecision*) of the reported value.

The uncertainty of a reported value is indicated by giving credible limits to its likely inaccuracy. No single form of expression for these limits is universally satisfactory. In fact, different forms of expression are recommended, the choice of which will depend on the relative magnitudes of the impression and likely bias; and on their relative importance in relation to the intended use of the reported value, as well as to other possible uses to which it may be put.

Four distinct cases need to be recognized:

1. *Both systematic error and imprecision negligible* in relation to the requirements of the intended and likely uses of the result.

2. *Systematic error not negligible*, but *imprecision negligible*, in relation to the requirements.

3. *Neither systematic error nor imprecision negligible* in relation to the requirements.

4. *Systematic error negligible*, but *imprecision not negligible* in relation to the requirements.

Specific recommendations are made below with respect to each of these four cases, supplemented by further discussion of each case in Paragraphs 23-2 through 23-5. These recommendations may be summarized as follows:

(a) Two numerics, respectively expressing the imprecision and bounds to the systematic error of the result, should be used whenever: (1) the margin is narrow between ability to measure and the accuracy or precision requirements of the situation; or, (2) the imprecision and the bounds to the systematic error are nearly equal in indicating possible differences from the *true value*. Such instances come under Case 3.

(b) A quasi-absolute type of statement with one numeric, placing bounds on the inaccuracy of the result, should be used whenever: (1) a wide or adequate margin exists between ability to measure and the accuracy requirements of the situation (Case 1); (2) the imprecision is negligibly small in comparison with the bounds placed on the systematic error (Case 2); or, (3) the control is so satisfactory that the extent of error is known.

(c) A single numeric expressing the imprecision of the result should be used whenever the systematic error is either zero by definition or negligibly small in comparison with the imprecision (Case 4).

(d) Expressions of uncertainty should be given in sentence form whenever feasible.

(e) The form "$a \pm b$" should be avoided as much as possible; and never used without explicit explanation of its connotation.

23-2 Systematic Error and Imprecision Both Negligible (Case 1)

In this case, the certified or reported result should be given correct to the number of significant figures consistent with the accuracy requirements of the situation, together with an explicit statement of its accuracy or correctness.

For example:

. . . the wavelengths of the principal visible lines of mercury 198 have been measured relative to the 6057.802106 A (Angstrom units) line of krypton 98, and their values in vacuum are certified to be

5792.2685 A
5771.1984 A
5462.2706 A
4359.5625 A
4047.7146 A

correct to eight significant figures.

It must be emphasized that when no statement of accuracy or precision accompanies a certified or reported number, then, in accordance with the usual conventions governing rounding, this number will be interpreted as being accurate within $\pm\frac{1}{2}$ unit in the last significant figure given; i.e., it will be understood that its inaccuracy before rounding was less than ± 5 units in the next place.

23-3 Systematic Error Not Negligible, Imprecision Negligible (Case 2)

In such cases:

(a) Qualification of a certified or reported result should be limited to a single quasi-absolute type of statement that places bounds on its inaccuracy;

(b) These bounds should be stated to no more than two significant figures;

(c) The certified or reported result itself should be given (i.e., rounded) to the last place affected by the stated bounds, unless it is desired to indicate and preserve such relative accuracy or precision of a higher order that the result may possess for certain particular uses;

(d) Accuracy statements should be given in sentence form in all cases, except when a number of results of different accuracies are presented, e.g., in tabular arrangement. If it is necessary or desirable to indicate the respective accuracies of a number of results, the results should be given in the form $a \pm b$ (or $a {+b \atop -c}$, if necessary) with an appropriate explanatory remark (as a footnote to the table, or incorporated in the accompanying text) to the effect that the $\pm b$, or ${+b \atop -c}$, signify bounds to the errors to which the a's may be subject.

The particular form of the quasi-absolute type of statement employed in a given instance ordinarily will depend upon personal taste, experience, current and past practice in the field of activity concerned, and so forth. Some examples of good practice are:

. . . is(are) not in error by more than 1 part in (x).

. . . is(are) accurate within $\pm$ (x units) (or $\pm$ (x)%).

. . . is(are) believed accurate within (. . .)

Positive wording, as in the first two of these quasi-absolute statements, is appropriate only when the stated bounds to the possible inaccuracy of the certified or reported value are themselves reliably established. On the other hand, when the indicated bounds are somewhat conjectural, it is desirable to signify this fact (and thus put the reader on guard) by inclusion of some modifying expression such as "believed", "considered", "estimated to be", "thought to be", and so forth, as exemplified by the third of the foregoing examples.

Results should never be presented in the form "$a \pm b$", without explanation. If no explanation is given, many persons will automatically take $\pm b$ to signify bounds to the inaccuracy of a. Others may assume that b is the *standard error* or the *probable error* of a, and hence that the uncertainty of a is at least $\pm 3b$, or $\pm 4b$, respectively. Still others may take b to be an indication merely of the imprecision of the individual measurements; that is, to be the *standard deviation, the average deviation, or the probable error of a SINGLE observation*. Each of these interpretations reflects a practice of which instances can be found in current scientific literature. As a step in the direction of reducing this current confusion, we urge that the use of "$a \pm b$" in presenting results in official documents be limited to that sanctioned under (d) above.

The term *uncertainty*, with the quantitative connotation of limits to the likely departure from the truth, and not simply connotating vague lack of certainty, may sometimes be used effectively to achieve a conciseness of expression otherwise difficult or impossible to attain. Thus, we might make a statement such as:

The uncertainties in the above values are not more than ± 0.5 degree in the range 0° to 1100°C, and then increase to ± 2 degrees at 1450°C;

or,

The uncertainty in this values does not exeed . . . excluding (or, including) the uncertainty of . . . in the value . . . adopted for the reference standard involved.

Finally, the following forms of quasi-absolute statements are considered poor practice, and should be avoided:

The accuracy of . . . is 5 percent.

The accuracy of . . . is ± 2 percent.

These statements are presumably intended to mean that the result concerned is not inaccurate, i.e., not in error, by more than 5 percent or 2 percent, respectively; but they explicitly state the opposite.

23-4 Neither Systematic Error Nor Imprecision Negligible (Case 3)

In such cases:

(a) A certified or reported result should be qualified by: (1) a quasi-absolute type of statement that places bounds on its systematic error; and, (2) a separate statement of its standard error or its probable error, explicitly identified, as a measure of its imprecision;

(b) The bounds to its systematic error and the measure of its imprecision should be stated to no more than two significant figures;

(c) The certified or reported result itself should be stated, at most, to the last place affected by the finer of the two qualifying statements, unless it is desired to indicate and preserve such relative accuracy or precision of a higher order that the result may possess for certain particular uses;

(d) The qualification of a certified or reported result, with respect to its imprecision and systematic error, should be given in sentence form, except when results of different precision or with different bounds to their systematic errors are presented in tabular arrangement. If it is necessary or desirable to indicate their respective imprecisions or bounds to their respective systematic errors, such information may be given in a parallel column or columns, with appropriate identification.

Here, and in Paragraph 23-5, the term *standard error* is to be understood as signifying *the standard deviation of the reported value itself*, not as signifying *the standard deviation* of a single determination (unless, of course, the reported value is the result of a single determination only).

The above recommendations should not be construed to exclude the presentation of a quasi-absolute type of statement placing bounds on the inaccuracy, i.e., on the overall uncertainty, of a certified or reported value, provided that separate statements of its imprecision and its possible systematic error are included also. Bounds indicating the overall uncertainty of a reported value should not be numerically less than the corresponding bounds placed on the systematic error outwardly increased by at least two times the standard error. The fourth of the following examples of good practice is an instance at point:

> The standard errors of these values do not exceed 0.000004 inch, and their systematic errors are not in excess of 0.00002 inch.

> The standard errors of these values are less than (x units), and their systematic errors are thought to be less than $\pm$ (y units).

> . . . with a standard error of (x units), and a systematic error of not more than $\pm$(y units).

> . . . with an overall uncertainty of ± 3 percent based on a standard error of 0.5 percent and an allowance of ± 1.5 percent for systematic error.

When a reliably established value for the relevant standard error is available, based on considerable recent experience with the measurement process or processes involved, and the dispersion of the present measurements is in keeping with this experience, then this established value of the standard error should be used. When experience indicates that the relevant standard error is subject to fluctuations greater than the intrinsic variation of such a measure, then an appropriate upper bound should be given, e.g., as in the first two of the above examples, or by changing "a standard error . . ." in the third and fourth examples to "an upper bound to the standard error . . .".

When there is insufficient recent experience with the measurement processes involved, an estimate of the standard error must of necessity be computed, by recognized statistical procedures, from the same measurements as the certified or reported value itself. It is essential that such computations be carried out according to an agreed-upon standard procedure, and that the results thereof be presented in sufficient detail to enable the reader to form his own judgment and make his own allowances for their inherent uncertainties. To avoid possible misunderstanding in such cases:

(a) the term *computed standard error* should be used;

(b) the estimate of the standard error employed should be that obtained from the relation

$$\begin{array}{c}\text{estimate of}\\ \text{standard error}\end{array} = \sqrt{\frac{\text{sum of squared residuals}}{n\nu}},$$

where n is the (effective) number of completely independent determinations of which a is the arithmetic mean (or, other appropriate least squares adjusted value) and ν is the number of degrees of freedom involved in the sum of squared residuals (i.e., the number of residuals minus the number of fitted constants and/or other independent constraints); and,

(c) the number of degrees of freedom ν should be explicitly stated.

If the reported value a is the arithmetic mean, then:

$$\text{estimate of standard error} = \sqrt{\frac{s^2}{n}}$$

where s^2 is computed as shown in ORDP 20-110, Chapter 2, Paragraph 2-2.2, and n is the number of completely independent determinations of which a is the arithmetic mean.

For example:

> The computed probable error (or, standard error) of these values is (x units), based on (ν) degrees of freedom, and

the systematic error is estimated to be less than ± (y units).

. . . which is the arithmetic mean of (n) independent determinations and has a computed standard error of . . . .

. . . with an overall uncertainty of ±5.2 km sec based on a standard error of 1.5 km sec and bounds of ±0.7 km sec on the systematic error. (The figure 5.2 equals 0.7 plus 3 times 1.5).

Or, if based on a computed standard error:

. . . with an overall uncertainty of ±7 km/sec derived from bounds of ±0.7 km/sec on the systematic error and a computed standard error of 1.5 km/sec based on 9 degrees of freedom. (The figure 7 is approximately equal to 0.7 + 4.3 (1.5), where 4.3 is the two-tail 0.002 probability value of Student's t for 9 degrees of freedom. As $\nu \rightarrow \infty$, $t_{.002}(\nu) \rightarrow 3.090$.)

23-5 Systematic Error Negligible, Imprecision Not Negligible (Case 4)

In such cases:

(a) Qualification of a certified or reported value should be limited to a statement of its standard error or of an upper bound thereto, whenever a reliable determination of such value or bound is available. Otherwise, a computed value of the standard error so designated should be given, together with a statement of the number of degrees of freedom on which it is based;

(b) The standard error or upper bound thereto, should be stated to not more than two significant figures;

(c) The certified or reported result itself should be stated, at most, to the last place affected by the stated value or bound to its imprecision, unless it is desired to indicate and preserve such relative precision of a higher order that the result may possess for certain particular uses;

(d) The qualification of a certified or reported result with respect to its imprecision should be given in sentence form, except when results of different precision are presented in tabular arrangement and it is necessary or desirable to indicate their respective imprecisions, in which event such information may be given in a parallel column or columns, with appropriate identification.

The above recommendations should not be construed to exclude the presentation of a quasi-absolute type of statement placing bounds on its possible inaccuracy, provided that a separate statement of its imprecision is included also. Such bounds to its inaccuracy should be numerically equal to at least two times the stated standard error. The fourth of the following examples of good practice is an instance at point:

The standard errors of these values are less than (x units).

. . . with a standard error of (x units).

. . . with a computed standard error of (x units) based on (ν) degrees of freedom.

. . . with an overall uncertainty of ±4.5 km/sec derived from a standard error of 1.5 km/sec. (The figure 4.5 equals 3 times 1.5).

Or, if based on a computed standard error:

. . . with an overall uncertainty of ±6.5 km/sec derived from a computed standard error of 1.5 km/sec (based on 9 degrees of freedom). (The figure 6.5 equals 4.3 times 1.5, where 4.3 is the two-tail 0.002 probability value of Student's t for 9 degrees of freedom. As $\nu \rightarrow \infty$, $t_{.002}(\nu) \rightarrow 3.090$.

The remarks with regard to a computed standard error in Paragraph 23-4 apply with equal force to the last two of the above examples.

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