PDHonline Course G527 (6 PDH)

Metrology

Instructor: Robert P. Jackson, PE

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

LIST OF FIGURES

TABLE OF CONTENTS

PAGE

<u>NOTE:</u> Before we begin this course I would like to make a recommendation. I have structured the quiz to follow the text. The course is not overly complex, but there are details and many of them. As you might suspect, Metrology, <u>THE SCIENCE OF MEASUREMENT,</u> is an exacting discipline. This course reflects that fact. If I may, please print off the quiz or at least read the quiz before you read the text so you will have an idea as to the areas of concentration. I also would ask you to pay <u>close attention</u> to the glossary of terms. Several questions are taken from the glossary.

INTRODUCTION:

Metrology is **<u>NOT</u>** meteorology. There is a very real difference. According to the "Bureau of Weights and Measures" (BIPM), Metrology is defined as follows:

<u>"The science of measurement embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology".</u>

That may be a bit nebulous so the definition I like is as follows:

<u>"The science of weights and measurement determining conformance to specifications or technical requirements and development of standards."</u>

From an application standpoint, the key word here is conformance. We measure to insure specifications are met to within an Upper Specification Limit (USL) and a Lower Specification Limit (LSL). These limits are called the range of acceptability. Within any basic field of science, technology or manufacturing environment, specification limits must be recognized and met. There always is a target value; a value from which accuracy and precision are measured. The USL and LSL represent acceptable tolerances from that target.

The importance of measurement was recognized very early in our country's history as can be seen from the following quote:

"Weights and measures may be ranked among the necessaries of life to every individual of human society. They enter into the economical arrangements and daily concerns of every family. They are necessary to every occupation of human industry: to the distribution and security of every species of property; to every transaction of trade and commerce; to the labors of the husbandman; to the ingenuity of the artificer; to the studies of the philosopher; to the researches of the antiquarian; to the navigation of the mariner; to the marches of the soldier; to all the exchanges of peace, and the operations of war. The knowledge of them, as in established use, is among the first elements of education, and is often learned by those who learn nothing else, not even to read and write. This knowledge is riveted in the memory by the habitual application of it to the employments of men through life." John Quincy Adams, Report to Congress, 1821.

Metrology comes from the Greek word "metron" and "logos" which literally means the study of measurement. This study covers both the experimental and theoretical aspects of measurement and determination of the levels of uncertainty. The study of measurement is a basic requirement in any field of science and technology, most importantly in engineering and manufacturing. Since metrology is the study of measurement, it is expected to enforce, validate and verify predefined standards for traceability, accuracy, reliability, and precision. All of these are factors that would affect the validity of measurement. Although these standards vary widely, they are mandated by the governments, specific agencies, and many international treaties. These standards are verified and tested against a recognized quality system and in calibration laboratories.

If metrology is the science of measurement, then measurement is the language of science. It is the language we use to communicate size, quantity, position, condition and time. A language consists of grammar and composition. Grammar is a science; composition is an art. There are three reasons why we need measurements, as follows:

- To make things, whether the things are our designs or the designs of others.
- To control the manner in which other people make things. This applies to ordering an engagement ring, fencing a yard or producing a million spark plugs.
- We need measurements for scientific descriptions. It would be absolutely impossible to give definite information to someone else about aircraft design, electron mobility, or the plans for a birthday party without specifying measurements.

The basic principles of dimensional metrology are fascinating as well as practical. They epitomize the scientific method that characterizes this modern age of manufacturing more than anything else. These principles rely on logic and reflect philosophy. They spring into life whenever we produce goods or search for scientific knowledge.

The experimental aspect of metrology is that which deals with the investigation of the relationship among variables. These variables are established depending on set of observations being considered or classified. As such, it is in this aspect that hypotheses are established and tested.

The theoretical aspect of metrology deals with the various concepts and principles underlying the study. This aspect is based on established theories and concepts which are derived from empirical observations that satisfy the baseline requirements. In other words, the theoretical aspect is expected to be functional and working.

In this six (6) hour course, we will investigate the following three sub-fields of metrology: 1.) Science or fundamental concepts, 2.) Applied or industrial concepts and 3.) Legal metrology.

HISTORY OF METROLOGY:

The need for accurate measurements is evident throughout history. Important steps for international metrology included the establishment of internationally agreed measurement units and standards. Also critical to the process was to enable recognition of measurement standards of the National Metrology Institutes and designated institutes around the world.

The system of measures, which is at the basis of all metric systems of the ancient world and China, had already been conceived prior to the appearance of cuneiform writing in Mesopotamia in approximately 2,900 B.C. The system of measures became necessary with the advent of agricultural development as far back as 6,000 B.C., as it became crucial to calculate the distribution of crops and the volume of food consumed by families.

In Oriental, Latin and Greek documents up to the Carolingian Age (approximately 800 A.D.), there is a consensus that an adult free male would consume two basic pints of wheat a day, while women and slaves were expected to subsist on half of the ration.

With the transition of mankind from nomadic groupings to established agricultural settlements, metrology was imperative in managing population growth and confronting famine.

It would not be until 1875 at the Metre Convention that scientists would recognize the need to establish a system of internationally agreed measurement standards. Prior to this, various systems existed across the world and were merged and transformed through trade and acculturation. Let's take a look.

The Egyptian Cubit

As measurements were sometimes formed from a natural basis, their accuracy is difficult to determine. The Egyptian cubit, an ancient unit based on the forearm length, ranged between 43 and 53 cm throughout antiquity and depended on the reigning Pharaoh. The Egyptian royal cubit is the earliest recognized standard of measurement.

The flood level of the Nile in approximately 3,000 B.C. was given as 6 cubits and 1 palm, and the royal cubit was a crucial measurement in ancient Egyptian architecture from as early as 2,700 B.C.

The Roman Mile

Although the standardization of the mile to 1.609 kilometers would not be established until an international agreement in 1959, the Roman mile had consisted of a thousand paces of two steps each.

Conquering armies marching through unchartered territory would drive sticks into the ground after each 1,000 paces, making the length of the mile dependent on a variety of factors, including weather conditions, army logistics and the physical conditioning of soldiers.

Medieval Metrics

Medieval metrics have generally been viewed as glaring chaos. In medieval England, one form of measurement was used to calculate ounces of bullion and other tradeable commodities, though its use was consistent with those recognized in both medieval Italian texts and ancient Athenian texts.

Evidently, the inconsistencies and regional and cultural differences of systems of measurement prevented any universal application of a single standard of metrology. Without an effective means for the exchange and distribution of knowledge in the ancient and medieval worlds it would be impossible for scientists, mathematicians, chemists and physicists to cooperate in the pursuit of progressive endeavors.

Standards of measurement before the 1700s were local and often arbitrary, making trade between countries, and even cities, very difficult. The need for standardization as an aid to commerce became apparent during the Industrial Revolution. Early standardization and metrology needs were based upon military requirements, especially those of large maritime powers such as Great Britain and the United

States. A major task of navies in the eighteenth and nineteenth centuries was protection of their countries international trade, much of which was carried by merchant ships. Warships would sail with groups of merchant ships to give protection from pirates, privateers, and ships of enemy nations; or they would sail independently to “show the flag” and enforce the right of free passage on the seas. A typical ship is the frigate USS Constitution. That vessel was launched in 1797 and armed with thirty-four twenty-four pound cannons and twenty thirty-two pound cannons. For reasons related to accuracy, efficiency, and economy, the bores of any particular size cannon all had to be the same diameter. Likewise, the iron shot had to be the same size. If a cannonball was too large, it would not fit into the muzzle; too small, and it would follow an unpredictable trajectory when fired. The requirement of ensuring that dimensions were the same led to the early stages of modern metrology systems, with master gauges, transfer standards, and regular comparisons. Over time, measurements became standardized within countries. The need then arose to standardize between countries. A significant milestone in this effort was the adoption of the Convention of the Metre treaty in 1875. This treaty set the framework for and still governs the international system of weights and measures. It can be viewed as one of the first voluntary standards with international acceptance, and possibly the most important to science, industry, and commerce. The United States was one of the first nations to adopt the Metre Convention.

It would not be until the Scientific Revolution, during the early modern period, that metrology would cease from being utilized largely for the measurements of length, time and weight. As science advanced, a coherent system of units was required.

The discovery and identification of fundamental scientific principles such as electricity, atoms, heat transfer, fluid flow, fundamental laws of friction and thermodynamics certainly required standards of measurement, thus facilitating the quantitative and qualitative assessment of physical properties in science. Let us now look at important chronology in the evolution of Metrology.

1875 - Meter Convention
Recognizing the need to work towards internationally agreed measurement standards, in 1875 governments from seventeen (17) countries worldwide signed this treaty and agreed to create and finance a permanent, scientific institute, the Bureau International des Poids et Measures (BIPM) as the centre for coordination of world measurement. The Comité International des Poids et Measures (CIPM) was established to oversee the BIPM and today there are 51 Member States of the Meter Convention, and twenty-three (23) Associate States and Economies of the General Conference.

1878—Queen Victoria declares the Troy pound illegal. Commercial weights could only be of the quantity fifty-six (56) pounds, twenty-eight (28) pounds, fourteen (14) pounds, seven (7) pounds, four (4) pounds, two (2) pounds, one (1) pound, eight (8) ounces, four (4) ounces, etc.

1960 - SI Units Established
The name Système International d'Unités (SI) was adopted in 1960 for the recommended practical system of units of measurement. There are seven (7) base units (meter, kilogram, second, ampere,

Kelvin, mole, and candela) and many derived units are formed by combining base units (e.g. volt, watt, Newton, Pascal, joule)

1999 - CIPM Mutual Recognition Arrangement (MRA)
This international arrangement was established in response to a growing need for an open, transparent and comprehensive scheme to provide users with reliable quantitative information on the comparability of national metrology services and to provide the technical basis for wider agreements negotiated for international trade, commerce and regulatory affairs.

In 1999, the directors of the national metrology institutes (NMIs) of 38 Member States of the Meter Convention and representatives of two (2) international organizations signed a Mutual Recognition Arrangement for national measurement standards and for calibration and measurement certificates issued by NMIs.

Defining the Meter

Even in the eighteenth century, unified systems of measurement did not exist even on a national level. France, a centre of science and enlightenment during the Scientific Revolution, recorded in 1795 that there were over 700 different units of measurement in the country.

In 1791 a commission was established to decide between three possible references of measurement:

- the length of a pendulum beating at a rate of one second at a latitude of forty-five (45) degrees
- the length of one quarter of the equator
- the distance from the North Pole to the equator (a quarter meridian)

The distance from the North Pole to the equator was chosen as the simplest reference of measurement to calculate. In the same year, the meter was defined as being equal to the ten millionth part of one quarter of the terrestrial medium.

The meter materialized the concept of a *“unit which in its determination was neither arbitrary nor related to any particular nation on the globe.”*

The length of the meridian had to be identified, and the triangulation work carried out by Jean-Baptiste Joseph Delambre and Pierre-Francois Meçhain took seven (7) years to complete. It was recognized to be equivalent to ten (10) million meters.

The Decimal Metric System

With the recognition of one base unit of measurement, others had to be established. The decimal metric system was introduced in 1795 by a weights and measures law, and by 1799 the system had extended to encompass the first standards of the meter and kilogram for everyday use.

The decimal metric system, as a simple, accessible and universal method, began to spread outside of France during the early 19th century. The metric system was mandatory in the Netherlands from 1816 and was adopted by Spain in 1849.

The Industrial Revolution

The emergence of the Industrial Revolution depended on the adoption of accurate units of measurement, as mass production, equipment commonality and assembly lines would be impossible without one.

In a typical act of Anglo-Franco rivalry, the British imperial system of units was adopted in the Weights and Measures Act of 1824 and was retained until the UK joined the European Economic Community in the 1970s. Some imperial measurements are still in use, such as the pint which is still a popular measure of volume today in British pubs.

The Industrial Revolution began around 1750. Technology began to progress quickly with materials, energy, time, architecture, and man’s relationship with the earth. Industry began to quickly evolve. With growing population, the need for clothing, transportation, medicines, and food drove industry to find better, more efficient methods to support this need. Technology had evolved sufficiently to support this growth.

During this time there were remarkable discoveries in quantum mechanics and molecular, atomic, nuclear, and particle physics. These discoveries laid the groundwork for much of the seven base units of the current International System of Units (SI). These seven units are well-defined and dimensionally independent and given as follows:

The Système International d'Unités (SI Units)

In 1960, the Système International d'Unités (SI) was adopted to ensure a practical system of measurement. It established the use of seven SI base units:

- meters (m) - a measure of length
- kilograms (kg) - a measure of mass
- seconds (s) - a measure of time
- amperes (A) - a measure of electric current
- Kelvin (K) - a measure of thermodynamic temperature
- moles (mol) - a measure of the amount of substance
- candelas (cd) - a measure of luminous intensity

Such developments have emerged due to the growing need in the 20th and 21st centuries to ensure an open, transparent and comprehensive system of metrology that would provide the technical basis for wider agreements negotiated in science, trade, commerce, and regulatory affairs.

Initially, metrology emerged as a scientific system of calculation from a natural basis in order to pre-empt the subsistence needs of growing populations. Since antiquity, it has progressed to become to a universal language within science, industry and commerce, to permit the continuing enlightenment and advancement of humankind, as well as the distribution of knowledge and resources across the international stage.

METROLOGY CONCEPTS:

FUNDAMENTAL or SCIENTIFIC:

Scientific and fundamental metrology concerns the establishment of *quantity systems*, unit systems, *units of measurement*, the development of new measurement methods, realization of measurement standards and the transfer of traceability from these standards to users in society. The International Bureau of Weights and Measures (BIPM) maintains a database of the metrological calibration and measurement capabilities of various institutes around the world. These institutes, whose activities are peer-reviewed, provide the top-level reference points for metrological traceability. In the area of measurement the BIPM has identified nine metrology areas including length, mass and time.

The field of metrology encompasses a multitude of disciplines: mathematics, statistics, physics, quality, chemistry, and certainly, computer science. Essential to metrology is an understanding of the fundamental methods by which objects and phenomena are measured. Also critical, an understanding of how values are assigned to these measurements and the certainty of these values.

The basic concepts and principles of metrology were formulated from the need to measure and compare a known value or quantity to an unknown quantity in order to define the unknown relative to the known. What is being described is a methodology for assigning numbers and units; i.e. inches, degrees, minutes, etc. to unknown quantities. Everything we buy, sell, consume, or produce can be compared, measured, and defined in terms of units of measurement. Without commonly agreed-upon units, it would not be possible to accurately quantify the passing of time, the length of an object, or the temperature of one's surroundings. Practically every aspect of our physical world can be related in terms of the units of measurements. Units allow us to count things. When we have determination of measurement units deemed acceptable and repeatable, standards may be written. These units and standards form the very heart of metrology.

APPLIED, TECHNICAL OR INDUSTRIAL:

Applied, technical or industrial metrology concerns the application of measurement science to manufacturing and other processes and their use in society, ensuring the suitability of measuring instruments, their calibration and the quality control of measurements. Although the emphasis in this area of metrology is on the measurements themselves, traceability of the calibration of the measurement devices is necessary to ensure confidence in the measurements. Traceability of calculated values is tremendously important to metrology

LEGAL METROLOGY:

Legal metrology "concerns activities which result from statutory requirements and concern measurement, units of measurement, measuring instruments and methods of measurement, and which are performed by competent bodies." Such statutory requirements might arise from, amongst others, the needs for protection of health, public safety, the environment, enabling taxation, protection of consumers and fair trade. The International Organization of International Metrology (OIML) was established to assist in harmonizing regulations across national boundaries to ensure that legal requirements do not inhibit trade. In Europe WELMEC was established to promote cooperation on the field of legal metrology. WELMEC is a body set up to promote European cooperation in the field of legal metrology. WELMEC members are drawn from the national authorities responsible for legal metrology in European Union (EU) and European Free Trade Association (EFTA) member states.

QUALITY SYSTEMS RELATIVE TO MEASUREMENT:

The basic premise and foundation of a good quality system is to say what you do, do what you say, record what you did, check the results, and act on the difference. Say what you do means write, in detail, how to do your job. This includes calibration procedures, standard operating procedures protocols, work instructions, work cards, and so on. Do what you say means to follow the documented procedures or instructions every time you calibrate, validate, or perform a function that follows specific written instructions. Record what you did means you precisely record the results of your measurements and adjustments, including what your standard(s) read or indicated both before and after adjustment. Check the results means to make certain the inspection, measurement, and test equipment meets the tolerances, accuracies, or upper and lower specification limits written in your procedures. Act on the difference means that if the measurements are out of tolerance and do not meet specified accuracies, or exceeds the specification limits, you are required to inform the user because he or she may have to reevaluate manufactured goods, change a process, or recall a product.

To help ensure all operations throughout a metrology department, calibration laboratory, or work area where calibrations are accomplished occur in a stable manner, one needs to establish a quality management system. The effective operation of such a system should result in stable processes.

There are two different classes of quality standards: 1.) Those that are required by law or regulation and 2.) Those that are voluntary. A government law, or regulation of a government agency, may include or specify quality standard requirements. In these cases, a business MUST comply if it is either in a regulated industry or wishes to sell products or services to the government body. As a practical matter, some quality standards are voluntary only to the extent that the organization can afford to lose business by not following them. All of this results in several forces that are driving the importance of voluntary quality standards. At any rate, the ability to measure a component, subassembly or complete product is critical to any commercial venture.

MEASUREMENT AND TOLERANCES INCUDING:

The two words, accuracy and precision, are very often used interchangeably. From a quality standpoint, this should not happen. A measurement system can be accurate but not precise, precise but not accurate, neither, or both. A measurement system can be considered valid if it is both accurate AND precise. Related terms include bias (non-random or directed effects caused by a factor or factors unrelated to the independent variable and error (random variability). In addition to accuracy and precision, measurements may also have a measurement resolution, which is the smallest change in the underlying physical quantity that produces a response in measurement. In numerical analysis, accuracy is the nearness of a calculation to the true value; precision is the resolution of the representation, typically defined by the number of decimal or binary digits.

As it is hopefully clear, accuracy is a measure of "trueness", while precision is a measure of variability. It is not necessarily the case that they are well correlated. Low precision is easily spotted; your data is simply scattered all over the place. Low accuracy isn't always so easy to spot. Imagine a scenario in which you didn't have the rings of a bull's-eye to visualize your data; would you be able to tell that the lower left image had poor accuracy? To be sure you'd need to already have a good idea of the value that you should be reading, and recognize that the results were not what you expected. This is in effect measuring a known standard, and using it to calibrate your sensor to provide meaningful real world values. Luckily, we already have resources on calibration.

Ideally a measurement device is both accurate and precise, with measurements closely clustered around the true value. Accuracy and precision of a measurement process is usually established by repeatedly measuring some traceable reference standard. Such standards are defined in the International System of Units or SI system and maintained by national standards organizations such as the National Institute of Standards and Technology in the United States.

The words have two very distinct meanings. We will detail both with the following descriptions, but let's take a look at a digital that represents accuracy vs. precision. Please note, the bull's eye is our target.

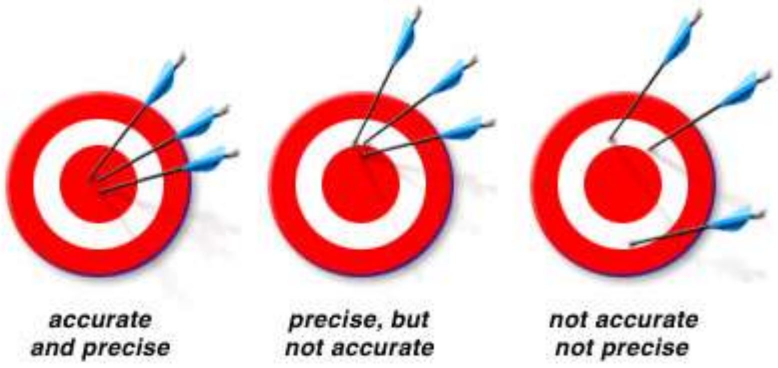
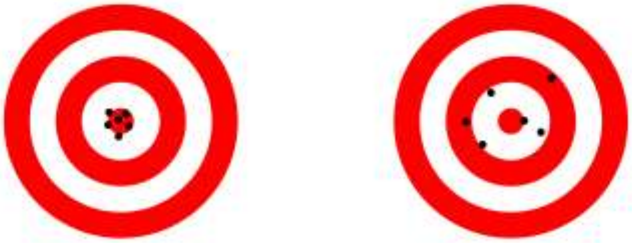


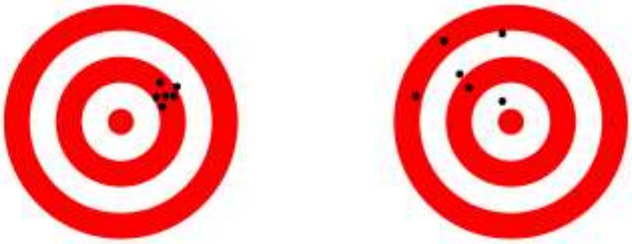
FIGURE 1: ACCURACY

Another graphic:



High Precision, High Accuracy

Low Precision, High Accuracy



High Precision, Low Accuracy

Low Precision, Low Accuracy

FIGURE 2: PRECISION

ACCURACY:

Accurate means "capable of providing a correct reading or measurement." In physical science it means 'correct'. A measurement is accurate if it correctly reflects the size of the thing being measured. Accuracy is how close a measured value is to the actual or true value. In short:

Accuracy = Number of true positives + Number of true negatives/Number of true positives +false positives+ false negatives + true negatives

PRECISION:

Precise means "exact, as in performance, execution, or amount."In physical science it means "repeatable, reliable, getting the same measurement each time." Precision is how close the measured values are to each other. Precision of measurement is related to reproducibility and repeatability. Two definitions are as follows:

- Repeatability is the variation arising when all efforts are made to keep conditions constant by using the same measuring instrument AND operator, and repeating during a short time period

- Reproducibility is the variation arising when using the same measurement process among different instruments and operators and over longer time periods.

Precision = Number of true positives/Number of true positives + False positives.

RESOLUTION:

From our glossary of terms: Resolution is the smallest change in a quantity being measured that causes a perceptible change in the corresponding indication. Resolution can be affected by internal or external factors like noise, friction, or temperature. The value of the measurand may also affect resolution.

Resolution is easily mistaken for precision, but it's not always the case that you will have a high precision just because you have a high resolution. Even with many decimal places in the values you are getting from a sensor, you may still find there is a lot of variability in the data, or in other words that there is low precision despite the high resolution. One way that the resolution and precision are always related is that resolution determines the upper limit of precision. The precision in your data cannot exceed your resolution.

TRACEABILITY:

A core concept in metrology is *metrological traceability*, defined by the Joint Committee for Guides in Metrology as "*property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty*". Metrological traceability permits comparison of measurements, whether the result is compared to the previous result in the same laboratory, a measurement result a year ago, or to the result of a measurement performed anywhere else in the world.

Traceability is most often obtained by calibration, establishing the relation between the indication of a measuring instrument and the value of a measurement standard. These standards are usually coordinated by national metrological institutes: National Institute of Standards and Technology; National Physical Laboratory, UK; Physikalisch-Technische Bundesanstalt; etc.

Traceability, accuracy, precision, systematic bias, evaluation of measurement uncertainty are critical parts of a quality management system.

GEOMETRIC DIMENSIONING AND TOLERANCING (GD & T):

Geometric Dimensioning and Tolerancing allows the proper depiction of an object or an assembly allowing measurements to determine accuracy and precision. This is accomplished through engineering tolerances.

GD & T is a system for defining and communicating engineering tolerances. It uses a symbolic language on engineering drawings and computer-generated three-dimensional solid models that explicitly describes nominal geometry and its allowable variation. It tells the manufacturing staff and machines what degree of accuracy and precision is needed on each controlled feature of the part. GD&T is used to define the nominal (theoretically perfect) geometry of parts and assemblies, to define the allowable variation in form and possible size of individual features, and to define the allowable variation between features.

- Dimensioning specifications define the nominal, as-modeled or as-intended geometry. One example is a basic dimension.
- Tolerancing specifications define the allowable variation for the form and possibly the size of individual features, and the allowable variation in orientation and location between features. Two examples are linear dimensions and feature control frames using a datum reference (both shown above).

There are several standards available worldwide that describe the symbols and define the rules used in GD&T. One such standard is American Society of Mechanical Engineers (ASME) Y14.5-2009. This article is based on that standard, but other standards, such as those from the International Organization for Standardization (ISO), may vary slightly. The Y14.5 standard has the advantage of providing a fairly complete set of standards for GD&T in one document. The ISO standards, in comparison, typically only address a single topic at a time. There are separate standards that provide the details for each of the major symbols and topics below (e.g. position, flatness, profile, etc.).

BENEFITS OF GD & T:

If properly used, GD&T has the following significant benefits:

- Clearly defines the intent of the part and provides descriptive geometry, dimensions, orthographic projections and tolerancing. It is a precise communication tool.
- Optimally uses the part's available tolerance and allows for the use of DFSS methodology
- Increases the correlation between customer and supplier
- Provides the basis to correctly determine whether a fabricated part is acceptable or not by providing the basis for produceability.
- The use of material condition modifiers allows "bonus" tolerances which lead to great ease in assembly.
- Explicitly controls ALL aspects of part geometry, particularly the shape.
- GD&T is important for calculating tolerance analysis accurately.

Many companies still use “linear dimensioning” to detail their component parts and assemblies. An example of linear dimensioning is shown by Figure 8. This can be fully acceptable but there are consequences to this process. These are as follows:

- The parts fail inspection but are still functional
- The parts pass inspection but do not work or do not work as intended
- Lack of correlation between customer/ supplier with difficulty in determining why there are issues
- Inability to make pass / fail analysis during inspection

The basic idea behind GD&T is to determine the datum features of the part or assembly of parts. This, of course, involves physical positions and relationships. The datums are selected as the origins for dimensioning and the application of tolerances or tolerance zones. You MUST select functional datums. A functional datum is simply one that uses the product features which physically locate the part relative to the final product. Using any other datum system; i.e. centerlines, will add variation in the final tolerance stack-up. [18]. Successful application of GD&T involves concurrent design and engineering teams consisting of representatives from responsible functions; i.e. engineering, quality control, reliability testing, purchasing, etc. are chosen for this process.

RULES:

The following rules detail the fundamentals in a very concise and readable method. These rules are taken from reference [1].

- All dimensions must have a tolerance. Every feature on every manufactured part is subject to variation; therefore, the limits of allowable variation must be specified. Plus and minus tolerances may be applied directly to dimensions or applied from a general tolerance block or general note. For basic dimensions, geometric tolerances are indirectly applied in a related Feature Control Frame. The only exceptions are for dimensions marked as minimum, maximum, stock or reference.
- Dimensioning and tolerancing shall completely define the nominal geometry and allowable variation. Measurement and scaling of the drawing is not allowed except in certain cases.
- Engineering drawings define the requirements of finished (complete) parts. Every dimension and tolerance required to define the finished part shall be shown on the drawing. If additional dimensions would be helpful, but are not required, they may be marked as reference.
- Dimensions should be applied to features and arranged in such a way as to represent the function of the features.

- Descriptions of manufacturing methods should be avoided. The geometry should be described without explicitly defining the method of manufacture.
- If certain sizes are required during manufacturing but are not required in the final geometry (due to shrinkage or other causes) they should be marked as non-mandatory.
- All dimensioning and tolerancing should be arranged for maximum readability and should be applied to visible lines in true profiles.
- When geometry is normally controlled by gauge sizes or by code (e.g. stock materials), the dimension(s) shall be included with the gauge or code number in parentheses following or below the dimension.
- Angles of 90° are assumed when lines (including center lines) are shown at right angles, but no angular dimension is explicitly shown. (This also applies to other orthogonal angles of 0°, 180°, 270°, etc.)
- All dimensions and tolerances are valid at 20° C unless otherwise stated on the drawing.
- Unless explicitly stated, all dimensions and tolerances are valid when the item is in a free state.
- Dimensions and tolerances apply to the full length, width, and depth of a feature.
- Dimensions and tolerances only apply at the level of the drawing where they are specified. It is not mandatory that they apply at other drawing levels, unless the specifications are repeated on the higher level drawing(s).

STATISTICS AND MATHEMATICS USED RELATIVE TO METROLOGY:

SIX SIGMA:

The statistical representation of Six Sigma describes quantitatively how a process is performing. To achieve Six Sigma, a process must not produce more than 3.4 defects per million opportunities. A Six Sigma defect is defined as anything outside of customer specifications. A Six Sigma opportunity is then the total quantity of chances for a defect. This definitely means you MUST measure and analyze the products being manufactured or provided for manufacturer. This might be the components or subassemblies furnished by a vendor for assembly.

The fundamental objective of the Six Sigma methodology is the implementation of a measurement-based strategy that focuses on process improvement and variation reduction through the application of Six Sigma improvement projects. This is accomplished through the use of two Six Sigma sub-methodologies: DMAIC and DMADV. The Six Sigma DMAIC process (defines, measure, analyze, improve, control) is an improvement system for existing processes falling below specification and looking for incremental improvement. The Six Sigma DMADV process (define, measure, analyze, design, verify) is an improvement system used to develop new processes or products at Six Sigma quality levels. It can also be employed if a current process requires more than just incremental improvement. Both Six Sigma processes are executed by Six Sigma Green Belts and Six Sigma Black Belts, and are overseen by Six Sigma Master Black Belts.

I would like to state the importance of meeting Six Sigma goals. Right now, most manufacturing companies are producing to a three-Sigma standard. Three Sigma produces a 93.32 % long-term yield. Reaching these goals gives us the following meaning of 3 Sigma---**"good"**.

- 20,000 lost articles of mail per hour.
- Unsafe drinking water for approximately fifteen minutes per day.
- 5,000 incorrect surgical operations per week.
- Two short or long landings at most major airports each day.
- 200,000 wrong drug prescriptions each year.
- No electricity for almost seven hours each month.

Even if we look at the profile of a 4 sigma company, we find the following characteristics:

1.) Profitable and growing, but with a decreasing market share.

2.) Market prices declining for certain products or product lines.

3.) Competitors increasing

4.) Has quality assurance program but deficiencies keep "slipping" through the Q.C. process.

5.) Spending 10-25% of sales dollars on repairing or reworking product before it ships. (This is crucial and a fact that will surface during benchmarking.)

6.) Unaware that **best in class** companies have similar processes that are greater than 110 times more defect free.

7.) Believes that a zero-defects goal is neither realistic nor achievable.

8.) Has 10 times the number of suppliers required to run the business. (Also critical. To "carry" a supplier can cost upwards to $10K just to maintain the database.)

9.) 5-10% of the firm's customers are dissatisfied with product, sales or service and will not recommend that others purchase products or services. The possible reason for this can be seen in the bell-shaped curve below.

Look at the graphic. This will demonstrate the savings in going from three Sigma to six Sigma.

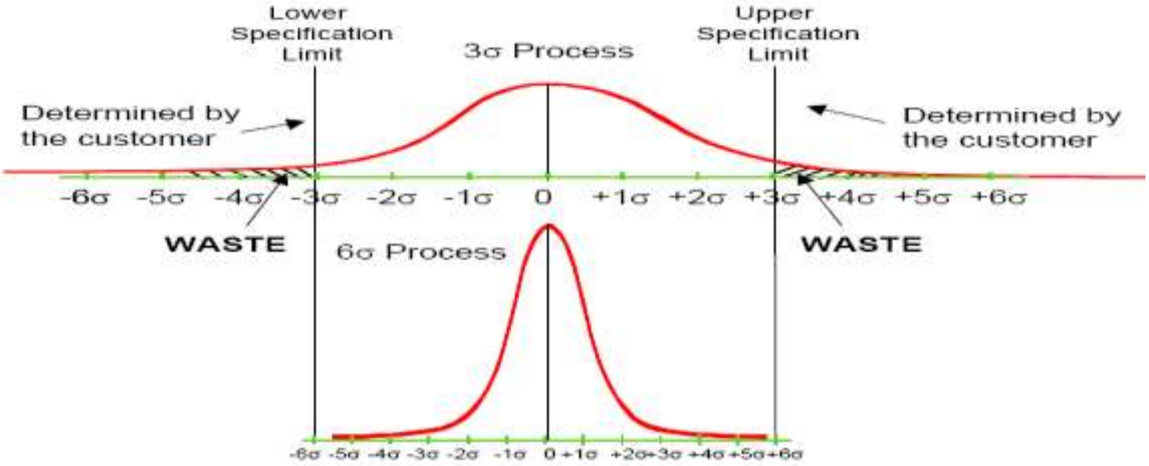


FIGURE 3: SIX SIGMA & STANDARD DEVIATION

If we can improve our process capability, we can eliminate the waste that occurs below the lower specification limit (LSL) and above the higher specification limit (HSL). Both limits are determined by the customer in the IDENTIFY (DEFINE) phase of our DMAIC process. Please notice that the lower "bell-shaped" curve represents a six sigma CENTERED process that yields a defect rate below 4 parts per million (PPM). This is definitely where we wish to be. Critical to the effort is the manner in which the components are ultimately defined and detailed. This is where application of GD&T comes in. It is critical that components be defined completely so there are no questions as to form, fit and function. Our next section will address how this is accomplished and those methods used to bring about a complete definition of the component or product.

MEASURE AND ANALYZE:

As a part of Identify, it is always a very good practice to "benchmark" existing products if they are similar to the product you are modifying and / or launching. Benchmarking is generally defined as follows: "Benchmarking is the process of continually searching for the best methods, practices, and processes and either adopting or adapting their good features and implementing them to become the best of the best". I would add to this definition the need to benchmark the proposed product design for components and subassemblies. This provides a comparison of the proposed design with existing competitive designs and can highlight areas of needed improvement. This process involves the customer and obtaining reliable information on product field failures. Understanding field failures and their cause is critical to improving the product performance. The following areas are critical to the DFSS benchmarking process:

- Competitive Benchmarking. (Comparisons between competition's products and your product.)
- Product Design Benchmarking (Determining the sigma value of existing and similar products now being produced by your company.)

- Process Benchmarking (Determining the sigma of the production processes.)
- Best Practices Benchmarking. (Are there better methods to fabricate and assemble your products?)

Customers can be a great aid in the benchmarking process and give us information that otherwise might be very difficult to obtain; i.e. field failure rates. This approach allows for the following:

1.) To find information that would, most likely, not surface during a typical sales call.
2.) To encourage the customer to think "out-of-the-box" and focus on specific behaviors and product designs that would make the product "best-in-class".
3.) To provide data to engineering that will promote needed changes in products. Customers have a vested interest in providing their accounts with the best and longest-lasting products. They generally know their competition.
4.) To find out customer concerns, other than price.
5.) To demonstrate long-term commitment to continuous product improvement.
6.) To encourage customers to provide data to substantiate their perceptions.
7.) To build account credibility by committing to actions which address product design complaints.
8.) To address issues with product performance and gain knowledge of field performance.
9.) To proactively define customer expectations by allowing them to define best-in-class products.

SAMPLING TECHNIQUES:

Successful statistical practice is based on focused problem definition. In sampling, this includes defining the population from which our sample is drawn. A population can be defined as including all people or items with the characteristic one wishes to understand. Because there is very rarely enough time or money to gather information from everyone or everything in a population, the goal becomes finding a representative sample (or subset) of that population.

Sometimes what defines a population is obvious. For example, a manufacturer needs to decide whether a batch of material from production is of high enough quality to be released to the customer, or should be sentenced for scrap or rework due to poor quality. In this case, the batch is the population.

Although the population of interest often consists of physical objects, sometimes we need to sample over time, space, or some combination of these dimensions. For instance, an investigation of supermarket staffing could examine checkout line length at various times, or a study on endangered penguins might aim to understand their usage of various hunting grounds over time. For the time dimension, the focus may be on periods or discrete occasions.

For the reasons detailed above, sample size is absolutely critical to insure measured data is both accurate and precise or to discover errors relative to upper specification limits (USL) and lower specification limits (LSL). The spread between the USL and LSL is generally considered to be the range of acceptability for the component or the product. The majority of statistical tests depend heavily on the assumption that all data were collected in a random manner. This is a very important assumption because of the significant probability during measurement of the occurrence of aggregations, change in conditions, assignable causes, trends, cyclical effects, progressive learning, and drift in natural, industrial and human processes. In other words, things change. Sampling methods are classified as either *probability* or *non-probability*. In probability samples, each member of the population has a known non-zero probability of being selected. Probability methods include random sampling, systematic sampling, and stratified sampling. In non-probability sampling, members are selected from the population in some nonrandom manner. These include convenience sampling, judgment sampling, quota sampling, and snowball sampling. The advantage of probability sampling is that sampling error can be calculated. Sampling error is the degree to which a sample might differ from the population. When inferring to the population, results are reported plus or minus the sampling error. In non-probability sampling, the degree to which the sample differs from the population remains unknown.

There are several methods of accomplishing an adequate size. These are as follows:

- **Random sampling** is the purest form of probability sampling. Each member of the population has an equal and known chance of being selected. When there are very large populations, it is often difficult or impossible to identify every member of the population, so the pool of available subjects becomes biased.

- **Systematic sampling** is often used instead of random sampling. It is also called an nth name selection technique. After the required sample size has been calculated, every nth record is selected from a list of population members. As long as the list does not contain any hidden order, this sampling method is as good as the random sampling method. Its only advantage over the random sampling technique is simplicity. Systematic sampling is frequently used to select a specified number of records from a computer file.

- **Stratified sampling** is a commonly used probability method that is superior to random sampling because it reduces sampling error. A stratum is a subset of the population that shares at least one common characteristic. Examples of stratums might be males and females, or managers and non-managers. The researcher first identifies the relevant stratums and their actual representation in the population. Random sampling is then used to select a *sufficient* number of subjects from each stratum. "*Sufficient*" refers to a sample size large enough for us to be reasonably confident that the stratum represents the population. Stratified sampling is often used when one or more of the stratums in the population have a low incidence relative to the other stratums.

- **Convenience sampling** is used in exploratory research where the researcher is interested in getting an inexpensive approximation of the truth. As the name implies, the sample is selected because they are convenient. This non-probability method is often used during preliminary research efforts to get a gross estimate of the results, without incurring the cost or time required to select a random sample.

- **Judgment sampling** is a common non-probability method. The researcher selects the sample based on judgment. This is usually an extension of convenience sampling. For example, a researcher may decide to draw the entire sample from one "representative" city, even though the population includes all cities. When using this method, the researcher must be confident that the chosen sample is truly representative of the entire population.
- **Quota sampling** is the non-probability equivalent of stratified sampling. Like stratified sampling, the researcher first identifies the stratums and their proportions as they are represented in the population. Then convenience or judgment sampling is used to select the required number of subjects from each stratum. This differs from stratified sampling, where the stratums are filled by random sampling.
- **Snowball sampling** is a special non-probability method used when the desired sample characteristic is rare. It may be extremely difficult or cost prohibitive to locate respondents in these situations. Snowball sampling relies on referrals from initial subjects to generate additional subjects. While this technique can dramatically lower search costs, it comes at the expense of introducing bias because the technique itself reduces the likelihood that the sample will represent a good cross section from the population.

In the appliance industry, it is customary to collect samples from production in all shifts; i.e. first, second and third. Thirty samples per shift generally represent a statistically valid sample size. Ninety total components or assemblies are measured to determine adherence to the USL and LSL. Generally, measuring the “critical-to-quality” dimensions on a drawing determine suitability. After a product is in production, spot checking for quality is accomplished by collecting five samples per shift. These measurements can determine trends in production from which CPk or process acceptability is measured.

The United States military developed MIL-STD-105E for the sole purpose of identifying and defining methodology for selecting samples. This is as follows:

Standard military sampling procedures for inspection by attributes were developed during World War II. Army Ordnance tables and procedures were generated in the early 1940's and these grew into the Army Service Forces tables. At the end of the war, the Navy also worked on a set of tables. In the meanwhile, the Statistical Research Group at Columbia University performed research and outputted many outstanding results on attribute sampling plans.

These three streams combined in 1950 into a standard called Mil. Std. 105A. It has since been modified from time to time and issued as 105B, 105C and 105D. Mil. Std. 105D was issued by the U.S. government in 1963. It was adopted in 1971 by the American National Standards Institute as ANSI Standard Z1.4 and in 1974 it was adopted (with minor changes) by the International Organization for Standardization as ISO Std. 2859. The latest revision is Mil. STD 105E and was issued in 1989.

These three similar standards are continuously being updated and revised, but the basic tables remain the same. Thus the discussion that follows of the germane aspects of Mil. Std. 105E also applies to the other two standards.

The steps in the use of the standard can be summarized as follows:

1. Decide on the AQL (Acceptable Quality Level or USL and LSL.)
2. Decide on the inspection level.
3. Determine the lot size.
4. Enter the table to find sample size code letter.
5. Decide on type of sampling to be used.
6. Enter proper table to find the plan to be used.
7. Begin with normal inspection; follow the switching rules and the rule for stopping the inspection (if needed). This includes sampling over shifts or a designated period of time.

MEASURING INSTRUMENTS:

We are going to look at two instrument classifications at this time: 1.) Hand-held and 2.) Automated. Please keep in mind, all measuring equipment must be calibrated annually or semi-annually. All measuring equipment must have associated Gauge R & R information. All equipment must have calibration certification documents on file for review. All equipment must be repaired or discarded if proper calibrations cannot be maintained and Gauge R & R falls outside acceptable limits.

HAND-HELD:

Dial Indicators-- In various contexts of science, technology, and manufacturing (such as machining, fabricating, and additive manufacturing), an indicator is defined as any instrument used to accurately measure small distances and angles, and amplify them to make them more obvious. The name comes from the concept of *indicating* to the user that which their naked eye cannot discern; such as the presence, or exact quantity, of some small distance (for example, a small height difference between two flat surfaces, a slight lack of concentricity between two cylinders, or other small physical deviations).

Many indicators have a dial display, in which a needle points to graduations in a circular array around the dial. Such indicators, of which there are several types, therefore; are often called dial indicators.

Non-dial types of indicators include mechanical devices with cantilevered pointers and electronic devices with digital displays.

Indicators may be used to check the variation in tolerance during the inspection process of a machined part, measure the deflection of a beam or ring under laboratory conditions, as well as many other situations where a small measurement needs to be registered or indicated. Dial indicators typically measure ranges from 0.25mm to 300mm (0.015in to 12.0in), with graduations of 0.001mm to 0.01mm (metric) or 0.00005 in to 0.001in (imperial/customary).

Various names are used for indicators of different types and purposes, including dial gauge, clock, probe indicator, pointer, test indicator, dial test indicator, drop indicator, plunger indicator, and others. A typical dial indicator is shown as follows:

FIGURE 4: DIAL INDICATOR

Gauge Blocks-- Gauge blocks (also known as gauge blocks, Johansson gauges, slip gauges, or Jo blocks) are a system for producing precision lengths. The individual gauge block is a metal or ceramic block that has been precision ground and lapped to a specific thickness. Gauge blocks come in sets of blocks with a range of standard lengths. In use, the blocks are stacked to make up a desired length.

An important feature of gauge blocks is that they can be joined together with very little dimensional uncertainty. The blocks are joined by a sliding process called *wringing*, which causes their ultra-flat surfaces to cling together. A small number of gauge blocks can be used to create accurate lengths within a wide range. By using 3 blocks from a set of 30 blocks, one may create any of the 1000 lengths from 3.000 to 3.999 mm in 0.001 mm steps (or .3000 to .3999 inches in 0.0001 inch steps). Gauge blocks were invented in 1896 by Swedish machinist Carl Edvard Johansson. They are used as a reference for the calibration of measuring equipment used in machine shops, such as micrometers, sine bars, calipers, and dial indicators (when used in an inspection role). Gauge blocks are the main means of length standardization used by industry.

FIGURE 5: GAUGE BLOCKS

Optical Flat— An optical flat is an optical-grade piece of glass lapped and polished to be extremely flat on one or both sides, usually within a few millionths of an inch (about 25 nanometers). They are used with a monochromatic light to determine the flatness of other optical surfaces by interference. When an optical flat's polished surface is placed in contact with a surface to be tested, dark and light bands will be formed when viewed with monochromatic light. These bands are known as interference fringes and their shape gives a visual representation of the flatness of the surface being tested. The surface flatness is indicated by the amount of curve and spacing between the interference fringes. Straight, parallel, and evenly spaced interference fringes indicate that the work surface flatness is equal to or higher than that of the reference surface. An optical flat utilizes the property of interference to exhibit the flatness on a desired surface. When an optical flat, also known as a test plate, and a work surface are placed in contact, an air wedge is formed. Areas between the flat and the work surface that are not in contact form this air wedge. The change in thickness of the air wedge will dictate the shape and orientation of the interference bands. The amount of curvature that is shown by the interference bands can be used to determine the flatness of the surface. If the air wedge is too large, then many closely spaced lines can appear, making it difficult to analyze the pattern formed. Simply applying pressure to the top of the optical flat alleviates the problem.

The determination of the flatness of any particular region of a surface is done by making two parallel imaginary lines; one between the ends of any one fringe, and the other at the top of that same fringe. The number of fringes located between the lines can be used to determine the flatness. Monochromatic light is used to create sharp contrast for viewing and in order to specify the flatness as a function of a single wavelength.

The digital photograph below will show an optical flat.

FIGURE 6: OPTICAL FLAT

Steel Rule— The steel rule is a basic measuring tool. When used correctly, a good steel rule is a surprisingly accurate measuring device. Some people confuse rules and scales. A scale is a measuring device used by architects and engineers that assists them in making drawings to a scale other than full size. A rule is used to measure actual sizes. Conventional wisdom is that the best steel rules are machine divided. This means the graduations are cut on a machine that uses gearing to ensure the graduation lines are evenly spaced and the correct distance apart. Most steel rules are now made by a photoengraving process called photo etching. A photosensitive resist is exposed through a precision master negative to create a pattern of masked and clean areas. An etching solution forms the graduations and other markings on the rule. Good steel rules have uniform graduation line widths. Variation in line width makes accurate measurement difficult. So let's take a look at the conventional wisdom. Are machine divided rules better than photo etched rules? When this marketing claim was first made, it was probably true. But now it is most certainly not true. The process of machine dividing rules was developed about 125 years ago. It probably produced a major improvement in the accuracy of rules. But anything that relies on gears and mechanics must involve some measure of error, simply because the machine cannot be perfectly made. Photoengraving, on the other hand, relies on a precision master to transfer the design to the rule. With a perfect master, each rule made from that master should also be virtually perfect. So the question becomes; how well can a master be made? And the answer is very well indeed. The basic process for making steel rules is the same process by which computer processors and other integrated circuits are made with extreme precision. Current technology can create a master negative that is orders of magnitude better than required to make a steel rule. The two major manufacturers of steel rules in the United States are the L. S. Starrett Company (Starrett) and Products Engineering Corporation (PEC). PEC makes steel rules for many of the other brands that are available in the United States. Starrett rules are machine divided, whereas PEC rules are precision etched.

The material that a steel rule is made of is also important to the quality. Good steel rules are made from high-carbon spring steel that is hardened and tempered to Rockwell "CL or Rc 47-52. They are chrome plated, usually with a satin finish, for corrosion resistance and readability. While you can find many inexpensive steel rules made of stainless steel, it is not a great material from which to make steel rules. The stainless steel used to make steel rules cannot be hardened to the level of spring steel and thus it tends to yield when bent, keeping the curve, and not snapping back to straight. Both the long edges and the ends of steel rules should be ground for straightness and accuracy. Ends that are ground square, and in proper relationship to the graduations allow accurate measurements from the ends of the steel rule. A properly made steel rule will have virtually no error in the graduations. Any error in the rule is between the first graduation and the end of the rule. The standards for this error are actually quite lenient. The first graduation can have an error between +0.004" and –0.002" and still meet the standards. Most steel rules will handily meet this standard.

The digital below shows a typical steel rule used for measuring actual components.

FIGURE 7: STEEL RULE

Vernier Calipers—A vernier caliper is defined as a linear measuring instrument consisting of a scaled rule with a projecting arm at one end, to which is attached a sliding vernier with a projecting arm that forms a jaw with the other projecting arm. This is a device that lets the user measure more precisely than could be done unaided when reading a uniformly divided straight or circular measurement scale. It is a scale that indicates where the measurement lies in between two of the marks on the main scale. Verniers are common on sextants used in navigation, scientific instruments used to conduct experiments, machinists' measuring tools (all sorts, but especially calipers and micrometers) used to work materials to fine tolerances, and on theodolites used in surveying. The main use of the vernier caliper is to measure the internal and the external diameters of an object. To measure using a vernier scale, the user first reads the finely marked "fixed" scale (in the diagram). This measure is typically between two of the scale's smallest graduations. The user then reads the finer vernier scale (see diagram), which measures between the smallest graduations on the fixed scale—providing much greater accuracy. It is also used in measuring an object to its lowest decimal point.

Vernier scales work so well because most people are especially good at detecting which of the lines is aligned and misaligned and that ability gets better with practice; in fact, far exceeding the optical capability of the eye. This ability to detect alignment is called 'Vernier acuity'. Historically, none of the alternative technologies exploited this or any other hyperacuity, giving the Vernier scale an advantage over its competitors.

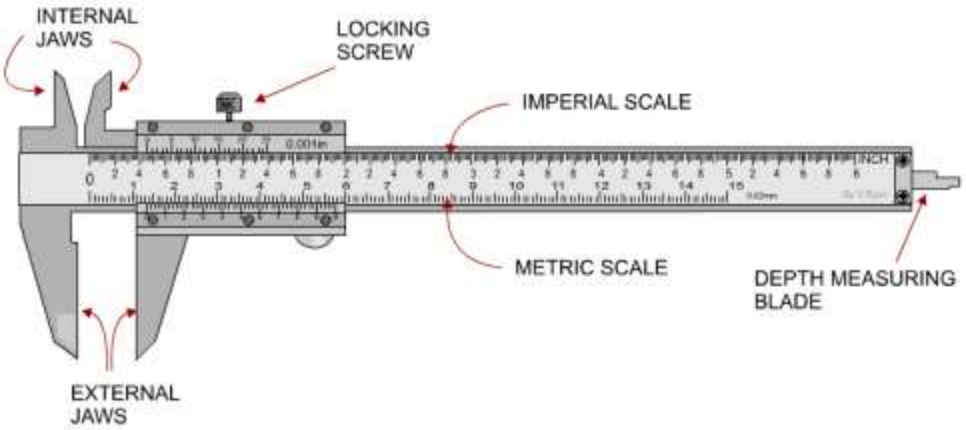


FIGURE 8: VERNIER CALIPER

Sine Bars-- A sine bar consists of a hardened, precision ground body with two precision ground cylinders fixed at the ends. The distance between the centers of the cylinders is precisely controlled, and the top of the bar is parallel to a line through the centers of the two rollers. The dimension between the two rollers is chosen to be a whole number (for ease of later calculations) and forms the hypotenuse of a triangle when in use.

When a sine bar is placed on a level surface the top edge will be parallel to that surface. If one roller is raised by a known distance, usually using gauge blocks, then the top edge of the bar will be tilted by the same amount, forming an angle that may be calculated by the application of the sine rule.

- The hypotenuse is a constant dimension—(100 mm or 10 inches in the examples shown).
- The height is obtained from the dimension between the bottom of one roller and the table's surface.
- The angle is calculated by using the sine rule. Some engineering and metalworking reference books contain tables showing the dimension required to obtain an angle from 0-90 degrees, incremented by 1 minute intervals.

$$\sin(angle) = \frac{perpendicular}{hypotenuse}$$

Angles may be measured or set with this tool.

Angles are measured using a sine bar with the help of gauge blocks and a dial gauge or a spirit level. The aim of a measurement is to measure the surface on which the dial gauge or spirit level is placed horizontally. For example, to measure the angle of a wedge, the wedge is placed on a horizontal table. The sine bar is placed over the inclined surface of the wedge. At this position, the top surface of the sine bar is inclined the same amount as the wedge. Using gauge blocks, the top surface is made horizontal. The sine of the angle of inclination of the wedge is the ratio of the height of the gauge blocks used and the distance between the centers of the cylinders. A sine bar may be seen as follows:

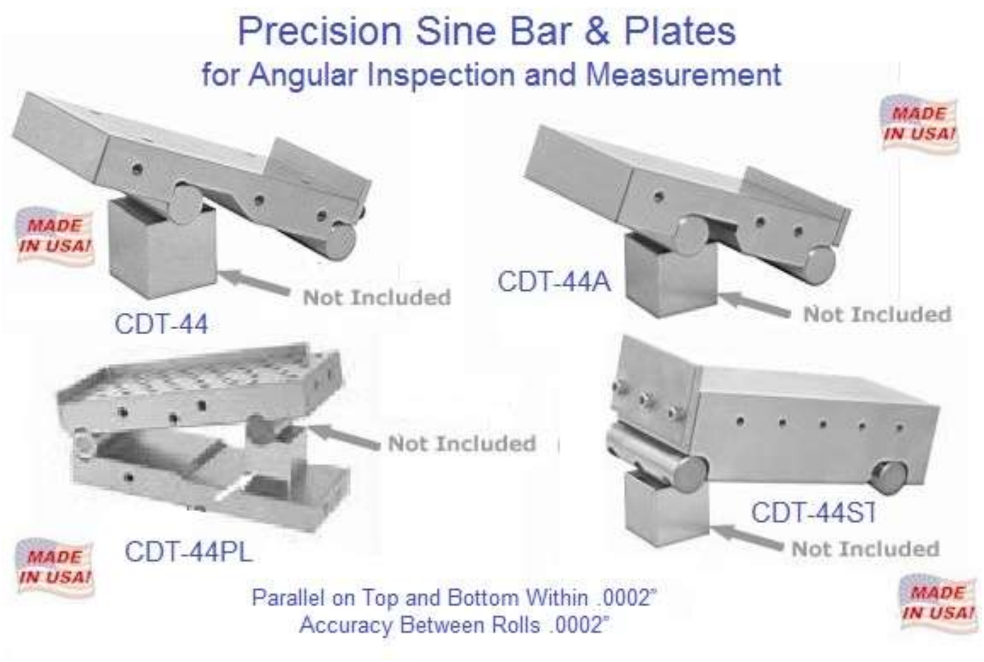


FIGURE 9: SINE BAR

Scales

Every time I hop on my bathroom scales I get data that allows me to make a determination relative to my weight for that day. Do I "pig out" or fast? Measuring weight can be absolutely critical to commerce. An ounce of gold could mean the difference in hundreds of dollars. A milligram of any ingredient in medications can mean the difference between health and unintended consequences. The scale below is an example of comparative weighing. A weight of known quantity is placed on the right side of the scale while a material or substance of unknown weight is placed on the left pan. The movable scale in the middle of the device is moved to provide balance to the indicating needle.

FIGURE 10: PAN SCALES

FIGURE 11: FLAT SCALES

Load Cells

A load cell is a transducer which converts force into a measurable electrical output. Although there are many varieties of load cells, strain gauge based load cells are the most commonly used type. Load cell designs can be distinguished according to the type of output signal generated (pneumatic, hydraulic, electric) or according to the way they detect weight (bending, shear, compression, tension, etc.)

Except for certain laboratories where precision mechanical balances are still used, strain gauge load cells dominate the weighing industry. Pneumatic load cells are sometimes used where intrinsic safety and hygiene are desired, and hydraulic load cells are considered in remote locations, as they do not require a power supply. Strain gauge load cells offer accuracies from within 0.03% to 0.25% full scale and are suitable for almost all industrial applications.

Before strain gauge-based load cells became the method of choice for industrial weighing applications, mechanical lever scales were widely used. Mechanical scales can weigh everything from pills to railroad cars and can do so accurately and reliably if they are properly calibrated and maintained. The method of operation can involve either the use of a weight balancing mechanism or the detection of the force developed by mechanical levers. The earliest, pre-strain gauge force sensors included hydraulic and pneumatic designs. In 1843, English physicist Sir Charles Wheatstone devised a bridge circuit that could measure electrical resistances. The Wheatstone bridge circuit is ideal for measuring the resistance changes that occur in strain gauges. Although the first bonded resistance wire strain gauge was developed in the 1940s, it was not until modern electronics caught up that the new technology became technically and economically feasible. Since that time, however, strain gauges have proliferated both as mechanical scale components and in stand-alone load cells.

Let’s now look at the three types.

Hydraulic load cells are force -balance devices, measuring weight as a change in pressure of the internal filling fluid. In a rolling diaphragm type hydraulic load cell, a load or force acting on a loading head is transferred to a piston that in turn compresses a filling fluid confined within an elastomeric diaphragm chamber. As force increases, the pressure of the hydraulic fluid rises. This pressure can be locally indicated or transmitted for remote indication or control. Output is linear and relatively unaffected by the amount of the filling fluid or by its temperature. If the load cells have been properly installed and calibrated, accuracy can be within 0.25% full scale or better, acceptable for most process weighing applications. Because this sensor has no electric components, it is ideal for use in hazardous areas. Typical hydraulic load cell applications include tank, bin, and hopper weighing. For maximum accuracy, the weight of the tank should be obtained by locating one load cell at each point of support and summing their outputs.

Pneumatic load cells also operate on the force-balance principle. These devices use multiple dampener chambers to provide higher accuracy than can a hydraulic device. In some designs, the first dampener chamber is used as a tare weight chamber. Pneumatic load cells are often used to measure relatively small weights in industries where cleanliness and safety are of prime concern. The advantages of this type of load cell include their being inherently explosion proof and insensitive to temperature variations. Additionally, they contain no fluids that might contaminate the process if the diaphragm ruptures. Disadvantages include relatively slow speed of response and the need for clean, dry, regulated air or nitrogen.

Strain-gauge load cells convert the load acting on them into electrical signals. The gauges themselves are bonded onto a beam or structural member that deforms when weight is applied. In most cases, four strain gauges are used to obtain maximum sensitivity and temperature compensation. Two of the gauges are usually in tension, and two in compression, and are wired with compensation adjustments as shown in Figure 7-2. When weight is applied, the strain changes the electrical resistance of the gauges in proportion to the load. Other load cells are fading into obscurity, as strain gauge load cells continue to increase their accuracy and lower their unit costs. Figure 12 below details a hydrostatic load cell. Figure 13 shows a typical application for this type of load cell.

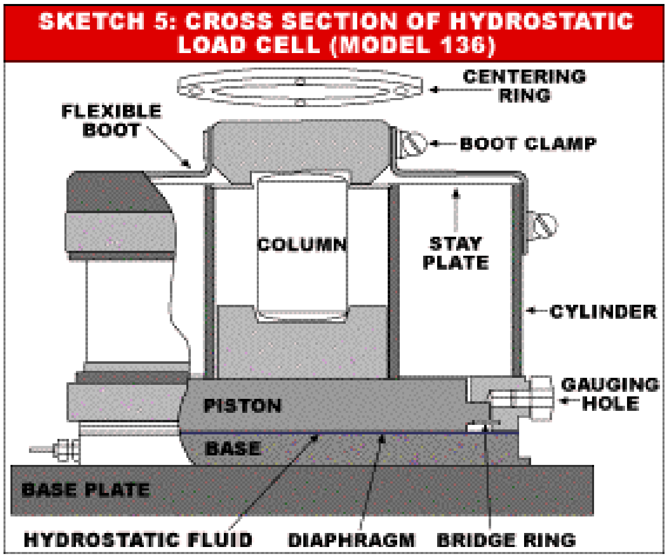

SKETCH 5: CROSS SECTION OF HYDROSTATIC LOAD CELL (MODEL 136)

FIGURE 12: LOAD CELL CROSS-SECTION

FIGURE 13: LOAD CELL APPLICATION

VOLTAGE, AMPERAGE, & RESISTANCE:

As you might expect, measurements for voltage, amperage and resistance are critical to many applications. I have copied an “Electric Power Wheel” to indicate the relationship between the measurable entities commonly used in defining the use of electricity in domestic and commercial applications. Please note the nomenclature for “E”,”P”,”I”, and “R”. You can see from the “wheel”:

P (Power measured in Watts) = E^2/R or Voltage squared divided by Resistance. These relationships indicate that measuring voltage by using a voltmeter, amperage by using an ammeter and resistance by using an ohmmeter, I can calculate power. This makes the measurement of voltage, current and resistance critical in calculations relating to industry and commerce. We will now take a look at instruments used in accumulating this type of data.

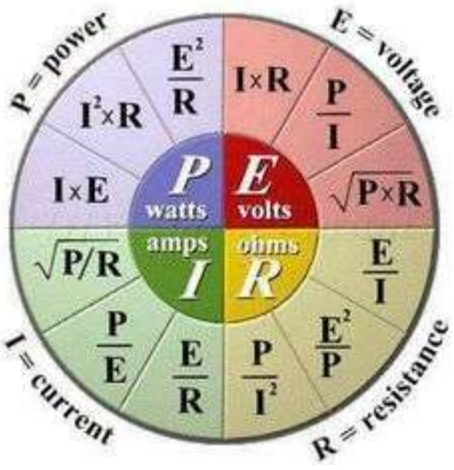


FIGURE 14: ELECTRICAL POWER WHEEL

Digital Voltmeter:

A voltmeter, also known as a voltage meter, is an instrument used for measuring the potential difference, or voltage, between two points in an electrical or electronic circuit. Some voltmeters are intended for use in direct current (DC) circuits; others are designed for alternating current (AC) circuits. Specialized voltmeters can measure radio frequency (RF) voltage.

A basic analog voltmeter consists of a sensitive galvanometer (current meter) in series with a high resistance. The internal resistance of a voltmeter must be high. Otherwise it will draw significant current, and thereby disturb the operation of the circuit under test. The sensitivity of the galvanometer and the value of the series resistance determine the range of voltages that the meter can display.

A digital voltmeter shows voltage directly as numerals. Some of these meters can determine voltage values to several significant figures. Practical laboratory voltmeters have maximum ranges of 1000 to 3000 volts (V). Most commercially manufactured voltmeters have several scales, increasing in powers of 10; for example, 0-1 V, 0-10 V, 0-100 V, and 0-1000 V.

Two types are shown below. One is a panel mount and one is a hand-held device.

FIGURE 15: VOLT METER, PANEL MOUNT

FIGURE 16: VOLT METER, HAND-HELD

Amp Meter:

An ammeter is a measuring instrument used to measure the current in a circuit. Electric currents are measured in amperes (A), hence the name. Instruments used to measure smaller currents, in the milliampere or microampere range, are designated as millimeters or micro ammeters. An ammeter is placed in series with a circuit element to measure the electric current flow through it. The meter must be designed to offer very little resistance to the current so that it does not appreciably change the circuit it is measuring. To accomplish this, a small resistor is placed in parallel with the galvanometer to shunt most of the current around the galvanometer. Its value is chosen so that when the design current flows through the meter it will deflect to its full-scale reading. A galvanometer full-scale current is very small: on the order of milliamperes.

FIGURE 17: AMP METER

Ohm Meter:

The purpose of an ohmmeter, of course, is to measure the resistance placed between its leads. This resistance reading is indicated through a mechanical meter movement which operates on electric current. The ohmmeter must then have an internal source of voltage to create the necessary current to operate the movement, and also have appropriate ranging resistors to allow just the right amount of current through the movement at any given resistance.

FIGURE 18: AMP METER, HAND-HELD

Electronic Clocks:

When we discuss precision electronic clocks we think of quartz clocks. A quartz clock is a clock that uses an electronic oscillator that is regulated by a quartz crystal to keep time. This crystal oscillator creates a signal with very precise frequency, so that quartz clocks are at least an order of magnitude more accurate than mechanical clocks. Generally, some form of digital logic counts the cycles of this signal and provides a numeric time display, usually in units of hours, minutes, and seconds. The first quartz clock was built in 1927 by Warren Marrison and J.W. Horton at Bell Telephone Laboratories. Since the 1980s when the advent of solid state digital electronics allowed them to be made compact and inexpensive, quartz timekeepers have become the world's most widely-used timekeeping technology, used in most clocks and watches, as well as computers and other appliances that keep time.

The relative stability of the resonator and its driving circuit is much better than its absolute accuracy. Standard-quality resonators of this type are warranted to have a long-term accuracy of about 6 parts per million (0.0006%) at 31 °C (87.8 °F); that is, a typical quartz clock or wristwatch will gain or lose 15 seconds per 30 days (within a normal temperature range of 5 °C/41 °F to 35 °C/95 °F) or less than a half second clock drift per day when worn near the body.

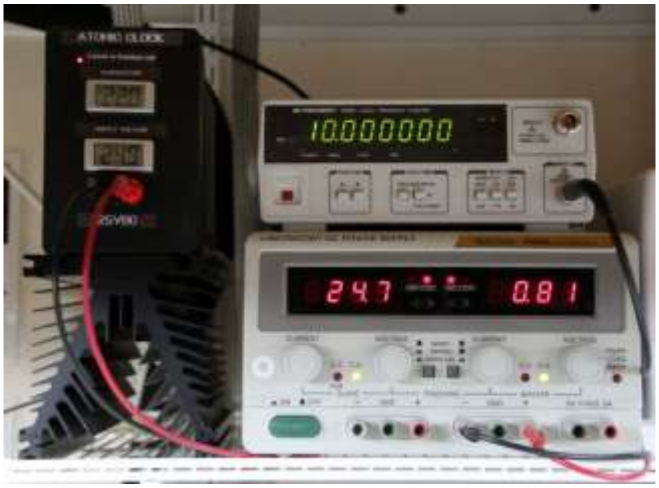


FIGURE 19: ELECTRONIC CLOCK

Oscilloscope:

Oscilloscopes are used to observe the change of an electrical signal over time; such that voltage and time describe a shape which is continuously graphed against a calibrated scale. The observed waveform can be analyzed for such properties as amplitude, frequency, rise time, time interval, distortion and others. Modern digital instruments may calculate and display these properties directly. Originally, calculation of these values required manually measuring the waveform against the scales built into the screen of the instrument.

The oscilloscope can be adjusted so that repetitive signals can be observed as a continuous shape on the screen. A storage oscilloscope allows single events to be captured by the instrument and displayed for a relatively long time, allowing observation of events too fast to be directly perceptible.

Oscilloscopes are used in the sciences, medicine, engineering, and telecommunications industry. General-purpose instruments are used for maintenance of electronic equipment and laboratory work. Special-purpose oscilloscopes may be used for such purposes as analyzing an automotive ignition system or to display the waveform of the heartbeat as an electrocardiogram.

Before the advent of digital electronics, oscilloscopes used cathode ray tubes (CRTs) as their display element (commonly referred to as CROs) and linear amplifiers for signal processing. Storage oscilloscopes used special storage CRTs to maintain a steady display of a single brief signal. CROs were later largely superseded by digital storage oscilloscopes (DSOs) with thin panel displays, fast analog-to-digital converters and digital signal processors. DSOs without integrated displays (sometimes known as digital) are available at lower cost and use a general-purpose digital computer to process and display waveforms.

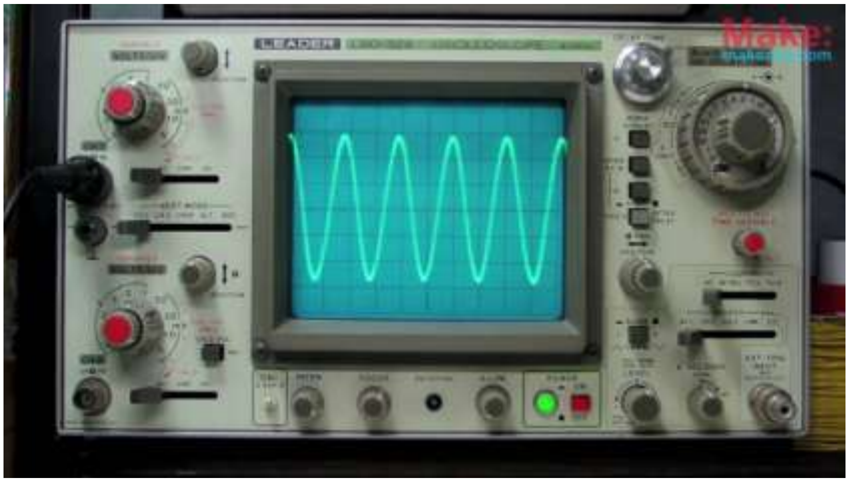


FIGURE 20: OSCILLOSCOPE

TEMPERATURE MEASUREMENT:

There are several methods that can be used to measure the temperature of a substance. These are categorized as follows:

- **Thermocouple Temperature Measurement Sensors**
  Thermocouples consist essentially of two strips or wires made of different metals and joined at one end. Changes in the temperature at that juncture induce a change in electromotive force (emf) between the other ends. As temperature goes up, this output emf of the thermocouple rises, though not necessarily linearly.

- **Resistance Temperature Devices (RTD)**
  Resistive temperature devices capitalize on the fact that the electrical resistance of a material changes as its temperature changes. Two key types are the metallic devices (commonly referred to as RTDs), and thermistors. As their name indicates, RTDs rely on resistance change in a metal, with the resistance rising more or less linearly with temperature. Thermistors are based on resistance change in a ceramic semiconductor; the resistance drops nonlinearly with temperature rise.

- **Infrared Temperature Measurement Devices**
  Infrared sensors are non-contacting devices. They infer temperature by measuring the thermal radiation emitted by a material.

- **Bimetallic Temperature Measurement Devices**
  Bimetallic devices take advantage of the difference in rate of thermal expansion between different metals. Strips of two metals are bonded together. When heated, one side will expand more than the other, and the resulting bending is translated into a temperature reading by mechanical linkage to a pointer. These devices are portable and they do not require a power

supply, but they are usually are not as accurate as thermocouples or RTDs and they do not readily lend themselves to temperature recording.

- **Fluid-Expansion Temperature Measurement Devices**
  Fluid-expansion devices, typified by the household thermometer, generally come in two main classifications: the mercury type and the organic-liquid type. Versions employing gas instead of liquid are also available. Mercury is considered an environmental hazard, so there are regulations governing the shipment of devices that contain it. Fluid-expansion sensors do not require electric power, do not pose explosion hazards, and are stable even after repeated cycling. On the other hand, they do not generate data that is easily recorded or transmitted, and they cannot make spot or point measurements.

- **Change-of-State Temperature Measurement Devices**
  Change-of-state temperature sensors consist of labels, pellets, crayons, lacquers or liquid crystals whose appearance changes once a certain temperature is reached. They are used, for instance, with steam traps - when a trap exceeds a certain temperature, a white dot on a sensor label attached to the trap will turn black. Response time typically takes minutes, so these devices often do not respond to transient temperature changes. And accuracy is lower than with other types of sensors. Furthermore, the change in state is irreversible, except in the case of liquid-crystal displays. Even so, change-of-state sensors can be handy when one needs confirmation that the temperature of a piece of equipment or a material has not exceeded a certain level; for instance, for technical or legal reasons during product shipment.

FIGURE 21: INFRARED TEMPERATURE MEASURING DEVICE

FIGURE 22: PROBE-TYPE TEMPERATURE MEASURING DEVICE

FLUID FLOW MEASURING DEVICES:

Fluid flow devices fall into a number of device categories as well as fluid classes. In general we can split the fluids into two classes: gasses and liquids. Within these two broad classes are a number of special classes that one should be careful of. Flammable liquids and gasses require special handling, as do those that are at temperature extremes (cold or hot). When selecting a transducer you should be cautious that the device you are selecting is compatible with the fluid and conditions you are working with. A few examples would be acids, food grade liquids, and DI water. Surprisingly de-ionized water is an extremely harsh liquid that can cause serious headaches.

The physical measurement devices come in a number of classifications. While the following classifications do not match any industry standards, they serve to break the transducers down into some reasonably functional groups. These are: Obstruction flow meters, Velocity flow meters – Including Moving Member meters, Positive Displacement meters, Variable area meters and Electronic meters.

- Obstruction flow meters are the simplest and oldest of the measurement classes. One of the first obstruction flow meters was used by the ancient Samarians. In order to measure the amount of water flowing through an aqueduct, they would place a board across the flow, and measure how high the water was when it flowed over the top of the board. In this way, they could easily calculate how much water was flowing in the duct. This was modified in later times to a device called a “notch” weir.

- Notch weirs are classified by the shape of their notch; rectangular weirs, triangular, or V-notch, weirs, trapezoidal weirs, and parabolic weirs.

- The equivalent of the notch weir in a tube would be an orifice plate. This flow device is created by inserting an obstructing plate, usually with a round hole in the middle, into the pipe and measuring the pressure on each side of the orifice. Pressure taps on each flange allow you to easily measure the pressure differential across the plate. This pressure differential, along with the dimensions are combined with certain fluid properties to determine the flow through the pipe.

- The venturi flow meter, while considered an obstruction flow meter, is less of an obstruction than the orifice type. It still does have a certain amount of pressure drop, but it is significantly less than the orifice type meter.
- A flow nozzle consists of a restriction with an elliptical contour approach section that terminates in a cylindrical throat section. Pressure drop between the locations one pipe diameter upstream and one-half pipe diameter downstream is measured. Flow nozzles provide an intermediate pressure drop between orifice plates and venturi tubes; also, they are applicable to some slurry systems that would be otherwise difficult to measure.

FIGURE 23: DIGITAL FLOW METER

VELOCITY FLOW MEASURING DEVICES:

Velocity flow measurement techniques allow for the measurement of total flow by measuring the velocity of the fluid within a fixed area duct or pipe. The technique uses a measuring probe to determine the velocity of the fluid in the center portion of the pipe. It is important to understand that with all fluid flows, there are boundary layer effects at the interface between the walls of the duct or pipe and the fluid flowing through it. For this technique to provide reasonably accurate results, the velocity measurement of the flow must be made well within the duct, to minimize the effects of the boundary layers. For this reason, ducts or piles of small diameter typically do not fair well with this technique. The technique also requires that you be in a laminar flow environment. The results in a turbulent flow area suffer in stability and accuracy. It is possible to calculate the location where the flow in a pipe or duct is fully laminar, but for most applications a general rule of thumb is sufficient. That rule is to make the measurement at least 10 pipe diameters upstream and 20 pipe diameters downstream of any junction, elbow or other flow disturbing point in the pipe.

- **Pitot Tube**-- The Pitot tube is a simple device that allows for the measurement of the flow pressure in a moving fluid. This device is a section of tube that measures the pressure at the tip and the pressure at the side of the tube. Reading this differential pressure and applying Bernoulli's equation will allow for the calculation of the fluid velocity.

- **Hot Wire**-- While Pitot tubes work well for high flow rates in gasses, and a variety of flow rates in liquids, the technique fails for low air velocities in gasses. To solve this gap in velocity measurement technology, the hot wire and hot film probes were developed. This technique is fairly straight forward in concept, but much more difficult in operation. The theory is that if you place a resistance wire in the flow of air (or other gas) and heat the wire with a fixed current, the voltage across the wire will indicate the resistance of the wire. If you know the properties of the wire you can deduce what its temperature is. Knowing this information, you can determine how much heat is being carried away by the moving stream of gas flowing across the wire or film. Simple… maybe. The difficulty with this is that the density, temperature and actual makeup of the gas flowing affect the heat absorption as well as the flow. This has been handled in a number of ways, but the most straightforward is to use two wires. One in the flow and one out of the flow, and make your measurement based on the difference of these two values. A second method is to make an assumption that the reading is being made in "standard air" which has a known coefficient of absorption. Using this method, the only values that are needed are hot wire value and the temperature of the air prior to the hot wire.

- **Moving Member Meters**-- Another method of measuring the flow velocity in a duct or pipe is the special class of transducers called "moving member" meters. These fall into two primary classifications, turbines and paddlewheels. Both of these measure the velocity of the fluid in the tube or duct. What makes them different from other velocity measurement devices is that they employ a moving element to determine the flow, unlike the pitot tube and hot wire probes.

- **Axial Turbine Flow Meters**-- The axial type turbine flow meter consists of a circular housing with a suspended blade system. This suspended blade is mounted on a shaft or bearing at the center of the housing. As fluid flows past the blades, they are rotated by the fluidic forces. The speed of rotation is proportional to the velocity of the fluid passing through the housing. A method of measuring the speed of rotation is employed, allowing a measurement of fluid velocity. The typical method is measuring the speed of the turbine rotation is to count the blades as they pass a sensor on housing body. This method is extremely accurate and essentially averages the velocity across the whole housing diameter. The construction of these devices can allow insertion into pipes and ducts of varying sizes and can be used with a wide variety of clean fluids over a very wide range of velocities. The design of the housing can be adjusted to allow the use of this type of transducer into a wide range of pressure systems. These systems frequently apply a flow straightener section immediately prior to the blade section. The Blancett model 1100 is typical of this type of flow meter.

- **Radial Turbine Flow Meters**-- The Axial style turbine flowmeter works well for smaller diameter pipes and ducts. If you have an application in a significantly larger pipe or duct, an alternate configuration will be required. In this alternate style device, a small turbine device is inserted in through the side of the pipe, and the flow across the turbine blades generates a measurement related to the general flow in the pipe, hence the common name of "insertion Turbine flow meter." The turbine flow meters shown to the left are one form of this type of device. The cartridge unit is inserted into the flow stream with the shaft of the turbine unit parallel to the flow. This allows the flow across the angled turbine element to rotate in proportion to the flow across the blades. This device works well as long as the flow is not turbulent. Since the meter is not actually measuring the full cross section of the flow, only the flow at a single point near the wall of the pipe, excessive turbulence will cause readings that are not representative of the real flow in the pipe. As a result it is best to use these flow meters with caution, and if you don't have the real flow characteristics of the pipe, at least use the standard rule of thumb (20 / 10) for your distance from flow disturbances.

- **Paddle Wheel Flow Meter**-- A lower cost alternate to the turbine flowmeter is the paddle wheel flowmeter. This device is somewhat similar to the insertion type turbine flowmeter, but instead of a turbine blade with the flow generating lift forces to cause the rotation, the paddle wheel is perpendicular to the flow and rotates much like an old fashioned steam boat paddlewheel. These devices are usually inserted into a specially made tee in the flow line. The paddlewheel shown in the photo, distributed by Omega, is shown inserted into its flow tee. The PVC fitting is then cemented onto two ¾" PVC pipes. In this size pipe, the meter is capable of reading flows from 1.7 to 34 gallons per minute to an accuracy of 1%. The sensor can also be used in pipe sizes from ½" to 36" in diameter for a flow range of 1 to nearly 7000 gallons per minute.

- **Variable Area Flow Meters--** These meters depend on the flow of the fluid to carry an object along. In a fixed diameter pipe, the object would be carried along with the flow based on the resistance to that flow. If the flow is moving in a variable diameter pipe, the force on that object changes with changes in the pipe diameter; and hence, the clearance between the sides of the object and the sides of t pipe. This class of flowmeters is generally represented by two main types: Rotameters and spring – plunger meters.

COMBUSTION (GAS) ANALYZERS:

Measurement of combustion samples can be critical to health and safety. Carbon monoxide emissions from a gas cooking product, automobile or gas-fired water heater can exceed safe levels thereby posing an imminent danger. Generally, 400 parts per million (PPM) is considered to be the maximum amount allowed. Exceeding this amount can be dangerous. Combustion analyzers have been developed to measure products of combustion. These devices always involve inserting a probe into the air stream, taking a sample and recording the percentage of objectionable constituent. The digital photographs below will indicate two types of measuring equipment.

FIGURE 24: COMBUSTION ANALYZER

FIGURE 25: COMBUSTION ANALYZER APPLICATION

PRESSURE MEASURING INSTRUMENTS:

Many techniques have been developed for the measurement of pressure and vacuum. Instruments used to measure pressure are called pressure gauges or vacuum gauges.

A manometer is an instrument that uses a column of liquid to measure pressure, although the term is currently often used to mean any pressure-measuring instrument.

A vacuum gauge is used to measure the pressure in a vacuum—which is further divided into two subcategories: high and low vacuum (and sometimes ultra-high vacuum). The applicable pressure ranges of many of the techniques used to measure vacuums have an overlap. Hence, by combining several different types of gauge, it is possible to measure system pressure continuously from 10 mbar down to 10^{-11} mbar.

Everyday pressure measurements, such as for tire pressure, are usually made relative to ambient air pressure. In other cases, measurements are made relative to a vacuum or to some other specific reference. When distinguishing between these zero references, the following terms are used:

- **Absolute pressure** is zero-referenced against a perfect vacuum, using an absolute scale, so it is equal to gauge pressure plus atmospheric pressure.
- **Gauge pressure** is zero-referenced against ambient air pressure, so it is equal to absolute pressure minus atmospheric pressure. Negative signs are usually omitted. To distinguish a negative pressure, the value may be appended with the word "vacuum" or the gauge may be labeled a "vacuum gauge."
- **Differential pressure** is the difference in pressure between two points.

The zero reference in use is usually implied by context, and these words are added only when clarification is needed. Tire pressure and blood pressure are gauge pressures by convention, while atmospheric pressures, deep vacuum pressures, and altimeter pressures must be absolute.

For most working fluids where a fluid exists in a closed system, gauge pressure measurement prevails. Pressure instruments connected to the system will indicate pressures relative to the current atmospheric pressure. The situation changes when extreme vacuum pressures are measured; absolute pressures are typically used instead.

Differential pressures are commonly used in industrial process systems. Differential pressure gauges have two inlet ports, each connected to one of the volumes whose pressure is to be monitored. In effect, such a gauge performs the mathematical operation of subtraction through mechanical means, obviating the need for an operator or control system to watch two separate gauges and determine the difference in readings.

Moderate vacuum pressure readings can be ambiguous without the proper context, as they may represent absolute pressure or gauge pressure without a negative sign. Thus, a vacuum of 26 in Hg gauge is equivalent to an absolute pressure of 30 in Hg (typical atmospheric pressure) − 26 in Hg = 4 in Hg.

Atmospheric pressure is typically about 100 kPa at sea level, but is variable with altitude and weather. If the absolute pressure of a fluid stays constant, the gauge pressure of the same fluid will vary as atmospheric pressure changes. For example, when a car drives up a mountain, the (gauge) tire pressure goes up because atmospheric pressure goes down. The absolute pressure in the tire is essentially unchanged.

Using atmospheric pressure as reference is usually signified by a *g* for gauge after the pressure unit, e.g. 70 psig, which means that the pressure measured is the total pressure minus atmospheric pressure. There are two types of gauge reference pressure: vented gauge (vg) and sealed gauge (sg).

A vented gauge pressure transmitter, for example, allows the outside air pressure to be exposed to the negative side of the pressure sensing diaphragm, via a vented cable or a hole on the side of the device, so that it always measures the pressure referred to ambient barometric pressure. Thus, a vented gauge reference pressure sensor should always read zero pressure when the process pressure connection is held open to the air.

A sealed gauge reference is very similar except that atmospheric pressure is sealed on the negative side of the diaphragm. This is usually adopted on high pressure ranges such as hydraulics where atmospheric pressure changes will have a negligible effect on the accuracy of the reading, so venting is not necessary. This also allows some manufacturers to provide secondary pressure containment as an extra precaution for pressure equipment safety if the burst pressure of the primary pressure sensing diaphragm is exceeded.

There is another way of creating a sealed gauge reference and this is to seal a high vacuum on the reverse side of the sensing diaphragm. Then the output signal is offset so the pressure sensor reads close to zero when measuring atmospheric pressure.

A sealed gauge reference pressure transducer will never read exactly zero because atmospheric pressure is always changing and the reference in this case is fixed at 1 bar.

To produce an absolute pressure sensor the manufacturer will seal a high vacuum behind the sensing diaphragm. If the process pressure connection of an absolute pressure transmitter is open to the air, it will read the actual barometric pressure.

FIGURE 26: PRESSURE MEASURING DEVICE

Fieldpiece SDMN5 duel port manometer

FIGURE 27: PRESSURING DEVICE WITH TUBING

HADRON COLLIDER:

The most sophisticated measuring device on the planet is the Hadron Collider. I only mention this device to show the remarkable complexity of some “measuring equipment”.

The Large Hadron Collider (LHC) is the world’s largest and most powerful particle accelerator. It first started up on 10 September 2008, and remains the latest addition to CERN’s accelerator complex. The LHC consists of a 27-kilometre ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way.

Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide. The beams travel in opposite directions in separate beam pipes – two tubes kept at ultrahigh vacuum. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. The electromagnets are built from coils of special electric cable that operates in a superconducting state, efficiently conducting electricity without resistance or loss of energy. This requires chilling the magnets to -271.3°C – a temperature colder than outer space. For this reason, much of the accelerator is connected to a distribution system of liquid helium, which cools the magnets, as well as to other supply services. Thousands of magnets of different varieties and sizes are used to direct the beams around the accelerator. These include 1232 dipole magnets 15 meters in length which bend the beams, and 392 quadrupole magnets, each 5–7 meters long, which focus the beams. Just prior to collision, another type of magnet is used to "squeeze" the particles closer together to increase the chances of collisions. The particles are so tiny that the task of making them collide is akin to firing two needles 10 kilometers apart with such precision that they meet halfway.

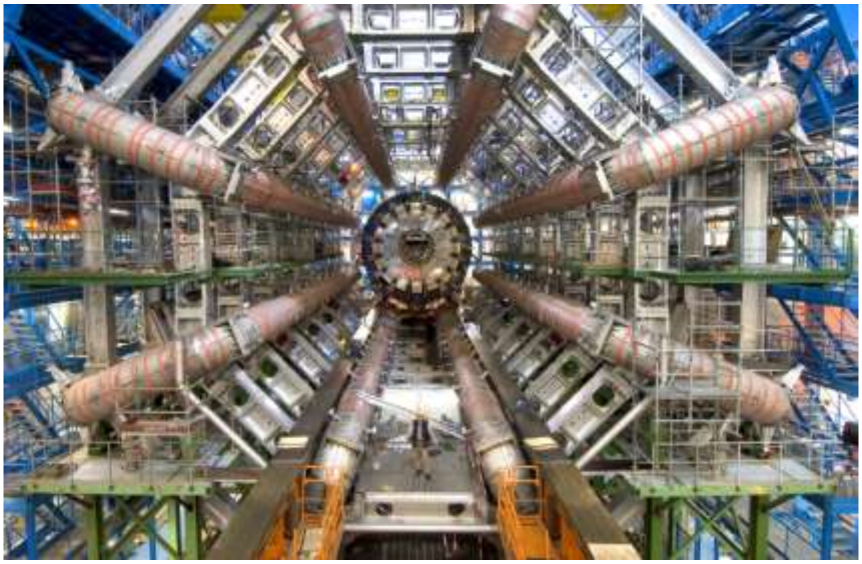


FIGURE 28: LARGE HADRON COLLIDER

AUTOMATED EQUIPMENT:

CMM (COORDINATE MEASURING MACHINE)-- A coordinate measuring machine (CMM) is a device for measuring the physical geometrical characteristics of an object. This machine may be manually controlled by an operator or it may be computer controlled. Measurements are defined by a probe attached to the third moving axis of this machine.

The CMM shown below is a very sophisticated device and costs thousands of dollars. Given certain circumstances, they are worth every penny of their costs. When accuracy is needed, a CMM is called for.

The typical 3D "bridge" CMM is composed of three axes, X, Y and Z. These axes are orthogonal to each other in a typical three-dimensional coordinate system. Each axis has a scale system that indicates the location of that axis. The machine reads the input from the touch probe, as directed by the operator or programmer. The machine then uses the X, Y, Z coordinates of each of these points to determine size and position with micrometer precision typically.

A coordinate measuring machine (CMM) is also a device used in manufacturing and assembly processes to test a part or assembly against the design intent. By precisely recording the X, Y, and Z coordinates of the target, points are generated which can then be analyzed via regression algorithms for the construction of features. These points are collected by using a probe that is positioned manually by an operator or automatically via Direct Computer Control (DCC). DCC CMMs can be programmed to repeatedly measure identical parts, thus a CMM is a specialized form of industrial robot.

FIGURE 29: COORDINATE MEASURING MACHINE

Coordinate-measuring machines include three main components:

- The main structure, which includes three axes of motion. The material used to construct the moving frame has varied over the years. Granite and steel was used in the early CMM's. Today all the major CMM manufacturers build frames from aluminum alloy or some derivative and also use ceramic to increase the stiffness of the Z axis for scanning applications. Few CMM builders today still manufacture granite frame CMM due to market requirement for improved metrology dynamics and increasing trend to install CMM outside of the quality lab. Typically only low volume CMM builders and domestic manufacturers in China and India are still manufacturing granite CMM due to low technology approach and easy entry to become a CMM frame builder. The increasing trend towards scanning also requires the CMM Z axis to be stiffer and new materials have been introduced such as ceramic and silicon carbide.
- Probing system
- Data collection and reduction system - typically includes a machine controller, desktop computer and application software.

GAUGE R & R:

A viable method for assessing the capability of a measurement system is known as Gauge R & R. “R” for repeatability and “R” for reproducibility. The process is a mathematical method of checking your measuring system to determine how much it is contributing to process variability. The best of all worlds would give a Gauge R & R of zero. The gage R & R study is designed to measure both repeatability and reproducibility of a measuring process.

REPEATABILITY: The variation in measurements obtained when one operator uses the same gage to measure identical characteristics of the same part.

REPRODUCIBILITY: The variation in the average of measurements made by different operators using the same gage, after measuring identical characteristics of the same part.

NOTE: The part being measured must represent the full range of the process variation or the tolerance band. In other words, the sample population must be pre-planned and NOT random. (This is very important.)

The Quality Technician's Handbook recommends the following elements of planning prior to performing a gauge R & R study:

- Select the proper measuring instrument
- Make sure the measurement method is appropriate
- Follow the ten percent (10%) rule of discrimination
- Look for obvious training/skill problems with observers
- Make sure all obvious use the same gauge (or same type of gauge)
- Make sure all measuring equipment is calibrated

GAUGE R & R can be accomplished by two methods: 1.) The short method and 2.) The long method.

SHORT METHOD:

- Requires only two (2) operators and five (5) parts
- The short method cannot separate reproducibility from repeatability
- Represents a very good and quick test of gauge acceptability

LONG METHOD:

- Ideally, requires three (3) operators and a minimum of ten (10) parts
- All measurements are done twice
- Allows separation of repeatability and reproducibility.

Now, if reproducibility error is large as compared to repeatability error, the possible causes are as follows:

- The operator is improperly trained in the use and reading of the measuring instrument.

- Calibrations on the instrument dial are not clear.

If repeatability error is large as compared to reproducibility error, the possible causes are:

- Measuring instrument needs maintenance
- Measuring instrument may not be rigid enough or
- Clamping or fixturing is unacceptable and may need improvement

Basic rule of thumb:

- The measuring instrument should have resolution better than ten percent (10%).
- Under ten percent (10%) is definitely acceptable
- Ten percent to thirty percent (10 to 30 %) –Gray area. May be acceptable based upon the importance of application, repair cost, etc.
- Over thirty percent (30%)—Generally unacceptable.

High Gauge R & R (above thirty percent) can lead to two types or errors:

ERROR NUMBER 1: The measurement from the gauge will lead you to believe the process has higher capability than it really does. Therefore, you may accept parts that are out of specification limits.

ERROR NUMBER 2: The measurement from the gauge may lead you to believe the process is NOT capable, when it really is. Therefore, you may be rejecting parts that are in specification limits.

Charts and table may be found on-line to facilitate entering measurements from one, two or three operators and calculating the Gauge R & R for each measuring instrument.

CALIBRATION:

PROCEDURES:

Calibration of measuring equipment is absolutely critical to ensure accuracy and precision of a measuring system.

Calibration may be called for:

- a new instrument
- after an instrument has been repaired or modified
- when a specified time period has elapsed
- when a specified usage (operating hours) has elapsed

- before and/or after a critical measurement
- after an event, for example
    - after an instrument has had a shock, vibration, or has been exposed to an adverse condition which potentially may have put it out of calibration or damage it
    - sudden changes in weather
- whenever observations appear questionable or instrument indications do not match the output of surrogate instruments as specified by a requirement, e.g., customer specification, instrument manufacturer recommendation.

In general use, calibration is often regarded as including the process of adjusting the output or indication on a measurement instrument to agree with value of the applied standard, within a specified accuracy. For example, a thermometer could be calibrated so the error of indication or the correction is determined, and adjusted (e.g. via calibration constants) so that it shows the true temperature in Celsius at specific points on the scale. This is the perception of the instrument's end-user. However, very few instruments can be adjusted to exactly match the standards they are compared to. For the vast majority of calibrations, the calibration process is actually the comparison of an unknown to a known and recording the results.

Proper calibration against a known standard is absolutely necessary for each piece of measuring equipment. This is a must. There are three basic sources regarding written calibration procedures.

- American National Standards Institute (ANSI)
- International Organization for Standards (ISO)
- American Society for Quality (ASQ)

ASQ Q10012-2003 states: ***"Measurement management system procedures shall be documented to the extent necessary and validated to ensure the proper implementation, their consistency of application, and the validity of measurement results."***

Documentation should be provided to contain sufficient information for the calibration of measurement equipment. This information generally includes the following:

- **Source**- The calibration procedure may be prepared internally, by another agency, by the manufacturer of the equipment, or by a composite of the three.
- **Completeness**—The procedure should contain sufficient instructions and information to enable qualified personnel to perform the calibration. Please note the phrase QUALIFIED PERSONNEL.
- **Approval**—All procedures should be approved and controlled, and evidence should be displayed on the document. The calibration standard should be available for review.

- **Software**—When used instead of an actual procedure, software should follow the computer software recommendations for control.
- **Performance Requirements**—This includes device description, manufacturer, type or model number, environmental conditions, specifications, and so on. I recommend the serial number of the measuring device if available. In this fashion, complete traceability may be had.
- **Measurement Standards**—This includes generic description of measurement standards and performance requirements, accuracy ratio and /or uncertainty, and any auxiliary tools.
- **Preliminary Operations**—This includes any safety or handling requirements, cleaning prerequisites, reminders, or operational checks.
- **Calibration Processes**—This includes the detailed set of instructions for process verification in well-defined segments, upper and lower tolerance limits, and required further instructions.
- **Calibration Results**—This is a performance results data sheet or form to record the calibration data when required.
- **Closing Operations**—This included any labeling, calibration safeguards, and material removal requirements to prevent contamination of product.
- **Storage and Handling**—These requirements are to maintain accuracy and fitness for use.

FREQUENCY OF CALIBRATION:

The exact mechanism for assigning tolerance values varies by country and industry type. The measuring equipment manufacturer generally assigns the measurement tolerance, suggests a calibration interval (CI) and specifies the environmental range of use and storage. The using organization generally assigns the actual calibration interval, which is dependent on this specific measuring equipment's likely usage level. Generally, a hand-held device will require calibration on an annual basis. Some devices will have recommended calibration frequencies on a simi-annual basis. The assignment of calibration intervals can be a formal process based on the results of previous calibrations. The standards themselves are not clear on recommended CI values, but guidelines may be found from the following documents:

ISO 17025

"A calibration certificate (or calibration label) shall not contain any recommendation on the calibration interval except where this has been agreed with the customer. This requirement may be superseded by legal regulations."

ANSI/NCSL Z540

"...shall be calibrated or verified at periodic intervals established and maintained to assure acceptable reliability..."

ISO-9001

"Where necessary to ensure valid results, measuring equipment shall...be calibrated or verified at specified intervals, or prior to use..."

MIL-STD-45662A

"... shall be calibrated at periodic intervals established and maintained to assure acceptable accuracy and reliability...Intervals shall be shortened or may be lengthened, by the contractor, when the results of previous calibrations indicate that such action is appropriate to maintain acceptable reliability."

RECORDS:

Once you've set the initial calibration intervals, it's important to keep good calibration records. These records should include the equipment's manufacturer, its model number, identification numbers associated with the instrument (serial number), and perhaps the location at which the equipment is normally used. It should also contain the procedure number for the procedure used to calibrate the equipment and an indication of how frequently that calibration is to be performed.

The record should also contain data on the calibrations and measurements performed. This information should include the date of the calibration, the technician who performed it, the equipment characteristic that was calibrated, and measurements of that characteristic before and after the calibration.

Using modern calibration management software can help you keep better records. As technicians perform calibrations, they enter the measurements directly into a computer database using computerized forms in the program. Once entered, these data are continually available, and you can easily use the information to calculate equipment measurement uncertainties, identify stability problems, and perform gauge repeatability and reproducibility (Gauge R&R) studies.

Record-keeping is absolutely critical for traceability and conformance with ISO standards.

STANDARDS:

The selection of a standard or standards is the most visible part of the calibration process. Ideally, the standard has less than 1/4 of the measurement uncertainty of the device being calibrated. When this goal is met, the accumulated measurement uncertainty of all of the standards involved is considered to be insignificant when the final measurement is also made with the 4:1 ratio. This ratio was probably first formalized in Handbook 52 that accompanied MIL-STD-45662A, an early US Department of Defense metrology program specification. It was 10:1 from its inception in the 1950s until the 1970s, when advancing technology made 10:1 impossible for most electronic measurements.

Maintaining a 4:1 accuracy ratio with modern equipment is difficult. The test equipment being calibrated can be just as accurate as the working standard. If the accuracy ratio is less than 4:1, then the calibration tolerance can be reduced to compensate. When 1:1 is reached, only an exact match between the standard and the device being calibrated is a completely correct calibration. Another common method for dealing with this capability mismatch is to reduce the accuracy of the device being calibrated.

For example, a gauge with three percent (3%) manufacturer-stated accuracy can be changed to four percent (4%) so that a one percent (1%) accuracy standard can be used at 4:1. If the gauge is used in an application requiring sixteen percent (16%) accuracy, having the gauge accuracy reduced to four percent (4%) will not affect the accuracy of the final measurements. This is called a limited calibration. But if the final measurement requires ten percent (10%) accuracy, then the three percent (3%) gauge never can be better than 3.3:1. Then perhaps adjusting the calibration tolerance for the gauge would be a better solution. If the calibration is performed at one hundred units, the one percent (1%) standard would actually be anywhere between ninety-nine and one hundred and one units. The acceptable values of calibrations where the test equipment is at the 4:1 ratio would be ninety-six (96) to one hundred and four (104) units, inclusive. Changing the acceptable range to ninety-seven (97) to one hundred and three (103) units would remove the potential contribution of all of the standards and preserve a 3.3:1 ratio. Continuing, a further change to the acceptable range to ninety-eight (98) to one hundred and two (102) restores more than a 4:1 final ratio.

This is a simplified example. The mathematics of the example can be challenged. It is important that whatever thinking guided this process in an actual calibration be recorded and accessible. Informality contributes to tolerance stacks and other difficult to diagnose post calibration problems.

There may be specific connection techniques between the standard and the device being calibrated that may influence the calibration. For example, in electronic calibrations involving analog phenomena, the impedance of the cable connections can directly influence the result.

SUMMARY:

I certainly hope you see how important the science of metrology is to all facets of our life. We simply would have no progressive technology without the science of measurement. We would have no way to carry on everyday commerce. This very brief course should give you some basic understanding so that you may continue your study if you feel more instruction is desired.

APPENDIX

- **GLOSSARY OF TERMS**
- **PROFESSIONAL ASSOCIATIONS**
- **REFERENCES**

GLOSSARY OF TERMS:

A

Accuracy
The closeness of a measured quantity to the actual quantity that was measured, the measurand. Sometimes thought of as a tolerance range on a measurement's value. Often used colloquially as a synonym for uncertainty of measurement.

Alignment
The state or orientation of an object or feature with respect to a set of datums or the act of putting an object or feature into a desired state or orientation. Example alignments include: setting several bearings supporting a shaft in a line (or not quite a line); mounting aircraft sensors in a specific direction with respect to an aircraft's navigation system; bore-sighting weapons mounted on aircraft; best-fitting point cloud data to a set of surfaces.

As-built
Or the As-built condition. Refers to the actual dimensions of a part or assembly as it was manufactured. Also sometimes called "As-found".

In reverse engineering, as-built models or drawings do not try to divine design intent. They try to exactly portray a part exactly as it is, including defects.

B

Ball-bar
A precision fixture that can be used as a standard of length. Ball-bars are often built with precision nests to accept Sphere Mounted Reflectors or precision ball bearings to aid in checking or calibrating laser trackers and CMMs.

Boresighting
This term refers to an old method for setting sights on a firearm, in which the bolt or part of the action was removed and a target point was viewed alternately through the bore and through the sights while adjustments were made until the sights pointed at the target point.

The term Boresighting today has been expanded to include determining the primary axis of a directional antenna, and aircraft weapons harmonization. Many techniques now exist including the use bore mounted lasers or laser trackers.

C

Calibration

"Calibration is the operation that, under specified conditions, establishes a relationship between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with measurement uncertainties." (VIM)

Thus, calibration involves measurements and comparisons, not an actual adjustment. For metrology, the formal comparison is of measuring equipment against a standard of higher level (a national standard defined in the U.S. by NIST) under controlled and specified conditions to document the accuracy of the instrument being compared.

CMM

This acronym stands for Coordinate Measuring Machine. These machines measure parts through the acquisition of points.
Many types of CMMs exist, traditional 3 axis contact probing machines, articulated arm CMMs, and laser trackers are a few examples. Laser scanners or "white light" scanners are other examples that don't require contact with the measured part. CMMs are often run with software that can compute features such as planes, cylinders, and lines from the measured points.

D

Datum

In metrology, a datum is simply an idealized reference feature from which another features' orientation, position, or other characteristic is defined. Datums can be many types of features, planes, cylinders, points, centerlines, constructions or offsets from other features, anything that can be measured or established for use in locating other features.

Although the plural form of datum is really data, many people, including the author, uses datums as the plural in this application.

Datum Feature

A datum feature is the measured or contacted feature which establishes a datum. It is an actual point, line or surface on the part being measured.

Dimensional Inspection

The process of characterizing an object's size and shape through measurements of points, lengths, and volumes. Usually such an inspection results in a report comparing the measured object to another object, an idealized object, or a previous state of the object.

Dimensional Metrology

The study or practice of high precision measurements to quantify physical sizes, orientations, and distances of objects and shapes.

Discrimination Threshold

"The largest change in a value of a quantity being measured that causes no detectable change in the corresponding indication. NOTE: Discrimination threshold may depend on, e.g. noise (internal or external) or friction. It can also depend on the value of the quantity being measured and how the change is applied." (VIM)

Dimensional inspection

A method that involves measuring a part's dimensions by way of a 3D laser tracker or scanner. There are several types of dimensional inspection services depending on the type of measurements that a project requires. Services offered by ECM: First Article Inspection, In-Line and In-Process Testing, As-Built Inspection as well as Calibration and Certification of machines, tooling and fixtures.

F

First Article Inspection (FAI)

As the name implies, first article inspection is usually performed on one or more of the first parts in production. The inspection is usually exhaustive, covering every dimension on the drawing, and provides a final verification of the manufacturing process. After the first article is proved out, subsequent parts are often inspected less exhaustively to save time and money.

Free-Form Shapes

In metrology, this refers to surfaces with unconventional or continuously varying shapes like bones, customized molds, boat hulls, or the sculptures of Henry Moore.

G

Gantry CMM

A gantry CMM has the measurement head mounted on a beam that overhangs and spans the measurement table. The head can move both vertically and side to side along the beam, providing two axes of motion. The third axis can be generated by moving either the towers that support the beam along a fixed table, or moving the measurement table between the towers.

Gage R&R (Gage Repeatability and Reproducibility)

A set of repeated measurements used to determine the fitness of a gage or other measuring instrument for a specific function. The test tries to account for the effects of equipment, method, and operator in an estimate of precision and uncertainty by having a number of operators use the equipment to measure a reference standard or part.

GD&T

Geometric dimensioning and tolerancing is a system and symbolic language for describing the permissible limits, or tolerances, in a part's physical dimensions and measured values. In the United States the standard describing GD&T is ASME Y14.5. In Europe ISO has a series of standards that cover the same material. The ASME and ISO standards use the same symbols, but interpretations are slightly different in some cases.

I

Influence Quantity

A quantity that, in a direct measurement, does not affect the quantity that is actually measured, but affects the relation between the indication and the measurement result.

An example in laser tracker work would be air temperature and humidity.

Instrumental Drift

Drift Change in a measured value "related neither to a change in the quantity being measured nor to a change of any recognized influence quantity." (VIM)

Instrumental Uncertainty

A component of measurement uncertainty arising from the measuring instrument or measuring system in use, and obtained by its calibration.

L

Laser Scanning

Using laser measurement systems to digitally capture the geometry of a product or part without contact between a probe and the part surface. The laser scanner will measure and record thousands or even millions of data points from a part's surface or a large area. Laser scanning is done on objects ranging in size from several inches to over 100 feet. These points, often called a point cloud, can then be used for comparison to customers' CAD models or to reverse engineer 3D models.

Laser Tracker

One form of portable CMM, a laser tracker can measure large objects or spaces with a relatively high degree of accuracy. The typical laser tracker uses two rotary encoders and a laser ranging system to make measurements at the center of an SMR which is placed on the project or at the point of interest. Measurements are therefore limited by line of sight between tracker and SMR, and the tracker's range. Depending on the tracker and measurement conditions measurements can be made 100 yards or more from the tracker head.

A 3d laser tracker can be used in measuring, aligning and even calibrating automated measurement systems, large and small parts, complex surfaces and even immobile manufacturing machinery.

M

Maximum Permissible Error

There are a few synonyms for this term but all pertain to measurements and limits of error. The "extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system.

NOTE 1: Usually, the term "maximum permissible errors" or "limits of error" is used where there are two extreme values.
NOTE 2: The term "tolerance" should not be used to designate 'maximum permissible error.'" (VIM)

Measurement Result

Any quantities attributed to a measurand from a measurement together with other relevant information. Environmental conditions or measurement uncertainty are two examples of other relevant information.

Measurement Traceability

Also known as "metrological traceability." This is simply how metrologists connect to the standard by which they measure. That standard in the U.S. is set and defined by NIST. Picture links in a chain. Each link represents a comparison that pertains to an instrument or tool's measurements to a NIST defined standard or requirement. Because ECM calibrates to a NIST traceable standard, ECM can determine the precision and accuracy of a tool or instrument.

Measurement Uncertainty

An estimate of the uncertainty of a measurement. Usually comprised of instrumental uncertainty, and a number of other factors such as procedural uncertainty, and environmental uncertainty.

Measuring System

A "set of one or more measuring instruments and often other devices, including any reagent and supply, assembled and adapted to give information used to generate measured quantity values within specified intervals for quantities of specified kinds.

NOTE 1 "A measuring system may consist of only one measuring instrument." (VIM)

Metrology
The science of measurement and how measurements are used. Used to measure and verify an objects dimensional quality.

Measurand
Any quantity being measured. The term applies to any type of measurement, mass, force, luminosity, etc. in dimensional metrology, one could also call an object or a feature of an object being measured a measurand and be understood.

Mesh
1. A type of model consisting of small usually triangular planar surface patches that approximate an object's shape. It is much like an STL model. This type of model is often produced from scanned data and may be used as an intermediate step to a Nurbs surface model.

2. Occasionally used to describe Nurbs surfaces because the mathematical model of a surface can be thought of as a series of intersecting curves that lie in the surface.

Micron or Micrometer (µm)
A unit in the metric system equal to one millionth of a meter or approximately 0.00003937 inches. It is commonly used to describe the uncertainty of precision measuring machines.

N

Noise
At ECM, we use "Noise" to refer to incorrect data within a point cloud generated during a laser scanning. Reflections from dust in the air, errant reflections from corners, surface texture, or highly reflective surfaces are sources of noise.

Nominal Dimensions
In dimensional metrology Nominal Dimensions are the dimension values given on a drawing or in a computer model. Measured values are compared to nominal to determine whether a part conforms to its design.

Non-Contact Measurement
This is simply the practices of taking an object's measurements without making physical contact with it. Often called scanning. Non-contact measurements can be used to measure an object with a delicate surface or weak structure that could not otherwise stand up to contact measuring.

Non-Parametric Model
Also known as a "dumb model", this is a 3D CAD model whose shape cannot usually be edited as easily as a parametric model. Commonly available file formats for porting files between CAD programs like IGES or STEP typically produce dumb models.

NURBS

With a full name of Non Uniform Rational B-Spline, this refers to NURBS curves and surfaces. The name comes from the mathematical technique used to model the curve or surface. It is one of the more common ways to model freeform geometry.

O

Outlier

A point which lies outside the expected range of variation for data. In scan data outliers are usually removed during post-processing of the point cloud using statistical algorithms. Sometimes the scanning instrument and software remove them during the point cloud acquisition. In data generated by CMM or laser trackers, outliers are considered for removal on a case by case basis, because the data is often too sparse for statistical methods and because the operator can usually tell by visual observation or confirming measurements if an outlier accurately represents the part or was acquired incorrectly, perhaps by probing debris on the surface instead of the surface itself.

P

Parametric Model

A parametric model is a CAD model that can be edited and changes will propagate through the model automatically preserving the relationships between features. Typically these models can only be edited in the CAD program that created them.

Photogrammetry

Non-contact imagery that takes 3D coordinate measurements (XYZ) through photographs.

Point Cloud

A type of data consisting of many points in 3D space. The number of points may run from hundreds or thousands in the case of a CMM or laser tracker, to hundreds of millions, or even more points in the case of a laser scanner. Point cloud data can be compared to a CAD model or used to reverse engineer an object.

Polygonal Modeling

A CAD model using small planar surfaces to approximate the shape of a surface. The surfaces are usually triangular and the model is quite similar to an STL model. (See Mesh definition 1)

Precision

How close one measurement result will be to another result or set of results. Precision should not be mistaken for accuracy. A precise instrument could give a consistently erroneous result. The term precision is often used as a synonym for an instrument’s repeatability.

Probe
A device attached to a CMM that is used in taking measurements. Typical CMMs have contact probes (called touch probes) but a probe can be non-contact like a portable CMM laser scanner.

R

Reference Model
Typically a CAD model, but occasionally a physical master, against which data on a measured part is compared.

Repeatability
A measurement system's precision under a set of measurement conditions, the repeatability condition.

Reproducibility
Measurement precision under the Reproducibility Condition of Measurement.

Repeatability Condition
In contrast to the Repeatability Condition of Measurement, the Reproducibility Condition specifies different measuring systems, locations, operators, and environmental conditions for measurement.

Resolution
1. *(of a measuring instrument or system)* Smallest change in a quantity being measured
that causes a perceptible change in the corresponding indication. Resolution can be affected by internal or external factors like noise, friction, or temperature. The value of the measurand may also affect resolution. Not to be confused with definition 2.
2. *(of a displaying device)* Smallest difference between indications that can be meaningfully distinguished or the number of digits in a digital display.

Reverse Engineering
This process involves producing a drawing or 3D digital representation of a pre-existing, tangible object usually via CAD, CAE or CAM type software. At ECM, the object is measured with a 3D laser scanner, the generated point cloud data is transferred into a NURBS surface or triangular mesh or a number of other options. From this point, the 3D digital CAD model is reconstructed to look like the original object that was laser scanned.

S

Scan Density
Laser scan density refers to the proximity between 3D coordinates in a given data point cloud.

Scan Speed

This refers to a laser scanner's speed regarding the collection of 3D coordinates. The speed is measured in points per second or even millions of points per second.

Spatial Reference System (SRS)

This is another name for a coordinate reference systems (CRS) that captures geo-location entities. This would be considered a civil engineering term or a term used in the utility field more so than in dimensional metrology.

T

Temperature Compensation

This is something to consider when using a CMM. If using a CMM in less than ideal weather or within extreme temperatures, the CMM will swell or contract. To prevent in accuracy, this behavior needs to be considered when taking a 3D measurement unless the measurement system was built to prevent this and is highly accurate.

Tooling Ball

A close tolerance sphere, usually on a precision shouldered shank used in aligning or locating parts or assemblies.

U

Uncertainty

See *Measurement Uncertainty*.

V

Validation

Demonstration by test or analysis that an instrument, system, or procedure is fit for a certain task.

Verification

The proof, by means of objective evidence, that an item meets its specification requirements. In dimensional inspection the object's dimensions would be measured and compared to the drawing or CAD model of the object.

PROFESSIONAL ASSOCIATIONS:

There are many associations dedicated to the science of Metrology. These organizations are certainly capable of answering any questions you may have. They will answer your questions or “point you in the right direction” for answers needed to solve problems relative to measurement and measurement techniques. The sharing of nonproprietary information throughout the Metrology community is one hallmark helping to keep industry, both public and private, on the cutting edge and with the latest technology.

- NATIONAL CONFERENCE OF STANDARDS LABORATORIES INTERNATIONAL
- AMERICAN SOCIETY FOR QUALITY
- THE INSTRUMENTATION, SYSTEMS, AND AUTOMATION SOCIETY (ISA)
- INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE)
- THE AMERICAN SOCIETY FOR NONDESTRUCTIVE TESTING
- THE AMERICAN SOCIETY OF TEST ENGINEERS
- THE NATIONAL SOCIETY OF PROFESSIONAL ENGINEERS (NSPE)
- THE EUROPEAN ASSOCIATION OF METROLOGY INSTITUTES (BIPM)
- NORTH AMERICAN COORDINATE METROLOGY ASSOCIATION (NACMA)
- EUROPEAN ASSOCIATION OF NATIONAL METROLOGY (EURAMET)
- COORDINATE METROLOGY SOCIETY (CMSC)
- INTERNATIONAL LEGAL ORGAZIONAL PRIMER
- METROLOGY INTEREST GROUP
- INTERNATIONAL COMMITTEE RADIONUCLIDE METROLOGY (ICRM)
- INTERNATIONAL BUREAU OF WEIGHTS AND MEASURES
- JOINT COMMITTEE FOR GUIDES IN METROLOGY
- WELMEC

REFERENCES:

1.) Connie Dotson, Roger Harlow & Richard L. Thompson, **Fundamentals of Dimensional Metrology**: Fourth Edition, Thompson—Delmar Learning, 2006.

2.) Jay L. Bucher, PhD, **The Metrology Handbook**: Second Edition, Quality Press.

3.) D. Dippold, W. Foley, C. Hendricks, R. Kelbaugh, **Six Sigma Blackbelt Training Manual, Session 1, Revision 5,** November 11, 1996.

4.) Robert P. Jackson, PE, **Geometric Dimensioning & Tolerancing and Design for Six Sigma,** PDHonline Course Number M347.

5.) NPL, **A Brief History of International Metrology**, March 25, 2010.

6.) Livio C. Stecchini, **A History of Measures,** 2015

7.) Mitchell Cottrell, **Fluid Flow Measurement**, Rev 1.0, 9/xx/06

8.) Dave K. Banerjea, **How to Optimize Equipment Calibration Intervals**, Quality Digest, March 12, 2004

9.) NCSL, **International Metrology—The Science of Measurement**, 164 Education Liaison & Outreach.

10.) Lafe Spietz, **Metrology: The Fabric of Science and Technology**, TMA Class of 1990.

11.) OMEGA**, Introduction to Load Cells**, 2003-2015

12.) LittleMechineShop.com, **Steel Rules**, 2009

13.) David Q. McDowell, **The Synergistic Relationship Between Standards for Data Exchange, Metrology, Process Control & Color Management,** Presented at 2006 Conference of Technical Association of the Graphic Arts.

14.) OMEGA, **Temperature Measurement**, 2003—2015

15.) AZO Materials, **The Measure of All Things: A Brief History of Metrology**, November 5, 2015

16.) Bright Hub Engineering, **What is Metrology**, 2012