TECHNICAL MANUAL

GENERAL INSTRUCTIONS

COMMON METROLOGY HANDBOOK

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SECTION 1

PHYSICAL DIMENSIONAL

1.1 DIMENSIONAL

1.1.1 Introduction

Metrology is comprised of measurements both theoretical and practical with varying degrees of uncertainty. Metrology and standardization are closely interwoven counterparts. The pervasive involvement of metrology in International Standards becomes apparent whenever such concepts as mechanical testing, interchangeability, tolerances, etc. are addressed. Dimensional Metrology involves the measurement of the physical characteristics or the geometry of the part. Flatness, parallelism, straightness, perpendicularity, coplanarity, and roundness are forms of physical measurement, which are determined by the part tolerances.

1.1.1.1 Geometric Dimensioning and Tolerancing (GD&T) is a universal language of symbols, much like the international system of road signs that advise drivers how to navigate the roads. GD&T symbols allow a Design Engineer to describe part features precisely and logically in a way they can be accurately manufactured and inspected. GD&T is expressed in the feature control frame. The feature control frame is like a basic sentence that can be read from left to right. For example, the feature control frame in Figure 1.1-1 would read: The 5 mm square shape (1) is controlled with an all-around (2) profile tolerance (3) of 0.05 mm (4), in relationship to primary datum A (5) and secondary datum B (6). The shape and tolerance determine the limits of production variability.

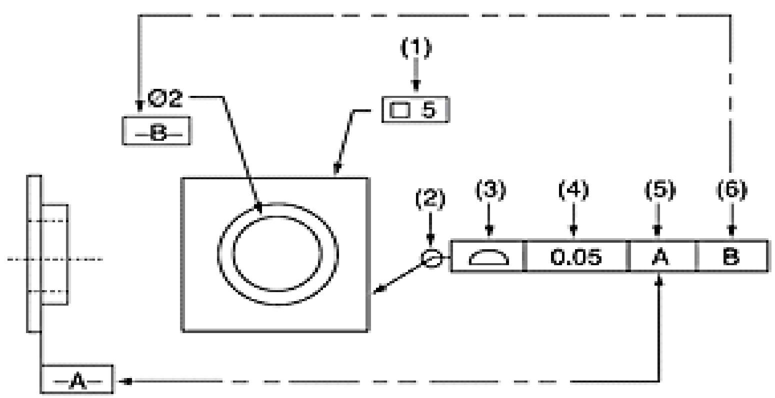
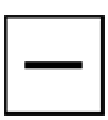


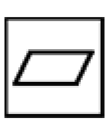
Figure 1.1-1: Feature Control Frame

1.1.1.2 There are seven shapes, called geometric elements, used to define a part and its features. The shapes are point, line, plane, circle, cylinder, cone, and sphere. There are also certain geometric characteristics that determine the condition of parts and the relationship of features. The purpose of these symbols is to form a common language that everyone can understand.

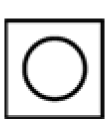
Geometric Characteristic Symbols



Straightness - A condition where all points are in a straight line, the tolerance is specified by a zone formed by two parallel lines.

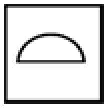


Flatness - All the points on a surface are in one plane, the tolerance is specified by a zone formed by two parallel planes.

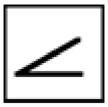


Roundness or Circularity - All the points on a surface are in a circle, the tolerance is specified by a zone formed by two concentric circles.

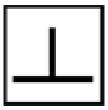
Cylindricity - All the points of a surface of revolution are equidistant from a common axis. The tolerance is specified by a zone bounded by two concentric cylinders within which the surface must lie.



Profile - A tolerancing method of controlling irregular surfaces, lines, arcs, or normal planes. Profiles can be applied to individual line elements or the entire surface of a part. The tolerance is specified by a uniform boundary along the true profile within which the elements of the surface must lie.

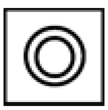


Angularity - The condition of a surface or axis at a specified angle (other than 90°) from a datum plane or axis. The tolerance is specified by a zone formed by two parallel planes at the specified basic angle from a datum plane or axis.

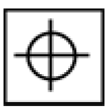


Perpendicularity - The condition of a surface or axis at a right angle to a datum plane or axis. The tolerance is specified by one of the following: a zone formed by two planes perpendicular to a datum plane or axis or a zone formed by two parallel planes perpendicular to the datum axis.

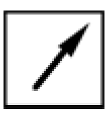
Parallelism - The condition of a surface or axis equidistant at all points from a datum plane or axis. The tolerance is specified by one of the following: a zone formed by two planes or lines parallel to a datum plane or axis, or a cylindrical tolerance zone whose axis is parallel to a datum axis.



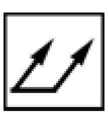
Concentricity - The axes of all cross sectional elements of a surface of revolution are common to the axis of the datum feature. The tolerance is specified by a cylindrical tolerance zone whose axis coincides with the datum axis.



Position - A positional tolerance defines a zone in which the center axis or center plane is permitted to vary from true (theoretically exact) position. Basic dimensions establish the true position from datum features and between interrelated features. The tolerance is the total permissible variation in location of a feature about its true location. For cylindrical features such as holes and outside diameters, positional tolerance is generally the diameter of the tolerance zone in which the axis of the feature must lie. For features that are not round, such as slots and tabs, the positional tolerance is the total width of the tolerance zone in which the center plane of the feature must lie.



Circular Runout - Provides control of circular elements of a surface. The tolerance is applied independently at any circular measuring position, as the part is rotated 360°. The tolerance is applied to surfaces constructed around a datum axis controls cumulative variations of circularity and coaxiality. When applied to surfaces constructed at right angles to the datum axis, it controls circular elements of a plane surface.



Total Runout - Provides composite control of all surface elements. The tolerance applied simultaneously to circular and longitudinal elements as the part is rotated 360°. Total runout controls cumulative variation of circularity, cylindricity, straightness, coaxiality, angularity, taper, and profile when it is applied to surfaces constructed around a datum axis. When it is applied to surfaces constructed at right angles to a datum axis, it controls cumulative variations of perpendicularity and flatness.

1.1.1.3 A surface plate is generally used as a reference surface or datum plane when making accurate measurements utilizing traditional metrology techniques. A datum plane or axis is defined as any reference surface from which dimensions or geometric characteristics of a part are established. A datum plane is established by at least three target points. Always ensure that the portion of the surface plate being used for measurements is clean and free of dirt. The preliminary steps of measurement such as cleanliness and set-up are very important and must be accomplished properly to ensure an accurate measurement.

1.1.1.4 Several parameters will be addressed in this handbook. An attempt will be made to define the parameter and explain how it is measured on a variety of parts. These parameters consist of flatness, parallelism, straightness, perpendicularity, coplanarity, and circularity. A brief explanation will also be given on the leveling procedure of a part on a leveling plate. The definition is most often times a theoretical simulation of the part. The measurement process is an attempt to quantify this parameter. Sometimes, the measurement process differs from the definition because it is not possible to measure the part in relation to the definition. We will also address tolerances and measurement uncertainty. Tolerances deal with the manufacturing process of the part, whereas measurement uncertainty is the ability for the user to measure the part. For obvious reasons, the measurement uncertainty must be less than the part tolerance otherwise the ability to accept or reject parts is impossible. The ideal ratio between the two should be 4:1 or greater, but as the requirement tolerances continue to get smaller and the ability to measure the parts has not improved much, this ratio draws closer to a 1:1. This makes the technician's job of accepting or rejecting a part very difficult. It also increases the amount time necessary to clean and setup the part for measurement.

1.1.2 Cleaning and Set-Up

1.1.2.1 Cleaning begins with the TI and area of the surface plate being used for the setup. A degreasing solution is used to remove the heavy weight preservative. Next, ethyl alcohol (200 proof) is used to remove any remaining residue. Once the part has been cleaned, it is usually examined for burrs or raised edges. For removal of high spots, use a cleaning stone or deburring stone depending on the location of the high spot. A cleaning stone is a close grained solid stone with either a smooth surface or a serrated patterned surface. These stones are usually made of either ceramic or granite. The deburring stone (Arkansas Stone) is manufactured with a fine abrasive material bonded to its exterior and is used to remove material. The cleaning stone is normally used on the precision surface itself, while the deburring stone is used for the edges. Once the TI has been cleaned and if it requires a datum plane, then a surface plate will be required. The area of a surface plate being used will determined based on the required flatness as verified by the flatness plot, then it will be cleaned with ethyl alcohol, and finally will be checked with a repeat reading gage to ensure the area being used is uniform enough. Once the TI has been cleaned and the setup equipment moved into place a suitable soak time must be applied before the measurement. Depending on the desired accuracy of the TI, a soak time is necessary to allow both the TI and measurement equipment to soak out after they have been handled. This time can vary greatly depending on the level of accuracy required and the physical size of the TI. Soak time is merely allowing the TI and measuring equipment to reach an equilibrium temperature and remain constant. Precision measurements should be made at stable temperatures. Precise measurements are made at 73 ±6 °F, while the most accurate measurements are made at 68 ±1 °F.

1.1.2.2 Often times a leveling plate is used to establish a datum plane on a part relative to the measuring equipment on the surface plate. This procedure is designed to achieve the best level condition for this datum plane and can be further used as a reference for measuring flatness on the part. The part should be leveled at a point near the four corners, which research has proven is a better leveling process than at three points. Four points should be used for all shapes except for a triangular part. The four points should represent the largest square possible on the top surface. How close to the corner depends on the size of the reference surface and the measuring equipment being used.

1.1.2.3 An initial step before beginning the leveling process is to take a ruler and roughly level the corners of the plate and ensure that they are roughly the same height from the surface plate. When using a leveling plate with three leveling feet adjust level side to side above the two leveling feet. Once this has been accomplished, adjust level from front to back using the established plane across the two leveling feet and a point above the single leveling foot.

1.1.2.4 Place the gage head of the electronic height gage near one of the corners on the top surface of the part being measured. Select one directly above a leveling foot, which will be known as the home position. Disregard any round-off (the chamfer of the corners and edges) on the edges of the surface. Zero the amplifier on an electronic height gage.

1.1.2.5 Slide the leveling plate so the gage head is on the diagonal corner of the reference surface and take a reading.

1.1.2.6 Adjust the single leveling foot screw in the appropriate direction to raise or lower the reading to half the amount of the home position reading. For example, the reading at the diagonal corner is 500 µin high.

1.1.2.7 Adjust the single leveling foot screw to take out half the difference between the two readings, after adjusting the leveling foot, that corner should read 250 µin now.

1.1.2.8 Return the gage head to the home position and zero the amplifier. Repeat this procedure until the two corners are approximately the same reading.

1.1.2.9 Repeat this procedure with the other two diagonal corners. After those two corners are virtually the same height check all the corners again and ensure the diagonal corner heights are as close to the same reading as possible. An example, two diagonal corners can read +20 µin and +40 µin with the other diagonal corners reading -130 µin and -150 µin. This difference in readings is dependent on the accuracy trying to be achieved and the surface flatness of the part.

1.1.2.10 Once the part is leveled, scan the surface of the part with the gage head. The best technique for measuring flatness is to keep the gage head stationary and move the part underneath the gage head. This means to move the leveling plate with the part on it. If the part is not heavy enough to be held stationary by its own weight, it may need to be held in place by some modeling clay.

NOTE

Do not move the part on the leveling plate, once it is leveled. Otherwise, the leveling process must be started again.

1.1.2.11 The gage head is the reference, so if the gage head must be moved because of the size of the part, find the area of the surface plate required to achieve the desired part accuracy to ensure the area is flat and uniform.

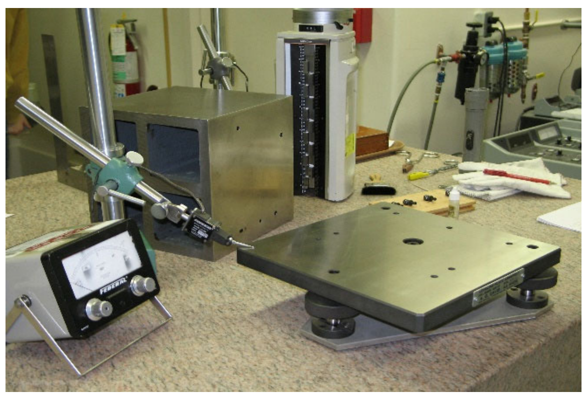


Figure 1.1-2: Electronic Height Gage and Leveling Plate

1.1.3 Flatness

1.1.3.1 Flatness is the condition of a surface having all elements in one plane. A plane is established by at least three points or areas not on a straight line. Flatness is generally measured on precision lapped surfaces. These surfaces could be found on the following parts: fixtures, angle plates, box parallels, gage blocks, standard measuring machine anvils, and optical flats. Flatness of non-reflective surfaces and large parts are generally measured using an electronic height gage, leveling plate, and a surface plate (See paragraph 1.1.2 for details of this method.)

1.1.3.2 Flatness of reflective surfaces can be measured with a flatness interferometer or monochromatic light and optical flat. Fundamentally, the light wave strikes the optical flat surface, and one part is reflected back by the surface of the optical flat, while the other part passes through and is reflected back by the surface under inspection. When these two light waves are re-combined either constructive (light portion of fringe) or destructive (dark portion of fringe) interference occurs. This happens whenever the distance between the reflecting surfaces is ½ of a wavelength (fringe) or multiples thereof. In most cases, the fringes will be convex, concave, or irregular. A contact point must be established when measuring flatness to determine if the part is concave or convex or to apply corrections from the optical flat being used to measure flatness. When using a flatness interferometer, the contact point is determined by pressing on the tilting table, and then the fringes will flow away from the contact point. When using the monochromatic light and optical flat, the contact point is determined by aligning the fringes across the part and moving head away from the monochromatic light, then the fringes will flow away from the contact point. Make note of where the contact point is on the optical flat. Now, examine the fringes to determine the geometry of the surface. If they are uniformly curved and curve around the contact point, this is a convex condition. If they curve away from the contact point, this is a concave condition. If the fringes are both concave and convex then this is an irregular condition. If it is irregular, determine if the majority of the fringe convex or concave by seeing the chart in T.O. 33K6-4-168-1.

1.1.3.3 Most flatness interferometers utilize a helium-neon laser or helium bulb. It is very important to know the wavelength of the light source being utilized in the interferometer. The flatness interferometer is a more accurate method than the monochromatic light and optical flat for two reasons. It is easier to align the fringes and determine the flatness of the surface. It is also a non-contact measuring procedure, which eliminates contact deformation. Some flatness interferometers are designed to magnify the part being viewed, which allows surface defects to be easily detected. In addition, most flatness interferometers come with a camera attachment, which allows a more precise measurement to be made on the picture. The flatness interferometer provides a sharper image of the fringes themselves.

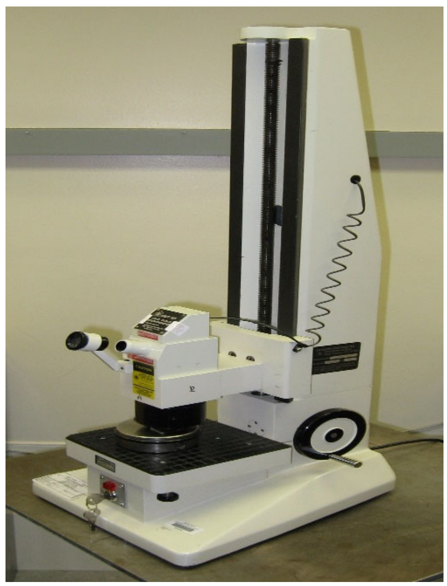
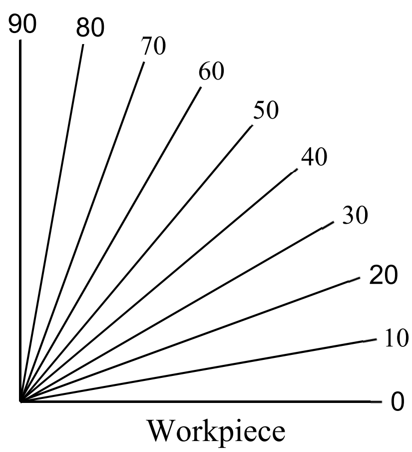


Figure 1.1-3: Gage Block Interferometer

1.1.3.4 A monochromatic light is used in conjunction with an optical flat to produce the same effect as the flatness interferometer. A clean stone and/or deburring stone should be used on the part and then cleaned with ethyl alcohol to remove any debris. Afterwards, an optical flat can be placed on the lapped surface but be careful not to damage the optical flat during this process. The optical flat is actually sitting on a small air wedge and produces fringes on the surface. Slide the entire part under the monochromatic light, so that the fringes can be observed. The value of the fringe is determined by the angle of observation on the optical flat. One should observe the fringes on the optical flat at a 90° angle. The bandwidth value at that angle is 11.6 µin. The highest accuracy measurements are made with the smallest bandwidth value. The bandwidth value and the viewing angle are inversely proportional as the viewing angle decreases the bandwidth value increases. At a 10° angle, the bandwidth value is 62 µin.

Figure 1.1-4: Monochromatic Light



Viewing Angle (Degrees)	Fringe Value (Microinches)
10	62.0
20	33.0
30	23.0
40	18.1
50	15.3
60	13.4
70	12.3
80	11.9
90	11.6

Figure 1.1-5: Viewing Angle vs Fringe Value.

1.1.4 Parallelism

1.1.4.1 Parallelism is the condition of a surface equidistant at all points from a datum plane or an axis equidistant along its length to a datum axis. We define this as true parallelism measured point to point across the part. Parallelism can be measured on the Standard Measuring Machine, the Gage Block Comparator, Micrometers, or Calipers. First, let us look at the parallelism of the Standard Measuring Machine flat anvils. These anvils must be both flat and parallel to make correct readings. Once the flatness of the anvils is within specifications, the parallelism can be measured. Place the optical parallel between the two anvils and press it against one of the anvils until all the air has been squeezed out. Once this is accomplished, place the monochromatic light near the anvil to ensure no fringes are visible. Sometimes, it seems almost impossible to remove all the fringes, but it can be accomplished. Move the other anvil in contact with the optical flat and observe the number of fringes on it. Count the number of fringes and multiply it by the fringe value to calculate the parallelism value.

1.1.4.2 The same method applies to any pair of flat measuring anvils being used to calibrate parts, such as the 0-1 inch micrometer. For larger micrometers, we employ a slightly different method. Since we do not have optical parallels larger than 1 inch thick, we use corresponding gage block stacks to check the parallelism at the four quadrants of the measuring anvils. This provides a functional check of the measuring anvils. During this check, the gage block covers the entire anvil surface. This procedure will detect tapered anvils but will not detect if the anvils are concave or convex. This condition will be identified when the flatness of the measuring anvils is measured.

1.1.4.3 The measuring jaws on calipers are checked by closing the jaws and holding it up to a light source and if any light appears then the jaws are checked with gage blocks. The gage blocks are placed at several locations along the jaws to measure the parallelism in those locations.

1.1.4.4 The Gage Block Comparator employs two diamond radius tips, which present a different scenario. These tips must be very closely aligned to each other or the user will see erroneous results due to offset of the tips. This offset provides for a larger parallelism error than actually exists on the part due to measuring the part at a slight angle rather than zero degrees. The tips must also be inspected periodically for wear or damage. Wear is inevitable and eventually will lead to flat spots on the tips. However, damage warrants replacement of the tips because they will scratch or damage the part being measured. Both the Standard Measuring Machine and the Gage Block Comparator are the most accurate for measuring parallelism.

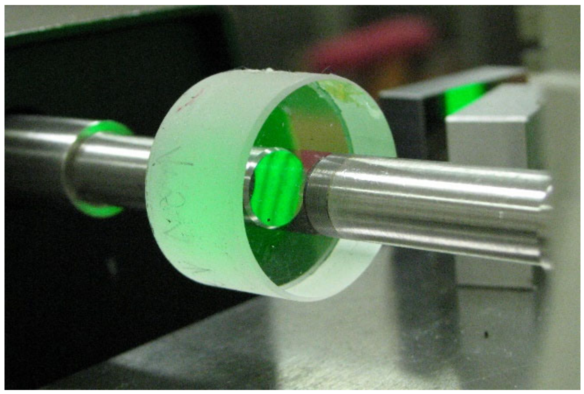


Figure 1.1-6: Anvil Parallelism using Optical Parallel

1.1.5 Straightness

1.1.5.1 We define straightness as functional parallelism. An electronic height gage and surface plate are most commonly used to measure straightness. The part being measured is placed on a surface plate and the gage head is placed on the top surface of the part. The part is preferably moved underneath the gage head until the entire surface has been measured. The gage head is kept stationary during this process. If the part being measured is too large to move, the gage head can be moved. The deviation between the highest point and the lowest point is the straightness error. The round-off on the edges and corners of the part are not measured. This round-off is the chamfered edges and corners of the part and can vary up to ¼ inch.

1.1.5.2 This method is employed by the Air Force to measure parallelism of parallel bars, box parallels, v-blocks, sine plates, etc., which are utilized in the same manner. It not realistic to measure a parallel bar for parallelism on a Standard Measuring Machine, because it is not used that way. The parallel bar is placed on a surface plate and used to establish a reference plane from that surface. The entire surface of the parallel bar is used to establish a parallel plane from the surface plate. Therefore, if the parallel bar is bowed then it will pass the parallelism test using the Standard Measuring Machine but fail the test using the Electronic Height Gage and Surface Plate. Since parallel bars and other like items are checked in this manner, it is important to let the manufacturer know the acceptance criteria. Otherwise, discussions will occur as to how the part is manufactured and tolerances associated with that measurement.

Figure 1.1-7: Straightness Measurement

1.1.6 Perpendicularity (Squareness)

1.1.6.1 Perpendicularity, or squareness, is the condition of a surface, median plane, or axis at a right angle to a datum plane or axis. Squareness can simply be measured by using a protractor, toolmakers square, or a cylindrical square. More accurate squareness measuring devices are a height measuring station (817CLM) or an autocollimator.

1.1.6.2 The 817CLM takes a trace of the granite angle plate to establish the reference plane. Next, the granite angle plate is moved aside, and the part being measured is moved into place. The 817CLM takes a trace of the part and calculates the squareness deviation in relation to the reference (granite angle plate).

Figure 1.1-8: Mahr 817CLM

1.1.6.3 The autocollimator is placed on the surface plate, aligned, and kept in a stationary position, because it is the reference for the measurement. A true square is moved in front of the autocollimator and a reading is taken. The autocollimator will be adjusted to read the deviation from the certification sheet of the true square. Next, the true square is moved aside, and the part is moved in front of the autocollimator. This reading is the deviation from squareness (90°). If the part is non-reflective, place a magnetic back mirror on the part and take a measurement. Next, rotate the mirror 180° and take a second measurement. The average of the two readings is the deviation from squareness. If the part is non-magnetic, hold the mirror onto the part with rubber bands or something similar. Ensure that the mirror is not being distorted by items holding the mirror in place. The part angle being measured is the relationship between the bottom side, which is the reference surface, and the measured side. The part angle is the inside angle, which will be 90° if the part is exactly square. The measured deviation from 90° regardless of sign is the out-of-squareness condition of the part.

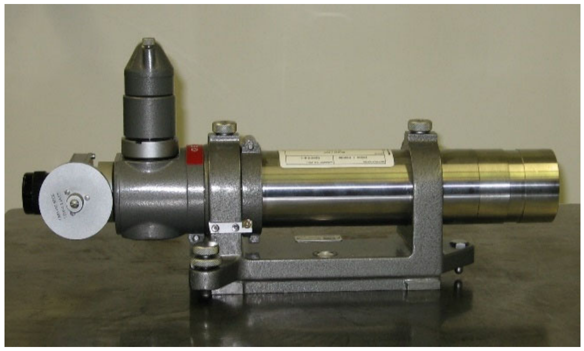


Figure 1.1-9: Autocollimator

1.1.7 Coplanarity

1.1.7.1 Coplanarity is the condition of two or more surfaces having all elements in one plane. The preferred method of measuring coplanarity involves the use of a height gage, leveling plate, and surface plate. The part must be placed on the leveling plate and leveled according to the procedures stated under the flatness paragraph. The best technique for measuring coplanarity is to keep the gage head stationary and move the entire measuring surface of the part underneath the gage head. This means to move the leveling plate with the part on it.

NOTE

Do not move the part on the leveling plate once it is leveled. Otherwise, the leveling process must be started again. The gage head is the reference.

1.1.7.2 Another method for measuring coplanarity involves an optical flat and monochromatic light source. The optical flat must be large enough to cover all the measuring surfaces being calibrated in order to establish a reference plane. This process is slightly more difficult as it involves interpreting the fringe patterns on the measured surfaces to arrive at the coplanarity deviation. The number of bands and the direction on the measuring surfaces define the shape of the item being measured.

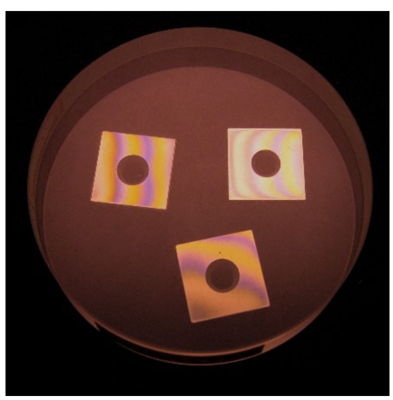


Figure 1.1-10: Coplanarity using Optical Flat

1.1.7.3 Example of How to Measure and Calculate Coplanarity.

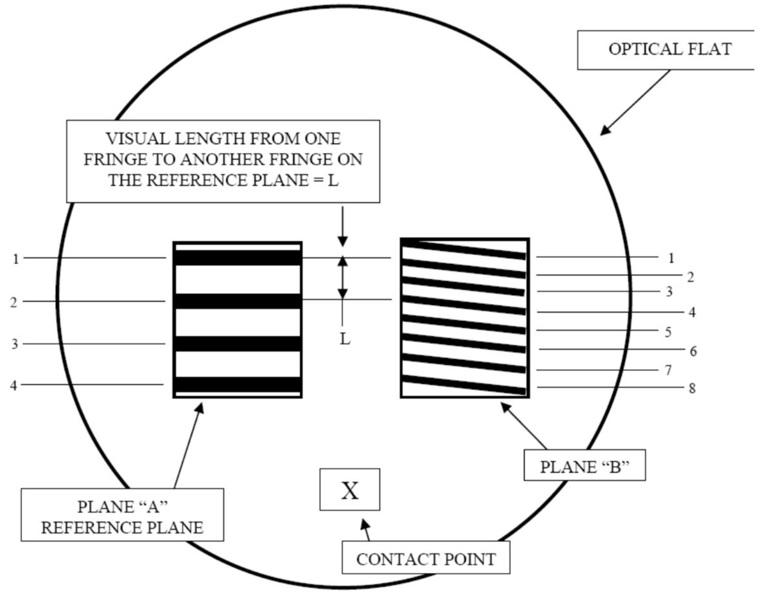


Figure 1.1-11

1.1.7.4 Planes A and B represent two pads on a fixture. The pads according to the drawing share the same datum. Therefore, they should share the same plane and be parallel to each other (Coplanarity).

For the example, ½ Wavelength of the Monochromatic Light Source = 11.6 µinches
Place the optical flat so it contacts Planes A and B.
Select one of the pads to be the reference plane. For this example, Plane A is the reference.
Align the fringes on the reference plane so they are visually parallel to the top edge of the Plane A.
Parallelism Error, Plane B Long Direction:
Equals Absolute Difference in the Number of fringes Between Planes A and B.
Plane A: 4 fringes, Plane B: 8 Fringes.
Parallelism Error, Plane B Long Direction = 4 Fringes x 11.6 = 46.4 µinches
Parallelism Error, Plane B Short Direction:
Equals the number of fringes on Plane B that fall between two fringes on Plane A.
Length L represents the length between two fringes on Plane A.
2.5 fringes on Plane B fall between the Length L.
Parallelism Error, Plane B Short Direction = 2.5 Fringes x 11.6 = 29.0 µinches
Coplanarity = the Maximum Parallelism Measured From Steps 4 and 5.
Coplanarity of the Example = 46.4 µinches

1.1.8 Circularity (Roundness)

1.1.8.1 Circularity is the condition of a surface where for a feature other than a sphere, all points of the surface intersected by any plane perpendicular to an axis are equidistant from that axis. For a sphere, all points of the surface intersected by any plane passing through a common center are equidistant from that center. Certain characteristic types of roundness errors can frequently be associated with particular manufacturing methods and circumstances. It is well known that improperly aligned or out-of-round center holes reflect the form of the object, which is turned or ground between bench centers. Clamping in three or four jaw chucks can distort parts to an extent where the essentially round form produced in the chucked condition will distort as soon as the clamping force has been relieved. Centerless grinding can produce odd lobed parts. Vibrations in the machine or part can cause undulations on the machined surface called chatter marks. The actual form of the finished part contour, when compared to a perfect circle, can differ in many ways, primarily depending on the manner in which the part has been produced.

1.1.8.2 The diameter is measured by rotating a part between two flat and parallel anvils such as a micrometer or caliper. This variation in diameter is often interpreted as out of roundness. This method is seldom used because of misleading results; it is only good for elliptical and even lobed parts. An example of this is shown below using the digital caliper.

Figure 1.1-12: Ineffective way to measure roundness

1.1.8.3 Roundness can be measured as simply as rotating a part in bench centers and measuring the out of roundness with an electronic height gage. There are some issues concerning this method, which may produce misleading results as well. The alignment of the two centers must be perfect along the x, y, and z axes. The angle and surface finish of the centers may also add to the uncertainty if the part contacts along the angle of the centers.

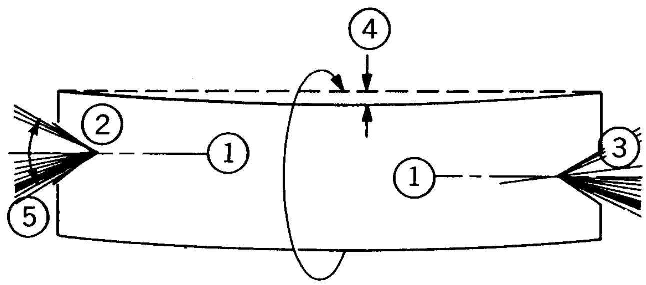


Figure 1.1-13

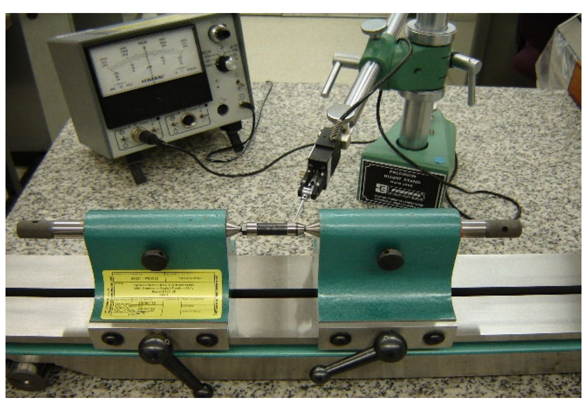


Figure 1.1-14: Bench centers to measure roundness

1.1.8.4 Sometimes a v-block is used in place of the bench centers. This method can also produce misleading results due to the v-block angle and the spacing of part irregularities. Once again, odd lobed parts cannot be measured correctly. As seen below, the same part is measured using two different v-block angles and the results are different.

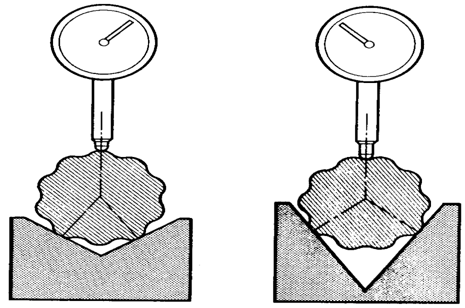


Figure 1.1-15

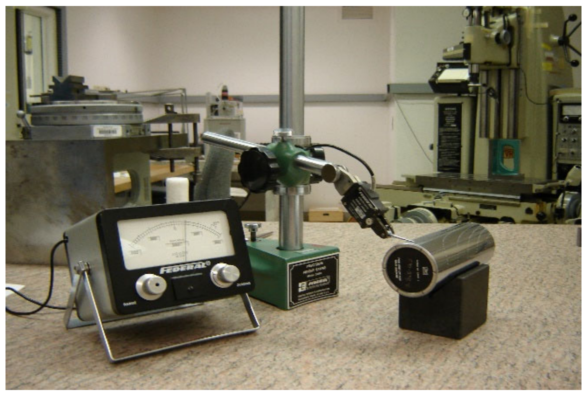


Figure 1.1-16: V-Blocks to measure roundness

1.1.8.5 The preferred method for measuring roundness is by using a roundness machine with a rotating table. It is a more reliable and accurate method of measuring roundness because of its part orientation. The part is placed on the rotary table and then centered and tilted along the centerline axis of the part. This process aligns the spindle axis of rotation to the centerline axis of the part. Circular profiles can be produced and analyzed. These profiles are compared to a perfect circle and the measurement error can be quantified. The measurement uncertainty of the roundness machine bearing error, gage head error, and column straightness error can also be quantified.

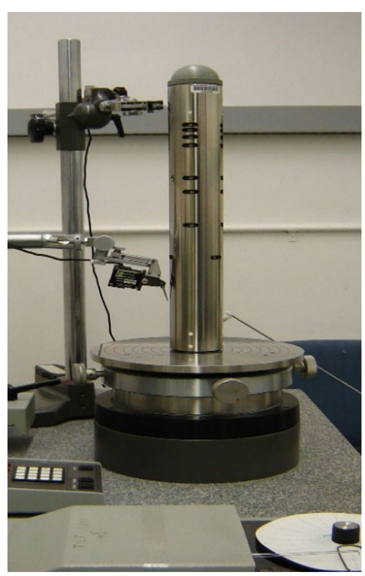


Figure 1.1-17: Roundness Machine measuring roundness of a collimator

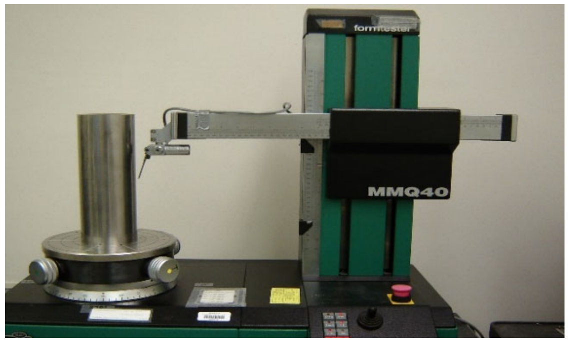


Figure 1.1-18: Roundness Machine measuring roundness of a cylindrical square

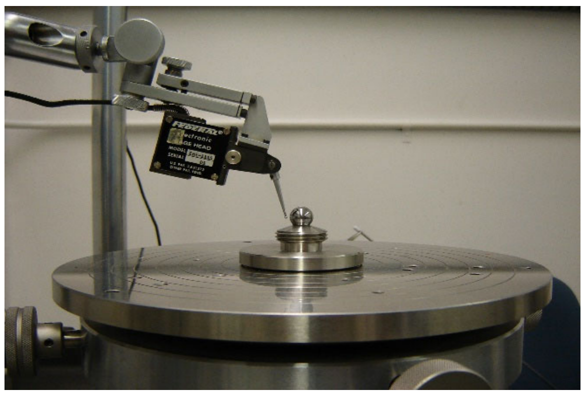


Figure 1.1-19: Roundness Machine measuring roundness of a sphere

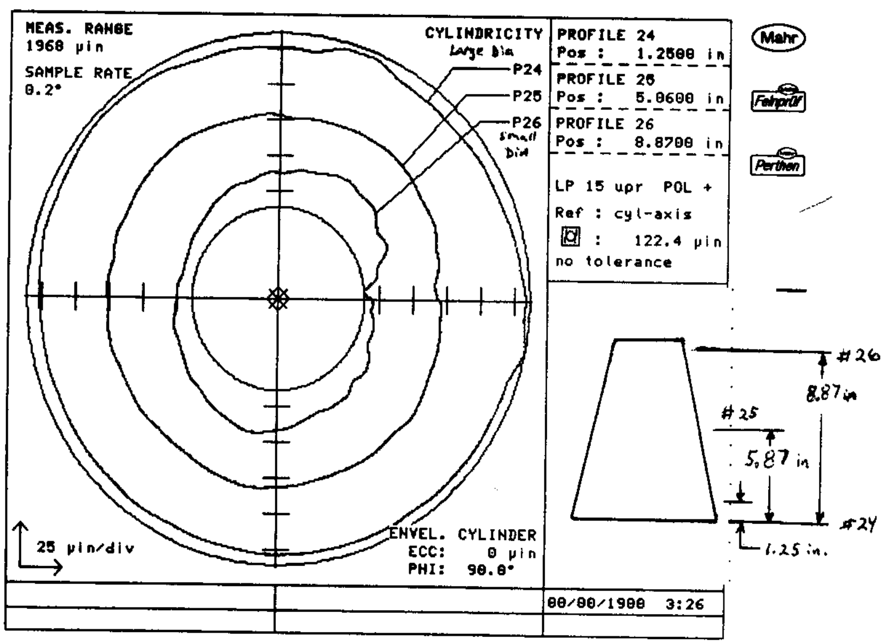


Figure 1.1-20: Roundness plot from roundness machine

1.2 GAGE BLOCKS

1.2.1 Introduction
Gage blocks consist of two precision lapped surfaces, which are extremely flat and parallel. These gage blocks are most commonly rectangular or square in shape. They are manufactured from tungsten carbide, chromium carbide, tool steel, or ceramic. Each of these materials has their own unique characteristics. Tungsten carbide is the hardest, most durable, and stable of the materials. However, it is very costly and not used in the Air Force. Chromium carbide is the next hardest, less stable, and does not rust. However, surface defects are harder to remove from its lapped surfaces. Tool steel is the most widely used material for gage blocks in the PMELs. It is easier to remove surface defects, and in most cases, has the same Coefficient of Thermal Expansion (CTE) as the items being calibrated. Ceramic has less than desirable characteristics. Ceramic requires twice as long to stabilize as tool steel, once handled. In addition, ceramic gage blocks wring together tightly but not uniformly, which indicates that the geometry of the gage blocks changes once wrung together. Surface defects are also very difficult to remove from ceramic lapped surfaces.

1.2.2 Sets
Gage block sets contain up to 121 blocks of various lengths. Each set is supplied in a fitted, hardwood case as shown below. If requested, accessories may accompany each set of gage blocks. Common accessories are the triangular base, half round jaws, straight jaws, scriber, and extension rods. Triangular bases are used as a reference surface to make measurements on. Half round jaws are wrung to the outside of a gage block stack and used to verify a hole diameter. Straight jaws are wrung to the outside of a gage block stack and used as masters to verify inside measurements. A scriber is used to mark a desired length, but this item is not calibrated, since its use is mainly for machine shop practices. Extension rods are used with long gage block stacks to prevent a stack from pulling apart. Sets of 8, 28, 36, 81, and 92 gage blocks are most common.

Figure 1.2-1: Gage Block Sets

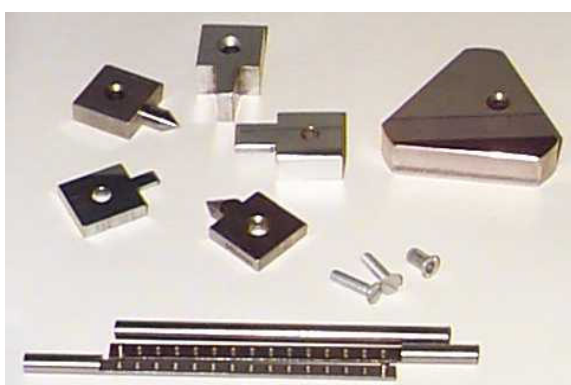


Figure 1.2-2: Gage Block accessories

Table 1.2-1: Gage Block Configurations

Set No. 8 contains 8 blocks, as listed below:		
4 Blocks	5" thru 8"	increments of 1"
1 Block	10"	
3 Blocks	12" thru 20"	increments of 4"
Set No. 28 contains 28 blocks, as listed below:		
1 Block	0.02005"	
9 Blocks	0.0201" thru 0.0209"	increments of 0.0001"
9 Blocks	0.021" thru 0.029"	increments of 0.001"
9 Blocks	0.010" thru 0.090"	increments of 0.010"
Set No. 36 contains 36 blocks, as listed below:		
1 Block	0.050"	
9 Blocks	0.1001" thru 0.1009"	increments of 0.0001"
9 Blocks	0.101" thru 0.109"	increments of 0.001"
9 Blocks	0.110" thru 0.190"	increments of 0.010"
5 Blocks	0.100" thru 0.500"	increments of 0.100"
3 Blocks	1", 2", 4"	
Set No. 81 contains 81 blocks, as listed below:		
9 Blocks	0.1001" thru 0.1009"	increments of 0.0001"
49 Blocks	0.101" thru 0.149"	increments of 0.001"
19 Blocks	0.050" thru 0.950"	increments of 0.050"
4 Blocks	1.000" thru 4.000"	increments of 1.000"
Set No. 92 contains 92 blocks, as listed below:		
4 Blocks	1/16", 5/64", 3/32", 7/64"	
3 Blocks	0.100025" thru 0.100075"	increments of 0.00025"
9 Blocks	0.1001" thru 0.1009"	increments of 0.0001"
49 Blocks	0.101" thru 0.149"	increments of 0.001"
4 Blocks	0.160" thru 0.190"	increments of 0.010"
19 Blocks	0.050" thru 0.950"	increments of 0.050"
4 Blocks	1.000" thru 4.000"	increments of 1.000"

1.2.3 Traceability

For gage block sizes 4 inches and under, the AFPSL has a set of gage blocks calibrated to 1 µin, using the wavelength of light. This set is used for inter-comparison with NIST to maintain traceability on interferometric calibrations. The AFPSL calibrates gage blocks interferometrically to 2 µin for internal use. The AFPSL utilizes a NIST-developed statistical software process and a gage block comparator to measure 2 µin gage blocks. Sets of masters calibrated to less than 2 µin, from NIST, are used as masters for this comparison process. The 2 µin gage blocks are used as masters to calibrate 6 µin gage blocks for the Type IIA & IIC PMELs. These PMELs use 6 µin gage blocks as masters to calibrate 12 and 20 µin gage blocks for all other PMELs. For sizes 5 inches and over, the AFPSL has four sets of gage blocks calibrated at NIST. These blocks are used as AFPSL masters to calibrate sets to better than 1 µin/in, using a gage block comparator. Once calibrated, these blocks are used as masters to calibrate blocks to 1 µin/in using a gage block comparator. They are sent to the Type IIA & IIC PMELs to be used as masters to calibrate gage blocks to 2, 3, or 5 µin/in for all other PMELs.

Figure 1.2-3: Interferometric Gage Block Calibration

1.2.4 Care and Handling
Two main materials used in the Air Force are steel and chromium carbide. New steel gage blocks have a light coating of oil on them to prevent rust. New chromium carbide gage blocks are not coated with oil. Always wear gloves or finger cots when handling gage blocks, moisture of the hands contains an acid, which induces rust if not promptly removed. Tongs, made of either wood or metal, should be used to maneuver gage blocks into the desired location. If metal tongs are used, the tips should be coated in plastic or shrink tubing to prevent marring of the gage blocks.

1.2.5 Cleaning
Cleaning begins with removal of preventative oil on the gage block's lapped surfaces, if applicable. A degreasing solution is used to remove the heavy weight preservative. Next, 200 proof alcohol is used to remove any remaining residue. This entire process is necessary before the inspection of gage blocks.

1.2.6 Inspection
Gage blocks must be inspected for surface defects before being wrung together. These surface defects include edge burrs, surface burrs, scratches, and rust. If a lapped surface contains any raised surface defects, it will not wring to the adjoining surface, but rather damage it. Surface defects can be detected using a flatness interferometer or an optical flat with a monochromatic light. A raised surface defect is identified when the fringes flow downward and then rise up in the particular location of the raised surface defect. Surface defects below the surface do not need lapped, and can be wrung without additional processes. If raised surface defects are observed, they should be removed using alcohol and a ceramic serrated stone. This process of lapping removes raised surface defects and allows the gage block lapped surfaces to be wrung.

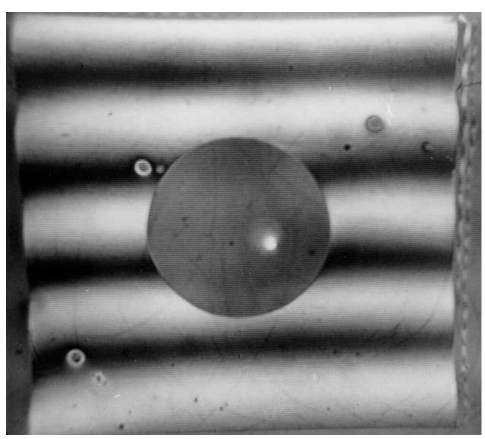
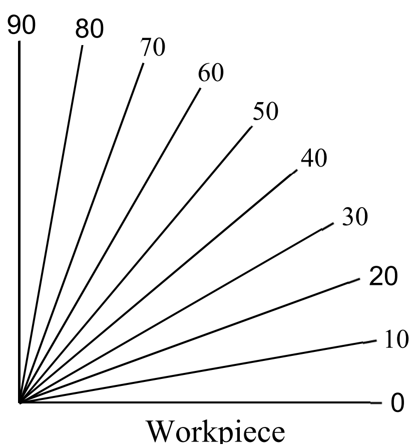


Figure 1.2-4: Gage Block Inspection

1.2.7 Flatness Calibration

Flatness is measured using a flatness interferometer or monochromatic light with an optical flat. A flatness interferometer utilizes a helium-neon laser, while monochromatic lights have helium bulbs. Light waves which strike the optical flat surface split, one ray is reflected back by the surface of the flat, while the other ray is refracted by the surface. Whenever split portions of a light wave cross each other (called interference) an invisible light wave is produced and dark bands (fringes) appear on the surface, fringes are ½ a wavelength. When using a flatness interferometer, the tilting table must be adjusted until 4 to 6 fringes appear. If a monochromatic light is used, the optical flat must be placed on the gage block surface. The optical flat is actually sitting on a small air wedge and produces fringes on the surface. The flat is moved horizontally until 4 to 6 fringes appear.

Figure 1.2-5: Monochromatic Light



Viewing Angle (Degrees)	Fringe Value (Microinches)
10	62.0
20	33.0
30	23.0
40	18.1
50	15.3
60	13.4
70	12.3
80	11.9
90	11.6

Figure 1.2-6: Viewing Angle vs Fringe Value

To determine the approximate flatness of a gage block, first determine the value of one fringe. This value will be labeled "B". If the gage block is being viewed from approximately 90 degrees, use 11.6 µin. Next, determine what percentage of the deviation "A" is to "B".

Example:
"B" = 11.6 µin
"A" = slightly less than one-half
Deviation of Flatness = 0.4 x 11.6
Deviation of Flatness = 4.6 µin

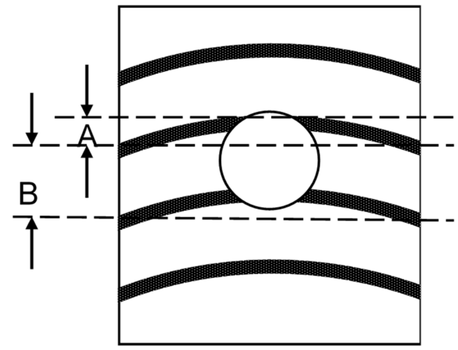


Figure 1.2-7

1.2.8 Parallelism and Length Calibration
Parallelism is measured on a gage block comparator at four locations, other than at the gaging point. After the raised surface defects have been removed, and flatness and parallelism measurements are complete, length calibration may begin. Length calibrations are performed on the gage block comparator at the gaging point. When calibrating thin gage blocks (under 0.050 inch) it is necessary to measure them twice, once on each lapped (gaging) surface. The smallest length is recorded. Grades of gage block sets are determined by the flatness and parallelism of the gage blocks in the set. These two numbers are not to be combined because parallelism error encompasses flatness error.

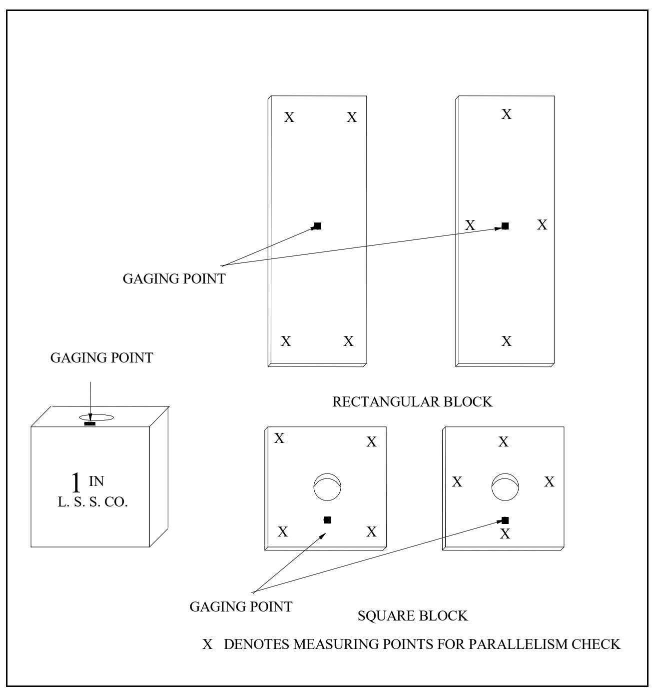


Figure 1.2-8: Gage Block check points

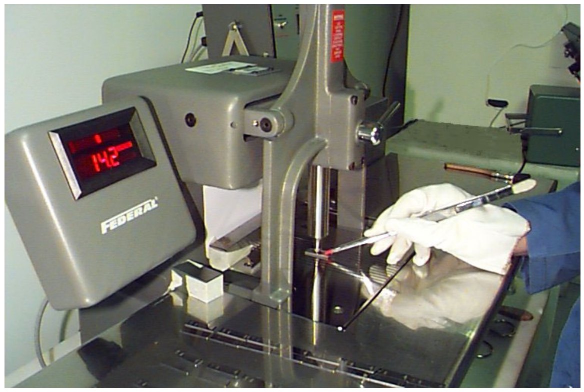


Figure 1.2-9: Gage Block Comparator

Table 1.2-2: Gage Block Tolerances

Gage Blocks - Parallelism and Flatness Tolerances			
Size (in)	Length Accuracy (from stated value)	TIR Parallelism (µin)	TIR Flatness (µin)
4 and under	2 µin	2	2
	6 µin	4	4
	12 µin	6	6
	20 µin	12	12
over 4 to 6	1 µin/in	3	3
	2 µin/in	5	5
	3 µin/in	8	8
	5 µin/in	16	16
over 6 to 10	1 µin/in	4	4
	2 µin/in	5	5
	3 µin/in	8	8
	5 µin/in	16	16
over 10 to 12	1 µin/in	4	4
	2 µin/in	6	6
	3 µin/in	10	10
	5 µin/in	18	18
over 12 to 16	1 µin/in	5	5
	2 µin/in	8	8
	3 µin/in	12	12
	5 µin/in	20	20
over 16 to 20	1 µin/in	6	6
	2 µin/in	10	10
	3 µin/in	14	14
	5 µin/in	24	24

1.2.9 Considerations Before Use

Before using gage blocks for calibration, an uncertainty analysis must be performed to determine the grade of gage blocks required. The uncertainties of the gage blocks in a stack are added together to determine the grade of gage blocks required. The CTE of a gage block, if not corrected for, is an uncertainty. This becomes an important issue when the environment is outside 68 ±1 °F. It can be corrected for when the CTE value is higher than the resolution of the instrument being used to measure. When making measurements to 100 µin or less, the gage block deviations on the report of measurement are to be used. Each gage block's deviation is added together to determine the actual length of a gage block stack.

1.2.10 Uses

All length measurements made in the Air Force are traceable back to gage blocks, the standard of length. Gage blocks are used for high accuracy measurements. They are used to calibrate several different measuring devices from Coordinate Measuring Machines (CMMs) to hand tools, such as micrometers and calipers. They are mainly used in the vertical position, but are occasionally used in the horizontal position. When used horizontally they should be supported at the airy points. Besides length, gage blocks can also be used to measure internal and external diameters.

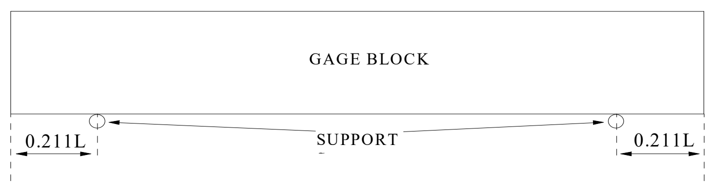


Figure 1.2-10: Gage Block Support

1.2.11 Wringing Process

When a desired length is required, a decision must be made to use either individual or stacks of gage blocks. A gage block stack consists of two or more different size gage blocks wrung together. The serial numbers on the blocks must match those listed on the calibration report. After cleaning and inspecting, a drop of silicon oil is placed on the two wringing surfaces. After the oil has been rubbed over the entire surface, it is then wiped dry using a lint-free cloth. The remaining microfilm of oil will allow the blocks to be wrung. Both surfaces being wrung together are cleaned using air or a camel hairbrush. Two corners of the gage blocks are brought together as shown in below. The gage points must be lined up. Slight pressure is applied on the top block and carefully slid over the bottom block, as shown below. There should be a grabbing or adhesion feeling between blocks.

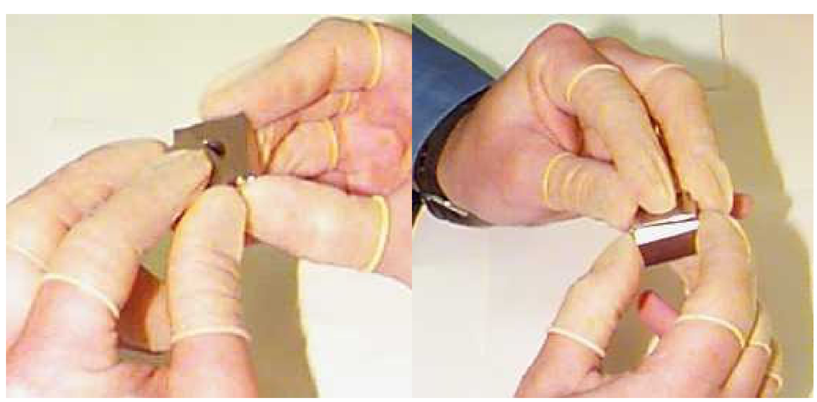


Figure 1.2-11: Wringing Gage Blocks

1.2.12. Construction of Gage Block Stacks
When constructing gage block stacks, the minimum amount of gage blocks should be used. This is dependent upon gage block set availability. In order to construct a 1.9683 inch gage block stack, four individual gage blocks will be wrung together. The four sizes are shown below:

Table 1.2-3: Gage Block Stack Calculation

Desired Gage Block Length: 1.9683 inches	
Gage Block Size (inches)	Deviation (µinches)
0.1003	-3
0.1180	+2
0.7500	-5
1.000	-6
Overall Gage Block Size: 1.9683	Overall Deviation: -12

1.2.13. Stabilization Time
Stabilization time is based on the desired accuracy of the part being measured. When gage blocks are handled, they heat up from the technician's body heat, regardless of the use of tongs. Tongs should be used whenever possible to reduce the amount of stabilization time. Gage block length is directly proportional to stabilization time. Studies performed at the AFPSL showed that gage blocks up to 12 inches in length were at least 75% stable after 1 hour soak time. This study encompassed gage blocks up to 20 inches in length and involved handling of up to three wrings. A 20 inch stack was completely stable after 5 hours.

1.2.14. Uncertainty
Uncertainty is used to describe how well the measured value is obtained and is expressed as ± or TIR. Length and geometry comprise the uncertainty value. Length uncertainty is a point-to-point measurement at the gaging point only and is 1 µin and 2 µin, respectively, for 2 µin and 6 µin gage blocks. This uncertainty value can only be used when measuring on a gage block comparator or horizontal (internal/external) comparator. Uncertainty is used to determine equipment requirements for calibration.

1.3. SURFACE PLATES

1.3.1. Introduction

A surface plate "the rock" is the most widely used reference for measuring dimensional equipment in the Air Force. Surface plates are manufactured from granite, a very porous material. The porosity structure means it acts like a sponge, absorbing any liquids. Therefore, it should not be exposed to liquids, except those used for cleaning, which will be discussed later. A surface plate is defined as an igneous rock (granite) plate used in precision locating, layout, and inspection work. They come in several sizes and flatness accuracies, depending on calibration requirements.

1.3.2. Materials

Surface plates are made of two different materials: granite or gabbro. Both granite and gabbro are among the hardest rocks. The word granite, which means hard stone, is often applied indiscriminately to both granite and gabbro. Diabase is a variety of a stone known as gabbro. While it is closely related to granite, diabase is not the same. Diabase is denser, less porous, and has no grain.

1.3.2.1 Granite is composed primarily of Feldspar and quartz. Wherever quartz occurs, mica is always found because both are silicates differing chemically only in amount of oxygen. Mica gives granite a grain with slivers of mica parallel to the grain. If the grain is horizontal to surface, flecks of mica can be readily chipped out. Therefore, all granite surface plates are made with the grain perpendicular to the surface. This greatly reduces the stiffness. It is comparable to a beam of wood with the grain perpendicular to the length instead of being parallel to the length.

1.3.2.2 Diabase is composed of Plagioclase and Pyroxene. It has no quartz and therefore no mica. The lack of quartz means that diabase is slightly less resistant to wear than the hardest granites. It does not have any grain, thus the result is that diabase is three times as stiff as granite. Diabase is uniform in hardness; scleroscope readings average about 95 RC. Granites vary greatly in hardness from 70 to 105 RC, Chelmsford gray granite is 102 RC. Diabase is used for multi-dimensional, very high accuracy applications that require a very smooth stable surface. Applications include the use of angle plates, parallels, master squares, and straight edges. More accurate flat surfaces may be lapped on the diabase, since temporary distortion, incurred while lapping, can be better controlled.

1.3.3. Color

At one time, a certain good plate happened to be a certain color, hence that color became synonymous with good. The color of a stone provides no indication of the physical qualities possessed by the stone itself. Color has erroneously come to signify good or bad qualities in a surface plate. The color of granite is determined simply by the presence or absence of minerals.

1.3.4. Streaks and Cracks

Black streaks are inclusions formed when the diabase was molten, and have no adverse effects on the hardness, stiffness, or other desirable characteristics. White streaks appear when there is an absence of black magnetite and have no effect on the physical properties of the surface plate. Cracks, on the other hand, are a cause for concern since it represents a weakened condition of the surface plate. The extent of the weakened area depends on the weight of the objects being used in that area. When cracks occur either contact the manufacturer and verify the replacement warranty or avoid the cracked area. The manufacturer should be contacted to obtain test procedures to evaluate the cracked area, which will determine whether the plate requires replacement.

1.3.5. Thermal Effects

The coefficient of thermal expansion for most types of granite is 3 to 4 µin/inch/°F. Since the expansion of granite is about half that of cast iron or steel, a surface plate shows a temporary bow due to unequal temperature of only half that of an iron plate. Furthermore, heat is transmitted through iron 300 times faster than through granite. Therefore, granite can be submitted to temperature irregularities for brief periods without materially affecting the accuracy. For example, a granite straight edge, when turned over, shows little change in geometry for one or two minutes and requires two hours to make the full transformation. On the other hand, an iron straight edge will make the full transformation in 30 seconds. Areas of the surface plate will acclimate to the temperatures around them. The temperature of a single surface plate will vary from area to area. One should be careful of where to locate the surface plate. The room's temperature control should maintain a constant temperature around the plate. The temperature requirements for the corresponding grade of plates are as follows: ±0.5 °F for Grade AA, ±1 °F for Grade A, and ±3 °F for Grade B plates.

1.3.6. Clamping Ledges

The width of the clamping ledges (lips) on surface plates shall not be less than 40% of the thickness for plates less than six inches thick. The plate's depth shall be ¼ of the surface plate thickness. This design requirement is used as a minimum specification to ensure the plate is structurally sound. It also ensures that the plate can be used to clamp work pieces to the plate without damaging the structure of it.

1.3.7. Supports

Three support points can rest solidly on any surface. Any attempt to use more than three points will cause the plate to receive its support on a various combination of three points, which probably will not be the same points at which it was supported while being lapped, thus causing errors. Unless otherwise specified, support of the surface plate shall be by three fixed supports on the stand, located at the airy points to minimize sag and warp. The two support pads at one end of a rectangular plate are generally located approximately ¼ of the length and width in from the ends and sides, respectively. The single support pad at the other end of a rectangular plate shall be located approximately ¼ of the length and in the center along the width. The support pads on round plates shall be located at three equally spaced positions (120° apart) on a circle with a radius equal to 0.7 x radius of the plate. When the three fixed supports have special requirements due to their location, abnormal load, and/or vibration conditions, the supports and their locations shall be clearly specified.

1.3.8. Characteristics

The five most important characteristics of a surface plate are original accuracy of measurements that can be made on it, retained accuracy under load, retained accuracy after use (wear), abrasiveness of granite surface on inspection equipment being used on them, and cost relative to accuracy required.

1.3.8.1 The surface plate should have a fine precision lapped working surface, which is free from rough lapping marks. Evidence of loosely bound crystals on the surface of Grade AA plates shall be cause for rejection. The average surface roughness for Grade AA and A plates is usually 32 µin, using a 0.030 inch cutoff, and 64 µin for Grade B plates. Holes, slots, and inserts should not deform or stress the work surface.

1.3.8.2 All edges and corners, with the exception of the work surface edges and corners, should be broken down smoothly and uniformly to an approximate ½ inch radius. The work surface edges and corners shall have an approximate 0.200 inch radius for 12 inch length or diameter plates. Then, the radius increases by approximately 0.100 inch per foot of length or diameter, up to 0.5 inch maximum radius. Below, in Figure 1.3-1, is a simple comparison of various units of length.

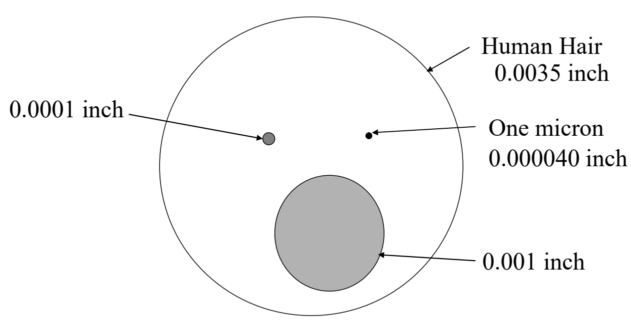


Figure 1.3-1: Size Comparison

1.3.9. Flatness Tolerance

A flatness tolerance is a tolerance zone defined by two parallel planes within which the surface must lie. The flatness tolerance is the maximum deviation as determined by one of the calibration methods.

Table 1.3-1:
Work Surface Flatness Tolerance in microinches (µin)

Width (in)	Length (in)	Grade AA	Grade A	Grade B
12	12	50	100	200
12	18	50	100	200
18	18	50	100	200
18	24	100	200	400
24	36	100	200	400
24	48	150	300	600
36	48	200	400	800
36	60	250	500	1000
36	72	300	600	1200
48	48	200	400	800
48	60	300	600	1200
48	72	350	700	1400
48	96	500	1000	2000
60	120	750	1500	3000
72	96	600	1200	2400
72	144	1100	2200	4400

The formula below applies to all plates not found in previous table; the tolerance is rounded off to the nearest 25 µinches.

Flatness Tolerance for Grade AA (µinches):

$$40 + D^2/25$$

Where: D = diagonal or diameter of the plate in inches

The tolerance of Grades A and B plates are 2 and 4 times, respectively, those for grade AA.

1.3.10. Cleaning Method
Cleaning the surface plate the day before and letting it soak overnight before calibration is preferable. The following day, clean only the line being run and straight edge with ethyl alcohol before each run.

1.3.10.1 The choice of cleaning solutions is important as well. If alcohol is used, the evaporation will chill the surface and distort it. In this case, it is necessary to allow the plate to normalize before using it or measurement errors may occur. The amount of time required for the plate to normalize varies with the size of the plate and the amount of chilling. If a water-based cleaner is used, there will also be some evaporative chilling. The plate will retain the water, and this could cause rusting of metal parts in contact with the surface. Waterless surface plate cleaner is recommended. Afterwards use ethyl alcohol to remove any residue.

1.3.10.2 The best and simplest way to reduce wear and extend the life of a surface plate is to keep the plate clean. Airborne abrasive dust is usually the greatest source of wear and tear on a plate, as it tends to embed in work pieces and the contact surfaces of gages. In addition to regular thorough cleaning, wear life can be extended by covering the plate when not in use and by using the entire plate so that a single area does not receive excessive use. In addition, setting food or (especially) soft drinks on the plate should be avoided. Most soft drinks contain either carbonic or phosphoric acid, which can dissolve the plate’s softer minerals, leaving small pits in the surface. If the plate becomes soiled, particularly with oily or sticky fluids, it should be cleaned immediately.

1.3.11. Repeat Measurement
A calibration performed on a surface plate with a flatness specification over the entire measurement area must be verified using the repeat reading gage. The flatness tolerance does not guarantee that accurate measurements can be taken on a plate. The repeat reading gage is used to measure waviness. Long before a plate has worn beyond specifications for overall flatness, it will show wavy worn spots, which produce measurement errors. It determines the accuracy to which measurements can be repeated. The maximum deviation of the surface from a true plane, when scanned with a repeat reading gage, shall not exceed 25, 50, or 100 µinches for Grades AA, A and B plates, respectively.

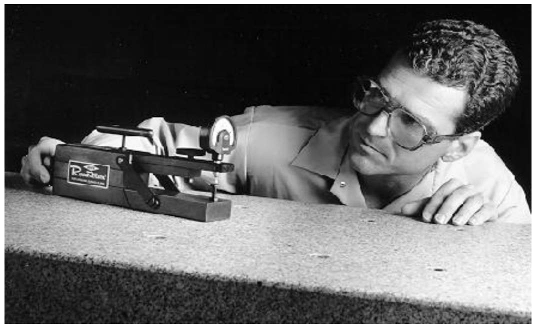


Figure 1.3-2: Repeat Reading Gage

1.3.12. Calibration
Since measurements are no more reliable than the surface plate on which they are referenced, it is important to know exactly the accuracy of the plate being used. Surface plates are manufactured to accuracies varying from 0.000050 to 0.002 inch of deviation from a true plane. The surface plate should be checked after installation to determine whether it meets specifications and periodically thereafter. A new plate should be calibrated as soon as it has been temperature normalized after installation. This normalization process is dependent on the environmental stability of the room and can take up to a month. It should also be checked with a repeat reading gage.

1.3.12.1 Ideally, the calibration should be performed in a room in which the temperature of the plate can be kept in equilibrium and from which thermal currents can be excluded. However, surface plates are often used under conditions, which may be less than ideal. Extreme temperature changes, thermal currents, and vibration should be avoided. The temperature gradient conditions should be stable during the calibration. The calibration will be valid only for the same temperature gradient conditions at which the calibration was made. When using an autocollimator or laser, a ±1 °F difference in 2 inches can cause an error of 100 µinches in 6 feet.

1.3.12.2 Surface plates can be calibrated by means of a planekator, autocollimator, electronic leveling system, or laser measurement system. The order in which they are listed above is from the least accurate to the most accurate. Some insight will be provided on each calibration process in the proceeding sections.

1.3.12.3 During calibration, eight lines of readings are taken: four perimeter lines, two diagonal lines, and two centerlines. The perimeter lines are laid out 3 to 4 inches from the edge of the plate. The precise stations at which readings along all eight lines are taken are measured off in steps equal to the increments on the straight edge. Many more readings could be taken, but a reasonable compromise between accuracy and economy is achieved by this method.

1.3.12.4 Planekator
The planekator is a granite straight edge with a high accuracy dial comparator as shown in Figure 1.3-3. The planekator rests on two supports; one has a fixed height and the other is adjustable. The dial comparator is attached to the base, which slides along the surface plate allowing the dial comparator to indicate along the bottom of the granite straight edge. The straight edge is calibrated at two inch intervals and correction values are recorded at each interval. The correction value is subtracted from the reading taken at the corresponding location during a surface plate calibration process. The planekator is placed along one of the lines, the end stations are leveled/balanced, and then the remaining intervals along the straight edge are compared to the end stations to produce final values. These values correspond to the difference in height from the end station to the respective location being measured.

Figure 1.3-3: Planekator

1.3.12.5 Autocollimator

The autocollimator, as shown in Figure 1.3-4, is essentially an optical lens system from which parallel rays are emitted. These rays strike the surface of a mirror and are reflected back into the autocollimator. The reflected rays produce an image at the focal plane of the autocollimator from which angular displacements can be accurately determined. The changing angle is converted to linear steps of rise or fall with trigonometry. An error in one reading will affect all other readings. The mirror is mounted to a base with support pads of which are separated by a distance arbitrarily chosen so that it will divide evenly into the dimensions of the surface plate.

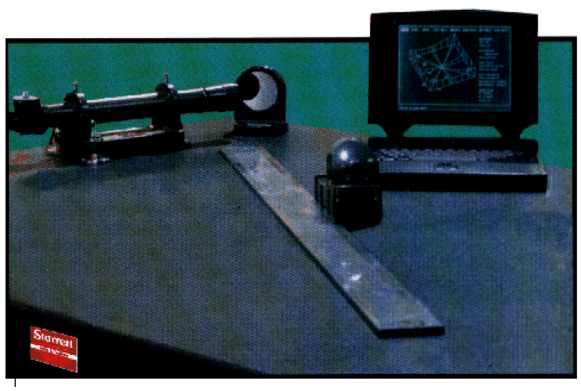


Figure 1.3-4: Autocollimator

A straight edge, graduated in increments equal to the distance between the support pads on the mirror, is used to position the mirror along a straight line. The mirror is moved along the line and readings are taken at each station. After each line is completed, the mirror is moved back to the first station on that line and another reading is taken. The reading must repeat within ±0.3 seconds or the whole line must be repeated.

1.3.12.6 Electronic Leveling System

The electronic leveling system consist of precision instruments for indicating angular deviations. This system consists of two level heads fitted with adjustable bases and a dual input digital amplifier as shown in Figure 1.3-5. Each pair of level heads is marked A or B for easy identification. When measuring a single surface to itself, the level heads input can be set for opposite responses to a common motion thereby ignoring that motion, the amplifier only responds to changes, which affect either head differently. Vibrations or shifts in the measured surface will not influence results. Therefore, deviations can be accurately determined, even though the object’s surface does not maintain a constant orientation.

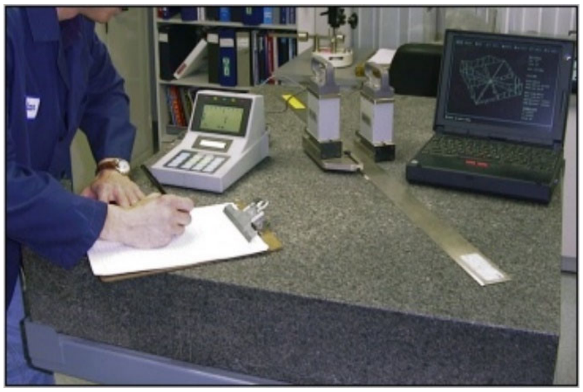


Figure 1.3-5: Electronic Leveling System

1.3.12.6.1 A pendulum is supported by 2 reed springs attached to an extension block at the top of the head's housing. Tilting of a level head causes a change in the position of the pendulum's shading loop relative to the center leg of the core. This produces an electrical imbalance in the amount of flux passing through the two secondary coils and delivers a signal proportional to the displacement of pendulum. The digital meter displays this signal in seconds of arc. The internal workings of the level heads are dampened by submersion in oil to slightly slow the response time but protect against shock. The level heads must always be used with a side tilt up to 1.5 degrees from vertical, with no changes in accuracy.

1.3.12.6.2 A straight edge, graduated in increments equal to the distance between the support pads on the moving level is used to position the level along a straight line. The level is moved along the line and readings are taken at each station. After each line is completed, the level is moved back to the first station on that line and another reading is taken. The reading must repeat within ±0.5 seconds or the whole line must be repeated.

1.3.12.7 Laser Measurement System
A laser is an optical instrument, which emits a concentrated beam of light in a straight line parallel to the line on a surface to be checked, as shown in Figure 1.3-6. The detector consists of two photoelectric cells centered on the laser beam. As the retro reflector moves along a line to be checked, an electronic readout shows the amount of rise or fall as a linear amount, reading to 10 µinches. Thus, a series of readings may be taken at any desired spacing and an error on one reading will have no effect on other readings. Since the laser detector reads in linear rise or fall, the readings may be used directly whereas the autocollimator readings must first be converted to linear rise or fall.

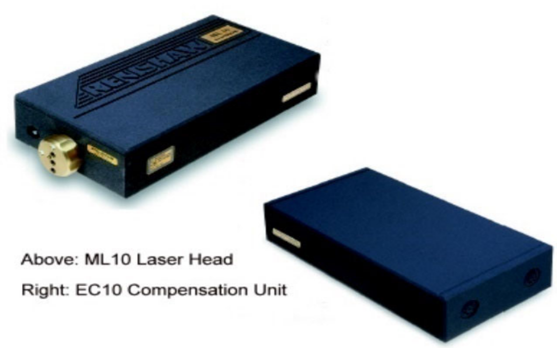


Figure 1.3-6: Laser Measurement System

1.3.12.7.1 A straight edge, graduated in increments equal to the distance between the support pads on the retro-reflector, is used to position the retro-reflector along a straight line. The retro-reflector is moved along the line and readings are taken at each station. After each line is completed, the retro-reflector is moved back to the first station on that line and another reading is taken. The reading must repeat within ±3 µin or the whole line must be repeated.

1.3.13. Troubleshooting
The following items are sources of error, which may contribute to the surface plate exceeding specified tolerances:

Surface plate not allowed to normalize throughout.
Surface plate does not have proper 3-point support.
Air not permitted to circulate all around surface plate.
Surface plate not supported on an open framework stand.
Working surface had been washed with cold or hot solution and the working surface has not stabilized.
Temperature change.
Careless or improper use of calibration instrument.
Surface error, due to wear.
Direct sunlight or other radiant heat on or above the plate.
Avoid drafts of varying temperature, which strike part of the plate.
Thermal gradient from ceiling to floor reverses due to season change and causes the surface to be changed toward convex or concave, respectively.

If all of these possible causes are investigated and eliminated, then it is likely that the plate was out of tolerance to begin with and the plate needs to be resurfaced.

1.4 ANGULAR TMDE

This area reserved for future use.

1.5. MASS

1.5.1 Introduction
Physics textbooks define mass as the amount of matter present in an object. The mass of an object is constant, and does not change, regardless of its location (or any change in the local gravity). There are two types of mass terms typically used, True Mass and Conventional Mass. These terms will be explained later in the sections to follow. Mass is the only SI measurement parameter still realized utilizing an artifact, a cylinder with a height and diameter of 39 mm, made of platinum-iridium alloy is kept at the International Bureau of Weights and Measures (BIPM) as the 1 kg absolute standard. Since 1889, this cylinder has served as a reference quantity for every weighing procedure that has been carried out anywhere in the world. Figure 1.5-1 below shows the 1 kg mass standards at the AFPSL. They are calibrated directly by NIST and used to calibrate the AFPSL master 1 kg mass standards used to calibrate the PMEL workload. Mass is measured through a comparison of two approximately equal masses, a standard known mass and an unknown mass, using a balance or comparator.

Figure 1.5-1: AFPSL 1 kg Mass Standards

1.5.2 Definitions

Mass: the quantity of inertia possessed by an object. The SI unit of mass is the kilogram (kg). Because of the relationship between weight and mass, these concepts are frequently confused. One can, in fact, convert exactly between weight and mass on the Earth's surface. The main difference is that if one were to leave the Earth and go to the Moon, one's weight would change but one's mass would remain the same.

Weight: as related to force**,** is defined as the mass of an object times the local gravity.

Local Gravity: is actual value of downward pull of earth's gravitational force at a given location, based on longitude, latitude, and distance from sea level.

Air Buoyancy: is the air's lifting force, which opposes the weight of an object. Air buoyancy reduces the weight of the mass being measured by the amount that equals the weight of the displaced air. This effect is calculated using the air's density and the displaced volume (mass's volume).

Air Density: is the mass of a molecule of air per unit volume.

Density: is mass of any object per unit volume.

True Mass: is the mass of an object if the item could be measured in a vacuum, where the air does not affect the measurement. It is sometimes used in calculations when performing Pressure calibrations due to software requirements, but rarely used in any other application.

Conventional Mass: is the mass of an object if the item could be measured in an environment at standard conditions, i.e., Air density is 1.2 mg/cm^3 and material density is 8.0g/cm^3 at 20 °C. It is commonly used in all other practical applications.

Linearity: measures the ability of an instrument to detect the same small change of mass at different points throughout the balance's measuring range.

Direct Readout: measures the ability of an instrument to detect the actual mass of an object being weighed on the weigh pan.

Readability: of a balance is the smallest difference between two measured values that can be read on the display. With a digital display, this is the smallest numerical increment, also called a scale division or resolution.

Repeatability: is a measure of the ability of an instrument to supply the same result in repetitive weighings using the same load under the same measurement conditions.

Corner Load/Shift Test: is a measure of the ability of an instrument to produce the same result in repetitive weighings using the same load at the center and at each quadrant of the weigh pan.

Balance Drift: is a measure of the balance's drift over time. This affect can be minimized by selecting the proper calibration method.

Temperature Drift: is a measure of the balance's drift over time due to a change in temperature. Electronic balances utilize an internal/external calibration features to minimize this error.

Standard Deviation: is used as a measure of the repeatability and is commonly calculated using 10 weighings.

Standard Weight: is a known mass, which is used to compare to an approximately equal test mass during a typical mass comparison calibration.

Tare Weights: are known masses used in combination with a Standard Weight or Unknown Weight in order to perform a comparison calibration. Tare Weights are frequently referred to as Standard Weights, as they are just smaller than the largest Standard Weight.

Sensitivity Weight: is a known mass used in combination with Standard and Tare Weights in a comparison calibration to ensure the balance is sensitive enough to measure a small difference between the known (Standard and Tare Weights) and unknown (test mass).

1.5.3. Environmental Factors

Shock and Vibration - Typically a balance sits on a heavy table or stand, which is away from the wall to reduce shock or vibrations. The AFPSL Mass Lab incorporates the use of concrete pillars directly supported by the earth's bedrock, and the floor is independent of the pillars as seen in Figure 1.5-2. The balances are placed on top of these pillars surrounded by draft shields to achieve the best measurement possible, as seen in Figure 1.5-3. When both the floor and wall cannot be avoided, ensure that the balance is located on a table that only touches either the floor or the wall - not both, and that the contacted wall or floor is not susceptible to any vibrations.

Figure 1.5-2: AFPSL Mass Lab

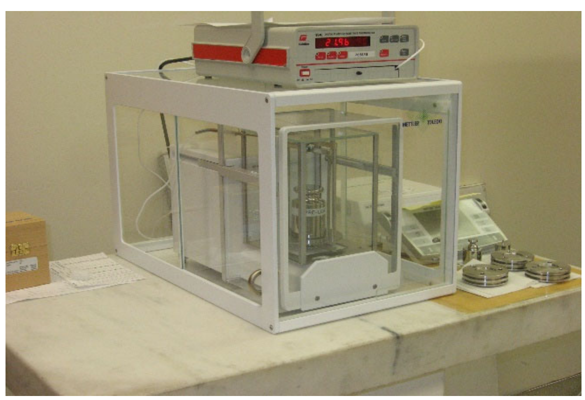


Figure 1.5-3: Balance with Draft Shield and Enclosure

1.5.3.1 Thermal Effects - Ideally, the balance should be placed as to avoid an air current flow. If possible, place the balance away from the door in an area utilizing minimal walking traffic. One must also consider how to shield the measurement area from vents, heat due to lights, windows, radiators, or other heat producing devices, including the balance itself. Usage of a draft shield is recommended, as it helps with any drafts caused by the door opening or a person walking by during a measurement. Sometimes even the weights can be kept in an enclosure for thermal stability as seen in Figure 1.5-4. An ideal room has no windows. Newer balances and comparators are sometimes designed with the weighing chamber separated from the processor in order to ensure the weighing chamber does not continuously heat up during a measurement, which could produce unrepeatable results. Regardless of the type of balance, the balance shall remain connected to the power supply with power on (or on standby) in order to maintain thermal equilibrium. Temperature drift is typically 1-2 ppm/°C. Humidity should be kept between 30 and 60% RH whenever possible. Changes in barometric pressure can cause repeatability issues when measuring mass weights. Sudden changes in the outside atmospheric pressure, like a storm coming in, can impact a measurement. Electrostatic charges are frequently caused by low barometric pressure and humidity <30% RH.

Figure 1.5-4: Mass Standards in an Enclosure

1.5.4. Inspection and Cleaning of Weights

Inspect the mass weights for cleanliness before weighing. Use a brush, air puffer, cotton ball, or a lint free cloth to remove all excess debris from mass standard weights, shown in Figures 1.5-5, 1.5-6, and 1.5-7. Do not use any alcohol, steam, or solvent. If a mass weight is received with oil residue, use ethyl alcohol to remove the residue. Wipe with a lint free cloth or cotton ball. If the alcohol does not remove the residue, contact AFPSL for further cleaning instructions. If a mass standard from the AFPSL is received with residue or with a loose two-piece top, contact the AFPSL for shipping instructions. The mass standard must be returned and recalibrated.

Never open a two-piece weight. If one comes loose or open, let it acclimate for at least 24 hrs. Moisture has likely entered the cavity and outgassing will occur.

After cleaning the weights, they must stabilize for the remainder of the day before making a measurement. This stabilization time will permit the weight to reach an equilibrium temperature and allow for more consistent readings.

Figure 1.5-5: Cleaning the TI Using a Brush

Figure 1.5-6: Cleaning the TI Using an Air Puffer

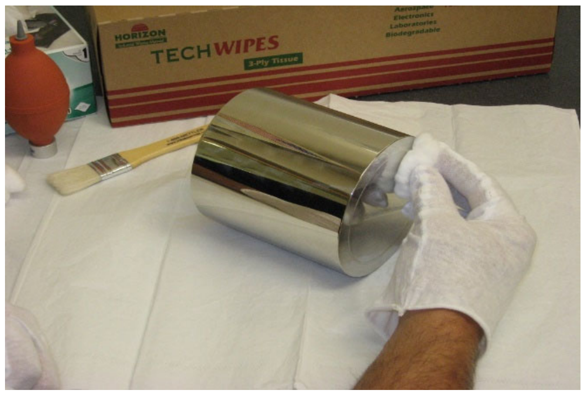


Figure 1.5-7: Cleaning the TI Using a Cotton Ball

1.5.5. Care and Handling

The mass of a standard weight can be affected significantly by the manner in which it is handled. Human contact can leave grease or oily films that affect the mass at the time of measurement and can even cause permanent damage due to corrosion.

1.5.5.1 Always use non-cotton gloves, finger cots, and non-metallic tweezers when handling the weights. Scratches on the bottom of the weight are due to sliding the weight on a surface. Other scratches or dents are from mishandling and hitting other objects, stacking of weights, etc. These scratches will affect the weight of the mass weight. Use extreme care.

1.5.5.2 Small weights should never be touched by hand, but handled using forceps with plastic tips, clean gloves, or swatches of lint free cloth, as in Figure 1.5-8. Larger weights are handled by metal lifting handles, which are covered by leather to protect the mass weights from damage, as in Figure 1.5-9. Large weights are a source of special problems, due to their weight. Depending on the size, these weights may involve the use of a hoist or crane. The technician should be adept in working with this equipment before lifting the mass weights.

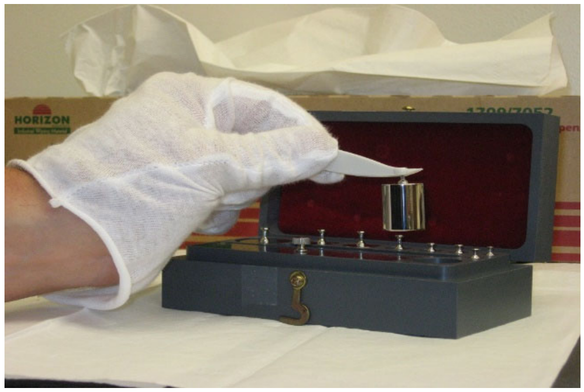


Figure1.5-8: Using forceps to Handle Small Weights

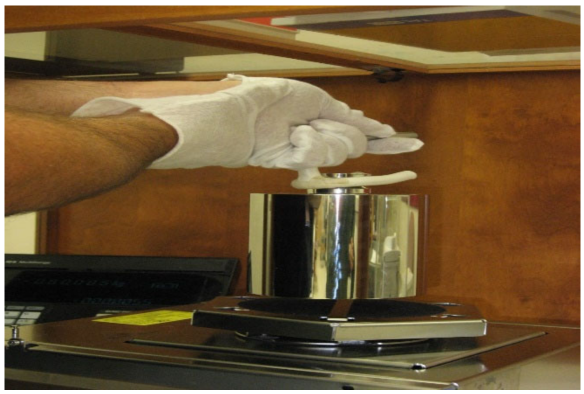


Figure 1.5-9: Leather-wrapped metal handle used to lift large weights

1.5.6. Measuring Techniques Using Various Balances
Balances are high precision instruments and shall be operated carefully. Excessive shock can damage a balance. Careful balance operation will improve the repeatability of measurements.

1.5.6.1 All measurements in a calibration should be performed at the same time interval, and within the shortest time possible. All balances should be exercised before taking readings. A load approximately equal to the load to be measured should be placed on the balance and the pan arrested, if appropriate, or the weight removed from electronic balances. This operation should be repeated multiple times before readings are taken for measurement purposes. Once the balance has been "warmed-up", better repeatability will be achieved. Balances can be very accurate even when used without being exercised first, but improved results can be obtained by going through a "warm-up" procedure. In addition, readings should be taken at the precise moment of achieving balance stability. Stabilization time differs for all balances, even among those of the same type and model.

1.5.6.2 Comparison Weighing - Mechanical Single Pan Balance
Mechanical Single Pan Balances are provided with partial and full release positions. The partial release position is used when determining if an unknown load will provide an on-scale reading. The balance beam has limited movement in this position. The partial release position provides some protection to the balance when the dialed-in weights are not close to the actual mass placed on the pan. It is good practice to arrest the pan each time a dial is being changed to protect the balance from shock loading. It is acceptable to change the dial representing the smallest built-in weights when in the partial release position because the small weight changes should not result in shock loading of the balance.

1.5.6.2.1 When releasing the pan to either the full or partial release position, the action should be done slowly and carefully. The objective is to minimize disturbances to the balance as much as possible. Similarly, all loads should be placed on the balance pan carefully and centered on the pan. When a mechanical balance is released, the beam goes through a series of oscillations. The frequency of these oscillations diminishes as time passes until they are almost imperceptible to the naked eye. At this point, optimal stabilization is achieved. This stabilization of the balance typically lasts for a very short period of time, after which the balance reading will usually drift.

1.5.6.2.2 Comparison weighing eliminates the errors of a mechanical balance's built-in weights, reduces disturbances during the measurement because dial settings are not changed during the measurement, and can cancel the effect of drift by selecting the appropriate weighing design. Therefore, the dial settings must not be changed during a comparison measurement; otherwise, the built-in weights could possibly be part of the measurement, or damage may occur if overloaded.

1.5.6.2.3 When comparison measurements are made on a single pan mechanical balance, all readings are taken from the optical scale. The unknown and the standard must have nearly the same mass so that the difference between them can be measured on the optical scale. Requirements for the maximum difference are mentioned in Section 1.5.7.

1.5.6.2.4 The first readings for the standard and the unknown in a comparison on a single pan balance should fall in the first quarter of the optical scale, but well ahead of zero, so the balance drift will not result in negative values for any readings. Although negative numbers may be used in calculations, they are avoided to simplify calculations and reduce calculation errors. Because the sensitivity weight may have a mass as large as one-half the range of the optical scale and the measured difference between the standard and the unknown may be as large as one-fourth the range of the optical scale, it is necessary to obtain the first two readings in the first quarter of the optical scale so all readings will remain on-scale for the measurement. In this way, it is not necessary to change the dial settings to measure the difference between the standard and the unknown.

1.5.6.3 Comparison Weighing - Electronic Balance
Measurements made on a full electronic balance are simplified because there are no built-in weights to consider. Although many electronic balances are equipped with a built-in calibration weight, the weight is not involved in the comparison weighing.

1.5.6.3.1 The principles for comparison weighing on a full electronic balance are the same as when using a single pan mechanical balance. The balance indications are used to measure the mass difference between the standard and the unknown, and a sensitivity weight is used to establish the mass value for a digital division on the balance. Since there are no built-in weights in the full electronic balance, the entire range of the digital indications can be considered for "optical scale" of the balance.

1.5.6.3.2 For comparison, weighing the standard and the unknown should be "nearly the same mass." Since a full electronic balance has a much larger range for indicating mass values, the masses do not have to be as close together as when a mechanical balance is being used. Requirements for the maximum difference and sensitivity weight are mentioned in Section 1.5-7.

1.5.6.4 Comparison Weighing - Electronic Mass Comparator
Mass Comparators, shown in Figures 1.5-9 and 1.5-10, are typically the most accurate of all balances over a short measuring range. The mass comparator allows only differential weighing whereas analytical balances can typically be used both for comparison weighing as well as for direct weighing. A comparator utilizes a very narrow digital measuring range, providing the best resolution possible when performing a comparison calibration. Requirements for the maximum difference are mentioned in Section 1.5.7.

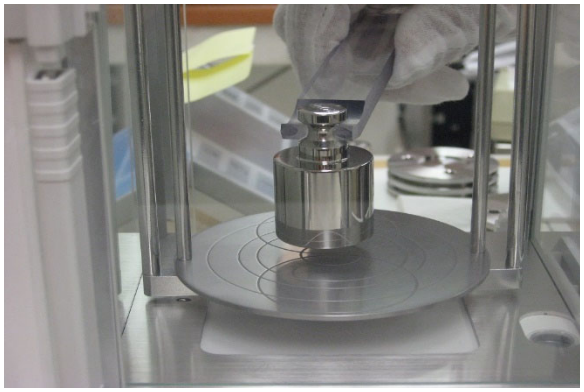


Figure 1.5-10: Place the Weight in the Center of the Mass Comparator

1.5.6.4.1 The major difference between the Mechanical and Electronic Balances/Comparators is that the mechanical balance is reading zero when the item is balanced, and the operator must simply determine the standard masses needed to balance out the unknown mass. This will be used to determine the unknown mass value. In contrast, an electronic balance comparison requires two steps to accomplish the same task as a mechanical balance: (1) the operator must place a standard mass approximately equal to the unknown's mass on the balance and record the reading, and (2) the operator would perform the same function with the unknown mass. These two values would be recorded and subtracted to determine the difference between the known and the unknown masses, thus providing the unknown mass value.

1.5.7. Good Measurement Practices

On Switch - Always leave the balance connected to the power supply and switched on so that a thermal equilibrium can be established in the balance. For most comparators, use only the tare bar to switch the balance off; it is then in standby mode and the electronics are still energized (no warm-up time needed).

Leveling the Balance - The balance is required to be level to function properly. To ensure this, verify the air bubble is in the center of the level and if necessary correct this by turning the leveling feet.

Zero Check - Check that the balance displays exactly zero at the start of the weighing and tare if need be. This avoids zero errors.

Timeliness - Taking the same amount of time to take each reading, but not taking an excessive amount of time, will minimize drift on the display as well as minimize the temperature changes due to body heat. Typically, this is around 10-30 seconds, depending on model and manufacturer.

Balancing Pan - Placing each mass in the center of the balance pan, shown in Figure 1.5-10, ensures that the measurement is not affected by tilting of the pan (introducing a corner load or shift test error). When placing a weight on the balance pan, stabilize the arm using the side of the balance if possible. This reduces the rocking motion of the balance pan when weight is placed in the center.

Cleanliness - Always keep the weighing chamber, balance pan, and weights clean. Any dust, dirt, or fluids in the case can adhere to the weights. Remove any dust with appropriate methods in Section 1.5.4. Keep weights in their case or under a protective covering when not in use. Never etch, scratch, or write on weights for any reason.

Maximum Allowable Difference between TI (X) and Standard Mass (S) - When performing a mass comparison, the difference between the two masses must be minimized and shall meet the following criteria:

Table 1.5-1: Allowable difference TI and Standard

Balance/Comparator Type	TI – Standard (X-S)
Mechanical	1/10 optical scale
Combination	1/10 digital range
Fully Electronic	0.05% capacity
Comparator	1/10 digital range

Proper Selection of Sensitivity Weight - When performing a mass comparison, always use a sensitivity weight, which meets the following criteria:

Table 1.5-2: Sensitivity Weight Selection

Balance/Comparator Type	Sensitivity Weight
Mechanical	≥4 times (X-S); ≤½ optical scale
Combination	≥4 times (X-S); ≤½ digital range
Fully Electronic	≤1% capacity; 2 times the applicable tolerance
Comparator	≥4 times (X-S); ≤½ digital range

1.5.8. Air Density and Buoyancy

Typically, mass calibrations are performed at the current environment's temperature and humidity, both of which affect the air's density. At standard conditions (20 °C and 50% RH) the air density is approximately 1.2 mg/cm^3. This value will change with an environmental change, and it should be accounted for to obtain an accurate measurement.

1.5.8.1 Below is the NIST (simplified) air density formula:

$$\rho_a = [(0.348444 * P) - H*(0.00252T - 0.020582)] / (273.15 + T)$$

Where: ρ_a = Air Density (kg/m^3)
P = Barometric Pressure (mbar)
H = Relative Humidity (% RH)
T = Temperature (°C)

1.5.8.2 Air buoyancy acts in the opposite direction of the mass; that is, air buoyancy is lifting the mass up, while gravity is pulling the mass itself down. This air buoyancy force must be accounted for to perform a high accuracy mass measurement. Air buoyancy is computed as the density of air times the volume of the mass that the air is lifting up. In a mass calibration, the air buoyancy affects both the standard mass and the unknown mass. Below is the equation for determining the correction of both the standard and unknown weights.

$$MABC = N*(\rho_a - \rho_n)*(1/\rho_x - 1/\rho_s)$$

Where: MABC = Air Buoyancy Correction (g)
N = Nominal Mass of weight (g)
ρ_a = Density of air at time of measurement (g/cm^3)
ρ_n = Density of normal air (0.0012 g/cm^3)
ρ_x = Density of unknown weight (g/cm^3)
ρ_s = Density of standard weight (g/cm^3)

8.0(g) - This is the value of the individual weight as if it were calibrated against a stainless steel standard of 8.0 g/cm^3 density. This value is to be used when calibrating balances with internal weights calibrated by the manufacturer using stainless steel standards. Use this value when calibrating a balance that was manufactured after January 1974 or when calibrating other weights and report their value in 8.0 g/cm^3 mass versus stainless steel.

8.4(g) - This is the value of the individual weight as if it were calibrated against a brass standard of 8.4 g/cm^3 density. This value is to be used when calibrating balances with internal weights calibrated by the manufacturer using brass standards. Use this value when calibrating a balance that was manufactured before January 1974 or when calibrating other weights and report their value in 8.4 g/cm^3 mass versus brass.

1.5.8.3 Below is a table containing typical weight materials and densities:

Table 1.5-3: Material Densities

Material	Density at 20 °C (g/cm^3)
American Balance Co. Stainless Steel	7.92
Brass (Normal)	8.3909
Stainless Steel	7.8
Platinum	21.5
Tantalum	16.6
Aluminum	2.7
Nichrome V	8.5
Nichrome	8.39
"Brunton" Metal (Ainsworth Stainless Steel)	7.89
Ainsworth Stainless Steel	7.85
Naval Brass (Ainsworth)	8.4
W. & L. E. Gurley Stainless Steel	7.916
Fisher "Permas" Stainless Steel	7.8
Troemner Stainless Steel	7.84
Voland Stainless Steel	7.8
Mettler Instrument Corp. Stainless Steel	7.76

1.5.9. Factors Affecting Measurement

In order to perform an accurate measurement, one must know what factors affect the mass measurement process. The technician must do their best to minimize controllable factors, and account for those, which are uncontrollable.

Factors one may be able to control or minimize:

a. Room and Bench Vibration effects
b. Room Draft/Airflow effects
c. Room Temperature and Humidity fluctuations
d. Gravity effects (calibrate balance on location)
e. Technician Temperature effects

Factors one must account for in the measurement or uncertainty calculation to produce the best measurement result:

a. Air Density and Air Buoyancy
b. Mass Density of Standard and Unknown Mass
c. Temperature, Humidity, and Barometric Pressure
d. Uncertainties associated with measuring/estimating factors 1, 2 and 3
e. Uncertainty associated with the operator’s process
f. Sensitivity of the balance/comparator
g. Shift Test error of the balance/comparator

1.5.9.1 In the PMEL mass laboratory's current process, the technician is directed to only address factors e and f. The effects of air buoyancy are not yet included in the measurement. However, it is expected that factors a through d will be addressed in a rewrite of the general mass (weight) calibration procedure. Once included in the measurement, the technician will have to measure environmental conditions at time of calibration, estimate the unknown weight's density, and use a spreadsheet to calculate the Conventional mass of the unknown mass.

Situation: The AFPSL has calibrated my 1 kilogram mass. What did they do to determine its True Mass and Conventional Mass, and what should I be doing with it in my PMEL mass calibration?

1.5.9.2 First of all, the AFPSL minimized any errors they could not account for in the uncertainty analysis. This includes all 7 factors mentioned above. They also considered all these factors in their measurement and uncertainty calculation.

1.5.9.3 The AFPSL most likely determined the mass of the unknown at time of calibration using a double substitution method. Then they determined the item's True Mass by removing the density information at time of calibration. They determined the item's Conventional Mass by removing the density information at time of calibration and replacing it with density information under standard conditions.

1.5.10. Troubleshooting

If the balance display is unstable, whether erratic or slowly increasing or decreasing, this is often due to one of the following undesired physical influences:
-Incorrect handling of the mass weight
-Unsuitable location of the balance
-Moisture gain or loss by the mass weight
-Electrostatically charged or magnetized mass weight
-Poor acclimatization of mass weights to the temperature of lab or weighing chamber
-Placing hand in the weighing chamber, causing a temperature increase
-Barometric pressure is changing rapidly causing an unrepeatable indication.

1.5.11. Weight Classifications

The most commonly used weight tolerance classifications are ASTM (Class 0 through 7), NIST (Class F), and OIML (Class E1, E2, F1, F2, M1, M2, and M3).
-ASTM tolerances are established by ASTM (American Society for Testing and Materials) in publication ASTM-E617.
-NIST (Class F) tolerances are established by NIST in publication NIST Handbook 150-1.
-OIML tolerances are established by OIML (International Organization of Legal Metrology) in publication OIML R111.
-Older NIST (NBS classes) are no longer made but specifications can be found in publication NIST NBS Circular 147.

Below is a table, which describes many of the typical classes:

Table 1.5-4: Weight Tolerance Applications

Typical Use	Class
Highest Accuracy Lab Standards (AFPSL)	OIML (E1), ASTM (00)
High Accuracy Lab Standards (PMEL Primary or similar)	OIML (E2), ASTM (0 and 1), NBS (M and S)
Medium Accuracy Lab Standards (PMEL Working or similar)	OIML (F1 and F2), ASTM (2 and 3), NBS (S-1)
Lower Accuracy Standards (PMEL field or User)	OIML (M1, M2, and M3), ASTM (4-7), NBS (P, Q and T), NIST (F)

All major weight manufacturers follow the same tolerances based on the publications listed above and will likely have the specifications listed on their respective websites. Two U.S. manufacturers are Troemner and Rice Lake Weighing Systems.

1.6 PRESSURE

1.6.1. Introduction

Whether it is applied via liquid or gas media, pressure, in its most basic form, can be defined as the amount of force applied per unit area. In the Air Force (AF), it is used for a variety of applications such as determining airspeed, aircraft cabin leakage testing, diagnostics testing on jet engines, and many more applications. In fact, the pressure measurement area is so important to the Air Force mission that all Precision Measurement and Equipment Laboratories (PMELs) retain some of the highest-echelon pressure standards in the world. Thus, a deeper understanding of pressure and its physical principles is vital among Air Force technicians. Basic pressure measurements are performed every day on pressure gauges, whereas more accurate measurements are obtained by pressure transducers and deadweight testers. This handbook is intended to familiarize its readers with various principles, hardware, and general practices in order to equip them with the necessary knowledge to perform quality calibrations. All PMEL calibrations are traceable to the National Institute of Standards and Technology (NIST) through the Air Force Primary Standards Laboratory (AFPSL) exchange standards and base working standards.

1.6.2. Absolute vs Gauge Pressure

Absolute pressure is defined as pressure referenced to an absolute vacuum. Typical units are PSIA, InHgA, Torr, etc. Notice that the suffix "A" is sometimes added to the end of the unit to designate absolute pressure. An example of its usage within the AF is standard atmospheric pressure. AFMETCAL defines standard atmospheric pressure as 14.696 psia. This number is close to atmospheric pressure, and it means that the ambient pressure is considered to be 14.696 psi above absolute vacuum. It is impossible to have a negative absolute pressure, since the lowest pressure attainable, defined as "absolute pressure," is 0.

1.6.2.1 Gauge pressure is defined as pressure reading referenced to ambient pressure. Typical units are PSIG, InHg, Bar, inH_2O, etc. Notice that the suffix "G" is sometimes added to the end of the unit to designate gauge pressure. An example of typical gauge pressure application is the pressure in a tire. Ambient pressure in gauge units is always zero, and this applies to all units.

1.6.3. Hoses and Materials

Some material types for pressure lines include flexible polymers, nylon, rubber, brass, copper, and 316 stainless steel. Each pressure line material has its own purpose or application based upon the user's needs. In general, nylon hoses can be used for low-pressure applications whereas stainless steel can be used for high-pressure applications. Some things to consider when choosing a material to suit the application are:

-Maximum pressure output
-Temperature of fluid media
-Fluid type (pneumatic or hydraulic)
-Corrosiveness/Material Incompatibility

Figure 1.6-1: Nylon Tubing

1.6.3.1 Once the application is known, work with a manufacturer or supplier who can provide further assurance that the purchase can support its intended use. In low pressure applications, the Inner Diameter of the pressure lines will be larger whereas in High Pressure applications, the Inner Diameter of the pressure lines will be small. Keep in mind that just because tubing is flexible does not mean that it is only intended for low pressure applications. Some manufacturers make tubing that is rated for high pressures. Always ensure the tubing is rated for pressures being generating.

1.6.4. Tubing vs Pipe
Tubing can be used for low or high pressure applications. Tubing is different from piping because piping has threads machined into the pipe itself. This makes pipe weaker at the connection due to a thinner wall. Tubing requires a compression fitting, nut and ferrule, weld, or some other external connection.

Figure 1.6-2: Stainless Steel Piping

Figure 1.6-3: Stainless Steel Tubing

1.6.4.1 Another advantage of tubing over piping is that it can be bent to fit certain applications. This means that it can require less fittings, since piping is typically straight. One disadvantage of tubing is that once a ferrule is placed on a tube, the ferrule cannot be taken off and used for a different application since it permanently deforms the tubing.

1.6.5. Pressure Fittings
It is good practice when adapting connections to use fittings of similar materials. A technician should not mix fitting material types. If he were to pressurize a stainless steel line with stainless steel fittings and a brass adapter to 5,000 psi, the brass adapter would catastrophically fail before the pressure even reaches 1,500 psi. The brass adapter is the limiting factor in this example. It is important, in this case, to use stainless steel adapters with stainless steel fittings in order not to limit the capability of the setup.

1.6.5.1 National Pipe Thread (NPT)
The threading diameter is tapered so that a pressure seal can be created with the threads. It can require Teflon® tape to create a better seal. This type of connection is good for low pressure applications.

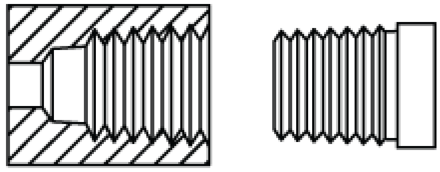


Figure 1.6-4: NPT Connections

1.6.5.2 Nut and Ferrule
This requires proper assembly onto tubing. Depending on materials, it will withstand high pressure and temperature applications. The front and back ferrules are plastically deformed upon assembly of the nut and body. Typically, this connection is assembled by placing the ferrules between the female and male connectors, hand-tightening the connection, and then turning the nut 1¼ times with two wrenches. Excess tubing is then cut off and de-burred before assembly and use.

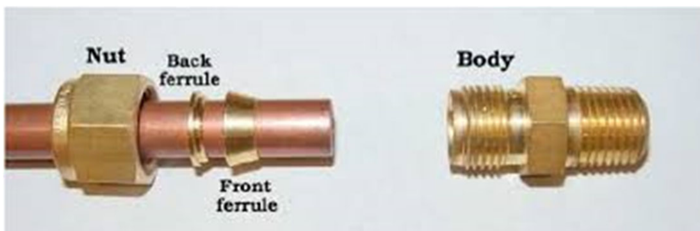


Figure 1.6-5: Nut and Ferrule Connections

1.6.5.3 High Pressure (AN Fitting)
A thick-walled pipe with a small inner-diameter is used for assembly of high pressure face-seal fittings. The pressure sealing surface is illustrated below.

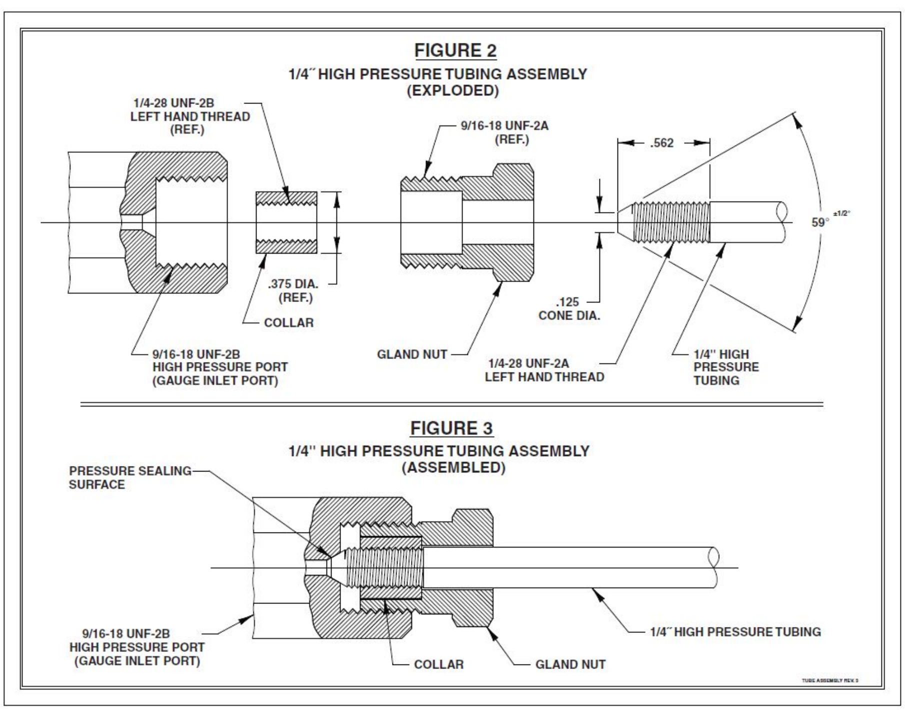


Figure 1.6-6: AN Fitting Connections

1.6.5.4 Sanitary (Clamp and Flange with O-Ring)
Sanitary fittings are typically used with vacuum calibrations.

Figure 1.6-7: Sanitary Connections

1.6.5.5 Quick-Connect
Quick-connect fittings are typically used with pressures around 100 psig or less. They can vary widely in appearance due to the ergonomics engineered into the disconnect mechanism.

Figure 1.6-8: Quick-connect Connections

1.6.5.6 Barbed
This type of connector attaches directly to tubing and is used for low pressure applications. The tube stretches over the barbs and is held by frictional forces.

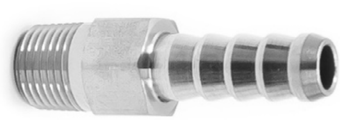


Figure 1.6-9: Barbed Connections

If the proper pressure fitting is selected, the hose/tube should fail before the fitting.

Figure 1.6-10: Tube Failure

1.6.6. Dithering
Dithering is the process of gently tapping on a gauge with a finger or tool in order to release potential frictional forces in the mechanism of a needle-type indicator. Dithering is typically performed on the gauge face by a technician and is performed with care so as to not damage the gauge. A truer indication is obtained by tapping the gauge to release potential friction on a needle-type indicator. ASME B40.100 states: “light tapping of the gauge case is permissible at each pressure reading.” It also states that for Grade 4A (0.1%FS) gauges: “Grade 4A gauges must remain within specified tolerance before and after being lightly tapped.”

1.6.7. Head Height
Pressure standards can indicate readings in different ways and using different mechanisms, but pressure devices will always have a “reference line.” The reference line is the altitude or height to which the reading of a pressure device is referenced. It can be invisible, it can be at the center of a dial face, or it can be an actual line drawn on the standard or Test Instrument (TI). It might also be visible on some digital screens. (Contact the OEM if unsure of the location of the reference line.)

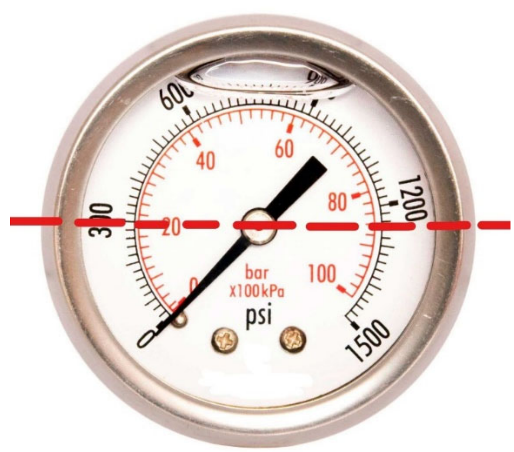


Figure 1.6-11: Dial Gauge Head Height Location

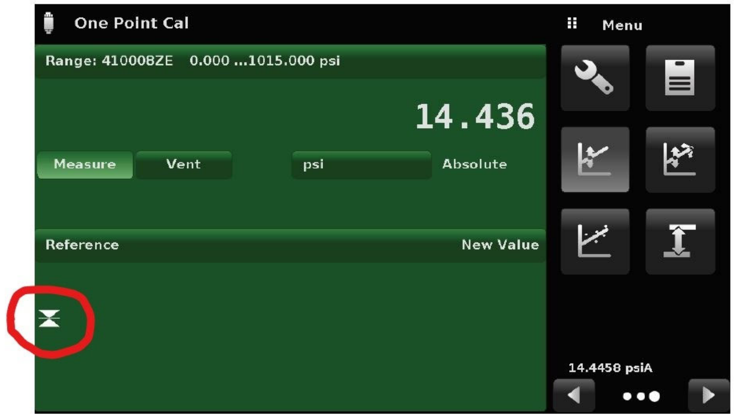


Figure 1.6-12: Digital Screen Head Height Location

1.6.7.1 When a TI is being calibrated, its reference line must be at the same level as the standard's reference line, or else a head height correction must be applied. Head height is the vertical distance between the reference line of the standard and TI.

1.6.7.2 Some standards have a built-in head height function. When this is the case, the technician will input a distance (typically in inches) that is equivalent to the vertical height difference between the standard and TI reference lines. AF convention is to apply the correction to the standard readings rather than the TI readings, if possible. In this case, the head height function could ask for what type of pressure media is being used in the calibration as head height correction varies with density.

1.6.7.3 Most AF pressure standards adhere to the following convention: If the TI's reference line is above the standard's reference line, the height entered into the head height correction will be positive. If the TI is below the standard, the head height correction will be negative.

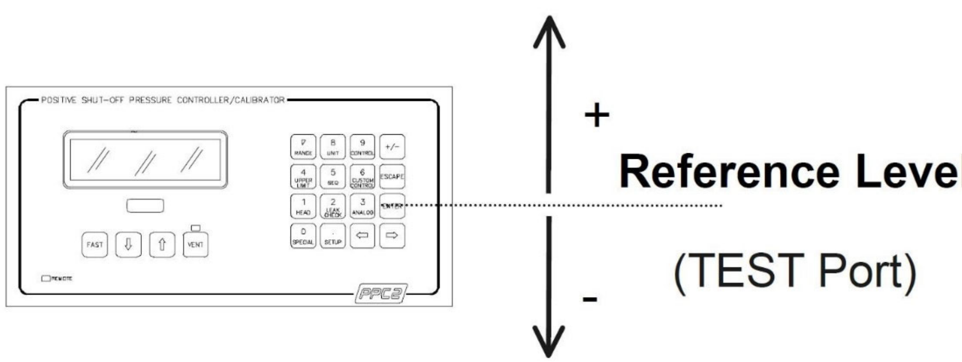


Figure 1.6-13: Head Height Correction Convention

1.6.7.4 Here is a real life exercise of how head height can affect readings. Take a barometer, put it in a low place or at floor-level, and observe the reading. Next, slowly raise the barometer until it is at head-level and observe the reading. There will be a difference in pressure from floor-level to head-level. When moving up in altitude, ambient pressure decreases. This is due to the pressure of air molecules built up in the atmosphere. To further illustrate this principle, imagine swimming in a pool. As you swim to the bottom, you can feel pressure build in your ears and sinuses because of the pressure due to all of the water that is "pressing down" on you. As you swim to the bottom, there are more molecules stacked on each other above you, thus pressure increases. As you swim back up, this pressure is relieved.

1.6.8. Pneumatic vs Hydraulic
The difference between pneumatic and hydraulic pressure is simple: “pneumatic” refers to a gaseous medium and “hydraulic” refers to a liquid medium. Typically, hydraulic pressure calibrations generate higher pressures than pneumatic pressure calibrations. One example within the AF inventory is the Fluke PG7601 Pneumatic Primary Pressure Standard (0-1000 psi) versus the Fluke PG7302 Hydraulic Primary Pressure Standard (0-30000 psi).

1.6.8.1 Technicians should not cross-contaminate pneumatic standards with hydraulic TI’s or vice versa. Otherwise, it could result in destruction of standards. Some pneumatic standards have oil traps built into the plumbing to capture some oil particles; however, they are not to be considered a failsafe for capturing excess hydraulic oil. It is always a good idea to clean out a hydraulic TI before attempting to calibrate it in a pneumatic system whether there is an oil trap or not. An exception to this rule is oxygen-clean devices, which should never be exposed to hydraulic fluid.

1.6.8.2 Some standards have a hydraulic/pneumatic separator. A common use for this item is for high pneumatic pressure calibrations where a pneumatic standard cannot generate enough pressure. In this case, a hydraulic standard would be used to calibrate a pneumatic TI with a separator placed in-between. Hydraulic pressure is delivered on one side of the separator and an equal amount of pneumatic pressure is delivered on the other side of the separator.

1.6.9. Operation Principles

1.6.9.1 Bourdon Tube

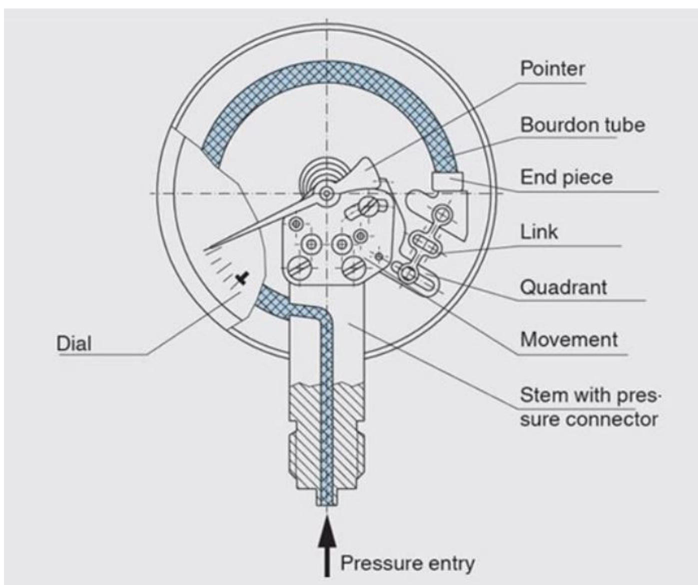


Figure 1.6-14: Bourdon Tube

1.6.9.1.1 Analog pressure gauges are typically operated by the principle of a Bourdon tube. A Bourdon tube is a sealed tube with an oval-shaped cross-section. For low pressure applications, the tube is bent into a “C” shape. Once this tube is pressurized, the oval cross-section expands to become more like a circle, which makes the tube want to straighten out. As a result, the diameter of the C-shape increases. This is a very slight movement as the far end of the tube moves only millimeters. This movement is harnessed and transferred into the circular motion of a needle pointer by way of gears attached to the pointer and Bourdon tube. The pointer position is superimposed upon the hash marks of a dial face, which can then be read by a technician. Because of the mechanical movement of the Bourdon tube and gears, it is important to check zero prior to using this type of standard. Bourdon tubes can be in the shape of a spiral or a helix in addition to the C-shape. Dithering is used for most analog pressure gauges.

1.6.9.2 Transducers (Absolute Pressure, Gauge Pressure, & Differential Pressure)
These three transducer types are different, but they have a similar operation principle. It all depends what the reference pressure is. For the sake of illustration, imagine there is one chamber with a sensing diaphragm separating it into two sections. Fluid cannot leak between the two sections.

1.6.9.2.1 The first illustration represents absolute pressure:

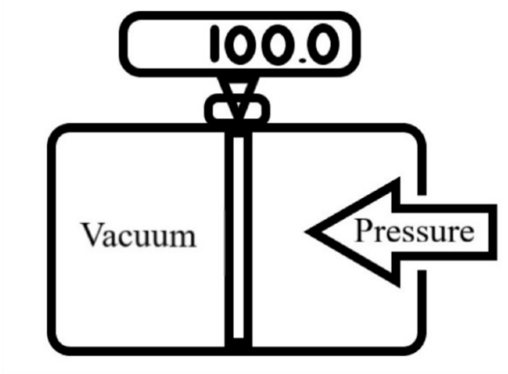


Figure 1.6-15: Absolute Pressure Transducer

1.6.9.2.2 The section on the left is referenced to vacuum, or 0 psia. The diaphragm is exposed to pressure from the section on the right. Absolute pressure is the difference between the incoming pressure on the right and vacuum pressure. Ideally, the reference will always have a value of 0 psia, but in the real world, the reference will drift slightly above zero since absolute vacuum cannot be achieved. Absolute pressure can never be negative.

1.6.9.2.3 The second illustration represents gauge pressure:

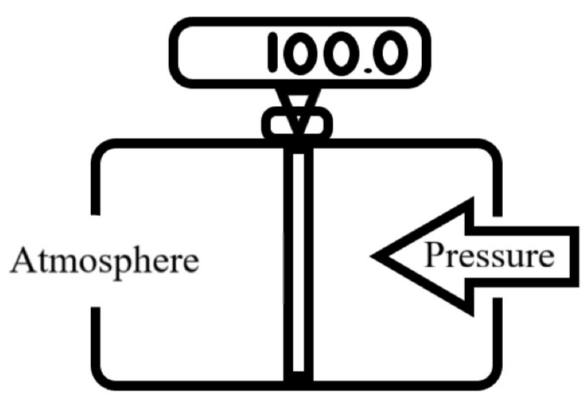


Figure 1.6-16: Gauge Pressure Transducer

1.6.9.2.4 With a gauge transducer, the pressure readout is referenced to atmospheric pressure. The reading on the indicator is the difference between incoming pressure and atmospheric pressure. Atmospheric pressure is semi-stable, but it can change due to weather or even opening/closing the laboratory door. The pressure readout is only positive if the applied pressure is greater than atmospheric pressure.

1.6.9.2.5 The third illustration represents differential pressure:

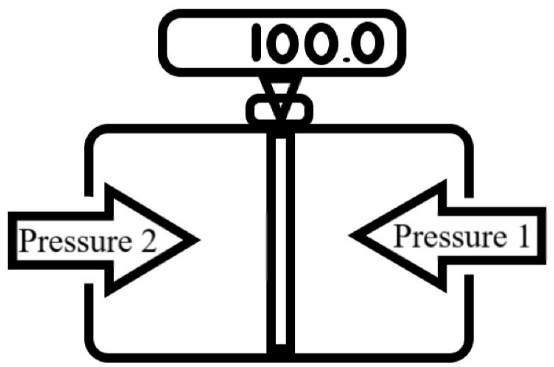


Figure 1.6-17: Differential Pressure Transducer

1.6.9.2.6 Differential pressure is the difference between Pressure 1 and Pressure 2. Unlike an absolute pressure transducer, the reference pressure can be varied greatly. Differential pressure is typically used for low pressure differences. This is not to be confused with a low pressure calibration. One example would be comparing two 1000 psi line pressures. While the difference between the two line pressures are small, the overall pressure is quite large.

1.6.9.3 Piston Gauges

The primary pressure standard, sometimes referred to as piston gauges or deadweight testers, operate on the basic equation of:

$$F = P * A$$

Where: F = force
P = pressure
A = area

Force can be further broken down into:

$$F = M * g$$

Where M = mass
g = local gravity

Thus,

$$M * g = P * A$$

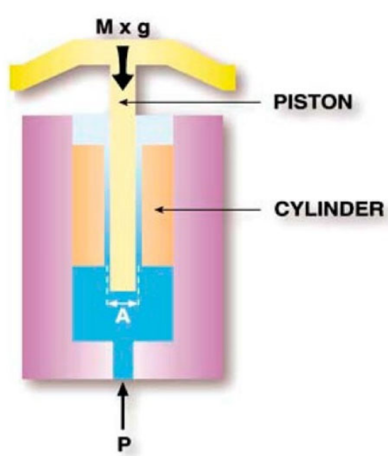


Figure 1.6-18: Piston Gauge

1.6.9.3.1 Pistons and cylinders are machined to very precise tolerances, allowing minimal leakage to pass between them. Calibrated masses are placed on top of the piston and pressure is generated below the piston pushing it up. When the pressure below the piston is equal to the pressure being generated from the top of the piston with the masses, the piston will “float”. Two factors determine pressure stability: centered (stable piston position or float position) and the piston spinning freely within the cylinder. A technician can tell when a certain pressure is achieved by the device when the float position of the piston is close to center on a vertical axis and not drifting much up or down. The piston must be spinning within the cylinder because it indicates a proper lack of friction force between the piston and cylinder walls. Piston gauges can be more precise than other types of standards, but they can vary in accuracy based on quality of manufacturing of both the piston-cylinder assembly and the masses used to generate pressure. For this reason, the types of TMDE it can calibrate may vary.

1.6.10 Calibrate It Like It’s Used
The principle of “Calibrate it like it’s used” is one that spans all areas of PMEL. If a pressure gauge requires adherence to oxygen-clean directives during field use, it only makes sense that a technician would take measures to ensure that the gauge is calibrated with the same directives in mind. Thus, it is the duty of every PMEL technician to calibrate a TI in a manner that resembles its usage, wherever possible and within reason. Referring back to the oxygen-clean gauge, it is not within reason for the PMEL to utilize oxygen to calibrate oxygen-clean instruments as it presents hazards to the technician as well as the physical PMEL. However, T.O. 15X-1-102 provides a suitable calibration gas alternative (Nitrogen gas, MIL-P-27401, TYPE I) for oxygen-clean TMDE calibration. Any corrections or considerations shall be taken into account while using a different calibration gas than what is used during the user’s process.

1.6.10.1 Some pressure sensors are density sensitive. These types of sensors will read different depending on the type of gas they are calibrated against (typically air or nitrogen). It is important to use the same media as the user or correct for the different densities of the gas being used.

In addition to cleanliness and pressure media, another factor that is at play during pressure calibrations is TI orientation. Some pressure gauges have rear mounts whereas others have mounts at the bottom of the dial. A rear-mounted pressure gauge is sometimes required to be calibrated with the face visible from a horizontal line of view, which means that proper orientation must be accomplished by the technician during calibration. Everything from bourdon-tube pressure gauges to pressure transducers should be checked for proper orientation before calibration, or else calibration may result in erroneous readings.

1.6.11 Safety Shields
Safety shields, although not always required, are recommended. Injuries have happened in the past from TIs experiencing total failure or accidental overpressure. When it comes to safety, a conservative attitude is usually the best policy. Always refer to applicable AF safety directives before starting a calibration.

Figure 1.6-19: Safety Shield

1.6.11.1 The pressure measurement area involves the use of both hydraulic and pneumatic standards. However, pneumatic pressure is considered more dangerous due to the higher compressibility of gases. A much greater amount of volume is compressed in order to generate pneumatic pressure. The incompressibility of hydraulic pressure makes it so failures do not release much material. This makes hydraulic pressure less dangerous, even though it can generate higher pressures.

1.6.12 Pressure vs Air Data
The pressure measurement area is very similar to Air Data, but there are a few differentiating factors: time, range, and units.

1.6.12.1 The Air Data measurement area is a very practical application of pressure since it focuses on the aircraft. One of the differentiating factors is time. A rate of climb measurement is a pressure divided by a time. Thus, pressure is not the only thing that goes into Air Data.

Figure 1.6-20: Aircraft dependent on Air Data

1.6.12.2 The second differentiating factor is range. The pressure an aircraft can experience only goes so high or so low. Aircraft are not subjected to aerodynamic forces of 1,000 psi. It is much lower, in fact. Aircraft use differential and absolute pressures to determine rate of climb, airspeed, and altitude. All of these measurements fall within a specific range (0-32 inHg), which is well within the capability of PMEL calibration.

1.6.12.3 The third differentiating factor is the units that are used. Sometimes, TIs will display an altitude rather than a common unit, such as inHg. The altitude will be based upon standard conditions and baseline pressures in some pressure unit. Internal firmware or software of a TI will register a baseline pressure, perform conversions, and then display a reading in units of feet above sea-level. for example, P/N: TTU-205 Air Data Test Set can calibrate altitude ranges from 0 to 80000 feet and airspeed ranges from 50 to 1000 knots. Both ranges are units of Air Data that are related to pressure.

1.6.13. How Temperature and Pressure are Related
In this section, it will help to make some assumptions using the perfect gas law. This equation states:

$$PV = nRT$$

Where: P = Pressure
V = Volume
n = Number of moles
R = Ideal gas constant
T = Temperature

1.6.13.1 This equation assumes that no inside, outside, or molecular forces will influence the predicted behavior of the gas in a system. Let us apply this equation to a scenario with a bottle of gaseous nitrogen under a pressure of 1000 psi at 70 °F.

1.6.13.2 Say that a technician decides to use this bottle as a gas flow source. The technician has brought his gas flow test setup into the lab and let it acclimate to ambient temperature for 24 hours. The technician then flows the nitrogen through his standards and notices that the temperature reading on his laminar flow elements are starting to decrease. Why? This is because as the pressure in the bottle decreases, the temperature of the gas goes down. Take a look at the ideal gas equation:

$$PV = nRT$$

1.6.13.3 The terms *R* and *V* are all constant in this scenario. As pressure decreases while gas is flowing out of the nitrogen bottle, the *n* and *T* terms both decrease as they are proportional to pressure changes within the bottle. Thus, as the gas cools down within the bottle, it is then flowed out and the temperature change can be observed by temperature probes in the standard.

1.6.13.4 On the other hand, as pressure increases, temperature increases. This can be seen in the operating principle of a diesel engine. As a diesel engine goes through a stroke and compresses the air, the fuel ignites almost immediately upon injection because once air is compressed, it increases in temperature to the flash point of the fuel. In AF applications, the temperature difference in piston gauges can affect both the diameter of the piston as well as the density of the gas media. These changes must be accounted for to obtain the necessarily low uncertainties associated with these standards.

1.6.14. Purpose Behind Added Volume

For low pressure applications, it is typical to add extra volume via added plenum chamber. The purpose behind adding an extra volume to a system is to increase stability. By placing a volume between the standard and the TI, it creates a larger space for gases to vent and come to a state of equilibrium.

1.6.14.1 Here is an example on a much larger scale: Take a box fan, for instance. If a box fan is ran on a high setting in one corner of a living room, a person sitting in that same room on the opposite side will probably feel a breeze. Take that same box fan and run it at the same setting at one end of a warehouse. A person standing on the other side of that warehouse will probably not feel much of a breeze, if at all. Now, translating that to an AF system, consider the PPC3. The low pressure standard comes with a Dual Volume Unit (DVU), which is connected between the standard transducer of the PPC3 and the TI. Alternately, if a DVU was not available, a normal pressure line would be used. The DVU would be the warehouse in this scenario, while a normal pressure line would be the living room. The breeze from the box fan stands for slight fluctuations in pressure. Using the DVU or a similar added volume reduces the effects of pressure fluctuations felt by the TI transducer.

1.6.14.2 The reason an added volume works is because the volume of gas being forced into the system is small compared to the total system volume. In addition, any pressure induced by the momentum of the gas is mitigated and resolved before it reaches the TI. Think of it like a tennis ball dropped in water. If a tennis ball is dropped in the middle of a lake versus a bowl of water, the waves would be of much less magnitude by the time they travel to the edge of the lake rather than in a bowl.

1.7 GAS FLOW

1.7.1 Introduction

Flowmeters are commonly used to measure the mass flow rate of a process (e.g. leak rates, mixing processes, combustion, etc.), not the volumetric flow rate. However, when we talk about flow, it is much easier to understand and visualize a measurement like liters/minute rather than a measurement such as kilograms/second. Over time, the notion of describing flow rate in terms of "volumetric" units has become typical.

1.7.1.1 Since there are two measurements of gas flow: mass and volume flow rates, why then do we have three different measures of flow rate: mass flow, actual (or volume) flow, and standard flow? The answer is that in reality, mass flow and standard flow are both mass flows.

1.7.1.2 Before we clarify the differences between mass flow, actual flow, and standard flow, we want to first discuss some flow background. This (unfortunately) requires discussion of gas state. For this, we turn to Boyle's Law, Charles' Law, and ultimately the Ideal Gas Law.

1.7.2 Boyle's Law
Boyle's Law: given a fixed mass of gas and holding temperature constant, the change in absolute pressure is inversely proportional to the change in volume.

1.7.2.1 This is stated as:

$$P \cdot V = k$$

Where k = constant amount of gas
V = Volume
P = Pressure

1.7.2.2 Volume can then be said to be inversely proportional to pressure:

$$V = \frac{k}{P}$$

Where V = Volume
k = constant amount of gas
P = Pressure

1.7.2.3 Knowing that mass does not change from one state to the next, we can say that:

$$P_1 \cdot V_1 = P_2 \cdot V_2$$

1.7.2.4 Rearranged, we can observe what happens to the volume as the other conditions change:

$$V_2 = V_1 \cdot \frac{P_1}{P_2}$$

1.7.2.5 An animation of Boyle's law can be seen at NASA Glenn's website: http://www.grc.nasa.gov/WWW/K-12/airplane/Animation/gaslab/chprmt.html

1.7.2.6 This concept is especially important to understanding standard flow. Therefore, here are some "balloons" that aim to solidify this concept. Note that in both balloons, the mass does not change, despite the change in pressure. Mass can neither be created nor destroyed-which we will get to later.

P1 = 300 kPa Pressure = 125 kPa

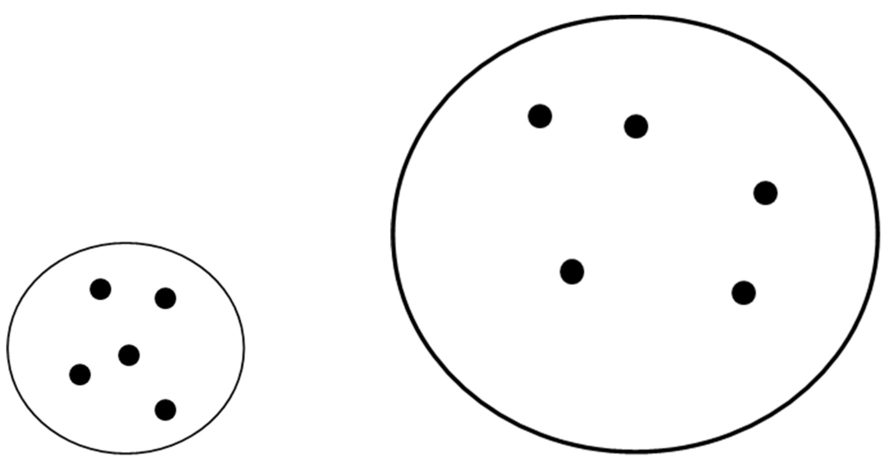


Figure 1.7-1: Mass Pressure Relation

1.7.3 Charles' Law
Charles' Law: given a fixed mass of gas and holding pressure constant, the change in absolute temperature is proportional to the change in volume.

1.7.3.1 This is stated as:

$$\frac{V}{T} = k$$

Where: k = constant amount of gas
V = Volume
T = Absolute Temperature

1.7.3.2 Volume can then be said to be directly proportional to temperature.

1.7.3.3 Knowing that mass does not change from one state to the next, we can say that:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

1.7.3.4 Rearranged, we can observe what happens to the volume as the other conditions change:

$$V_2 = V_1 \cdot \frac{T_2}{T_1}$$

1.7.3.5 An animation of Charles' law can be seen at NASA Glenn's website: http://www.grc.nasa.gov/WWW/K-12/airplane/aglussac.html

1.7.3.6 This concept is also important to understanding standard flow. Therefore, here are our balloons again to drive home the point. Note that in both balloons, the mass does not change, despite the change in temperature. Mass can neither be created nor destroyed.

T_1 = 21.1 °C (294.25 K)
(273.15 + 21.1 °C = 294.25 K)

T_2 = 0 °C (273.15 K)

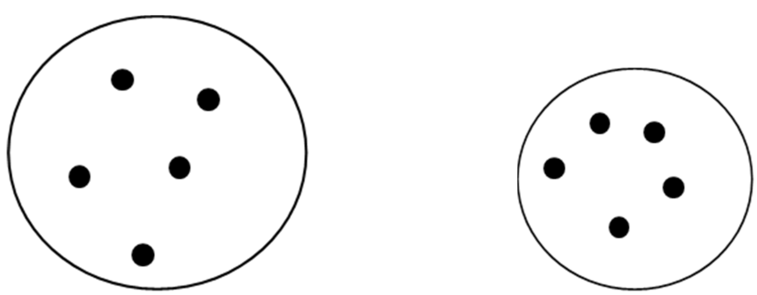


Figure 1.7-2: Mass Temperature Relation

1.7.3.7 Notice two things here: 1) a large change in temperature, 21.1 °C, has a small impact on volume, this is because temperatures are expressed in absolute terms, and 2) 21.1 °C (70 °F) and 0 °C are the most common temperatures used for standard flow reference temperature.

1.7.4 Ideal Gas Law
The Ideal Gas Law allows us to observe the interaction between the different components, which define a gas' state. It serves as the foundation upon which we can derive and understand flow rate.

1.7.4.1 Combining Boyle's and Charles' laws, we can define the state of a gas, given pressure, temperature, and volume. Based on the balloon example, as a variable(s) change in the second state, the remaining variable(s) must adjust accordingly since there is no change in mass.

$$\frac{P_1 \cdot V_1}{T_1} = \frac{P_2 \cdot V_2}{T_2}$$

1.7.4.2 Recalling the balloon experiment, we blow up the balloon and as a result there is a fixed amount of mass in the balloon. We know that no matter what happens to P, V, or T, the mass in that balloon cannot change. Therefore, we can relate the mass state of the balloon to its P, V, and T state:

$$\frac{P \cdot V}{T} = n \cdot Z \cdot R_u$$

Where: n = number of moles (mass of gas equal to its molecular weight), mol
Z = Gas compressibility factor, unitless
R_u = universal gas constant, $\frac{J}{mol \cdot K} = \frac{N \cdot m}{mol \cdot K}$

1.7.4.3 Rearranged:

$$P \cdot V = n \cdot Z \cdot R_u \cdot T$$

1.7.4.4 This is <u>Real</u> Gas Law. The difference between the real gas law and ideal gas law is Z, gas compressibility factor. For common applications, Z is close to 1.0 and is therefore set to 1.0, resulting in ideal gas law:

$$P \cdot V = n \cdot R_u \cdot T$$

1.7.4.5 Knowing the state of a gas from the ideal gas law, we can then determine the gas' density as follows:

$$n = \frac{m}{M_w}$$

Where: n = Gas density
m = Mass of gas, kg
M_w = Molecular weight of gas, g/mol

1.7.4.6 The equation then becomes:

$$P \cdot V = \frac{m}{M_w} \cdot R_u \cdot T$$

1.7.4.7 This can be rewritten to reduce the universal gas constant to a *specific* gas constant. In the context of gas flow calibration, the gas does not change during the calibration, so this is a reasonable approach and it cleans up the equation a bit. The specific gas constant, R, is R_u divided by the molecular weight of the gas, M_w of interest (i.e. R = R_u/M_w). Therefore, the equation can be rewritten as:

$$P \cdot V = m \cdot R \cdot T$$

Where: R = specific gas constant, $\frac{N \cdot m}{g \cdot K}$

1.7.4.8 Rearranged for density:

$$\frac{m}{V} = \frac{P}{R \cdot T}$$

$$\rho = \frac{P}{R \cdot T}$$

1.7.5 Mass Flow
Understanding the ideal gas law gives us a good foundation for understanding gas flow. Another powerful law in understanding mass flow, actual flow and ultimately standard flow is conservation of mass - specifically for a control volume under steady state conditions. First, let us define the law of conservation of mass.
1.7.5.1 The law of conservation of mass states that matter can neither be created nor destroyed. For steady state flow, the rate at which mass enters a control volume (a system) must equal the rate at which mass exists the control volume. Mass flow in must equal mass flow out.

1.7.5.2 Steady state? Let us address this also. Steady state is a concept that we strive for when we are calibrating gas flowmeters; it says that over a period of time a fluid's state (defined by its properties) does not change. When we calibrate a flowmeter, we allow plenty of stabilization time so that the gas properties stabilize. With this, we have conservation of mass: the mass into a system must equal the mass out of a system.

1.7.5.3 For clarity, we derive and explain conservation of mass.

1.7.5.4 For a system (referred to as a control volume), we can state that the initial mass in the control volume at time, t = 0, plus the mass which has moved through the control volume inlet, must be equal to the final mass in the control volume at the final time, t = n, plus the mass which has moved through the control volume exit. This is stated as:

$$m_{CVi} + m_{in} = m_{CVf} + m_{out}$$

1.7.5.5 Recall that:

$$P \cdot V = m \cdot R \cdot T$$

1.7.5.6 And therefore:

$$m = \frac{P \cdot V}{R \cdot T}$$

1.7.5.7 Conservation of mass can be restated as follows using our ideal gas law relationship

$$\left(\frac{P \cdot V}{R \cdot T}\right)_{CVi} + \left(\frac{P \cdot V}{R \cdot T}\right)_{in} = \left(\frac{P \cdot V}{R \cdot T}\right)_{CVf} + \left(\frac{P \cdot V}{R \cdot T}\right)_{out}$$

1.7.5.8 This allows us to quantify the mass state for each of the four terms based on the values of P, V, R, and T.

1.7.5.9 What happens if steady state is achieved? In other words, what happens if the fluid state - as defined by its properties - does not change over a sample time? This can be show graphically.

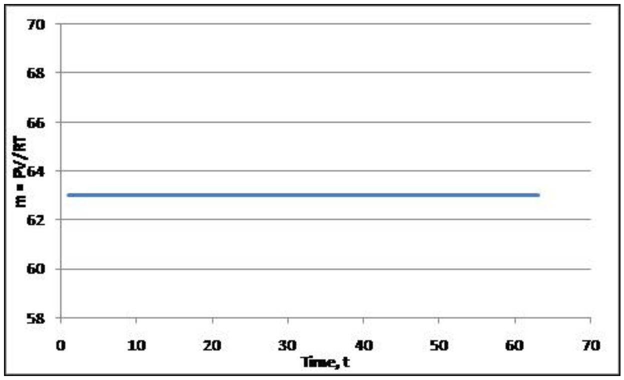


Figure 1.7-3: Steady State over Time

1.7.5.10 The line is flat; therefore, the slope is zero, there is no net gain or loss in mass in the control volume over a time period. Therefore, the "CV" terms are equal and drop out.

$$\cancel{\left(\frac{P \cdot V}{R \cdot T}\right)_{CVi}} + \left(\frac{P \cdot V}{R \cdot T}\right)_{in} = \cancel{\left(\frac{P \cdot V}{R \cdot T}\right)_{CVf}} + \left(\frac{P \cdot V}{R \cdot T}\right)_{out}$$

$$\left(\frac{P \cdot V}{R \cdot T}\right)_{in} = \left(\frac{P \cdot V}{R \cdot T}\right)_{out}$$

1.7.5.11 Therefore, back to mass:

$$m_{in} = m_{out}$$

1.7.5.12 But where does mass *flow* come from…the above equation is for mass. We can develop this relationship going back to the ideal gas law:

$$m = \frac{P \cdot V}{R \cdot T}$$

1.7.5.13 This relates mass to P, V, R, and T; however, we can also use this expression to understand change in mass over a change in time:

$$\dot{m} = \frac{P \cdot \dot{V}}{R \cdot T}$$

1.7.5.14 The "dot" above the mass and volume variables is the indication that the variable is considered with respect to time. Therefore, $\dot{m}$ means the change in mass over a change in time and $\dot{V}$ means the change in volume over a change in time - or volumetric flow.

$$\dot{m} = \frac{\Delta m}{\Delta t}$$

$$\dot{V} = \frac{\Delta V}{\Delta t}$$

$\dot{V}$ is commonly referred to as Q, so we can say:

$$\dot{m} = \frac{P}{R \cdot T} \cdot Q$$

1.7.5.15 Recall when we solved for density above? That formula, $\rho = \frac{P}{R \cdot T}$, appears before Q. Substituting density into the above equation reveals the fundamental mass flow equation:

$$\dot{m} = \rho \cdot Q$$

1.7.5.16 Conservation of mass can now be expressed in terms of mass flow:

$$\dot{m}_{in} = \dot{m}_{out}$$

Or

$$(\rho \cdot Q)_{in} = (\rho \cdot Q)_{out}$$

Or

$$\left(\frac{P}{R \cdot T} \cdot Q\right)_{in} = \left(\frac{P}{R \cdot T} \cdot Q\right)_{out}$$

1.7.5.17 These are extremely important relationships in gas flow.

1.7.6 Actual Flow

1.7.6.1 We just indicated that:

$$\dot{m} = \rho \cdot Q$$

Where: ρ = density
Q = volumetric flow rate

1.7.6.2 Volumetric flow rate (or actual flow rate) is qualitatively expressed as the change in volume over a change in time. This can be broken down further based on flow through a pipe, duct, etc. Volumetric flow rate can be defined as the product of a cross sectional area and the velocity of the gas which passes across that area.

$$Q = v \cdot A$$

Where: v = gas velocity
A = cross sectional area

$$\dot{m} = \rho \cdot Q$$

Or

$$\dot{m} = \rho \cdot v \cdot A$$

1.7.6.3 Given conservation of mass again, we can say:

$$\dot{m}_{in} = \dot{m}_{out} \text{ or } \rho_{\text{in}} \cdot v_{in} \cdot A_{in} = \rho_{\text{out}} \cdot v_{out} \cdot A_{out}$$

1.7.6.4 Conservation of mass is powerful, and we can study the effects of changing pressure, temperature, and volume on flow through a system under its control.

1.7.6.5 We know that $\rho_{\text{in}} \cdot Q_{in} = \rho_{\text{out}} \cdot Q_{out}$, so let us explore the interaction between the “in” state and the “out” state.

1.7.7 Standard Flow

Have you ever heard that standard flow is mass flow? How can that be since the units of standard flow are expressed in volume terms such as liters, cubic feet, cubic centimeters, etc.? Hopefully, this section will make it clear why standard flow is referred to as a mass flow.

1.7.7.1 Now that we understand mass flow and actual flow, what then is standard flow? This concept can be best understood speaking in terms of mass and volume rather mass flow rate and volume flow rate. Once understood, the concept is easily transferred to the flow rate realm.

1.7.7.2 Standard volume can be defined as the volume required to contain an amount of mass at a defined fluid state (a function of its properties).

1.7.7.3 To help, let us step through where the equation for standard volume (and standard flow in turn) comes from.

1.7.7.4 Remember from above when we stated this mass flow relationship:

$$\dot{m} = \rho \cdot Q$$

1.7.7.5 We can restate this in terms of mass and volume rather than mass flow and volume flow:

$$m = \rho \cdot V$$

1.7.7.6 From conservation of mass, we can say:

$$\rho_{\text{in}} \cdot V_{in} = \rho_{\text{out}} \cdot V_{out}$$

(Remembering unit analysis, we can quickly see that this is an equation for mass: kg/~~m^3~~·~~m^3~~ = kg).

1.7.7.7 This is based on conservation of mass: the density multiplied by the volume at one position must equal the density multiplied by the volume at another position. This equation does not need to be exclusively for an “in” and “out” analysis.

1.7.7.8 Therefore, we can simply restate the equation as follows:

$$\rho_1 \cdot V_1 = \rho_2 \cdot V_2$$

Where: V_1 = actual volume at condition 1
V_2 = actual volume at condition 2

1.7.7.9 Therefore, if we know an actual volume at condition 1 but want to convert it to actual volume at condition 2, the following equation can be used:

$$V_2 = V_1 \cdot \frac{\rho_1}{\rho_2}$$

Or

$$V_2 = V_1 \cdot \frac{P_1}{P_2} \cdot \frac{T_2}{T_1}$$

1.7.7.10 Note the best way to make this calculation is to truly determine the density of the gas under each of the actual conditions rather than using density ratio estimates based on pressure divided by temperature. The above equation is really using ratios of one density to another where the specific gas constant, Z, has been cancelled out, but this approach assumes an ideal gas and therefore assumes that compressibility is equal to 1.0. Gas compressibility is a function of pressure and temperature; therefore, the difference between P_1, T_1, and P_2, T_2 will result in a different compressibility and therefore a different density between the density at actual conditions and at standard conditions.

1.7.7.11 The reason we can use this approximation though is that the difference in density as a result of the difference in gas compressibility is nearly always insignificant. Most flow standards, including the molbox1-AF, always determine density based on the full equation for density when making calculations.

1.7.7.12 For reference:

When TEMPERATURE INCREASES, actual flow rate increases (as a result of increased velocity) in order to pass the same amount of mass over the same period of time.

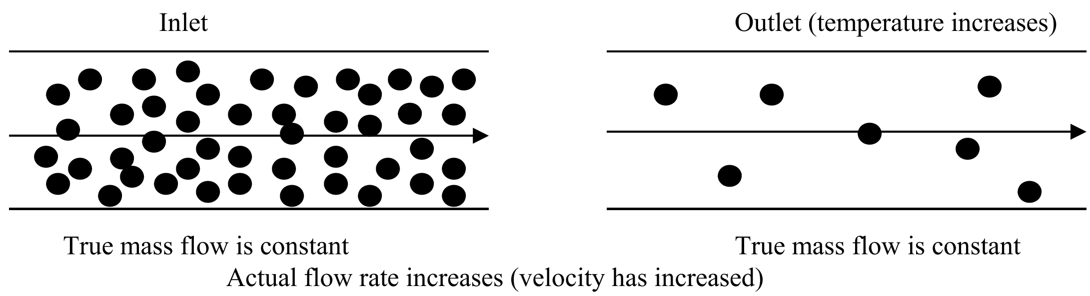


Figure 1.7-4: Temperature Flow Rate Comparison

When PRESSURE DECREASES, actual flow rate increases (as a result of increased velocity) in order to pass the same amount of mass over the same period.

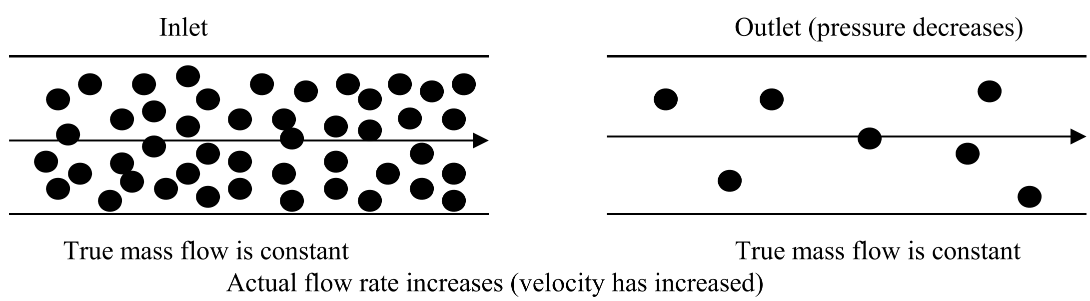


Figure 1.7-5: Pressure Flow Rate Comparison

The inverse for each scenario is also true.

1.7.7.13 When working with standard flow - either as the calibration lab or as the user of the equipment - it is necessary to define reference conditions to which standard flow is described. If we calibrate a mass flowmeter that states on it that it references standard flow to 14.7 psia and 0 °C using our reference flowmeter referenced to 14.7 psia and 70 °F, and then we do not inform the customer that we calibrated it to a different reference pressure and temperature, their measurements may be in error.

1.7.8 Test Instruments

1.7.8.1 Test Instrument Designs
Primary standards and transfer standards are the two types of standards that are employed for gas flow calibrations. What is the difference?
1.7.8.1.1 A primary flow standard is one that measures based on the fundamental units of the parameter. for mass flow, that is mass over time (e.g., kg/s).

1.7.8.1.2 Mass flow can be achieved by monitoring the change in mass in a cylinder over time. This can be very time consuming for lower flows.

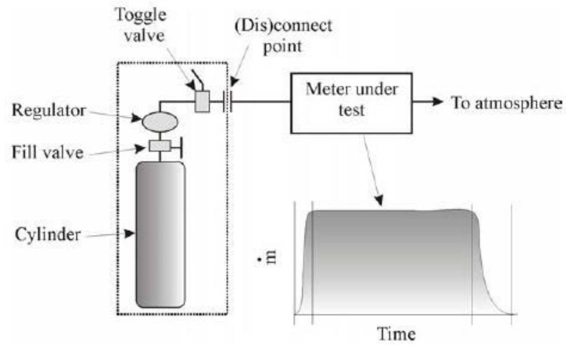


Figure 1.7-6: Primary Flow Standard (From NIST Final Report for CCG 549)

1.7.8.1.3 What would a primary flow standard look like for measuring volumetric flow? A piston of known area travelling a known length over a known amount of time: $m^2 \cdot m/s = m^3/s$.

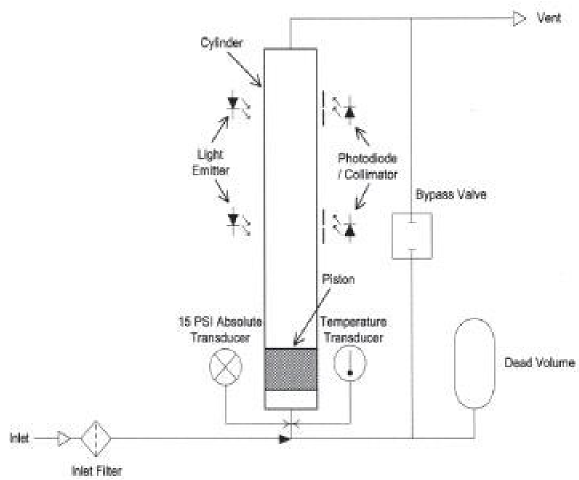


Figure 1.7-7: Primary Volumetric Flow Standard (From Sierra Instruments literature)

1.7.8.1.4 The main benefit of primary standards is their low uncertainties. The downside to primary standards is that they tend to be more time consuming to operate, require careful attention, and can be expensive.

1.7.8.1.5 Transfer standards are those that measure a parameter through a derived method. In gas flow, transfer standards would be laminar flow elements, nozzles, rotameters, etc. These tend to be standards that can make measurements quickly, are easy to operate, and are less expensive than a primary standard. Higher accuracy transfer standards can be calibrated on a primary standard and then used to calibrate other transfer standards.

1.7.8.1.6 In the Air Force, NIST calibrates AFPSL molblocs (transfer standards) using their molblocs which were calibrated on their gravimetric standard (primary standard). The AFPSL then calibrates PMEL molblocs using its NIST calibrated molblocs.

1.7.8.1.7 Determining which to use - a primary or transfer standard - depends on the context of the measurement being made. It surely does not make sense to use a static gravimetric calibration standard to calibrate a ±5% rotameter.

1.7.8.2 Piston Flowmeters (or Bubble Flowmeters)

Piston flowmeters use the fundamental units of length and time to determine flow rate. Is the flow rate determined by a piston flowmeter volumetric (actual) or mass flow? If you read the above section, you already know. Piston flowmeters are volumetric flow devices. They measure the change in volume over a change in time:

$$Q = \frac{\Delta V}{\Delta t} = \frac{V_{t_{final}} - V_{t_{initial}}}{t_{final} - t_{initial}}$$

1.7.8.2.1 These meters are also not designed to withstand large pressures and therefore are almost always used downstream of any application - open to atmosphere. This is because the seal between the piston and the cylinder is either an air gap (as a result of finely machined components) or mercury, and high pressurization will cause gas to flow by the piston.

1.7.8.2.2 Recall our discussion about actual and standard flow rates. Is it possible to determine what the mass flow is through a piston flowmeter despite it being a volumetric flowmeter?

1.7.8.2.3 Many piston flowmeters will have on-board pressure and temperature sensors for measuring the flowing gas' pressure and temperature. However, some do not. What does that mean for how we calibrate them?

1.7.8.3 Thermal Mass Flowmeters
Thermal mass flowmeters (MFMs) are designed to measure true mass flow rate. The most common type of MFM uses a constant temperature approach. This type of MFM has two temperature sensors: a heated sensor and a reference temperature sensor.

1.7.8.3.1 The heated sensor is controlled and stabilized at higher temperature than that of the gas passing across it. The temperature to which it is controlled is based on the reference temperature sensor, which is able to measure the temperature of the flowing gas, and therefore, provide feedback to the upstream heated sensor.

1.7.8.3.2 As gas flows across the heated sensor (which is heated to a temperature higher than that of the flowing gas), heat is transferred from the heated sensor to the cooler flowing gas. As the gas velocity increases through the flowmeter (and therefore the flow rate increases), the amount of heat carried away by the gas molecules increases. Ultimately, the heated sensor is informed by the downstream reference temperature sensor of the gas' temperature. The heated sensor is then supplied with more or less current in order to keep the *difference* between the two sensors at some value determined by the manufacturer. The current required to achieve this is the MFM's output and can be related to the mass flow rate through the MFM.

1.7.8.3.3 Different gases have different heat capacities and properties such that in order to achieve the manufacturer's stated accuracy, the MFM must be calibrated in the gas in which it will be used - its process gas. Unfortunately, not all process gases - such as oxygen and hydrogen - can be flowed easily in a lab. To overcome this, MFM manufacturers supply K-Factors (correction factors) that allow the MFM to be calibrated in a "surrogate" gas such as air or Nitrogen, and then by applying the K-Factor, the process gas flow rate can be predicted. These predicted flow rates are related to the output of the MFM - typically 0 to 5 VDC or 4 to 20 mA.

1.7.8.3.4 Many of these K-Factors are determined mathematically versus empirically and therefore come with a high reduction in flow rate accuracy. Some manufacturers will inform the user in their manuals of the expected reduction in accuracy; however, some do not. Because of this, when the highest accuracy is required, the calibration/surrogate gas should be the same as the user's process gas.

1.7.8.3.5 Even though MFMs are inherently mass flow devices (i.e., they measure true mass flow), most manufacturers provide a reference pressure and temperature to which the mass flow rate is converted to standard flow rate.

NOTE

COMPASS for molbox accommodates a K-Factor correction. In many cases, based on the manufacturer of the MFM, COMPASS supplies the K-Factor. However, be sure to always double-check these since manufacturers can, and do change these occasionally.

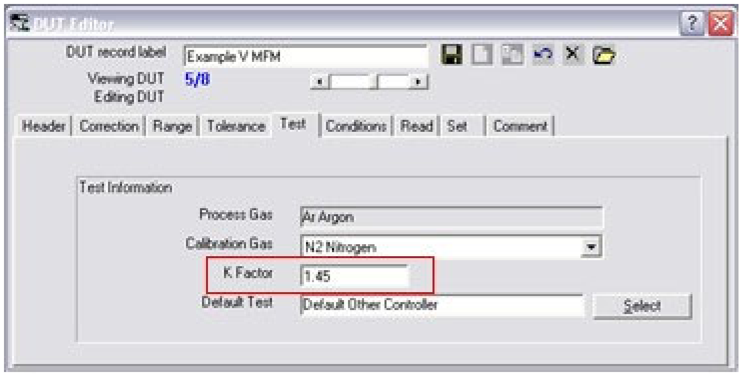


Figure 1.7-8: K-Factor Input

1.7.8.4.1 Rotameters (Variable Area Flowmeters)
A rotameter is a simple flow measuring device, which uses a tapered tube and float. The tapered tube's cross sectional area increases from the bottom to the top - thus the name variable area flowmeter.

1.7.8.4.1.1 The rotameter operates based on obtaining a design differential pressure between the bottom and the top of the float - this is based on the weight of the float.

1.7.8.4.1.2 Based on the design of the rotameter (including the weight of the float), there is a set differential pressure across the float that once achieved will cause the float to stabilize at a vertical point in the tube.

1.7.8.4.1.3 When there is no flow, the float rests at the bottom of the rotameter - where the cross sectional area of the tube is the smallest. When a flow rate is generated, the small gap between the tube and float obstructs the gas flow and causes pressure to build up beneath the float. The flow rate is increased until the pressure beneath the float becomes greater than the weight of the float. At this point, the float will begin to rise. This can also be expressed in terms of force acting upward on the float caused by the pressure acting on the float, and the force acting downward on the float caused by the exhaust pressure acting on the float. The figure below shows this.

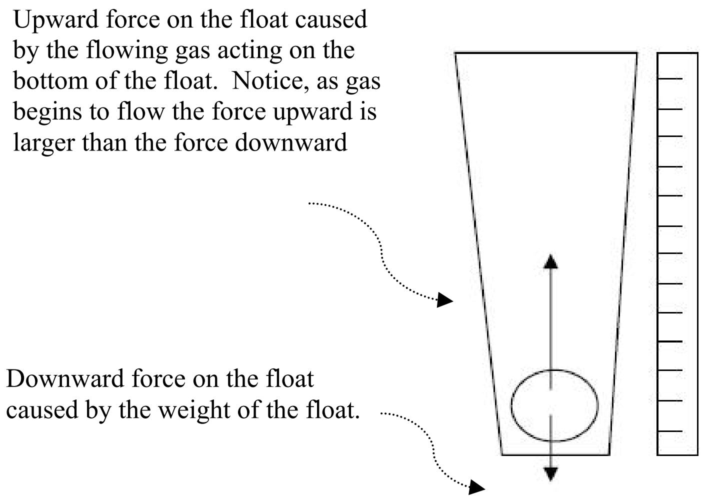


Figure 1.7-9: Rotameter without flow

1.7.8.4.1.4 As the flow rate increases, the float is forced further upward. However, as the float moves upward, the gap between the tube and the float increases which causes the upward force to begin to decrease. Eventually, the upward force on the float caused by the flowing gas becomes equal to the downward force on the float caused by the weight of the float. The rotameter has reached equilibrium and the scale can be read.

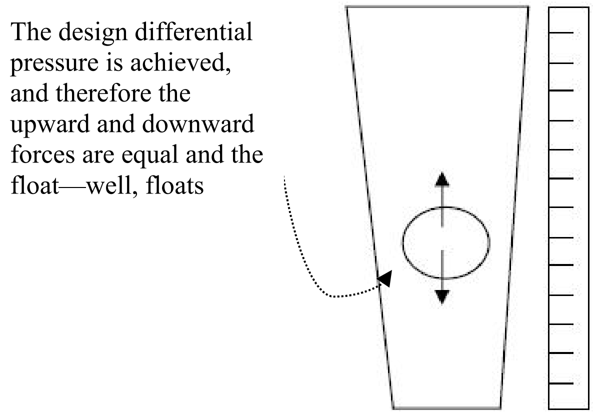


Figure 1.7-10: Rotameter with flow

1.7.8.4.1.5 The above explanation is almost inclusive of how a rotameter operates; however, in reality it leaves out two factors: the pressure force pushing downward on the float as a function of the rotameter exhaust pressure, and the buoyancy force pushing upward on the float as a function of the gas' density. The complete diagram of forces is shown below.

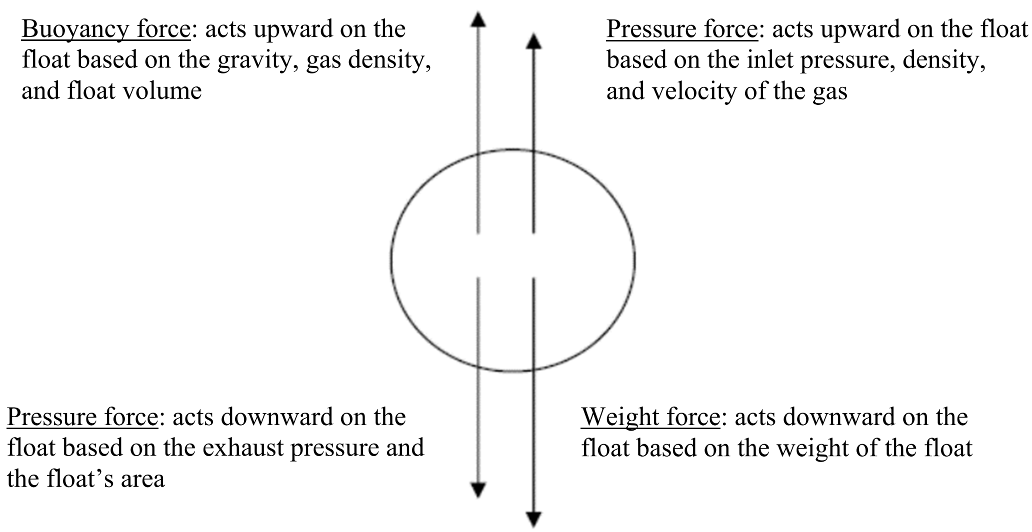


Figure 1.7-11: Float forces

1.7.8.4.1.6 When the rotameter is operated in gas (they can be used in gases or liquid), the buoyancy term is not typically considered. This is because the density of gas is low; therefore, the corresponding buoyant force is small compared to the other forces.

1.7.8.4.1.7 When these forces are considered altogether, the behavior of a rotameter can be predicted.

1.7.8.4.1.8 Rotameters are dependent upon gas density, and since their flow outputs are printed, etched, etc. onto the flowmeter, as the density of the gas deviates from that which the scale was designed to, a correction factor must be applied. Recall that density varies primarily based on gas, pressure, and temperature.

1.7.8.4.1.9 Before we proceed with the correction formulas for rotameters, we should be clear that there are two different "reference conditions" that we refer to when talking about rotameters. The first is the typical reference pressure and reference temperature when referring to standard flow. Most rotameters are designed to indicate in standard flow rate units. However, some manufacturers do not state clearly on the item or otherwise what the reference pressure and temperature is. It is common to use 14.7 psia and 70 °F in cases like this. The other "reference condition" is referred to as "scale conditions". Scale conditions refer to the pressure and temperature conditions to which the rotameter scale was printed, etched, etc. A typical off-the-shelf rotameter may not indicate these values. It is common to use 14.7 psia and 70 °F in cases like this also. However, for flow systems that use rotameters and which are designed for a specific purpose, it is not uncommon for the rotameter in the system to have been scaled based on a known back pressure that it will experience during its actual use.

1.7.8.4.1.10 In all cases, it is always best to calibrate the rotameter as close as possible to the conditions under which it will be used; however, this is not always possible. Typically, this means controlling a rotameter back pressure to its scaled back pressure or to the back pressure under which it will be used (some rotameters do not have flow scales; rather, they have length scales such as millimeters. In cases like this, the customer can use charted values of the flowmeter's output based on the conditions in which it will be used.).

1.7.8.4.1.11 It is always best to apply the rotameter correction formula even if you are close to its designed or normally operated conditions. However, in cases where the rotameter cannot be calibrated to its designed or normally operated conditions, we *must* apply a rotameter correction factor. When calibrating a rotameter, the correction factor is typically applied to the flow rate indication from the standard (e.g. molblocs, laminar flow elements), such that the standard's indicated flow rate can be compared directly to the rotameter's indicated flow rate.

Rotameters can be scaled with three different flow rate units: mass flow, actual flow, or standard flow rates. These are addressed one-by-one below.

1.7.8.4.2 Mass Flow

Mass flow through a rotameter is proportional to (that is what the ∝ represents) the square root of density, $\sqrt{\rho}$

$$\dot{\boldsymbol{m}} \propto \sqrt{\boldsymbol{\rho}}$$

1.7.8.4.2.1 Given the relationship between mass flow rate and density, we know that as density changes, the resultant mass flow rate changes.

1.7.8.4.2.2 for a given rotameter flow rate, if the gas density during calibration is different than the density for which the rotameter was designed, we can determine what the flow rate should actually be.

A change in the $\sqrt{\rho}$ factor will result in an equal change in mass flow. Knowing this, we can say:

$$\frac{\dot{m}_{ref,designed\ or\ normally\ operated}}{\dot{m}_{ref,calibration}} = \frac{\sqrt{\rho_{designed\ or\ normally\ operated}}}{\sqrt{\rho_{calibration}}}$$

Where: $\dot{m}_{ref,designed\ or\ normally\ operated}$ = reference mass flow corrected to the designed or normally operated density

$\dot{m}_{ref,calibration}$ = mass flow rate as indicated by the reference (i.e. the flow standard, such as the molbloc)

$\sqrt{\rho_{designed\ or\ normally\ operated}}$ = density of the rotameter for which it was designed or for which it is normally operated

$\sqrt{\rho_{calibration}}$ = density during calibration

This can be rearranged then to solve for $\dot{m}_{ref,designed\ or\ normally\ operated}$

$$\dot{m}_{ref,designed\ or\ normally\ operated} = \dot{m}_{ref,calibration} \cdot \frac{\sqrt{\rho_{designed\ or\ normally\ operated}}}{\sqrt{\rho_{calibration}}}$$

1.7.8.4.2.3 This equation corrects $\dot{m}_{ref,calibration}$ to what the TI should be indicating at calibration based on its designed or normally operated conditions. Because of this, it is easiest and least confusing to restate $\dot{m}_{ref,designed\ or\ normally\ operated}$ as $\dot{m}_{corrected}$. Therefore,

$$\dot{\boldsymbol{m}}_{\boldsymbol{corrected}} = \dot{\boldsymbol{m}}_{\boldsymbol{ref,calibration}} \cdot \frac{\sqrt{\boldsymbol{\rho}_{\boldsymbol{designed\ or\ normally\ operated}}}}{\sqrt{\boldsymbol{\rho}_{\boldsymbol{calibration}}}}$$

1.7.8.4.2.4 This is the simplest way to express this correction. However, during a calibration, actually calculating density can be difficult and open to error. Since density is a function of pressure, temperature, and the specific gas, we can rearrange the above equation in terms of pressure, temperature, and specific gravity—values which we have easy access to during a calibration.

$$\dot{\boldsymbol{m}}_{\boldsymbol{corrected}} =$$

$$\dot{\boldsymbol{m}}_{\boldsymbol{ref,calibration}} \cdot \sqrt{\frac{\boldsymbol{P}_{\boldsymbol{designed\ or\ normally\ operated}}}{\boldsymbol{T}_{\boldsymbol{designed\ or\ normally\ operated}}} \cdot \frac{\boldsymbol{T}_{\boldsymbol{calibration}}}{\boldsymbol{P}_{\boldsymbol{calibration}}} \cdot \frac{\boldsymbol{SG}_{\boldsymbol{designed\ or\ normally\ operated}}}{\boldsymbol{SG}_{\boldsymbol{calibration}}}}$$

1.7.8.4.2.5 Specific gravity is based on the ratio of molecular masses (M_x) of a subject gas and air. Therefore, the way specific gravity is used in this approach (ratio of the two different specific gravities) results in the expression of molecular mass of each gas. This is because the molecular mass of air cancels out, leaving the molecular masses of each gas.

$$\frac{SG_1}{SG_2} = \frac{\frac{M_{gas1}}{M_{air}}}{\frac{M_{gas2}}{M_{air}}} = \frac{M_{gas1}}{\cancel{M_{air}}} \cdot \frac{\cancel{M_{air}}}{M_{gas2}} = \frac{M_{gas1}}{M_{gas2}}$$

1.7.8.4.2.6 The advantage of using specific gravity values rather than molecular mass values is that specific gravity values are easily obtained and are unit less. Therefore, without units, there is no concern about mixing terms with different units and making incorrect calculations.

1.7.8.4.2.7 Compressibility, Z, can be included also, but is nearly always negligible. Flow computers and calibration software, however, typically calculate the correction using density calculations - which includes compressibility - rather than the ratios of pressure, temperature, and specific gravity.

1.7.8.4.2.8 The mass flow rotameter correction is a straightforward correction, which can be applied for rotameters that are designed to read in units of mass flow. However, rotameters are most commonly scaled to reading in units of standard flow, and in some cases actual flow. These are addressed next.

1.7.8.4.3 Standard Flow
The correction formula for standard flow is derived in a similar manner as follows.

$$\frac{Q_{ref(std),designed\ or\ normally\ operated}}{Q_{ref(std),calibration}} = \frac{\sqrt{\rho_{designed\ or\ normally\ operated}}}{\sqrt{\rho_{calibration}}}$$

Where: $Q_{ref(std),designed\ or\ normally\ operated}$ = reference standard flow corrected to the designed or normally operated density
$Q_{ref(std),calibration}$ = standard flow rate as indicated by the reference (i.e. the flow standard, such as the molbloc)
$\sqrt{\rho_{designed\ or\ normally\ operated}}$ = density of the rotameter for which it was designed or for which it is normally operated
$\sqrt{\rho_{calibration}}$ = density during calibration

This can be rearranged then to solve for $Q_{ref(std),designed\ or\ normally\ operated}$

$$Q_{ref(std),designed\ or\ normally\ operated} = Q_{ref(std),calibration} \cdot \frac{\sqrt{\rho_{designed\ or\ normally\ operated}}}{\sqrt{\rho_{calibration}}}$$

1.7.8.4.3.1 This equation corrects $Q_{ref(std),calibration}$ to what the TI should be indicating at calibration based on its designed or normally operated conditions. Because of this, it is easiest and least confusing to restate $Q_{ref(std),designed\ or\ normally\ operated}$ as $Q_{corrected}$. Therefore,

$$Q_{corrected} = Q_{ref(std),calibration} \cdot \frac{\sqrt{\rho_{designed\ or\ normally\ operated}}}{\sqrt{\rho_{calibration}}}$$

1.7.8.4.3.2 One issue arises here though. What if the reference density of the reference is different than the design reference density of the TI? For example, what if the flow standard is measuring standard flow rate with air referenced to 14.7 psia and 0 °C, whereas the TI is designed to indicate standard flow rate with Helium referenced to 14.7 psia and 70 °F? This is addressed below.

Knowing what we know about mass flow and volume flow, we can restate $Q_{ref(std),calibration}$ as

$$\frac{\dot{m}}{\rho_{ref(std),calibration}}$$

We can then adjust this to indicate standard flow with TI design reference density as follows:

$$\left[\frac{\dot{m}}{\rho_{ref(std),calibration}}\right] \cdot \frac{\rho_{ref(std),calibration}}{\rho_{TI(std),design}}$$

Therefore:

$$Q_{corrected} = \left[\frac{\dot{m}}{\rho_{ref(std),calibration}}\right] \cdot \frac{\rho_{ref(std),calibration}}{\rho_{TI(std),design}} \cdot \frac{\sqrt{\rho_{designed\ or\ normally\ operated}}}{\sqrt{\rho_{calibration}}}$$

Or

$$Q_{corrected} = Q_{ref(std),calibration} \cdot \frac{\rho_{ref(std),calibration}}{\rho_{TI(std),design}} \cdot \frac{\sqrt{\rho_{designed\ or\ normally\ operated}}}{\sqrt{\rho_{calibration}}}$$

1.7.8.4.3.3 This is the simplest way to express this correction. However, during a calibration, actually calculating density can be difficult and open to error. Since density is a function of pressure, temperature, and the specific gas, we can rearrange the above equation in terms of pressure, temperature, and specific gravity - values which we have easy access to during a calibration. Note: in a lot of cases, the $\rho_{ref(std),calibration}$ and $\rho_{TI(std),design}$ are the same (e.g. TI is designed for standard flow in air with reference conditions of 14.7 psia and 70 °F and the flow standard is flowing air and referencing standard flow to 14.7 psia and 70 °F), which reduces their ratio to 1.0.

$$\boldsymbol{Q_{corrected}} = \boldsymbol{Q_{ref(std),calibration}} \cdot \frac{\boldsymbol{P_{ref(std),calibration}}}{\boldsymbol{T_{ref(std),calibration}}} \cdot \frac{\boldsymbol{T_{TI(std),design}}}{\boldsymbol{P_{TI(std),design}}} \cdot \frac{\boldsymbol{SG_{ref(std),calibration}}}{\boldsymbol{SG_{TI(std),design}}} \cdot \sqrt{\frac{\boldsymbol{P_{designed\ or\ normally\ operated}}}{\boldsymbol{T_{designed\ or\ normally\ operated}}} \cdot \frac{\boldsymbol{T_{calibration}}}{\boldsymbol{P_{calibration}}} \cdot \frac{\boldsymbol{SG_{designed\ or\ normally\ operated}}}{\boldsymbol{SG_{calibration}}}}$$

1.7.8.4.3.4 While these corrections address density differences, they do not correct for viscosity differences. There are no real viscosity corrections. However, there are a variety of float designs available, which are fairly insensitive to changes in viscosity.

1.8 TEMPERATURE

1.8.1 Introduction

Temperature is a quantitative measure of an amount of heat associated with an object. Temperature measurements are integral to virtually all aspects of activities within the Department of Defense and are thus important to the successful completion of our many Air Force missions. Temperature is measured by a variety of instruments in different ways, but all instruments that measure temperature directly are generally called thermometers.

1.8.1.1 PMELs annually calibrate thousands of temperature measuring devices that are used in a variety of applications and environments. Different types include resistance thermometers, thermocouples, thermistors, bimetal dial thermometers, liquid-in-glass thermometers, and thermo-hygrometers, which measure both temperature and humidity. Many of the latter are designed as chart recording devices. All PMEL calibrations are traceable to NIST through AFPSL exchange standards and base working standards, most of which the PMELs can calibrate. Most calibrations incorporate International Temperature Scale (ITS)-90 values for resistance-temperature conversions for resistance thermometers and voltage-temperature conversions for thermocouple devices.

1.8.1.2 Temperature can be measured via a diverse array of sensors. All of them infer temperature by sensing some change in a physical characteristic. The most common types are thermocouples, resistive temperature devices (Platinum Resistance Thermometers [PRTs] and thermistors), bimetallic devices, and liquid expansion devices.

1.8.2 Thermometer Types

1.8.2.1 Liquid-In-Glass Thermometry

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 heating and cooling cycles.

1.8.2.1.1 Liquid-In-Glass (LIG) Thermometers are the easiest type of thermometers to both use and calibrate, and everyone has likely had some experience at home or in school with LIG thermometers before entering the PMEL laboratory. A LIG thermometer consists of a sealed glass tube filled with Mercury or an organic fluid that remains a liquid within the normal temperature ranges of interest. The Air Force has, in recent years, moved to eliminate the use of Mercury-filled thermometers because Mercury is considered a hazardous material. LIG thermometers can be used over a temperature range of -40 to over 300 °C (-40 to 572 °F); several individual thermometers comprise a set to cover that range.

Figure 1.8-1: Liquid-in-Glass Thermometer

1.8.2.2 Resistance Thermometry
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.

1.8.2.2.1 All resistance thermometry is based on the measure of sensor resistance at the Triple Point of Water (TPW), or 0.01 °C. That value helps define the type of probe being calibrated. The most accurate resistance sensors used as standards by the PMELs are Platinum Resistance Thermometers (PRTs) with a TPW resistance of 25.5 or 100 Ohms. A lower TPW resistance indicates a greater sensitivity, and consequently greater accuracy, of the sensor. All standard PRTs fielded by AFMETCAL are calibrated by the AFPSL because only the AFPSL owns the most accurate standards required for these calibrations. Those standards are briefly discussed in a later section.

1.8.2.2.2 Thermistors and RTDs are resistive devices, and they function by passing a current through a sensor. Even though only a small current is generally employed, it creates a certain amount of heat and thus can throw off the temperature reading. This self-heating in resistive sensors can be significant when dealing with a still fluid (i.e., neither flowing nor agitated), because there is less carry-off of the heat generated. This problem does not arise with thermocouples, essentially zero-current devices.

Figure 1.8-2: Resistance Thermometer

1.8.2.3 Thermocouple Thermometry
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.

1.8.2.3.1 A Thermocouple, or thermoelectric couple, is formed by the junction of two dissimilar metals for the purpose of producing a thermoelectric current. Common thermocouples are formed with metals such as Copper, Iron, Chromium, Aluminum, Nickel, Platinum, and Rhodium. Thermocouples are possibly the most widely used temperature sensors in the Air Force because they are relatively cheap, durable, and cover a wide temperature range.

1.8.2.3.2 Thermocouples are less stable than RTDs. On the other hand, as a class, their temperature range is broader: RTDs operate from about -250 to 850 °C whereas thermocouples range from about -270 to 2,300 °C. Thermistors have a more restrictive span, being commonly used between -40 and 150 °C, but offer high accuracy in that range.

Figure 1.8-3: Thermocouple Thermometer

1.8.2.4 Bimetallic Thermometry
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 will 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 not as accurate as thermocouples or RTDs and they do not readily lend themselves to temperature recording.

Figure 1.8-4: Bimetal Thermometer

1.8.3 AFPSL STANDARDS

1.8.3.1 Triple Point of Water

Figure 1.8-5: Triple Point of Water

1.8.3.1.1 The reference for all temperature measurements is at the Triple Point of Water (TPW). It is the single combination of pressure and temperature at which liquid water, solid ice, and water vapor can coexist in a stable equilibrium occurring at exactly 273.16 °K (0.01 °C; 32.02 °F) and a partial vapor pressure of 611.657 Pascal (6.11657 mbar; 0.00603659 atm). At that point, it is possible to change all of the substance to ice, water, or vapor by making arbitrarily small changes in pressure and temperature. Even if the total pressure of a system is well above the triple point of water, provided that the partial pressure of the water vapor is 611.657 °Pascal, then the system can still be brought to the triple point of water. Strictly speaking, the surfaces separating the different phases should also be perfectly flat, to negate the effects of surface tension.

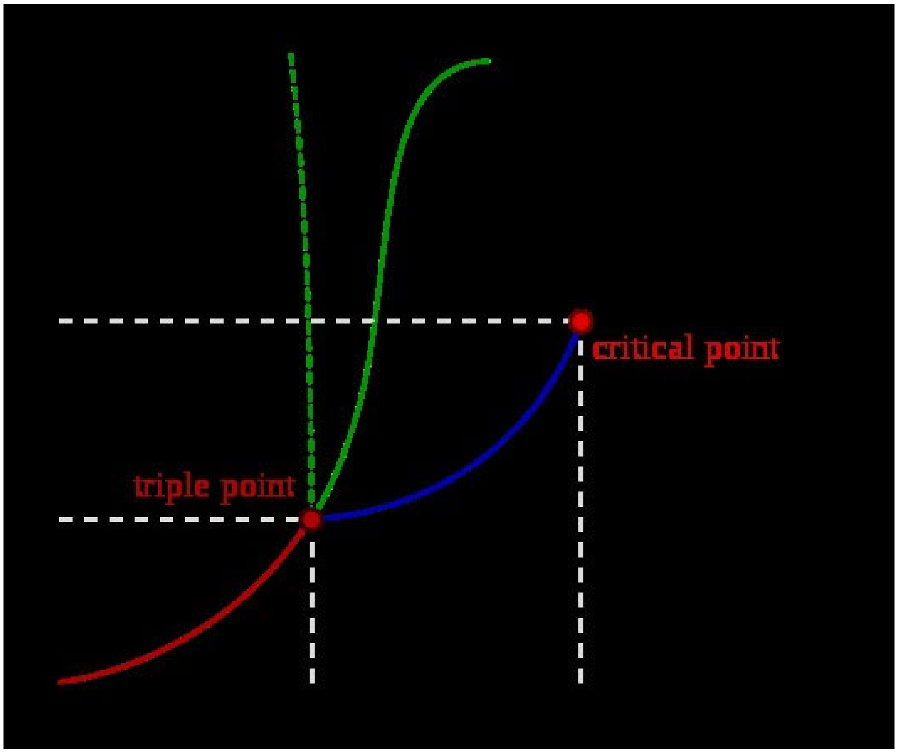


Figure 1.8-6: Triple Point Relationship

1.8.3.2 SPRT
Standard Platinum Resistance Thermometers (SPRTs) are the PMEL Base Measurement Standard and are calibrated by the AFPSL mostly as an Exchange Standard on a 3-year interval. Nearly all Air Force SPRTs have a Quartz sheath, which makes them even more fragile than metal-sheathed PRTs.

Figure 1.8-7: SPRT

1.8.3.2.1 SPRT Care and Handling
All PRTs should be handled with extreme care due to the fragility of the Platinum element. These are very fragile instruments and should be handled with extreme caution. They should be handled with gloves, never with bare hands. They should be cleaned with alcohol and wiped with a lint free cloth. They should not be placed on a desk without being in a case. They should not be hit on any surface or damage will be caused to the platinum sensing element. Even if the sheath does not break, unseen damage can be caused to the thermometer.

NOTE

The fragility of these instruments cannot be overstated.

1.8.3.2.2 SPRT Drift Check
The PRT Drift Check is performed on PRTs used as standards to ensure the resistance measurement does not drift beyond some acceptable amount. The resistance is measured at the Triple Point of Water and compared against some previous measurement and can be either long term or short term. This is checked before and after the TI is calibrated. The drift check can be found in Appendix B of T.O. 33K5-4-42-1.

1.8.3.3 Resistance Bridge
F18AS2 Resistance Bridge, 0 to 1 kΩ, ±1 ppm. The F18AS2 is a high accuracy AC transformer ratio arm bridge for calibration of resistances by comparison with a known standard. Calibration is achieved by balancing the ratio between two resistance thermometers or between a reference resistor and a resistance thermometer. AC measurement eliminates thermometric EMF errors and the inherent instability of DC measurement systems.

6625T Resistance Bridge, 0 to 1 kΩ, ±1 ppm. This standard is a microprocessor-based, direct-current-comparator bridge designed for the automatic measurement and display of the ratio of two resistances to an accuracy of better than 5 ppm. The ratio of the two resistances is determined from a direct measurement of the voltage of the bridge imbalance while an ampere-tum balance is maintained. This fully automated measurement process achieves optimum resistance ratio resolution and accuracy at the ppm level. The newly upgraded units are now as accurate as the F-18.

1.8.3.4 AFPSL Fixed Point Cells
The AFPSL uses fixed point cells which allow it to calibrate Exchange Standards to internationally recognized fixed-point temperatures, including Triple Points of Water, Mercury, and Argon, Freezing Points for Aluminum, Zinc, and Tin, and Melting Point of Gallium. Tin and Zinc Freeze Point Mini-Cells are also utilized in the Temperature Laboratory for calibrating PRTs down to 9 or 12 inches in length.

Figure 1.8-8: AFPSL Fixed Point Cells

1.8.4 PMEL Standards

1.8.4.1 Mini-Triple Point of Water Cell (9210 with 5901)
Triple point of water cells fills four critical purposes. First, they provide the most reliable way to identify unacceptable thermometer drift between calibrations-including immediately after a calibration if the thermometer has been shipped. Interim checks are critical for maintaining confidence in thermometer readings between calibrations. Second, they provide a critical calibration point with unequaled uncertainties.

Figure 1.8-9: Mini-Triple Point of Water Cell

Third, for users who characterize probes using ratios (that is, they use the ratios of the resistances at various ITS-90 fixed points to the resistance of the thermometer at the triple point of water, indicated by “W"), interim checks at the triple point of water allow for quick and easy updates to the characterizations of critical thermometer standards, which can be used to extend calibration intervals.

And lastly, the triple point of water is where the practical temperature scale (ITS-90) and the thermodynamic temperature scale meet since the triple point of water is assigned the value 273.16 K (0.01 °C) by the ITS-90 and the Kelvin is defined as 1/273.16 of the thermodynamic temperature of the triple point of water.

Good triple point of water cells contains only pure water and pure water vapor. (There is almost no residual air left in them.) When a portion of the water is frozen correctly and water coexists within the cell in its three phases, the “triple point of water" is realized. Water cells achieve this temperature with expanded uncertainties of less than 0.0001 °C and reproducibility within 0.00002 °C. In simple terms, water cells are made from just glass and water, but there is much more to it than that.

1.8.4.2 Temperature Indicator (TTI-7R)
The TTI-7R is a very high accuracy multipurpose digital thermometer for both platinum resistance thermometers and thermocouples. Laboratory users will welcome the features to eliminate Thermal EMF Errors and Self Heating Errors along with provision to store the calibration data of up to 20 PRT probes. The rugged aluminum case, internal battery pack, and integrated power supply ensure reliable portable field use for demanding measurement applications.

Dual Channel input allows a probe on Channel B to be calibrated against a standard on Channel A - directly comparing any combination of PRT and Thermocouple. The TTI-7 PLUS supports thirteen thermocouple types (B, C, D, E, J, K, L, N, R, S, T, U, Au/Pt) along with 25 and 100 Ohm platinum resistance thermometers.

Figure 1.8-10: Temperature Indicator

1.8.4.3 Thermocouple Simulator-Calibrator (1140B)
The accuracy of this unit is established using ultra-precision film resistor networks and a precision, monolithic voltage reference. Separate offsets for each thermocouple type may be specified from the front panel. These offsets allow the user to compensate for variations in the thermocouple or extension wire being used. It is used to calibrate thermocouples types E, J, K, and T.

Figure 1.8-11: Thermocouple Simulator-Calibrator

1.8.4.4 Ice Point Dry Well (K57)
It is designed to provide a stable and uniform temperature environment for the preparation and maintenance of ice point conditions inside each of the four wells located on the front panel. It accommodates four PRTs in an arrangement of four wells in a tapered square pattern on the front panel. The wells are 7 mm inside diameter and approximately 150 mm deep. It replaces the labor-intensive PMEL-manufactured Ice Bath used in many thermocouple calibrations.

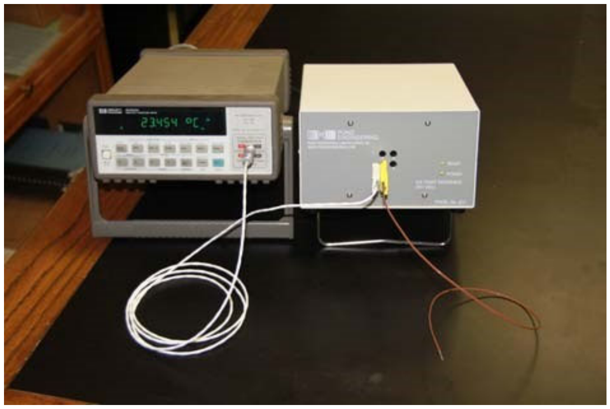


Figure 1.8-12: Ice Point Dry Well

1.8.5. Calibration Mediums

1.8.5.1 Wet Baths

Precision calibration of thermometers calls for the use of stirred liquid calibration baths. Liquid baths offer good immersion depth, parallel tube action, giving the best uniformity and smallest calibration uncertainties, and wide temperature ranges. Some models use molten salts with a pumping system to maintain the necessary consistent fluid level required to meet the required accuracy of the thermometers. Some models may also have a carousel for holding several glass thermometers in the correct calibration position.

Figure 1.8-13: Liquid Bath

1.8.5.2 Dry Wells

1.8.5.2.1 Temperature Range

The temperature limits of the dry well must meet the minimum test requirements for the sensors being calibrated. The ideal calibration spans the entire usable range of the test sensor. However, extrapolating a non-critical temperature point may save time while not affecting the overall system uncertainty.

Even after a full-range calibration of the temperature sensor, it is a good idea to check its accuracy in the precise range it is most often used. If calibrating a RTD between 0 °C and 100 °C, but it is used to only monitor a room temperature, recommend setting the dry well to 25 °C and see how the calibrated sensor performs at its most important temperature.

Figure 1.8-14: Dry Well

1.8.5.2.2 Sensor Immersion
Sensor immersion depth is a recurring topic when considering a dry-well for calibration of temperature probes. Immersion can be the single largest contributor of error in dry-well calibrations. In the ideal world, all of our sensor assemblies would be the same size and depth. Unfortunately, this is not the ideal world.

Immersing a 2-inch sensor assembly into a 6-inch well could yield an error up to 10 °C. This is inherent in all dry-wells. In many cases, a bath is a better calibration medium, but not always practical. There are some techniques to use to counter this error and bring a dry-well into a workable uncertainty level.

1.8.5.2.2.1 When calibrating a short-stem probe, always use a comparison technique. Do not compare the test reading to the dry-well display; it does not give the best results. It is better to use a reference probe of similar size and diameter. The closer the sizes match, the more accurate the comparison. Size impacts the amount of heat lost to ambient through the probe stem.

1.8.5.2.2.2 Immerse the similarly sized probes, the reference and test probe, at exactly the same depth into the block in holes that have a similar fit and distance from the heating source of the unit. This is done to achieve identical heat properties inside the block, ensuring that both sensors are sensing the same temperatures in the same way. Any deviation will cause further error.

Figure 1.8-15: Immersion Depth

1.8.5.2.3 Throughput

If like the rest of the world in trying to calibrate as many sensors as possible in a limited time period, get a block calibrator that allows the insertion of more than one probe at a time. If the unit only has one calibration well, have the manufacturer drill several holes into the removable sleeve.

Figure 1.8-16: Multi-hole sleeve

1.8.6 Oven and Environmental Chamber
Ovens, environmental chambers, and autoclaves are used throughout the Air Force. The temperature probes are the only item calibrated on these systems. Ovens and autoclaves are used to cure epoxy on aircraft components, while environmental chambers are used to control the environment for a particular situation. Temperature probes are evenly distributed throughout the testing area to monitor the temperature and ensure it is uniform throughout the testing area. Below is an autoclave used to hold an aircraft wing for the purpose of repairing the skin on the wing.

Figure 1.8-17: Environmental Chamber

1.9 TORQUE

1.9.1 Introduction
The parameter of torque is defined as a turning force that produces rotation. It is a derived unit and is equal to the applied force times the length of the lever arm the force is applied to. Gage blocks and mass weights are used as standards for this derived unit. The SI unit for torque is the Newton-meter, but in the United States and the Air Force, the most common torque units are lbf-ft, lbf-in, or ozf-in.

1.9.1.1 The most common torque standards are torque transducers. Torque transducers are normally part of a torque calibrator system, which consists of a set of torque transducers of various ranges, a digital indicator, and a mechanical loader. The primary use for torque standards in the Air Force is to calibrate torque wrenches. The Air Force also uses torque standards to calibrate torque multipliers, which are large capacity torque wrenches that contain gears to multiply the applied torque. The smallest workload is torque dynamometers, which are used to calibrate torque items.

1.9.1.2 The torque measurement area has traceability from NIST to the PMELs through AFPSL exchange standards of mass weights and gage block length standards. The PMELs use the exchange standard mass weights and gage blocks to calibrate working standard mass weights and gage blocks. The PMELs use the working standard gage blocks to calibrate the length of torque arms. The PMELs then use the working standard mass weights and torque arms to calibrate torque transducers. The PMELs then use the working standard torque transducers to calibrate torque multipliers, torque wrenches, and torque screwdrivers.

1.9.1.3 Torque wrenches are used for thousands of different applications in the Air Force. They are used to tighten nuts, bolts, and fasteners of all types on all aircraft and missile weapon systems. They are used to apply torque from as small as 2 ozf-in to as large as 20,000 lbf-ft. Figure 1.9-1 shows an Airman holding a large torque wrench (2,000 lbf-ft) used on the C-130 aircraft. Torque multipliers are used in critical applications requiring large torques such as propeller shaft retaining nuts, jet engine thrust bearing nuts, and helicopter rotor nuts.

Figure 1.9-1: 2,000 lbf-ft Torque Wrench

1.9.2 Types of Torque Wrenches

1.9.2.1 Deflecting Beam
Figure 1.9-2 shows the parts of a deflecting beam type torque wrench. The Drive Square is attached to the fastener to be tightened. When the handle is pulled, the Beam or Measuring Element bends slightly while the Pointer does not move. The scale, which is attached to the Beam or Measuring Element, moves under the pointer to show the amount of torque applied. The greater the torque applied, the further the scale moves under the pointer, which indicates the torque value.

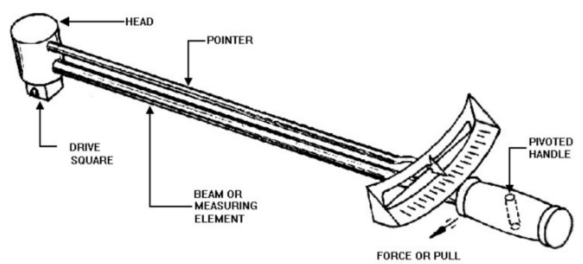


Figure 1.9-2: Deflecting Beam Torque Wrench

1.9.2.2 Rigid Case Dial Indicating
Figure 1.9-3 shows a Rigid Case Dial Indicating type torque wrench. It is similar to the Deflecting Beam type torque wrench except it uses a Dial Indicator to display the torque value. As the handle is pulled, the Lever Arm remains still. The Pinion gear, which is mounted on the Wrench Frame, rotates against the Rack, which causes the pointer of the Dial Indicator to rotate and indicate the torque.

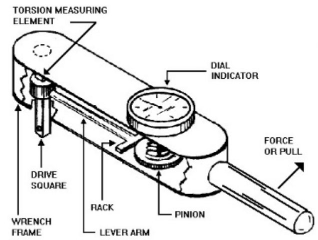


Figure 1.9-3: Rigid Case Dial Indicating Torque Wrench

1.9.2.3 Snap Action (Impulse)

There are two types of snap action torque wrenches: preset and adjustable. Figure 1.9-4 shows a Snap Action adjustable type torque wrench. This is the most common type of torque wrench used in the Air Force. It is also called a micrometer adjustable snap action torque wrench. Different torque values can be set by rotating the handle (Item 22) to different torque values on the scale (Item 18a) similar to the way the thimble on a micrometer is adjusted to measure the size of a part. Figures 1.9-2 and 1.9-3 and Figure 1.9-4 shows the internal parts of the snap action wrench. The pivot arm (Item 15) is attached to the head (Item 11) which is placed on the bolt to be tightened. The pivot arm can rotate slightly around the pin (Item 18). The right end of the pivot arm presses against a square block called the pivot block (Item 23), the pivot block is also called a pawl. The pivot block is held in place with a spring (Item 34), which is compressed by rotating the handle (Item 22). When the head (Item 11) is attached to a bolt and the handle is rotated downward, the pivot arm (Item 15) is rotated upward until the pivot block tips and the pivot arm strikes the inside wall of the torque wrench. When the pivot arm hits the inside wall, it causes a clicking sound that indicates the set torque has been reached. When the torque wrench is released, the pivot block will tip back into place and the wrench is reset. To increase the torque value, the handle (Item 22) is rotated clockwise, which compresses the spring, which increases the torque value that will be needed to cause the pivot block to tip. Preset torque wrenches are similar but are set to a single torque value by the manufacturer or calibrating technician.

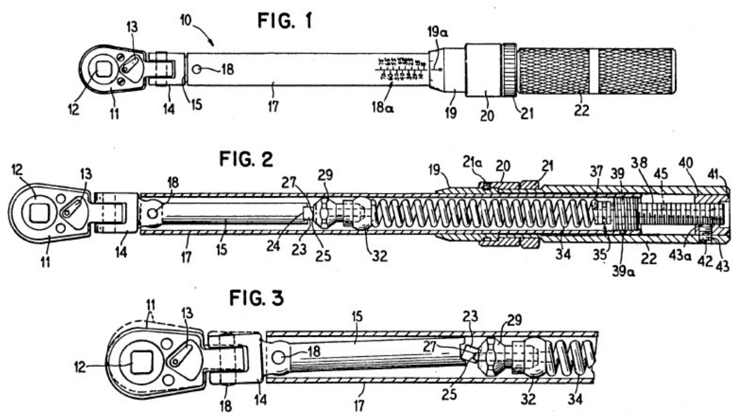


Figure 1.9-4: Snap Action Type Torque Wrench

1.9.2.4 Torque Screwdriver

Torque Screwdrivers can only be used to apply low torque, since they do not have a long lever arm like a torque wrench. The torque screwdriver contains a clutch mechanism, which can be set to release at different torque values. The clutch mechanism consists of a Ball Retainer, which contains steel balls. The Ball Retainer is pressed against the Dimple Plate with the steel balls sandwiched between the Ball Retainer and the Dimple Plate. The spring presses the Ball Retainer and Dimple Plate together. When the torque applied to the Torque Screwdriver is large enough, it will cause the balls in the Ball Retainer to press back against the spring and roll to the adjacent hole in the Dimple Plate allowing the handle to slip. The torque at which the Torque Screwdriver releases is set by adjusting the spring to press the Ball Retainer and Dimple Plate together. Figure 1.9-5 shows a Sturtevant-Richmont torque screwdriver.

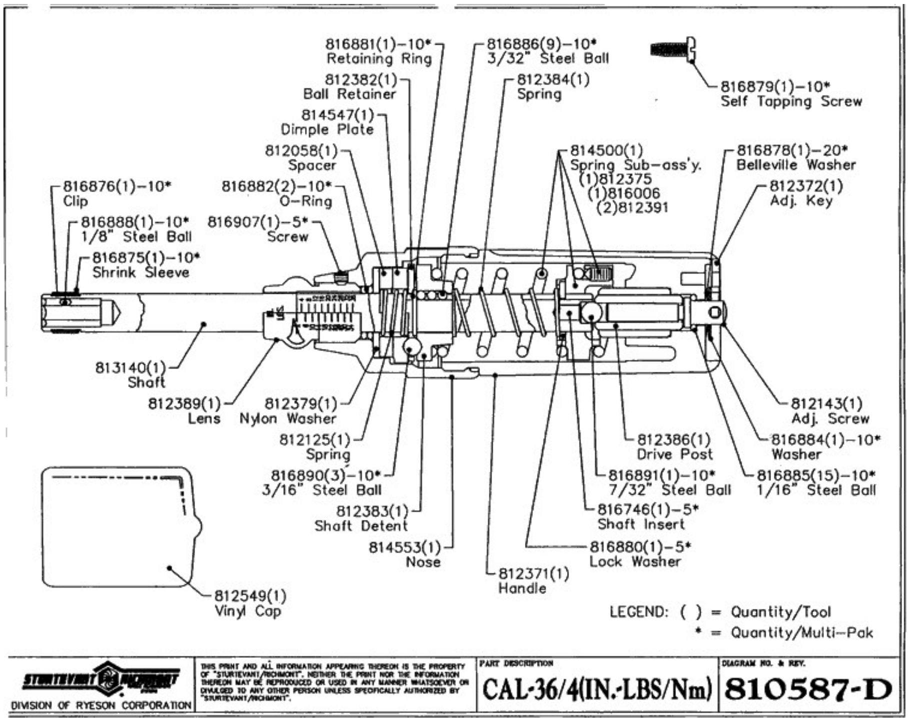


Figure 1.9-5: Sturtevant Richmont Torque Screwdriver

1.9.2.5 Electronic Torque Wrench

An Electronic Torque Wrench contains a strain gage, which senses the torque and gives an electrical output on a display. Figure 1.9-6 shows a close up of the square drive of an electronic torque wrench, the strain gages (Item 13) are shown with the cross hatching.

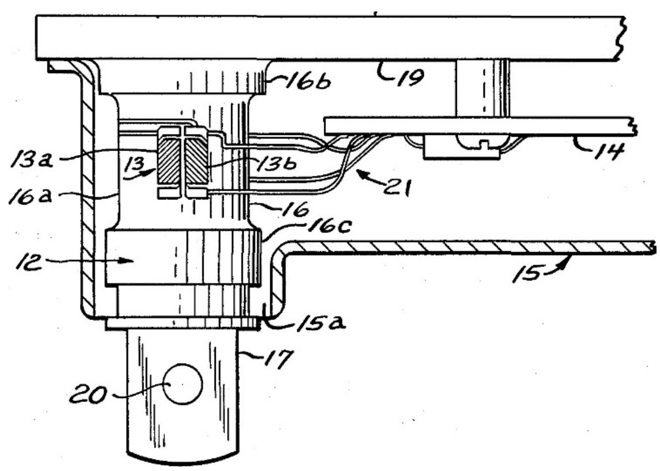


Figure 1.9-6: Strain Gage on Electronic Torque Wrench

1.9.2.6 Torque Limiters

There are many types of torque limiters. Shear Pin limiters are single use items and are not calibrated by the PMEL. Slip ring, friction plate, and clutch type limiters are similar to torque screwdrivers, which are placed in line between a torqueing device and an object desired to be torqued. Once the torque setting is reached, the Ring/Plate/Clutch will disengage causing part of the torque limiter to spin freely reducing or removing all torque being applied to the object being torqued. Figure 1.9-7 is an example of Clutch type torque limiter.

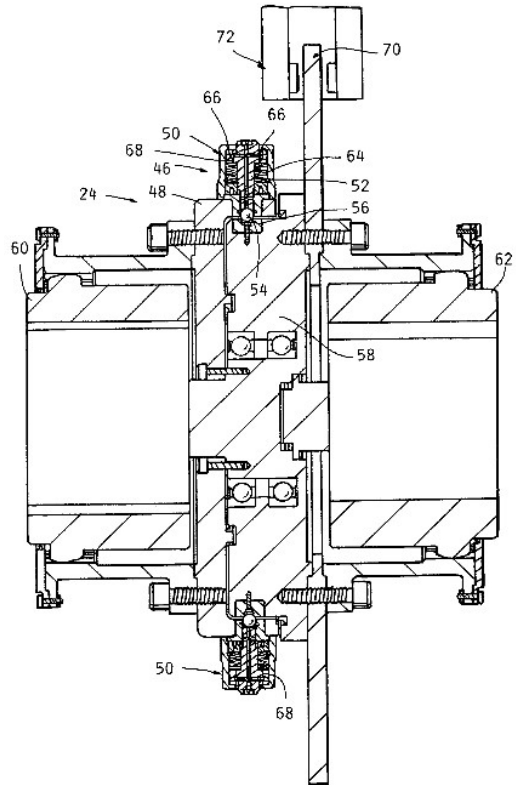


Figure 1.9-7: Clutch type torque limiter

1.9.3 TORQUE MULTIPLIERS

A torque multiplier is a tool used to provide a mechanical advantage applying torque to turn bolts, nuts, or other items designed to be actuated by application of torque, such as the actuation of valves, particularly where there are relatively high torque requirements.

1.9.3.1 Torque multipliers are often used instead of extension handles, often called "cheater bars", especially when there are space limitations that disallow the use of long handles. Extension handles use leverage instead of gear reduction to achieve torque, which is transmitted through the driving tool and could become dangerous in the case of a sudden catastrophic failure of the drive tool with the extension handle attached. They are also safer to a cheater bar as lever length and operator effort are both reduced. Torque multipliers only have a fraction of the final torque pressure on the drive tool.

1.9.3.2 Torque multipliers typically employ an epicyclical gear train having one or more stages. Each stage of gearing multiplies the torque applied. In epicyclical gear systems, torque is applied to the input or sun gear. A number of planet gears are arranged around and engaged with this sun gear and therefore rotate. The outside casing of the multiplier is also engaged with the planet gear teeth but is prevented from rotating by means of a reaction arm, causing the planet gears to orbit around the sun gear. The planet gears are held in a ‘planet carrier', which also holds the output drive shaft. As the planet gears orbit around the sun gear, the carrier and the output shaft rotate together. Without the reaction arm to prevent rotation of the outer casing, the output shaft cannot apply torque.

1.9.3.3 Along with the multiplication of torque, there is a decrease in rotational speed of the output shaft compared to the input shaft. This decrease in speed is inversely proportional to the increase in torque. For example, a torque multiplier with a rating of 3:1 will turn its output shaft with three times the torque, but at one-third the speed of the input shaft. However, due to friction and other inefficiencies in the mechanism, the output torque is slightly lower than the theoretical output.

1.9.3.4 Torque multipliers are most often used when an impact wrench is unavailable due to remote locations without power, or where cost considerations require manually operated tools, which do not require any power supply or power source of any kind. There are many instances where screws, bolts, and other fasteners are secured so tightly that using a typical lug wrench with a cheater bar is not sufficient to loosen them. A torque multiplier allows the user to generate high torque output without the use of an air compressor or impact gun.

1.9.3.5 Finally, torque multipliers allow for torque that is more accurate. By reducing the amount of effort needed to tighten, a torque multiplier allows for slow and smooth application, ensuring more accurate torque levels.

Figure 1.9-8 shows Newman tools X-4 torque multiplier. Torque Multipliers consist of a series of gears (Items 1, 8, 14, 15, and 16) which input torque and multiplies it to be supplied to the output head (Item 11).

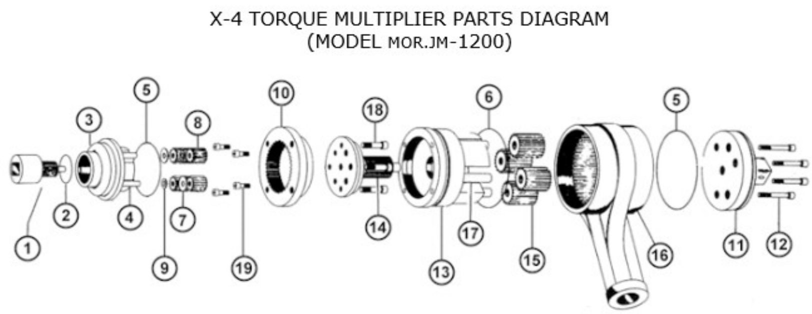


Figure 1.9-8: Newman tools X-4 torque multiplier

1.9.4 TORQUE TRANSDUCERS

A torque transducer, shown in Figure 1.9-9, is a device for measuring and recording the torque on a rotating system, such as an engine, crankshaft, gearbox, transmission, or rotor. Static torque is relatively easy to measure. Dynamic torque, on the other hand, is not easy to measure, since it generally requires transfer of some effect (electric, hydraulic, or magnetic) from the shaft being measured to a static system.

1.9.4.1 One way to achieve this is to condition the shaft or a member attached to the shaft with a series of permanent magnetic domains. The magnetic characteristics of these domains will vary according to the applied torque, and thus can be measured using non-contact sensors. Such magneto elastic torque sensors are generally used for in-vehicle applications on racecars, automobiles, aircraft, and hovercraft.

1.9.4.2 Commonly, torque sensors or torque transducers use strain gauges applied to a rotating shaft or axle. With this method, a means to power the strain gauge bridge is necessary, as well as a means to receive the signal from the rotating shaft. This can be accomplished using slip rings, wireless telemetry, or rotary transformers. Newer types of torque transducers add conditioning electronics and an A/D converter to the rotating shaft. Stator electronics then read the digital signals and convert those signals to a high-level analog output signal, such as ±10VDC.

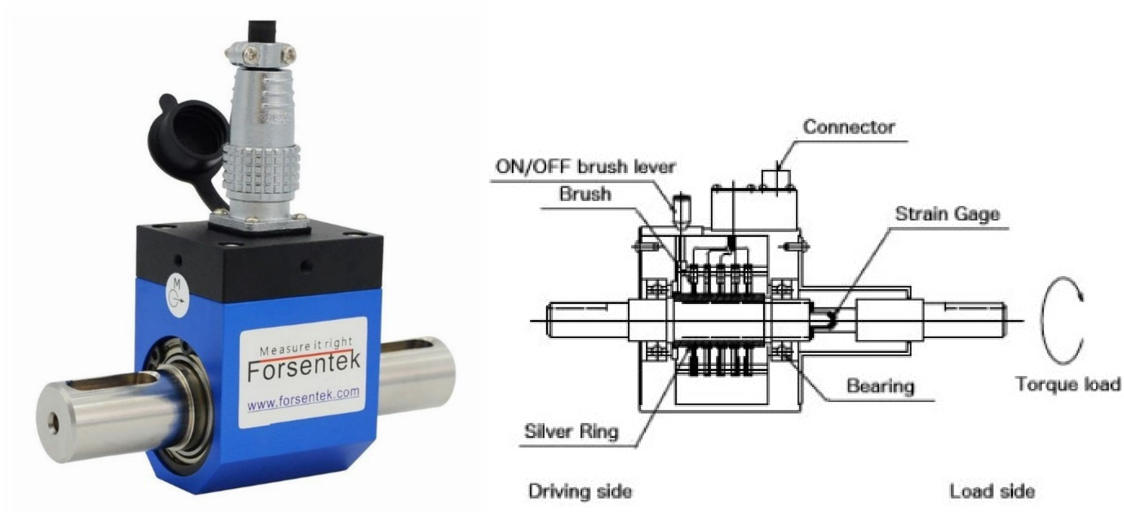


Figure 1.9-9: Torque Transducer

1.9.5 ADJUSTMENTS

1.9.5.1 Deflecting Beam
Deflecting Beam Torque Wrenches are not adjustable. These torque wrenches may not always read zero when no torque is applied, but the zero is not a certifiable parameter. Do not NRTS the TI if it does not align with the zero mark; perform the calibration to determine TI health of item.

1.9.5.2 Rigid Case Dial Indicating
Use a scribe to scratch a mark next to the push rod or sliding screw. This is for reference purposes only. Adjust the push rod or sliding screw in tiny (meaning no more than a millimeter or two) amounts. Also, if there appears to be linearity problems on dial wrenches with push rods, try bending the rod up or down a little bit but don't adjust the rod so much that it touches the plate or comes out of the loop.

1.9.5.3 Snap Action (Impulse)

<u>Method 1</u>: For most of these wrenches, there are two basic ways to adjust them. The first way is called "slipping the handle". This involves removing the locking nut on the load screw, (the long threaded rod that runs through the center of the handle) pulling the handle down until it disengages from the other, not visible nut, and then turning the handle CCW to increase torque or CW to decrease torque. Then push the handle back up to engage the not visible nut and reinstall the locking nut. During this process, if the wrench has a handle with a spring locking mechanism, push up on the spring mechanism to keep the two internal ball bearings from falling out of the handle.

<u>Method 2</u>: This method should only be used when the first method is insufficient, it involves removing the locking nut on the load screw (see the first method for a description), taking a pair of slip-joint pliers and gently grasping the load screw, and turning it CW to increase torque or CCW to decrease torque. Extreme care must be taken during this process to avoid crushing the threads of the load screw. Try to clean the threads of the load screw with a scribe so that the locking nut does not catch on it.

1.9.5.4 Torque Screwdriver
Remove the end cap, unlock or remove locking screw, and turn the handle CW to increase torque or CCW to decrease torque. Then lock or reinstall locking screw and reinstall cap. Some items may require special tools to adjust torque wrench. If decreasing torque value decrease torque below the desired setting (CCW direction), then slowly increase torque (CW Direction) until desired torque setting is obtained.

1.9.5.5 Electronic
These use software adjustments; no mechanical adjustment is possible. Follow OEM user manual for adjustment procedures.

1.9.5.6 Torque Limiter
Remove the locking ring and tap the drive end of the limiter on a bench to remove the scalloped washer. Then put a handle in the top end of the limiter and, using an adjustable wrench, grasp the black area above or below the drive (depending on the orientation) and turn it CW to increase torque or CCW to decrease torque. This is a coarse adjustment and adjust it enough for the scalloped washer to fit back in.

1.9.5.7 Torque Multiplier
Torque Multipliers cannot be adjusted. If Torque Multiplier fails, verify it has had maintenance performed on it prior to calibration. If maintenance has not been performed, send item back to customer to perform maintenance prior to recalibration. If maintenance has been performed and item fails, contact the customer for approved limitation or return to manufacturer for repair.

1.9.6 CALIBRATION

1.9.6.1 Exercising
All torque indicating devices need to be exercised before use. Exercising will be at approximately F.S. of the item being exercised. The recommended number of times a device must be exercised is three, but the device may be exercised more if the technician feels the need to.

1.9.6.2 Calibration Check Points
Calibration check points are approximately the minimum, middle, and maximum position of the torque wrench calibrated range. If the calibration points of the torque wrench sit on the minimum or maximum range of the torque transducer, adjust the calibration points to ensure the readings will be within the torque transducer calibrated range (Preferred Method) or use multiple torque transducers. More calibration points can be taken if technician feels the need to.

1.9.6.3 Erroneous/Bad readings
If while performing a calibration and the readings seem to be erroneous, bad, or feel off, the calibration point may be rechecked or restart the entire calibration. Make sure to re-check any connections, proper alignment, and verify proper torque is being applied.

1.9.6.3.1 Many different factors can influence a torque wrench reading. Ideally, a force applied along the handle, so that it causes rotation through the center of the square will produce a pure torque. Most likely, if not getting relatively consistent readings along any part of the handle, the torque wrench is no longer good, cheaply made, or extremely sensitive. Some generic things that could cause a good wrench to vary in readings could be the placement of force in a different direction, application of torque about a different axis, bending/stretching of the casing, or binding/misalignment of the internal components.

1.9.6.3.2 Assuming the case is rigid, so it is not bending or stretching during application of force, if force is applied in the direction of the red arrow (red target), then a pure torque is produced about the green axis, as shown in Figure 1.9-10. Assuming the case is rigid so it is not bending or stretching during application of force, if force is applied in the direction of the grey arrow (grey target), in addition to the red arrow, a misalignment error will occur causing torque not to be supplied about the green axis. This will cause the torque transducer to see only a percentage of the torque being applied by the torque wrench. This could be caused by the torque wrench not being leveled or pushing/pulling the torque wrench during hand torquing.

1.9.6.3.3 In addition, a misalignment error occurs if a torque is produced about the centerline axis of the torque wrench shown in the blue arrows. This can be caused by rotating the hand during the torquing processes or high coefficient of friction during manual loader torquing process. A high coefficient of friction can be caused by rubber sleeves, rough handles, or clamping of the torque wrench.

1.9.6.3.4 The next factor could be if the torque wrench does not have a rigid case, or a case designed for small torque only. If force is applied only in the red arrow direction but the readings vary, depending on where the force is applied on the handle, this could be caused by bending or stretching of the casing. This can also happen if grasping a sensitive torque wrench or one with a weak casing too hard. This could cause the torque wrench to see higher readings (if binding/ misalignment of internal components) or looser readings (if elongating the spring).

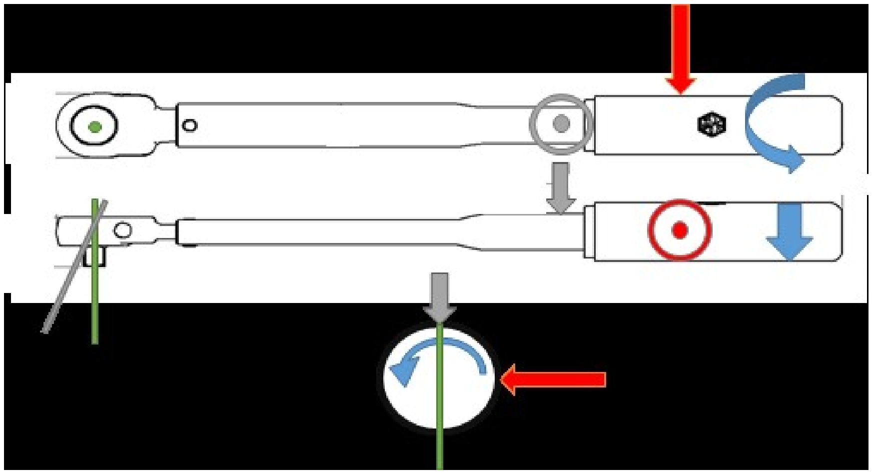


Figure 1.9-10: Influencing Torque Wrench Readings

1.9.6.4 Application of Force
When setting up a torque wrench ensure that the wrench is set up so that the force is applied at approximately the center of the handle.

1.9.6.5 Extension handles
If torque wrench comes with extension handles, annotate serial number of extension handle on calibration label. Apply the force in the center of the handle when using the extension handle.

1.9.6.6 Rubber handles
Rubber handles may cause un-expected readings during calibration. If they cannot be removed and friction is causing issues between the TI and the standard; perform calibration by hand or troubleshoot to reduce friction.

1.9.6.7 Proper Torque Alignment
If a torque wrench is calibrated in the horizontal position, it needs to be leveled, as shown in Figure 1.9-11. Leveling the wrench to the calibrator is important to prevent cross axis error. Use a bubble level along the main line of the wrench. On click type wrenches, this is the main shaft, not the head or handle. On rigid case, dial, and electronic wrenches use the top of the case to level the wrench, assuming that the top of the case is not sloping. On torque screwdrivers and torque watches, keep the shaft perpendicular to the calibrator. Use an adapter, if necessary, to maintain proper alignment. Angle of handle should be set in line with the head (neutral position) to create proper torque alignment.

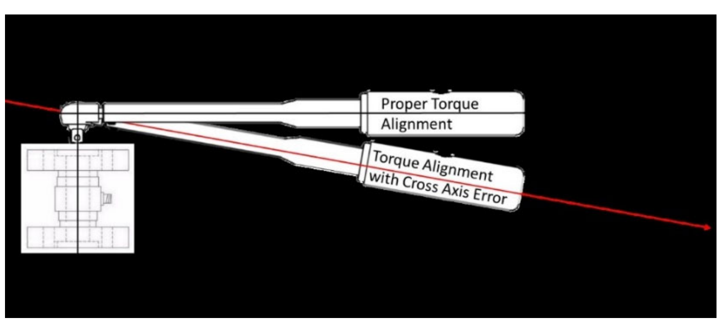


Figure 1.9-11: Alignment of a Torque Wrench

1.9.6.8 Adjustable Flex or Angle Heads
For torque wrenches that have adjustable angle heads or flex heads; calibration will be calibrated in the neutral position. This means the torque wrench handle will be perpendicular to the torque wrench square drive.

1.9.6.9 Fixed Angle Heads
For torque wrenches with fixed heads, at a non-neutral angle from the torque wrench handle, the torque wrench shall be positioned so that the head applies torque in line with the torque transducer axis of rotation.

1.9.6.10 Horizontal vs Vertical Calibration
Both horizontal and vertical calibrations are acceptable. Most of the time torque wrenches are calibrated horizontally. Horizontal orientation places the torque transducer axis of rotation in line with gravity. The CDI/Snap-On and AKO systems are designed in this way. for torque wrenches, this will place the handle along the horizon during calibration, while torque watches and torque screwdrivers will be standing vertically during calibration. Less commonly, torque wrenches are calibrated vertically. Vertical orientation places the torque transducer axis of rotation perpendicular to gravity. This is how torque transducers for CDI/Snap-On, AKO, and Mountz are normally calibrated. The torque transducer will have to be mounted to a calibration stand/block for set up. For large torque wrenches and torque multipliers, a vertical calibration can allow for easier application of torque.

1.9.6.11 CW and CCW
Calibration will be done in any combination of CW and CCW, or in the direction of arrow. Clockwise (CW) is in the motion moving from the 12 to the 3 on an analog clock, Counterclockwise (CCW) is in the motion moving from the 12 to the 9 on an analog clock, and Direction of Arrows needs to be used for open end, box end, and interchangeable head type torque wrenches since this type of wrench can be rotated and used in the opposite direction.

1.9.6.12 Torque Wrench Range
Range of a torque wrench refers to its calibrated range; this is the minimum to maximum torque that a manufacturer will warrant the accuracy. Some Torque Wrenches may have multiple ranges with different accuracies associated with each of them. For most torque wrenches, this range will be from 20% to 100% F.S.

1.9.6.13 Tips
-When a torque wrench is received, open container to allow for stabilization throughout entire wrench.
-Allow readings to stabilize before zeroing or recording readings.
-Torque transducers that are infrequently used should be exercised on a routine basis.
-Ensure wrenches and calibration equipment are free from any dirt or debris prior to calibration.
-Snap Action (Impulse): In order to maintain proper spring tension, torque wrenches should be set at the lowest setting indicated on the shaft when not in use.
-Torque Screwdriver may have multiple break points for every 360 degrees of rotation, typically 3-12.
-Batteries: check batteries for corrosion.
-For Snap-On TECH series TIs, recommend using the Main Loader (P/N: CDI 2000-600-02), appropriate range transducer, and Linear Ball Bearing (P/N: CDI S/2000-173-11).
-Rotate wrenches with ratcheting heads by hand and feel for any roughness in the movement. If feeling any roughness in the movement, disassemble and check for worn ratchet teeth, then replace the ratchet if necessary.
-Adapters are used to attach torque wrenches to transducers, verify adapters are not warn or damaged prior to use. Verify they fit snugly and do not delay transfer of torque from the wrench to the transducer.
-When possible select torque transducers where the TI is being calibrated in the center of the torque transducers range and always try to use a single torque transducer to accomplish a calibration.

1.9.7 TORQUE TRANSDUCER CALIBRATION

1.9.7.1 Proper Alignment
For Proper alignment during calibration of a torque transducer. The torque transducer axis of rotation should be placed perpendicular to gravity.

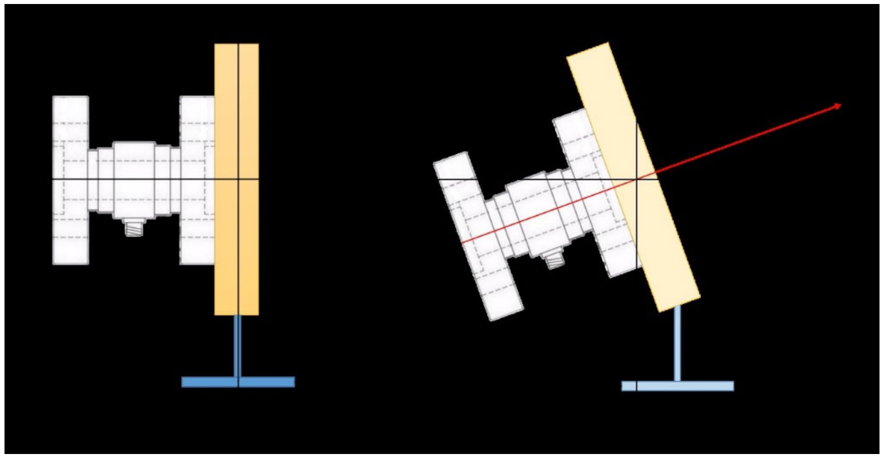


Figure 1.9-12: Alignment of Transducer

The calibration beam should be flush with the torque transducer.

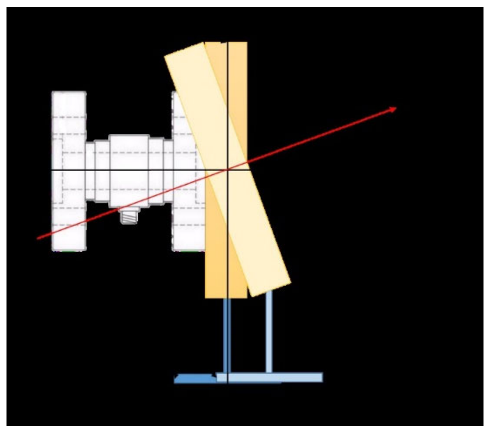


Figure 1.9-13: Alignment of Transducer

1.9.7.2 Positive torque bias
When calibrating a torque transducer, make sure a positive bias is applied to the torque transducer in the direction of calibration before zeroing out the indicator. For evenly balanced torque Arms/Wheels/Disks, it may be necessary to add a hanger, hook, weight, or cable to add a positive bias.

1.9.7.3 Warm up time
For use of torque transducers, a warmup time is not typically required, but when calibrated, a recommended 10 minute warmup time is suggested by some manufactures. The older the system, the more likely a warmup time will need to increase. See individual user's manuals for warm up time requirements.

1.9.7.4 Placement of weights
When adding or removing weights during torque transducer calibration, always apply weight slowly in a smooth fashion (do not allow the weight to fall).

1.9.7.5 Local Gravity
A local gravity prediction can be obtained at https://www.ngs.noaa.gov/cgi-bin/grav_pdx.prl

1.9.7.6 Calibration Aid K6-9024
If errors are occurring in spreadsheet, re-download spreadsheet prior to contacting AFMETCAL. Most errors that occur are usually unique incidents caused by excel and can normally be resolved by re-downloading the spreadsheet.

1.9.7.7 Static Electricity
In some laboratory, environment static electricity can cause issues, this will be more apparent in the low torque transducers. This may cause the indicator to reset or error out. If static electricity build up and discharge is an issue, it may be necessary to ground the outside case or outer cage of the indicator and/or transducer.

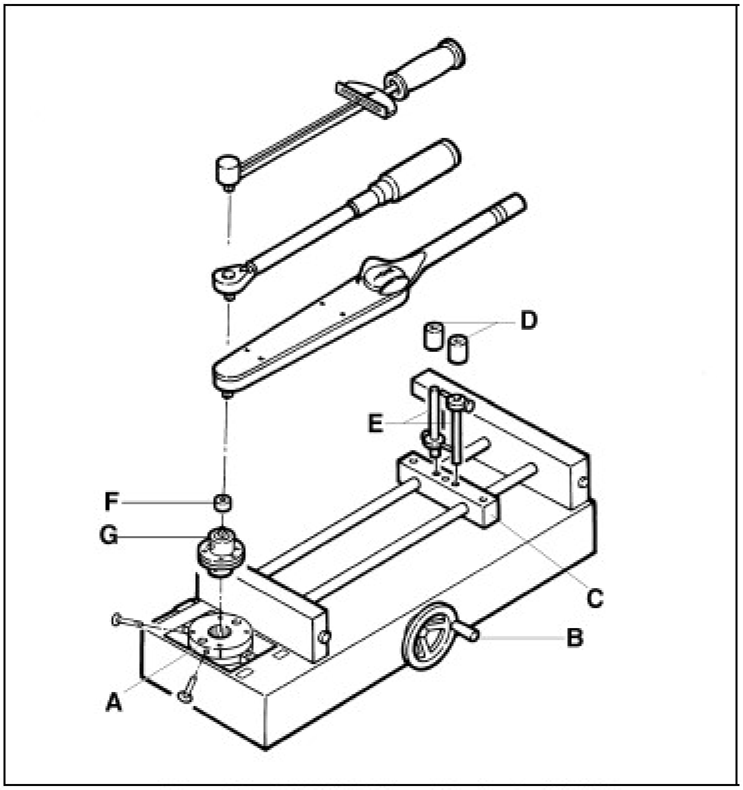


Figure 6-2: 2000-600-02 Manual Loader, Exploded View

Figure 1.9-14: CDI TFC200 Torque Calibrator

1.10 FORCE

1.10.1 Introduction
The definition of force is (F=ma), where force is equal to the mass of an object times its acceleration. In the force measurement area, the acceleration is usually gravity. Gravity varies across the world and depends on your latitude in relation to the Earth's equator along with altitude from sea level. At sea level and along the equator, gravity is 9.80665 m/s^2 (32.174 ft/s^2). This value is also known as standard gravity. Gravity value will change depending on your location.

The Force Measurement Area provides traceability from NIST to the PMELs through the Force Exchange Kit. The AFPSL Standards are traceable to NIST through mass weights. AFPSL calibrates (Secondary) Force Exchange Kits for the PMELs using deadweight calibrators. The PMELs use these (Secondary) Standards to calibrate TMDE. Major applications of force measurement are Aircraft Weighing Kits, Aircraft and Truck Scales, Load Cells, Aircraft Cable Tensiometers, and Force Gages. Force is derived primarily from mass standards and a geodetic survey, and includes temperature, humidity, and barometric pressure standards.

1.10.2 Gravity Corrections
A Gravity Correction Factor (GCF) corrects for the difference between local and standard gravity when the standard being used is not of the same measurement parameter as the TI. This means that a Force Standard (lbf) is calibrating a Mass TI (lbm) or a Mass Standard (lbm) is calibrating a Force TI (lbf). The application of a GCF depends on the local gravity and the accuracy of the TI being calibrated. When the % Difference between Local Gravity and Standard Gravity is > 20% of the TI's accuracy, a GCF must be used to determine the actual force or mass applied.

If the % Difference is < or = 20% of the TI accuracy, and the TAR is 4:1 or better, then the GCF does not need to be used. If the TAR is < 4:1, the GCF must be used under all circumstances. All these calculations are now performed in the Calibration Aid K6-9065 Gravity Correction Factor Calculator.

Corrected Applied Load = Applied Load x GCF

1.10.2.1 Mass Standard - Force TI

$$GCF = \frac{Local\ Gravity}{Standard\ Gravity}$$

1.10.2.2 Force Standard - Mass TI

$$GCF = \frac{Standard\ Gravity}{Local\ Gravity}$$

1.10.3 Force Gauges

Force gages are force measuring devices and are calibrated by Mass Weights, Deadweight Calibrators, or Vertical Force Press. A determination has to be made whether to apply a gravity correction factor when calibrating with mass weights. Usually, mass weights are used when the TI has a measuring range up to 50 lbs.

1.10.3.1 Analog Force Gauges with a dial indicator must be tapped lightly to eliminate any potential friction error. If the TI has a single shaft all the way through the gage and the dial indicator operates in only one direction, the TI only needs calibrated in either Tension or Compression. If the dial rotates in both the CW and CCW directions, calibrate the TI in both directions.

1.10.4 Load Cells

A load cell is a transducer that converts the force applied into an electrical voltage. Though load cells are not as accurate as a deadweight calibrator, they are a much cheaper alternative. Every PMEL has a Load Cell Exchange Kit that includes four load cells spanning from 2K lbf to 60K lbf. They are paired with a digital indicator that stores the load cell calibration data. These load cells serve as the Base Reference Standard for force measurements. Load Cell Exchange Kits are calibrated at the AFPSL using deadweight calibrators and are in turn used in the PMEL to calibrate a variety of TIs.

1.10.4.1 Load cells have an effective range of 10% to 100% FS. They have a sweet spot of 20% to 100% FS. The load cells used in our PMELs have a calibrated range of 5% to 100%, which is not ideal but allows the PMEL technician to use one load cell for TMDE calibrations in most instances. Because the AFPSL calibrates the load cells below 10%, an uncertainty is provided for the following ranges: 5-10, 10-20, and 20-100% FS. The worst uncertainty is for the range between 5 to 10% FS.

1.10.4.2 Load Cell Definitions

Creep is the change in load cell signal occurring with time while under load and with all environmental conditions and other variables remaining constant. When a force is applied to a solid material within its elastic limit, the resulting deflection will increase very subtly with time if the force is held constant.

Hysteresis - algebraic difference between output at a given load descending from maximum load and output at the same load ascending from minimum load. (The difference between the outputs at the ascending point and correspond descending point).

Linearity - the algebraic difference between output at a specific load and the corresponding point on the straight line drawn between minimum load and maximum load.

Rated Output - the output corresponding to capacity, equal to the algebraic difference between the signal at (minimum load + capacity) and the signal at minimum load.

Repeatability - the maximum difference between output readings for repeated loadings under identical loading and environmental conditions.

Reproducibility - the ability to take measurements on one test setup and then repeat them on a different test setup.

Static Error Band (SEB) - the band of maximum deviations of the ascending and descending calibration points from a best fit line through zero output. It includes the effects of linearity, hysteresis, and non-return to minimum load.

Shunt Calibration - the electrical simulation of output by connection of shunt resistors of known values at appropriate points in the circuitry.

Strain Gage - the device that converts a force to a resistance that can be measured. The resistance of a length of wire will increase if we stretch it. When the wire is stretched, the diameter of the wire will get smaller to maintain the same volume. The smaller diameter of the wire means that its resistance per unit length will be higher.

Using this phenomenon, the wire can be bonded onto a flexure and the change in resistance can be used to measure the change in length of some dimension in a load cell flexure when a force is applied.

Temperature Effect on Output - the change in output due to a change in ambient temperature.

Temperature Effect on Zero - the change in zero balance due to the change in ambient temperature.

Zero Balance - the signal of the load cell in the no load condition.

1.10.4.3 Load Cell Troubleshooting
The major contributor to repeatability error of a load cell system is the mechanical connections of the external fixtures.

Contributors to reproducibility errors are as follows:
Tightness of the mechanical connection of fixtures
Rigidity of the load frame or force application system
Repeatability of the hydraulic forcing system itself
Application of a dead weight load too quickly, causing over-application of the force due to impact.
Poor control of reading times, introducing creep into the data.
Unstable electronics due to temperature drift, power line susceptibility, noise, etc.

1.10.4.4 Load Cell Alignment
The most important rule is always avoid applying a compression load flat-to-flat from a plate to the top surface of a load cell hub. The reason for this is that it is impossible to maintain two surfaces parallel enough to guarantee that the force will end up being centered on the primary axis of the load cell. Any slight misalignment, even by a few µinches, could move the contact point off to one edge of the hub, thus inducing a large moment into the measurement.

1.10.4.4.1 One common way to ensure alignment in compression mode is to use a load button. Most compression cells have an integral load button, and a load button can be installed in any universal cell to allow compression loading. Minor misalignments merely shift the contact point slightly off the centerline. In addition to compensating for misalignment, the use of a load button of the correct spherical radius is absolutely necessary to confine the stresses at the contact point within the limits of the material.

1.10.4.5 Load Cell Sensitivity
The sensitivity of a load cell measures how its output signal changes as the load cell excitation voltage varies when subject to a load at rated capacity. Systems that have low sensitivity ranges, or are of lower quality, will not be able to detect small changes that occur when a load cell experiences a force from a minimal weight.

Typical unamplified analog load cells have a sensitivity rating in units of mV/V. This load cell sensitivity rating is specified on a load cell data sheet often in the 1 mV/V – 3 mV/V range. Most quality load cells will come with a factory calibration sheet, which specifies the actual sensitivity rating for that individual load cell. This load cell sensitivity value can be used to convert the load cell's output to scientific units of weight or force.

1.10.4.6 Load Cell Excitation Voltage

Load cells require an excitation voltage to produce an output signal. This is directly related to the fundamental workings of the internal Wheatstone bridge. Load cell excitation values are often listed by a manufacturer as "recommended" and "maximum" excitation voltage. As their names imply, the recommended value is that which the manufacturer recommends for best output results and the maximum value is that which should not be exceeded.

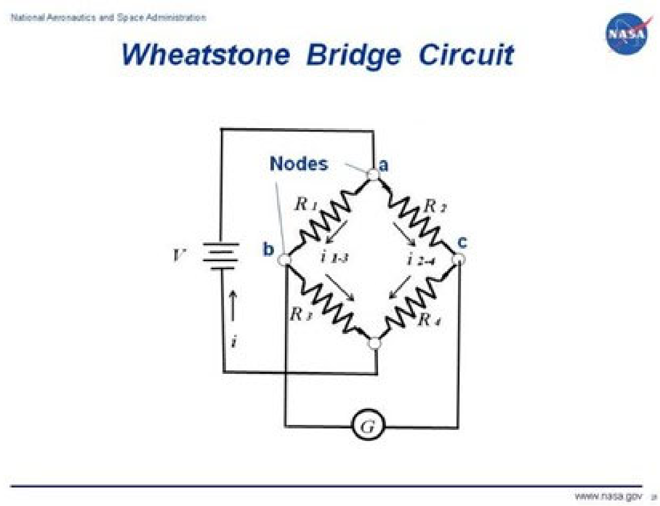


Figure 1.10-1: Wheatstone Bridge Circuit

A higher excitation voltage will produce a higher output voltage swing when a load is applied to the cell. So, bigger is better, right?

Yes, to a degree. Larger signals are easier to measure and digitize. Additionally, assuming the noise is constant, the ratio of signal to noise (SNR) increases. This is good from a data quality standpoint.

However, a high excitation voltage has drawbacks. Higher voltages through the resistive strain gauges (which comprise the Wheatstone bridge) will cause more current to flow and heat the strain gauges. The cell body acts as a heat sink to keep the gauges cool. If the maximum rated excitation voltage is exceeded, the heating will cause signal perturbation or gauge failure. Additionally, in battery operated devices, high excitation voltage (and thus, current) will cause the battery to be depleted much faster than lower excitation voltages through the circuit.

Excitation voltages lower than the manufacturer's stated maximum are acceptable for the given load cell. The manufacturer's recommended value is obviously best, but there is no harm in a lower excitation voltage. For example, 5V is a common excitation voltage for modern load cells. Modern instrumentation amplifiers are much better than old designs and their output signals are not compromised by the lower excitation voltage. It is perfectly fine to use a 5V excitation amplifier with a 10V recommended excitation load cell. (However, the converse is not true!)

Finally, when choosing the excitation voltage, consider the common mode voltage produced by the cell's output. The amplifier or other signal conditioning electronics must be able to handle this common mode voltage, whose value is 50% of the excitation voltage. For example, a 10V excitation produces a 5V common mode voltage. Typically, these amplifiers provide the excitation voltage to the cell; when this is the case, an external excitation voltage is not recommended.

Source: https://tacunasystems.com/knowledge-base/load-cell-faq/

1.10.4.7 Convert Load Cell Output Voltage to Pounds, Kilograms, or Newtons
As mentioned above, each load cell should come with a calibration certificate denoting its sensitivity. This value can be used to convert the load cell's output signal to units of weight or force. To calculate the raw output voltage of the cell relative to its rated full capacity, use the following equation:

$$V_{out,max} = SV_e$$

Where: $V_{out,max}$ = output voltage from load cell when loaded to 100% of rated capacity (mV)
S = load cell sensitivity (mV/V)
V_e = excitation voltage (V)

Typically, load cells are used with amplifiers to transform the small output voltage to an easily measurable voltage (while conditioning the signal with filters, etc.). If we add an amplifier to the mix, the equation changes to:

$$V_{out,max} = SV_eA$$

Where: A = amplifier gain (V/V)

If we were to convert this output voltage to force or weight, we would use the ratio of the actual output voltage to the maximum output voltage, which is equal to the ratio of the actual load to the maximum rated load:

$$\frac{V_{out}}{V_{out,max}} = \frac{L}{L_{tot}}$$

Or

$$\frac{V_{out}}{SV_eA} = \frac{L}{L_{tot}}$$

Rearranging, we can solve for L:

$$L = \frac{L_{tot}\,V_{out}}{SV_eA}$$

Where: L = load on cell (Kg, LB, N, etc.)
L_{tot} = total rated capacity of the load cell (Kg, LB, N, etc.)
V_{out} = output voltage from load cell when loaded (mV)

1.10.4.8 Calculate the Load Cell Sensitivity if a Factory Calibrated Value is not given.
If the load cell is not factory calibrated, it must be field calibrated to determine the sensitivity. This is done through the following steps:

Record the no-load output voltage of the load cell,
Load the cell with a known load,
Record the output voltage with the known load.
Subtract the known no-load output voltage from the known load voltage and use the resulting voltage as the calibration factor:

$$S = \frac{L_{tot}\,(V_1 - V_2)}{V_eL_{cal}A}$$

Where: V_1 = known no-load output voltage (mV)
V_2 = known load output voltage (mV)
L_{cal} = known load (Kg, LB, N, etc.)

The units for the known load and total rated capacity should match and thus cancel out.

1.10.5 GENERAL FORCE PRESS SETUP AND OPERATION

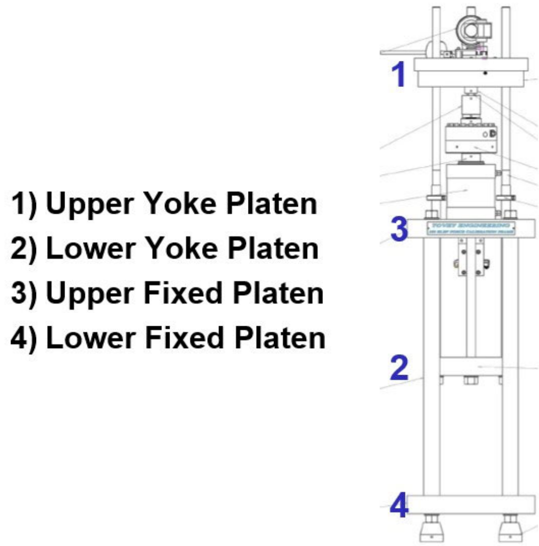


Figure 1.10-2: Vertical Force Press

1.10.5.1 Spacer Blocks
Tension TIs require large bolt like adapters to be installed through the bottom of the machine. It has been found that often times the space between the floor and the Lower Fixed Platen is not large enough to fit these adapters. Raising the machine onto spacer blocks helps alleviate this problem. Spacer blocks should be made of appropriate material that will remain level and not compromise safety.

1.10.5.2 Leveling
Vertical Force Presses typically come with a bubble level; however, using a stride level produces much better results. Place the 12 inch stride level on the Lower Fixed Platen along both axes and diagonals. Level the press by adjusting the leveling screws in the feet first side to side and front to back, then across both diagonals. It should be leveled as best as possible within one division. This will ensure the press will function as it should.

1.10.5.3 Locking Collars
It is important that all the collars are level in respect to one another. Misalignment is noticeable when raising or lowering the Upper Yoke Platen from the standard load cell. The platen will visually not be centered with the ball adapter and the platen will appear to translate laterally in reference to the load cell when it is raised and lowered. When the Upper Yoke Platen is lowered down on the load cell, the compression ball should not engage a side of the cup first and slide into place. The compression ball should appear to engage the entire diameter of the adapter at the same time.

The locking collars may become difficult to tighten and slip occasionally. If this problem arises, perform the following procedure:

1) Lower the Upper Yoke Platen onto the standard load cell
2) Remove the bolt from the collar; then clean both the collar thread and bolt thread with alcohol
3) Apply a thin film of grease to bolt thread; then reinsert bolt into threaded hole in collar

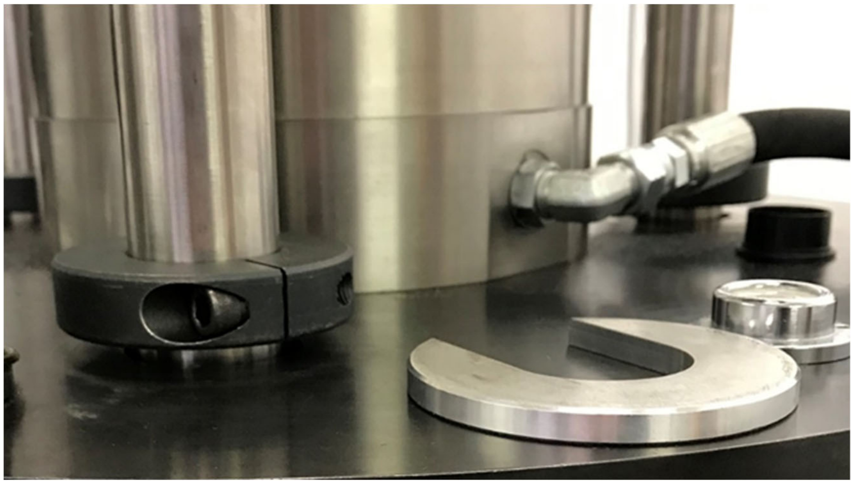


Figure 1.10-3: Vertical Force Press Locking Collar

1.10.5.4 Counterbalance Arm
The Counterbalance Arm needs to be adjusted to ensure the platen rods move smoothly through the holes in the Upper Fixed Platen reducing off axis error. The Arm swings from side to side and the counterbalance weight can be moved along the Arm. This adjustment is more or less a trial and error process until smooth movement is observed. This means that the platen rods move through the center of the hole without contacting the sides.

The following procedure may be used to help with counterbalance alignment:

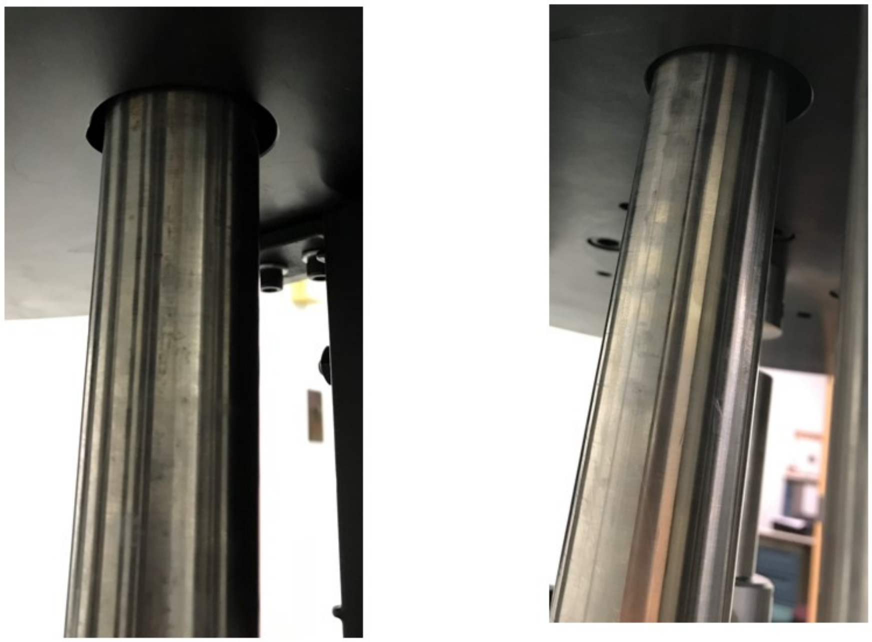
1) Setup two standard load cells with ball adapters. One load cell shall be placed in the standard position while the other is in the TI position.

2) Lower the Upper Yoke Platen onto the standard load cell to lift the yoke off the collars

3) The Platen Rods should not make contact with the Upper Fixed Platen.

4) Raise the TI until the compression ball is about to make contact with the adapter. The compression ball should not engage the side of the cup first and slide into place. The compression ball should appear to engage the entire diameter of the adapter at the same time.

5) Make adjustments as applicable to meet steps 3 and 4.



Centered Slightly off to the Left

Figure 1.10-4: Platen Rod Locations

Figure 1.10-5: Compression Ball Centered with Adapter

1.10.5.5 Standard and TI Cables
Any cables connecting a load cell or other TI to an indicator or power source should not be taut. The cables should be placed in a way that prevents them from being stretched or pinched. It is desirable to have them mounted so that they hang free. They can be mounted on the wall or using the machine load frame.

1.10.5.6 Clean Mating Surfaces
The load cells and the adapters should be cleaned on all mating surfaces and threads. Use a lint free cloth and alcohol to remove any excess dirt and grime, which may affect the seating of the mating surfaces. A brush can also be used to clean the loose debris from the mating surfaces and threads.

1.10.5.7 Warm Up
Ensure the standard load cells, indicator, and TI are properly warmed up before beginning calibration, consult the OEM manual to verify the proper warm up times.

1.10.5.8 Exercise
Force TMDE is generally exercised three times to full capacity in order to erase all history of previous temperature cycles and mechanical stresses.

1.10.6. AIRCRAFT AND TRUCK SCALES
Aircraft and truck scales come in different sizes and capacities. Each scale contains a specific combination of load cells used to weigh the item. They contain two, four, or six load cells depending on the size of the tire being supported. Truck scales normally contain two load cells, one in the front and one in the back. The scales with four will have a pair of load cells in the front and back of the scale. The scales with six will have a pair of load cells in the front, middle and back of the scale. The scale is designed to measure the correct weight when the tire is in the approximate center location.

Figure 1.10-6: Aircraft on scales

Aircraft scale specifications are determined by the engineers who design the aircraft. General guidance is provided by the Weight and Balance 1-1B-50 document for the applicable aircraft.

There are two main manufacturers of aircraft and truck scales: Intercomp Company and General Electrodynamics Corporation (GEC). Both have a different philosophy on how to simulate the aircraft or truck tire during calibration.

Intercomp Company uses an Aluminum Distribution Plate and a Rubber Pad to simulate the tire of the aircraft or truck. The size and thickness is specified by the manufacturer, who sells them along with the scales.

General Electrodynamics Corporation (GEC) uses a Hardened Steel Puck, Steel Distribution Plate, and an Aluminum Distribution Plate. These are stacked together in wedding cake orientation to simulate the tire of the aircraft or truck.

The Air Force has not performed an independent study to verify which setup best simulates an aircraft or truck tire. Until then, the Air Force will continue to use the calibration setup recommended by the OEM of the scale.

Under no circumstances should the standard load cell be applied directly to the TI. This point load can damage the TI and the standard load cell. If the OEM does not provide any guidance for distribution plates, it is recommended to use a Hardened Steel Puck directly under the load cell. Then use an Aluminum Distribution Plate roughly the same size but never larger than the weighing platform between the steel puck and the TI. Applying the standard load cell directly to an Aluminum Distribution Plate may cause damage to the plate over time due to Aluminum being a softer metal.

The short 3 month calibration interval of aircraft scales is a common issue for the users of these scales. These scales need to be handled with care. They are not to be left out in the environment (rain, dirt, and sand) and not thrown out of the back of a truck on a flight line. Ensuring that the scales are properly cared for will ultimately help the calibration interval be extended.

1.10.7 CABLE TENSIOMETERS

It is important that the cable used during calibration is the same as the cable used by the end user. The cable can be obtained by contacting the PMEL or USER that sent the cable tensiometer. In addition, request a cable be sent from a depot or a PMEL that maintains aircraft. Lastly, contact an OEM and procure cable. There are four main specifications to verify: Flexible vs. Nonflexible, Composition, Type, and Construction.

Flexible: MIL-DTL-83420

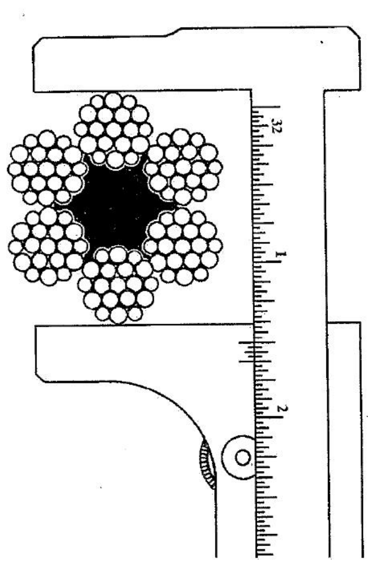
Composition A: Carbon steel, zin, or tin over zinc coated
Composition B: Corrosion resistant steel
Type I: Non-jacketed wire rope
Type II: Jacketed wire rope
Construction: 3x7, 7x7, 7x19

Nonflexible: MIL-DLT-87161

Composition A: Carbon steel, zinc, zinc coated
Composition B: Corrosion resistant steel
Type I: 1 x 7 class
Type II: 1 x 19 class
Construction 1: Right Lay
Construction 2: Left Lay

Both MIL-DLT-83420 and MIL-DLT-87161 include tables that list the minimum diameter and tolerances.

When measuring a cable, the wire shall be in a free-state and not under tension.



Right way. Set the machinist's caliper to read the widest diameter. Vernier scale reads to 1/128th of an inch.

Figure 1.10-7: Correct way to measure cable

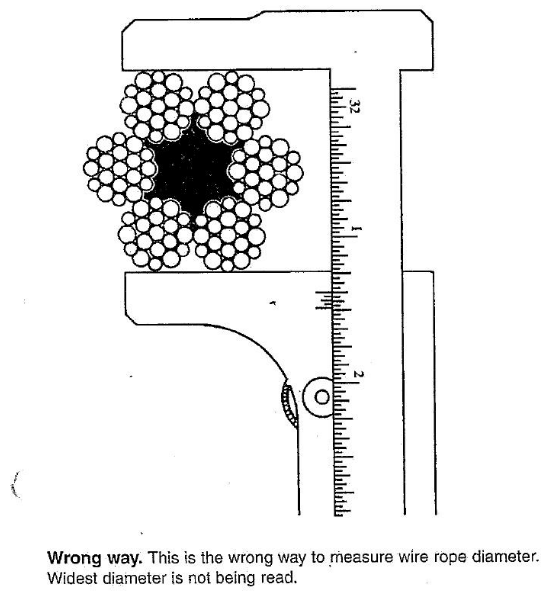


Figure 1.10-8: Incorrect way to measure cable

1.10.8 DYNAMOMETERS vs CRANE SCALES

These two items appear similar since they are both used for tension measurements; however, they have a distinct difference: Dynamometers are FORCE measuring devices that have eyelets on either end to attach clevises or adapters. Crane Scales are MASS measuring devices that typically have a clevis on the top and a hook on the bottom. Dynamometers should be calibrated with the end users' shackles whenever possible.

Figure 1.10-9: Dynamometer (left) vs Crane Scale (right)

1.10.9 SPRING TESTERS

Springs are measured by the USER using Spring Testers, which are calibrated by the PMELs. The USER is looking for either a Spring Constant or Load Rate of a Spring (a force at a specified compression or tension of the spring).

$$F = -kx$$

Where F = force
$-k$ = spring constant
x = distance traveled

The spring constant can be determined by adding weight to the end of the spring and recording the length of travel of the spring. This data can be plotted on a graph and the k is the slope. This can also be accomplished applying force from a load cell. This is true for both compression and tension of a spring.

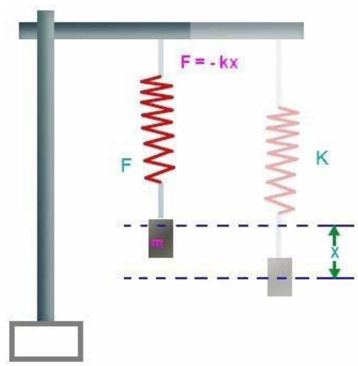


Figure 1.10-10: Spring Constant relationship

In general, spring tester accuracy is 1% FS for analog and 0.1% FS for digital. If the tester comes with a scale it must be calibrated, otherwise the deflection must be measured with another length measuring device.

1.10.10 TOVEY C3-100 AUTOMATED VERTICAL FORCE PRESS

The Tovey Engineering C3-100 Automated Force Press was procured in 2011 for the calibration of Force TMDE such as Load Cells, Force Gauges, and Tension Links. The item was directly shipped to the PMELs and the technicians were responsible for installing it. A training video along with the manual was provided with each press. The manual should be read as well as viewing the video to become familiar with this force press before operation. With an automated hydraulic pump applying force, it is much more likely that a load cell is damaged if a mistake is made during the calibration process. It is imperative that a technician using this system is properly trained.

1.10.10.1 Emergency Stop Button

The Emergency Stop Button on the force press should be activated (depressed) unless a calibration run is being performed. Certain safety precautions are enabled when the Emergency Stop Button is activated. If the Emergency Stop button is not used, unnecessary pressure is applied to the system causing seals to leak.

1.10.10.2 TI Spacing

The Tovey Software must perform the Auto-Zero of the yoke before the TI engages. Watch for the auto-zero to occur then quickly look at the TI; it should also read zero. If the TI does not read zero, adjust the spacing between the TI and the load frame. This is a trial and error process. For compression measurements, the more space must be created between the TI and the Upper Fixed Platen. For tension measurements, adjust either the size of the tension test space or the bottom adapter.

1.10.10.3 Manual Mode vs Manual Load Setting

The system was designed to be used in either automatic mode (default) or in Manual Mode. Do not use the Manual Load Setting menu to perform calibrations. This mode does not have all the built in safety features that are found in the Automatic and Manual modes.

1.10.10.4 Results Table

The error column is not the intuitive error between the Standard and the TI. It is the difference between the results and the terminal line.

1.10.11 TOVEY 9150 DIGITAL INDICATOR

The Tovey 9150 is the digital indicator for the Tovey CS Series Force Exchange Kit Load Cells.

1.10.11.1 Standardization

The 9150 is required to be standardized once daily before use. It is important that the 9150 has warmed up for the OEM's recommended 1.5 hours and that the environmental temperature has been stable during this time. It has been observed that the 9150 is sensitive to rapid temperature swings. There are two ways to perform the standardization: manually or semi-automatic through the C3-100 software. The manual procedure can be found in the Force Exchange Kit Manual and the software procedure can be found in the Software User Manual. Perform the applicable procedure to the channel being used.

Figure 1.10-11: Transducer Simulator

For the manual procedure connect the TS-2-300 Transducer Simulator to the 9150 and allow for a 30 minute warm up. The indicator must be with ±20 counts of the calibrated values of the simulator.

$$-4.00010 = -4.00030\ to - 3.99990$$
$$4.00015 = 3.99995\ to\ 4.00035$$

CAUTION

When performing the 9150 standardization with the indicator connected to the C3-100, the hydraulic unit must be kept off to help ensure the machine will not accidentally react to the simulated load. If not strictly observed, could result in damage to, or destruction of, equipment or loss of mission effectiveness.

1.10.11.2 TARE

9150 used with the C3-100
- Channel A should be set to mV/V
- DO NOT TARE the indicator after the standardization procedure. This includes after the yoke weight is applied.

9150 used without C3-100
- Channel A can be set to lbf
- TARE out the weight of the yoke

1.10.11.3 Sensor Select

9150 used with the C3-100
- Sensor Select = 210. The software uses the Standard Load Cell file within the software.

9150 used without C3-100
- Sensor Select = Standard Load Cell S/N

Sensor Select Location
- Enter Setup Mode by pressing “< >” at the same time. Scroll over to Sensor Select

1.10.11.4 Load Cell Zero Balance

The Zero Balance Verification is used to check the overall health of a load cell. It serves as a quick way to see if a load cell has been damaged.

CS Series load cells have a Zero Balance tolerance of 1% of Rated Output. This tolerance is applied to the Zero Balance value provided by the AFPSL. The example below is a generic example. Please use the Rated Output value provided by the AFPSL.

10K, 30K, 60K, 100K: 4mV/V Rated Output = 0.04 mV/V Zero Balance Tolerance
2.5K: 2 mV/V Rated Output = 0.02 mV/V Zero Balance Tolerance

1.10.11.5 Data Validation
AFMETCAL is frequently asked why the 5% calibration point is not found loaded into the indicator. The 9150 was designed to store 10 ascending and 10 descending points, so the 5% point is not input. When the load cell is calibrated at the AFPSL, the 5% calibration point is checked. The coefficients used to derive the data found in the indicator is derived from a larger data set that includes the 5% point.

1.11 VIBRATION

1.11.1 Introduction
Vibration is an oscillation that defines the motion of a system. It is a quantitative measure used to verify that frequencies and amplitudes do not exceed any structural limits and is used to detect performance issues and possible failures before they occur. Vibration measurements are vital to many various Air Force missions such as validating major rotating components' balance and serviceability on aircraft, AFRL tests, and test cell fan component balancing. Vibration can be measured via a diverse array of sensors, which sense a change in a physical characteristic, either acceleration, velocity, or displacement. Displacement is any change in position. Velocity is the rate (speed) at which position is changing. Acceleration is the rate at which the speed is changing. PMELs annually calibrate thousands of vibration measuring devices that are used in a variety of applications and environments, consisting primarily of accelerometers and velocity sensors (displacement sensors are less common). All PMEL calibrations are traceable to the NIST through AFPSL exchange standards and base working standards, most of which the PMELs can calibrate.

1.11.2 SENSOR TYPES

1.11.2.1 Accelerometers
Accelerometers are the type of sensors most used for vibration monitoring, due to their versatility and reliability as they can be used for measuring low to very high frequencies. An accelerometer is simply a transducer that converts a mechanical acceleration into a proportional electrical signal. There are two main types of accelerometers used for vibration measurements, Integrated Electronics Piezoelectric (IEPE) (these may also be referred to as Integrated Circuit Piezoelectric (ICP), Isotron, Delta-Tron, or Piezotron sensors, depending on the manufacturer) and Charge (may be referred to as 4-20 mA) sensors. Both IEPE and Charge sensors are considered piezoelectric sensors. A characteristic of piezoelectric material is high impedance, so these sensors require electrical amplification to convert to a lower impedance signal that responds to acceleration for effective measurement. IEPE sensors integrate the amplifier into the sensor itself, while charge sensors require an external charge amplifier for signal conversion. These converted signals are signal conditioning for powering the devices. IEPE sensors are more commonly used today and some of their advantages include better system reliability, simpler operation, and the capability to run continuously. The main limitation of IEPE sensors is that they are unable to run at elevated temperatures above 325 °F, compared to Charge sensors which can operate >500 °F without issue.

Figure 1.11-1. Example of IEPE and Charge sensors

1.11.2.1.1 Accelerometer output is generally expressed in terms of millivolts per g (mV/g) for IEPE sensors or pico-coulombs per g (pC/g) for charge sensors, where g is the acceleration of gravity (9.8 m/s^2). The majority of accelerometers are uniaxial, but triaxle accelerometers are available that simultaneously measure vibration in three axes. Also to note, seismic accelerometers are a type of accelerometer used to detect low level vibrations (can be used for earthquake testing) and are quite larger than most accelerometers and have higher outputs and limited frequency range. Shock accelerometers are another specific type of accelerometer with higher shock overload limits used to also capture pulse width activity. Though not as widely used, applications where shock accelerometers are utilized include drop tests, blast tests, pyrotechnic tests, and shock tests.

1.11.2.2 Velocity Sensors
Like accelerometers, velocity sensors (or pickups) are also used for measuring vibration. They are primarily used for low and medium frequency measurements, typically for vibration monitoring and balancing of rotating machinery applications. Compared to accelerometers, they have lower sensitivity to high frequency vibrations. Velocity sensors measure vibration by responding to velocity, as opposed to accelerometers, which measure vibration by responding to acceleration. There are also two different types of velocity sensors, electrodynamic moving coil and piezoelectric. Older moving coil sensors contain a coil supported by a fixed magnet and springs and require no signal amplification because the coil movement relative to the magnet generates a voltage proportional to the velocity at which the coil is moving. Moving coil velocity sensors are filled with an oil to dampen the springs. Due to gravity, moving coil velocity sensors behave differently for vertical or horizontal mounting and typically have an axis that is more sensitive and are thus calibrated in both axes. Piezoelectric velocity sensors, like accelerometers, require amplification (external or internal if equipped) to generate an output signal. The piezoelectric type provides better noise reduction in addition to durability and more versatility for mounting. A special type, called a Velocimeter (the 7310 and 8866 are examples) is a piezoelectric transducer that responds to acceleration, but has an integrated velocity output signal. Velocity sensor output is generally expressed in millivolts per inch per second (mv/in/s or mv/ips) and typically have a lower frequency range compared to accelerometers (maximum frequency usually no more than 2500 Hz).

Figure 1.11-2. Example of velocity sensors

1.11.2.2.1 Relationship between Acceleration, Velocity, and Displacement
The two sensors primarily seen in PMELs are discussed above, though the characteristics of all are related through the physics of sinusoidal motion. Acceleration (a) is expressed in meters per second squared (m/s^2). Velocity (v) is expressed in meters per second (m/s). Displacement (d) is expressed in meters (m). Given a simple vibrating system, the conversion from displacement to acceleration and vice versa can be calculated as shown below.

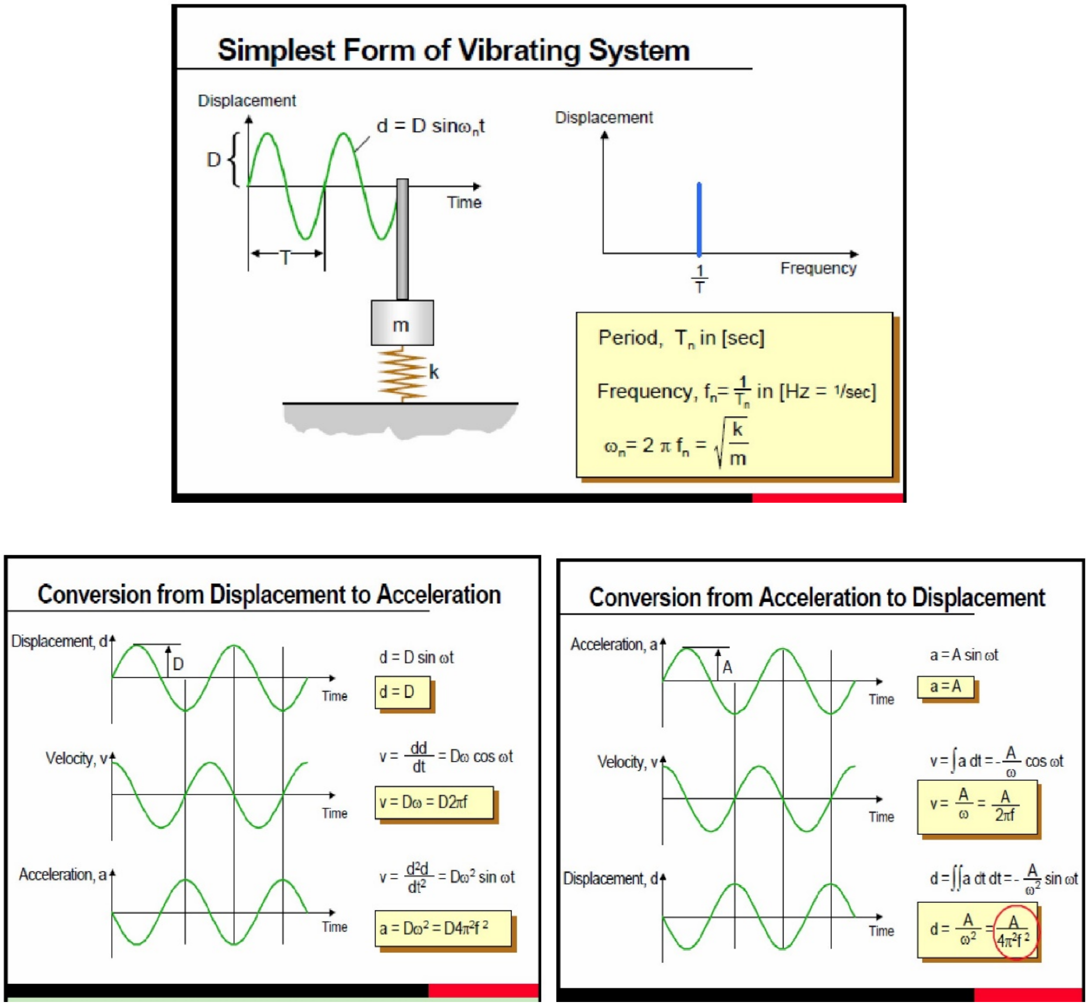


Figure 1.11-3. Relationship graphs

1.11.3 AFPSL & PMEL STANDARDS

1.11.3.1 9155D and K9155D23

The 9155D is the primary vibration calibration standard located at the AFPSL and the K9155D23 is the secondary vibration calibration standard located at the PMELs. Consisting of two subsystems, excitation and measurement, both the 9155D and K9155D23 utilize the calibration methodology known as the back-to-back method. In both systems, a standard (internal reference) consisting of an inverted design accelerometer is paired with a signal conditioner. This standard is designed to measure vibration on its top surface and test sensors are mounted on top of it. In theory, the vibration measured on the standard's top surface should be the same as the vibration measured on the test sensor's bottom surface. Therefore, the standard can determine the sensitivity at any frequency of the test sensor's test range using a simple ratio:

$$Sens_{TEST} = \frac{Voltage_{TEST}}{Voltage_{STANDARD}} \; x \; Sens_{STANDARD}$$

As the standard sensitivity is already known and the system provides the measured voltage output of both standard and test sensor. The internal reference's mounting surface is made of Beryllium (with nickel-plated coating) as it provides minimal relative motion between the two surfaces for more accurate calibration results.

The calibration described above is what we refer to as a secondary calibration and both systems are capable of this. However, as the primary standard, the AFPSL's 9155D also includes a laser interferometer providing greater accuracy. Calibrating using the laser interferometer is an absolute (or intrinsic) method as it compares measurements to a natural constant – laser light wavelength.

Figure 1.11-4. K9155D23 system

The K9155D23 provides automated calibration over a frequency range of 5 Hz to 15 kHz. It provides a wide variety of tests available to monitor and check sensor health and supports calibration of the aforementioned types of sensors. The excitation subsystem produces test conditions (constant vibration) and is provided by the power amplifier (2100E21-C), the shaker (or exciter) (396C10), and function generator (on PCI card inside computer). The power amplifier supplies regulated DC current to the shaker and provides the suspension of the 396C10 armature. The power amplifier also regulates the air supply to the 396C10 via an internal regulator. The function generator provides the signal to the power amplifier, which excites the shaker.

NOTE

If at any time the shaker must be picked up, ALWAYS pick it up from the bottom. Picking up the shaker by the top plate could cause transverse performance issues, which could affect uncertainties.

Unlike older systems, which utilized flexure-based electrodynamic shakers, these standards use air-bearing shakers. Flexures introduce rocking and bending motion into the shakers armature, which is not in the direction of pure axial movement. This flexure contributed greater error to the uncertainty of calibrations and the use of air bearings eliminates (or greatly reduces) this error.

The measurement subsystem measures outputs of the standard and the test sensor and calculates the sensitivity of the test sensor. Measurement is provided by the vibration standard (080A207 internal reference paired with the 442A102 signal conditioner - ALWAYS paired), the test sensor signal conditioner (443B101), and PC-based data acquisition system (DAQ) on the same PCI card inside computer. The 443B101 provides excitation and gain (if needed) for the test sensor and the DAQ measures the voltage from the reference and test sensor channels to calculate the test sensor's sensitivity.

The 9155D behaves the same as the K9155D23, except it has extended calibration capability down to 0.2 Hz up to 20000 Hz, due to laser interferometer, as well as an additional lower frequency shaker. The 9155D also includes a pneumatic shock exciter capable of performing shock accelerometer calibrations up to 10,000g.

1.11.3.2 353B04

The exchange transfer standard that is used to calibrate the field's K9155D23, the 353B04, is calibrated annually at the AFPSL using the laser interferometer. Upon receipt, PMELs are directed to follow steps outlined in T.O. 33K-2-11. If results are good, return prior 353B04 to the AFPSL. PMEL should then use the newly received 353B04 to perform the frequency response calibration portion of certifying their K9155D23 as described later.

1.11.4 CALIBRATIONS

1.11.4.1 Vibration Sensor Specifications

The sensitivity of the accelerometer is the ratio of the sensor's electrical output to its mechanical input. Vibration sensor manufacturers specify a nominal reference sensitivity on their data sheets. This sensitivity is normally valid at one frequency, typically 100 Hz. This frequency is widely chosen because it is usually in a flat region for all sensors (not too high or too low) and the area with the lowest uncertainty. Reference sensitivities may also be at 159, 159.2, or 160 Hz on occasion. Usually manufactured in Europe, those manufacturers do not choose 100 Hz as the reference to avoid line power measurement issues, as 100 Hz is a harmonic of 50 Hz, the line frequency in Europe. Since they have a much lower range of frequencies, the sensitivity of seismic sensors is usually referenced to 10 Hz. The sensitivity is specified with a tolerance, usually ±5% or ±10%, and means that that the accelerometer's sensitivity should be within this stated tolerance deviation from the stated nominal sensitivity. On occasion, the accuracy may be expressed in terms of dB, instead of a percentage (conversions can be found in section 1.11.6 below).

Similar to the sensitivity specification, the frequency response also tells the user the ratio of the sensor's electrical output to its mechanical input with the additional variable of frequency added. Frequency response is the sensitivity specified over the transducer's entire frequency range and may also be referred to from some manufacturers as "amplitude response", since the phase response is rarely specified. Likewise, while it is an option, we do not calibrate our sensors for phase. Frequency response is always specified with a tolerance relative to the reference sensitivity. On occasion, some manufacturers may list frequency response specifications as bands instead of separate ranges similar to:

1 Hz - 7 kHz - ±5%
0.7 Hz - 11 kHz - ±10%
0.35 Hz - 20 kHz - ±3 dB

This is sometimes misunderstood, but this is just a condensed way to express what actually translates to:

0.35 Hz - <0.7 Hz - ±3 dB
0.7 Hz - <1 Hz - ±10%
1 Hz - 7 kHz - ±5%
>7 kHz - 11 kHz - ±10%
>11 kHz - 20 kHz - ±3dB

Again, the frequency response is referenced to the sensitivity at the reference frequency. For example, if the sensor measures 10.1 mV/g at a reference frequency of 100 Hz, the value at 10 kHz must be ±10% of 10.1 mV/g (or between 9.09 and 11.11 mV/g) to be in tolerance. Likewise, it must be ±5% of 10.1 mV/g at 500 Hz (or between 9.595 and 10.605 mV/g).

1.11.4.2 Mounting

The internal reference armature contains a Nickel-plated mounting surface, though below the plating, the armature inserts if made of Beryllium.

WARNING

Beryllium is safe in solid form but harmful in dust form. Therefore, it is EXTREMELY IMPORTANT to take caution when mounting test sensors. If not strictly observed, could result in injury to, or death of, personnel or long term health hazards.

Test sensor surfaces shall be clean and smooth, and one must inspect all test sensor and necessary adapter plate mounting surfaces for any raised burrs, scratches, or other surface defects. If necessary, deburr prior to mounting.

The two mounting techniques most commonly used in PMELs are stud mounting and adhesive mounting. Stud mounting provides best frequency response with high repeatability and is recommended whenever possible. If using a stud, make sure to not apply more than the recommended torque when tightening. One consideration when using studs is that we must make sure that no stud “bottoming out” occurs (i.e., the ends of the studs do not touch the ends of the holes). Stud bottoming or interference between the base of the accelerometer and the structure affects accelerometer transmission and measurement accuracy. In addition, having the armature “bottoming out” affects the response. The gage block provided with the system is used to set the armature at an appropriate height before beginning calibration eliminates the possibility of armature bottoming.

In cases where stud mounting is not possible, adhesive mounting is the next best alternative. Though not as good as stud mounting, the frequency response is fairly high with good repeatability. If possible, using a separate adhesive mounting base will prevent the adhesive from potentially damaging the accelerometer base and mounting threads. If a sensor was adhesively mounted, DO NOT scrape, file, or grind the armature to remove adhesive. That should be accomplished using an appropriate solvent, such as Acetone. Allow the solvent time (a few minutes) to penetrate the surface to react with the solvent and twist sensor off using a proper removal tool. Remnant adhesive can be then cleaned using a paper towel.

In rarer cases, for lower frequency response items, magnet mounts may be used.

for best frequency response, the mechanical stress from connecting cables shall be minimized. It is also important to decrease triboelectric noise from independent cable vibration.

For best surface contact, apply a thin layer of silicone grease between the accelerometer base and mounting surface for best high-frequency transmissibility. It is also important to note that if there is odd behavior at the upper end of a sensor’s frequency range during a calibration, it is most likely due to a mounting issue. On the other hand, if there is odd behavior at the lower end of a sensor’s frequency range, it is most likely due to a cabling issue.

1.11.4.3 Performing a Calibration.
Prior to performing the first calibration of the day, a daily system verification shall be performed. If it has not been done in over 24 hours, the VERIFICATION button will be red on the Test Measurement panel screen. Using the mounting tips above, perform verification using the 353B04 that was provided with the system (not to be confused with the reference 353B04 provided by the AFPSL). The daily system verification is a tool that can be used to identify issues with the system’s repeatability that may need to be addressed. Ensure proper mounting technique as described in section 1.11.4.2 is used when mounting a test sensor.

Accelerometers will either be a top mount or a bottom mount sensor, which describes the side the sensing unit is located. The overwhelming majority of sensors are top mount and for these calibrations, the internal reference (080A207 with the 442A102) is the reference sensor. As mentioned in section 1.11.3, the science behind the back-to-back method requires that the reference see the same acceleration as the test sensor. As the 080A207 is inverted, a “top mount” test sensor is mounted on top of it so that both surfaces are measuring the same acceleration (or as close to it as possible). In very rare cases where the test sensor is a bottom mount, the 353B04 accelerometer will act as the reference and will be mounted on top of the test sensor, as bottom mount sensors are mounted under the reference.

The screen below is the Test Management screen where parameters are set pre-calibration. Detailed directions are in calibration procedures, but first ensure that the proper reference is selected for the 396C10 – the 080A207/442A102 for top mount test sensors (practically every sensor) or the 353B04 for a bottom mount test sensor. Double clicking on any of the three boxes under (1) Sensor Under Test Information will bring up the Test Sensor Setup to select the appropriate test sensor. Calibration data for each test sensor is stored in a database where previous calibrations can be recalled. Each test sensor model number must be added as a model number template to the database before a particular test sensor can be added.

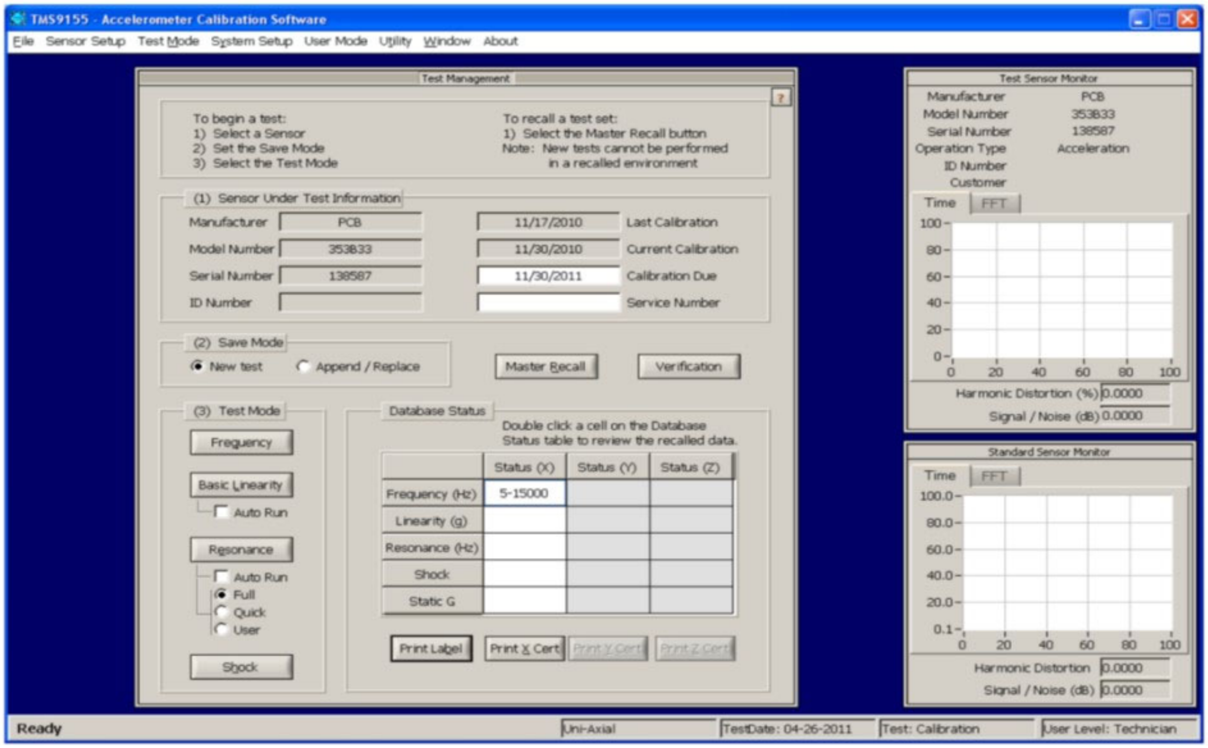


Figure 1.11-5. Test Management screen

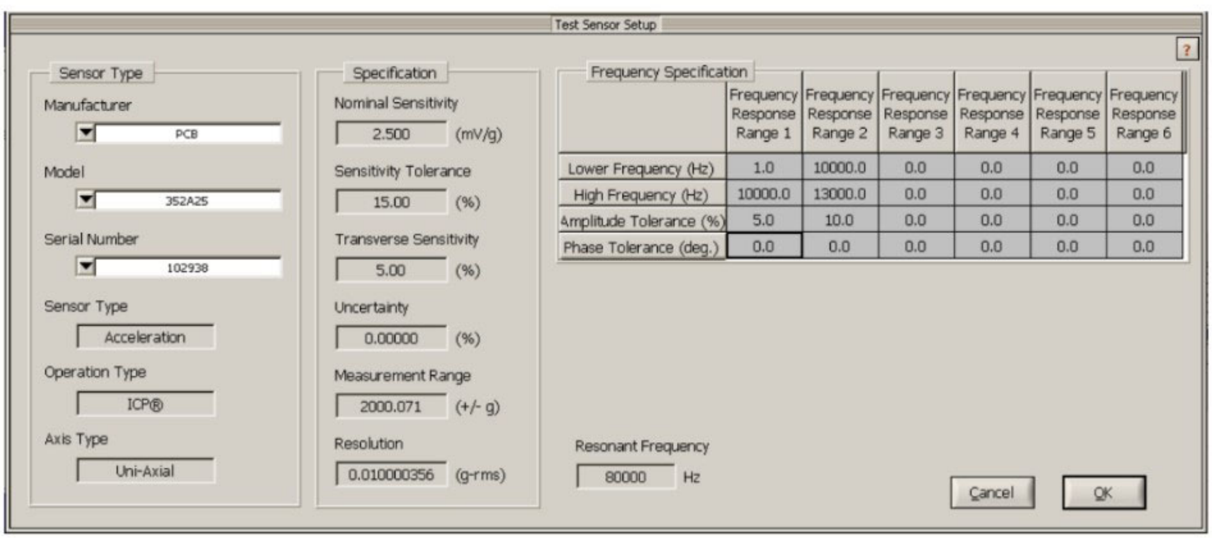


Figure 1.11-6. Test Sensor Setup screen

When ready to begin calibration, under (3) Test Mode, click Frequency to bring up the Frequency Response Calibration screen. Unlike previous calibration standards, after selecting a test level to begin, the K9155D23 automatically adjusts the test level elsewhere throughout the frequency range to ensure calibration stays within the acceleration limits of the test sensor. As a general rule of thumb, technicians are directed to select 1g as the test level if the nominal sensitivity of the TI is ≥50 mV/g or pC/g or 10 g if the nominal sensitivity is <50 mV/g or pC/g. for most velocity sensors, test points are listed in tech data in AFCAV. In rarer cases, the technician can determine test points by checking the TI's nomograph (see section 1.11.7). Technicians can enter preferred test points in the Running SUT Record for a given test sensor (for each specified frequency, enter the test level under Amplitude).

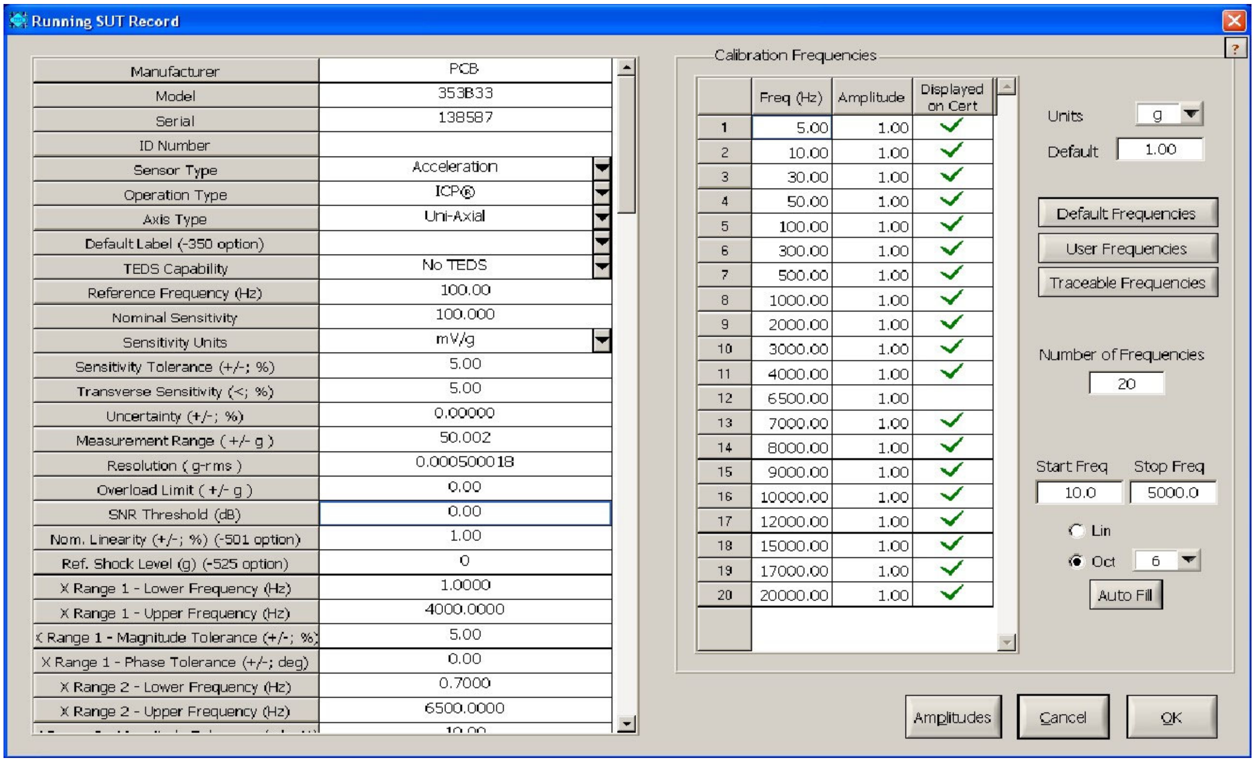


Figure 1.11-7. Running SUT Record screen

The screen below is the Sine Calibrator calibration screen. Technicians have the option of starting the frequency sweep at either the upper end or the lower end of the test sensor's range, by selecting Sweep Up or Sweep Down as the Test Mode. The test level is selected per T.O. or AFCAV direction. The first point calibrated will be the reference frequency. From here, the software will automatically adjust the test level as needed elsewhere. As mentioned above, in those situations where test points are manually chosen, select 'Profile' as the Test Level before beginning a calibration; then select the low and high frequency for the test sensor being calibrated. Once test settings are correct, click Run Calibration to perform a calibration. The curve that is displaying "Deviation" shows the frequency response curve and displays the deviation of the test sensor's frequency response relative to the sensitivity measured at the reference frequency. The phase difference between the test sensor and reference sensor is also displayed, though as previously mentioned, it is not calibrated as most manufacturers do not specify it. Save and/or print certificates as necessary when complete.

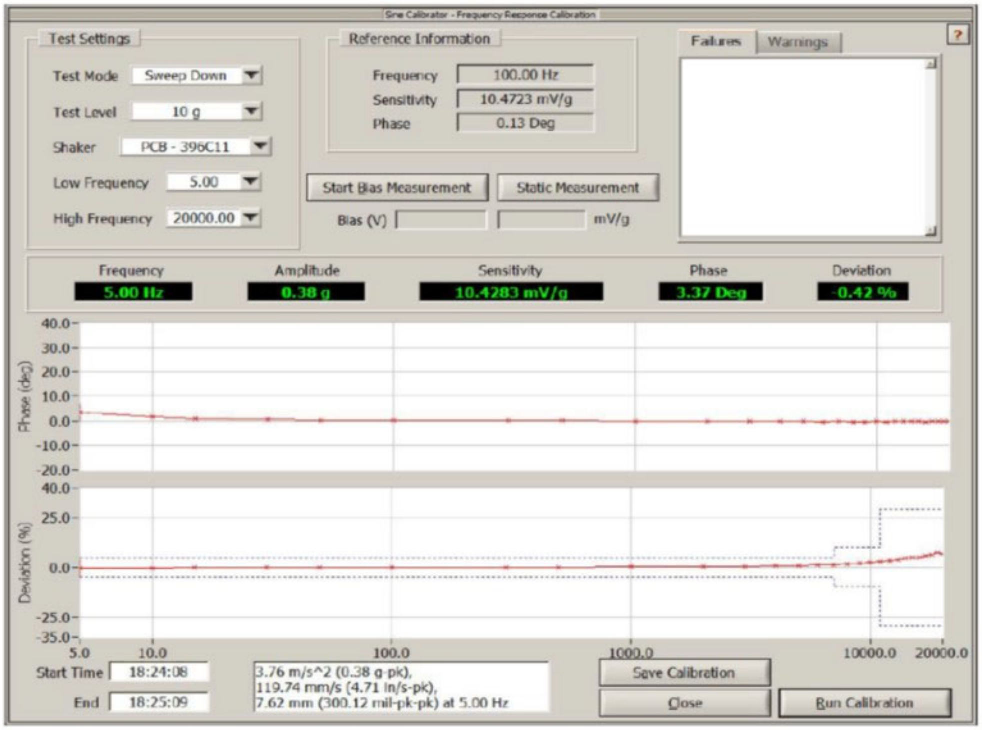


Figure 1.11-8. Sine Calibrator screen

1.11.4.4 K9155D23 System Calibration
The K9155D23 is calibrated annually and consists of three parts that must be completed in sequence per T.O. 33K3-4-1192-1. The first is a frequency check of the system signal generator's output. The second is a semi-automated calibration of the DAQ system channels and 443B101 signal conditioner. The last portion of the system calibration is a frequency response calibration of the internal reference (080A207/442A102) using the 353B04 reference accelerometer as the standard.

Upon receipt of the new 353B04 sensor, technicians should check the tolerance of their internal reference by running a calibration of the new sensor and compare the difference between the results and the AFPSL 353B04 calibration report and verify the differences are within the tolerance of the K9155D23 (±3% from 5 Hz to 5kHz and ±4% from >5 to 15 kHz). If they are within tolerance, the old exchange 353B04 can be returned to the AFPSL and now calibrate the system using the new 353B04. If the above differences are not within system tolerances, calibrate the system using the new 353B04 as a standard and then re-verify that the differences are within tolerance. If not, contact the TCM for further instruction. Otherwise, the old exchange 353B04 can be returned to the AFPSL.

To calibrate the internal reference, making sure the software is in "Advanced Mode" (vs "Technician Mode"; see calibration procedures and/or user manual), first add the new 353B04 to the database by creating standard data files based off of the AFPSL certificate per directions in T.O. 33K3-4-1192-1 and then select it as the standard sensor for the 396C10. Next, select the 080A207/442A102 as the "Sensor Under Test" on the main panel screen. Though the equipment is setup as a normal calibration, select to run this as a Reference Calibration from the Test Mode menu and then run as if a normal calibration.

Once completed, press the Ref Update button to automatically update the calibration information for the internal reference. It is also recommended to press Ref Export to manually create copies of the new data files for backup. Technician should then re-select the 080A207/442A102 as the standard sensor for the shaker and run a calibration of the 353B04 for comparison. Since the AFPSL charted values were just used to create the new data files for the working standard, the newly calibrated results should be very close to the AFPSL values.

1.11.5 VARIOUS TIPS

-When using an adapter plate larger in diameter than the shaker armature to accommodate larger test sensors, such as the 144-144-000-401, use a spacer such as a 0.1 in. gage block between the shaker armature and the larger adapter plate if the adapter plate could contact the signal wires in any shaker travel position. This will help to prevent possible damage to the internal reference signal wires.
-All cables should be strapped down as much as possible to prevent cable whip. Suggest using clay to secure the cables to the Air Bearing Shaker.
-The suggested guidelines in procedures for choosing test levels will generally work for the majority of sensors. The technician should adjust the test level, as necessary, if the selected test level does not produce clean, stable signals on the Standard Sensor and Test Sensor plots on the calibration screen, not to exceed 10 g.
-For CEC velocity sensor test levels, select 'Profile' instead for the Test Level and use the test points found in test plan uploaded in AFCAV for the appropriate part number to set up the calibration points.
-If the system is unable to locate a stable signal when calibrating a test sensor in Voltage mode using an external voltage source (such as the Wilcoxon 991D, for example), it may be necessary to bypass the test sensor signal conditioner and plug the test sensor output directly into the SUT Input.
-Test sensor signal conditioner should be bypassed for velocity sensor calibration.
-If stud mounting a test sensor with a base geometry that does not enable the use of a Torque Wrench, the test sensor shall be torqued hand tight.
-In the horizontal position, height adjustment of the armature using the gage block is unnecessary. Gain should be set to ZERO.

1.11.5.1 Maintenance

There are some maintenance checks that would be beneficial to perform periodically. Anti-rotation bands on the vibration shaker will need to be replaced on occasion because they had either completely broken or dry rotted. These anti-rotation bands are important as they minimize armature rotation when shaking (unnecessary rotation could affect calibration, especially in the horizontal position). This is normal wear and tear on the system and they will need to be replaced periodically, though areas in dryer climates may experience this more often.

A link to a general Shaker Maintenance video has also been uploaded to the AFMETCAL SharePoint under Engineering POCs>K-Areas>K3>Vibration. This video demonstrates how to perform the above maintenance checks, which include alignment of the shaker, as well as visual inspection of the anti-rotation bands. There is also a Shaker Insert Installation video there that could also be useful. There have been a few instances in the field where there has been distortion in the test sensor signal. This distortion is likely due to mounting adhesives such as wax or glue that may be present on the outside of the armature surface and may be removed by cleaning the armature, as shown in the Insert Installation video. Note that at 3:45 in the Insert Installation video, the narrator states that continuity should be found between the DC shell and insert screws during an electrical test. This is an error, as continuity should NOT be found.

If there is ever a need to remove the armature insert from the shaker, replace and tighten the four mounting screws in an alternating pattern as shown below and torque screws to 25 in-lbs.

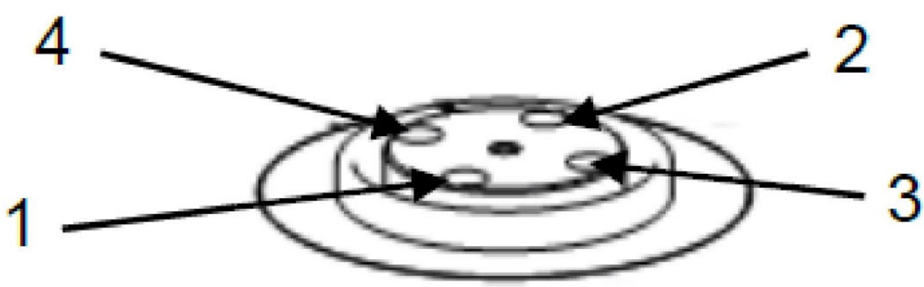


Figure 1.11-9. Armature torque pattern

1.11.6 CONVERSIONS

1.11.6.1 Conversion factors.
Whenever average, RMS, or peak values are required, the following conversion factors must be applied.

MULTIPLY

TO OBTAIN	**AVERAGE**	**RMS**	**PEAK**	**PEAK TO PEAK**
AVERAGE	1.000	0.900	0.636	0.318
RMS	1.111	1.000	0.707	0.354
PEAK	1.571	1.414	1.000	0.500
PEAK TO PEAK	3.142	2.828	2.000	1.000

1.11.6.2 Equation for Acceleration to Displacement:

$$D = \frac{19.56 * G}{F^2}$$

Where: *D* = Displacement (inches pk-pk)
G = Acceleration (g-pk)
F = Frequency (Hz)

For example:

$$D = \frac{19.56 * 10}{10^2}$$

Where: D = 1.1056 in or 1956 mils pk-pk

1.11.6.3 Equation to convert dB to percent.

$$Tp = \left(10^{(Td/20)} - 1\right) * 100$$

Where: *Tp* = Tolerance expressed as a percentage
Td = Tolerance expressed in decibels

Common conversions:

+1 dB =+12.20% +3 dB =+41.25%

-1 dB = -10.87% -3 dB = -29.21%

1.11.7 NOMOGRAPHS
Manufacturers of velocity sensors usually include unique vibration nomographs on the data sheets or manuals for these items to show a graphical method for determining the expected maximum capability of the item. The following example is a nomograph for the 4-128-0127 Velocity Sensor.

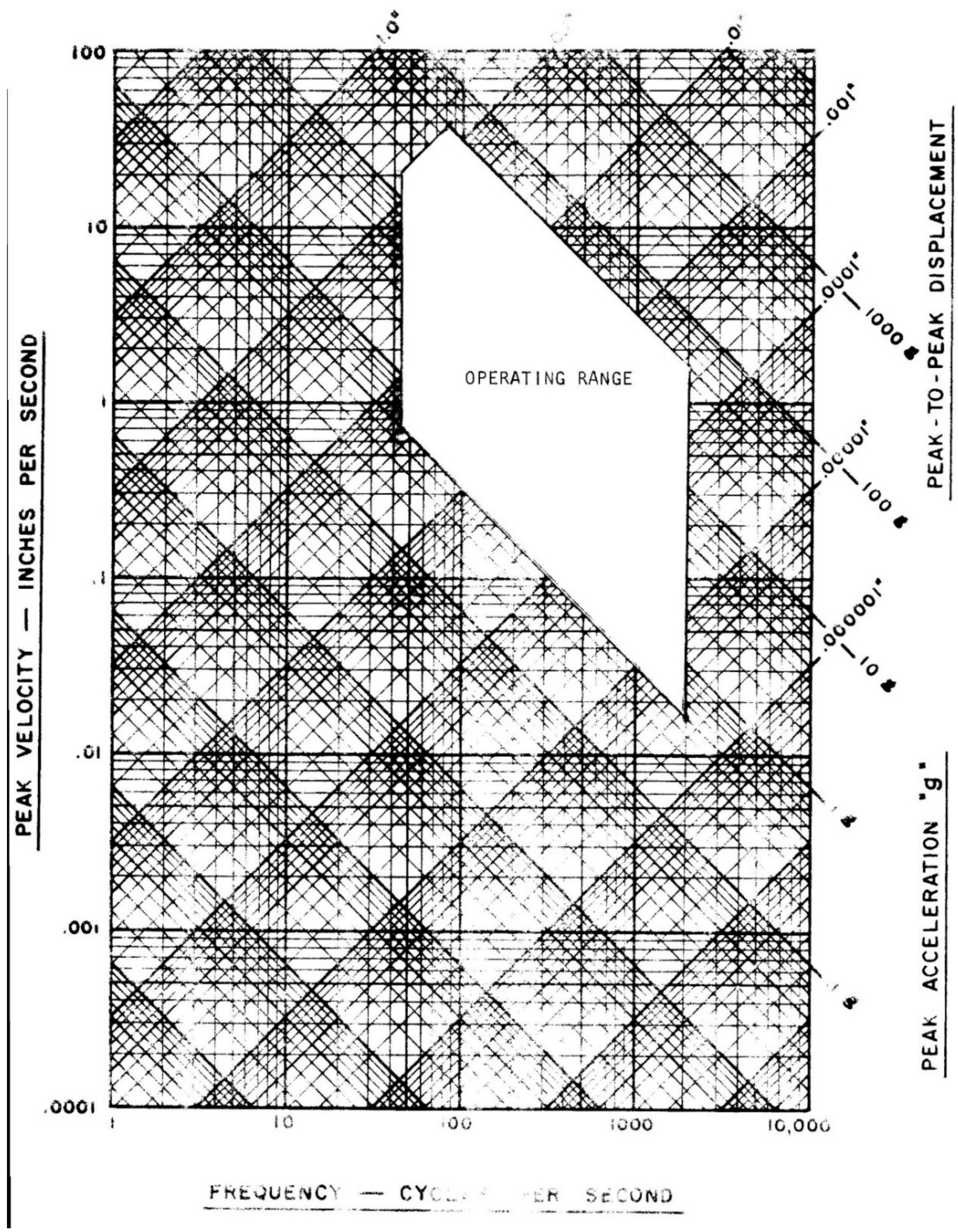


Figure 1.11-10. Nomograph

It is composed of four logarithmic scales: Frequency (horizontal scale), Velocity (vertical Scale), Acceleration (diagonal downward left to right), and Displacement (diagonal upward left to right). A vibration of simple harmonic motion (a pure sinusoidal wave shape) exhibits these four quantities. If two of the four quantities are known, the remaining quantities can be determined from the nomograph. Technicians (in cases where test points are not provided) may determine the maximum velocity (or acceleration if applicable) possible for a given frequency and choose a test level that is found within the operating range of the TI's nomograph. For example, at 45 Hz, the nomograph shows that the minimum inches per second is 0.7 ips, while the maximum is 20 ips. For 500 Hz, the nomograph shows a minimum and maximum of 0.065 and 6 ips. For 1000 Hz, the nomograph shows a minimum and maximum of 0.032 and 3.2 ips, and so on. For this particular part number, the ATP provided in AFCAV lists appropriate test points.

SECTION 2

ELECTRONICS

2.1. GENERAL VOLTAGE MEASUREMENTS

(Reference paragraph 2.2 Voltage Measurements from T.O. 31-1-141-8 for additional information)

2.1.1. Making the Invisible Visible

One difficulty that electrical metrologists have in general is that the electrons they work with are not something you can pick up, touch or feel. In reality, you infer their existence based on how they affect objects. You do not see the current flowing in a light bulb…you see the heat generated by the current flowing in a light bulb. Given this, tools that can measure various attributes of electricity are invaluable in electrical metrology.

2.1.1.1 Meters

When using a meter (and this applies generally to all tools) is to have some idea of what you are looking for. For example, if you are trying to read an Alternating Current (AC) signal, do not set up meter to Direct Current (DC). This may sound overly simplistic, but poor tool setup is the most common mistake made by the average metrologist. You can extrapolate from this rule to solve other misreading problems. This leads to a second rule and a case in point. The rule: do not trust auto set-ups implicitly. The case in point is in trying to read a motor voltage; the voltage across the motor is a Pulse-Width Modulation (PWM) signal with a peak of 140V. Attempting to read the average voltage across this motor with a Fluke 87 for example, the readings do not make sense (note the application of rule one). Find that when the meter is in auto-range mode, the brains of the meter is confused by the PWM input. Setting the meter manually to the correct range results in an accurate and stable reading.

2.1.1.2 The two most common signals you will examine with a meter are voltage and current. In setting up a meter to read voltage, remember that you are hooking the leads up in parallel with the signal you are going to examine. When reading current, the meter must be hooked up in series in the circuit. Remember that current is a measurement of flow. Nearly all meters require you to hook the leads into different plugs when reading voltage vs. current. This is so the signal can be routed through an internal shunt resistor across which a voltage is measured and scaled to represent current.

2.1.1.3 Typically, there is a fuse in the meter to protect this shunt from overload. On some meters the shunt is a different value for different ranges of current.

2.1.1.4 All meters will affect the circuit they are hooked to whether they are in voltage mode or current mode. The question you should ask is "How much?" A typical digital multimeter (DMM) has 1 MΩ to 10 MΩ of impedance in the voltage-measuring circuit. As you hook the leads up to the circuit, consider that you are adding a resistor to the same points.

2.1.1.5 An example. Let's assume the meter has a 10 MΩ input impedance, and we are measuring the output of a voltage-divider circuit.

2.1.1.6 Let's calculate the effect this has on the circuit. We will start by calculating the parallel resistance of the meter and the resistor it is hooked to.

2.1.1.7 It is the product over the sums, so that would be (1K * 10M)/(1K + 10M) or 0.9999K.

2.1.1.8 Now we apply the voltage divider rule. We see that without the meter the output will be at 2.5 V, but with the meter the output will be 2.4999 V. So we will probably all agree that the meter does not have a significant effect in this case.

2.1.1.9 Let's change the value of the resistors and see what happens. We will make them 1 MΩ resistors. The first thing you should notice is that without the meter the voltage output will be the same as the previous circuit. But what happens when you hook up the meter? 1M//10M (the "//" marks mean "in parallel with") gives a value of 909.09K. Run that through the voltage divider rule and you get 2.3809 V at the output. Do you see how the meter can make a difference? Hopefully, what your intuition is telling you is that the effect of the meter depends on the ratio of the meter impedance to the impedance of the circuit you are reading.

Now try an experiment. Change either resistor in the 1M divider to 1K and run through the same analysis. You will see that the meter no longer has a significant effect. This is because the overall impedance of the circuit is about 1K. Make sure to consider the overall impedance of the circuit you are measuring when determining the effect a meter will have on your circuit.

2.1.2 Performing DC and AC Voltage Measurements

2.1.2.1 Five (5) Foundational Best Practices for Maximizing Measurement Performance

2.1.2.1.1 Use Remote Sense to Offset the Effects of Lead Resistance
In a typical 2-wire measurement, the resistance of your leads is unaccounted for. This results in a voltage drop across the lead and introduces error in measurements. The effects of lead resistance are especially noticeable when taking low-resistance and low-voltage measurements. Remote sense is a 4-wire measurement setup designed to counteract the effects of lead resistance. With remote sense, one set of leads carries the output current while another set of leads measures voltage directly at the device-under-test (DUT) terminals. This allows the instrument to compensate for the voltage drop and improve measurement results.

2.1.2.1.2 Compensate for Offset Voltage
A common source of offset voltage error is thermal Electromotive Force (EMF), which is produced when two dissimilar metals at different temperatures come in contact with each other. This forms a thermocouple that produces voltage in the measurement circuit. Error due to thermal EMF is typically in the range of microvolts, which makes this an important consideration when making low-voltage or low-resistance measurements. Offset compensation and current reversal are two methods that eliminate offset voltage and improve the accuracy of results.

2.1.2.1.3 Minimize External Noise
A variety of sources like electromagnetic interference or parasitic capacitance can introduce noise into your measurement system. Electromagnetic interference can come from things like Amplitude Modulation/Frequency Modulation (AM/FM) radio, television (TV), or power lines. Parasitic capacitance occurs when a charged object is close to your measurement circuit. This can show up as an oscillating noise or an offset to your measurement. Adding shielding to your measurement setup reduces these sources of error, which results in a cleaner signal for your instrument to measure.

2.1.2.1.4 Guard against Leakage Current
A guard is a conductive layer added between the HI and LO terminals of your measurement device that is driven to the same voltage potential as the HI terminal. Whereas shielding protects against external sources of electromagnetic interference, guarding prevents leakage current from flowing between the shield and the measurement circuit. This is especially critical for low-current measurements. As an added benefit, the guard layer reduces the effects of parasitic capacitance from the shield, which improves your signal's settling time.

2.1.2.1.5 Understand the Importance of Calibration
Calibration is necessary for your instrument to achieve its warranted specifications. Many are familiar with external calibration where your device is sent to a metrology lab to correct for drift over time, but another form of calibration called self-calibration is just as important and helps the instrument perform consistently as the device temperature changes. Simple changes in the room temperature of your lab or testing your device over its operating temperature range can have major effects on your measurements. Self-calibration ensures your measurements are accurate every time.

2.1.3 General CTOs for Analog Voltmeters and Multimeters

(Various Manufacturers)

T.O. 33K1-4-1548-1	AC Voltmeters
T.O. 33K8-4-176-1	DC Voltmeters
T.O. 33K1-4-1586-1	AC/DC Voltmeters
T.O. 33K1-4-141-1	Multimeters
T.O. 33K1-4-716-1	Multimeters

2.1.4 General CTOs for Digital Multimeters

T.O. 33K1-4-2278-1	A.W. Sperry Inst.
T.O. 33K1-4-3178-1	Agilent
T.O. 33K1-4-2347-1	Amprobe
T.O. 33K1-4-2234-1	Radio Shack/Micronta
T.O. 33K1-4-2478-1	Bluepoint/Snap-On
T.O. 33K1-4-2440-1	Craftsman/Sears
T.O. 33K1-4-2320-1	Extech
T.O. 33K8-4-14-1	Fluke
T.O. 33K8-4-15-1	Fluke
T.O. 33K1-4-2284-1	Tektronix
T.O. 33K8-4-343-1	Wavetek/Beckman/Meterman
T.O. 33K1-4-2522-1	Various

2.1.5 DC and AC Voltage Measurements, Defined

(Reference ‘Schoolhouse Lesson Plans’; ‘3 - Electrical Indicating Devices’; paragraph 3-6 ‘Voltage Measuring Devices’ for additional information)

2.1.5.1 Voltage Measurements

Determination of the difference in electrostatic potential between two points. The unit of voltage in the International System of Units (SI) is the volt, defined as the potential difference between two points of a conducting wire carrying a constant current of 1 ampere when the power dissipated between these two points is equal to 1 watt.

2.1.5.2 Direct-Current Voltage Measurements

2.1.5.2.1 The chief types of instruments for measuring direct-current (constant) voltage are potentiometers, resistive voltage dividers, pointer instruments, and electronic voltmeters.

2.1.5.2.2 The most fundamental DC voltage measurements from 0 to a little over 10 V can now be made by direct comparison against Josephson systems. At a slightly lower accuracy level and in the range 0 to 2 V, precision potentiometers are used in conjunction with very low-noise electronic amplifiers or photocoupled galvanometer detectors. Potentiometers are capable of self-calibration, since only linearity is important, and can give accurate measurements down to a few nanovolts. When electronic amplifiers are used, it may often be more convenient to measure small residual unbalance voltages, rather than to seek an exact balance.

2.1.5.2.3 Voltage measurements of voltages above 2 V are made by using resistive dividers. These are tapped chains of wire-wound resistors, often immersed in oil, which can be self-calibrated for linearity by using a buildup method. Instruments for use up to 1 kV, with tappings typically in a binary or binary-coded decimal series from 1 V, are known as volt ratio boxes, and normally provide uncertainties down to a few parts per million. Another configuration allows the equalization of a string of resistors, all operating at their appropriate power level, by means of an internal bridge. The use of series-parallel arrangements can provide certain easily adjusted ratios.

2.1.5.2.4 Higher voltages can be measured by extending such chains, but as the voltage increases above about 15 kV, increasing attention must be paid to avoid any sharp edges or corners, which could give rise to corona discharges or breakdown. High-voltage dividers for use up to 100 kV with an uncertainty of about 1 in 105, and to 1 mV with an uncertainty of about 1 in 104, have been made.

2.1.5.2.5 For most of the twentieth century the principal DC indicating voltmeters have been moving-coil milliammeters, usually giving full-scale deflection with a current between 20 microamperes and 1 milliampere and provided with a suitable series resistor. Many of these will certainly continue to be used for many years, giving an uncertainty of about 1% of full-scale deflection.

2.1.5.2.6 The digital voltmeter has become the principal means used for voltage measurement at all levels of accuracy, even beyond one part in 107, and at all voltages up to 1 kV. Essentially, digital voltmeters consist of a power supply, which may be fed by either mains or batteries; a voltage reference, usually provided by a Zener diode; an analog-to-digital converter; and a digital display system. This design provides measurement over a basic range from zero to a few volts, or up to 20 V. Additional lower ranges may be provided by amplifiers, and higher ranges by resistive attenuators. The accuracy on the basic range is limited to that of the analog-to-digital converter.

2.1.5.2.7 Most modern digital voltmeters use an analog-to-digital converter based on a version of the charge balance principle. In such converters the charge accumulated from the input signal during a fixed time by an integrator is balanced by a reference current of opposite polarity. This current is applied for the time necessary to reach charge balance, which is proportional to the input signal. The time is measured by counting clock pulses, suitably scaled and displayed. Microprocessors are used extensively in these instruments.

2.1.5.3 Alternating-Current Voltage Measurements

2.1.5.3.1 Since the working standards of voltage are of the direct-current type, all AC measurements have to be referred to DC through transfer devices or conversion systems. A variety of techniques can be used to convert an AC signal into a DC equivalent automatically. All multimeters and most AC meters make use of AC-DC conversion to provide AC ranges. These are usually based on electronic circuits. Rectifiers provide the simplest example.

2.1.5.3.2 In a commonly used system, the signal to be measured is applied, through a relay contact, to a thermal converter. In order to improve sensitivity, a modified single-junction thermal converter may be used in which there are two or three elements in a single package, each with its own thermocouple. The output of the thermal converter is measured by a very sensitive, high-resolution analog-to-digital converter, and the digital value memorized. When a measurement is required, the relay is operated, and the thermal converter receives its input, through a different relay contact, from a DC power supply, the amplitude of which is controlled by a digital and analog feedback loop in order to bring the analog-to-digital converter output back to the memorized level. The DC signal is a converted value of the AC input and can be measured. Modern versions of this type of instrument make use of microprocessors to control the conversion process, enhance the speed of operation, and include corrections for some of the errors in the device and range-setting components.

2.1.5.3.3 As in the DC case, digital voltmeters are now probably the instruments in widest use for AC voltage measurement. The simplest use diode rectification of the AC to provide a DC signal, which is then amplified and displayed as in DC instruments. This provides a signal proportional to the rectified mean. For most purposes an arithmetic adjustment is made, and the root-mean-square value of a sinusoidal voltage that would give the same signal is displayed. Several application-specific analog integrated circuits have been developed for use in instruments that are required to respond to the root-mean-square value of the AC input. More refined circuits, based on the logarithmic properties of transistors or the Gilbert analog multiplier circuit, have been developed for use in precision instruments. The best design, in which changes in the gain of the conversion circuit are automatically compensated, achieves errors less than 10 ppm at low and audio frequencies.

2.1.5.3.4 Sampling digital voltmeters are also used, in which the applied voltage is switched for a time very short compared with the period of the signal into a sample-and-hold circuit, of which the essential element is a small capacitor. The voltage retained can then be digitized without any need for haste. At low frequencies this approach offers high accuracy and great versatility, since the voltages can be processed or analyzed as desired. At higher frequencies, for example, in the microwave region, it also makes possible the presentation and processing of fast voltage waveforms using conventional circuits.

2.1.5.3.5 Voltage measurements at radio frequencies are made by the use of rectifier instruments at frequencies up to a few hundred megahertz, single-junction converters at frequencies up to 500 MHz, or matched bolometers or calorimeters. At these higher frequencies the use of a voltage at a point must be linked to information regarding the transmission system in which it is measured, and most instruments effectively measure the power in a matched transmission line, usually of 50 Ω characteristic impedance, and deduce the voltage from it.

2.1.5.3.6 Pulse voltage measurements are made most simply by transferring the pulse waveform to an oscilloscope, the deflection sensitivity of which can be calibrated by using low-frequency sine waves or DC. Digital sampling techniques may also be used.

2.1.6 Performing High Accuracy DC Voltage Measurements (Example: Keysight 3458A)

The 3458A comprises 8½ digits of resolution and is the fastest, most flexible/accurate multimeter by Keysight. With a 1-yr DCV accuracy of 0.0008% (0.0004% optional), it is ideal for demanding applications. It has been a workhorse for the Air Force for decades.

2.1.6.1 In the power-on state, DC voltage measurements are selected and the multimeter automatically triggers and selects the range. In the power-on state, you can make DC voltage measurements simply by connecting a DC voltage to the input terminals. The connections also apply for AC voltage, 2-wire resistance, AC+DC voltage, digitizing, and frequency or period measurements from a voltage input source.

2.1.6.2 Configuring the multimeter for making DC voltage measurements: The multimeter measures DC voltage on any of five ranges. A Table in the User's Guide for the unit shows each DC voltage range and its full scale reading (which also shows the maximum number of digits for the range), and, the maximum resolution and the input resistance for each range (Resolution is a function of the specified integration time).

2.1.7 Performing High Accuracy AC Voltage Measurements (Example: Fluke 5790B/5/AF)

AC Voltage is a physically derived quantity. It is usually realized in an electro-thermal device whereby AC and DC voltages (or currents) are equivalent when they produce an identical average power in a pure resistance. The AF establishes the electrical parameter of AC Voltage through the use of Multi-Range AC/DC Solid State Thermal Transfer Standards, Thermal Voltage Converters (TVCs), AC Measurement Standards, and various AC Voltage calibrators. At the Air Force Primary Standards Laboratory (AFPSL), a Multi-Range AC/DC Solid State Thermal Transfer Standard is maintained with traceability to the National Institute of Standards and Technology (NIST) through the Fluke Corporation. Additionally, wideband AC Voltage frequency response is maintained using thermal voltage converters directly traceable to NIST. The AFPSL in turn, uses these standards to calibrate AC Measurement Standards for the PMELs as their Base Measurement Standard for AC Voltage. The PMELs use the AC Measurement Standard to calibrate various AC Voltage Calibrators and high accuracy digital multimeters for use at the PMEL working standard level and user level.

With the 5790B/5/AF you can measure an AC or DC voltage just as you would with a voltmeter. When in measurement mode, among many other things, the 5790B/5/AF automatically:

- Compares the heating effect of the incoming signal to that of the 5790B/5/AF internal DC source, through the Fluke rms sensor. This method results in direct detection of true rms value.
- Adjusts the internal DC source for a null at the output of the rms sensor, in the process eliminating many sources of error.
- Applies correction factors saved at the time of calibration.
- Presents the results of the AC-DC transfer on the display. The display shows rms amplitude and frequency of the signal being applied, accurate to within the uncertainty of the internal DC standard combined with the transfer uncertainty.
- The measurement mode provides a direct absolute measurement.

2.1.7.2 In measurement mode, the 5790B/5/AF is a precise DMM and measures a voltage applied to the selected input. Depending on trigger mode, the 5790B/5/AF takes single readings when you push TRIG or it takes continuous readings.

2.1.7.3 Two examples of measurement mode applications are determining the error of an AC source and determining the error of an AC voltmeter. No external calibrators or standards are required during measurement mode operations unless you are calibrating a voltmeter.

2.1.7.4 To determine the error of an AC source, check the specifications for proper test uncertainty ratios and measure the source. To determine the error of an AC voltmeter using measurement mode, apply an AC source to the 5790B/5/AF input and the AC voltmeter input in parallel.

2.2 STANDARD CELL INTERCOMPARISION

2.2.1 This area reserved for future use.

2.3. RESISTANCE

The Air Force establishes the electrical parameter of resistance through the use of the intrinsic standard Quantum Hall Resistor. Using the QHR and a resistance bridge, base reference standards can be measured. To disseminate this parameter to other echelon levels of the Air Force, 1 Ω and 10 kΩ Base Reference Standards are used and calibrated. A resistance measurement system, such as the Guildline RMS 6625, can be used in conjunction with a standard to calibrate a resistor. Commonly used resistance reference standards include, but are not limited to, the MI 4310, MI 4304, ESI RS925D, and SR104.

2.3.1 Performing Resistance Measurements

As with all measurements, it is important to ensure that you have proper training to operate all TMDE, a stable environment in which to perform measurements, standards that are traceable back to a national standard, and that all sources of uncertainty from setup, process, equipment, and/or environment in the measurement are considered.

When attempting to make a precise resistance measurement, common practice dictates the use of the 4-wire method. This consists of a potential (P) and a current (C) connection, as shown below in Figure 2.3-1. The current from the measurement device is provided through the C1 and C2 connections, while the potential or sense path, which measures the DC voltage signal, is done at the P1 and P2 connections. This method is used to remove the lead resistance of the wires present in 2-wire measurements, thus granting a more accurate result. Though this is a useful measurement method, not all devices are capable of a 4-wire configuration. When conducting a measurement with 4-wire leads on a 2-wire port/device, you must match C1 and P1 together on the same terminal, and then likewise match C2 and P2 together on the other terminal (observing polarity).

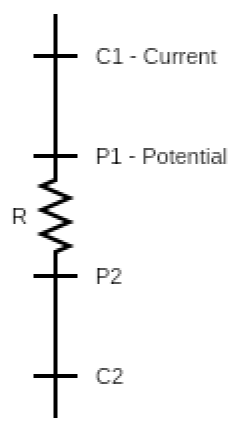


Figure 2.3-1 4-wire method diagram

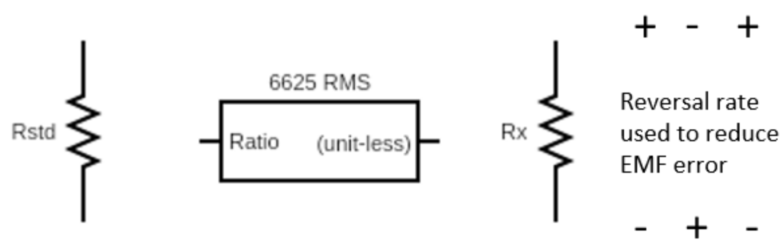
There are multiple methods for measuring the value across an unknown resistance, most involving passing a known current through the unknown resistor and measuring the voltage drop across it. When a test current is flowing through a resistor, heat is created. An important quality of resistors is that their value changes with heat. Heat, in turn, is proportional with power.

$$Heat = Power = Vi = i^2R$$

Where: V = Voltage
I = Current
R = Resistance

As can be seen above, even small changes in current will result in large changes in the power, and thus the heat. That heat can change the resistor's value and (if high enough) damage it, so it is important to not approach or exceed the max rated current when testing a resistor. So if heat/power changes the resistance, how do we know what power to calibrate at? In order to standardize the way resistors are calibrated, a power of 10mW is used as the point at which most resistors are calibrated. Certifying all values at 10 mW provides the standard required to perform resistor calibration, insuring that all resistors are at the same power and excess heat does not alter resistance values. So when testing, keep the power in the range of 1mW to 10mW, as above 10mW the resistor will get hot enough to change the resistance value.

Resistance bridges are a common way to calibrate an unknown resistor to a standard. Bridges like the RMS 6625 use a direct comparator bridge to make a ratio comparison between the two resistors, one standard and one unknown. The bridge is a ratio measurement device, it measures the ratio between your standard resistor and your unknown resistor. An overly simplified description of this process is that ratio is determined by driving current/voltage through both the standard and U.U.T. resistors, measuring the voltage drops across each, and then balancing the bridge with null voltage output between the two resistors. This ratio is used with the known standard value to determine the unknown resistance, as shown below in equation below 2.



$$R_{std} \times Ratio = R_x$$

Figure 2.3-2 RMS 6625 Diagram

When the bridge begins to take a measurement, it takes a reading at one polarity and then switches the polarity for the next reading at a set rate. This is called the reversal rate and is used to reduce the thermal EMF error present in the measurement. The lower the reversal rate (lowest limit being 4 seconds) on a measurement, the higher the uncertainty, so this is a balance of accuracy and time. The determination of what reversal rate to use will differ with equipment and requirement. Now depending upon the value of the unknown resistor (low, normal, or high Ω), the 6625 uses two different comparator methods to calibrate these resistors, a current comparator or a voltage comparator. The 10 mW discussed earlier marks the key point used to determine which type of comparator method is used, between Current and Voltage, as shown in Table 1 below. Low Ohm measurements use a current comparator up to 100 kΩ, while high Ohm measurements greater than 100kΩ use the voltage comparator.

Table 1: 2.3-1 Current and Voltage Comparator

@ 10mW

Current Comparator	Voltage Comparator
.001 Ω – 100 kΩ	>100 kΩ – 100 MΩ

A leakage voltage can develop between terminals on standard resistors, it is common practice to apply a guard voltage matching the voltage through the terminals, thus nulling out any leakage possible and eliminating added measurement error.

Once results from the measurement are finished, it is time to analyze them. Results of a resistor value may take many samples to become “stable” enough to receive useable data. Many times the beginning values will have a very high standard deviation as the bridge starts the process of balancing and closing in on the true value. So it is common practice to erase the first couple data points from your analysis in order to receive real information about the measurement. A good rule of thumb is to set the test to stop when the last ten sample points are at a standard deviation that is $1/10^{th}$ of the uncertainty. These last ten points can then be analyzed to access the value of the resistor. The compilation of these results can then be stored over months and years to create a history of a resistor. The history and behavior of a resistor is very important to record, analyze, and understand. The value of a resistor should, over time, increase. With enough history on a particular resistor, values can be predicted and long term drift can be analyzed. This gives metrologists the ability to assess the health and reliability of not only the resistor itself, but of the measurements being made on the resistor. Outliers in the data can signify a bad measurements, and therefore be addressed as such. Resistors are unique in that they become more stable the older they are, so metrologists benefit greatly by supporting a resistor for many years and keeping an accurate, up to date history.

2.3.1.1 Performing High Resistance Measurements

The Air Force establishes high value resistance through the use of high value resistance standards, which are calibrated by the National Institute of Standards and Technology (NIST). Using NIST certified resistance standards and a teraohmmeter, the resistance standards can be measured at rated voltage(s). To disseminate this parameter to other echelon levels of the Air Force, 1GΩ through 1TΩ Base Reference Standards are used and calibrated. PMELs further disseminate the parameter through calibration of teraohmmeters, electrometers and other resistance transfer standards.

When trying to calibrate large resistances up to 1 TΩ and 10 TΩ, large errors start to add up as you try to keep the traceability chain. In order to calibrate these large resistances, the ladder method is used. The ladder method is the chain of 10:1 comparisons from 100 MΩ to 10 TΩ, as shown below. This retains the chain of traceability from the intrinsic standard all the way to 10 TΩ, while keeping an acceptable amount of uncertainty in the measurement.

Intrinsic→100 MΩ→1 GΩ→10 GΩ→100 GΩ→1 TΩ→10 TΩ

2.4. CURRENT

As with all measurements, it is important to ensure that you have proper training to operate all TMDE, a stable environment in which to perform measurements; standards that are traceable back to a national standard, and that all sources of uncertainty from setup, process, equipment, and/or environment in the measurement are considered.

2.4.1 Current Shunts

Now that some basic concepts has been presented, it’s time to look at practical ways to accurately measure current in an electrical system. One way to achieve this is through the use of current shunts. Current shunts are low ohm resistors used measure AC or DC electrical currents by the voltage drop those currents create across the resistance. One can insert a shunt of a known resistance into a circuit whose current you want to determine, measure the voltage drop across the shunt, and then calculate the current using Ohm's law, as shown below:

$$I = \frac{V}{R}$$

Where: I = Current
V = Voltage
R = Resistance

Current shunts can have several specifications describing their behavior including, but not limited to: current rating, output voltage, accuracy, and drift. The sum of the accuracy and drift errors indicate by how much the current shunt output will be incorrect compared to the specified ideal output resistance. Since current shunts are resistors and dissipate heat from the current flowing through them, they get hot.

$$Heat = Power = Vi = i^2R$$

Where: V = Voltage
I = Current
R = Resistance

As can be seen above in equation above, even small changes in current will result in large changes in the power, and thus the heat. That heat can change the shunt's resistance and damage it, so they are often given a power rating. In reality, shunts are often specified to be used continuously at only 2/3 of their rated current.

2.4.2 Performing High Current Measurements

High current measurement is subjective and can be defined at different values to different people. for the purpose of this handbook, we will define high current as any current equal to or above 20 A.

2.4.3 Clamp Meters

One common tool to perform high current measurement is the current clamp meter. In order to calibrate a current clamp meter, one can use the current coil method. This involves using a current source (such as the Clark-Hess 8100 Transconductance Amplifier) to provide a current and a coil to transform or step up the applied current in order to calibrate clamp meters. It is impractical to calibrate 500A rated current clamp meters using a 500A source. However, one can effectively multiply the current of the current source by the factor of the number of turns in the coil (i.e. a 50 turn coil will multiply the current by 50) to support the calibration and verification of these clamp on type current meters (Fluke Model 5500A/Coil). Commercial options for a current coil exist, such as Fluke's 5500A/Coil, but if you are building the current coil yourself, there are a few common practices you can use to insure an effective current coil. To properly construct the coil, use 14 gage wire, or heavier, and follow Figure 2.4.3-1 as a guide.

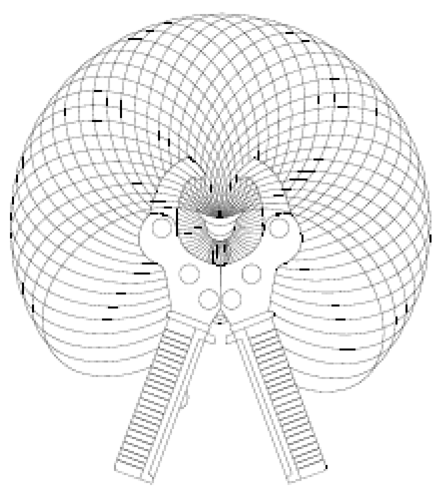


Figure 2.4.3-1. Current Coil Orientation

The coil should have a diameter of about 4 inches. Fan out coil to 270° with spacing 0.375 inch (1 cm) using tape to maintain coil's shape. These dimensions are not critical, only a guide to ensure an effective current coil.

Some clamp meters are calibrated for use with a particular tong, hook, or clip handle. Do not interchange meter movements with tong, hook, or clip handles with differing sets. Ensure the serial number stamped on the back of each meter matches the serial number of the tong, hook, or clip handle with which the meter is used. The positon of the clamp meter with respect to the cable also effects the results. In order to minimize operational error and make the most accurate and repeatable measurement, make sure the clamp is centered carefully on the coil.

2.5 CAPACITANCE

Capacitance is the ability of a conductor to store energy in an electric field. This energy results in a stored charge of the conductor and associated dielectric. The construction of capacitors are often generalized into two common dielectric categories, electrolytic and electrostatic. Electrolytic capacitors are constructed to utilize dielectrics of metal oxide film and require polarizing DC Voltage. Electrostatic capacitors are constructed to use ceramic, liquid or vacuum gas as a dielectric. Electrostatic capacitors do not require polarized DC Voltage for proper function. Electrostatic capacitors are generally constructed for use with low capacitance; 1 µF and below.

Capacitance is an electrical property that opposes changes in the magnitude of a voltage contained in a circuit. The SI unit of capacitance is the farad (F). The farad can be derived from the volt (V), second (s), and ampere (A); the ampere being realized through the derivation of the coulomb (C), the SI unit of electric charge. One farad (F) is equal to one coulomb (C) divided by one volt (V) where one coulomb (C) is equal to one ampere (A) multiplied by one second (s):

$$F = C / V$$
$$C = A * s$$

By definition a one farad capacitor will increase the voltage across it at a rate of one volt per second when a constant current of one ampere is applied.

When capacitors are utilized in a DC circuit the equivalent resistance in series with the capacitor will exhibit an exponential relationship through a universal time constant curve. This curve represents the increase in voltage across the capacitor with respect to time. The universal time constant curve is the capacitors voltage (Vc) expressed as:

$$Vc = V * (1 - e^{(-(t / (R * C)))})$$

Where: V = applied circuit voltage in volts
e = base of natural logarithms
t = time in seconds
R = resistance in ohms
C = capacitance in farads

When the universal time constant curve for t is equal to RC the voltage across the capacitor will be approximately 63% of the theoretical maximum voltage assuming the initial voltage was zero volts. Taking the limit of the universal time constant curve as time increases to infinity would provide the theoretical maximum voltage equivalent of V, the applied voltage to the circuit. The relationship of R, C, t and the universal time constant curve are applied in many electronic circuits such as, integrators, differentiators, oscillators, and timing circuits.

When an ideal capacitor is used in an AC circuit with ideal sine wave voltage applied an ideal cosine wave of current flows in the capacitor. This current leads the applied voltage by 90 degrees. The net effect of the voltage and current relationship produces a capacitive reactance, Xc, equal to:

$$Xc = 1 / (2 * pi * f * C)$$

Where: f = frequency in Hertz
C = capacitance in farads

The magnitude of the rms current, Irms, is equal to:

$$Irms = Vrms / Xc$$

The amplitude of the qualities expressed above are related in the same form as those of DC voltage, current and resistance, but with current leading voltage by 90 degrees.

As functionality and implementation of less than ideal capacitors are applied to electronics, parasitic losses become apparent. The effect of parasitic losses on an electrostatic capacitor can be described in three ways:

Power Factor, PF = cos(phase angle) = W/I * V

Where phase angle is the angle between the leading current and voltage when both are expressed as sine waves. W is power in watts, I is the rms current in Amperes and V is the rms voltage in volts.

Dissipation Factor, DF = tan(loss angle) = 90 degrees - (phase angle)

Quality Factor, Q = 1 / DF = 2 * pi * f * C/G

Where: f = frequency in Hertz
C = capacitance in Farads
G = Conductance

As frequency increases electrical components exhibit more qualities of parasitic components combined in series and parallel with the circuit. The dielectric of a capacitor will exhibit a leakage resistance around the plates of the capacitor. This leakage resistance responds as a small value resistor in series with the capacitor. The connection leads of the capacitor will respond as a series resistor and inductor. A parasitic capacitor will also be realized between the capacitor plates and the surrounding faraday shield. These components are not physically connected to the capacitor; however, they naturally occur due to the electrical properties of the components.

Laboratory capacitance standards must take losses and interference into account during design of the standards. High quality dielectrics can reduce the parasitic components implemented on the capacitance plates. Hermetically sealed standard capacitors in inert gas can also reduce parasitic components and how they react to the capacitive plates. Most standard capacitors have a three-terminal design; two connectors for the capacitor and one for the faraday shield. Five-terminal capacitors can also be utilized as in four wire resistance; one terminal pair applies current and the voltage drop is measured by the other pair. The fifth terminal is used the same way as the three-terminal connection to the faraday shield.

2.5.1 Capacitance traceability

Capacitance traceability is maintained though Capacitance Bridges and Capacitance Standards. While making precision capacitance measurements there are a many sources of error that can negatively influence calibration. High and low frequency noise can be produced from power sources or lines, light fixtures, electronic equipment, and human electrostatic discharge. Poorly shielded equipment and ground lines can also add noise while making precision capacitance measurements. The broadest possibility of noise in reference to precision capacitance measurements is anything that has a frequency could adversely influence measurements. There is a simplicity to limiting the effect of noise on precision capacitance measurements. Making measurements in low traffic areas and making measurements while other noisy equipment is not in use can greatly reduce the effect of noise.

2.5.2 Measurement techniques

Measurement technique can also be utilized to reduce noise. When making capacitance measurements noise is proportional to the inverse of the square root of measurement time. If measurements are taken with an average time of two seconds and the average time is changed to four seconds you can expect to see noise reduced by a factor of two. If the average time is increased to 16 seconds the noise is expect to be reduced by a factor of four. As you can see measurement time can be increased to reduce the effect of noise, but an increase of measurement time can quickly become an issue on its own.

Shielding is also a valuable technique that can greatly reduce noise for capacitance measurements. Unshielded cables can act as antennas that pick up noise while making capacitance measurements. Shielded cables should be utilized while making precision capacitance measurements to reduce the possibility of picking up noise. A faraday shield can also be used to shield capacitance bridges or capacitors from laboratory noise.

Three terminal measurements are almost always used with precision capacitance measurements. Three terminal devices have an internal enclosure surrounding the internal structure of the device. The enclosure shields the device itself and functions as a faraday cage. The third terminal of the device is used to ground this enclosure. The enclosure itself acts as an antenna that prevents the coupling of noise and reduces interference caused by the noise.

2.6 INDUCTANCE

2.6.1 This area reserved for future use.

2.7 VOLTAGE PHASE SHIFT

2.7.1 This area reserved for future use.

2.8 FREQUENCY

Frequency is the rate of a repetitive event. If T is the period of a repetitive event, then the frequency f is its reciprocal, 1/T. Conversely, the period is the reciprocal of the frequency, T = 1/f. Since the period is a time interval represented in seconds (s), the relationship between time interval and frequency is readily apparent. The SI unit for frequency is the hertz (Hz). One hertz is also known as one cycle per second.

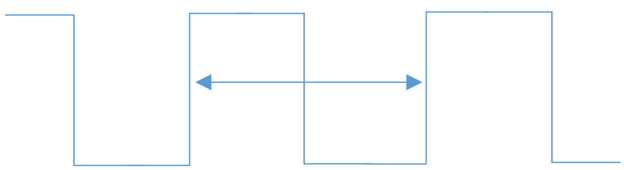


Figure 2.8-1: Frequency cycle.

The frequency measurement is one that is often made in the PMEL, especially the frequency reference oscillator. It is found in most all frequency counters, signal generators, spectrum analyzers and vector network analyzers. The reference oscillator has an aging rate which will result in frequency drift. The aging rate is verified during each calibration.

2.9 WAVEFORM ANALYSIS

2.9.1 Time Domain

Waveform analysis is best accomplished on an oscilloscope due to its graphical representation of the electrical signals. An oscilloscope operates in the time domain with the voltage on the Y-axis and time on the X-axis. Older oscilloscopes required manual measurement of the waveform against the scales built into the screen of the TI. Modern oscilloscopes can perform the measurements automatically with the ease of a few settings. Waveforms can be sinusoidal, square, sawtooth, triangular or pulse in nature.

Waveform measurements such as amplitude, width, frequency, period, time interval, rise time, fall time, preshoot, overshoot and ringing are typical measurements made with the oscilloscope. Some waveform analysis measurements are more accurate when measured on a frequency counter, such as pulse width, period, and time interval.

2.9.2 Performing Waveform Measurements

It is always good to start with the basics of making manual measurements in order to have a grasp on the concepts of what is happening when the modern oscilloscope is set for making automatic measurements. The most basic measurements that can be made on the oscilloscope are amplitude and time/frequency.

The first step would be to connect the output of the oscilloscope calibrator to the oscilloscope. Ensure the oscilloscope volts/division is set to the highest value, typically 5 volts/div, in order to not overdrive the input. Next set the oscilloscope calibrator to sinewave at 1 kHz at 1 volt with the multiplier set to 6. Decrease the oscilloscope volts/division to 1 volts/division. Set the oscilloscope time/division to 200 µseconds, which will allow the waveform to display horizontally across 5 divisions since reciprocal of 1 kHz is 1 millisecond. There will be a 6 volt peak-to-peak sinewave on the display now. Align the bottom of the waveform to a horizontal graticule and count the number of major divisions vertically to the top of the waveform to measure the vertical deflection. Multiply the result by the volts/division setting, which in this case is 1 volt.

To measure the time, align the leading edge of the sinewave with a vertical graticule and count the number of horizontal divisions it takes to complete one cycle. Multiply the result by the time/division setting, which in this case is 200 µseconds (example: 5.1 X 200 µS = 1.02 mS or $f = \frac{1}{t} = \frac{1}{1.02mS}$ = 980.39 Hz).

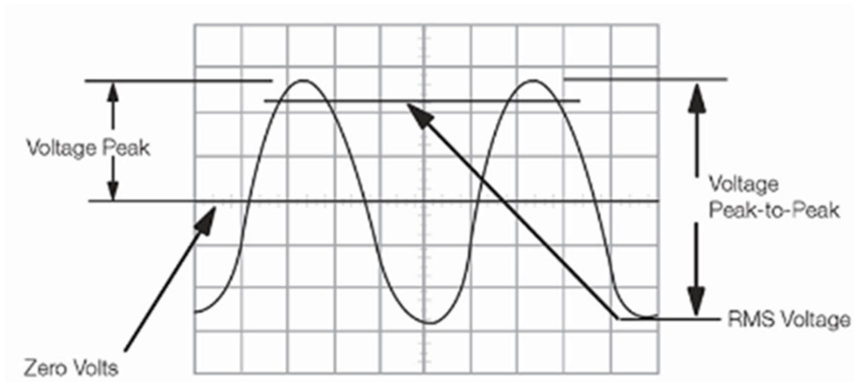


Figure 2.9-1: Waveform breakdown

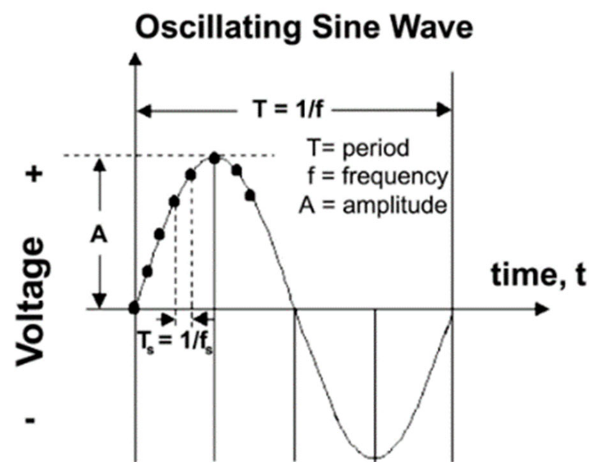


Figure 2.9-2: Waveform measurement components

2.9.3 Performing Pulse Measurements

Pulse generators all have different specifications as to what must be calibrated. Some of the measurements include pre-shoot, overshoot, ringing, pulse width, rise time, fall time, settling time, and pulse repetition interval. All measurements are measured in seconds.

The first step to performing pulse waveform measurements is to set up the TI. For example purposes, the following will be used for settings:

Period	1.00 µsecond (1 MHz)
Amplitude	8 V
Mode	Normal
Function	Square

Set the oscilloscope for input impedance of 50 ohms, then set the volts/division and the variable knob as necessary to view the waveform presentation below, using the 0 and 100% marks on the screen. Observe the pulse settling time does not exceed the specified limits as seen in Figure 2.8-3.

Next the following settings would be made to the TI:

Period	100 nanoseconds (10 MHz)
Amplitude	2 V

Set the oscilloscope up again to the waveform presentation below using the 0 and 100% marks on the screen. Next measure the pre-shoot, overshoot, and ringing as seen in Figure 2.8-3.

The rise time is measured from the 10 to 90% points along and the fall time is measured from the 90 to 10% points, both along the horizontal axis. The rise and fall time are also known as leading and trailing edge measurements.

The pulse width measurement is always made at the 50% point of the pulse along the horizontal axis.

The pulse repetition interval is usually measured from the leading edge of the pulse along the horizontal axis, to the leading edge of the next pulse. It can be measured from trailing edge to trailing edge as well.

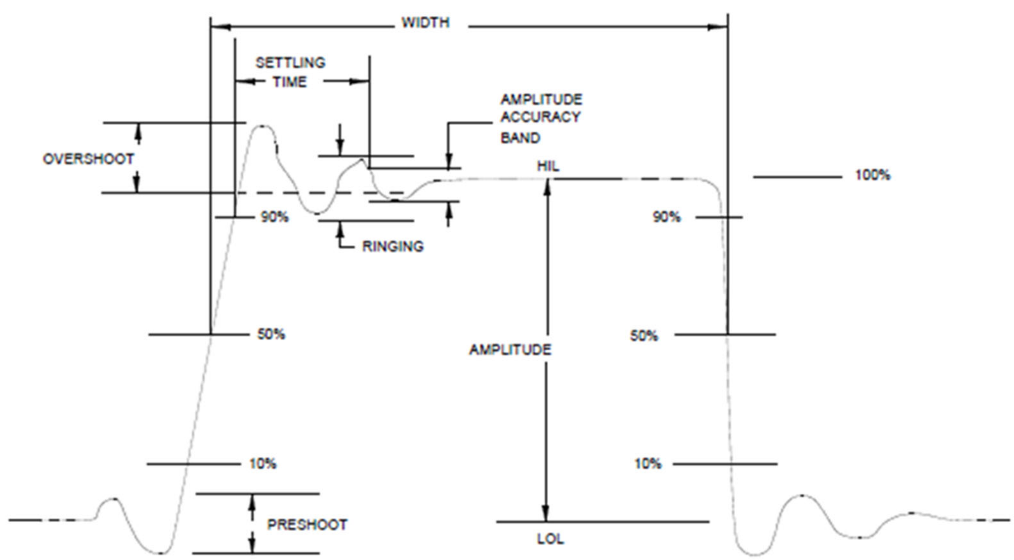


Figure 2.9-3: Pulse waveform breakdown.

2.10 Rise Time Calculations and Measurements

Rise/Fall Time is also known as “Transition Duration.” Rise time is now a positive transition duration and fall time is a negative transition duration. The IEEE defines Transition Duration as the difference in time between two reference levels of the same transition. In pulse metrology this is the time difference between the displayed 10% and 90% amplitude value if the input signal is an ideal voltage step.

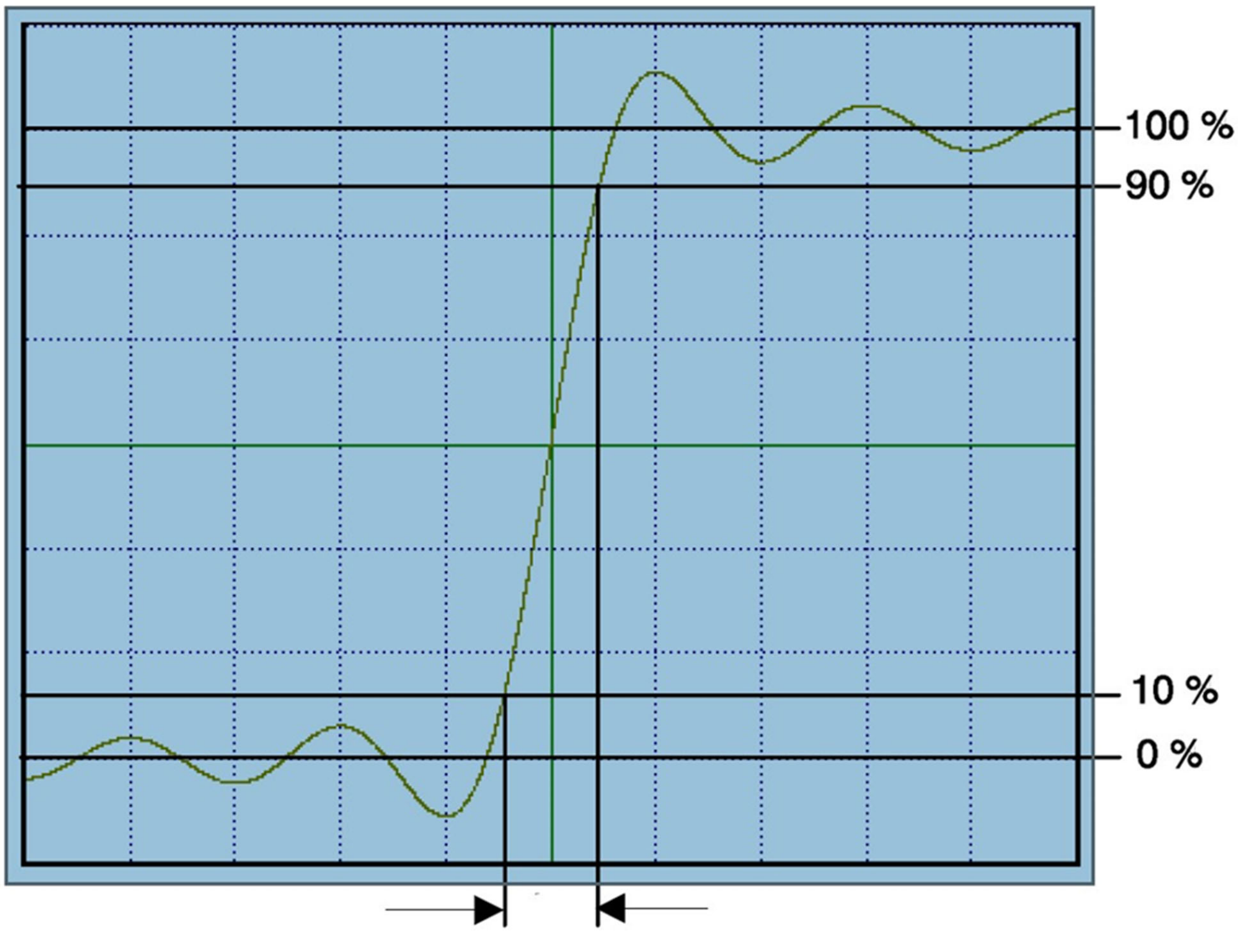


Figure 2.10-1.

The time markers between the 10% and 90% represents the measured rise time of the signal.

Knowing the rise time of the equipment in use is important to making accurate and reliable pulse measurements. Rise Time describes the useful frequency of an Oscilloscope.

In some applications you may only know the rise time, others you may only know the bandwidth, if this occurs, there is a constant value that can be used to calculate rise time or bandwidth, dependent on which value is unknown. This equation you would use in this scenario is; Bandwidth = k / Rise Time, where k is a constant value (usually 0.35 or 0.40, dependent on the Bandwidth of the Oscilloscope).

There is another way to calculate the rise time of an Oscilloscope. First, you have to have a calibrated unit with a known/warranted rise time specification (Tref), this should be on the calibration certificate and it is labeled as “Transition Duration.” You apply the signal from the calibrated unit to the Oscilloscope and measure rise time of the signal on the Oscilloscope (Tmeas). Using the equation below and the values gathered as mentioned above will allow the technician to calculate the Rise Time of an Oscilloscope.

$$\text{Rise Time} = \sqrt{(Tmeas^2 - Tref^2)}$$

Below is a picture of the Keysight 86100C Sampling Oscilloscope measuring the transition duration or fall time of a pulse.

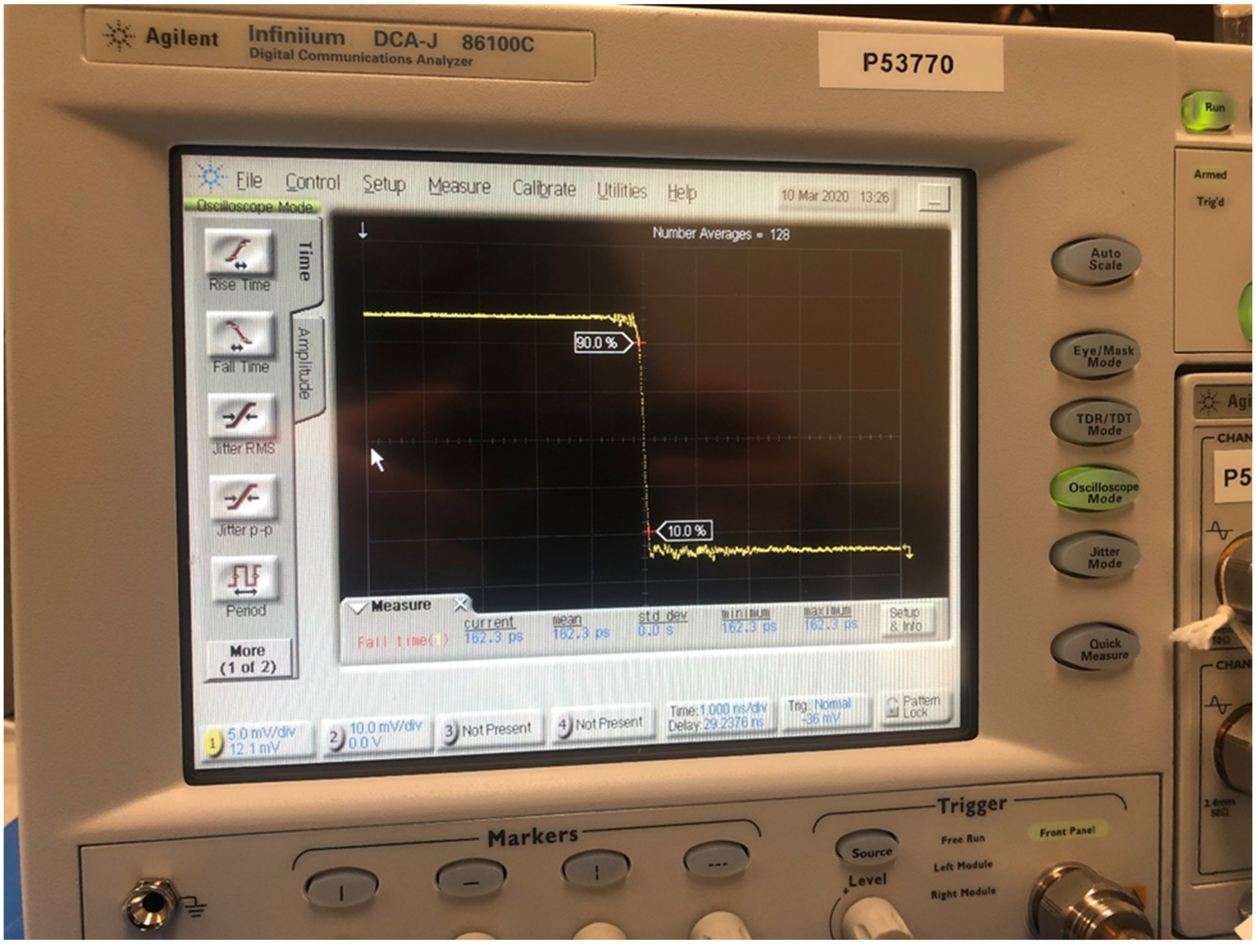


Figure 2.10-2.

2.11 Microwave Coaxial Connectors and Torque

Most microwave calibrations and measurements require connectors in the setup. It is further granted that the integrity of these calibrations and measurements is dependent, at least in part, on the integrity of these connections. The basics of common coaxial microwave connectors including care, frequency ranges, connection techniques, and industry consensus torque values are discussed in detail in the following paragraphs.

Speaking of torque values, some issues have surfaced for which clarification is needed. Torque values for each of the main coaxial microwave connector types are listed in Table 1 below. These torque values listed are a consensus after surveying professional trade organizations such as IEEE and ANAMET, as well as referencing old and current MIL-STDs and MIL-PRFs, and querying OEMs. In reality there is a permissible "mating torque range" for each connector type. Torqueing within this range ensures connectors are aptly seated to produce a connection with integrity without inducing first-order damage.

The first issue of clarification regards fears of audits tracing torque values back to OEM Com Data where stated values are different than recommended in Table 1 of this technical order. Within this new Table, we have added for the main coaxial connector types a permissible mating torque range. This should preclude audit failures due to the technical order having precedence over Com Data. Any torque value used within the permissible range for a respective connector type as stated in Table 1 will not cause first-order damage to the connector and ordinarily will result in a connection with integrity. Stating the torque range there will provide authority to use, so there should not be an audit write-up just for using a different torque value than in the Com Data that is still within the permissible mating torque range.

The second issue of clarification regards why torque values are not in calibration TOs. The goal is achieving a connection of integrity, not ritually torqueing connectors to a particular value. Hence we do not state HOW a connection is achieved. While calibrated fingers seems a far stretch, as does using a crescent wrench, there is a touch/feel to mating connectors. Sometimes finger tight is good enough. Some connectors only have knurled machining and torque wrenches cannot be used. Most times proper torqueing is required. Using a torque wrench calibrated to within the ranges stated in T.O. 33K-1-100-2 and this technical order respective to connector type provides the highest probability for success in making a connection with integrity. The mechanical torque values are not a traceable quantity in the electrical measurement chain, so we do not list torque values in calibration TOs. Similarly, we do not include torque wrenches with minimum use and TAR requirements. Albeit, we are not ignoring connector mating effects. Normally we include connector repeatability to account for electrical uncertainty, among which torquing is one of many possible sub-contributors (mismatch is typically handled on its own). As an application, torque wrenches for several types of connectors could be on the same bench and as long as each torque wrench is calibrated respective to its connector type within its proper mating torque range everything should be fine. The golden rule should be: If a torque wrench is used, it must be calibrated respective to within the mating torque range of the relevant connector type, and correct techniques using it must be employed.

In conclusion, mating of coaxial microwave connectors in calibrations is an important part of setups. Using torque wrenches presents the best option for making connections with integrity. Each connector type has a permissible mating torque range. Because mating torque values are not in the traceability chain, neither they nor torque wrenches are listed in calibration TOs. This technical order will now contain the torque ranges to provide authority for use and assessment purposes.

Table 2.11-1: Recommended torque settings

Coaxial Connector	Upper Frequency (Mode-free)	Torque	
		Recommended	Range
BNC (standard)	4 GHz	NA	NA
BNC (precision)	10 GHz	NA	NA
TNC (standard)	12.4 GHz	5 in-lbs (brass)	4 to 6 in-lbs (brass)
TNC (precision) MPC/TNC (stainless with contacts gold plated or heat treated beryllium)	18 GHz	12 in-lbs (stainless)	12 to 15 in-lbs (stainless)
AFTNC (MIL-C-87104/2) compliant with low VSWR due to high precision tolerances and with contacts gold plated or heat treated beryllium	19 GHz 20 GHz (Maury claims some VNA Cal Kits)	12 in-lbs	12 to 15 in-lbs
Type-N (older)	12.4 GHz	12 in-lbs Finger tight if knurled	11.5 to 15.0 in-lbs
Type-N (precision)	18 GHz	12 in-lbs Finger tight if knurled	11.5 to 15.0 in-lbs
Type-N (precision) (HP, Agilent, Keysight claims warranted extended range)	22 GHz or 26.5 GHz (possible moding can occur above 18 GHz at the following frequencies; 18.700, 18.765, 19.375, 20.125, 20.720, 21.292, 21.825, 23.398, 23.4825, 23.780, 23.875, 24.375, 24.727, 24.8425, 24.890, 24.920, 25.250, 25.875 GHz)	12 in-lbs Finger tight if knurled	11.5 to 15.0 in-lbs
7 mm	18 GHz	12 in-lbs or Finger tight if knurled	11.5 to 15.0 in-lbs
SMA (brass/older)	18 GHz	5 in-lbs (SMA to SMA) 5 in-lbs (pin SMA to socket 3.5mm) 8 in-lbs (pin 3.5mm to socket SMA)	3 to 5 in-lbs 7 to 10 in-lbs
SMA (stainless/ contemporary)	26.5 GHz	8 in-lbs (SMA to SMA) 8 in-lbs (pin SMA to socket 3.5mm) 8 in-lbs (pin 3.5mm to socket SMA)	7 to 10 in-lbs

WSMA	26.5 GHz	Not approved for PMEL use due to electrical incompatibility with 3.5 mm connectors (see General Connector Information).	Not approved for PMEL use due to electrical incompatibility with 3.5 mm connectors (see General Connector Information).
3.5 mm	33 GHz	8 in-lbs	7.08 to 8.85 in-lbs
2.92 mm (K)	40 GHz	8 in-lbs	5.31 to 8.85 in-lbs
2.4 mm (Q)	50 GHz	8 in-lbs	7.08 to 8.85 in-lbs
1.85 mm (V)	65 GHz	8 in-lbs	7.08 to 8.85 in-lbs
1 mm (W)	110 GHz	4 in-lbs	3.54 to 4.43 in-lbs

2.12 AUDIO, MICROWAVE, AND DISTORTION MEASUREMENTS

2.12.1 Phase Measurements

Electronic waveforms can be defined in terms of amplitude and phase. A complete phase (period) is defined as a waveform completing 360º or 2π radians of phase. The phase of a waveform is described as a specific point in time.

2.12.1.1 Performing Phase Measurements

Figure 2.12-1.

The phase difference between two waveforms can be measured using an oscilloscope and finding the time delay between them. Placing the cursors of the oscilloscope on either the maxima or minima of the two waveforms will yield the time delay (the period can also be measure using the cursors), and the phase difference can be measured with the following equation:

$$\Phi = \frac{t_d}{t_p} \times 360°$$

Where: t_d = time delay
t_p = period of the waveforms

NOTE

To convert to radians, $\Phi_{degrees} \times \frac{\pi}{180}$

2.12.2 Modulated Signal Measurements
The modulation of RF signals refers to the addition of baseband information onto a higher frequency signal (carrier) so that the information can be transmitted to a device for recovery (demodulation). The characteristics of the carrier signal can modified in one or more ways to produce different types of modulation. These types of modulation include:

Amplitude Modulation (AM)
Frequency Modulation (FM)
Phase Modulation (PM)

In amplitude modulation, the amplitude of the original sine wave varies, whereas the frequency and phase are constant.

Frequency modulation and phase modulation share a class of carrier modulation called angle modulation. In frequency modulation, the instantaneous frequency of the original sine wave is varied. In phase modulation, the phase is varied.

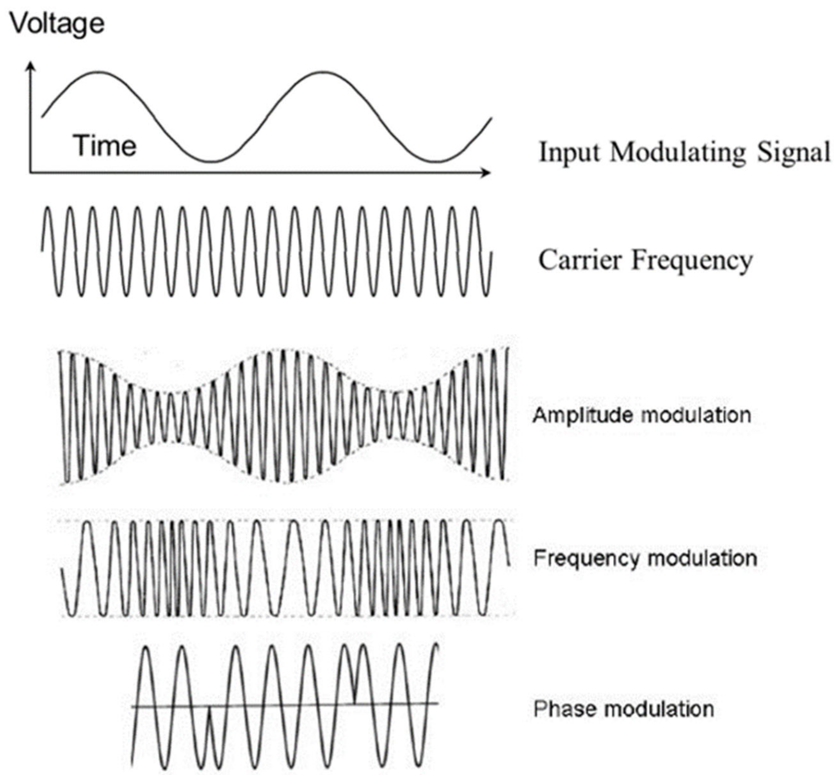


Figure 2.12-2.

Modulation Index: A measure of the amount of modulation applied to a carrier. It determines the number of sidebands created by the modulation process. The index is common to AM, FM, and PM with different representations.

Modulation Index
AM (m): 0 to 100%
FM (β): >0
PM (radians): 0 to 2π radians

2.12.2.1 Perform Modulated Signal Measurements

Figure 2.12-3.

AM Measurements

AM measurements can be performed with an oscilloscope or with a spectrum analyzer.
With an oscilloscope, the modulation index can be calculated with the equation:

$$\frac{E_{max} - E_{min}}{E_{max} + E_{min}} = m$$

NOTE

Accuracy is limited depending on the amount of modulation. AM measurements with a spectrum analyzer can show modulations as low as 0.1%

FM/PM Measurements

FM/PM measurements can be performed with a spectrum analyzer. The modulation index can be calculated with the equation:

$$\frac{\Delta f}{f_{mod}} = \frac{\Delta\omega}{\omega_{mod}} = \beta$$

Where: $\Delta f / \Delta\omega$ =frequency deviation
f_{mod}/ω_{mod} = modulation frequency

NOTE

For PM, the frequency deviation and modulation frequency are measured in radian/sec

2.12.3 Distortion Measurements
THD stands for Total Harmonic Distortion and can be used to estimate the degree to which a system is nonlinear. A THD measurement can be made by applying a sine wave as an input to a system, and measuring the total energy which appears at the output of the system at harmonics of the input frequency. A sinusoidal input is used because sinusoids contain energy at only a single frequency; output energy that appears at any other frequency is thus the result of nonlinearities or time-varying system behavior. Energy that appears exactly at harmonics of the input frequency is almost certainly generated by nonlinearities in the system. Other periodic test signals or broadband signals are not ideal for THD measurements, because energy contained in the input signal can mask energy created by nonlinearities in the system. It is therefore important to have a pure input signal, i.e., one that has almost all of its energy contained at a single frequency.

2.12.3.1 Perform Distortion Measurements

Figure 2.12-4

Total Harmonic Distortion (THD) can be measured using a spectrum analyzer using either power or voltage. The THD is usually calculated by taking the root sum of the squares of the first five or six harmonics of the fundamental. In many practical situations, there is negligible error when only the second and third harmonics are included, as long as the higher harmonics are three to five times smaller than the largest harmonic. If the measurement data is in power, THD can be calculated using the equation below:

$$THD(\%) = \sqrt{\frac{P_2 + P_3 + P_4 + \ldots + P_n}{P_1}} \times 100$$

Where: P = measured in watts.

NOTE

Converting the power in dBm to watts: $P(W) = 0.001 \times 10^{P/10}$, Where P is in dBm.

THD can also be described as the ratio of the root mean square (RMS) voltage of all the harmonic frequencies above the 2nd harmonic over the RMS voltage of the fundamental frequency. The THD can be evaluated using the equations below:

$$THD(\%) = \frac{\sqrt{\sum_{n=2}^{\infty} V_{n\_rms}^2}}{V_{fund\_rms}} \times 100$$

Where: $V_{n\_rms}^2$ = RMS voltage of the nth harmonic
V_{fund_rms} = RMS voltage of the fundamental frequency

NOTE

Converting V_{pk} (peak voltage) to V_{RMS} (RMS voltage): $V_{RMS} = V_{pk}/\sqrt{2}$

2.13 DECIBELS AND POWER RATIOS

Attenuation is measured in decibels. The decibel is a ratio between any two amounts of electrical power and is usually expressed in units on a logarithmic scale. The decibel is a logarithmic unit for expressing a power ratio.

$$PR_{(dB)} = 10 \log \frac{P_2}{P_1}$$

Where: PR = power ratio in dB
P_1 = power in (small)
P_2 = power out (large)

When the output of a circuit is larger than the input, the device is an AMPLIFIER and there is a GAIN. When the output of a circuit is less than the input, the device is an ATTENUATOR and there is a LOSS. In the last example, use the same formula as above and place the larger power over the smaller power, and put a minus sign in front of the PR to indicate a power loss or attenuation.

Equal Impedance's $dB = 20 \log \frac{E_2}{E_1}$ $dB = 20 \log \frac{I_2}{I_1}$

Where: E_1 = input voltage
I_1 = input current
E_2 = output voltage
I_2 = output current

Unequal Impedance's $dB = 20 \log \frac{E_2\sqrt{R_1}}{E_1\sqrt{R_2}}$ $dB = 20 \log \frac{I_2\sqrt{R_2}}{I_1\sqrt{R_1}}$

Where: R_1 = impedance of the input in ohms
R_2 = impedance of the output in ohms
E_1 = voltage of the input in volts
E_2 = voltage of the output in volts
I_1 = current of the input in amperes
I_2 = current of the output in amperes

dBm

The decibel does not represent actual power, but only a measure of power ratios. It is desirable to have a logarithmic expression that represents actual power. The dBm is such an expression and it represents power levels above and below one milliwatt.

The dBm indicates an arbitrary power level with a base of one milliwatt and is found by taking 10 times the log of the ratio of actual power to the reference power of one milliwatt.

Conversion from Power to dBm	**Conversion from dBm to Power**
$P(dbm) = 10 \log \frac{P}{1mw}$	$Power(mW) = (1mW)antiLog\frac{dBm}{10}$ or $Power(mW) = 10^{\frac{dBm}{10}}$

Where:
P(dbm) = power in dbm
P = actual power
1mw = reference power

Power Ratio	**Conversion from Power Ratios to Decibels**
$PowerRatio(PR) = \frac{Pout}{Pin}$	$dB = 10logPR$ or $dB=10log\frac{Pout}{Pin}$

Conversion from Decibels to Power Ratios

$PR = anti \log \frac{dB}{10}$

or

$PR = 10^{\frac{dB}{10}}$

dBm Gains and Losses

1. Amplifiers add

2. Attenuation subtracts

Conversion from % to Decibels

$$dB = 10\log\frac{x\%}{100}$$

Example: The output power is equal to 5% of the input power. What is the attenuation x in dB?

$dB = 10\log\frac{5\%}{100}$ = -13.01 dB

Conversion from Decibels to %

$$\% = 10^{\frac{xdB}{10}} * 100\%$$

Example: Calculate output power of a 3 dB attenuator as a percentage of the input power (attenuation means negative dB value).

$\% = 10^{\frac{-3dB}{10}} * 100\%$ = 50.1%

The power at the output of the 3 dB attenuator is about half the amount as at the input.

2.13.1 Performing Attenuation Measurements

Now that some of the basic principles have been presented, the main attenuation measurement technique used in the Air Force PMEL will be discussed. The workhorse for measuring attenuation in the Air Force PMELs is the microwave measuring receiver (MMR). It is generally comprised of a spectrum analyzer, power meter and several different power sensors. For attenuation measurements, only the spectrum analyzer is used in tuned RF level mode. The setup connection is shown in Figure 2.12-1 below:

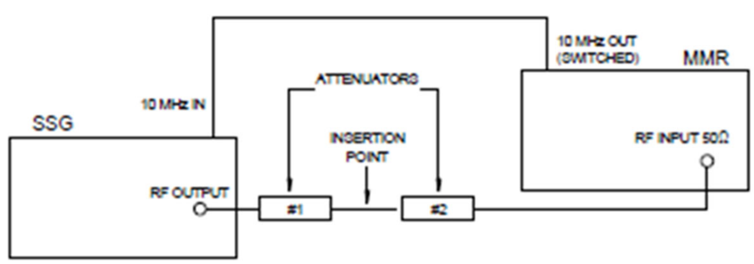


Figure 2.13-1: Attenuation measurement setup configuration

The values of attenuators #1 and #2 aren't very important and are typically between 3-10 dB, their purpose is to establish an insertion point and are sometimes referred to as pads. The synthesized signal generator will be set to the first frequency of interest and then the MMR will be set to tuned RF level mode and a reference will be set, which will result in a 0 dB reading on the MMR. This tuned RF level mode is a relative measurement, meaning that a reference has been set and subsequent readings are relative to that reading. The attenuator under test will now be inserted into the insertion point. The resultant relative dB reading is the attenuation of the attenuator.

2.14 SPECTRUM ANALYSIS

At the most basic level, a spectrum analyzer can be described as a frequency-selective, peak-responding voltmeter calibrated to display the rms value of a sine wave. It is important to understand that the spectrum analyzer is not a power meter, even though it can be used to display power directly. As long as we know some value of a sine wave (for example, peak or average) and know the resistance across which we measure this value, we can calibrate our voltmeter to indicate power. With the advent of digital technology, modern spectrum analyzers have been given many more capabilities. In this note, we describe the basic spectrum analyzer as well as additional capabilities made possible using digital technology and digital signal processing.

2.14.1 Absolute Amplitude

This test verifies that displayed measured power levels on the TI meet absolute power specifications. Absolute amplitude is verified by comparing the TI indicated power level to a known power level. The timebases are tied to ensure correct frequency is achieved. This test is normally performed at 50 MHz using a Synthesized Level Generator.

2.14.2 Reference Level or IF Gain

This test verifies that the TI's Reference Level accuracy meets or exceeds the specification provided by the manufacturer. Specifications state how much the error is induced with a varying reference level. The reference level is changed in conjunction with the injected signal and the delta is measured. The signal is kept on the same part of the screen as the reference level and injected signals are adjusted.

2.14.3 Residual FM

Test verifies that the residual FM of the TI meet specification. Residual FM specifies the instability of the TI's oscillator. This residual FM determines the minimum usable RBW. A signal is injected into the analyzer and the Residual FM is measured.

2.14.4 Phase Noise

Test verifies that phase noise (or single-sided noise sidebands) of the TI meets specification. This test is also commonly known as a Noise Sidebands test. It would more properly be termed Single Sided Noise Sidebands test since only the noise sidebands on the positive side of the carrier are calibrated. A reference source with better phase noise performance than TI is input and the phase noise of the TI is measured and compared to specifications.

The basic calibration theory is to first measure the carrier frequency amplitude on the TI using the marker amplitude function. Then the marker is moved on the positive side of the carrier by an offset frequency as required in Table 1 specifications and the amplitude of the TI phase noise is then measured at the respective offset from the marker amplitude. The next step is to turn off the RF input power from the source and measure the TI noise floor at the respective offset using the marker amplitude. Each of these values is then used in a formula to calculate a corrected sideband.

Some of the other phenomena that must be included in the corrected noise sideband include correction of the RBW to a 1 Hz bandwidth, the Rayleigh distribution for noise adds +1.05 dB correction and noise from the logarithmic response effect adds +1.45 dB correction to the measurement. There is a RBW Equivalent Noise Bandwidth that is dependent upon the TI. For the E4440 series, for example, it is -0.25 dB. This RBW Equivalent Noise Bandwidth is not always stated by the OEM, so in cases where it is not stated, it will not be included in the calculation (making the corrected sideband measurement more conservative, at a very slight increased probability of failing a good unit).

2.14.5 Input Attenuator

This test verifies that the TI's attenuator meets the input attenuation accuracy as specified by the manufacturer. This test is also referred to as Input Attenuator, Attenuator, Input Attenuation Switching, or Attenuator Switching Error. This module calibrates a spectrum analyzer's internal attenuator used to control the level the mixer gets. The SLG (Fluke RF Reference source) will be used to inject a 50 MHz signal at an amplitude of +16 dBm. An external attenuator will be used in conjunction with the RF Reference Source's internal attenuator to control the level to the mixer insuring that -70 dBm is consistently used. The power to the mixer level can be calculated using: Mixer Level = SLG Amplitude - External Attenuation - Internal TI Attenuation. The SLG amplitude is changed in conjunction with the TI attenuator and Reference Level to check only the TI attenuator uncertainty.

2.14.6 Displayed Average Noise Level

This test verifies that the TI noise floor is within specifications. Test is performed across the entire frequency range of the TI but is tested in the respective frequency bands of the TI independently. This test calibrates the Displayed Average Noise Level (DANL) of the TI throughout each warranted frequency band with a general purpose termination applied to the TI input. Each frequency point tested within a specified frequency band is measured and must pass comparison to the Original Equipment Manufacturer (OEM) warranted performance limit. Where applicable, Table 1 required settings are imported, otherwise AFMETCAL defined default settings for the TI are included below in the generalized calibration procedure. Traceability resides in the marker amplitude and / or scale fidelity function within the spectrum analyzer which was previously calibrated.

The generalized calibration procedure below includes considerations for digital spectrum analyzers regarding a phenomenon in sampling data that requires a sufficiently long integration time (dwell time on each "data bucket" sampled) to ensure acceptably low variability. For general calibration purposes, this methodology is tailored for approximately 0.75 dB variability at k = 2 standard deviations. The appropriate formula for two sigma standard deviation is:

$$2\,\sigma\,(dB) = 2\,\times\,\frac{5.2}{\sqrt{\frac{Sweep\ Time}{Number\ Points}\times \#Averages\ \times \#Buckets\ \times Resolution\ Bandwidth}}$$

The required TI settings to achieve two-sigma variability of approximately 0.75 dB are included in the Generalized Calibration Procedure below. Deviations from the settings below may induce increased variability. For purposes of keeping the automated procedure and the manual methodology consistent only one "bucket" of data from the number of points is sampled, when setting the marker to the Center Frequency.

2.14.7 Frequency Response

Frequency Response is the variation in trace amplitude given constant amplitude over the applicable TI frequency band. The absolute specification is taken relative to 50 MHz, unless otherwise specified. The relative specification states that the frequency will stay within the specified tolerance throughout each TI frequency band relative to 50 MHz. The Synthesized Level Generator and Spectrum Analyzer timebases are tied together to ensure correct frequency stepping. This test will verify the Low Frequency portion (10 Hz to 4 GHz) using a Synthesized Level Generator. The reference (50 MHz default) CW signal from the Synthesized Level Generator is applied to the TI RF input. The Synthesized Level Generator is then set at the frequencies listed in the standardized frequency table throughout the frequency bands listed for the TI under test. The maximum deviation from the 50 MHz reference point is noted on the TI and compared to the absolute frequency response specification for TI under test. The deviation between the minimum and maximum readings is taken throughout a specified band and compared to the relative specification.

2.14.7.1 High Frequency

Frequency Response is tested by stepping a flat signal over the entire TI frequency range and observing the peak to peak variation in trace amplitude. This test will verify the High Frequency portion (to 50 GHz) using a signal generator monitored by a power sensor/meter and relative to 50 MHz, unless otherwise specified. The timebases of the Signal Generator and Spectrum Analyzer are tied together to ensure correct frequency stepping.

A CW signal from the SIG GEN is split and applied to the TI RF input and monitored with a power sensor/meter. The signal level is monitored on the power meter and used to level the SIG GEN. The SIG GEN is then set at the frequencies listed in the standardized frequency table throughout the frequency bands listed for the TI under test. The maximum peak to peak deviation from the reference signal is noted on the TI and compared to the frequency response specification for TI under test. This is to be used in conjunction with the low frequency direct comparison methodology for TIs with frequencies throughout lower and upper frequency ranges.

2.14.7.2 Buried Sensor Notes
-Buried sensor method in CTO is only used when the 9640A is in the picture to improve TAR.
-The 9640A frequency starts at 100 kHz and goes to 3590 MHz for the buried sensor method.
-To cover the lower frequencies from 20 to 300 Hz, the 9640A is connected directly to the 3458A and the values are recorded and computed to determine the dBm levels. Then the 9640A is connected to the TI. We would use the direct connect method in NextGen for the lower frequencies.
-When signal generator (E8257D) is used, the TAR is generally greater than 4:1 from what I have seen with the exception of the Preamp checks (which we have improved with removing the 20 dB attenuator and using the low power sensors, 8487D or 8485D).

2.14.8 Other Input Related Spurious Responses
Test verifies that TI does not produce other input related spurious response as per TI specification. Also known as Image response, other spurious, input related spurious, or Immunity to Interference. Signal is input to TI at specific frequencies and offset is measured as per TI specifications.

2.14.9 Scale Fidelity - Linear
This test verifies that the TI display scale meets the specified display linearity accuracy. May also be referred to as Linear Display Accuracy, Amplitude Linearity, or Linear Level Display Accuracy. This module is developed using a Synthesized Leveled Generator (SLG) through 20 dB of attenuation provided by the High Precision Programmable Attenuator (HPPA) to utilize the most accurate power range of the SLG.

The test is performed referenced to a -10 dBm to the TI and walked down in 2 dB steps verifying the correct linear display from the reference.

2.14.9.1 Scale Fidelity - Cumulative with specified reference
Test verifies TI display scale meets specified cumulative fidelity accuracy for TIs with a reference to a specific mixer level. This module is developed specifically for the logarithmic cumulative display scale accuracy at 50 MHz when a reference power level into the TI mixer is specified by the OEM.

A 50 MHz CW test signal is output from a generator and applied to the TI RF input through a charted High Precision Programmable Attenuator (HPPA) such that the power level at the TI mixer is as specified in the OEM warranted specifications. The HPPA provides the required traceable standard signal. The HPPA is varied to achieve the lowest uncertainties possible throughout the full range of the TI's display cumulative logarithmic range. Marker amplitude values are recorded at each respective step and delta values are calculated relative to the TI reference level and compared to Table 1 specifications to determine pass or fail criteria.

In older spectrum analyzers, a related calibration or adjustment can be the IF Amplitude, or the Log and Linear Amplitude

2.14.9.2 Scale Fidelity – Cumulative without specified reference
Test verifies TI display scale meets specified cumulative linearity accuracy. This module is developed specifically for the logarithmic cumulative display scale accuracy at 50 MHz for an unspecified power level into the TI mixer. A 50 MHz CW test signal is output from a generator through a High Precision Programmable Attenuator (HPPA) which has a high power level linearity and it is applied to the TI RF input. The precision charted HPPA comprise the required traceable standard signal to achieve the lowest uncertainties possible throughout the full range of the TI's display cumulative logarithmic range.

The synthesized level generator is adjusted for a signal reference peaking at the TI reference level. The HPPA is stepped down through the full range of the display scale. The amplitude variation displayed on the TI is compared to the reference signal variation to determine the scale fidelity error. The cumulative maximum deviation from the reference level is nominally measured every 5 dB throughout the full range of the TI display. Marker amplitude values are recorded at each respective step and delta values are calculated relative to the TI reference level and compared to Table 1 specifications to determine pass or fail criteria.

NOTE

In older spectrum analyzers, a related calibration may be termed IF Amplitude, or Log Amplitude or Linear Amplitude.

2.14.9.3 Scale Fidelity - Incremental
This test verifies that the TI display scale meets the specified logarithmic incremental linearity accuracy. May also be referred to as Display Accuracy, Amplitude Linearity, Logarithmic Display Accuracy, or Level Display Accuracy. This module is developed specifically for the logarithmic incremental display scale accuracy at 50 MHz as generally 50 MHz is regarded as the conventional frequency for establishing traceability for RF power.

A 50 MHz CW test signal is output from a highly linear synthesized level generator and applied to the TI RF input through a charted High Precision Programmable Attenuator (HPPA) . The attenuator is used to drop the signal throughout the dynamic range of the TI as specified. This provides the lowest overall uncertainty possible for linearity throughout the range of the TI. This test methodology is specifically oriented to calibrate the TI incremental accuracy. TI marker and delta marker values are recorded at each incremental step to calculate the TI incremental scale accuracy which is compared to the warranted OEM specifications for pass/fail criteria. In older spectrum analyzers, a related calibration and adjustment can be the IF Amplitude, or the Log Amplitude.

2.14.10 Second Harmonic Intercept Test
Test verifies that the TI Second Harmonic produced from an injected signal is below warranted specifications. This test calibrates the internally generated second harmonic throughout the specified frequency band when a signal is applied to the TI. If a signal generator with low enough second harmonics is available, this test can be performed without using low pass filters. Otherwise, low pass filters must be used to knock the second harmonic generated by the signal generator down. Traceability resides in the marker amplitude and scale fidelity (previously calibrated in TI), signal generator second harmonic specification and low pass filter rejection specification. The specification used is taken based on the fundamental frequency. In other words, when the second harmonic crosses specification bands, the limit used is that of the fundamental frequency. If possible, choose test points which the second harmonic doesn’t cross frequency bands, preselector bands, or require mixer levels changes. When not possible, use the table 1 requirements of the fundamental frequency band.

2.14.10.1 Explanation of the use of Filters for Spectrum Analyzer Calibrations
Low pass filters are sometimes used to calibrate the second harmonic characteristic of spectrum analyzers. The calibration of second harmonic content in a spectrum analyzer is calibrated by injecting a signal into the spectrum analyzer, measuring the carrier content and then measuring the second harmonic (or the power in 2 times the carrier's frequency). The signal generator used has a second harmonic level that is specific for the generator. If this specification is worse than the spectrum analyzer under test's second harmonic specification, then a Low Pass Filter (or 2) must be used to knock down the level of the signal generator second harmonic. This is why the Table 2 accuracy for LPFs states "Verify before use." We are verifying that it meets our needs for the test, not necessarily matches the manufacturer's specifications.

Here are the parameters verified for the 2nd harmonic test:

1. Cutoff frequency (Fco) - Power will pass below this frequency. This is a frequency that is slightly greater than or equal to our carrier value under test.

2. Rejection - This is the amount of power that must be knocked down at a specified frequency. The frequency is less than or equal to the 2nd harmonic frequency under test and greater than the carrier frequency.

TI Specification

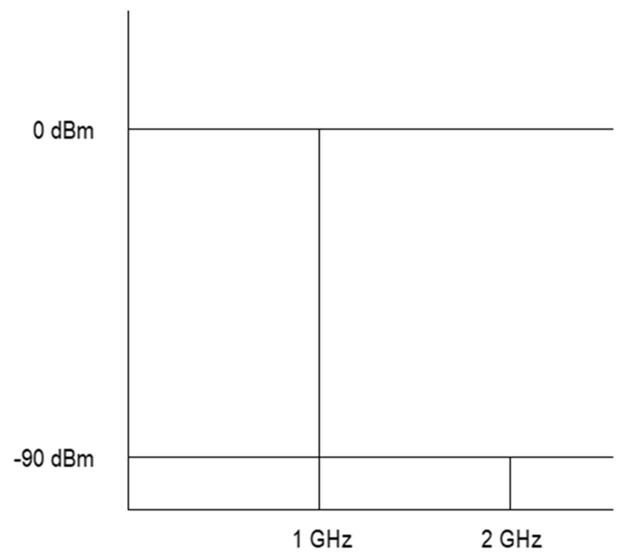


Figure 2.14-1. Specification: 2nd Harmonic ≥-90 dBc at 1 GHz.
Signal Generator Specification

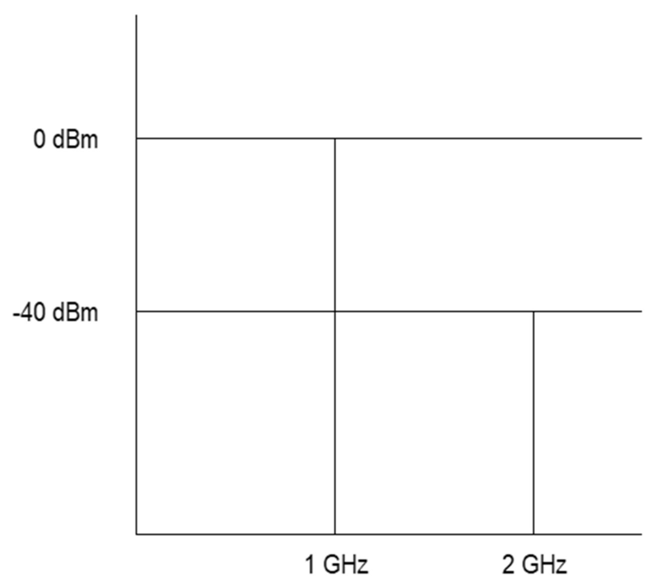


Figure 2.14-2 Specification: 2nd Harmonic ≥-40 dBc at 1 GHz.
Filter Specification

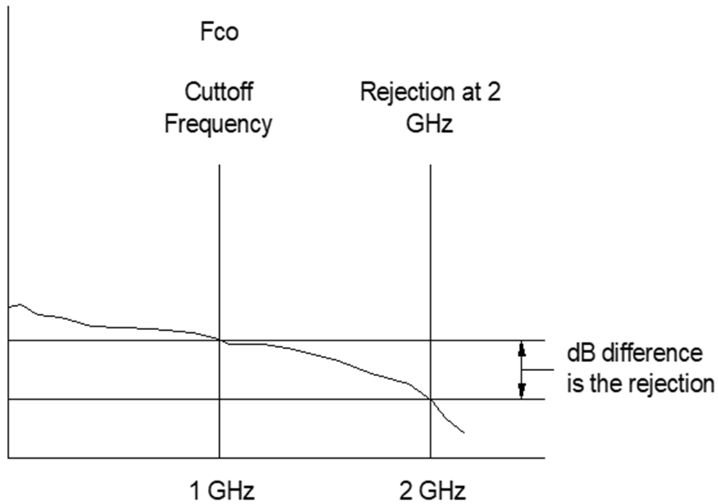


Figure 2.14-3 Specification: Fco = 1 GHz (or slightly greater)
Rejection = >50 dB at 2 GHz

Signal Generator with Filter Specification

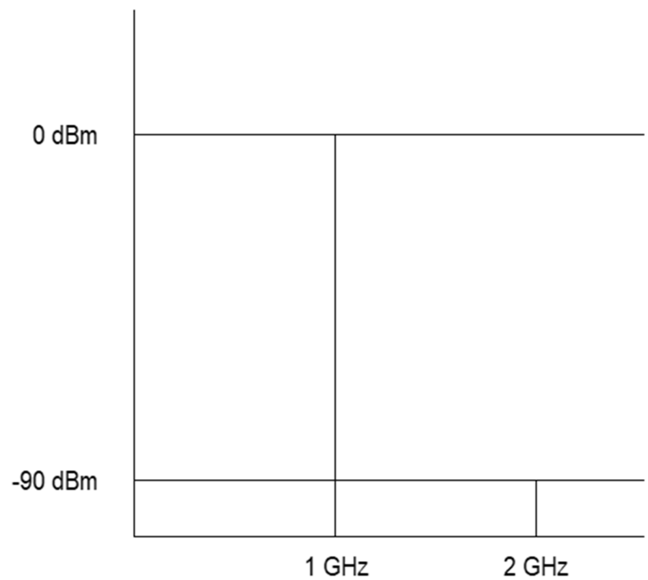


Figure 2.14-4 Specification: Signal Generator ≥-40 dBc
Filter Rejection >50 dB
Total ≥-90 dBc (meets or exceeds TI Specification)

2.14.11 Third Order Intermodulation
This test verifies that the TI's Third Order Intermodulation Distortion accuracy meets or exceeds the specification provided by the manufacturer. Specifications may be given as Third Order Intercept (e.g. >+7.5 dBm) or as the Third Order Intermodulation Distortion (e.g. <-75 dBc). These are mathematically related by the equation:

$$TOI = ML - (dBc/2)$$

Where: TOI = Third Order Intercept
ML = TI Specified Mixer Level
dBc = Third Order Intermodulation Distortion

May also be referred to as Third Order Intermodulation Distortion, Third Order Distortion, Two-tone 3rd order distortion, Intermodulation distortion, Third Order, or as part of Spurious Responses. This module calibrates the intermodulation distortion created from inputting two high-level products of nearby frequencies into the mixer. Two independent fundamental carrier signals separated by a frequency defined by the OEM are input into the TI at the same time and are adjusted for a common power level (reference), and the distortion products on both sides of the two fundamental carriers are measured and compared to the TI specification. The intermodulation distortion products can be measured directly in dBc, and the Third Order Intercept (TOI) can also be computed. TOI is given by the mixer tone level (in dBm) minus (worst case distortion product/2) where the distortion products are relative to the reference level in dBc.

2.15 VOLTAGE STANDING WAVE RATIO (VSWR) MEASUREMENTS

2.15.1 Definition

The formal definition of Voltage Standing Wave Ratio is the ratio of the maximum voltage (V_{max}) divided by the minimum voltage (V_{min}) of the resultant standing wave along a transmission line.

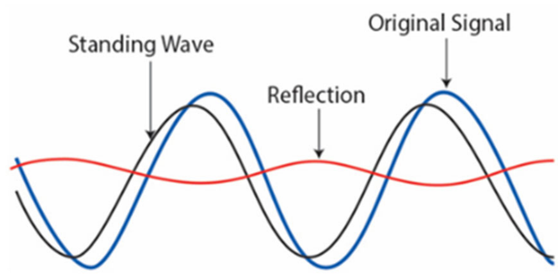


Figure 2.15-1

When two waveforms of equal frequency interact with one another, they can either create a constructive interference (when both signals are in phase with one another) or destructive interference (if signals are out of phase with each other) that is not traveling in either the forward or reflected direction; hence, standing wave.

Ultimately, VSWR is used to describe the mismatch error located from the source port to the load port and the efficiency at which power is transferred and how much is being reflected back. Whether it be Return Loss (RL), Reflection Coefficient (Γ), or VSWR, they are all directly related to each other:

$$\Gamma = \frac{VSWR-1}{VSWR+1} \qquad \mathrm{VSWR} = \frac{1+\Gamma}{1-\Gamma}$$

$$RL = -20\log_{10}\frac{VSWR-1}{VSWR+1} \quad VSWR = \frac{1+10^{\frac{-RL}{20}}}{1-10^{\frac{-RL}{20}}}$$

2.15.1.1 Theory

The best way to visualize mismatch error and reflection is the "two hoses analogy".

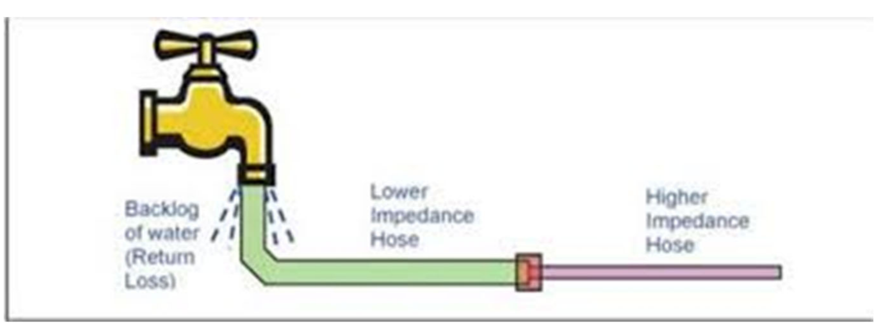


Figure 2.15-2.

Here you have your water faucet (source) supplying water into the lower impedance hose, which is also connected to the higher impedance hose. The water can clearly flow at a much faster rate in the lower impedance hose than it can the higher impedance hose. Therefore, once the water is transferred from the first hose to the second, a portion of the water won't be able to flow through and will be reflected back towards the faucet and becomes our return loss. With the faucet, the higher the rate the water is flowing, the more backlog will be created and reflected back; as well as, the lower the rate water, the less backlog/return loss you will have. The same concept applies with RF/Microwave transmission lines. Mismatch error/VSWR is more prevalent the higher you go in frequency.

2.15.2 Measurement

2.15.2.1 Setup

The easiest method for making a VSWR measurement is with a Vector Network Analyzer (VNA). The Vector Network Analyzer station should be set on an Electro-Static Discharge (ESD) mat with the User also grounded with an ESD wrist-strap.

If the user is using a cable connected to the VNA to make the VSWR measurement, the cable should be lying flat so that it is not hanging off the VNA, potentially damaging the VNA port or the cable itself. Most users will set a piece of Styrofoam for the cable to rest on if the VNA is slightly elevated.

2.15.2.2 Prep

Gaging - Before any device is connected to the VNA, it should be gaged first to ensure of any protrusion or receding connectors. Protruding connectors can also cause failing readings or, worse, fatal damage to the VNA. Most labs are equipped with a gaging kit and if not are encouraged to do so.

Cleaning **-** The inside of DUTs can collect dust and grime from sitting out and constant connection/disconnection. The inside of the connector (inside the grooves and around the center conductor) should be cleaned with isopropyl and a Q-Tip to clean out all of the grime. The dust buildup can also create mismatch and erratic readings, causing false failures of devices.

Torque **-** If cables are being used for the test, proper torque must be applied to ensure to ensure accurate readings. Over-torqueing can also cause damage to the VNA output ports.

Connector Type	**Torque (lb-in.)**
7 mm	12
Type N	12
3.5 mm	8
2.4 mm	8
2.92 mm	8
SMA	9
TNC	5
1.0 mm	4

2.15.2.3 Calibration

Before a VSWR measurement can be made on the VNA, a 1-Port Calibration with either a mechanical calibration kit or an electronic calibration (e-cal) kit must be performed to ensure accurate readings. In this case, the calibration of the VNA is essentially an adjustment/alignment of the internal components of the standard. There are 3 systematic errors (Directivity, Source Match, and Reflection Tracking,) within the VNA that causes irregular measurements and this calibration will correct for them. The mechanical calibration kits are more stable and typically stay within tolerance longer than the e-cal kits.

Adapters **–** Whatever adapters are needed to measure the DUT should be added before the calibration. The calibration plane will end at the last adapter and the VNA will compensate for it, ensuring that it doesn't add to the uncertainty. If any adapters are added after the calibration, it will add additional uncertainty/mismatch error and potentially cause a failing measurement.

Cable Movement – The VNA will take into account the position of the cable during the calibration of the standard. Minor cable movement is acceptable when measuring the different standards of the calibration kit but should not be drastically changing position. Essentially, during and after calibration, connect the devices needed and then don't touch the cable.

Calibration Interval – The calibration of the VNA is typically good for around 24 hours and the same calibration can used for multiple devices as long as they are all the same connector type and have the same operational frequency. If you are calibrating a DUT with a Type-N connector type, a separate calibration should be made if the next DUT is a 3.5 mm connector type for example.

2.15.2.4 Verification
Most labs should also be equipped with a Verification Kit. This kit comes with a 20 and 50 dB attenuator as well as a 25 and 50 Ohm airline. This kit is used to verify if the calibration of the VNA is good. This does not have to be done for all calibration but should be used following a DUT failing a calibration to eliminate the possibility the VNA is not within tolerance and caused the failing measurement. This check can be performed on Keysight VNA's using the "Verification" wizard.

2.15.3 TAR/Substitution
When verifying if a standard can meet a 4:1 TAR for a VSWR measurement, the Directivity specification for a VNA is what you want to look at. Directivity is synonymous with Return Loss in this case. Most DUT's, for a VSWR measurement, are specified with Return Loss. The Return Loss specification is also typically stated as being greater than or equal to a positive value but on the VNA it will be indicated as a negative value (so if the spec is ≥30 dB, the VNA should indicate ≤-30 dB for the DUT within tolerance). To ensure the VNA can meet a 4:1 TAR, the Directivity specification should be at least 6 dB greater than the Return Loss specification of the DUT (i.e. if Return Loss spec is 30 dB, Directivity of VNA should be at least 36 dB). The rule of thumb for that is: 3 dB is twice the power of the incident signal and 6 dB would be 4 times the power. If the DUT has a VSWR specification, it can be calculated into RL using the equation in paragraph 1a.

2.16 VOR, ILS, IFF, TACAN, RADAR

2.16.1 This area reserved for future use.

2.17 FIBER OPTIC

2.17.1 This area reserved for future use.

SECTION 3

MEASUREMENT AND CALIBRATION HANDOUT

This handout is used in the PMEL Apprentice Course E3ABR2P031 0B1D and the PMEL Physical Measurement and Calibration Course E8AZR2P051 0P1B/1P1B. The handout contains formulas for numerous calculations that are used by PMEL students including general information, mathematics, physical-dimensional, and electronic principles. Additionally the handout contains a glossary of terms common to the PMEL career field.

DESIGNED FOR REFERENCE USE ONLY
NOT INTENDED AS TECHNICAL GUIDANCE FOR USE ON THE JOB

3.1 GENERAL INFORMATION

3.1.1 Conversion Factors

1 centigram =
0.1543 grains
0.01 grams

1 grain =
6.480×10^{-2} grams
2.286×10^{-3} ounces

1 gram =
100 centigrams
980.7 dynes
15.43 grains
9.807×10^{-5} joules/cm
9.807×10^{-3} joules/meter (Newtons)
1.0×10^{-3} kilograms
1,000 milligrams
0.03527 ounces
2.2046×10^{-3} pounds

1 kilogram =
980,665 dynes
1000 grams
9.807×10^{-2} joules/cm
9.807 joules/meter (Newtons)
2.2046 pounds
9.842×10^{-4} tons (long)
1.102×10^{-3} tons (short)

1 ounce =
28.349527 grams
437.5 grains
16.0 drams
6.25×10^{-2} pounds

1 ounce (fluid)=
2.957×10^{-2} liters
1.805 cu. in.

1 pound =
0.4536 kilograms
7000 grains
453.5924 grams
256 drams
44.4823×10^{4}dynes
4.448×10^{-2} joules/cm
4.448 joules/meter (Newtons)
16.0 ounces
5.0×10^{-4} tons (short)

Length/Speed

1 angstrom =
1.0×10^{-8} centimeters
1.0×10^{-10} meters
3.9370×10^{-9} inches
1.0×10^{-4} microns

1 centimeter =
0.3937 inches
3.281×10^{-2} feet
1.094×10^{-2} yards
6.214×10^{-6} miles

1 foot =
0.3333 yards
30.4801 centimeters
3.048×10^{-4} kilometers
0.3048 meters
1.645×10^{-4} nautical miles
1.894×10^{-4} statute miles

1 inch =
2.540 centimeters
8.33×10^{-2} feet
2.778×10^{-2} yards
2.54×10^{-2} meters
25.40 millimeters
25,400 microns

1 kilometer =
0.6214 statute miles
3280.8399 feet
1,094.0 yards
3.937×10^{4}inches

1 knot =
1.0 nautical mile/hr

1 meter =
100 centimeters
39.37 inches
3.281 feet
1.094 yards
5.396×10^{-4} nautical miles
6.214×10^{-4} statute miles

1 micron =
1.0×10^{-4} centimeters
1.0×10^{-6} meters
3.937 x 10-5 inches

1 nautical mile =
6076.1155 feet
1852.0 meters
1.1508 statute miles
2,027 yards

1 statute mile =
5280 feet
1.6093 kilometers
1760 yards
1.609×10^{5} centimeters
6.336×10^{4} inches
0.8684 nautical miles

1 yard =
0.9144 meters
3 feet
36 inches
91.44 centimeters
9.144×10^{-4} kilometers
4.934×10^{-4} nautical mile
5.683×10^{-4} statute mile

Power, Work and Heat Conversion

1 BTU =
251.9958 calories/gram
777.649 ft-lbs
3.931×10^{-4}
horsepower-hrs
1,054.8 joules

1 watt =
44.2537 ft-lbs/minute
3.4144 BTU/hr
1 joule/sec

1 kilowatt =
1.3410 horsepower

1 horsepower =
745.7 watts
550 ft-lbs/sec
745.7 joules/sec

1 joule =
1.0×10^{7} ergs
0.2390 calories/gram

1 erg =
1 dyne/cm
7.3756×10^{-8} ft-lbs
1 calorie/gram
4.184 joules

3.1.2 Mathematical Symbols

+	Positive, Plus, or Add	⊥	Perpendicular to
-	Negative, Minus, or Subtract	$\parallel$	Parallel to
± or +/-	Positive or Negative Plus or Minus	π	Pi
X or *	Multiply	∈	Base of natural log 2.718
÷ or /	Divide	$\sqrt{\ }$	Square root
= or ::	Equals	$\sqrt[3]{\ }$	Cube root
≡	Identical	$\sqrt[n]{\ }$	n^{th} root
≠	Not equal to	$\lvert n \rvert$	Absolute value of n
≈ or ≅	Approximately equal to	n°	n degrees
>	Greater than	n'	minutes of a degree, feet, or prime
<	Less than	n"	seconds of a degree, inches, or second
≥	Greater than or equal to	$\bar{n}$	Average value of n
≤	Less than or equal to	j	Square root of -1
::	Proportional to	%	Percentage
:	Ratio	n_l	Subscript of n
∴	Therefore	( )	Parentheses
∞	Infinity	[ ]	Brackets
Δ	Increment or change	{ }	Braces
∠	Angle	—	Vinculum

3.1.3 Mathematical Constants

Symbol	Number	Log10
π	3.1416	0.4971
π^2	9.8696	0.9943
2π	6.2832	0.7982
$2\pi^2$	19.7392	1.2953
3π	9.4248	09742
4π	12.5664	1.0992
$4\pi^2$	39.4784	1.5964
8π	25.1327	1.4002
$\frac{\pi}{2}$	1.5708	0.1961
$\frac{\pi}{3}$	1.0472	0.0200
$\frac{\pi}{4}$	0.7854	9.8951^{-10}
$\frac{\pi}{6}$	0.5236	9.7190^{-10}
$\frac{\pi}{8}$	0.3927	9.5941^{-10}
$\frac{2\pi}{3}$	2.0944	0.3210
$\frac{4\pi}{3}$	4.1888	0.6221
$\frac{1}{\pi}$	0.3183	9.5029^{-10}
$\frac{2}{\pi}$	0.6366	9.8039^{-10}

Symbol	Number	Log10
4	1.2732	0.1049
$\frac{1}{2\pi}$	0.1592	9.2018^{-10}
$\frac{1}{4\pi}$	0.0796	8.9008^{-10}
$\frac{1}{6\pi}$	0.0531	8.7247^{-10}
$\frac{1}{8\pi}$	0.0398	8.5998^{-10}
$\frac{\pi}{180}$	0.0175	8.2419^{-10}
$\frac{180}{\pi}$	57.2958	1.7581
$\frac{1}{\pi^2}$	0.1013	9.0057^{-10}
$\frac{1}{2\pi^2}$	0.0507	8.7047^{-10}
$\frac{1}{4\pi^2}$	0.0253	8.4036^{-10}
$\sqrt{\pi}$	1.7725	0.2486
$\frac{\sqrt{\pi}}{2}$	0.8862	9.9475^{-10}
$\frac{\sqrt{\pi}}{4}$	0.4431	9.6465^{-10}
$\sqrt{\frac{\pi}{2}}$	1.25330	0.0980
$\sqrt{\frac{2}{\pi}}$	0.7979	9.9019^{-10}
π^3	31.0063	1.4914
$\frac{1}{\pi^3}$	0.03225	8.5086^{-10}

3.1.4 Numerical Constants

π or h = 3.14159 26535 89793 23846 26433 83279 50288 41971

∈ or j = 2.71828 18284 59045 23536 02874 71352 66249 77572

3.1.5 Greek Alphabet

NAME	UPPER CASE	COMMONLY DESIGNATES	LOWER CASE	COMMONLY DESIGNATES
Alpha	A		α	Angles, area, absorption factor, atten. constant, I gain CB config.
Beta	B		β	Angles, coefficients, phase constant, flux density, I gain CE config.
Gamma	Γ	complex propagation constant	Γ	Angles, specific gravity, elect. conductivity, propag'n constant
Delta	Δ	increment, determinant, permittivity, variation	δ	Angles, density, increment
Epsilon	E		∈	Base of natural logs, dielectric constant, electrical intensity
Zeta	Z	impedance	Γ	coordinates, coefficients
Eta	H		η	hysteresis, coordinates, efficiency intrinsic impedance
Theta	θ		θ	angular phase displacement, time constant, reluctance
Iota	I	current	ι	unit vector
Kappa	K		κ	coupling coefficient, susceptibility, dielectric constant
Lambda	Λ	permeance	λ	wavelength, attenuation constant
Mu	M		μ	prefix micro, amplification factor, permeability
Nu	N		ν	frequency, reluctivity
Xi	Ξ		ξ	coordinates, output coefficients
Omicron	O		ο	reference point
Pi	Π		π	3.1416
Rho	P		ρ	resistivity, volume charge density, coordinates
Sigma	Σ	summation	σ	electrical conductivity, leakage coefficient, complex propag'n constant
Tau	T		τ	time constant, time phase displacement, transmission factor, torque
Upsilon	Υ		υ	
Phi	Φ	sealer potential, magnetic flux, radiant flux	ϕ	phase angle
Chi	Χ		χ	angles, electrical susceptibility
Psi	Ψ		ψ	angles, coordinates, dielectric flux, phase difference
Omega	Ω	resistance in ohms	ω	angular velocity (2 π f)

3.1.6 Power of Ten Multiplier Chart

Multiple or Submultiple	Symbol	Prefix	Name
10^{12} = 1,000,000,000,000	T	Tera	Trillion
10^{9} = 1,000,000,000	G	Giga	Billion
10^{8} = 100,000,000			Hundred Million
10^{7} = 10,000,000			Ten Million
10^{6} = 1,000,000	M	Mega	Million
10^{5} = 100,000			Hundred Thousand
10^{4} = 10,000			Ten Thousand
10^{3} = 1,000	K	Kilo	Thousand
10^{2} = 100	H	Hecto	Hundred
10^{1} = 10	D	Deka	Ten
10^{0} = 1			One
10^{-1} = .1	d	Deci	One Tenth
10^{-2} = .01	c	Centi	One Hundredth
10^{-3} = .001	m	Milli	One Thousandth
10^{-4} = .0001			One Ten-Thousandth
10^{-5} = .00001			One Hundred-Thousandth
10^{-6} = .000001	□	Micro	One Millionth
10^{-7} = .0000001			One Ten-Millionth
10^{-8} = .00000001			One Hundred-Millionth
10^{-9} = .000000001	n	Nano	One Billionth
10^{-12} = .000000000001	p	Pico	One Trillionth
10^{-15} = .000000000000001	f	Femto	One Quadrillionth
10^{-18} = .000000000000000001	a	Atto	One Quintillionth

3.1.7 Power of Ten Conversion Chart

Move the decimal point the number of places and direction noted

To From	Tera	Giga	Mega	kilo	basic	Deci	Centi	Milli	micro	Nano	pico	Femto	Atto
Tera		3 →	6 →	9 →	12 →	13 →	14 →	15 →	18 →	21 →	24 →	27 →	30 →
Giga	3 ←		3 →	6 →	9 →	10 →	11 →	12 →	15 →	18 →	21 →	24 →	27 →
Mega	6 ←	3 ←		3 →	6 →	7 →	8 →	9 →	12 →	15 →	18 →	21 →	24 →
kilo	9 ←	6 ←	3 ←		3 →	4 →	5 →	6 →	9 →	12 →	15 →	18 →	21 →
basic	12 ←	9 ←	6 ←	3 ←		1 →	2 →	3 →	6 →	9 →	12 →	15 →	18 →
Deci	13 ←	10 ←	7 ←	4 ←	1 ←		1 →	2 →	5 →	8 →	11 →	14 →	17 →
Centi	14 ←	11 ←	8 ←	5 ←	2 ←	1 ←		1 →	4 →	7 →	10 →	13 →	16 →
Milli	15 ←	12 ←	9 ←	6 ←	3 ←	2 ←	1 ←		3 →	6 →	9 →	12 →	15 →
micro	18 ←	15 ←	12 ←	9 ←	6 ←	5 ←	4 ←	3 ←		3 →	6 →	9 →	12 →
Nano	21 ←	18 ←	15 ←	12 ←	9 ←	8 ←	7 ←	6 ←	3 ←		3 →	6 →	9 →
pico	24 ←	21 ←	18 ←	15 ←	12 ←	11 ←	10 ←	9 ←	6 ←	3 ←		3 →	6 →
Femto	27 ←	24 ←	21 ←	18 ←	15 ←	14 ←	13 ←	12 ←	9 ←	6 ←	3 ←		3 →
Atto	30 ←	27 ←	24 ←	21 ←	18 ←	17 ←	16 ←	15 ←	12 ←	9 ←	6 ←	3 ←	

3.1.8 Binary Conversion

EXAMPLE:

2^9	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0	
512	256	128	64	32	16	8	4	2	1	= 172
0	0	1	0	1	0	1	1	0	0	

BINARY NUMBER	DECIMAL NUMBER
1	1
10	2
11	3
100	4
101	5
110	6
111	7
1000	8
1001	9
1010	10
110010	50
1100100	100

3.1.9 Powers of Two Chart

2^n	n	2^{-n}
1	**0**	1.0
2	**1**	0.5
4	**2**	0.25
8	**3**	0.125
16	**4**	0.0625
32	**5**	0.03125
64	**6**	0.015625
128	**7**	0.0078125
256	**8**	0.00390625
512	**9**	0.001953125
1024	**10**	0.0009765625
2048	**11**	0.00048828125
4096	**12**	0.000244140625
8192	**13**	0.0001220703125
16384	**14**	0.00006103515625
32768	**15**	0.000030517578125
65536	**16**	0.0000152587890625
131072	**17**	0.00000762939453125
262144	**18**	0.000003814697265625
524288	**19**	0.0000019073486328125
1048576	**20**	0.00000095364731640625
2097152	**21**	0.000000476837158203125
4194304	**22**	0.0000002384185791015625
8388608	**23**	0.00000011920928955078125
16777216	**24**	0.000000059604644775390625
33554432	**25**	0.0000000298023223876953125

3.2 MATHEMATICS

3.2.1 Sequence of Mathematical Operations

Remember

Please Excuse My Dear Aunt Sally

Parentheses	(**P**)
Exponents	(**E**)
Multiply	(**M**)
Divide	(**D**)
Add	(**A**)
Subtract	(**S**)

3.2.2 Significant Figures/Significant Digits

Figures arrived at by counting are often exact. On the other hand, figures arrived at by measuring are approximate. Significant figures express the accuracy of the measurement.

When counting significant figures, all digits (including zeros) are counted **EXCEPT** those zeros that are to the left of the number.

Example:	4.3	contains 2 significant figures/digits
	0.0234	contains 3 significant figures/digits
	0.1100	contains 4 significant figures/digits

3.2.3 Rounding Off Numbers

Rule 1: If the first digit to the right of the last significant digit is a 6, 7, 8, or 9 round up by increasing the last significant digit by one and dropping all the following digits. (Example rounded off to three significant digits to the right of the decimal).

45.784624 becomes 45.785

Rule 2: If the first digit to the right of the last significant digit is a 0, 1, 2, 3, or 4, round down by leaving the last significant digit unchanged, and dropping all the following digits. (Example rounded off to two significant digits to the right of the decimal).

45.784624 becomes 45.78

Rule 3: If the first digit to the right of the last significant digit is a 5, and there are additional digits other than 0, round up by increasing the last significant digit by one, and dropping all the following digits. (Example rounded off to two significant digits to the right of the decimal).

7.1450004 becomes 7.15

Rule 4: If the first digit to the right of the last significant digit is a 5, and there are no additional digits other than 0, round to the nearest even digit. This rule is also known as the odd-even rule for rounding off numbers. (Example rounded off to two significant digits to the right of the decimal).

7.1550000 becomes 7.16

3.2.4 Exponents

Zero exponent	a= = 1	Power of a power	$(a^x)^y = a^{xy}$
Negative exponent	$a^{-x} = \frac{1}{a^x}$	Root of a power	$\sqrt[y]{a^x} = a^{x/y}$
Multiplication	$a^x * a^y = a^{(x+y)}$	Fractional exponents	$a^{\frac{1}{4}} = \sqrt[4]{a}$ $\frac{x}{a^y} = \sqrt[y]{a^x}$
Division	$a^x \div a^y = \frac{a^x}{a^y} = a^{(x-y)}$		
Power of a product	$ab^x = a^x b^x$	Radicals	$\sqrt{\frac{a}{b}} = \frac{\sqrt{a}}{\sqrt{b}}$ $\sqrt{ab} = \sqrt{a} * \sqrt{b}$

3.2.5 Interpolation

To interpolate a value for any number in a given table

$$X = \frac{(A_m - A_1)(B_2 - B_1)}{(A_2 - A_1)} + B_1$$

Where:

X = unknown
A_m = measured amount
A_1 = lower of the two amounts bracketing the measured amount
A_2 = higher of the two amounts bracketing the measured amount
B_1 = value (from table) for A_1
B_2 = value (from table) for A_2

3.2.6 Logarithms

The exponent of that power of a fixed number, called the base, which equals a given number.

$10^2 = 100$, therefore 2 = log of 100 to the base 10.

Exponential form	Logarithmic form
$2^4 = 16$	$4 = \log_2 16$
$10^2 = 100$	$2 = \log_{10} 100$
$10^3 = 1000$	$3 = \log_{10} 1000$
$a^b = c$	$b = \log_a c$

Multiplication: log (6*4) = log 6+log 4

Division:

$$\log\frac{3}{4} = \log^3 - \log^4$$

Raising to a power: $\log N^3 = 3 \log N$

Extracting roots:

$$\log\sqrt[3]{N} = \frac{\log N}{3}$$

Common to natural	$\log_{10} N = 2.3026 \log_e N$
Natural to common	$\log_e N = 0.4343 \log_{10} N$

3.2.7 Scientific Notation

A whole number between 1 and 10 times the proper power of ten, also called standard form. Example: $4.30 \times 10^4 = 43000$

3.2.8 Trigonometry and Geometry

$$\frac{\text{Oscar}}{\text{Had}} = \text{Sick} \qquad \frac{O}{H} = S$$

$$\frac{\text{A}}{\text{Heap}} = \text{Call} \qquad \frac{A}{H} = C$$

$$\frac{\text{Of}}{\text{Apples}} = \text{Tomorrow} \qquad \frac{O}{A} = T$$

H = Hypotenuse

A = Adjacent Side

O = Opposite Side

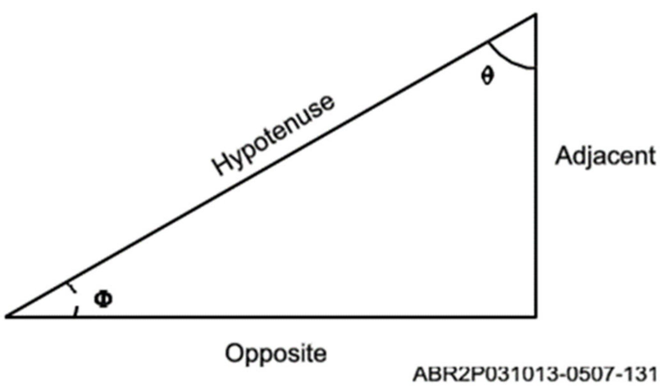
S = Sine

C = Cosine

T = Tangent

θ =angle between hypotenuse and adjacent side

ϕ =angle between hypotenuse and the opposite side

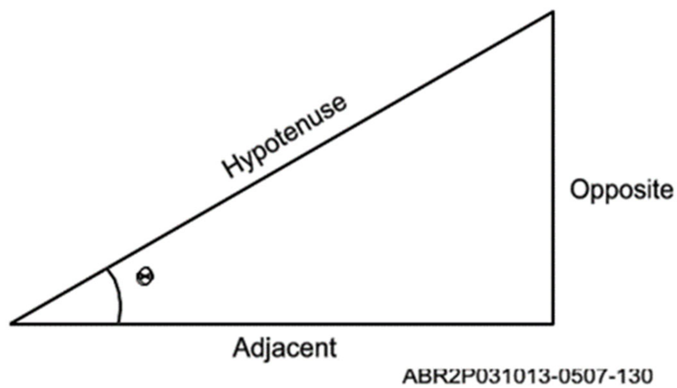


$$\sin\theta = \frac{O}{H} \qquad \csc\theta = \frac{H}{O} \qquad \sin\theta = \cos\emptyset \qquad \csc\theta = \sec\emptyset$$

$$\cos\theta = \frac{A}{H} \qquad \sec\theta = \frac{H}{A} \qquad \cos\theta = \sin\emptyset \qquad \sec\theta = \csc\emptyset$$

$$\tan\theta = \frac{O}{H} \qquad \cot\theta = \frac{A}{O} \qquad \tan\theta = \cot\emptyset \qquad \cot\theta = \tan\emptyset$$

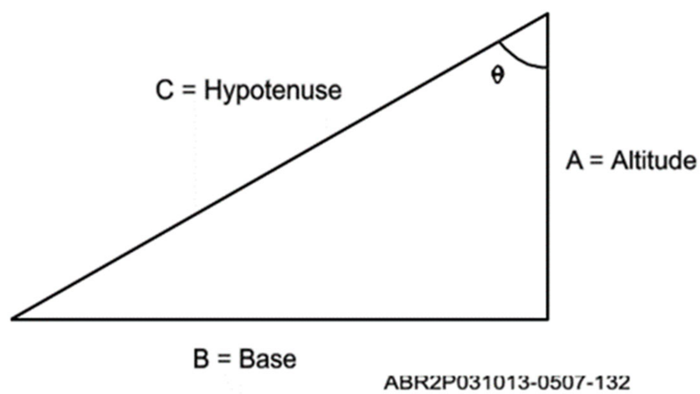
3.2.9 Trigonometric Relations



3.2.10 Pythagorean Theorem

In a right triangle, the square of the hypotenuse is equal to the sum of the squares of the other two sides.

$c^2 = a^2 + b^2$ $a^2 = c^2 - b^2$ $b^2 = c^2 - a^2$



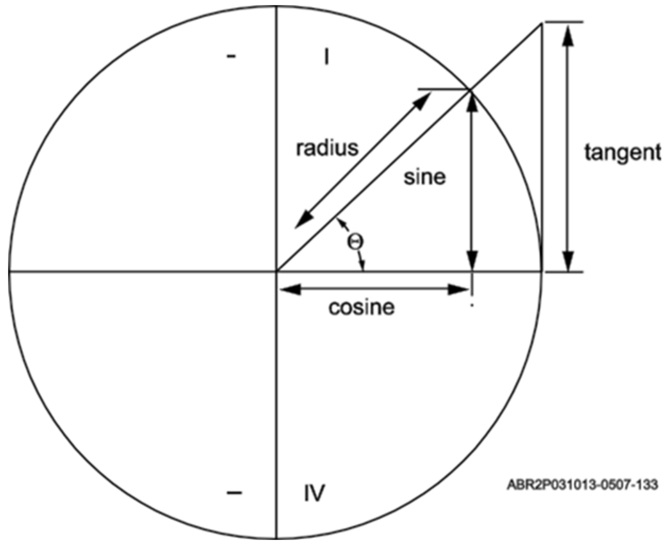
Length of Sides for Right-Angle Triangles

Length of Hypotenuse = Side Opposite * Cosecant
Side Opposite/Sine
Side Adjacent * Secant
Side Adjacent/Cosine

Length of Side Opposite = Hypotenuse * Sine
Hypotenuse/Cosecant
Side Adjacent * Tangent
Side Adjacent/Cotangent
Length of Side Adjacent = Hypotenuse * Cosine
Hypotenuse/Secant
Side Opposite * Cotangent
Side Opposite/Tangent

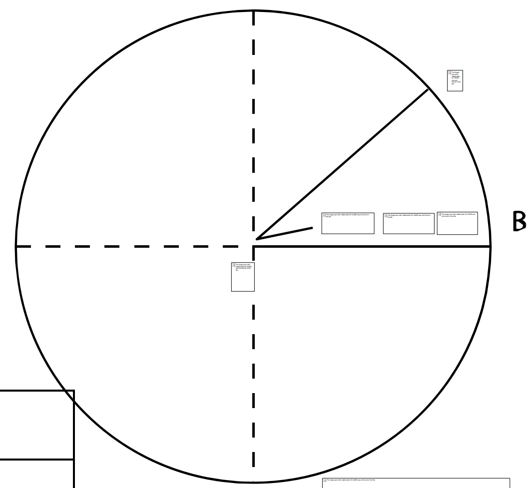
Signs of the Functions

QUADRA	sinθ	cosθ	tanθ
I	+	+	+
II	+	-	-
III	-	-	+
IV	-	+	-



3.2.11 Radian Measure

The circular system of angular measurement is called radian measure. A radian is an angle that intercepts an arc equal in length to the radius of a circle as illustrated…

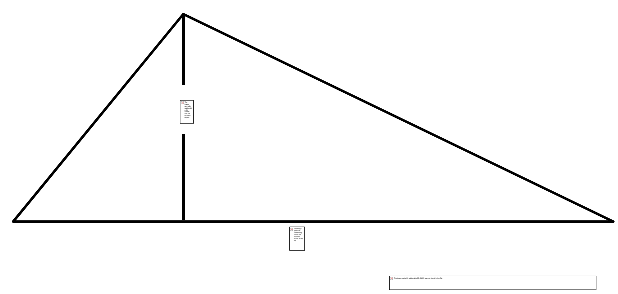


Length of arc BC = radius of circle
6.28 radians = 360°
2π radians = 360°
π radians = 180°
1 radian = 57.2958°
1 degree = 0.01745 radian
To convert

FROM → TO ↓	DEGREES (ANGLE)
QUADRANTS	.01111
RADIANS	.01745
SECONDS	3600

3.2.12 Various Measurements

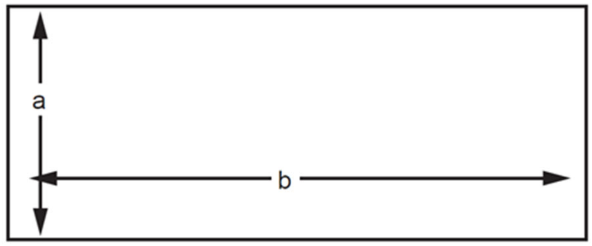
Plane Figures Bounded by Straight Lines.



Area of a triangle with base (b) and altitude (h).

$$\text{area} = \frac{bh}{2}$$

Area of a rectangle with sides (a) and (b).
area = ab



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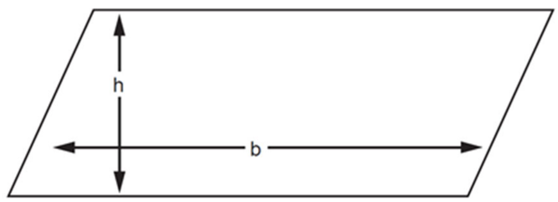
<u>Area of a parallelogram</u>
with side (b) and perpendicular distance to the parallel side (h).
area = bh



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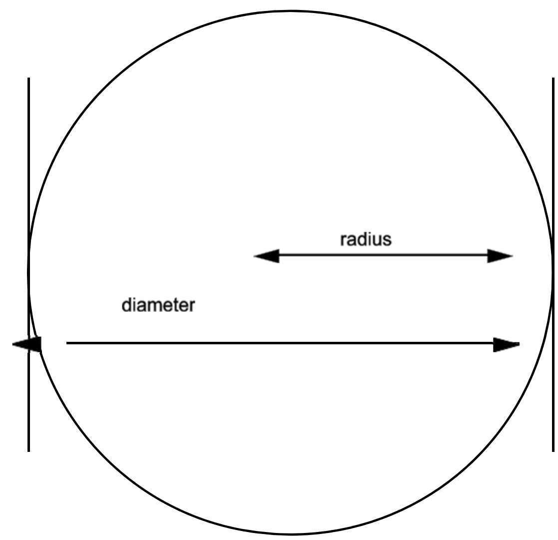
Plane Figures Bounded by Curved Lines.

<u>Circumference of a circle</u>
whose radius is (r) and diameter (d)

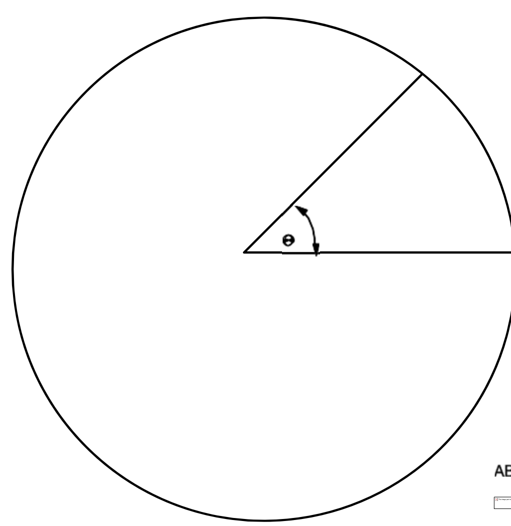
circumference = $2\pi r = \pi d$



ABR2P031013-0507-139<u>Area of a circle</u>
area = $\pi r^2 = \frac{1}{4}\pi d^2 = .7854d^2$

<u>Length of an arc</u>
of a circle for an arc of θ degrees.

$$\text{length of arc} = \frac{\pi r \theta}{180}$$



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3.2.13 Error Calculations

Relative Error

$$e_r = \frac{M - T}{T}$$

Where: e_r = relative error
M = Measured Value
T = True Value

$$e_r = N - A$$

Where: e_r = error
N = Nominal
A = Actual

Percent Relative Error

$$e_r(\%) = \frac{M - T}{T} \times 100$$

Where: e_r (%) = percent relative error
M = Measured Value
T = True Value

Correction

$$C = A - N$$

Where: C = Correction
N = Nominal
A = Actual

The true value is usually replaced by accepted or nominal value because the true value is never exactly known.

Correction Factor (%)

$$CF(\%) = \frac{A - N}{N} \times 100$$

Correction Factor (PPM)

$$CF_{ppm} = \frac{A - N}{N} \times 10^6$$

Where: CF = Correction Factor (in Percent or Parts Per Million
A = Actual Value
N = Nominal Value

(1) To convert from Percent (%) to Parts-Per-Million, move the decimal place 4 places to the right.
(2) To convert from Parts-Per-Million to Percent (%), move the decimal place 4 places to the left.

Calculation of Acceptable Limits

________% of Range (FULL SCALE)
________% of Reading (INPUT/OUTPUT)
________#of Digits (RESOLUTION)
TOTAL =

________Where any of these quantities are given,
________cross multiply the values across,
________and then add to fill the total block.
________This value is then applied to the %READING

Example: 930V applied, 1200 Volt Range, 8 1/2 digit display, tolerance +/- (.015% input + .01% range + 5 digits)
.01% Range * 1200 = 0.12
.015% Input * 930 = 0.1395
8 1/2 digits 1 2 0 0.0 0 0 0 5 (note: eliminate #'s left of decimal)
Total = ± or +/- 0.25955 which is then applied to 930v for limits of 929.74045 to 930.25955

3.2.14 Dimensional Analysis

Example: To convert from $\frac{\text{ft}}{\text{sec}}$ to $\frac{\text{km}}{\text{hr}}$

$$\frac{80\ \text{ft}}{\text{sec}} = \frac{80\ \text{ft}}{\text{sec}} \times \frac{12\ \text{in}}{1\ \text{ft}} \times \frac{2.54\ \text{cm}}{1\ \text{in}} \times \frac{1\ \text{m}}{100\ \text{cm}} \times \frac{1\ \text{km}}{1000\ \text{m}} \times \frac{60\ \text{sec}}{1\ \text{min}} \times \frac{60\ \text{min}}{1\ \text{hr}} = \frac{87.78\ \text{km}}{\text{hr}}$$

3.2.15 Densities of Various Substances

	ρ(grams/cm^3)	D (lbs/in^3)	Conditions
Acetone	0.792	0.02858778	20° C
Alcohol, ethyl	0.791	0.02858778	20° C
methyl	0.810	0.02922435	0° C
Carbon tetrachloride	1.595	0.05763852	20° C
Gasoline	0.66 - 0.69	0.0237267 - 0.0248841	
Kerosene	0.82	0.02962944	
Mercury	13.5955	.49116	
Milk	1.028 - 1.035	0.03715254 - 0.03738402	
Oils, Castor	0.969	0.03501135	15° C
Cotton seed	.926	0.03344886	16° C
Lubricating	.852 - .877	.0307 - .0318	15° C
Fuel	.928 - .979	.0336 - .0353	15° C
Seawater	1.025	0.037031013	15° C
Turpentine (spirits)	0.87	0.03142341	
Water	1.000	0.036128241	4° C

3.2.16 Metric Conversion lb ft to nm

The chart below can be used to convert pound foot to newton meter. The left-hand column lists pound foot in multiples of 10 and the numbers at the top of the columns list the second digit. Thus 36 pound foot is found by following the 30 pound foot line to the right to the "6" and the conversion is 49 N•m.

lb ft	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	N•m	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**
0	0	1.36	2.7	4.1	5.4	6.8	8.1	9.5	10.9	12.2
10	13.6	14.9	16.3	17.6	19.0	20.3	21.7	23.1	24.4	25.8
20*	27	28	30	31	33	34	35	37	38	39
30	41	42	43	45	46	47	49	50	52	53
40	54	56	57	58	60	61	62	64	65	66
50	68	69	71	72	73	75	76	77	79	80
60	81	83	84	85	87	88	90	91	92	94
70	95	96	98	99	100	102	103	104	106	107
80	109	110	111	113	114	115	117	118	119	121
90	122	123	125	126	127	129	130	132	133	134
100	136	137	138	140	141	142	144	145	146	148

* Above 20 lb. ft the converted N•m readings are rounded to the nearest N•m

3.2.17 Metric Conversion kg cm to n m

The chart below can be used to convert kilograms centimeter to newton meter. The left-hand column lists kg•cm in multiples of 10 and the numbers at the top of the columns list the second digit. Thus 72 kg•cm is found by following the 70 kg•cm line to the right to the "2" and the conversion is 7.1 N•m.

kg cm	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	N•m	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**	**N•m**
0	0	.098	.20	.29	.39	.49	.59	.69	.78	.88
10	.98	1.08	1.18	1.27	1.37	1.47	1.57	1.67	1.76	1.86
20*	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
30	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8
40	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8
50	4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8
60	5.9	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8
70	6.9	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8
80	7.9	7.9	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.7
90	8.8	8.9	9.0	9.1	9.2	9.3	9.4	9.5	9.6	9.7
100	9.8	9.9	10.0	10.1	10.2	10.3	10.4	10.5	10.6	10.7

* Above 20 kg•cm the converted N•m readings are rounded to the nearest N•m

One oz. in = 28.35 gms. in
One lb. in = 1.152 kg•cm
One lb. ft. = kg•m

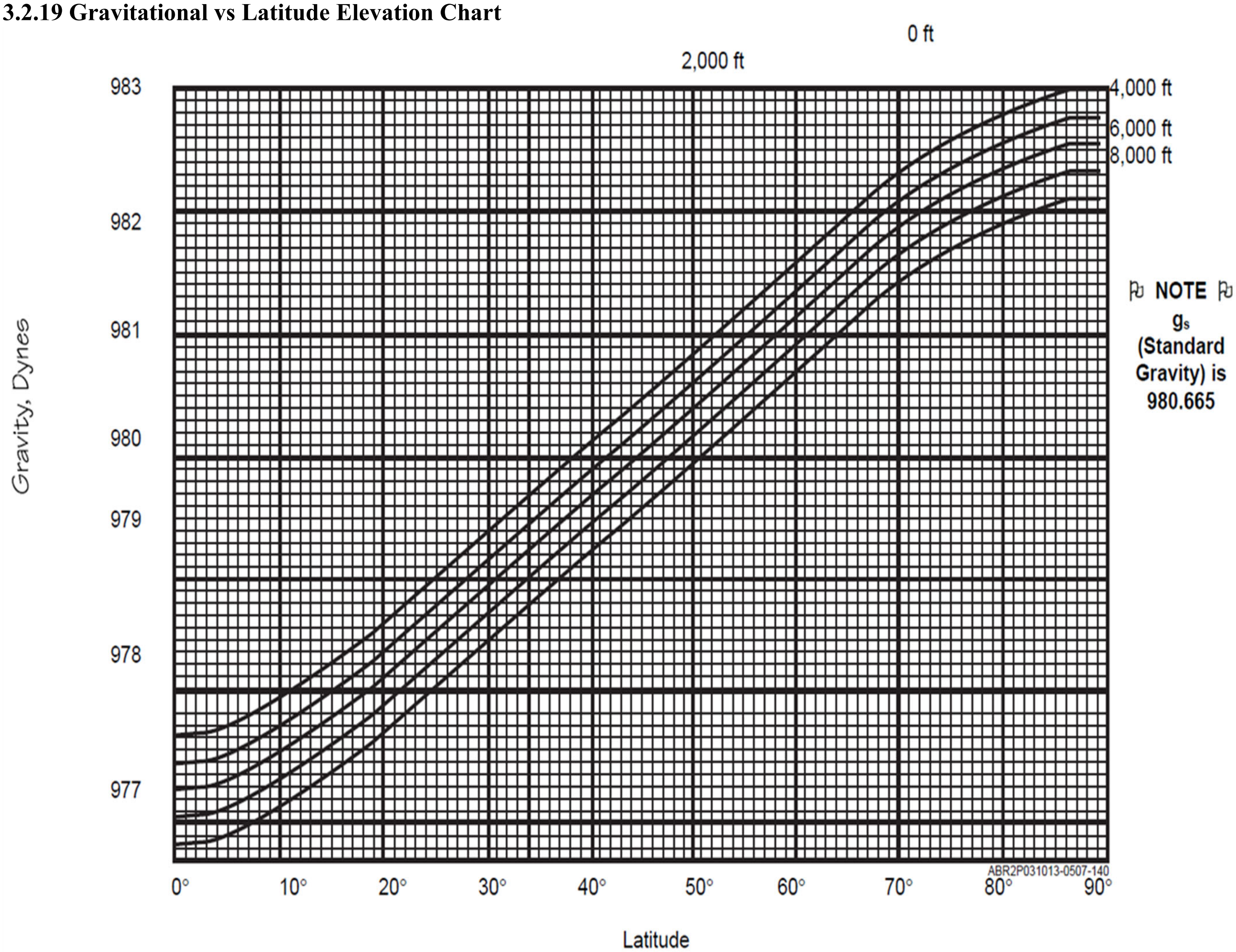
One kg•cm = 8679 lb. in.
One kg•cm = 7.233 ;b. ft.
One N•cm = .0885 lb. in.
One N•m = .7375 lb. ft.

3.2.18 Conversion of Various Units of Torque

Convert from	To	Multiply
lb.in	oz.in.	16
lb.in	lb.ft.	.08333
lb.in	kg.cm.	1.1519
lb.in	kg.m	.011519
lb.in	N.m	.113
lb.in	dN.m	1.13
lb.ft	kg.m	.1382
lb.ft	N.m	1.356
N•m	dN.m	10
N•m	kg.cm	10.2
N•m	kg.m	.102

Convert from	To	Multiply
oz.in.	lb.in	.0625
lb.ft.	lb.in	12
kg.cm.	lb.in	.8681
kg.m	lb.in	86.81
N.m	lb.in	8.85
dN.m	lb.in	.885
kg.m	lb.ft	7.236
N.m	lb.ft	.7376
dN.m	N•m	.10
kg.cm	N•m	.09807
kg.m	N•m	9.807

3.2.19 Gravitational vs Latitude Elevation Chart



3.2.20 Linear Coefficients of Expansion

SUBSTANCE	$\frac{n \times 10^{-6}}{°C}$	$\frac{n \times 10^{-6}}{°F}$
Aluminum	25.0	13.89
Brass (Yellow)	18.9	10.5
Chromium Carbide	8.1	4.5
Copper	16.6	9.22
Iron (Cast)	12.0	6.67
Nickel	13	7.22
Platinum	9.0	5.0
Steel (Hardened)	11.5	6.4
Steel (Carbon)	11.3	6.30
Tungsten	4.50	2.50
Tungsten Carbide	5.40	3.0
Zinc	35.0	19.4

$L_f = L_o (1 + \alpha \Delta t)$
Where:

$\Delta L = (Lo) (\alpha) (\Delta t)$
Where:

L_f = Length Final

L_o = Length Original

ΔL = Change in Length

α = Linear Coefficient of Expansion

t_1 = Original Temperature (68 ºF or 20 ºC) *

t_2 = Final Temperature

Δt = Change in Temperature (t2 - t1)
ºC/ºF = Diff in temperatures (unit of measure)

* T.O. 00-20-14, Para 8.2.3.1.2 states that "by international agreement the true size and shape of an object is that which exists at a uniform temperature of 68 ºF (20 ºC)"

3.2.21 Gage Block Classification

	Grade 0.5		Grade 1		Grade 2		Grade 3	
Nominal Size(in)	Length	Flatness & Parallelism	Length	Flatness & Parallelism	Length	Flatness & Parallelism	Length	Flatness & Parallelism
0-1	±1	1	±2	2	+4-2	4	+8-4	5
2	±2	1	±4	2	+8-4	4	+16-8	5
3	±3	1	±5	3	+10-5	4	+20-10	5
4	±4	1	±6	3	+12-6	4	+24-12	5
5			±7	3	+14-7	4	+28-14	5
6			±8	3	+16-8	4	+32-16	5
7			±9	3	+18-9	4	+36-18	5
8			±10	3	+20-10	4	+40-20	5
10			±12	4	+24-12	5	+48-24	6
12			±14	4	+28-14	5	+56-28	6
16			±18	4	+36-18	5	+72-36	6
20			±20	4	+40-20	5	+80-40	6

Gage Block Set No. 4-81 (Inch system)						
.050	.102	.114	.126	.138	.150	.750
.100	.103	.115	.127	.139	.200	.800
.1001	.104	.116	.128	.140	.250	.850
.1002	.105	.117	.129	.141	.300	.900
.1003	.106	.118	.130	.142	.350	.950
.1004	.107	.119	.131	.143	.400	1.000
.1005	.108	.120	.132	.144	.450	2.000
.1006	.109	.121	.133	.145	.500	3.000
.1007	.110	.122	.134	.146	.550	4.000
.1008	.111	.123	.135	.147	.600	
.1009	.112	.124	.136	.148	.650	
.101	.113	.125	.137	.149	.700	

Seven extra blocks used to make up an 88 Block set						
$.0625 = \frac{1}{16}$	$.078125 = \frac{5}{64}$	$.093750 = \frac{3}{32}$	$.109375 = \frac{7}{64}$	.100025	.100050	.100075

Angle Block Sets						
Set No. 6	6 Blocks, 1 deg. smallest increment					
6 Blocks	1°	3°	5°	15°	30°	45°
Set No. 11	11 Blocks, 1 min. smallest increment					
6 Blocks	1°	3°	5°	15°	30°	45°
5 Blocks	1’	3’	5’	20’	30’	
Set No. 16	16 Blocks, 1 sec. smallest increment					
6 Blocks	1°	3°	5°	15°	30°	45°
5 Blocks	1’	3’	5’	20’	30’	
5 Blocks	1”	3”	5”	20”	30”	

3.3 PHYSICAL-DIMENSIONAL TEMPERATURE

3.3.1 Temperature Conversion Chart

FROM	TO	FORMULA
FAHRENHEIT	CELSIUS	(F - 32) ÷1.8
	KELVIN	(F + 459.67) ÷1.8
	RANKINE	F + 459.67
RANKINE	KELVIN	R ÷ 1.8
	CELSIUS	(R - 491.67) ÷1.8
	FAHRENHEIT	R - 459.67
CELSIUS	FAHRENHEIT	(1.8 * C) + 32
	RANKINE	(1.8 * C) + 491.67
	KELVIN	C + 273.15
KELVIN	RANKINE	1.8 * K
	FAHRENHEIT	(1.8 * K) - 459.67
	CELSIUS	K - 273.15

3.3.2 Stem Corrections

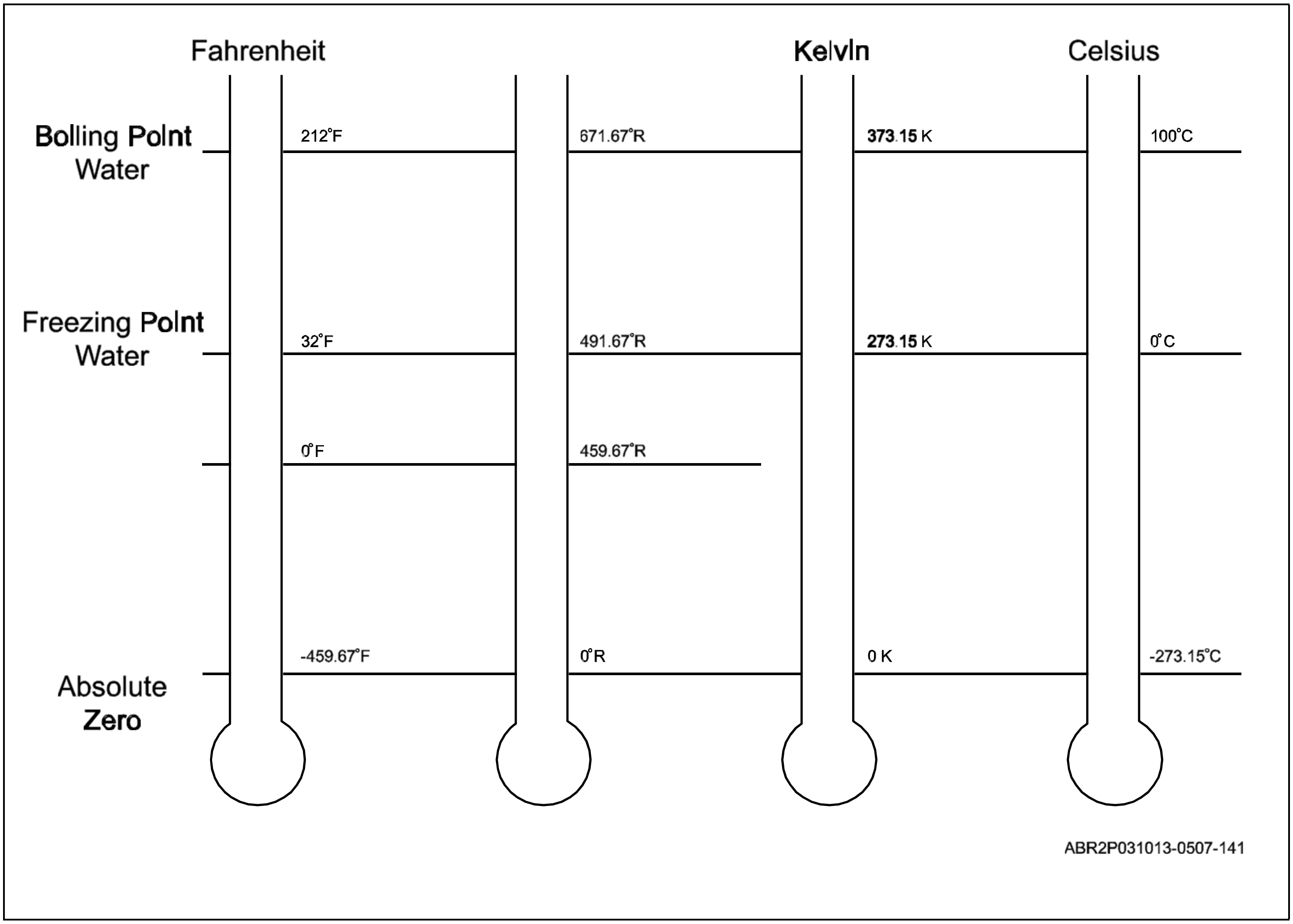
$$C = KN\,(t_i - \overline{t_s})$$

Where: C = Correction
K = Differential expansion coefficient between mercury and glass
K = .00016/ºC or K = .00009/ºF
N = Number of thermometer scale degrees the mercury is out of the bath
t_i = Temperature of the thermometer bulb
$\overline{t_s}$ = Average temperature of the portion of the stem containing mercury which is out of the bath
t_a = Actual temperature

$$\overline{t_s} = \frac{t_1 + t_2}{2}$$

$$t_a = t_i + [K \times N \times (t_i - \overline{t_s})]$$

3.3.3 Temperature Comparison Chart



3.3.4 Thermocouples

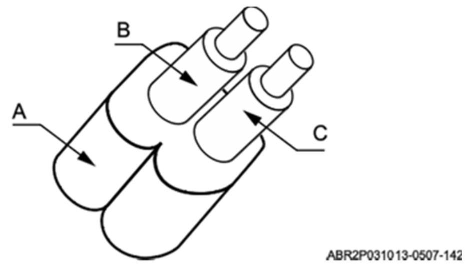
$$E_t = E_r + E_m$$

Where: E_t = EMF value corresponding to the actual temperature at the Hot Junction

E_r = EMF output of the thermocouple if one junction were at 0 °C and the other junction were at a temperature equal to the one being used as the reference under discussion.

E_m = Measured EMF output of the couple in its configuration of use (that is, reference junction not at 0 °C).

3.3.5 Thermal Identification Table



ANSI Code	Alloy Combination		Color Coding						Magnetic Lead	Temperature Range	EMF (mv)	Limits of Error (Whichever is greater)	
	+ Lead	- Lead	Thermocouple Grade (TG)			Extension Grade (EG)						Standard	Special
			A	B (+)	C (-)	A	B (+)	C (-)					
J	IRON Fe	CONSTANTAN COPPER-NICKEL Cu-Ni	BRN	WHT	RED	BLK	WHT	RED	IRON (+)	TG 0 to 750 °C EG 0 to 200 °C	0 to 42.283	2.2 °C or .75%	1.1 °C or 0.40%
K	CHROMEL NICKEL-CHROMIUM Ni-Cr	ALUMEL NICKEL-ALUMEL Ni-Al	BRN	YEL	RED	YEL	YEL	RED	ALUMEL (-)	TG -200 to 1250 °C EG 0 to 200 °C	-5.973 to 50.633	2.2 °C or <0 °C .75% >0 °C 2.0%	1.1 °C or 0.40%
T	COPPER Cu	CONSTANTAN COPPER-NICKEL Cu-Ni	BRN	BLU	RED	BLU	BLU	RED	-	TG -200 to 350 °C EG -60 to 100 °C	-5.602 to 17.816	1.0 °C or <0 °C .75% >0 °C 1.5%	0.5 °C or 0.40%
E	CHROMEL NICKEL-CHROMIUM Ni-Cr	CONSTANTAN COPPER-NICKEL Cu-Ni	BRN	PUR	RED	PUR	PUR	RED	-	TG -200 to 900 °C EG 0 to 200 °C	-8.824 to 68.783	1.7 °C or <0 °C 0.5% >0 °C 1.0%	1.0 °C or 0.40%

ANSI Code	Alloy Combination		Color Coding						Magnetic Lead	Temperature Range	EMF (mv)	Limits of Error (Whichever is greater)	
N*	NICROSIL Ni-Cr-Si	NISIL Ni-Si-Mg	BRN	ORN	RED	ORN	ORN	RED	-	TG -270 to 1300 °C EG 0 to 200 °C	-4.345 to 47.502	2.2 °C or <0 °C .75% >0 °C 2.0%	1.1 °C Or 0.40%
R	PLATINUM-13% RHODIUM Pt-13% Rh	PLATINUM Pt	-	-	-	GRN	BLK	RED	-	TG 0 to 1450°C EG 0 to 150°C	0 to 16.741	1.5 °C or .25%	.60 °C or 0.10%
S	PLATINUM-10% RHODIUM Pt-10% Rh	PLATINUM Pt	-	-	-	GRN	BLK	RED	-	TG 0 to 1450°C EG 0 to 150 °C	0 to 14.973	1.5 °C or .25%	.60 °C or 0.10%
B	PLATINUM-30% RHODIUM Pt-30% Rh	PLATINUM-6% RHODIUM Pt-6% Rh	-	-	-	GRY	GRY	RED	-	TG 0 to 1700 °C EG 0 to 100 °C	0 to 12.426	<800 °C .50%	none est.
G*	TUNGSTEN W	TUNGSTEN-26% RHENIUM W-26% Re	-	-	-	WT/ BL	WHT	RED	-	TG 0 to 2320 °C EG 0 to 260 °C	0 to 38.564	4.5-425 °C 1.0% - 2320 °C	none est.
C*	TUNGSTEN - 5% RHENIUM W-5% Re	TUNGSTEN-26% RHENIUM W-26% Re	-	-	-	WT/ RED	WHT	RED	-	TG 0 to 2320 °C EG 0 to 870°C	0 to 37.066	4.5-425 °C 1.0% - 2320 °C	none est.
D*	TUNGSTEN - 3% RHENIUM W -3% Re	TUNGSTEN-25% RHENIUM W-25% Re	-	-	-	WT/ YEL	WHT	RED	-	TG 0 to 2320 °C EG 0 to 260 °C	0 to 39.506	4.5-425 °C 1.0% - 2320 °C	none est.

* Not Official Symbol or Standard

3.3.6 Thermal-Spectrum

Celsius Scale	Fahrenheit Scale	Results
1410	2570	Silicon Melts
1083.4	1982.12	Copper Melts
1064.43	1947.974	Freezing Point of Gold
937.4	1719.32	Germanium Melts
961.93	1763.474	Freezing Point of Silver
660.37	1220.666	Aluminum Melts
630.74	1167.332	Silver Solder Melts
630.74	1167.332	Antimony Melts
444.674	832.4132	Boiling Point of Sulfur
216	420	50/50 Lead/Tin Solder Melts
156.61	313.898	Indium Melts
100	212	Steam Point at Sea Level
57.8	136.04	Highest Recorded World Temperature
37	98.6	Human Body Temperature
4	39.2	Maximum Density of Water
0.010	32.018	Triple Point of Water
0	32	Ice Point
-38.87	-37.966	Mercury Freezes
-78.5	-109.3	Sublimation Point of CO
-88.3	-126.94	Lowest Recorded World Temperature
-182.962	-297.3361	Oxygen Boils
-273.15	-459.67	Absolute Zero

3.3.7 Resistance Thermometer

$$RR = \frac{RR_t}{RR} \qquad ID = \frac{1}{RR_{tt} + RR_{(t-1)}}$$

Where:

RR = Resistance Ratio Computed
RR_t = Resistance Ratio at a given temperature (t)
$RR_{(t-1)}$ = Resistance Ratio at temperature 1 °C below (t)

$$R_t = R_o\left(1 + A_t + B_t^{\,2}\right)$$

Where:

Rt = the resistance at some temperature (°C)
Ro = the resistance at 0 °C
t = the temperature in °C
A & B = constants for a particular element which best describe its behavior with temperature

$$t = t_2 + [(RR - RR_2) \times ID]$$

Where:

t = the measured temperature
t_2 = the lower of two (2) temperatures from the table which bracket the resistance ratio computed
RR_2 = Resistance Ratio at t_2
ID =Inverse difference for the temperature which has the resistance ratio which is just greater than RR

3.3.8 Volumetric Coefficients of Expansion

SUBSTANCE	$\frac{n \times 10^{-4}}{C°}$	$\frac{n \times 10^{-4}}{F°}$
Alcohol, Ethyl	11.0	6.10
Benzene	13.9	7.70
Mercury	1.82	1.01
Petroleum (Pennsylvania)	9.0	5.0
Sulfuric Acid	5.56	3.10
Turpentine	9.70	5.40
Water	2.07	1.15

$$V_f = V_o (1 + \beta \Delta t) \quad \Delta V = (V_o)(\beta)(\Delta t)$$

Where:

V_f = Volume Final
V_O = Volume Original
ΔV = Change in Volume
β = Volumetric Coefficient of Expansion
Δt = Change in Temperature (t_2 - t_1)
t_2 = Final Temperature
t_1 = Original Temperature

3.3.9 Boyles Law

The relationship between volume and pressure. Remember that the law assumes the temperature to be constant.

$$\frac{V_1}{V_2} = \frac{P_1}{P_2} \quad \text{or} \quad V_1 P_1 = V_2 P_2$$

Where:

V_1 = original volume
V_2 = new volume
P_1 = original pressure
P_2 = new pressure

3.3.10 Charles Law

The relationship between temperature and volume. Remember that the law assumes that the pressure remains constant.

$$\frac{V_1}{V_2} = \frac{T_2}{T_1} \qquad \frac{V_1}{T_2} = \frac{V_2}{T_1}$$

Where:

V_1 = original volume
T_1 = original absolute temperature
V_2 = new volume
T_2 = new absolute temperature

3.3.11 Ideal Gas Law

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Where:

P_1 = Initial Pressure
V_1= Initial Volume
T_1= Initial Temperature
P_2= Final Pressure
V_2= Final Volume
T_2= Final Temperature

3.4 HUMIDITY

$$P_s(t_{dew}) = \frac{\%RH}{100} \times P_s(t_a)$$

3.4.1 Dew Point

$$\%RH = \frac{P_s(t_{dew})}{P_s(t_a)} \times 100$$

Where:

P_s (t_a) = saturation pressure of the gas from a reference table at temperature t_a
P_s (t_{dew}) = saturation pressure of the gas from a reference table at temperature (t_{dew})

$$D = t_a - t_w$$

Where:

D = Wet bulb depression
t_a = Dry bulb temperature
t_w = Wet bulb temperature

3.4.2 Humidity

$$\%RH = \frac{B}{C} \times 100 = \frac{P_v}{P_s} \times 100$$

Where:

B = P_v = Pressure of the water vapor
C = P_s = Saturation pressure
% RH = Percent relative humidity

3.5 FORCE

3.5.1 Stress

$$\sigma(\text{sigma}) = \frac{F}{A}$$

Where:

F = the force
A = the area

3.5.2 Strain

$$\varepsilon\ (\text{epsilon}) = \frac{\Delta\ell}{\ell}$$

Where:

$\Delta\ell$ = change in length
ℓ = original length

3.5.3 Young's Modulus
Stress divided by strain

$$Y = \frac{\sigma}{\varepsilon} \qquad Y = \frac{F/A}{\Delta\ell/\ell} \qquad Y = \frac{F\ell}{A\Delta\ell} \qquad \Delta\ell = \frac{F\ell}{AY}$$

3.5.4 Transverse Strain

$$\varepsilon_{\text{transverse}} = \frac{\Delta D}{D}$$

3.5.5 Poisson's Ratio

$$\mu = \frac{\varepsilon_{\text{transverse}}}{\varepsilon_{\text{axial}}} = \frac{\Delta D/D}{\Delta\ell/\ell}$$

Transverse strain to axial strain

$$\Delta D = \frac{\mu D \Delta\ell}{\ell}$$

3.5.6 Hooke's Law

$$F = \frac{YA}{\ell} \times \Delta\ell = KK$$

$$K = \frac{YA}{\ell} = \text{force constant}$$

Where:
$X = \Delta\ell$ = elongation or change in length
F = force

3.5.7 Load Cells

$$F(\text{lbs}) = \frac{E_o}{E_s(\text{sens})} \times C(\text{lbs})$$

Where:
E_s = source voltage across the bridge
Sen = sensitivity of the cell (mv/v)
E_o = output voltage of the bridge
C = range of the cell
F = force acting on the cell

3.6 TORQUE

$$T = F \times S$$

Where:
F = the force applied
S = the distance through which the force is acting
T = torque

3.6.1 Cosine Error

$$\text{COS} = \frac{\text{side adjacent}}{\text{hypotenuse}}$$

$$T = F \times S \times \text{COS}$$

3.7 MASS AND WEIGHT

$$m_E = m_t - F_b \qquad m_T = m_E + F_b \qquad F_b = \frac{m}{\rho_b} \times \rho_{air}$$

Where:

m = Mass
m_E = Effective Mass
m_T = True Mass
Fb = Air Displaced by Mass
ρb = Density of Brass = 8.4 gm/cm3
ρss = Density of Stainless Steel = 8.0 gm/cm3
ρair = Density of Air = .0012 gm/cm3

3.7.1 Weighing Methods

R = Optical scale reading
RP = Rest point
m_{sen} = Sensitivity weight
IRP = initial rest point
FRP = final rest point
SRP = sensitivity rest point
m_x = unknown mass
m_s = known mass
Cr_s = correction of standard weight
Cr_x = correction of test weight
Δ = Difference not direction

3.7.2 Rest Points

Three Turning Point Method

$$RP = \frac{B + \frac{A+2}{2}}{2}$$

Five Turning Point Method

$$RP = \frac{\frac{B+D}{2} + \frac{A+C+E}{3}}{2}$$

A, B, C, D, E = Values recording for consecutive turning points.

3.7.3 Direct Weighing

$\Delta m = \Delta RP \times SR$ $\qquad$ $SR = \frac{m_{sen}}{FRP - SRP}$

Where:

$\Delta RP = |FRP - IRP|$
If $m_x > m_s$: $m_x = m_s + \Delta_m$
If $m_x < m_s$: $m_x = m_s - \Delta_m$

3.7.4 Substitution Weighing

$$CR_x = SR \times (IRP - FRP) + CR_s$$

Note: Always add CR_x to the nominal value of m_x.

$$Cr_s = m_s - \text{Nominal Value of } m_s$$

3.7.5 Transposition Weighing

$$CR_x = SR \times \left(\frac{IRP - FRP}{2}\right) + CR_s$$

Note: Always add CR_x to the nominal value of m_x.

$$Cr_s = m_s - \text{Nominal Value of } m_s$$

3.7.6 Differential Weighing

$$CR_x = R - M_{sen}$$

3.8 DENSITY, VISCOSITY, AND FLOW

3.8.1 Specific Gravity

$$\text{sp. gr.} = \frac{D_x}{D_w} \qquad \text{sp. gr.} = \frac{\rho_x}{\rho_w}$$

$$\text{sp. gr.} = \frac{W_a}{W_a - W_w} \qquad \text{sp. gr.} = \frac{m_a}{m_a - m_w}$$

$$\text{sp. gr.} = \frac{W_a - W_x}{W_a - W_w} \qquad \text{sp. gr.} = \frac{m_a - m_x}{m_a - m_w}$$

$$V = \frac{W_a - W_w}{D_w} \qquad V = \frac{m_a - m_w}{\rho_w}$$

Where:

ρ = Density in CGS system	x = unknown substance
D = Density in FPS system	w = water
W = Weight	m = mass
V = Volume	a = air

mass density of water at 4°C = 1 gm/cm^3
weight density of water at 39.2°F = .03612 lb/in^3
weight density of water at 39.2°F = 62.426321 lb/ft^3
weight density of water at 60°F = 62.277354 lb/ft^3

3.8.2 Pycnometer

$$\text{sp. gr.} = \frac{W_a - W_p}{W_b - W_p}$$

Where:
Wp = weight of empty pycnometer vessel
Wa = weight of pycnometer vessel and test liquid
Wb = weight of pycnometer vessel and water

3.8.3 Specific Gravity Tables

3.8.3.1 Solids

Aluminum	2.7	Ice	0.917
Brass	8.2 - 8.7	Iron, Steel	7.6 - 7.8
Carbon	1.9 - 3.5	Lead	11.34
Copper	8.9	Oak	0.60 - 0.98
Gold	19.3	Pine	0.37 - 0.64
Human Body	1.07	Silver	10.5

3.8.3.2 Gases

Air	1.000	Neon	0.696
Ammonia	0.596	Nitrogen	0.967
Carbine dioxide	1.529	Oxygen	1.105
Hydrogen	0.069		

3.8.3.3 Liquids

Water, Distilled @ 4 °C	1.000	Mercury @ 0 °C	13.5951
Alcohol, Ethyl	0.789	Milk	1.029
Carbon Tetrachloride	1.60	Oil, Linseed	0.942
Gasoline	0.66 - 0.69	Water, Sea	1.025
Kerosene	0.82		

3.8.4 Viscosity

3.8.4.1 Absolute

$$\eta = \frac{F/A}{\Delta V/\Delta L}$$

Where:

H = absolute viscosity
F = force
A = area
ΔV = change in velocity
ΔL = change in length (thickness)

3.8.5 Kinematic

$$v = \frac{\eta}{\rho}$$

Where:

η = absolute viscosity
ρ = density
v = kinematic viscosity

MKS: $v = \frac{\text{meter}^2}{\text{sec}}$ FPS: $v = \frac{\text{ft}^2}{\text{sec}}$

3.8.6 Viscometer

$$V_\theta = k_\theta t$$

Where:

V_θ = viscosity at temperature
k_θ = instrument constant at temperature
t = efflux time

3.8.7 Flow

$$\frac{Q_s P_s}{Z_s T_s} = \frac{Q_a P_a}{Z_a T_a} \quad \text{or} \quad Q_s = \left(\frac{Z_s T_s P_a}{Z_a T_a P_s}\right) Q_a \quad \text{or} \quad Q_a = \left(\frac{Z_a T_a P_s}{Z_s T_s P_a}\right) Q_s$$

Where:

Q = a volume or volume rate
P = pressure (absolute)
T = temperature (absolute)
Z = compressibility factor (correction for non-ideal gas behavior)
a = actual
s = standard

3.9 PRESSURE AND VACUUM

3.9.1 Pressure

$$P = \frac{F}{A}$$

Where:

P = Pressure (lbs/in^2, newtons/m^2, dynes/cm^2)
F = force (lbs, newtons, dynes)
A = Area (in^2, m^2, cm^2)

$$P = \rho g h$$

Where:

P = Pressure (lbs/in^2, newtons/m^2, dynes/cm^2)
ρ = density of the fluid
h = vertical height of the fluid
g = gravitational acceleration

$$P = Dh$$

Where:

P = Pressure (lbs/in^2)
D = weight density (lbs/in^3)
h = vertical height of the fluid

3.9.1 True Pressure

$$P_t = \frac{m}{A_o}\left[\frac{\left(1-\frac{\rho_a}{\rho_b}\right)\left(\frac{g_l}{g_s}\right)}{(1+bP)[1+(\alpha_k+\alpha_c)(t_2-t_1)]}\right]$$

Where:
P_t = true pressure
m = mass
ρ_a = density of air
ρ_b = density of brass
g_l = local gravitational acceleration
g_s = standard gravitational acceleration
A_o = Area of piston
b = pressure coefficient
P = nominal pressure
α_k = coefficient of thermal expansion of piston
α_c = coefficient of thermal expansion of cylinder
t_1 = reference temperature
t_2 = ambient temperature

3.9.3 Pressure Conversion Chart

TO → FROM ↓	psi	in H2O	ft H2O	in Hg	ATM	gm/cm^2	kg/cm^2	cm H2O	mm Hg
1 psi	multiply by	27.66	2.307	2.036	0.06805	70.31	0.07031	70.31	51.72
1 in H2O (4 °C)	0.03612		0.08333	0.07355	0.002458	2.540	0.002450	2.540	1.868
1 ft H2O (4 °C)	0.4335	12.00		0.8826	0.02950	30.45	0.03048	30.48	22.42
1 in Hg (0 °C)	0.49116	13.60	1.133		0.03342	34.53	0.03453	34.53	25.40
1 ATM	14.696	406.8	33.90	29.92		1033	1.033	1033	760
1 gm/cm^2	0.01422	0.3937	0.03281	0.02896	0.0009678		0.0010	1.000	0.7356
1 kg/cm^2	14.22	393.7	32.81	28.96	0.9678	1000		1000	735.6111
1 cm H2O (4 °C)	0.01422	0.3937	0.03281	0.02896	0.0009678	1.000	0.0010		0.7355
1 mm Hg (0 °C)	0.01934	0.5353	0.04461	0.03937	0.001316	1.360	0.001360	0.001360	

3.10 ROTARY MOTION

$$\omega = \frac{\theta}{\tau}$$

Where:

ω = angular velocity (radians/second)
θ = angular displacement
τ = elapsed time

3.11 VIBRATION

$$f = \frac{1}{t} = \frac{V_{ave}}{2D} \qquad f = \frac{V}{D\pi} \qquad g = .0512f^2DA$$

Where:

f = frequency in hertz
t = time in seconds
V_{ave} = average velocity (in/sec)
V = velocity (in/sec pk)
DA = double amplitude
g = acceleration in "g" units

$$Sens_{oc} = Sens_{Loaded}\left(\frac{R_1 + R_2}{R_2}\right)$$

Where:

Sen_{soc} = Open circuit sensitivity
$Sens_{Loaded}$ = Pickup sensitivity in the calibration load at frequency used
R_1 = Pickup impedance
R_2 = Pickup calibration load impedance

$$Sens_{Corr} = Sens_{oc}\left(\frac{R_3}{R_1 + R_3}\right)$$

Where:

$Sens_{Corr}$ = Sensitivity into open circuit
$Sens_{OC}$ = Sensitivity corrected for loading effect
R_1 = Pickup impedance
R_3 = Input impedance on readout device

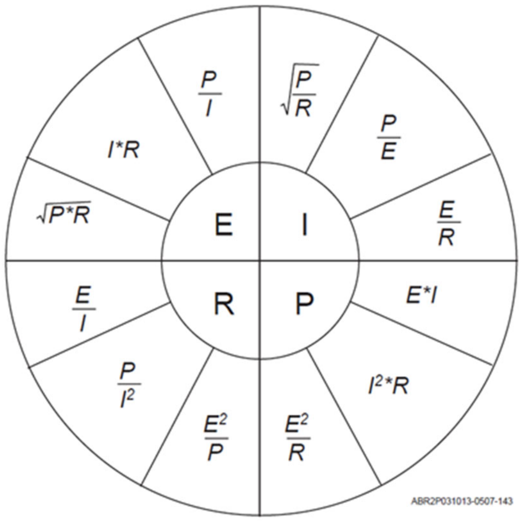
$$\text{Sensitivity (mV)} = \frac{\sqrt{2} \times mV(rms)}{\pi f \times DA}$$

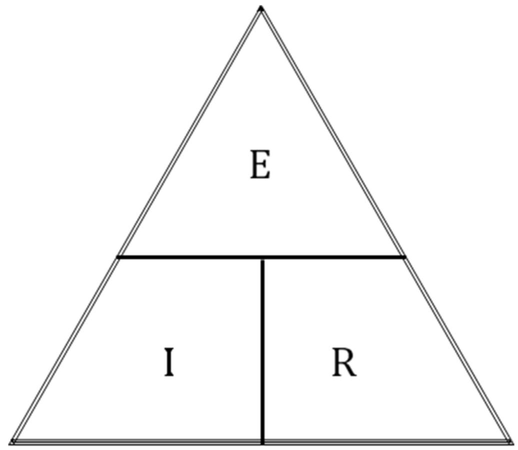
Where:

mV(rms) = meter reading
f = frequency in Hz
DA = peak-to-peak displacement

3.12 ELECTRONIC PRINCIPLES

3.12.1 Voltage, Current, Power, and Resistance Relationships





Voltage, Resistance, Current and Power Wheel

Ohm's Triangle

3.12.1.1 Decibels and Power Ratios
The ratio between any two amounts of electrical power is usually expressed in units on a logarithmic scale. The decibel is a logarithmic unit for expressing a power ratio.

$$PR_{db} = 10 \log \frac{P_2}{P_1}$$

Where:

PR = power ratio in db
P_1 = power in (small)
P_2 = power out (large)

When the output of a circuit is larger than the input, the device is an AMPLIFIER and there is a GAIN. When the output of a circuit is less than the input, the device is an ATTENUATOR and there is a LOSS. In the last example, use the same formula as above and place the larger power over the smaller power, and put a minus sign in front of the PR to indicate a power loss or attenuation.

Basically, the decibel is a measure of the ratio of two powers. Since voltage and current are related to power by impedance, the decibel can be used to express voltage and current ratios, provided the input and output impedances are taken into account.

Equal Impedances: $dB = 20\log\frac{E_2}{E_1}$ $dB = 20\log\frac{I_2}{I_1}$

Where: E_1 = input voltage; I_1 = input current
E_2 = output voltage; I_2 = output current

Unequal Impedances: $dB = 20\log\frac{E_2\sqrt{R_1}}{E_1\sqrt{R_2}}$ $dB = 20\log\frac{I_2\sqrt{R_2}}{I_1\sqrt{R_1}}$

Where: R_1 = impedance of the input in ohms; R_2 = impedance of the output in ohms
E_1 = input voltage in volts; E_2 = output voltage in volts
I_1 = input current in amperes; I_2 = output current in amperes

dB, Power, Voltage, Current Ratio Relationships				
Decrease (-) Voltage and Current Ratio	Decrease (-) Power Ratio	Number of dB's	Increase (+) Voltage and Current Ratio	Increase (+) Power Ratio
1.0000	1.0000	0	1.0000	1.0000
.9886	.9772	.1	1.0120	1.0230
.9772	.9550	.2	1.0230	1.0470
.9661	.9330	.3	1.0350	1.0720
.9550	.9120	.4	1.0470	1.0960
.9441	.8913	.5	1.0590	1.2220
.9333	.8710	.6	1.0720	1.1480
.9226	.8511	.7	1.0840	1.1750
.9120	.8318	.8	1.0960	1.2020
.9016	.8128	.9	1.1090	1.2300
.8913	.7943	1	1.1220	1.2590
.7943	.6310	2	1.2590	1.5850
.7079	.5012	3	1.4130	1.9950
.6310	.3981	4	1.5850	2.5120
.5623	.3162	5	1.7780	3.1620
.5012	.2512	6	1.9950	3.9810
.4467	.1995	7	2.2390	5.0120
.3981	.1585	8	2.5120	6.3100
.3548	.1259	9	2.8180	7.9430
.3162	.1000	10	3.1620	10.0000
.1000	.01000	20	10.0000	100.000
.03162	.0010	30	31.6200	1000.00
.0100	.0001	40	100.000	10000.0
.00316	.00001	50	316.20	1×10^{5}
.0010	1×10^{-6}	60	1000.0	1×10^{6}
.000316	1×10^{-7}	70	3162.0	1×10^{7}

dBm

The decibel does not represent actual power, but only a measure of power ratios. It is desirable to have a logarithmic expression that represents actual power. The dBm is such an expression and it represents power levels above and below one milliwatt. The dBm indicates an arbitrary power level with a base of one milliwatt and is found by taking 10 times the log of the ratio of actual power to the reference power of one milliwatt.

Conversion from Power to dBm

$$P_{(dBm)} = 10\log\frac{P}{1mW}$$

Where:

$P_{(dbm)}$ = power in dBm
P = actual power
1mW = reference power

Conversion from dBm to Power

$$\text{Power (mW)} = (1mw)\text{antilog}\frac{dBm}{10}$$

Power Ratio

$$\text{Power Ratio (PR)} = \frac{P_{out}}{P_{in}}$$

Conversion from Power Ratios to decibels

$$dB = 10\log PR \text{ or } dB = 10\log\frac{P_{out}}{P_{in}}$$

Conversion from decibels to Power Ratios

$$PR = \text{antilog}\frac{dB}{10}$$

dBm Gains and Losses

1. Amplifiers add
2. Attenuation subtracts

3.12.1.2 Resistor Color Codes
The charts on the following pages reflect how color codes are designated for both resistors and capacitors. While not every combination is shown, most popular color codes markings are indicated.

Some resistors have the ohmic value and tolerance printed right on the side of the resistor itself. It is easy to identify this type of resistor. The alpha-numeric code may be broken down as follows:

Example: part number **RN60D1001F**

RN - This code represents the type of resistor. This designation refers to a high stability, fixed film resistor. Other designations are RCR (a carbon resistor) and RW (a fixed wire wound resistor)

60 - This number represents the power rating of the resistor (wattage). In this case, the power rating is 1/8 watt. Other examples are 10 (1/4 watt) and 25 (1 watt)

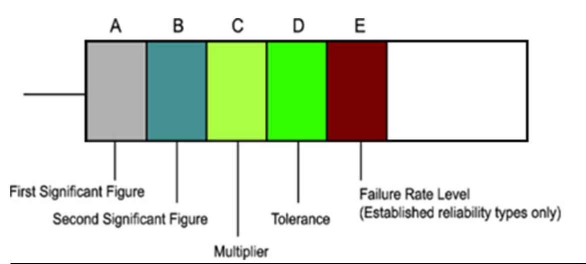
D - This letter designates the temperature coefficient, usually stated in ppm/ºC. This resistor has a temperature coefficient of 200 ppm/ºC.

1001 - This is the ohmic value of the resistor. The last number in this group of numbers represents how many zeros are to be added to the remaining group of numbers. For 1001, the value is 100 Ω with one zero added to it, or 1000 Ω. Another example is 4023; this indicates 402 Ω with three zeros added, or 402,000 Ω. Another code indicates fractional values. In 53R4, the R stands for a decimal place, so this value is 53.4 Ω.

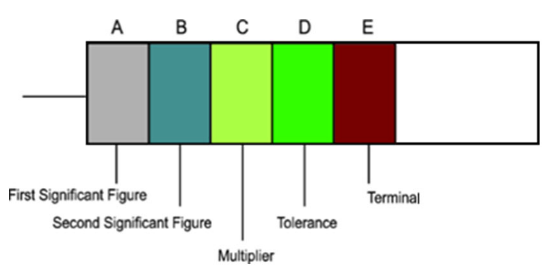
F - This code represents the tolerance of the resistor. The F is 1%. The other codes used are as follows:
G = 2%; J = 5%; K = 10%, and M = 20%.

Color Code Marking for Resistors

Composition Type Resistors



Film Type Resistors



NOTE

Bands "A" thru "D" are of equal width.

Band A: The first significant figure of the resistance value.

Band B: The second significant value of the resistance value.

Band C: The multiplier is the factor by which the two significant figures are multiplied to yield the nominal resistance value

Band D: The resistor's tolerance

Band E: When used on composition resistors, band E indicates the established reliability failure rate level. On film resistors, this band is approximately 1.5 times the width of the other bands and indicates type of terminal.

COLOR CODE CHART										
BAND "A"	1st FIG	BAND "B" COLOR	2nd FIG	BAND "C"	MULTI	BAND "D"	TOLERANCE	BAND "E" COLOR	FAIL RATE	TERMINAL
BLACK	0	BLACK	0	BLACK	1	SILVER	+/-10%	BROWN	1%	
BROWN	1	BROWN	1	BROWN	10	GOLD	+/-5%	RED	0.1%	
RED	2	RED	2	RED	100	RED	+/-2%	ORANGE	0.01%	
ORANGE	3	ORANGE	3	ORANGE	1000	NONE	+/-20%	YELLOW	0.001%	
YELLOW	4	YELLOW	4	YELLOW	10000			WHITE		SOLDER
GREEN	5	GREEN	5	GREEN	100000					
BLUE	6	BLUE	6	BLUE	1000000					
PURPLE (VIOLET)	7	PURPLE (VIOLET)	7							
GRAY	8	GRAY	8	SILVER	0.01					
WHITE	9	WHITE	9	GOLD	0.1					

Bad Booze Rots Our Young Guts But Vodka Goes Well

3.12.1.3 Capacitor Color Codes
READING COLOR CODES FOR CAPACITORS - Different marking schemes are used on capacitors mainly because of the varying needs fulfilled by the various capacitor types. Temperature coefficient is of minor importance in an electrolytic filter capacitor, but it is very important in ceramic trimmers for attenuator use you never find temperature coefficient on an electrolytic label, but it is always present on ceramic trimmers.

CERAMIC DISC CAPACITORS - Information is usually printed. Capacitance is in pf. Capacitance tolerance is shown in percent or by letter. Temperature coefficient is indicated by P200 which means +200ppm/°C which means +200 P/M/°C, or N100 for -100 P/M/°C, etc. F = ±1%

M = ±20%
K = ±10%
J = ±5%
G = ±2%
F = ±1%

CERAMIC TUBULAR CAPACITORS - These capacitors are usually white enamel coated with parallel radial leads and look like "dog bones". The code consists of color dots which indicate temperature coefficient, capacitance, and tolerance

BUTTON MICA CAPACITORS - The most difficult part of reading the code on these capacitors is to remember to read the dots moving in a clockwise direction. The dots are usually printed more to one side than the other.

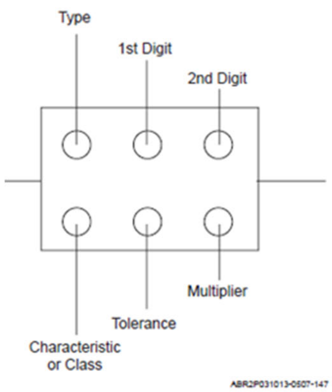
MOLDED MICA CAPACITORS - This was once a very popular type, rectangular with dots and arrow or similar directional indicator. Standard color code applies.

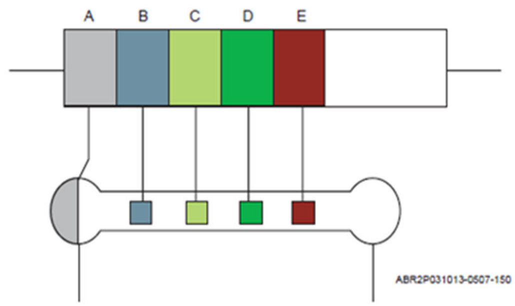
DIPPED MICA CAPACITORS - This type of capacitor has a printed label like that appearing on ceramic disk capacitors.

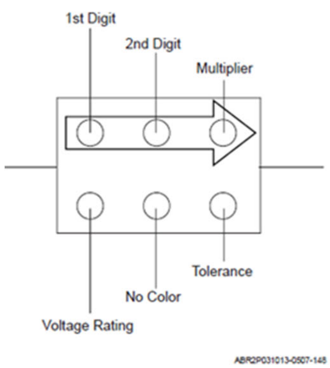
PAPER AND FILM CAPACITORS - Aluminum and tantalum electrolytic capacitors, in nearly all cases, have printed or stamped labels indicating capacitance, tolerance, and voltage ratings. Other characteristics are usually unimportant.

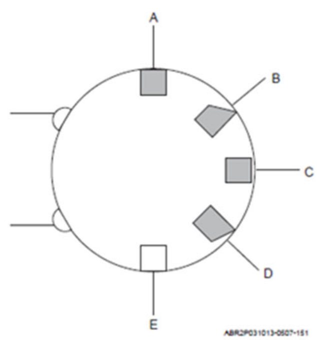
AIR TRIMMERS - The same information applies as with paper and film capacitors. Often, only the range is indicated.

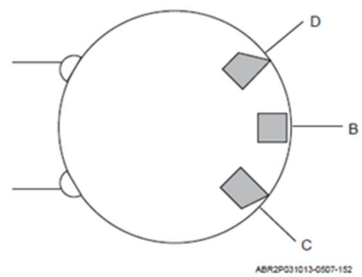
CAPACITOR COLOR CODES



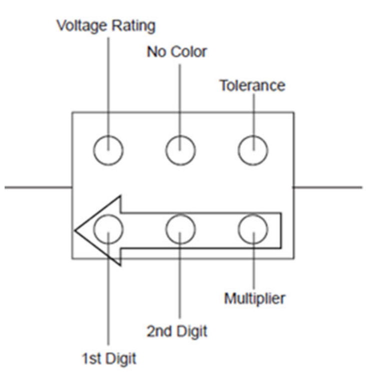


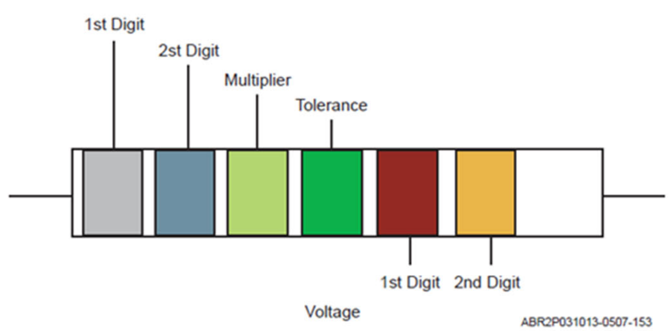






A	Temperature Coefficient
B	1st Digit
C	2nd Digit
D	Multiplier
E	Tolerance





CAPACITOR COLOR CODE NUMBERING SYSTEMS

6-DOT RMA-JAN-AWS Standard Capacitor Color Code

Color	Type	1st Digit	2nd Digit	Multiplier	Tolerance (%)	Characteristic or Class
Black	JAN mica	0	0	1		
Brown		1	1	10	1	Applies to temperature coefficients or methods of testing
Red		2	2	100	2	
Orange		3	3	1000	3	
Yellow		4	4	10000	4	
Green		5	5	100000	5	
Blue		6	6	1000000	6	
Purple		7	7	10000000	7	
Gray		8	8	100000000	8	
White	RMA mica	9	9	1000000000	9	
Gold				.1		
Silver	AWS paper			.01	10	
Body					20	

5-Color Capacitor Color Code

Color	1st Digit	2nd Digit	Multiplier	Tolerance (%)	Voltage
Black	0	0	1		
Brown	1	1	10	1	
Red	2	2	100	2	
Orange	3	3	1000	3	
Yellow	4	4	10000	4	
Green	5	5	100000	5	
Blue	6	6	1000000	6	
Purple	7	7	10000000	7	
Gray	8	8	100000000	8	
White	9	9	1000000000	9	
Gold			.1		
Silver			.01	10	
Body				20	

Ceramic Capacitor Color Code

Color	1st Digit	2nd Digit	Multiplier	Tolerance over 10 pf	Tolerance under 10 pf	Temperature
Black	0	0	1	±20%	2.0 pf	0
Brown	1	1	10	±1%		-30
Red	2	2	100	±2%		-80
Orange	3	3	1000			-150
Yellow	4	4	10000			-220
Green	5	5		±5%	0.5 pf	-330
Blue	6	6				-470
Purple	7	7				-750
Gray	8	8	.01		0.25 pf	+30
White	9	9	0.1	±10%	1.0 pf	+500 to -330
Gold				±0.5%		+100

3.12.2 Direct Current Calculations

3.12.2.1 Series DC Circuits

Total Resistance = Sum of individual resistances
$R_T = R_1 + R_2 + R_3 +$
Where R_T = Total Resistance

Total Voltage = Sum of the individual voltage drops.
$E_a = E_{R1} + E_{R2} + E_{R3} +$
Where E_a = Applied Voltage

Total Current is determined by the Total Resistance (RT) of the circuit and Applied Voltage (Ea). It will be the same value at any point within the circuit.

$$I_T = \frac{E_a}{RT}$$

Total Power = sum of all power losses in the circuit.
$P_T = P_{R1} + P_{R2} + P_{R3}$

3.12.2.2 Parallel DC Circuits

Total Resistance = reciprocal of the sum of the reciprocals.

for Multiple Branches: $R_t = \frac{1}{\frac{1}{R_{B1}} + \frac{1}{R_{B2}} + \frac{1}{R_{B3}} \ldots}$

for branches of like value: $R_T = \frac{R_B}{N_B}$

Where: R_B = resistance of one branch
N_B = # of branches

for only two branches: $R_t = \frac{R_{B1} \times R_{B2}}{R_{B1} + R_{B2}}$

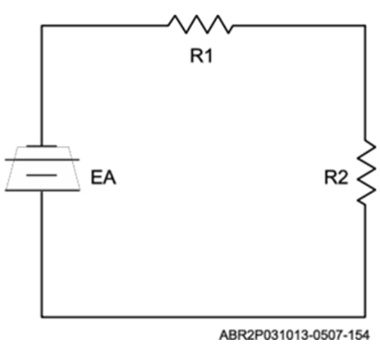
Total Voltage is applied to each branch of a parallel circuit
$E_A = E_{B1} = E_{B2} = E_{B3} =$

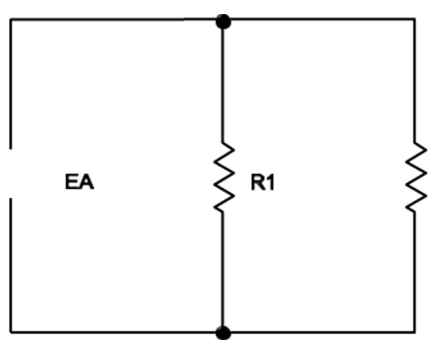
Total current = sum of the current in the individual branches.
$I_T = I_{T1} + I_{T2} + I_{T3}$

Total Power = sum of all power losses in the circuit
$P_T = P_{R1} + P_{R2} + P_{R3}$

3.12.2.3 Divider Networks

The division of voltage and current in a circuit can be determined in the following manner:





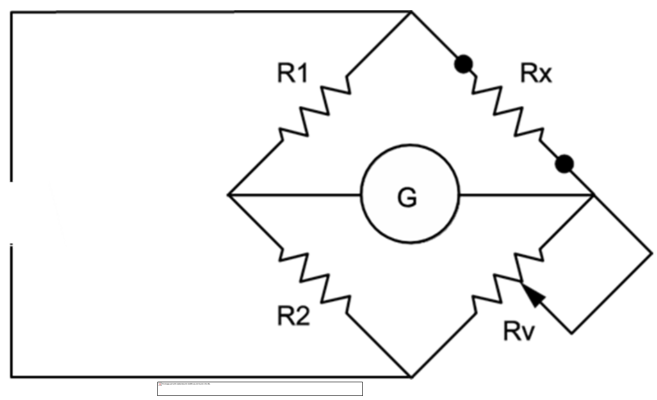
Voltage Divider

$$E_{R1} = \frac{R_1}{R_1 + R_2}(E_a)$$

Current Divider

$$E_{R1} = \frac{R_1}{R_1 + R_2}(E_a)$$

3.12.2.4 Bridge Circuits
The relationships that exist in a bridge are indicated below:



$$R_x = \frac{R_1(R_v)}{R_2} \qquad \frac{R_1}{R_2} = \frac{R_x}{R_v} \qquad \frac{R_1}{R_x} = \frac{R_2}{R_v} \qquad R_1(R_v) = R_2(R_x)$$

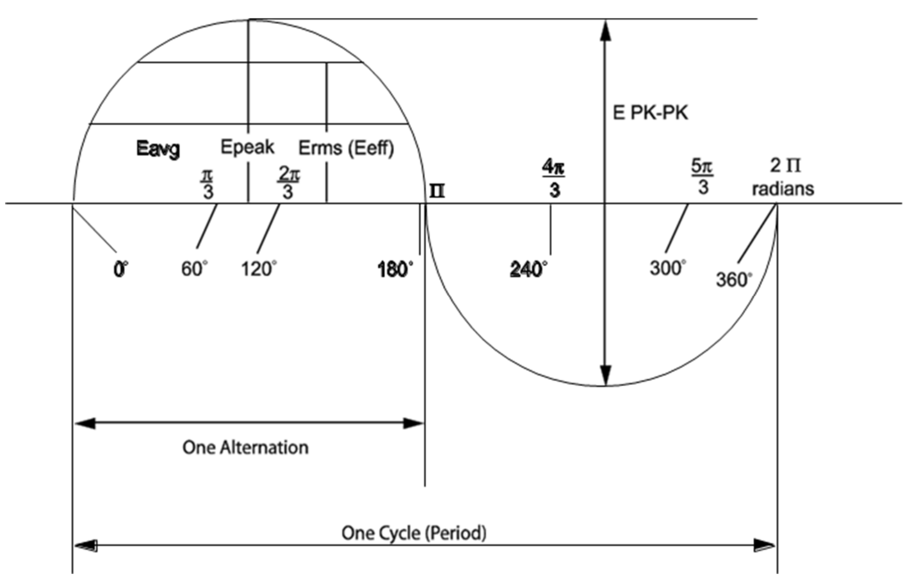
3.12.3 Alternating Current Calculations

3.12.3.1 Sine Wave Voltage Conversion Chart

	TO			
FROM	Effective (RMS)(VAC)	Average	Peak	Peak-to-Peak
Effective (RMS)(VAC)	1	0.900	1.414	2.828
Average	1.110	1	1.571	3.142
Peak	0.707	0.637	1	2.000
Peak-to-Peak	0.354	0.318	0.500	1

3.12.3.2 Frequency and Period (Time)

$f = \frac{1}{p}$ $\qquad p = \frac{1}{f}$



3.12.3.3 Wavelength

$$\lambda \text{ meters} = \frac{300 \times 10^6}{f} = (300 \times 10^6)(p)$$

3.12.3.4 Phase Angle

$$\theta\theta = \frac{P_{meas}}{P_{tot}} \times 360°$$

3.12.3.5 Square Wave Asymmetry

$$TS = \left(\frac{P}{2}\right) - W$$

Where:
TS = Square Wave Asymmetry
P = Time of the full cycle of the square wave
W = Time of the positive alternation of the square wave
IF TS is equal to 0, it is a square

3.12.3.6 Transformers
The relationship between voltage, current, and number of turns in a transformer is shown in the following formulas:

$$\frac{E_p}{E_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s} \qquad \frac{(N_p)^2}{(N_s)^2} = \frac{Z_p}{Z_s}$$

Where:
E_p = Voltage in primary
E_s = Voltage in secondary
I_p = Current in primary
I_s = Current in secondary
N_p = Number of turns in primary
N_s = Number of turns in secondary
Z_p = Impedance of the primary
Z_s = Impedance of the secondary

3.12.3.7 Inductance

$$L = \frac{N^2 A\mu}{l}$$

Where: L = Inductance measured in Henrys (h)
A = Cross sectional area
l = Length of coil
N = Number fo turns
μ = Permeability of core

3.12.3.8 Capacitance

$$C = \frac{A \times K}{D}$$

Where: C = Capacitance measured in Farads (fd)
A = Area of Plates
K = Dielectric Constant
D = Distance between the plates

Total Inductance

$$L_r = L_1 + L_2 + L_3 + \cdots$$

Parallel

$$L_r = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots}$$

Total Capacitance

$$C_r = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots}$$

Parallel

$$C_r = C_1 + C_2 + C_3 + \cdots$$

3.12.3.9 Reactance

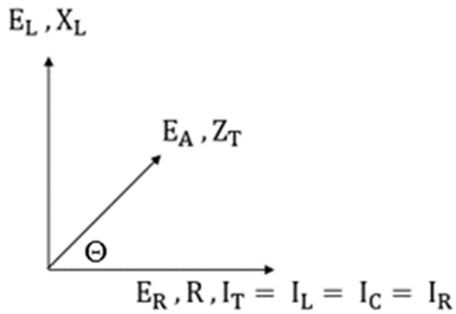
Inductance

$$X_l = 2\pi FL$$

Capacitance

$$X_c = \frac{1}{2\pi FC}$$

3.12.3.10 Series RL Circuit



$$I_T = I_R = I_L$$

$$Z = \sqrt{R^2 + X_L^2}$$

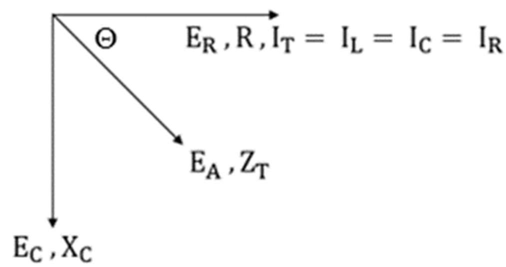
$$E_A = \sqrt{E_R^2 + E_L^2}$$

$$I_T = \frac{E_A}{Z}$$

$$\theta = \tan^{-1}\frac{X_L}{R}$$

$$\theta = \tan^{-1}\frac{E_L}{E_R}$$

3.12.3.11 Series RC Circuit



$$I_T = I_R = I_C$$

$$Z = \sqrt{R^2 + X_C^2}$$

$$E_A = \sqrt{E_R^2 + E_C^2}$$

$$I_T = \frac{E_A}{Z}$$

$$\theta = \tan^{-1}\frac{X_C}{R}$$

$$\theta = \tan^{-1}\frac{E_C}{E_R}$$

3.12.3.12 Series RCL Circuit

$$Z = \sqrt{R^2 + (X_L - X_C)}$$

$$Z = \sqrt{E_R^2 + (E_L - E_C)}$$

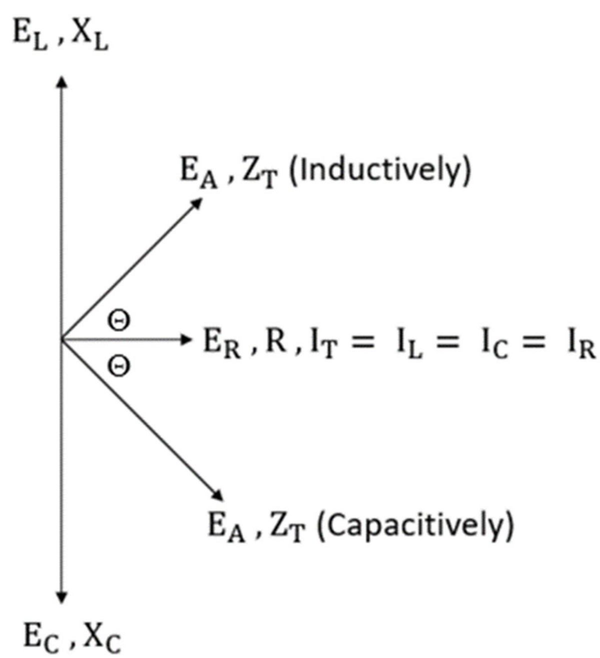
$$I_T = \frac{E_A}{Z}$$

$$\theta = \tan^{-1}\frac{X_C - X_L}{R}$$

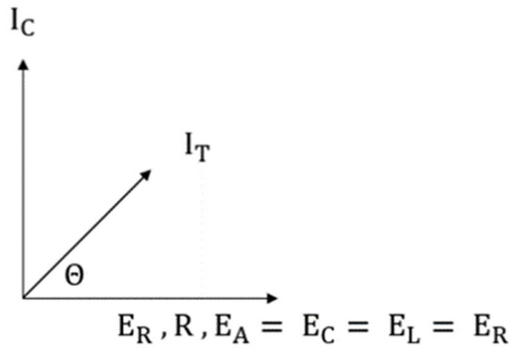
$$\theta = \tan^{-1}\frac{E_C - E_L}{E_R}$$

$$Q = \frac{X_L}{R}$$

$$BW = \frac{f_r R}{X_L}$$



3.12.3.13 Parallel RL Circuit



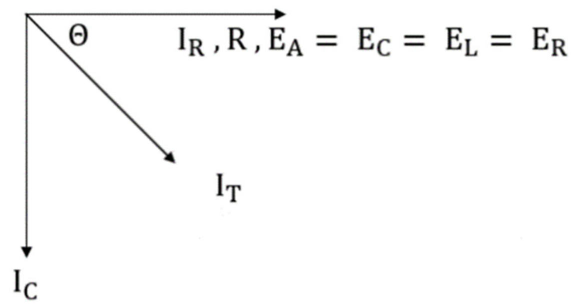
$$E_A = E_R = E_C$$

$$I_T = \sqrt{{I_R}^2 + {I_C}^2}$$

$$Z = \frac{E_A}{I_R}$$

$$\theta = \tan^{-1}\frac{I_C}{I_R}$$

3.12.3.14 Parallel RC Circuit



$$E_A = E_R = E_L$$

$$I_T = \sqrt{{I_R}^2 + {I_L}^2}$$

$$Z = \frac{E_A}{I_R}$$

$$\theta = \tan^{-1}\frac{I_L}{I_R}$$

3.12.3.15 Parallel RCL Circuit

$$E_A = E_R = E_L = E_C$$

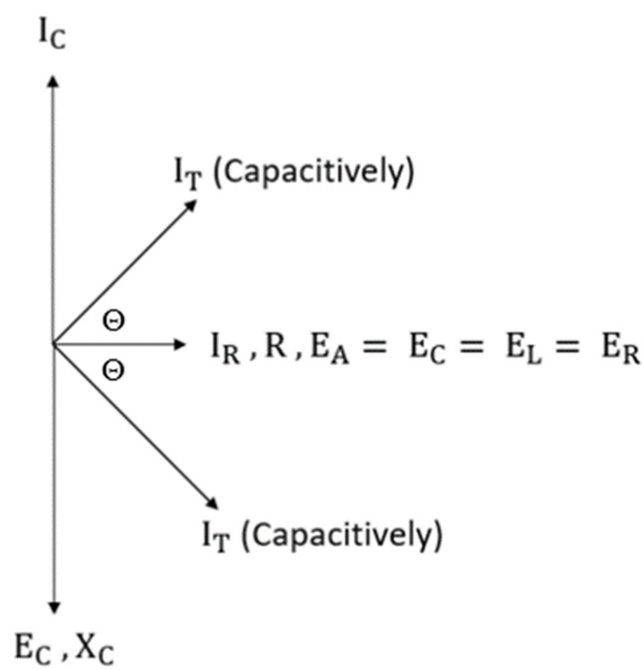
$$I_T = \sqrt{{I_R}^2 + (I_C - I_L)}$$

$$I_T = \frac{E_A}{Z}$$

$$\theta = \tan^{-1}\frac{I_C - I_L}{I_R}$$

$$Q = \frac{X_L}{R}$$

$$BW = \frac{f_r X_L}{R}$$



3.12.3.16 Bandwidth

Series

$$BW = \frac{f_R}{Q}$$

$$BW = \frac{f_R R}{X_L}$$

Parallel

$$BW = \frac{f_R X_L}{R}$$

3.12.3.17 Power

True Power

$$P_T = (I_R)^2 \times R$$

Apparent Power

$$P_A = E_A(I_T)$$

Power Factor

$$PF = \frac{P_T}{P_A} = \cos\Theta$$

3.12.3.18 Resonance

$$f_R = \frac{1}{2\pi\sqrt{LC}}$$

$$C = \frac{1}{4\pi^2(f_r)^2 L}$$

$$L = \frac{1}{4\pi^2(f_r)^2 C}$$

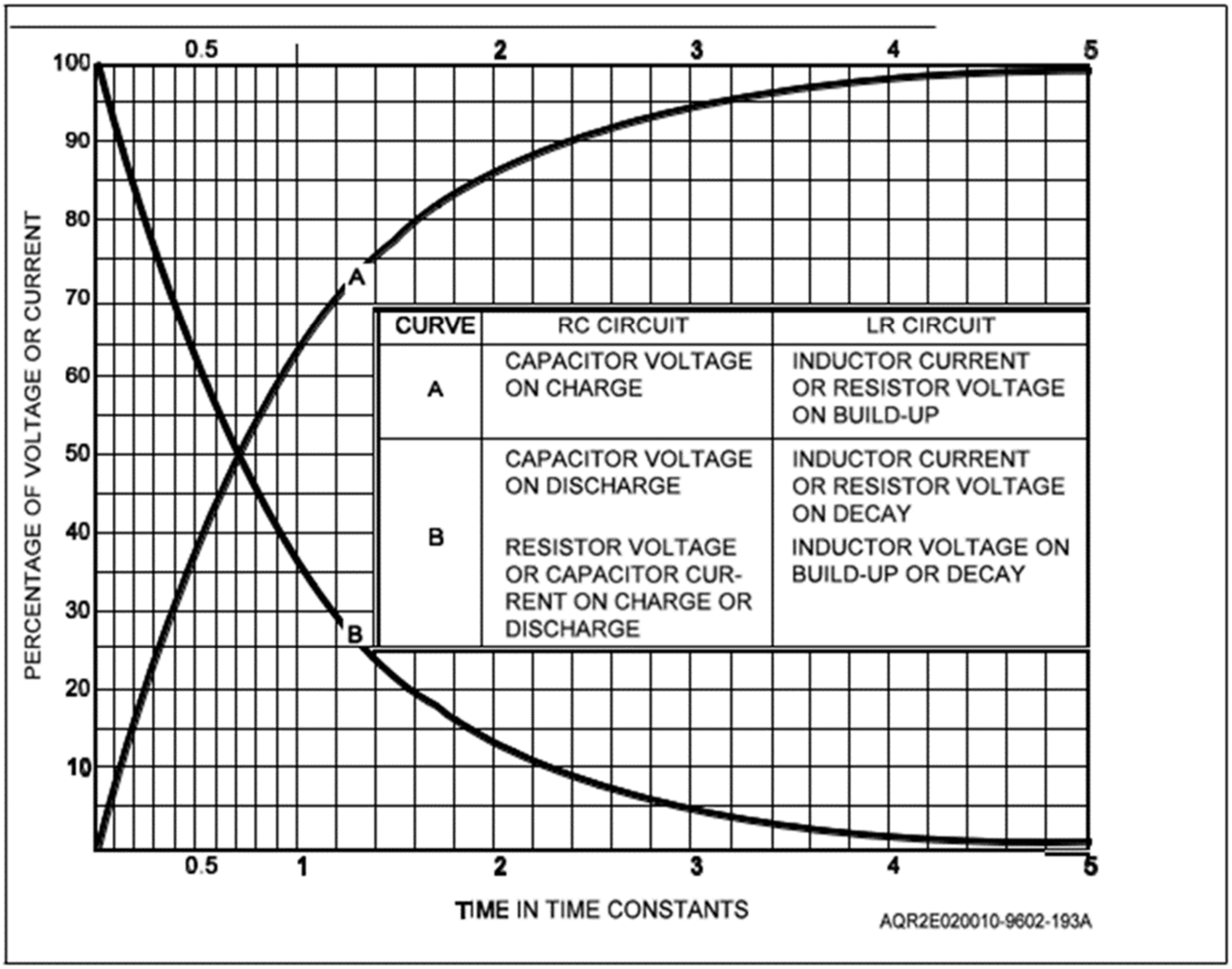
3.12.3.19 Time Constants

$$TC = \frac{L}{R}$$

$$TC = R \times C$$

$$\#TC = \frac{t}{TC}$$

$$\#TC = \frac{t}{TC}$$



3.13 MICROWAVE FORMULA

3.13.1 Velocity Constant

$$K = \frac{1}{\sqrt{c'}} \qquad K = \frac{\lambda g}{\lambda o} \qquad K = \frac{Vg}{Vo}$$

3.13.2 Characteristic Impedance

$$Zo = \sqrt{\frac{L}{C}} \qquad Zo = \frac{138}{\sqrt{c'}} \log \frac{D}{d} \qquad Zo = \sqrt{Xl \times Xc}$$

3.13.2 Time Delay

$$TD = n\sqrt{L \times C}$$

3.13.4 Velocity of Propagation in Free Space

$$V_O = \frac{30 \times 10^9 cm}{sec} \qquad V_O = \frac{300 \times 10^6 m}{sec}$$

3.13.3 Wavelength in Free Space

$$\lambda_0 = \frac{V_0}{Freq} \qquad \lambda_{0(m)} = \frac{300 \times 10^6 m/sec}{Freq} \qquad \lambda_{0(cm)} = \frac{30 \times 10^9 cm/sec}{Freq}$$

3.13.4 Velocity of Propagation on a Transmission Line

$$V_g = V_o \times K$$

3.13.7 Wavelength on a Transmission Line

$$\lambda_g = \frac{V_0 \times K}{Freq} \qquad \lambda_g = \frac{V_g}{Freq}$$

3.13.5 Voltage Standing Wave Ratio

$$VSWR = \frac{Emax}{Emin} \qquad VSWR = \sqrt{\frac{Pmax}{Pmin}} \qquad VSWR = \frac{\sqrt{Pi} + \sqrt{Pr}}{\sqrt{Pi} - \sqrt{Pr}} \qquad VSWR = \frac{Ei + Er}{Ei - Er} \qquad VSWR = \frac{1 + P}{1 - P}$$

$VSWR = \frac{Zo}{Rl}$ when $Zo > R_L$ $\qquad$ $VSWR = \frac{R_L}{Zo}$ when $R_L > Zo$

3.13.6 Voltage Relationships

$$E_I = \frac{E_{max} + E_{min}}{2} \qquad E_R = \frac{E_{max} - E_{min}}{2} \qquad E_{max} = E_I + E_R \qquad E_{min} = E_I - E_R$$

3.13.7 Reflection Coefficient

$$P = \frac{E_R}{E_I} \qquad P = \sqrt{\frac{P_R}{P_I}} \qquad P = \frac{VSWR - 1}{VSWR + 1} \qquad P = \frac{1}{\log^{-1}\frac{dB}{20}}$$

3.13.8 Transmission Loss

$$L_T = 10\log\frac{Pwr_{large}}{Pwr_{small}} \qquad L_T = 10\log\frac{P_{load}}{P_{source}}$$

3.14 POWER FORMULAS

% Power Reflected: $\quad P_{REF} = p^2 \times 100$

% Power Absorbed: $\quad P_{ABS} = (1 - p^2) \times 100$

$$Pwr_{REF} = Pwr_{INC} \times p^2$$

$$Pwr_{ABS} = Pwr_{INC}(1 - p^2)$$

3.14.1 Mismatch Loss

$$L_{mm} = 10\log\frac{Pwr_{INC}}{Pwr_{ABS}} \qquad L_{mm} = 10\log\frac{1}{(1-p^2)}$$

3.14.2 Smith Chart

$$Z_{normalized} = \frac{Z_{actual}}{Zo} \qquad Z_{actual} = Z_{normalized} \times Zo$$

3.14.3 Return Loss

$$L_R = 10\log\frac{Pwr_{INC}}{Pwr_{REF}} \qquad L_R = 20\log\frac{E_I}{E_R} \qquad L_R = 20\log\frac{1}{p} \qquad L_R = 10\log\frac{1}{p^2}$$

3.14.4 Waveguide

$$F_{co} = \frac{Vo}{\lambda co} \qquad \lambda co = 2a = \frac{2}{\sqrt{\frac{m^2}{a} + \frac{n^2}{b}}} \qquad \lambda o = \frac{\lambda g}{\sqrt{1 - \left(\frac{\lambda g}{\lambda co}\right)^2}} = \frac{Vo}{F} \qquad \lambda g = \frac{\lambda o}{\sqrt{1 - \left(\frac{\lambda g}{\lambda co}\right)^2}}$$

3.14.5 Directional Couplers

Different Arms $\quad CF = 10\log\frac{Pwr_{IN}}{Pwr_{OUT}}$

Same Arm $\quad LI = \log\frac{Pwr_{IN}}{Pwr_{OUT}}$

$D = 10\log\frac{P_{P3}(fwd)}{P_{P3}(rev)} = Lr_4 + LI \qquad CF \text{ or } LI = -10\log[1 - \log^{-1}\left(\frac{db}{10}\right)$

3.14.7 Mount Calibration Factors

3.14.7.1 Effective Efficiency

$$\eta e = \frac{K_b}{\left(1 - p^2{}_{Meter}\right)} \qquad \eta e = \frac{Pwr_{DCSUP}}{Pwr_{DISSIPATED}} \qquad \eta e = \frac{Pwr_{IND}}{Pwr_{ABS}}$$

3.14.7.2 Calibration Factors

$$K_b = \eta e\left(1 - p^2{}_{Meter}\right) \qquad K_b = \frac{Pwr_{DCSUP}}{Pwr_{INC}} \qquad K_b = \frac{Pwr_{IND}}{Pwr_{Zo}}$$

3.14.8 Reflection Coefficient of the Mount

$$P_{Meter} = \sqrt{1 - \left(\frac{Kb}{\eta e}\right)} \qquad P_{Meter} = \frac{Pwr_{REFLECTED}}{Pwr_{INCIDENT}}$$

3.14.9 Limits of Power

$$\text{LIMITS OF POWER}_{IND} = \frac{Pwr_{zO} \times kB}{(1 \pm P_G \times P_L)^2}$$

3.14.10 Nominal Power Levels

Power Available on the Line

$$Pwr_{Zo} = PC(1 - p^2{}_g)$$

PC is conjugate power, generator power, or maximum power available

Power Absorbed by the Load

$$Pwr_{ABS} = Pwr_{Zo}(1 - p^2{}_L)$$

3.15 GLOSSARY

A

aberration
A broad term covering several types of image defects in a lens or lens system.

abscissa
The horizontal or x-axis on a chart graft.

absolute measurement standard
Standards based on natural physical constraints whose values can be accurately repeated under controlled conditions.

absolute pressure
Actual pressure on a confined gas, irrespective of the atmosphere on the outside. Absolute pressure = gage pressure + atmospheric pressure.

absolute system
A system of units in which a small number of units is chosen as fundamental and all other units are derived from this group.

absolute temperature
Temperature measured from absolute zero as in the Kelvin and Rankine scales.

absolute zero
1) This is the temperature at which the volume of an ideal gas would become zero. The value calculated from the limited value of the coefficient of expansion of various real gases is - 273.15°C.

2) The temperature at which all thermal (molecular) motion ceases; zero point in absolute temperature scale equal to -273.15°C or -459.69°F. Absolute temperature T is given by the equation: 1/2 mv av 2 = 3/2 kT

absorption
1) The loss of energy in traveling through a medium. Examples: A yellow filter absorbs all wavelengths except yellow just as red paint will absorb all colors except red which is reflected.

2) The internal taking up of one material by another.

3) Transformation of radiant energy into other forms of energy when passing through a material substance.

absorption wave meter
An instrument for measuring wavelength containing a variable tuned circuit which absorbs a small portion of the radiated energy under measurement.

AC generator
1) A rotating electric machine, generally known as an alternator, that converts mechanical power into alternating current power.

2) A vacuum-tube oscillator, or any other device, that is designed for the purpose of producing an alternating current.

AC plate resistance
The ratio of a small change in plate voltage to the resulting change in plate current, other tube voltage remaining constant. Alternating current plate resistance is usually designed by rp and is expressed in ohms. (It is often called dynamic plate resistance)

AC resistance
The total resistance offered by a device in an alternating current circuit, including resistance due to eddy current, hysteresis, dielectric, and corona loss as well as the direct current resistance.
Also called high-frequency resistance and radio-frequency resistance.

accelerating electrode
An electrode used in cathode - ray tubes and other electronic tubes to increase the velocity of the electrons in a beam. Such an electrode is operated at a high positive potential with respect to the cathode.

acceleration
1) A rate of change in velocity per unit time. Positive acceleration means an increase in velocity while negative acceleration means a decrease in velocity per unit time. Avoid the use of the term "deceleration."

2) The time rate of change of velocity in either magnitude or direction. CGS Unit: cm/sec.

acceleration due to gravity (g)
The acceleration of a freely falling body in a vacuum, 980.665 cm/sec or 32.174 ft/sec at sea level and 45° latitude.

acceptor
A substance (impurity) which, when added to a pure semiconductor material, results in an increase in the number of holes so that major conduction through the material takes place as a transfer of the hole structure from molecule to molecule. Since this is equivalent to the transfer of a positive charge, the resulting alloy is called a P-type semiconductor.

accommodation
Changes in focus of the crystalline lens to adjust the eye for various object distances.

accuracy
The term accuracy refers to how close we are to the nominal value. In the past we have used this term to indicate error in a measurement device. for instance, the accuracy of a standard cell is plus or minus 0.01 percent. Use of the word accuracy in this sense is incorrect because what we mean is the inaccuracy or error is plus or minus 0.01 percent. However, this is still a common method of describing accuracies. To remedy this practice, the National Bureau of Standards has dropped the term accuracy, when used in this respect, and uses instead the term "uncertainty."

achromat
A lens doublet, to two lenses combined to eliminate chromatic aberration.

achromatic
Free from hue

acorn-tube
An acorn-shaped vacuum tube is designed for use at ultra-high frequencies. It has a low interelectrode capacitance because of the small size of electrodes, and low electron transit time because of the close spacing of the electrodes. The electrode leads are brought directly out through the sides of the tube. There is no base.

activation energy
The energy necessary to start a particular reaction.

actual value (true value)
It is not possible to determine a completely true value of a quantity as there is always some error in every measurement. Theoretically we could say the "true" value of a measured quantity can be derived by taking the average of an infinite number of measurements assuming that the conditions contributing to deviations act is a completely free and random manner.

acuity
Visual acuity is the resolving power of the eye, normally taken as 1 minute arc. Vernier acuity is the ability of the eye to make coincidence settings.

adhesion
The molecular attraction exerted between the surfaces of bodies in contact.

admittance
The measure of ease with which an alternating current flows in a circuit. It is the reciprocal of impedance.

adsorption
The adhesion of one substance to the surface of another.

AGC (automatic gain control)
A circuit arrangement which continuously adjusts the gain of an amplifier in a specified manner in response to changes in the input signal. This is also called AVC (automatic volume control)

air core coil
A coil with no iron in its magnetic circuits no iron either inside or outside the wire).

algebra
A continuation of arithmetic in which letters and symbols are used to represent definite quantities whose actual values may or may not be known.

algorithm
Step-by-step procedure for the solution to a problem. First the problem is stated and the algorithm is devised for its solution.

alignment telescope
A telescope specifically designed to be mounted and used in conjunction with an end target in order to form a fixed line of sight. Can also be used to measure linear displacement (alignment of a rail for straightness) by using the optical micrometers.

alloy
A mixture of two or more metals, such as brass (zinc and copper), bronze (copper and tin), and manganin (nickel, manganese, and copper).

alnico
An alloy consisting chiefly of aluminum, nickel, and cobalt. It has high retentivity and is used to make powerful small-size permanent magnets which hold their magnetism indefinitely.

alpha
The current amplification factor when connected in a common base configuration.

alpha particle
1) Particle identical with a helium nucleus emitted from the nucleus of a radioactive atom.

2) A helium nucleus, consisting of two protons and two neutrons, with a double positive charge. Its mass is 4.002764 a mu (mass units).

alpha ray
A stream of fast-moving helium nuclei; a strongly ionizing and weakly penetrating radiation.

alphanumeric
Set of all alphabetic and numeric characters.

alternating current
An electric current that is continually varying in value and reversing its direction of flow at regular intervals. Each repetition, from zero to maximum in one direction and then to a maximum in the other direction and back to zero, this is called a cycle.

alternation
One half of a complete cycle, consisting of a complete rise and fall of voltage or current in one direction. There are 120 alternations per second in 60 Hz alternating current.

altimeter
An aircraft instrument that indicates the elevation in respect to a reference. The aneroid altimeter is referenced to sea level, while an electronic altimeter uses the radar method. See barometer

ambient temperature
The temperature of the air in the immediate vicinity.

ambiguity
The quality of having more than one meaning.

amici prism
Direct vision prism, beam of light is dispersed into a spectrum without mean deviation.

ammeter
An instrument used for measuring the amount of current in amperes. A meter that indicates the current value in milliamperes is a milli-ammeter, and one that indicates values in micro-amperes is a micro-ammeter.

ampere
Unit of electric current. The constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular sections, and placed 1 meter apart in a vacuum, will produce between these conductors a force equal to 2×10^{-7} newtons per meter of length. The practical unit of current.

amplifier
An amplifier is a device used to increase the voltage, current, or power of a signal to a desired level.

amplification
As a related to detection instruments, the process (either gas, electronic, or both) by which ionization effects are magnified to a degree suitable for their measurement.

amplification factor
The ratio of a small change in plate voltage to the small change in control grid voltage, under the conditions that the plate current remains unchanged and that all other electrode voltages are maintained constant. It is a measure of the effectiveness of the control grid voltage with respect to that of the plate voltage in controlling the plate current.

amplitude
The extent of a vibratory movement measured from the mean position to an extreme.

amplitude modulation (AM)
A form of modulation in which the amplitude of the carrier is varied above and below its normal value in accordance with the amplitude of the modulating signal.

angle of incidence
The angle formed by the line of an incident ray and a perpendicular line arising from the point of incidence.

angle of lag
The angle with which one alternating electrical quantity lags behind another quantity in time, expressed in degrees (1 cycle equals 360°) or in radians (1 cycle equals 2 radians).

angle of reflection
The angle formed by the line of a reflected ray and a perpendicular line arising from the point of incidence.

angle of refraction
The angle formed between the line of a refracted ray and a perpendicular line drawn through the point of refraction.

angular acceleration
The time rate of change of angular velocity either in angular speed or in the direction of the axis of rotation. CGS unit: radians/sec.

angular velocity
1) The speed of a rotating object measured in radians per second and generally designated by the lower-case Greek letter omega. In the case of a periodic quantity, such as alternating current, the angular velocity is equal to a 2 f.

2) The time rate of angular displacement about an axis. CGS unit: radians/sec.

angstrom unit
10 cm, a convenient unit for measuring wavelength of light. Abbreviation: A.

anode
That electrode of an electron tube, or semi conductive material, toward which the principal electron stream flows. It is a positive potential with respect to the corresponding negative electrode called the cathode.

antenna
A conductor or system of conductors for radiating or receiving RF energy exclusive of the connecting wires, transmission line, or waveguide between its main portion and the apparatus associated with it.

antilogarithm
Number from which the log was derived. Obtained as a result of using the inverse procedure of obtaining a log. It is often written as "antilog."

Anti-Miller effect
The decrease in the effective grid-cathode capacitance of a vacuum tube due to the charge induced electro statically on the grid by the cathode thru the grid-cathode capacitance.

aperture
An opening or gap. In optics, the effective aperture is the portion of an objective lens that is actually used.

aplanatic lens
A lens that is corrected for spherical, coma, and chromatic aberrations.

apparent power
The power value obtained in an alternating current circuit by multiplying the effective values of voltage and current. The result is expressed in volt-amperes and must be multiplied by the power factor to secure the average or true power in watts.

apses
The point at which an orbiting body is the greatest or least distance from the center of attraction. The greatest distance is called the higher apses and the least distance is called the lower apses.

aquadag
A graphite coating on the inside of cathode-ray tubes for collecting the secondary electrons emitted by the screen.

arc
A portion of the circumference of a circle.

Archimedes' principle
When a body is placed in a fluid, it is buoyed up by a force equal to the weight of the displaced fluid.

armature
1) A piece of ferromagnetic material that is placed between or across the pole pieces of a magnet in such a manner that it may have motion relative to the pole pieces.

2) The buzzer, relay, magnetic phonograph pickup, or other electromagnetic device that depends on physical motion of a part of its magnetic circuit.

3) Originally the rotating part of an electric motor or generator. It carries the conductors that have motion relative to the magnetic field.

armstrong oscillator
An inductive feedback oscillator.

artificial line
A network which simulates the electrical characteristics of a transmission line.

astable multivibrator
A free running multivibrator

astigmatism
1) visual aberration caused by lack of sphericity of the cornea.

2) A blurring of the trace of an oscilloscope.

atom
Smallest particle of an element that can enter into combination with other elements.

atomic number
1) The number of protons in the nucleus, hence the number of positive charges on the nucleus.

2) The number of protons in the nucleus, hence the number of positive charges on the nucleus. It is also the number of electrons outside the nucleus of a neutral atom. Symbol: Z.

atomic weight
The relative weight of the atom of an element based on an atomic weight of 16 for the oxygen atom as the usual chemical standard. The sum of protons plus neutrons is the approximate atomic weight of an atom.

attached method (optics)
A method of measuring when all test equipment and standards are physically located on the same reference plane.

attenuation
1) The ratio of initial to final load power, expressed in decibels, when a network is inserted into a measuring system in which both the generator and load impedances have been adjusted so that they are nonreflecting.

2) The insertion loss measured in a nonreflecting system. audio frequency
Any frequency in the range from about 20 to 20,000 Hz, corresponding to audible sound waves.

autocollimation
A process in which collimated rays of light emanating from an instrument, and carrying the image of a reticule, are aimed at a reflective surface. The reticule image is reflected back into the focal plane of the telescope for comparison with the actual reticule as a measure of relative tilt,
between the optical axis and the reflective surface. An instrument used for this purpose is called an autocollimator.

autocollimator
An instrument designed for comparing tilt being received back from a mirror image of the reticule carried by the collimated light and then superimposing the image on the actual reticule. It contains at least an objective lens eyepiece reticule and light source to illuminate the reticule.

autotransformer
A transformer having one winding that is tapped somewhere along its length to provide three terminals. Usually, a part of the windings is considered the primary and the secondary includes all the turns on the coil.

auto reflection
A process in which the reflected image of a target surrounding the front end of a telescope is compared with the telescope reticule as a measure of relative tilt. (The focal length is twice the dimension from the instrument to reflective surface.)

autumn equinox
First day of autumn in the northern hemisphere. It usually falls on September 21st in the northern hemisphere. There are about 12 hours of light and 12 hours of darkness every place on the Earth during an equinox.

avalanche breakdown
In semiconductors, the condition when the applied voltage is sufficiently large to cause the covalent structure of the crystal to break down. Sometimes called the Zener point.

AVC (automatic volume control)
See AGC

average value
1) The value obtained by dividing the sum of a number of quantities by the number of quantities represented.

2) The average of many instantaneous amplitude values taken at equal intervals of time during an alternation (half-cycle). The average value of an alternation of a pure sine wave is 0.637 times its maximum or peak amplitude value.

Avogadro's law
The hypothesis that equal volumes of all gases at the same pressure and temperature contain equal numbers of molecules. Hence the number of molecules contained in 1 cm^3 of any gas under standard conditions is a universal constant.

Avogadro's number
The number of molecules in a gram-molecular weight of any substance (6.03×10^{23} molecules); also, the number of atoms in a gram-atomic weight of any element.

axis
A straight line, real or imaginary, passes through a body, on which the body revolves.

axis, optical
A line formed by the coinciding principal axes of a series of optical elements.
* Note * optical axis as described on pg. 4-6 of OM 3&2 (Opticalman 3 & 2) is stated wrong, the glossary is correct.

axis, principal
A line through the centers of curvature of a refracting lens.

Ayrton-Perry winding
Consists of two parallel opposed windings, either in a single layer crossing at every turn, or one layer wound over the other.

azimuth
Horizontal direction or bearing of one object with respect to another, expressed as an angle measured in a horizontal plane and in a clockwise direction from the north (true north, unless otherwise indicated).

B

B+ (B plus)
The positive terminal of a B battery or other plate-voltage source for a vacuum tube, or the plate-circuit terminal to which the positive source terminal should be connected.

B- (B minus)
Symbol used to designate the point in a circuit to which the negative terminal of the plate supply is to be connected.

B-H curve
A characteristic curve showing the relation between magnetic induction (B) and magnetizing force (H) for a magnetic material. It shows the manner in which the permeability of a material varies with flux density. Also called "magnetization curve."

backlash
A form of mechanical hysteresis (lag) in which there is a lag between the application of a driving force and the response of the driven object.

ballast resistor
A self-regulating resistor, usually connected in the primary circuit of a power transformer, which tends to compensate for variations in line voltage.

ballast tube
A tube which contains a ballast resistor, usually an iron wire resistor in a hydrogen-filled bulb, which reduces the radiation of heat from the resistor.

band
Frequencies within two defined limits. Example: The standard broadcast band extends between 550 and 1600 kHz.

bandpass
The number of hertz, cycles per second, expressing the limiting frequencies at which the desired fraction (usually the half-power points) of the maximum output is obtained.

bandpass filter
A filter that passes a desired band of frequencies, while frequencies above and below the desired frequencies band are attenuated.

band rejection filter
An electrical device or circuit which suppresses an unwanted band of frequencies.

bandwidth
The number of cycles, kilocycles, or megacycles per second expressing the difference between the limiting frequencies of a frequency band. It can be applied to any entity having frequency limits, as a tuned circuit, a combination of tuned circuits, a modulated radio signal, or a group of radio station channel assignments.

barn
The unit expressing the probability of a specific nuclear reaction taking place in terms of cross- sectional area. It is 10^{-24} cm^2. (See Cross Section)

barometer
An instrument for measuring atmospheric pressure. There is a direct relationship between atmospheric pressure and altitude and many barometers are equipped with an altitude scale. Two types of barometers are "mercury" and "aneroid." The aneroid barometer with an altitude scale is an altimeter.

barretter
A bolometer consisting of an appropriately mounted short length pf very fine wire, usually platinum, or a metallic film which a positive temperature coefficient of resistance.

base
The center semiconductor region of a double junction (NPN or PNP) transistor. The base is comparable to the grid of an electron tube.

beam
A beam of light can be regarded as the path traced by a small section of an advancing wave front, which is comprised of an infinite number of light rays.

beam-power tube
A vacuum tube having special deflecting electrodes that concentrate the electrons into a beam, giving high power output and other desirable characteristics. Another feature of this type is to minimize screen current and to create a concentration of electrons, between screen grid and plate, which acts as a suppressor grid.

beat frequency
One of the two additional frequencies obtained when signals of two different frequencies are combined in a nonlinear device. Their values are equal to the sum and difference, respectively, of the original frequencies.

Bernoulli's principle
With a fluid in motion, if the velocity is low, the pressure is high and vice versa.

beta
The current amplification factor of a transistor when connected in a common-emitter configuration.

beta particle
1) Particle identical to an electron emitted from the nucleus of a radioactive atom.

2) A charged particle emitted from the nucleus and having a mass and charge equal in magnitude to those of the electron.

beta ray
A stream of beta particles, more penetrating but less ionizing than alpha rays; a stream of high-speed electrons.

bias
The average DC voltage between the control grid and cathode of a vacuum tube used to establish the quiescent operating condition of the tube.

The average DC voltage between the base and emitter of a semiconductor used to establish the quiescent operating condition of the semiconductor.

bidirectional coupler
A device with two outputs, designed for insertion in a waveguide. It simultaneously samples and presents at one output a voltage that is largely a function of the wave traveling in one direction, and at the other output a voltage that is largely a function of the wave traveling in the opposite direction.

bifilar winding
A method of winding transformers in which the wires are placed side by side, and wound together.

bilateral
Having, or arranged upon, two sides

bimetallic element
Two strips of dissimilar metal bonded together so that a change in temperature will be reflected in the bending of the element, as a result of differential expansion. Used in thermostats, dial thermometers, and temperature compensating devices in the better pressure gages.

binding energy
The energy represented by the difference in mass between the sum of the component parts and the actual mass of the nucleus.

bistable multivibrator
A circuit having two stable states. One side of the multivibrator will be cut off while the other side will be at a high level of conduction. This circuit is often called the Eccles-Jordan multivibrator in honor of the inventors. In some literature the bistable is mistakenly called a flip-flop multivibrator.

bleeder resistor
A resistor connected in parallel with the output of a power supply to improve voltage regulation by drawing a fixed bleeded current. Also used to dissipate the charge remaining in filter capacitors when the power supply is turned off.

blocked oscillator
A blocking oscillator is biased to cutoff and must be triggered. It develops a sharp pulse for each trigger input.

blocking capacitor
Any capacitor used in a circuit to block the flow of DC while allowing AC signal to pass.

blocking oscillator
A free running oscillator operating intermittently with grid bias increasing during oscillation to a point where oscillation stops, and then decreasing until oscillation resumed. The output consists of sharp pulses.

blooming
Term applied to a CRT when too many electrons strike the screen and increase spot size. This is usually caused by an improperly set intensity control.

boiling
Rapid vaporization which disturbs a liquid, and which occurs when the vapor pressure within a liquid is equal to the pressure on its surface.

bolometer
A small resistive element used in the measurement of low and medium RF power. It is characterized by a large temperature coefficient of resistance which is capable of being properly matched to a transmission line. The barretter and thermistor are widely used bolometers.

bonded strain gage
A thin metallic resistance element, usually of wire or foil, chemically cemented to a device being subject to loading or stress. As the load (stress) changes, the electrical resistance of the strain gage changes. Thus, for a fixed value of applied voltage, the output voltage from the strain gage varies in proportion to the strain and provides an indication proportional to the load causing the stress and resultant strain.

Boolean Algebra
The branch of symbolic that is used extensively for binary computer applications.

bourdon element
A curved, hollow tube sealed at one end. When fluid under pressure is forced in the tube it has a tendency to straighten out. With a pointer attached to the sealed end and allowed to move across a scale it becomes a bourdon gage.

Boyle's Law
If the temperature of a gas is kept constant, then the volume of the gas will be inversely proportional to the pressure.

breakdown voltage
The voltage at which the insulation between two conductors or parts will break down.

bridge circuit
An electrical network that is basically composed of four branches connected in the form of a square. One pair of diagonally opposite junctions is connected to the input, and the other pair is connected to the output circuit which contains an indicating device.

bridge rectifier
A full-wave rectifier with four elements connected as in a bridge circuit. Alternating voltage is applied to one pair of junctions.

British Thermal Unit (BTU)
The amount of heat that will raise the temperature of 1 pound of water 1° Fahrenheit from 62°F to 63°F.

broadband amplifier
An amplifier that maintains a flat response over a wide range of frequencies.

buffer
An isolating circuit used to avoid reaction of a driven circuit upon the corresponding driving circuit.

buncher
1) The input resonant cavity in a conventional klystron oscillator.

2) The electrode of a velocity-modulated tube which concentrates the electrons in a constant current electron beam into bunches.

bucking-in
To place an instrument so that its line of sight passes through two given points or fulfills two requirements simultaneously. Usually the first operation in setting up control is to establish a width plane.

buoyancy
The power to float or rise in a fluid.

buoyant force
The upward force which any fluid exerts on a body placed in it.

bus
An uninsulated conductor. Its cross section may be solid, hollow, square, or round.

by-pass capacitor
A capacitor that is used to provide a comparatively low impedance path for alternating currents around a circuit element.

C

calibrate
To determine by measurement or comparison the correct value of each scale reading on a meter or other device being calibrated. To determine the settings of a control that corresponds to particular values of voltage, current, frequency, or some other characteristic.

calibration
Is the comparison between items of equipment, one of which is a measurement standard of known accuracy, to detect, correlate, adjust, and report any variation in the accuracy of the other item(s).

calibration chart
A chart prepared for a specific item to show the actual value of the parameter(s) calibrated. (Differences between nominal and actual).

calorie
The amount of heat required to raise the temperature of 1 gram of water 1° Celsius at 15° Celsius.

candela
Unit of luminous intensity. It is of such a value that the luminous intensity of a full radiator at the freezing temperature of platinum (1773°C) is 60 candela per centimeter squared. Candela was formerly termed candlepower, or simply candle.

capacitance
1) The ability to store electrical energy, measured in farads.

2) The property of a capacitor or circuit which determines the amount of electrical energy which can be stored in it by applying a given voltage.

3) In semiconductor diode, the small signal capacitance measured between the terminals of the diode under specified conditions of bias and frequency.

capacitive reactance
That type of reactance which is caused by the capacitance of a circuit. It is measured in ohms, designated by XC, and is equal to the reciprocal of 2π FC $\left(\frac{1}{2\pi\ FC}\right)$ where C is in farads and F is in hertz.

capacitor
Two conducting surfaces, or sets of conducting surfaces, separated from each other by an insulating material (dielectric) such as air, paper, mica, glass, or oil. A capacitor stores electrical energy, blocks the flow of direct current, and limits the flow of alternating current to a degree dependent upon the capacitance and the frequency.

capacitor input filter
A filter which has a capacitor connected directly across (in parallel with) its input.

capillarity
The characteristic of a liquid to be raised or depressed in a tube or small bore. This action is caused by a combination of cohesive, adhesive, and surface tension forces.

carbon resistor
A resistor made of carbon particles and a ceramic binder molded into a cylindrical shape, with leads attached to opposite ends.

carrier frequency
The frequency of the unmodulated carrier wave, if sinusoidal, or the center frequency of the unmodulated carrier, when a recurring series of pulses is used.

cascade
In sequence, as tuning circuits, an amplifier stages used one after another.

cascade amplifier
An amplifier of several stages, the output of one being the input of the next.

cascade amplifier
A two-stage amplifier circuit combining a grounded-cathode input section with a grounded-grid output section. This amplifier provides good gain and low noise.

cathode
1) The electron-emitting electrode of a semiconductor device.

2) The electron-emitting electrode of a radio tube. Thermionic vacuum tubes employ heated cathodes. Gas tubes employ cold cathodes.

cathode interface
An additional tube capacitance caused by separation of the cathode coating from the metal. It causes an overshoot at the leading edge of a square wave.

cathode bias
A method of biasing a vacuum tube by placing the biasing resistor in the common cathode return circuit.

cathode ray tube (CRT)
An electron tube containing an electron gun that directs a beam of electrons at a fluorescent screen inside the large end of the tube. A glow is produced at the point where the beam strikes the screen. Electrostatic deflection plates or electromagnetic deflecting coils are used to sweep the beam over the screen and produce a pattern or complete image.

cavitation
Sudden formation and collapse of low-pressure bubbles in liquid by mechanical forces, such as the rotation of a turbine flow meter or a fuel pump.

cavity resonator
A space totally enclosed by a metallic conductor and excited in such a way that it becomes a source of electromagnetic oscillations. The size and shape of the enclosure determines the resonant frequency. for a cylinder, the maximum resonators wavelength is 2.61 times the radius. Cavity resonators have an extremely high Q factor, which can be as great as 50,000. They are used in ultrahigh frequency systems.

celestial
Of the sky or the heavens. A celestial telescope is one in which the image appears inverted, as in astronomical telescopes with no erector.

Celsius temperature scale
A temperature scale based on mercury in glass thermometer with the freezing point of water defined at 0°C and the boiling point of water defined at 100°C, both under conditions of normal atmospheric pressure. formerly called the Centigrade scale.

center of instrument
In optics, the intersect point of the vertical, horizontal, and optical axis of a transit or similar instrument when perfectly calibrated.

Centigrade scale
See Celsius temperature scale

centripetal force
The force required to keep moving mass traveling in a circular path. The force is directed toward the axis of the circular path.

certification
A document designation that standards and TMDE have been calibrated and meet established technical requirements, or that a PMEL has the capability to perform accurate measurements.

certified value
The value that can be obtained by using the most recent measurement techniques and equipment.

certify
To attest as being true or as represented, or to meet a certain standard.

cgs system
The common metric system of units (centimeter-gram-second).

chain reaction
Any chemical or nuclear process in which some of the products of the process are instrumental in the continuation of magnification of the process.

Charles Law
The volume of a gas is directly proportional to its absolute temperature, providing the pressure is constant.

characteristics
Functions of the equipment under test, that are checked.

characteristic curve
1) A graph which shows the interrelation between two changing values, as the effect of a change in grid voltage on the plate current of a vacuum tube.

2) A graph which shows the interrelation between two changing values, as the effect of a change in base voltage on the collector current of a transistor.

characteristic impedance
The ratio of applied voltage to steady state current at a given frequency for a uniform and infinitely long transmission line. It is measured in ohms and designated ZO.

charge
1) The electrical energy stored in a capacitor or held on an insulated object. An object having more electrons than normal has a negative charge. An object having fewer electrons than normal has a positive charge.

2) To furnish electrical energy to a capacitor insulated metal object, or storage battery.

charging current
1) The current flowing into a capacitor when a voltage is applied.

2) A current flowing in the correct direction to charge a storage battery.

3) The correct current at which a particular storage battery should be charged.

chassis
The metal framework on which the parts of the circuitry are mounted.

chemical compound
A pure substance composed of two or more elements combined in a fixed and definite proportion by weight.

choke coil
An inductor that is used to limit or suppress the flow of alternating current without appreciably the flow of direct current. Also called an impedance coil.

chopper circuit
A circuit that produces a square wave from a DC voltage by opening and closing the circuit.

chromatic aberration
A property of lenses that causes the various colors in a beam of light to be focused at various points, this causing a spectrum to appear.

circuit
A closed conductive path, including a voltage source and a load, over which electrons can flow.

clamping circuit
A circuit in which either amplitude extreme of a waveform is maintained at a certain potential level. Also known as a DC restorer.

class A amplifier
1) An amplifier in which plate current flows at all times and amplification is essentially linear. The grid voltage is chosen to place the operating point in such a way that the input signal voltage will swing over a straight portion of the tube characteristic curve at all times but will never swing positive and never swing down to the curve portion near cutoff.

2) An amplifier in which collector current flows at all times and amplification is essentially linear. The base voltage is chosen to place the operating point in such a way that the input signal voltage will swing over a straight portion of the transistors characteristic curve at all times but will never swing positive (saturation) and never swing down to the curve portion near cutoff.

class B amplifier
1) An amplifier in which the grid bias is at, or very near, cutoff so that the plate current is essentially zero when there is no input signal. Plate current then flows for approximately one-half of each input signal cycle. If grid current does not flow during any part of the input cycle, the subscript “1” is used; if grid current flows at any time, the subscript “2” is used. Class B operation is used in both radio frequency and audio frequency amplifiers, generally in push-pull stages.

2) An amplifier in which the base bias is at, or very near, cutoff so that the collector current is essentially zero when there is no input signal. Collector current then flows for approximately one-half of each input signal cycle. If base current does not flow during any part of the input cycle, the subscript “1” is used; if base current flows at any time, the subscript “2” is used. Class B operation is used in both radio frequency and audio frequency amplifiers, generally in push-pull stages.

Class C amplifier
1) An amplifier in which the grid bias is considerably greater than cutoff, so that the plate current is zero with no input signal to the grid and flows for appreciably less than one-half of each input signal cycle. The grid may swing positive far beyond saturation.

2) An amplifier in which the base bias is considerably greater than cutoff, so that the collector current is zero with no input signal to the grid and flows for appreciably less than one-half of each input signal cycle. The base may swing positive far beyond saturation.

clinometer
The clinometer is, in principle, a level mounted on a rotatable member, whose angle of inclination relative to its base can be measured by a circular drum scale.

coaxial cable
A cable consisting of one conductor (usually a small copper tube or wire) and insulated from, another conductor of larger diameter (usually copper tubing or braid).

coaxial transmission line
Consists of two conductors, one of which is hollow. The second conductor is placed inside the hollow conductor and spaced uniformly throughout the length of the line. It can be used for frequencies up to 12.4 GHz.

coefficient of coupling
A numerical rating between 0 and 1 that specifies the degree of coupling between two circuits. Maximum coupling is 1 and no coupling is 0.

coefficient of linear expansion
The change in unit length in a solid when its temperature is changed 1°.

coefficient of volume expansion
The change in unit volume of a solid when its temperature is changed 1°.

cohesion
The force that causes molecules which are brought close together, as in liquids and solids, to stick together. This force is especially strong in solids when the distance between molecules is very small.

coincidence
Exact correspondence. In optics, a coincidence bubble is equipped with a prismatic or mirror arrangement for simultaneously viewing both ends of the bubble for more precise adjustment.

coincidence tube
An electronic tube that requires a positive potential on its control grid and suppressor grid before it will conduct.

cold cathode
A cathode that is not heated. Electrons may be pulled out of the cathode by field emission.

collector
An electrode of a transistor. One of the outer layers of a junction-type transistor. It corresponds roughly to the plate of a triode tube. It collects charge carriers.

collimation
The process of aligning the axis of the optical elements with respect to the mechanical axis of an instrument.

collimator
An instrument designed to produce collimated (parallel) rays of light, usually equipped with displacement and tilt graticules.

collinear
Lying on or passing through the same straight line.

color
1) Effect produced on the eye and its associated nerves by light waves of different wavelength or frequency.

2) That aspect of things that is caused by differing qualities of the light reflected or emitted by them, definable in terms of the observer or of the light.

3) A property of light that depends on wavelength, whether absorbed or reflected by an object. Black is said to result from the absence of color (full absorption), and white from the presence of all colors mixed together (full reflection).

Colpitts oscillator
An oscillator in which the parallel-tuned tank circuit is connected between grid and plate. The tank capacitor consists of two series voltage divider capacitors. The regenerative feedback is developed across one of these capacitors.

commutator
A cylindrical arrangement of copper segments mounted radially on the shaft of anarmature, separated from each other and the armature by insulation, and connected to individual armature coils.

complex number
The expression resulting when a real number is united with an imaginary number by a plus or minus sign.

complex vibration
The combination of two or more sinusoidal vibrations existing simultaneously.

composition resistor
A resistor made of a mixture of carbon and clay molded into a cylindrical shape with wire terminals imbedded in each end of the unit.

compound
Two or more substances combined in definite proportions by weight and united chemically.

concave
A lens that is thicker at the ends than the middle. A concave lens diverges (spreads) rays of light.

concentricity
Having a common center, as circles or spheres one within another.

condensation
The change of state from a gas or vapor to a liquid.

conductance
The ability of a material to conduct or carry an electric current. Conductance is the reciprocal of resistance and is measured in mhos.

conduction band
The minimum energy level an electron must obtain to become a free electron.

conductivity
The specific conductance of a unit specimen of a material. Reciprocal of resistance.

conservation of energy
The principle that energy can neither be created nor destroyed, and therefore the total amount of energy in the universe is constant. This law of classical physics is modified for certain nuclear reactions. (See Conservation-of-Mass-Energy)

conservation of mass-energy
The principle that energy and mass are interchangeable in accordance with the equation
$E = mc2$; where E is energy, m is mass, and c is velocity of light.

constant amplitude signal generator
A signal generator that keeps a constant amplitude as the frequency of the output is changed.

contact resistance
The resistance in ohms caused by the resistance of the contact of terminal connections, relays, and switches. The value of resistance is generally only a fraction of an ohm but is important because it can cause a large error in precise measurement of low value resistors.

continuous wave (CW)
An unmodulated, constant amplitude wave.

control grid
1) That electrode in a vacuum tube which has the most effective control over the plate current passed by the tube. The control grid is usually the electrode nearest the cathode.

2) In basic terms works very similar to the base of a transistor.

converge
Tend to meet at a point.

convex lens
A lens that is thicker in the middle than the ends. A convex lens converges rays of light.

copper-oxide rectifier
A rectifier consisting of a disk of copper coated with copper oxide on one side, with a soft lead washer providing electrical contact with the oxide surface. The resistance is considerably lower for electron flow from the copper to the oxide than for electron flow in the reverse direction; hence rectification is obtained in alternating current circuits.

correction
The correction is the value in proportional parts, that must be algebraically added to the nominal value to obtain the certified value. The correction is equal in absolute magnitude but opposite in sign to the error. Correction is what must be done to the nominal to reach the actual.

correction chart
A chart prepared for a specific item to show corrections that must be applied to indicated reading to obtain actual values.

cosmic rays
Rays of higher frequency than radioactive gamma rays; highly penetrating, of unknown origin, traversing interplanetary space.

coulomb
Unit of quantity of electricity. The quantity of electricity transported in 1 second by a current of 1 ampere, or a movement of 6.28×10^{18} electrons past a given point in 1 second.

Coulomb's law of electrostatic charges
The force of attraction or repulsion exerted between two electrostatic charges, Q1 and Q2, a distance, s, apart separated by a medium of dielectric value, Î

counter electromotive force
In an inductor, an induced voltage that opposes the inducing voltage at every instant of time in an effort to oppose any change in the magnetic flux linkage.

counting circuit
A circuit that receives uniform pulses representing units to be counted and produces a voltage in proportion to their frequency.

coupling
The means by which signals are transferred from one circuit to another circuit.

creep
The long-term change in dimensional characteristics of a body under load, in an elastic force measurement device. This term refers to the change in reading which occurs when a constant load is applied for a period of time.

critical angle
The angle at which total reflection begins, when the angle of incidence of a light ray entering glass from air is increased to the extent that reflection, instead of refraction occurs.

critical coupling
The degree of coupling that provides maximum transfer of energy at the resonant frequency. Also called optimum coupling.

critical damping
The minimum viscous damping that will allow a displaced system to return to its initial position without oscillation about the neutral position.

critical frequency
A particular resonant frequency at which damage to or degradation of performance of equipment may or does result.

critical size
for fissionable material, the minimum amount of a material which will support a chain reaction.

cross section (Nuclear)
The area subtended by an atom or molecule for the probability of a reaction; that is, the reaction probability measured in units of area.

cryogenic
The science of refrigeration pertaining to the methods for producing and measuring very low temperatures.

crystal
Piezoelectric or oscillation-control crystal; a natural substance such as quartz or tourmaline, which is capable of producing a potential difference when subjected to mechanical pressure (deformation), or is capable of undergoing mechanical deformation when subjected to a potential difference. In a suitable feedback circuit, it vibrates at its mechanical resonant frequency and thereby produces stable electrical oscillations.

crystal controlled oscillator
An oscillator in which a crystal is used to determine the frequency and increase frequency stability.

crystal detector
Consists of a very small piece of semiconducting material mounted in a suitable container. It is widely used in microwave measurements due to its high sensitivity and wide frequency response.

crystal oven
An electrically heat enclosed space in which piezoelectric crystals are mounted so as to keep their temperature constant, thus assuring freedom from frequency drift due to temperature changes.

current saturation
The condition in which the plate current of a thermionic vacuum tube cannot be further increased by increasing the plate voltage. The electrons are then being drawn to the plate at the same rate as they are emitted from the cathode. Also called plate saturation or voltage saturation.

cutoff
1) The minimum value of negative grid bias that will prevent the flow of plate current in a vacuum tube.

2) The maximum amount of reverse bias the will cause a transistor to turn off.

3) In selective circuit, the frequency above and below which the circuit fails to respond.

cutoff frequency
Generally taken as the frequency at which the gain of a device is 3 db below its low frequency value. Used when referring to variations of alpha or beta with respect to frequency.

cycle
1) The complete sequence of instantaneous values of a periodic event that occurs during one period.

2) In electricity, one complete positive alternation and one complete negative alternation of an alternating current.

D

damped waves
Alternating current waves that progressively decrease in amplitude during successive cycles.

damping
1) The prevention of free swinging or vibration by some means, usually friction or resistance.

2) The dissipation of energy with motion or time.

Damping (galvanometer)
When an induced current flows in a direction to oppose motion of the coil, the galvanometer is said to be damped and the coil moves slowly. It is possible to control damping in a galvanometer circuit by controlling the amount of induced current. for some particular value of external resistance placed across the terminals of the galvanometer the pointer will return to its zero position in a minimum time without swinging past zero. The galvanometer is then critically damped and the value of the external resistance is the external critical damping resistance (CDRX). When the external resistance is less than the CDRX, the pointer approaches zero sluggishly and the galvanometer is over damped. If the external resistance is greater than the CDRX, the pointer swings past zero and tends to oscillate and the galvanometer is under damped.

D'Arsonval movement
The basic moving coil meter movement. It consists of a coil of many turns suspended between the poles of a permanent magnet.

dBm
Units used in communications for measuring absolute power level; power in decibels measured from a 1 milliwatt reference level.

DC amplifier
An amplifier that is capable of amplifying small variations in direct current. It employs direct coupling between stages.

DC plate resistance
The value of the DC plate voltage divided by the DC plate current of a vacuum tube.

DC restorer
See clamping circuit

decade box
In measurement work, a special device containing two or more sections. Each section is divided into 10 equal parts and has a value of 10 times the value of the preceding section. Switching arrangements permit selection of any desired value in its range.

decay
The disintegration of the nucleus of an unstable element by the spontaneous emission of charged particles and/or photons.

decay time (legacy term - see transition duration)
The time required for the trailing edge of a pulse to decrease from 90 percent to 10 percent of its maximum amplitude. Also referred to as fall time.

decibel
A standard unit used for comparison of two quantities of electrical or acoustical (sound) power. One decibel is roughly the amount that the intensity of a pure sine wave sound must be changed in order for the change to be just barely detectable by the human ear. The amount of change in power level, expressed in decibels, is equal to 10 times the common logarithm of the ratio of the two powers.

decoupling network
A network that is used to prevent the interaction of two circuits.

definition
The fidelity with which an oscilloscope forms an image having fine detail. When the image is sharp and has definite lines and boundaries, the definition is said to be good.

deflecting coil
An inductor used to produce a magnetic field that will bend the electron beam a desired amount in the CRT of an oscilloscope. Also called the deflecting yoke.

deflection factor
The voltage required on the deflection plates to produce a unit deflection on the CRT screen. It is the reciprocal of the deflection sensitivity.

deflection sensitivity
The amount of displacement of the electron beam at the screen of a CRT per unit change in the deflecting field. Usually expressed in millimeters per volt applied between deflecting electrodes. It is the reciprocal of deflection factor.

degeneration
A circuit arrangement-wherein a signal is fed back from the output to the input in such a way that it tends to cancel the input signal. It is used to stabilize the operation of the circuit.

degree
1) A unit division of a temperature scale.

2) A unit of latitude or longitude, equal to 1/360 of a great circle.

3) Mathematics: A planar unit of angular measure equal in magnitude to 1/360 of a circle.

4) Synonym: arcdegree

5) A degree (or degree of arc), usually symbolized by the symbol °, is a measurement of plane angles, or of a location along a great circle of a sphere, representing 1/360 of a full rotation. One degree is divided into 60 minutes (of arc), and one minute into 60 seconds (of arc). These units, also called the arcminute and arcsecond, are respectively represented by a single (‘) and double closing quotation (“) marks.

deionization potential
The potential at which the ionization of the gas within a gas-filled tube ceases and conduction stops.

delay line
A real or artificial transmission line consisting of inductance and capacitance to delay a signal a prescribed amount.

delay time
The time required to change the charge of the emitter base capacitance from the reverse condition to the forward biased condition.

density
The mass per unit volume. CGS unit: gm/cm.

De Santy bridge
An AC bridge used to measure capacitance and dissipation factor. It is composed of resistors and a standard capacitor. A variable resistor is used to obtain the amplitude null and a variable resistor as used to obtain the phase null.

detection
The process of extracting the intelligence, audio or video frequency component from the modulated RF signal. Also called demodulation.

detached method
A very flexible method of optical tooling. The instruments are mounted on stands or on optical tooling bars which are free of the actual work.

deuterium
A heavy isotope of hydrogen having 1 proton and 1 neutron in the nucleus. Symbol: D or 1 H2.

deuteron
The nucleus of a deuterium atom containing 1 proton and 1 neutron.

dew point
The temperature at which the water vapor in the air begins to condense. At this temperature the relative humidity is 100%.

dial indicator
This is a mechanical lever system used for amplifying small displacements and measuring it be means of a pointer which transverses a graduated dial.

dielectric
The insulating material between the plates of a capacitor; generally air, mica, paper, or oil. All insulating materials are dielectrics in that-they are capable of sustaining an electric field and undergoing electric polarization.

dielectric absorption
The property of an imperfect dielectric whereby all electric charges within the body of the material caused by an electric field are not returned by the field. Dielectric absorption increases with a decrease in frequency.

dielectric hysteresis
A power loss in a capacitor due to a lag in the placement of the electric field across a capacitor when an AC voltage is applied.

differential synchro
A synchro in which both rotor and stator are wound so that they produce rotating magnetic fields. Changing the position of the rotor causes a differential angle to be put into the system.

differential voltmeter
A voltmeter that operates on the potentiometric principle. The unknown voltage is compared to an adjustable calibrated voltage developed within the differential voltmeter.

differentiating circuit
A circuit in which the output voltage is proportional to the rate of change of the input voltage. In an RC circuit the output is taken across the resistor, and in an RL circuit it is taken across the inductor.

diffraction
The bending of waves, light, sound, or radio, as they pass an obstruction or pass through a small aperture.

diffusion
1) The penetration of one type of particle into a mass consisting of a second type of particle.

2) To spread out in all directions.

digit
Sign or symbol used to convey a specific quantity of information either by itself or with other numbers of its set; 2, 3, 4, and 5 are digits. The base or radix must be specified and each digit's value assigned.

digital voltmeter
An automatic electronic measuring instrument which displays its measurements directly in the decimal system. It is an automatic potentiometric measurement.

dimensional analysis
A process whereby the metrologist separates a quantity into its constituent parts to facilitate the solution to a problem.

diopter
The unit of lens power, is usually denoted by D and is the power of a lens of 1 meter focal length.

direct coupling
The use of a conductor to connect two amplifier stages together and provide a direct path for signal currents. This allows very low frequencies and DC to pass between stages.

discriminator
A circuit whose output voltage varies in amplitude and polarity in accordance with the frequency of the applied signal. Its principal uses are as a demodulator in a frequency modulation receiver and as an automatic frequency controlling device.

displacement
1) The amount of change in position from a reference.

2) Misalignment from a line of sight, usually measured vertically and horizontally

dissipation factor (DF)
The ratio of the energy dissipated to the energy stored. It represents the total power loss of a capacitor or inductor.

dissipative loss
That portion of attenuation contributed to the actual dissipative of energy as compared to the reflection of energy, used when referring to dissipative losses only in lieu of the common term "attenuation."

displacement graticule
A graduated reticule used in Collimators measuring vertical and horizontal displacement. Generally in terms of linear displacement.

distortion
Any deviation from the desired waveform.

distortion analyzer
A measuring instrument used to determine the distortion present on a sinusoidal waveform.

distributed capacitance
Capacitance distributed between wires, parts or conducting elements, and the ground, as distinguished from capacitance concentrated in a capacitor.

diverge
To spread out, as in the effect of a concave or negative lens. Diverges away from the focal point.

dominant mode
The waveguide mode that produces the longest operating wavelength, has the-greatest energy transfer efficiency, and has the simplest configuration.

donor
A substance (impurity) which, when added to a pure semiconductor material, results in .an increase in the number of free electrons so that major conduction through the material takes place as a movement of electrons. Since this is equivalent to the transfer of a negative charge, the resulting alloy is called an N-type semiconductor.

dove
A prism which inverts the image without displacement. Also called a rotating prism.

Doppler effect
The change in the observed frequency of a wave reaching an observer, due either to motion of   the source (toward or away from the observer), motion of the observer, or a shift in the reflecting layer.

drift
The movement of majority carriers in an electric field supplied by an external source, that is, electrons move toward a positive pole, holes toward a negative pole.

drift space
In an electron tube, a region substantially free of externally applied alternating fields, in which relative repositioning of the electrons takes place.

dropping resistor
A series resistor used to decrease the voltage by the amount of the voltage drop across the resistor.

ductility
That property of a material which will permit it to be drawn into a wire.

duty cycle
Ratio of the on-time to the total time or the pulse width to pulse recurrence time.

dynamic plate resistance
See AC plate resistance

dynamic response
The ability of a measuring device to follow changes in a circuit or instrument under test. for example, the ability of the indication from a force measuring device to keep up with rapidly changing loads.

dynamic transfer curve
A curve that shows the variation of output current (dependent variable) with variation of input current under load conditions.

dynamometer movement
A meter using three electromagnetic coils. The dynamometer movement can be used to measure power, voltage, or current. It is best suited for measuring low frequency AC. However, it can also be used to measure DC.

dyne
That unit of force which, when acting upon a mass of 1 gm, will produce an acceleration of 1 cm/sec/sec.

E

Eccles-Jordan multivibrator
See bistable multivibrator

echo
A wave that has been reflected or otherwise returned with sufficient magnitude and delay to be seen (or heard) in some manner.

eddy currents
Circulating currents induced in a conductor by a varying magnetic field. These currents are undesirable in most instances because they represent loss of energy and cause heat. In the iron cores of transformers and other iron core devices carrying alternating current, laminated construction is used to shorten the paths for eddy currents and thus keep eddy current losses to a minimum.

Edison effect
The emission of electrons from hot bodies. The rate of emission increases rapidly with temperature. Also known as thermionic emission.

effective mass
The mass of a body which is being acted upon by the buoyant forces of air. The effective mass of a weight is its true mass minus the buoyant force of air displaced by the weight.

effective value (RMS)
The alternating current value that will produce the same amount of heat in a resistance as the corresponding direct current value. All alternating current meters, unless otherwise marked, indicate effective values of voltage or current. The effective value is also called RMS (root-mean-square) value.

efficiency
The ratio of useful output energy to input energy, usually expressed as a percentage. A perfect electrical device would have an efficiency of 100 percent.

elasticity
The property of material to return to its original shape after stress is removed.

elastic limit
The maximum unit stress which can be obtained in a structural material without causing permanent deformation.

E Layer
An ionized layer in the E region of the ionosphere. This layer occurs during daylight hours; its ionization depends on the angles of the sun.

electric field intensity
The magnitude of the intensity of an electric field at a particular point, equal to the force which would be exerted upon a unit positive charge placed in the field at that point. The direction of the electric field is the direction of this force.

electrical angle
A means of specifying a particular instant in an alternating current cycle. One cycle is considered equal to 360°, hence a half-cycle is ISO" and a quarter-cycle is 90°. If one voltage reaches a peak value a quarter of a cycle after another the electrical angle between the voltages (the phase difference) is 90°.

electric field
A region in space surrounding a charged object, or the electric component of the electromagnetic field associated with radio waves and with electrons in motion. Lines drawn to represent the direction in which the electric field will act on other charged objects are called electric lines of force.

electricity
A fundamental quantity in nature, consisting of electrons and protons at rest, or in motion. Electricity at rest has an electric field that possesses potential energy and can exert force, as in charged pith balls. Electricity in motion ordinarily consists of a movement of electrons through a conductor or through space.

electrode
A terminal at which electricity passes from one medium into another, as the individual elements of a vacuum tube, the plates of battery cells or the plates of capacitors.

electrolyte
The liquid, chemical paste, or other conducting medium used between the electrodes of a battery, electrolytic capacitor, or electrolytic rectifier.

electrolytic capacitor
A capacitor consisting of two metallic places separated by an electrolyte. Under the action of the applied DC voltage a film of hydrogen gas is formed on one plate. This film acts as the dielectric. The electrolyte is actually the negative electrode.

electromagnet
A core of soft iron that is temporarily magnetized by sending current through a coil or wire wound around the core.

electromagnetic spectrum
Total range of frequencies of electromagnetic waves.

electromagnetic waves
Radiation taking many different forms and exhibiting widely differing properties. Long wavelength radiations (radio waves) consist of electric and magnetic fields perpendicular to each other and the line of travel. As wavelength decreases, the radiation acts less like waves and more like energy particles.

electromagnetism
Magnetic effects produced by currents rather than by permanent magnets.

electromotive force (EMF)
Difference of electrical potential, or pressure, measured in volts. The property of a device which, tends to produce an electric current in a circuit.

electron
(1) A subatomic particle possessing a unit negative charge.

(2) A negatively charge particle which is a constituent of every atom. A unit of negative electricity equal to 4.80 x 10^{-10} esu. Its mass is 0.00548 mu.

electron coupled oscillator
An oscillator circuit employing a screen grid tube so connected that its screen grid is used as a plate in connection with the control grid and cathode. It acts as an ordinary triode oscillator circuit, with the output taken from the plate circuit.

electron gun
The beam-forming structure in the neck of a CRT, consisting of an electron emitting cathode and associated electrodes that concentrate, control, and focus the stream of emitted electrons in a beam that produces a spot of the desired size on the screen at the end of the tube.

electron emission
The ejection of electrons from the surface of a material into surrounding space under the influence of heat, light, high voltage, impact, or any other cause. Quantitatively, electron emission is the rate at which electrons are emitted from an electrode.

electron volt
Energy required to move an electron between two points which have potential difference of 1 volt.

electronic switch
An electronic circuit designed to cause a start and stop action or a switching action.

electronics
That branch of physics which relates to the emission behavior and effects of electron conduction through a vacuum, gaseous media or semiconductors.

electrostatic
Pertaining to electricity at rest, such, as charges on an object (static electricity).

electrostatic field
The region surrounding an electric charge in which another electric charge experiences a force.

electrostatic unit of charge (Stat coulomb)
That quantity of electric charge which, when placed in a vacuum 1 cm distant from an equal and like charge, will repel it with a force of 1 dyne. Abbreviation: esu.

electrostatic voltmeter
A voltmeter that works on the principle of attraction or repulsion of like electrical charges. The electrostatic voltmeter could be likened to a capacitor with, one movable plate, on which a pointer is mounted. The electrostatic voltmeter is used to measure high values of AC and DC voltages.

element
(1) In chemistry, one of the 100-odd primary substances that cannot be divided into simpler substances by chemical means.

(2) A pure substance consisting of atoms of the same atomic number, which cannot be subdivided by ordinary chemical means.

elevation
The vertical distance above a reference level, usually sea level, to a point or object on the surface of the Earth, as distinguished from altitude, which refers to points above the Earth's surface.

empirical
Based on actual measurement, observation, or experience without regard to science and theory.

endoergic reaction
A reaction which absorbs energy.

energy
Capacity for performing work. Energy due to the motion of a piece of matter is called kinetic energy. Energy due to the position of a piece of matter is called potential energy.

envelope
(1) The glass or metal housing of a vacuum tube.

(2) A curve drawn to pass through the peaks of a graph showing the waveform of a modulated RF carrier signal.

equivalent circuit
A relatively simple circuit arrangement of resistors, inductors, and/or capacitors which is electrically equivalent to a more complicated circuit or device. Used to simplify circuit analysis.
erect
Not inverted, the normal position.

erector lens
Additional optics fitted to the eyepiece lens system enabling the image to be viewed in the normal (erect) position.

erg
The unit of work done by a force of 1 dyne acting through a distance of 1 cm. The unit of energy which can exert a force of 1 dyne through a distance of 1 cm. CGS units: dyne-cm, or gm- cm^2/sec^2.

error
The error is the difference between an observed value or calculated value and the true or actual value.

evaporization
The change of state from a liquid to a gas.

exoergic reaction
The reaction which liberates energy.

exponent
Power of ten by which a number is multiplied, used in floating point representation. For example, the exponent in the decimal number $0.9873 \text{ X } 10^7$ is 7.

exponential
Pertaining to varying exponents or to an expression having varying exponents. Any constant base affected with an exponent is exponential.

extinction potential
The lowest value to which the plate voltage of a gaseous tube can be reduced from a higher value under given conditions, without stopping the flow of plate current.

eyepiece
An essential component of a telescope which receives a real image in its focal plane and forms a magnified virtual image.

F

Fahrenheit scale
A thermometric scale on which the freezing point of water is 32° and boiling point 212°, both at standard pressure.

fall time
1) In transistors, the time needed for the output pulse to decrease from 0.9 to 0.1 of its maximum amplitude. Often used to describe the decay time of a pulse. (legacy term in this context- see transition duration)

2) In dead weight testers, a leak test wherein the system is closed and the rate of fall of the piston is indicative of the overall leakage.

farad
Unit of electric capacitance. The capacitance of a capacitor between the plates of which there appears a difference of potential of 1 volt when it is charged by a quantity of electricity equal to 1 coulomb.

feedback
The transfer of energy from the output circuit of a device back to its input. Degenerative feedback is the process whereby a part of the power in the output circuit reacts upon the input circuit in such a manner as to reduce initial power, thereby decreasing the amplification. Regenerative feedback is the process whereby a part of the power in the output of an amplifying device reacts upon the input circuit in such a manner as to increase the initial power, thereby increasing the amplification.

fermi level
The Fermi level in a semiconductor is located at that value of energy at which there is a 50% probability of an energy state at that level) being occupied by an electron. It is merely a mathematical marker in energy terms and is not a physical entity in the same sense as an atomic level.

fidelity
The degree with which equipment reproduces the essential characteristics of the signal which is impressed upon its input.

filament
Directly heated cathode which carries its own heating current, as distinguished from an indirectly heated cathode.

filter
A network of resistors, inductors, and capacitors, or any one or two of these, which offers comparatively little opposition to certain frequencies or to direct current, while blocking the passage of other frequencies. An example is the filter used in a power supply, which allows the direct current to pass, but filters out the ripple.

firing potential
The grid-cathode voltage required in a gaseous triode to make the tube conduct or fire.

fixed bias
A bias voltage of constant value, such as obtained from a battery, generator, or other power supply.

field of view
Expressed as an angle and representing the arc through which observations are possible through a telescope. The field angle is controlled by the aperture of the eye lens and decreases as magnification increases.

filar
1) Also known as; cross hair, reticule. In optics a superimposed reference line. for two parallel lines called; bifilar.

2) See also; reticule

fission products
The elements and/or particles produced by fission.

fixed point
The point where all heat energy applies or removed is used to change the state of a substance.

flat line
A transmission line that has no standing waves. At every point along the line the amplitude of voltage is the same.

flat response
Term used to indicate that the gain varies only slightly within a stated frequency range. The response curve plotted for such an amplifier is almost a straight line.

fluorescence
The property of emitting electromagnetic radiation, usually as visible light due to the absorption of radiation from some other source.

flux
1) A material used to promote fusion or joining of metals in soldering, welding, or smelting. Rosin is widely used as a flux in electric soldering.

2) A general term used to designate collectively all the electric or magnetic lines of force in a region.

flux linkage
A value obtained by multiplying the number of turns in a coil by-the number of magnetic lines of force passing through the turns.

fly back
A portion of the time base in the operation of a CRT in which the spot is returning to the starting point.

fly wheel effect
The ability of a resonant circuit because of its energy storage, to operate continuously from short pulses of energy of constant frequency and phase.

focal length
The distance from the optical center of a lens to the point where light rays converge.

focal plane
A plane that is perpendicular to the optical axis at the focal point. All light coming from infinity will focus somewhere on the focal plane.

focal point
The point at which light rays converge after passing through a convex (positive) lens.

focus
Correct adjustment of a lens to produce a clear image.

focusing anode
One of the electrodes in a CRT, the potential of which may be varied to focus the electron beam.

focusing control
The control that is used to obtain a sharp, clear image on the screen of a CRT in a television system or an oscilloscope.

force
A push or pull. That which produces or prevents motion or has a tendency to do so.

force measurement device
Refers to any device by which a quantitative determination of an applied force can be made.

forced vibration
Motion caused by some mechanical excitation.

form factor
Term used in describing the quantity of rectified current. It is the ratio of the effective current to the average current (1.11 in the case of a sinewave).

forward bias
Voltage applied across a semiconductor in order to neutralize repelling forces at the junction and permit a flow of current in a forward direction at low resistance.

Foster-Seely discriminator
A discriminator that produces a DC voltage output proportional to the deviation of frequency from a center frequency.

foot-candle
The amount of illumination which a standard source of 1 candle (candlepower) will throw upon a surface placed 1 foot away and at right angles to the rays of light.

foot-pound
A term used in the study of torque representing a force of 1 pound applied perpendicular to a moment arm 1 foot long.

free vibration
Vibration that occurs without forcing, as after a tuning fork is struck.

frequency
The number of recurrences of a periodic phenomenon in a unit of time. In specifying electrical frequency, the unit of time is the second.

frequency distortion
Distortion caused when different frequency components in a signal are given unequal amplification.

frequency divider
A circuit which produces an output frequency equal to a submultiple of the input frequency.

frequency meter
An instrument for measuring the frequency of an AC signal.

frequency modulation (FM)
A form of modulation in which the frequency of the carrier is varied in accordance with the frequency of the modulating signal. The amplitude of the carrier remains constant at all times.

frequency multiplier
A circuit that is used to develop multiples of a precise frequency.

frequency response
The operating range over which a circuit or device handles all frequencies uniformly.

frequency response curve
A graph showing the frequency response of a circuit or device.

full-wave rectification
Rectification in which both halves of each alternating current cycle are used to produce direct current.

fundamental frequency
The lowest frequency component of a complex waveform.

fundamental mode of vibration
The lowest natural frequency.

fusion (heat)
The change of state from a solid to a liquid.

G

gage
An instrument for measuring or testing; a device for determining whether specific dimensions are within specified limits.

gage block
A block of alloy steel, usually square or rectangular, with two gaging surfaces. The standard length as nominally represented on the side is in inches between two gaging surfaces with an uncertainty in the neighborhood of 6 µin. The primary end for linear measurements.

gain
The ratio of output voltage, current, or power in an amplifier stage or system to the input voltage, current, or power, respectively; usually expressed in decibels. Increasing the gain means increasing output signal strength.

Galilean telescope
Devised and constructed by Galileo in 1609. The device consists of a positive objective lens and a negative eyepiece with their focal points in coincidence. The system is suitable for two or three power magnification and produces an erect image.

galvanometer
A D'Arsonval laboratory instrument usually of the suspension type capable of measuring very small electrical currents. It is usually used to indicate a null. Since the galvanometer is used in this application, to indicate whether or not a current is present, and not necessarily the actual magnitude of the current, the primary requirement of the galvanometer is to show a readable deflection for the smallest current that is significant for a particular measurement.

gamma
1) The current amplification factor when connected in a common collector configuration.

2) Reflection coefficient of voltage in microwave applications.

gamma ray
Radiant energy of extremely short wavelength emitted spontaneously by a radioactive substance.

gas
The state of matter that has no definite shape or volume. The molecules of a gas have almost no cohesive forces, hence the expansion of a gas in free space is almost unlimited.

gauss
Unit of magnetic induction (also called magnetic flux). One gauss represents one line of flux per square centimeter.

generator
1) A machine that changes mechanical energy into electrical energy.

2) An oscillator that generates an alternating voltage at a desired frequency when energized with DC or low frequency AC power.

geometry
Study of the properties, measurement, and relations between lines, angles, surfaces, and solids.

gilbert
The unit of magnetomotive force in the centimeter-gram-second electromagnetic system.

glow-discharge voltage regulator
A gas tube (VR tube) that varies in resistance between about 5,000 and 30,000 ohms, depending on the value of the applied voltage. It is used to maintain the supply voltage constant.

glow lamp
A lamp in which light is produced by a glow discharge between two electrodes in an evacuated envelope into which a small quantity of gas such as neon or argon has been introduced.

Go and No-go gages
These are gages that do not measure actual size but merely determine whether parts are within specified limits.

Gon
The metric system of defining a decimal degree, with 100 decimal degrees in a right angle, or 400 decimal degrees in a circle.

grain
A measure of mass in the English gravitational system equal to one seven-thousandth (1/7000th) pound.

gram
Metric unit of mass or weight. One pound is equal to 453.59 grams.

gram-atomic weight
The relative atomic weight of an element, expressed in grams.

gram-molecular weight (Gram-Mole)
The relative molecular weight of a compound, expressed in grams.

graph
A pictorial presentation of the relation between two or more variable quantities.

grass
The pattern on the CRT display of a radar or similar system, which is produced by the random noise output of the receiver.

graticule
A scale on a transparent material in the focal plane of an optical instrument for the location and measurement of objects.

gravity
Any two bodies in the universe attract each other with a force that is directly proportional to the product of their mass and inversely proportional to the square of their distance apart.

gravitational acceleration
The acceleration due to the force of gravity.

gravitational units or "G" units
The usual way of expressing acceleration intensity, in terms of gravitational constant, is equal to the acceleration in inches/sec/sec divided by 386.087 inches/sec/sec.

grid bias
The DC difference in potential between the control grid and the cathode of a vacuum tube.

grid circuit
The circuit connected between the grid and cathode of a vacuum tube, forming the input circuit to the tube.

grid leak
The resistance in the grid circuit of a vacuum tube.

grid leak bias
The bias obtained by grid current flowing through the grid leak resistance. The amount of grid leak bias depends on the amplitude of the signal input.

grid leak resistor
A resistor used in the grid circuit of a vacuum tube to provide a discharge path for the grid coupling capacitor. The value of the resistor determines the average value of the grid leak bias.

grid limiting
Limiting the positive grid voltage of a vacuum tube circuit by means of a high resistance grid resistor.

gross error
A gross error is simply a mistake.

ground
A reference point in an electrical circuit which is usually a connection between an electrical circuit and the Earth or some conducting body serving in place of the Earth.

group velocity
The axial velocity at which a signal travels through a waveguide. Group velocity is always less than the velocity of a signal in open air.

guarding
A feature provided on many high-precision measuring instruments which refers to the use of special circuitry, insulated from ground, to provide freedom from adverse effects of leakage currents. The stray current is bypassed through a noncritical path so that it does not affect the accuracy of measurement.

H

half life
The length of time during which half of a given number of atoms of a radioactive element will disintegrate.

half thickness
The thickness of absorbing material necessary to reduce the intensity of radiation by one-half.

half power points
The 70.7% point of a curve.

hardness
The internal resistance of an object to having its molecules forced further apart or closer together.

harmonic
A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency. Thus, a component whose frequency is twice the fundamental frequency is called the second harmonic.

Hartley oscillator
An oscillator circuit characterized by a tuned circuit having a tapped winding whose outer ends is connected to the grid and plate, respectively, of the vacuum tube, with the tap going to the cathode.

hay (parallel inductance) bridge
An AC bridge that permits measurement of inductors with a high Q in terms of- capacitance. The bridge contains resistors and a variable standard capacitor. The amplitude null is obtained with the variable standard capacitor and the phase null with a variable resistor.

head
The vertical depth of any point below the free surface of a liquid.

heat
The energy of molecular motion measured in terms of the effect on some material substance.

heat of fusion
The amount of heat needed to melt a unit mass or weight of a substance at its normal melting point.

heat of vaporization
Heat required to vaporize a unit mass or weight of a liquid at its normal boiling point.

heat sink
A device for the absorption or transfer of heat away from a device.

heavy water
The popular name for water which is composed of 2 atoms of deuterium and 1 atom of oxygen.

Helipot
A multi-turn spirally wound potentiometer used in many instruments to get a high resolution.

Henry
Unit of electric inductance. The inductance of a closed circuit in which the electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at a rate of 1 ampere per second.

hertz
A unit of frequency equal to 1 cycle per second.

Heterodyne
The mixing of two alternating currents of different frequencies in a nonlinear impedance device which generates a current having the sum and difference frequencies, either or both of which may be selected by properly tuning the output.

high-frequency resistance
See AC resistance

high pass filter
A filter designed to pass currents at all frequencies above a critical frequency, while substantially reducing the amplitudes of currents of all frequencies below this critical frequency.

hole
A mobile vacancy in the electronic valance structure of a semiconductor, which acts as a positive electronic charge.

Hooke's Law
Within the limits of perfect elasticity, stress is directly proportional to strain.

horizontal
Of, relating to, or near the horizon. An orientation relating to, or in parallel with the horizon; at right angles to a vertical line.

horizontal sweep
The scanning motion from left to right across a CRT.

horizontally polarized waves
Electromagnetic waves in which the electric field (E) is parallel to the horizon (or Earth's surface).

hunting
Refers to a tendency of a mechanical system to oscillate about a normal condition, or about the point of alignment.

humidity
See relative humidity

hydrogen atom
The atom of lightest mass and simplest atomic and nuclear structure, consisting of 1 proton with 1 orbital electron. Its mass is 1.008123 mu.

hydrometer
An instrument used to determine the specific gravity of liquids.

hydraulics
The study of liquids in motion.

hydrostatics
The study of liquids at rest.

hygrograph
An instrument for automatic recording of variations in atmospheric humidity.

hygrometer
Any of several instruments for measuring the humidity of the atmosphere.

hygroscopic
Readily absorbing and retaining moisture, often reflecting this absorption by changing physical appearance and shape.

hysteresis
1) The word hysteresis means "lag." One example is the lagging of the magnetic flux, in a magnetic material, behind the magnetizing force which is producing it. Another example is the lag of a standard cell in returning to its initial voltage following a change in temperature.

2) In force measurement, hysteresis may refer to the difference in indication for two identical loads, one obtained by reducing from a larger load and the other built up from a lesser value.

hysteresis loss
Power loss in an iron core transformer or other alternating current device due to the magnetic hysteresis.

I

ice point
0.01 ºC below the triple point of water.

illumination
To supply or brighten with light.

image
1) A virtual image is the impression of an object as viewed by an observer. Rays do not pass through, but only appear to come from the image.

2) A real image is one through which rays actually pass and can be projected onto a screen.

imaginary number
The indicated square root of a negative number.

impedance (Z)
An indication of the total opposition that a circuit offers to the flow of alternating current or any other varying current at a particular frequency, measured in ohms.

impedance coil
See choke coil

impedance match
The condition in which the impedance of a connected load is equal to the internal impedance of the source, thereby giving maximum transfer of energy from source to load.

impedance triangle
A diagram which is a right-angle triangle with sides proportional to the resistance and reactance of an alternating current circuit. The hypotenuse represents the impedance of the circuit. The cosine of the angle between the sides representing resistance and impedance is the power factor of the circuit.

incident ray
A ray of light entering into a lens or mirror.

incident wave
Energy moving from the generator toward the termination of a transmission line.

increment
Adding the value one to the contents of a register or memory location.

incremental attenuation
The difference in attenuation between a given setting and the zero setting of an attenuator.

inclination
Refers to a difference between the slope of the line or place in question and some other reference line or plane.

index of refraction
The ratio of the speed of light in a vacuum to its speed in a given substance.

inductance
The property of a circuit that opposes any change in current, or property of an electric circuit or two neighboring circuits which determines how much electromotive force will be induced in one of the circuits by a change of current in either of them. Inductance is measured in henrys and designated by L.

induced voltage
A voltage produced in a circuit by a change in the number of magnetic lines of force passing through a coil in the circuit.

inductive reactance
That type of reactance which is due to the inductance of a circuit or coil. It is measured in ohms, designated by XL and is equal to $2\pi FL$.

inductronic amplifier
A sensitive DC automatic potentiometer. It senses a small difference in EMF and develops a corrective voltage in a voltmeter calibration system.

inertia
That property of mass which resists a change in motion.

infinite
Subject to no limitation or external determination, extending indefinitely.

infinite line
A transmission line having characteristics corresponding to those which would be obtained with an ordinary line that is infinitely long.

infinity (optical)
An infinite distance from which collimated or parallel light rays are assumed to emanate (approximately 2000 yards).

initialization
Setting a system to a known state.

insertion loss
A special case of substitution loss. The ratio of the initial load power to the final load power, expressed in decibels, when a network is inserted into a measuring system. The value of insertion loss measured depends upon the reflection coefficients of the generator and load as well as the network under test.

instability
An undesired change over a period of time, which change is unrelated to input, operating conditions, or load.

intensity modulation
Control of the brilliance of the trace on the screen of a CRT. This is also known as "Z axis modulation."

intensity of radiation
The amount of radiant energy emitted in a specific direction per unit time and per unit surface area.

interface
In optics, a boundary between two media in which light travels with different velocities.

interference
In optics, when two sets of light waves of equal wavelength and amplitude from the same source meet, so that the crests of one coincide with the troughs of another, they cancel out. Similarly, if two sets of light waves meet when the crests of one coincide with the crests of the other, they reinforce each other.

interferometer
An instrument that is used to measure minute linear displacement through the phenomena of light interference.

interferometry
The use of light interference patterns for measurements with apparatuses such as the optical flat.

interpolation
1) Is the selection of the nearest graduation when a measurement lies between. The observational equivalent to the rounding off process in computation.

2) Mathematically determining a point between two known values. intrinsic attenuation
The attenuation in a transmission line due to power dissipation.

inversion
The condition that exists when both axes of an image are reversed.

inverter
Any mechanical or electrical device for converting direct current into alternating current.

inverse peak voltage
The peak value of the instantaneous voltage across a rectifier tube during the half of the cycle in which current does not flow.

ion
An atomic particle, atom, or chemical radical (group of chemically combined atoms) bearing an electrical charge, either positive or negative, caused by an excess or deficiency of electrons.

ionization
The process by which molecules of a gas are converted into positive ions by loss of electrons, or into negative ions by gain of electrons. Ionization can be produced in a number of ways, by collisions of ions with electrons, by the action of ultraviolet light or other radiations.

ionosphere
That region of the atmosphere, 70 to 250 miles above the surface of the Earth, containing layers of highly ionized air that are capable of bending or reflecting radio waves back to Earth. Reflection from the ionosphere makes possible long-distance reception of radio waves.

ionization potential
The potential necessary to separate 1 electron from an atom.

ionizing event
An event in which an ion is produced.

iron vane movement
A meter movement in which the movable element is an iron vane which is drawn into the magnetic field produced by flow of the current being measured. Iron vane meters have a square law response and scale.

isobars
Elements having the same mass number but different atomic numbers.

isolation transformer
Used in conjunction with AC bridge circuits to isolate the AC null detector from the AC power source. Isolation transformers can also provide a greater measure of safety for personnel.

isotope
One of two or more forms of an element having the same atomic number (nuclear charge) and hence occupying the same position in the periodic table. All isotopes are identical in chemical behavior but are distinguishable by small differences in atomic weight. The nuclei of all isotopes of a given element have the same number of protons but have different numbers of neutrons.

Instability
An undesired change over a period of time, which change is unrelated to input, operating conditions, or load.

J

j
The square root of minus one (-1).

JAN specification
A military specification which covers all branches of the military.

jitter
Small, rapid variations in a waveform due to mechanical disturbances or to changes in the supply voltages.

Johnson (thermal) noise
The noise caused by the thermal agitation of charges in a conductor. It is proportional to the absolute temperature and the frequency bandwidth over which the noise is measured.

joule
Unit of energy. The work done when the point of application of 1 newton is displaced a distance of 1 meter in the direction of the force.

junction transistor
A type of transistor employing a sandwich type of construction where the outside layers are quite thick as compared to the thin center layer. The semiconductor material is used alternately to form PNP or NPN transistors.

K

k
Symbol for 1000 (103). When referring to bits or words, K=1024 (210).

keeper
Iron or steel bar placed across the poles of a horseshoe magnet. The keeper prevents gradual demagnetization by providing a low reluctance path for the magnetic circuit.

Kelvin bridge
A double Wheatstone bridge requiring two conditions of balance. Primarily used for precision measurement of low value resistances.

Kelvin degree
Unit of temperature. The unit of temperature determined by the Carnot cycle with the triple-point temperature of water defined as exactly 273.16 °K.

Kelvin temperature scale
The absolute temperature scale in the CGS system. Kelvin is equal to degrees Celsius plus 273.15.

kilogram
Unit of mass. The mass of a particular cylinder of platinum-iridium alloy, called the International Prototype Kilogram, which is preserved in a vault at Sevres, France, by the International Bureau of Weights and Measures.

kinetic energy
Energy due to motion.

Kirchhoff's Laws
1) The sum of the currents flowing to a given point in a circuit is equal to the sum of the currents flowing away from that point.

2) The algebraic sum of the voltage drops in any closed path in a circuit is equal to the algebraic sum of the electromotive forces in that path. Also called the laws of electric networks.

Klystron
A vacuum tube for converting DC energy into RF energy by alternating current that delivers power to a cavity resonator.

L

laminated core
An iron core for a coil, transformer, armature, etc., built up from laminations stamped from sheet iron or steel. The laminations are more or less insulated from each other by surface oxides and sometimes by application of varnish. Laminated construction is used to minimize the effect of eddy currents.

lapping
A smoothing or polishing operation.

laser

An optical cavity capable of oscillating in the visible and non-visible light spectrum. The laser is a true light amplifier because light energy is used for excitation.

lateral
From the side. Usually refers to movement of a given reference made from left to right to left.

lecher wire
A transmission line which uses the characteristics of standing waves for the determination of wavelength at the higher frequencies.

leakage current
1) Undesirable flow of current through or over the surface of an Insulating material or insulator.

2) The flow of direct current through a capacitor.

3) The alternating current that passes through a rectifier without being rectified.

4) The current that flows between two or more electrodes of a tube by any path other than across the vacuous space between the electrodes.

leakage inductance
The difference between the total inductance of a transformer winding and that used in transferring energy from one winding to another.

left-hand rule
1) for generators: If the thumb, first, and-second fingers of the left hand are stretched at right angles to one another, with the thumb representing the direction of motion, the first finger representing the direction of magnetic lines of force, and the second finger representing the direction of electron flow, the relations between the directions will then be correct for a conductor in the armature of a generator.

2) for a current-carrying wire: If the fingers of the left hand are placed around the wire in such a way that the thumb points in the direction of electron flow, the fingers will be pointing in the direction of the magnetic field.

lens
A body of glass or similar material ground to fine limits, used to either converges or diverge rays of light by refraction.

lens, converging
See convex

lens, diverging
See concave

Lenz's Law
The current induced in a circuit as a result of its motion in a magnetic field is in such a direction that it exerts a mechanical force opposing the motion. Also called "law of induced current."

level
Perpendicular to the force of gravity. Also, a device for determining true level by means of a gravity seeking level.

light
A narrow band of radiation which is the visual section of the electromagnetic spectrum. It consists of wavelengths of 15.7 to 27.5 µin.

light beam chopper
A circuit that produces a square wave from DC. It uses photosensitive resistors, a light beam, and a synchronous motor turning a disc with apertures, to control the operation of the photosensitive resistors.

lighthouse tube
A single tube oscillator operating at a frequency of about 2500 MHz. It gets its name because of its construction which resembles a lighthouse.

limited calibration
A calibration performed which does not check all of the required parameters.

limited certification
A limited certification (Yellow form) is used to document the limitation (Red Line).

limiter (clipper)
A circuit which removes amplitude variations from the signal by cutting off all positive and/or negative peaks that exceed certain amplitude.

line of force
An imaginary line in an electric or magnetic field that coincides in direction with the field intensity at each point. It was conceived by Faraday, and is used for convenience in the study of magnetic and electric fields. When used as a unit of magnetic flux, a line of force is sometimes called a maxwell.

line of sight
A straight line that passes through the cross hairs and the principal point of lens is called the line of sight or the line of collimation; it always strikes the object where the cross hairs appear to fall. Accordingly, the cross hairs and the principal point of the lens are said to define the line of sight.

linear
A relation such that any change in one of two related quantities is accompanied by an exactly proportional change in the other.

linearity check
The process of checking the meter across the entire scale, at specified or cardinal points on a designated range.

liquid
The state of matter which has definite volume but no definite shape.

Lissajous pattern
A family of scope patterns used to show phase relationships, make frequency comparison measurements, and indicate the percentage of AM modulation.

load cell
A type of force transducer designed primarily for the measurement of load or weight. Electric load cells usually employ bonded strain gage resistance elements to provide an electrical output signal proportional to the load. Hydraulic and pneumatic load cells generally make use of a bourdon-type device, such as a Heise gage.

load line
A straight line drawn across a series of plate current-plats' voltage characteristic curves on a graph to show how plate current will change with grid voltage when a specified plate load resistance is used. The slope of the load line is proportional to the reciprocal of the plate load impedance in ohms.

loading effects
An error of measurement resulting in a change of the system under test caused by insertion of the test instrument.

logarithm
The logarithm of a number is the power to which a second number, called the base, must be raised in order to yield the original number. Bases in common use are 10 and 2.718.

logarithmic meter scale
A nonlinear scale used with a moving coil meter, where the pointer deflection is directly proportional to the logarithm of the applied voltage. Power is directly proportional to the logarithm of the applied voltage if the meter has a linear voltage response.

logic
The synthesizing of a network of logical elements to perform a specified function.

logic circuits
Circuits whose functions can be described by simple statements of formal logic using connective words and, or, not.

logic diagram
A circuit diagram which represents the function of logic circuits and their interconnections without necessarily expressing their construction or engineering details.

logical element
In a computer or data processing system, the smallest building blocks which can be represented by operators in an appropriate system of symbolic logic.

loop
The point, line, or surface of a stationary wave system, at which maximum amplitude exists.

loose coupling
A small amount of coupling between two coils or circuits.

lossy
An adjective applied to a dielectric material which dissipates energy.

lossy line
A transmission line with a high degree of attenuation.

low pass filter
A filter designed to pass currents at all frequencies below a critical frequency, while substantially attenuating the amplitude of other frequencies.

lumen
Unit of luminous flux. It is the luminous flux emitted in a solid angle, 1 steradian, by a uniform point source having an intensity of 1 candela.

luminous flux
The visible energy emitted by a source per unit time. MKS system - The meter-kilogram- second system.

M

magnet
Any object which has the property of attracting iron, nickel, or cobalt objects with forces which are much greater than those of gravitation and which do not depend on the presence of electric charges on either body.

magnetic deflection
Method of bending electrons in a CRT by means of the magnetic field produced by coils placed outside the tube.

magnetic induction
1) The magnetic quantity (number of magnetic lines of force) that determines how much voltage will be induced in a conductor moving through a particular point in a magnetic field. It is expressed in gausses. It is also called magnetic flux density.

2) The process of magnetizing an object by bringing it into the magnetic field of an electromagnet or permanent magnet.

magnetic saturation
That condition in an iron core in which further increases in magnetizing force produces little or no increase in magnetic flux density.

magnetism
A property possessed by iron, steel, and certain other materials when in a particular condition of internal structure, by which these materials can exert a mechanical force on neighboring masses of magnetic materials and can cause voltages to be induced in conducting bodies moving relative to the magnetized bodies.

magneto motive force
Magnetic potential difference. Expressed in gilberts, that is, ergs per magnetic pole.

magnetron
A high vacuum thermionic tube (containing two electrodes) in which the flow of electrons from cathode to anode is controlled by an externally applied magnetic field. It is used for generating microwaves.

magnification
The value of magnification is the apparent size of an object viewed through a telescope divided by the size it appears to the unaided eye from the same distance.

majority carriers
In semiconductors, the type of carrier constituting more than half of the total number of carriers. The majority carrier may be either holes or free electrons found in P-type or N-type semiconductors, respectively.

malleability
The property of a metal which allows it to be hammered or rolled into sheets.

manganin
An alloy used in making precision wire wound resistors because of its low temperature coefficient of resistivity. Many standard resistors are made of manganin.

marker generator
A generator that develops pulses (markers) from a-calibrated circuit. These markers are used to calibrate the time base of an oscilloscope.

mantissa
Fractional value used as part of a floating-point number. for example, the mantissa in the number $0.9873 X 10^7$ is 0.9873.

mass
The measure of the quantity of matter that a body contains.

mass density (ρ)
Mass per unit volume.

mass number
The number of nucleons in the nucleus of an atom. Symbol: A.

mass unit
A unit of mass based upon 1/16 the weight of an oxygen atom taken as 16.00000. Abbreviation: mu, or atomic mass unit, amu.

master flat
A surface plate, usually round rather than square with a high degree of surface flatness.

master line
A line, either horizontal or vertical, between the master point and a second arbitrary reference point.

matched line
A transmission line terminated in its characteristic impedance in order to maximize power flow and minimize the voltage standing wave ratio.

matter
Anything which has weight and occupies space.

Maxwell (series inductance) bridge
An AC bridge that permits measurement of inductors with a low Q, in terms of capacitance. The bridge contains resistors and a variable standard capacitor. The amplitude null is obtained with the variable standard capacitor and the phase null with a variable resistor.

McLeod gage
A primary instrument for the measurement of pressure in a vacuum system. The gage consists of a glass bulb with a vertical capillary tube at the top.

mean free path
The average distance a particle moves between collisions. Abbreviation: mfp, symbol, I.

mean solar day
The average of all apparent solar days in a given year.

measurement
The overall process that a person goes through in reaching a decision as to the magnitude of some quantity.

mechanical axis
The true centerline of the mechanical components within the telescope. for a perfectly calibrated instrument the mechanical axis would be coincident with the optical axis.

meniscus
The curved upper surface of a column of liquid which is concave when the walls of the container are wet and convex when the walls of the container are dry.

mercury
A heavy, silver-colored metal which is liquid at ordinary room temperatures.

meson
A short-lived particle carrying a positive, negative, or zero charge, and having a variable mass in multiples of the mass of the electron. Also called mesotron.

metastable state
An excited state of nucleus which returns to the ground state by the emission of a gamma ray over a measurable half-life.

metallic insulator
A shorted quarter wave section of a microwave transmission line which acts as an electrical insulator at the frequency for which its length is one quarter wavelength.

meter
Unit of length. The length of exactly 1,650,763.73 wavelengths of the radiation in vacuum corresponding to the unperturbed transition between the levels 2p10 and 5d of the atom of Krypton 86, the orange-red line

metrology
The science of measurement.

mev
The abbreviation for million electron volts. See Electron-Volt

micron
A unit of length equal to one-millionth of a meter.

microphonic
A condition in which mechanical movement of a vacuum tube, variable capacitor, or other part in an amplifier system causes corresponding variations in circuit current.

microwave
Electromagnetic waves in the frequency range from 300 MHz up to the infra-red spectrum which starts at 30 GHz.

mil
1) A unit of length equal to one thousandth of an inch, or 0.001 inch.

2) A unit of angular measurement equal to 1/6400 of a complete revolution or circle (202 ½ seconds).

Military Specification Code
A code developed to ensure that devices purchased by the government would meet the military standards regardless of the manufacturer.

Miller effect
The increase in the effective grid-plate capacitance of a vacuum tube due to the charge induced electrostatically on the grid by the plate through the grid-plate capacitance.

Miller integrator
A circuit used to develop a linear sawtooth (ramp) voltage.

minority carrier
In semiconductor devices there always exists a small but measurable reverse current which results from the presence of current carriers which are opposite to the predominate carriers. These may be either holes or excess electrons found in N-type or P-type semiconductors, respectively.

minute
A minute is 1/60th of a degree. This is more correctly described as a "minute of arc."

mixer
That stage in a super heterodyne receiver in which the incoming modulated radio frequency signal is mixed with the signal from the local oscillator to produce the intermediate frequency signal.

MKS system
The meter-kilogram-second system.

mode
1) One of several types of electromagnetic waves that may be sustained in a given resonant system. Each type of vibration is designated as a particular mode and has its own particular electric and magnetic field configuration.

2) One of several methods of exciting a resonant system.

modulation
The process in which the amplitude, frequency, or phase of a carrier wave is varied with time in accordance with an intelligence signal.

modulation index
In frequency modulation, the ratio of the frequency deviation to the modulation frequency. It determines the number of significant sidebands and bandwidth occupied.

molecule
The smallest particle of any substance which can exist free and still exhibit all properties of the substance.

molecular weight
The sum of the atomic weights of all the atoms in a molecule.

moment arm
The length of a torque wrench from the center of pivot to the point where force is applied.

momentum
The product of the mass of a body and its velocity. CGS unit: gm-cm/sec.

monitoring
Periodic or continuous determination of the amount of some quantity. This is often achieved by use of a recorder.

monochromatic light
Light of only one wavelength or color.

monostable multivibrator
Referring to a circuit with one stable state. The circuit requires one trigger to perform a complete cycle. This circuit is also called a one-shot multivibrator or a, flip-flop multivibrator.

moving coil meter
The basic D'Arsonval meter movement consisting of an electromagnetic coil mounted between the poles of a permanent magnet.

multi-vibrator
A form of relaxation oscillator which uses two stages, so coupled that the input of each one is derived from the output of the other. A multivibrator can be free running or synchronized. Its frequency can be determined by the value of its own circuit parameters or an external synchronizing voltage. The output is essentially a square or rectangular wave.

mutual inductance
The common property of two associated electric circuits determining, for a given rate of change of current in one of the circuits, the amount of electromotive force induced in the other. Mutual inductance is measured in henrys.

N

nadir
The point of the celestial sphere that is directly opposite the zenith and vertically downward from the observer.

National Institute of Science and Technology (NIST)
formerly the National Bureau of Standard (NBS). An independent agency of the U.S. Department of Commerce charged with the improvement and maintenance of all kinds of standards. The bureau operates radio stations WWV, WWVH, WWVB, and WWVL which broadcast accurate frequency and time standards.

natural frequency
(1) The natural resonant frequency of an object
(2) The frequency at which an object will vibrate, when struck.

negative feedback
See degenerative feedback

negative lens
A concave lens, thicker at the edges than the center, which diverges or spreads rays of light through refraction.

negative mirror
A convex mirror curved out. Produces reflected diverging light rays away from the focal point.

negative resistance
A resistance that varies with current in such a way that when the current increases the voltage drop across the resistance decreases. This characteristic is possessed by an electric arc and by vacuum tube circuits under certain conditions.

network
A system of interconnected resistors, inductors, or capacitors or any combination thereof.

neon
An inert element which is a gas at room temperature. When ionized by current flow it produces a bright orange-red glow.

neutrino
A particle with zero rest mass and zero charge, emitted to preserve spin, momentum, and energy in decay and other processes.

neutron
An elementary nuclear particle with a mass approximately the same as that of a hydrogen atom and electrically neutral; a constituent of the atomic nucleus. Its mass is 1.00893 mu.

newton
Unit of force. That force which gives to a mass of 1 kilogram an acceleration of 1 meter per second. One newton equals 100,000 dynes.

Newtonian fluid
A fluid whose absolute viscosity is the same for all values of shear stress.

neutralization
The process of canceling the voltage fed back through the interelectrode capacitance of an amplifier tube by providing an equal voltage of opposite phase. Generally this is necessary only with triode tubes.

neutron
A neutral particle found in the nucleus of an atom.

node
Any point, line, or surface in a stationary wave system at which the amplitude of the wave shaping variable is minimum.

noise
The sum of all undesirable signals. These may be generated within the circuit in question and/or induced from external circuits. Noise can be caused by atmospheric conditions as well. Noise is characterized by randomness of amplitude and frequency distribution.

noise suppression
A circuit used in a receiver or amplifier to reduce noise.

nominal value
This is normally the value indicated by the manufacturer.

nomograph
A chart or diagram with which equations can be solved graphically by placing a straightedge on the two known values and reading the answer where the straightedge crosses the scale of the unknown values.

non-axial loading
The condition existing when a force, or a component of a force, is not aligned with the major axis (primary loading axis) of the force measuring device to which it is applied.

noncorrosive flux
Flux that is free from acid and other substances which might cause corrosion in soldering.

non-linear device
A device having a response that is not directly or inversely proportional to a given variable.

non-resonant line
A transmission line on which there are no standing waves at the operating frequency. Also called a "flat line."

non-sinusoidal wave
Any waveform that differs from that of a sine wave.

nor-gate
A gate whose output is energized only when no signals are present-at the inputs. A combination of a Nor and an Or gate.

normal
Perpendicular to a tangent at a point of tangency.

normalized impedance
In microwave, the complex impedance of the transmission line in use is normalized to the Zo of the line for. use with the Smith chart, that is, the number in use has been modified to conform to a reference value.

not-circuit
A circuit used to invert a binary signal.

N-type semiconductor
An extrinsic semiconductor in which the conduction electron density exceeds the hole density.

nuclear fission
A special type of nuclear transformation characterized by the splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy.

nuclear fusion
The act of coalescing two or more nuclei.

nucleon
The common name for the constituent parts of the nucleus. At present applied to protons and neutrons but will include any other particle that is found to exist in the nucleus.

nucleus
The heavy central part of an atom in which most of the mass and the total positive electric charge are concentrated. The charge of the nucleus, an integral multiple Z of the charge of the proton, is the essential factor which distinguishes one element from another. Z is the atomic number.

nuclide
A general term referring to all nuclear species--both stable (about 270) and unstable (about 500)-- of the chemical elements, as distinguished from the two or more nuclear species of a single chemical element which are called isotopes.

null method
Any method of measurement in which the reading is taken at zero. Galvanometers, sensitive voltmeters, oscilloscopes, and earphones are used as null detectors.

O

objective lens
The objective lens of a telescope optical system causes a real image to be formed which, when adjusted to lie within the focal plane of the eyepiece lens can be magnified as a virtual image.

oersted
The unit of magnetic intensity (magnetizing force) in the cgs electromagnetic system. The value of the magnetic intensity in oersteds, at any point in a vacuum, is equal to the force in dynes exerted on a unit magnetic pole placed at the point.

ohm
Unit of electrical resistance. The electric resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between these two points, produces in this conductor a current of 1 ampere, this conductor not being the source of any electromotive force.

ohmmeter
An instrument for measuring resistance.

Ohm's Law
A fundamental electrical law which expresses the relationship between voltage, current, and resistance in a DC circuit, or the relationship between voltage, current, and impedance in an AC circuit.

opaque
Neither reflecting nor emitting light.

open circuit voltage
The voltage at the terminals of a battery or other voltage source when no load is connected.

operating conditions
Those conditions, such as ambient temperature, pressure-, vibration, humidity, etc., to which a device is subjected, but does not include the variable measured by the device.

operating point
That point on a grid voltage-plate current characteristic curve of a vacuum tube which corresponds to the direct voltage values being used for the grid and plate. Also called quiescent point.

operational amplifier
An amplifier having DC stability and immunity to oscillation, generally achieved by using a large amount of negative feedback. Used- to perform analogue-computer functions such as summing and integrating.

optical axis
Centers of curvature of a lens define a line called the axis of the lens. When several lenses combine to form an optical system, the line defined by these axes is called the optical axis.

optical flat
A piece of glass or quartz which is accurately flat to within one-tenth of a wave length on one or both surfaces, used as a reference (proof plane) for comparison of flatness.

optical infinity
A section of a wave front which has advanced a great distance from its source and assumed essentially a zero curvature. In optics approximately 2000 yards.

optical pyrometer
An instrument designed to estimate the temperature of glowing surfaces.

optical surveying
Used to take measurements over a vast scale; referenced to north.

optical tooling
The geometric method of optically establishing a precise line and/or reference plane.

optics
The branch of physics which deals with the phenomena of light.

optimum
The most favorable degree or condition.

optimum coupling
See critical coupling

ordinate
The vertical or y-axis on a chart or graph.

oscillator
Any nonrotating device for generating and maintaining oscillations of a frequency determined by the physical constants of the system.

oscilloscope
An instrument that shows the instantaneous voltage waveform of a signal. It can be used to measure voltage, period, and frequency of a signal. Phase relationship and percentage of AM modulation can also be measured with an oscilloscope.

out of phase
Having waveforms that are of the same frequency but not passing through corresponding values at the same instants.

out-of-round
The high and low spots in a true circle. It is also the ovality or lobing effect which causes a change of true roundness of cylindrical objects.

output impedance
The impedance as measured between the output terminals of a circuit. for maximum power transfer, the load impedance should match or be equal to this output impedance.

overload
A load that is greater than the device is designed to handle.

overshoot
The initial transient response to an unidirectional change in input which exceeds the steady state response.

oxide
An element combined with oxygen. Rust is an oxide of iron.

P

packing fraction
The difference between the atomic weight in mass units and the mass number of an element divided by the mass number and multiplied by 10,000. It indicates nuclear stability. The smaller the packing fraction, the more stable the element.

padder
Any small capacitor inserted in series with a main capacitor to adjust its capacity to some predetermined value.

pair production
The description of an electron leaving the valence band to enter the conduction band due to absorption of energy (usually heat). This provides a free electron carrier and a free hole carrier at the same time.

parallax
The apparent displacement of the position of an object caused by a shift in the point of observation. Thus, the pointer of a meter will appear to be at different positions on the scale depending on the angle from which the meter is read. To eliminate errors in meter reading due to parallax, the line of sight should be perpendicular to the pointer.

parallel (optical)
A piece of glass with one side parallel to the other side. An optical parallel gives linear displacement.

parallel circuit
A circuit in which two or more components are connected across the same pair of lines or terminals so that the current is divided between the components.

parallel resonant circuit
A circuit consisting of inductance and capacitance connected in parallel. This is also known as a "tank" circuit. It offers high line impedance to .the resonant frequency. It is often used to determine the frequency in an oscillator circuit.

paramagnetic
A term used to describe materials with magnetic permeability greater than that of a vacuum, such as iron, cobalt, and nickel.

parameter
1) In mathematics, one of the constants entering into a functional equation and corresponding to some characteristic property, or dimension.

2) In an electronic circuit, a characteristic element or constant factor, such as: resistance, capacitance, or inductance values.

paraphrase inverter
A phase inverter consisting of one or two amplifiers which provides two output signals of opposite polarity from a single source.

parasitic oscillations
Undesired, self-sustaining oscillations at a frequency different from the operating frequency, occurring chiefly in vacuum tube circuits.

Pascal's Law
The pressure applied on a confined fluid is transmitted undiminished in every direction.

peaking coil
A coil placed in an amplifier circuit to obtain better high frequency response.

peak inverse plate voltage (rating)
The maximum instantaneous plate voltage the tube can withstand in the direction opposite to the direction in which the tube is designed to pass current.

peak-to-peak amplitude
The amplitude of an alternating quantity measured from positive to negative peak. This is the value indicated on an oscilloscope.

peak-to-peak value
The algebraic difference between extreme values (as DA or double amplitude is twice the single amplitude).

peak voltage
A maximum voltage which can be applied to electrolytic capacitors for a period not to exceed 30 seconds. Also called "surge" voltage. Also, the maximum instantaneous value of an alternating quantity.

Peltier effect
When two unlike conductors are joined and kept at a constant temperature while a current passes through the junction, heat is generated or absorbed at the junction. This is in addition to the I^2R loss. The Peltier effect is the inverse of the Seebeck effect.

pentaprism
A five-sided prism which deviates rays of light by 90° without reversing or inverting the image.

pentavalent impurity
Any impure atom that has five electrons in its valence band.

pentode
A five-electrode vacuum tube containing an anode, a cathode, a control grid and two additional electrodes ordinarily in the form of grids.

period
The time corresponding to one cycle of a periodic phenomenon. The period of a galvanometer is the elapsed time between consecutive passages of the pointer in the same direction through its zero point.

permanent magnet
A magnet which retains its magnetism without the action of external electric or magnetic fields.

perpendicular
Being at right angles to a given line or plane.

persistence
A measure of the length of time that phosphorescent light is emitted from the screen of a CRT.

phantastron
A stable circuit whose operation is similar to that of a monostable multivibrator. It can only be triggered when in the quiescent condition. The circuit values determine the time required to return to quiescence. The phantastron is often used as a frequency divider.

phase distortion
An undesired alteration of a signal waveform caused by different phase shifts for various harmonics within a complex waveform.

phase inverter
A stage in an amplifier or other circuit whose chief function is to change the phase of a signal by 180°.

phase shift oscillator
An oscillator produced by connecting, between the output and the input of an amplifier, a network producing a 180° phase shift for the desired frequency of operation.

phase splitter
A circuit that produces two output signals of equal magnitude and opposite polarity from one amplifier using a single signal input.

phase velocity
(1) The velocity with which a point of a certain phase in an electromagnetic wave travels in the direction of propagation.

(2) An illusion that wave peaks travel through a waveguide faster than the speed of light. It appears because the elementary waves travel at an angle to the walls of the guide. The true speed is group velocity.

photoelectric effect
The electrical effect of light or other radiation. This effect can be emission of electrodes, penetration of voltage, or a change in electrical resistance upon exposure to light.

photometry
The measurement of luminous intensity from a light source by comparison to a known standard.

photon
Small particles of light energy according to the quantum theory of light.

photon generator
A light source.

physics
The physical science which deals with matter and energy and with the transformations of energy.

physi-optics
Physi-optical practices combine the use of specific physical measuring standards with optical instruments and physical indicating apparatus.

pickup
See transducer

Pierce oscillator
An oscillator in which a piezoelectric crystal unit is connected between the grid and the plate of an electronic tube, in what is essentially a Colpitts oscillator. The capacitive voltage division is provided by the grid-cathode and plate-cathode capacitances of the circuit.

piezoelectric effect
Generation of a voltage between opposite faces of certain crystals (such as quartz) as a result of strain due to pressure or twisting and the reverse effect in which application of a voltage to opposite faces of the crystal causes deformation to occur at the frequency of the applied voltage.

pigtail
A flexible metallic connection usually consisting of braided wire used between a stationary terminal and a terminal having a limited range of motion.

Planck's constant
A natural constant of proportionality h relating the frequency of a quantum of energy to the total energy of the quantum;

$$h = \frac{E}{v} = 6.6 \times 10^{-27} \text{erg} - \text{sec}$$

plate resistance
The ratio of a small change in plate voltage to the corresponding small change in plate current.

plate saturation
See current saturation

plate voltage
The DC voltage that exists between the plate and cathode of a vacuum tube.

plug-in
Having terminals such that connections are made automatically by plugging the device into a socket or series of jacks.

plumbing
Common slang term for microwave coaxial or waveguide circuits.

plunge
To rotate the telescope of a theodolite 180° about the horizontal axis of the instrument.

pointer
The needle-shaped rod that moves over the scale of a meter or dial.

polar coordinates
A system of coordinates in which a point is located by its distance from a fixed point and the angle that the line from this fixed point to the given point makes with a fixed reference line called the polar axis.

polarized light
Light in which vibrations occur in a single plane perpendicular to the ray.

polyethylene
A tough, flexible, plastic compound that has excellent insulating properties, even at the ultra-high frequencies. It is widely used as the insulating material in coaxial cable.

polystyrene
A clear thermoplastic material having very desirable dielectric properties. Many standard capacitors use polystyrene as dielectric.

porosity
Small openings or spaces between particles of matter.

porro prism
A prism which causes an image to be rotated 180° or reflected. The image is reversed in the plane in which the reflection takes place.

positive feedback
See regenerative feedback

positive lens
A convex lens, thicker at the center than at the edges, which converges rays of light through refraction.

positive mirror
A concave mirror that is curved toward the middle, which converges rays of light through refraction.

positron
A nuclear particle equal in mass to the electron and having an equal but opposite charge. Its mass is 0.000548 mu.

potential
The amount of voltage or charge between a point and a zero-reference point. Bodies with an excess of electrons have a negative potential. Bodies with a deficiency of electrons have a positive potential. The electric potential at any point in an electric field is equal to the work done on a unit charge to bring the charge to that point from a place where the potential is zero.

potential difference
The difference in potential between any two points in a circuit; the work required to carry a unit positive charge from one point to another.

potential energy
Energy due to position.

potentiometer (pot)
A variable resistance unit having a rotating contact arm that can be set at any desired point along a resistance element. The voltage source is connected to the end terminals of the resistance element, and the output circuit is connected between one end terminal and the moveable contact to give a voltage dividing action.

potentiometric measurement
DC voltage can be most accurately measured using the potentiometric method. It consists of comparing the unknown voltage with a known voltage from a calibrated potentiometer.

power
The time rate of doing work, or the rate of expending, transferring, or transforming energy. It is measured in watts.

power amplifier
An amplifier designed to produce a gain in signal power, as distinguished from a voltage amplifier.

power factor
The ratio of the actual power of an alternating or pulsating current, as measured by a wattmeter, to the apparent power, as indicated by ammeter and voltmeter readings; it is equal to the cosine of the phase angle between a sinusoidal voltage and the resulting sinusoidal current.

power supply
An electronic circuit that produces the multiple output voltage currents required to operate other electronic circuits from a single power source.

precision
The term precision can best be defined as repeatability. If a measurement is made a number of times and nearly the same value is read each time, it is a precise measurement, the readings may be all incorrect (I.E. Reading on the wrong scale). Care should be taken not to confuse precision with accuracy.

pressure
(1) force per unit area (closed system).
(2) Height times density (open system). primary colors
Colors in terms of which all colors may be described or from which all colors may be evolved by mixtures.

primary electron
The electron ejected from an atom by an initial ionizing event, as caused by an photon or beta particle.

primary standard
A unit established by some authority or developed through practical exact application of a formula. Secondary standards are calibrated against the primary standard.

primary winding
The transformer winding which is connected to the source of power.

principle axis
Line through the centers of curvature of a refracting lens.

principal focus
A point to which rays parallel to the principal axis converge, or from which they diverge after reflection.

principal quantum number
The number, n = 1, 2, 3, …which describes the basic state of atomic system in quantum theory.

printed circuit technique
A method by which circuit connections and many of the components are printed or painted on a plane surface with conductive or resistive media. These techniques permit the construction of extremely compact circuits.

prism
A transparent body bounded in part by two plane faces that are not parallel, used to deviate or disperse a beam of light.

probability
The likelihood of the occurrence of any particular form of an event, figured as the ratio of the number of ways in which that form might occur to the whole number of ways in which the event might occur in any form.

probe
A probe is a link between the measuring instrument and the circuit under test. It is considered as part of the measuring equipment. Probes are used for isolation, to extend the voltage range of the measuring equipment or to rectify an AC input.

program
for computers, a set of instructions arranged in proper sequence to instruct a computer to perform a desired operation or operations.

propagation
In communications or electronics, the travel of electromagnetic waves or sound waves through a medium, or the travel of a sudden electrical disturbance or sharp change in value along a line or scale.

proving ring
An elastic ring in which the deflection of the ring, when loaded along a diameter, is measured by means of a micrometer screw and a vibrating reed. Note that all ring-type elastic force measuring devices are not proving rings, and such devices which do not make use of a micrometer screw and vibrating reed should not be called proving rings.

proving ring deflection
The difference between the reading for a given load and the reading for no load.
proton
A positively charged particle occupying the nucleus of an atom that has a charge equal to that of an electron.

psychrometer
An instrument for measuring relative humidity.

pulse
A non-sinusoidal waveform resulting from a sudden change in voltage or current levels for a specified period of time.

pulse amplitude modulation (PAM)
The form of modulation in which the amplitude of a pulse carrier is varied in accordance with the amplitude and frequency of the modulating signal.

pulse recurrence frequency (PRF)
The rate, usually given in pulses per second, which pulses occur.

pulse repetition time (PRT)
Time from the beginning of one pulse to the start of the next. Equal to 1/PRF.

pulse width
The elapsed time between the 50 percent point in the rise of a pulse to the 50 percent point in the trailing edge of the pulse.

punch through
It is unique to transistors and results when the reverse bias supply completely ionizes the base region.

push-pull amplifier
An amplifier circuit containing two tubes arranged with the control grids connected to opposite ends of the input transformer secondary winding or to other out-of -phase feed points and with the plates connected to opposite ends of the output transformer primary winding. Grid voltage is then a maximum on one tube when it is minimum on the other tube, so that the sum of the plate currents is constant. Signal components add in the output to give twice the output of a single tube. This arrangement also tends to cancel even harmonics that would otherwise cause distortion.

pyrometer
A device for measuring high temperatures, generally above 600 degrees Celsius; also known as an optical pyrometer.

Q

quadrant
One of the four sections in which a plane is divided by two perpendicular lines.

quadrature
Two alternating quantities are in quadrature when the phase angle between them is 90° .

quality (Q)
A quality factor rating applied to a coil, capacitor, or resonant circuit. The ratio of the energy stored in a circuit to the energy dissipated.

quantum
One of the very small parts into which many forms of energy are subdivided.

quantum level
An energy level of an electron or of any atomic system, distinct from any other of its energy levels by discrete quantities dependent upon Planck's constant.

quantum mechanics
The science of description of atomic systems in terms of discrete quantum states.

quantum number
One of a set of integral or half-integral numbers, one for each degree of freedom, which determines the state of an atomic system in terms of the constants of nature.

quantum state
A term defining the way in which an atomic system exists at any specific time. This state is often described by means of a complex mathematical function called quanta.

quantum theory
The transfer of light and matter occurs only in discrete quantities proportional to the frequency of the energy transferred.

quartz crystal
A thin square or rectangular slice of quartz which, when precision-ground and smoothed, will vibrate at a frequency determined by its thickness and its original position in the natural quartz.

quiescence
A term used to describe the state of a circuit that exists before a-trigger is applied. A stable operating condition.

R

radar
Radio detection and ranging. Widely used in military and civilian applications.

radian
The angle for which the arc length is equal to the radius. There are 2π radians in 1 revolution (360°). A radian represents an angle of approximately 57.3°.

radiant energy
Energy in the form of electromagnetic radiation such as radio waves, heat waves, light waves, ultraviolet rays or X-rays.

radiation
A method of transmission of energy. Specifically:
1) Any electromagnetic wave (quantum).

2) Any moving electron or nuclear particle, charged or uncharged, emitted by a radioactive substance.

radioactivity
The process whereby certain nuclides undergo spontaneous atomic disintegration in which energy is liberated, generally resulting in the formation of new nuclides. The process is accompanied by the emission of one or more types of radiation, such as alpha particles, beta particles, and gamma radiation.

radio
General term denoting radio wave transmission and reception.

radioactivity
The spontaneous, uncontrollable disintegration of the nucleus of an atom with the emission of particles and rays.

radio-frequency resistance
See AC resistance

radius
The shortest distance from the center of a circle or arc, to a point on the circumference.

ramp voltage
A popular name for a positive linear saw tooth waveform. It is composed of a sine wave fundamental and an infinite number of odd and even harmonics. The even harmonics starting out of phase and the odd frequencies starting in phase.

random error
Random errors are sometimes called "accidental" errors because they are as likely to occur in one direction as the other. They are the error left when all gross errors and systematic errors have been corrected.

range
1) Extent of coverage of effectiveness.

2) Measure of distance.

Rankine temperature scale
A temperature scale which corresponds to the Kelvin scale but is based on the absolute zero of the Fahrenheit system, so that 0° Fahrenheit = 459.69 Rankine.

ratio bridge
A bridge circuit that uses a calibrated resistive or calibrated inductive voltage divider for one side of the bridge. Precision resistors, inductors, and capacitors are measured with ratio bridge circuits.

ratio transformer
A precisely wound auto transformer used as an AC voltage divider.

ray of light
Can be considered as the path traced by a point on an advancing wave front.

RC constant
The time constant of a resistor-capacitor, equal in Seconds, to the value of the resistance multiplied by the value of the capacitance.

RC coupling
Resistor-capacitor coupling between two circuits. It has a long time constant and produces negligible wave shaping of a non-sinusoidal waveform.

reaction
Any process involving a chemical or nuclear change.

real image
A real image is one through which light rays actually pass and can be projected onto a screen.

reactance
The opposition in ohms offered to the flow of an alternating current by inductance or capacitance in a circuit. It is the component of the impedance of a circuit which is not due to resistance.

reactive kick
Surge currents produced in a galvanometer circuit when power is interrupted. These are due to the discharge of the circuit's capacitance and inductance. Reactive kick causes violent deflection of the galvanometer.

recorder
An instrument that makes a graphic record in which the value of a quantity (voltage, current, power, temperature) varies with time.

rectangular wave
periodic wave which alternately assumes one of two fixed values, the time of transition being negligible in comparison with the duration of each fixed value.

rectification
The process of converting AC into a unidirectional current by removing or inverting that part of the wave lying on one side of the zero-amplitude axis.

rectifier
The component that accomplishes the process of rectification of AC.

reference level
The level used as a starting point when designating the value of an alternating quantity or a change in the quantity by means of decibel units. A common reference value in voltage, current, and power designations is 0.001 watt for 0 db. for sound loudness, the reference level is usually the threshold of hearing.

reference line
A line from which all other measurements are taken.

reference plane
A reference line that has been rotated through 360 degrees.

reflected Impedance
The impedance value that appears to exist across the input of a transformer or any four- terminal passive network as a result of the characteristics of the impedance connected across the output.

reflected wave
The sky radio wave reflected back to Earth from an ionosphere layer.

reflection
The change in direction of waves after striking a surface.

reflection coefficient (F)
The magnitude and phase angle of the reflected wave on a transmission line.

reflex klystron
A velocity-modulated klystron serving as a feedback oscillator.

refraction
The bending of a ray of light, heat, sound, or a radio wave passing obliquely from one medium into another in which the velocity of propagation is different from the first medium.

regenerative feedback
A method of securing increased output from an amplifier, by feeding part of the output back in such a way as to reinforce the input signal. It is also called positive feedback.

regulated power supply
A power supply containing a regulator device for maintaining constant voltage or constant current under changing load conditions.

relative humidity
The ratio of the amount of water vapor in the air at a given temperature to the maximum water vapor (capacity of the air) at the same temperature.

relaxation oscillator
A device which generates a non-sinusoidal wave by the charge and discharge of a capacitor through a resistor.

relay
The most common type of relay is an electromechanical device by means of which a current change in one circuit produces an armature movement that opens or closes contacts to produce a change in the electrical condition of another circuit.

reluctance
The property of a magnetic circuit that determines the amount of magnetic flux that will be produced as a result of the application of a given magnetomotive force.

remote cutoff tube
A tetrode or pentode tube in which the spacing of the control grid wires is wider at the center than at the ends. It is also called a "variable mu" tube. It will give higher amplification of small signals and less amplification of larger signals.

repeatability
See precision

repulsion
A force tending to separate objects or particles having like electrical charges or magnetic polarities.

reset
To place a binary circuit in the initial state.

residual loss
1) The minimum or initial loss of a variable attenuator or isolator

2) The loss or attenuation of a component which is ideally lossless.

resilience
The resilience of a body measures the extent to which energy may be stored in it by elastic deformation.

resolution
1) The term resolution pertains to the scale of an instrument. It is the smallest readout at calibrated points. Resolution is sometimes referred to as "least count."

2) When uncalibrated adjustments are made, resolution is the smallest change which can be obtained by manipulation of the instrument controls. Resolution can be increased by use of vernier scales.

resolver
A type of transformer used for solving a vector for two mutually perpendicular components or resolving a vector into two mutually perpendicular components.

resonance
The frequency whereby any system responds with maximum amplitude to an applied force having a frequency equal or nearly equal to its own.

resonant cavity
A form of resonant circuit in which the current is distributed on the inner surface of an enclosed chamber. By making the chamber of the proper dimensions, the circuit can be made to have a high Q at microwave frequencies. The resonant frequency of a cavity can be changed by the adjustment of screws that protrude into the cavity or by changing the shape of the cavity. The cross-section of the cavity may be circular, rectangular, or any other shape.

resonant frequency
1) Frequency, of a crystal unit, for a particular mode of vibration to which, discounting dissipation, the effective impedance of the unit is zero.

2) That frequency, for a given resonant circuit, at which the inductive reactance is equal to the capacitive reactance.

resonant line
One having standing waves.

resultant
An entity or quantity obtained by means of, or as a result of, a given process.

restoring force
The constant mechanical force provided.

rest point
The equilibrium point or the point at which the pointer of the balance would come to rest once it has been set into oscillation.

retentivity
The ability of a material to retain its magnetism.

reticule
Cross lines found in the telescope of sight levels, transits, and theodolites. Initially in the form of a fine hair. They are now produced by engraving glass with a diamond point to achieve a line of 2.5 to 3 seconds thickness. Also known as; cross hair, filar, (for two parallel lines called); bifilar

retrace
The path traced by the electron beam in a CRT in going from the end of one line to the start of the next line or trace.

reverse
In optics, to rotate a Theodolite 180° about the vertical axis.

reverse current
The small flow of electricity between the junction of a diode receiving reverse bias; usually measured as only a few microamperes in contrast to a forward current measured in milliamperes.

rheostat
A variable resistor having one fixed and one movable terminal. rho - The magnitude of the reflection coefficient.

rho
The magnitude of the reflection coefficient.

rhomboid prism
A prism which displaces the axis of a beam without introducing and without reverting the image.

right angle prism
A simple prism used when deviations of 90° are required. Reversion of the image takes place.

ringing
Damped oscillations occurring as the transient response of a resonant circuit to a shock excitation. Usually occurs as an unwanted effect in poorly designed circuits.

ripple
The AC components present in the output of a DC generator, rectifier system, or power supply.

rise time (legacy term - see transition duration)
The time needed for the leading edge of a pulse to rise from the 10 percent reference point to the 90 percent reference point.

roentgen
The quantity of X or radiation which produces 1 esu of positive or negative electricity/cm^3 of air at standard temperature and pressure or 2.083 x 10^9 ion pairs/cm of dry air.

rosin-core solder
Solder made up in tubular form with the inner space containing rosin flux for effective soldering.

rotary motion
Motion in which every particle of a body moves in a circle and all circles have their centers on same straight line.

rotating joint
A device for permitting one section of a transmission line to rotate continuously with respect to another and still maintain a matched impedance.

rotor
1) A rotating member such as the armature of a motor, generator, or synchro.

2) The rotating plates of a variable capacitor.

S

saturable reactor
A device consisting of a DC winding and an AC winding on the same core. The DC winding is used to vary the core saturation and thus controls the impedance to current in the AC winding.

saturation
The point in operation where an increase in a given quantity will have a negligible effect on the output or end result.

saturation current
The collector current flowing with a zero-emitter current. Sometimes called leakage current or collector cutoff current. Abbreviated Ico or Icbo.

scale
1) Something graduated when used as a measure or rule. A series of spaces marked by lines to indicate the magnitude of some quantity.

2) A weighing device.

schematic diagram
A diagram which shows all of the electronic parts by means of symbols.

scintillation counter
A device used for the detection of radioactivity.

Schering bridge
An AC bridge comprised of resistors and capacitors used to measure the capacitance and dissipation factor of a capacitor. Variable capacitors are used to obtain the amplitude and phase nulls.

Schmitt trigger circuit
A variation of a bistable multivibrator. It always produces a rectangular or square wave output of constant amplitude, regardless of the input waveform. It is widely used as a wave-shaping circuit.

screen
A metal partition or shield used to isolate an instrument or device from external magnetic or electric fields.

screen grid
A grid of a vacuum tube placed between the control grid and the plate, and usually maintained at a fixed positive potential for the purpose of reducing the electrostatic influence of the plate in the space between the screen grid and the cathode.

second
1) A unit of time equal to one sixtieth of a minute, or the time needed for a cesium-133 atom to perform 9,192,631,770 complete oscillations.

2) Mathematics. A unit of angular measure equal to one sixtieth of a minute.

second (ephemeris second)
Unit of time. Exactly 1/31,556,925.9747 of the tropical year of 1900, January, 0 days and 12 hours ephemeris time.

secondary emission
Electron emission that is the direct result of the impact of electrons against a surface.

Seebeck effect
The EMF produced in a circuit containing two contacting conductors of different metals having two junctions at different temperatures.

selectivity
The degree to which a receiver is capable of discriminating between signals of different carrier frequencies

self-bias
Production of grid bias voltage, by a vacuum tube itself, by the flow of plate and other electrode currents through a resistor in the cathode lead. The resulting voltage drop across this resistor serves as the grid bias.

semiconductor
A class of solids whose electrical conductivity is between that of a conductor and that of an insulator.

sensitivity
1) The degree of response of a circuit to signals of the frequency to which it is tuned.

2) An indication of the gain of a receiver.

3) A measure of the minimum signal to which a device shows a measurable response.

4) The ratio of a small change in instrument reading to the change in the measured quantity required to produce it.

5) Ratio between electrical output to mechanical output.

series circuit
An electrical circuit in which the component parts are connected end to end to form a single continuous path for the current.

series motor
A commutator-type motor having armature and field windings in series. Characteristics are high starting torque, variation of speed with load, and dangerously high speed on no- load.

series resonant circuit
An inductor and capacitor in series, having electrical values such that the inductive reactance of the inductor is equal to the capacitive reactance of the capacitor at the frequency being handled. At resonance, the circuit current is a maximum and the voltage across either the inductor or the capacitor may be several times the voltage applied to the combination.

servo system
An electromechanical system which is used for positioning one element of a system in relation to another, for example, a PPI sweep in relation to the antenna. The change in position of one element of the system results in the reproduction of an error voltage that is used indirectly to cause a motor to drive the other element of the system to the point where the error voltage no longer exists.

shaded poles
A moving coil meter movement that has its permanent magnet poles offset to produce a logarithmic response.

sharp cutoff
Term applied to a tube or grid of a tube in which the control grid spirals are uniformly spaced. The result is that as grid voltage is made negative, plate current decreases steadily to cutoff.

shear
An action or stress from applied forces that causes two contacting parts of a body, to slide relative to each other, in a direction parallel to their place of contact.

shell
One of a series of concentric spheres, called signals, which are designated in the order of increasing distance from the nucleus of an atom, as K, L, M, N, O, P, and Q shells. The number of electrons contained in each shell is limited.

shielded wire
Insulated wire covered with a metal shield, usually of tinned braided copper wire.

shielding
A construction feature of electrical instruments which refers to the grounding of the metal case and top plate, thus serving as an electrostatic shield and diverts external charges that might otherwise pass through the measuring circuit.

short circuit
A low resistance connection between two points of different potential in a circuit.

short' waves
A general term usually applied to a wavelength shorter than the lower limit of the standard U.S. broadcasting band (200 meters).

shunt
1) A precision low-value resistor placed across the terminals of an ammeter to increase the range by allowing a definite part of the circuit current to go around the meter.

2) Any part connected, or the act of connecting any part of a circuit in parallel with some other part.

shunt box
A precision low resistance voltage divider used to enable measurements of high currents.

sidebands
The new frequencies above and below the carrier frequency produced as a result of the frequency modulation of the carrier. The sum frequencies form the upper sideband, the difference frequencies form the lower sidebands.

signal-to-noise-ratio
Ratio of signal amplitude to the amplitude of the noise. This is an important consideration when the input signal is of very low amplitude.

signal tracing
This consists of checking the input and output stages of an amplifier for the desired signal to localize a malfunction.

silicon controller rectifier (SCR)
A three-junction semiconductor device which is capable of handling large values of current and voltage. It is similar to the gas-filled thyratron tube, yet it has a variety of applications for which a thyratron tube is not generally used.

sine wave
A wave in which the amplitude varies as the sine of an angle or time function.

sinusoidal vibration
A simplified back and forth motion of a constrained object which varies sinusoidally with time.

single phase
Pertaining to a circuit or device that is energized by a single alternating voltage.

skin effect
The tendency of high frequency alternating currents to concentrate near the surface of a conductor, thus increasing the effective resistance of the conductor. The skin effect increases with frequency.

Smith chart
A diagram used to find the impedances, wavelength, and standing wave ratio of a transmission line.

Snell's Law
(Index of refraction) x (sine of incident angle) = (index of refraction) x (sine of refracted angle).

soft tube
A vacuum tube that has been fully evacuated then injected with enough gas to change its operating characteristics appreciably. Examples are: neon, thyratron, VR tubes. However, a vacuum tube in which a gas has developed is sometimes called a "soft tube" or a "gassy tube."

solder
An alloy of lead and tin which melts at a fairly low temperature (about 500°F) and is used for making permanent electrical connections in electrical circuits.

solder gun
A soldering iron having an appearance similar to that of a pistol. Usually has a fast- heating resistance element at the tip.

solder bridge
Glob of excess solder that shorts two conductors. A common problem on production PC boards.

soldering iron
A device used to apply heat to a joint which is to be made permanent by soldering.

solenoid
An electromagnet having an energizing coil which is approximately cylindrical in form, acting on an armature positioned in the center of the coil.

solid
The state of matter which has a definite shape and definite volume.

solid state physics
That branch of physics which deals with the structure and properties of solids. In electronics, solid state refers to those devices which can control current without the use of moving parts, heated filaments or vacuum gaps.

sonar
Sound navigation and ranging. Electronic equipment used for underwater detection of objects and determination of their range.

sound
A vibration of a body which can be heard by human ears. The extreme limits of human hearing is 20 Hz to 20 kHz. Sound can travel through any medium which possesses the ability to vibrate; the vibrations are called sound waves.

space charge
The negative charge produced by the cloud of electrons existing in the space between the cathode and plate of a thermionic vacuum tube; formed by electrons emitted from the cathode in excess of those immediately attracted to the plate.

special calibration
When a TI is calibrated to full specification IAW 33K series technical order, but additional parameters are calibrated (not specified in the 33K series TO.). These parameters are certified using additional technical data found in maintenance TOs, commercial data manuals, or other applicable technical information.

specific gravity
The ratio of the density of a substance to the density of a standard (distilled water).

specific heat
The ratio of the heat capacity of a body to its mass or weight.

spectral lines
Sidebands of a modulated RF signal as displayed on spectrum analyzer CRT.

spectroscope
Any of various instruments for forming and examining the optical spectra.

spectrum
1) The entire range of wavelengths within which electromagnetic radiations occur.

2) A segment of wavelengths which has a special function or possesses special properties.

spectrum analysis
The study of energy distribution across the frequency spectrum for a given electrical signal.

spectrum analyzer
A test instrument which provides a visual or panoramic display of the radio frequency electrical signal on a CRT, in the form of a graphical plot of amplitude (Y axis) and frequency (X axis).

spectrum width
The widest range of frequencies that can be observed or a spectrum analyzer CRT in a single sweep.

spherical aberration
The failure of parallel rays to meet at a single point after reflection, causing a blurred image.

spin
The inherent, intrinsic angular momentum of an atomic particle; a quantum number in modern atomic theory.

spindle axis
An axis found on theodolites and transits that goes directly through the center of the instrument.

square law detection
The term applied to the response of a detector whose response is a function of the square of the input voltage. Square law detection is used for microwave power measurements.

square law scale
A scale in which the deflection is proportional to the square of the applied voltage or current. The iron vane type meter movement has a square law response. Therefore they. must use a square law scale.

square wave
The waveform of a quantity that shifts abruptly from one to the other of two definite values producing a square waveform. The square wave is considered to consist of a sine wave fundamental frequency and an infinite number of odd harmonics, all starting in phase. RMS, average, and peak values of this waveform are the same.

standard
Anything taken as a basis of comparison. An authorized weight or measure having recognized excellence. It is desirable that the standard have an uncertainty that is one- tenth or less than the equipment being calibrated. A standard is a physical embodiment of a unit. In general it is not independent of physical condition, and it is a true embodiment of the unit only under specified conditions. For example: a yard standard has a length of one yard when at some definite temperature and supported in a certain manner.

standard cell
A very accurate battery used as a voltage standard. There are two types used, the saturated (normal) and the unsaturated cell. The saturated cell is used as the voltage standard.

standard deflection
A standard deflection of a galvanometer is defined as a deflection of the center of the light beam 1 millimeter in the scale when the scale is the optical equivalent of 1 meter from the reflecting mirror.

standard deviation
The square root of the sum of the squares of the deviations from the arithmetic mean of a frequency distribution. The deviations from the arithmetic mean are squared and added, and the square root of this sum is the standard deviation.

standard pressure
The pressure exerted by a column of mercury exactly 760 mm high.

standard temperature
The temperature of melting ice.

standing wave ratio (SWR)
The ratio of voltage (or current) at a loop (maximum) on a transmission line to the value at a node (minimum). It is equal to the ratio of the characteristic impedance to the impedance of the load connected to the output end of the line.

static error
The maximum difference between the true quantity and the indicated quantity when the applied (true) quantity is not changing.

stator
A portion of a machine which contains the stationary parts of the magnetic circuit, with their associated windings.

steradian
One-fourth of the solid angle around a point.

Stoke's Law
the basis of kinematic viscosity which states that the terminal velocity of a sphere (or any object) falling freely through a fluid is controlled by the density of the sphere and the absolute viscosity of the fluid.

storage circuit
Any circuit in which information can be stored. Often called a memory circuit.

storage time (Ts)
The time required to drain off the injected minority carriers in the base caused by saturating the collector.

strain
Deformation of a material body under the action of applied forces (stress).

straightness
This is the uniformity of direction throughout the extent of that feature, such as the freedom from bend, warp, or twist of a shaft.

stray capacitance
A capacitance that exists between circuit elements, between adjacent conductors, and between those elements and conductors and the equipment chassis.

stray inductance
The inductance that exists between circuit elements, between adjacent conductors, and between those elements and conductors and the chassis.

stress
Mutual force between contacting surfaces of bodies caused by an external force, such as tension or shear.

stress testing
Introducing mechanical, electrical, or thermal stress on electrical devices so as to modify their operation and allow intermittent problems to be observed.

stroboscope
An instrument used to determine the speed of a rotating body. It creates the optical illusion of slowing down or stopping the motion of an object by illuminating it with flashes of intense light at regular intervals.

sublimation
The change of state from a solid to a vapor or gas without going through the liquid state.

substitution loss
The ratio of the initial to final load power, expressed in decibels, when an initial waveguide junction (a connector pair, two-port network, etc.) is removed and another substituted in its place.

summer solstice
Longest day of the year. It usually falls on June 21st in the northern hemisphere. The sun casts its shortest shadows in the summer solstice.

super heterodyne
A receiver in which the incoming signal is mixed with a locally generated signal to produce an intermediate frequency that is then amplified and detected.

support equipment
Equipment used to verify the operation of other equipment, including a broad category of equipment and tools used to maintain mission equipment.

suppressor grid
An electrode used in an electron tube to minimize the effects of unwanted secondary emission from the plate.

surface tension
The tendency of the surface of a liquid to contract.

swamping resistor
A resistor placed in parallel with a tank circuit to reduce the Q.

sweep voltage
The periodically varying voltage produced by a sweep oscillator and applied to the deflecting plates of a CRT to give a displacement that is a function of time.

synchro
The universal term applied to any of the various synchronous devices such as the "selsyn," "autosyn," "motor-torque generator," "magslip," and "siemens." The standard signal and control synchro today has a two-pole single-phase rotor field and a delta or Y- wound single-phase variable-voltage stator.

systematic error
Systematic errors tend to bias all the measurements in one direction. The same error is occurring in measurement after measurement. Systematic errors can usually be blamed for trends, jumps, or drifts in a reading. They are also called persistent errors. 143

T

table
Collection of data in a form suitable for ready reference, frequently stored in sequential memory locations.

table look-up
Obtaining a value from a table of values stored in the computer.

tachometer
An instrument for measuring rotational speed in revolutions per minute (rpm).

tank circuit
A resonant circuit, consisting of inductance and capacitance in parallel, or series; one value is usually variable.

telescope
An instrument for making objects appear nearer and larger. The telescope forms the basis upon which physi-optical instruments are designed, such as the transit and Theodolite.

temperature
The quantitative measure of the relative hotness or coldness of an object.

temperature coefficient
A numerical value that indicates the relation between a temperature change and the resulting change in another property. The numerical value can be either negative or positive.

tensile strength
The force required to break a rod or wire of unit cross-sectional area.

terminal linearity
Ratio of the actual error voltage in the output to the total input voltage. This will vary with the setting of the ratio voltage divider.

termination
The load connected to the output end of a circuit or transmission line.

terrestrial
Relating to earthly matters. A terrestrial telescope is one in which the image appears normal, not reversed or inverted.

tertiary winding
A third winding added to a transformer in addition to the conventional primary and secondary winding. In most applications it is used as an additional secondary winding.

testing machine
A machine for applying forces to specimens of steel and other material to determine the applied force which the test specimen will withstand.

test instrument (TI)
The device which is being compared with the calibration standard. The test instrument is the instrument whose accuracy is being tested, sometimes referred to as unit under test (UUT) or device under test.

test set
A combination of instruments needed for making a particular combination of tests, or for servicing a particular type of equipment.

telescope
An instrument for making objects appear nearer and larger. The telescope forms the basis upon which many physi-optical instruments are designed, such as the transit and theodolite.

theodolite
An optical instrument used for measuring horizontal or vertical angles.

thermal agitation
Random movement of free electrons in a circuit due to the presence of heat.

thermal capacity
The amount of heat required to produce a unit temperature change. Water has the highest thermal capacity of any common substance.

thermal converter meters
Meters that employ a thermocouple to convert the meter input to a DC voltage proportional to the EMS value of the input. They are widely used for accurate measurement of AC voltage and current.

thermal energy
The potential and kinetic energy of the particles of a body which can be evolved as heat.

thermal runaway
A result of a regenerative increase in collector current and junction temperature.

thermionic emission
The evaporation of electrons from a heated surface.

thermistor
A resistor whose value varies with temperature in a definite desired manner, used in circuits to compensate for temperature variations in other parts. It may have either a negative or a positive temperature coefficient. One type is made from a semiconducting material such as uranium oxide or silver sulfide, having a relatively large negative temperature coefficient of resistance. The name is a contraction of thermal resistor.

thermocouple
Two dissimilar metals joined at one end. When a difference of temperature exists between the ends, and EMF is generated across the thermocouple. This DC voltage is proportional to the heat applied to the thermocouple junction.

threshold sensitivity
Refers to the smallest fractional load which will cause a pressure system to indicate that a load is starting to be applied.

Thyratron
A hot-cathode gas-filled triode or tetrode which is used as an electronic switch. It controls electrostatically (with grids) the starting of the unidirectional current flow. To cut off the discharge, the plate-cathode potential must be reduced to the extinguishing potential for the particular gas and pressure used.

tickler coil
A small coil connected in series with a vacuum tube plate circuit and inductively coupled to the grid circuit to provide regenerative feedback.

tilt graticule
A graduate reticule used in Collimators for measuring vertical and horizontal tilt, or angular deviation.

time
The period during which an action or process continues; measurement of duration.

time base
The time reference plotted along the X-axis of a CRT.

time constant
The time required for a quantity that varies exponentially to change by an amount equal to 0.632 times the total change that will occur. In a capacitor-resistor circuit, it is the number of seconds required for the capacitor to reach 63.2% of its full charge after a voltage is applied. In an inductor-resistor circuit, it is the number of seconds required for the current to reach 63.2% of its final value.

time delay relay
A relay with a heating element designed to delay full circuit operation until the filaments of the vacuum tubes have had time to reach operating" temperatures.

time signals
One of the technical radio broadcast services of NBS radio stations.

TMDE (Test, Measurement and Diagnostic Equipment)
Those devices used to test, measure, evaluate, inspect, or otherwise examine materials, supplies, equipment, and systems to identify or isolate any actual or potential malfunction, or to determine compliance with specifications established in technical documents.

Toroid
A doughnut-shaped coil wound on a core of the same configuration. A toroid coil produces little Interference to other circuits and is relatively unaffected by the magnetic fields of other circuits.

torque
The cause of rotary motion. Torque is equal to the applied force multiplied by the distance from the center of rotation. (lb/ft, oz/in, etc...)

torque wrench
A wrench with which the mechanic can apply specific amounts of torque, usually as indicated by the setting of the handle.

torr
1/760 of an atmosphere - 1 mm Hg.

total force
The force acting against the entire area of a particular surface.

trace
The path followed by the spot as it is in motion across the screen of a CRT.

traceability
The ability to reference all measurements back to a higher level of accuracy and eventually to the National Institute of Standards and Technology (NIST).

transconductance
The ratio of the amplification factor of a vacuum tube to its AC plate resistance expressed in mhos or µmhos. The change in plate current divided by the change in grid voltage when the plate voltage is held constant.

transducer
1) Generally, a device which converts energy from one form into another, always retaining the characteristic amplitude variations of the energy converted.

2) A device which transfers energy from one circuit to another without changing the form of energy.

3) A device which converts vibratory motion into an electrical signal that is a function of some parameter of the experienced motion.

transfer method
An accurate method of measuring voltages and currents using a thermocouple meter and the universal potentiometer. It consists of measuring the Input, and then duplicating the input reading with an internal source. The internal source voltage is then read with, the universal potentiometer.

transformer
An electrical device which, by electromagnetic induction, converts electrical energy from one voltage-current level to another voltage-current level.

transient
The instantaneous surge of voltage or current that occurs as the result of a change from one steady-state condition to another.

transient vibration
Abrupt changes or shocks in the levels of other motion.

transit
Similar to a Theodolite; can only make measurements with the use of accessories. Readings are linear deviation.

transit time
1) In electron tubes, the time required for an electron to travel from one electrode to another.

2) In semiconductors, the time required for the charge carrier to travel from the emitter to the collector.

transient
The instantaneous surge of voltage or current that occurs as the result of a change from one steady-state condition to another.

transient response
The ability of an amplifier circuit to reproduce faithfully the shape and amplitude of transient voltages.

transistor
An electronic device for rectification and/or amplification consisting of semiconducting material to which contact is made by three or more electrodes which are metal points or soldered junctions. In general, the resistance between two electrodes is controlled by the current supplied to another electrode.

translucent
Shining or glowing through; admitting and diffusing light so that objects beyond cannot be clearly distinguished.

transition duration
The difference in time between two reference levels of the same transition, commonly at the 10% and 90% levels. Transition duration is a rise time or fall time. A rise time can be described as a leading edge or a rising edge or a positive-going transition. A fall time can be described as a trailing edge or a falling edge or a negative-going transition.

transmission
Transfer of electric energy from one location to another through conductors or by radiation. The transfer always is accompanied by energy loss.

transmitter
A comprehensive term applying to all of the equipment used for generating and amplifying an RF carrier signal, modulating this carrier with intelligence, and radiating the modulated RF carrier into space.

transmutation
A change in the identity of a nucleus because of a change in its number of protons.

transparent
Having the property of transmitting light without appreciable scattering so that bodies lying beyond are entirely visible.

transverse electric (TE) mode
A field configuration in a waveguide in which all components of the electric field lie in a plane that is transverse, or perpendicular to the direction of propagation.

transverse magnetic (TM) mode
A field configuration in a waveguide in which all components of the magnetic field lie in a plane that is transverse, or perpendicular, to the direction of propagation.

traveling wave
Energy moving toward the termination of a waveguide or energy reflected from the termination.

trickle charge
The continuous charging of a storage battery at a low rate over a prolonged period of time.

trigger
1) To start action in a circuit, which then functions for a period of time under its own control.

2) A short pulse, either positive or negative, which can be used to set into motion a chain of events.

trimmer
Any small capacitor inserted in parallel with a main capacitor to adjust its capacity to some predetermined level.

trivalent impurity
Any impure atom that has three electrons in its valence band.

troubleshoot
To seek the cause of a malfunction or erroneous program behavior in order to remove the malfunction.

troubleshooting tree
Flow diagram consisting of tests and measurements used to diagnose and locate faults in a product.

tropical year
The time between two successive vernal equinoxes. Our calendar is based on the tropical year. It is equal to 365 days, 5 hours, 48 minutes, and 49.7 seconds.

true mass
Mass as measured in a vacuum.

true power
The average value of power consumed by a circuit during one complete cycle of AC. In a DC circuit, the power is equal to the current times the voltage. In an AC circuit, the true power is equal to the current times the voltage, times the power factor. The formula, the true power in any circuit.

true value
The value of a physical quantity that would be attributable to a material object or physical system if that value could be determined without error.

tube
The word "tube," without any qualification, refers to an electronic tube.

tuning
1) Adjusting the inductance or capacitance (or both) in a coil-capacitor circuit.

2) Adjusting all circuits in electronic equipment for optimum performance.

tuning fork
A convenient device for producing a comparatively pure harmonic vibration frequency at nearly constant value. They are usually made of steel and are designed to vibrate at their natural resonant frequency.

tunnel diode
A very heavily doped PN junction.

turn-off time (Ts and Tf)
The time required for the Ic wave to go from its maximum value to 10 percent of its maximum value. It can be expressed as the sum of the storage time and the fall time (transition duration). Ts is storage time, and Tf is fall time (transition duration).

turn-on-time (Td and Tr)
The sum of the delay time and the rise time (transition duration). This is the time necessary for Ic to go from its minimum value to 90 percent of its maximum value. Tr is rise time (transition duration), and Td is delay time.

turns ratio
The ratio of the number of turns in the primary windings to the number of turns in the secondary winding of a transformer.

twin "T" network
A network of capacitors and resistors that will provide maximum attenuation and a 180° phase shift to a selected frequency. Other harmonics will be attenuated much less, and they will appear to receive a negligible phase shift.

true value
The value of a physical quantity that would be attributable to a material object or physical system if that value could be determined without error.

two-wire transmission line
Two metallic conductors spaced equidistant apart and separated by dielectric or metallic insulators, used for frequencies up to 200 MHz.

twisted pair
A cable composed of two insulated conductors twisted together either with or without a common covering.

U

ultraviolet
A range of invisible radiation frequencies beyond the visible spectrum at the high frequency end and extending into the region of low frequency X-rays.

unblanking
A signal applied to the control grid of a CRT to allow the CRT to conduct. This is also called gating.

uncertainty
The degree of doubt concerning the exactness of a measurement. It is the estimated maximum amount that the numerical value of a measured quantity may differ from the true value. In some cases, it is referred to as accuracy.

undamped wave
A continuous wave with undamped oscillation. unifilar - Having or using one fiber, wire, or thread.

unifilar
Having or using one fiber, wire or thread.

uniform line
A transmission line that has identical electrical properties throughout its length.

unit
A value, quantity, or magnitude in terms of which other values, quantities, or magnitudes are expressed. In general, a unit is fixed by definition and is independent of such physical conditions as temperature. Examples: yard, pound, gallon, meter, liter, gram.

unit under test (UUT)
See test instrument

unity coupling
Perfect magnetic coupling between two coils, so that all the magnetic flux produced by the primary winding passes through the entire secondary winding.

V

vacuum
Any pressure below atmospheric. In gage pressure measurement, 5 psig vacuum means 5 psi below atmospheric pressure. In absolute pressure measurements, any pressure from zero psia (perfect vacuum) up to atmospheric pressure.

vacuum tube voltmeter (VTVM)
A voltmeter that has a high input impedance and therefore takes only a small amount of power from the circuit. The small power input is amplified before being applied to the meter movement of the VTVM.

valence
The number representing the combining or displacing power of an atom; number of electrons lost, gained, or shared by an atom in a compound; the number of hydrogen atoms with which an atom will combine, or the number it will displace.

valence band
The outermost orbit of an atom that will contain electrons at absolute zero.

valence electrons
Electrons which are gained, lost, or shared in chemical reactions.

vaporization
The production of a vapor or gas from matter in another physical state.

variable-mu tube
A vacuum tube having the control grid wires irregularly spaced so that at different points within its operating range the grid has a different amount of control over the electron stream. This shifts the operating point from one section of the characteristic curve to another. Thus, by adjusting the grid bias voltage over a comparatively wide range the amplification factor and mutual conductance can be varied.

vector quantity
A quantity having both magnitude and direction, as a force or a velocity.

velocity
The time rate of change of position.

velocity constant
The ratio of the velocity of propagation in a transmission line to the velocity of light.

vernal (spring) equinox
First day of spring in the northern hemisphere. It usually falls on March 21st in the northern hemisphere. There are about 12 hours of light and 12 hours of darkness every place on the Earth during an equinox.

vernier
An auxiliary scale made to work in conjunction with the divisions of a graduated instrument for indicating parts of a division.

vertically polarized wave
An electromagnetic wave in which the electric field (E) is perpendicular to the horizon and the magnetic field (H) is horizontal (parallel to the Earth's surface).

vertical
(1) Being or situated at right angles to the horizon, or to level ground: perpendicular, plumb, upright.

(2) In science, parallel with the direction of the force of gravity.

vertical axis
The axis about which the telescope rotates when sweeping a horizontal plane.

vibration
Mechanical oscillations or motion about a reference point or equilibrium.

video frequencies
A wide range of frequencies including the audio range and frequencies as high as 4 MHz. Some video amplifiers will amplify frequencies as high as 10 MHz.

virtual image
The impression of an object as viewed by the observer. Light rays do not pass through, but only appear to come from the image.

viscosity
The internal friction of a fluid. Also, a quantitative measure of a fluid's lubricity.

VLSI
Very Large Scale Integration.

volatile
Readily vaporizable at a relatively low temperature.

Volt
Unit of electric potential difference and electromotive force. The difference of electric potential between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

voltage saturation
See current saturation

volume
The amount of space which matter occupies.

W

wave front
A surface composed at any instant of all the points just reached by a vibrational disturbance in its propagation through a medium.

wedge
A weak prism used when very small deviations of a beam are required. The wedge is also used in conjunction with penta and other prisms for corrective purposes.

weight
The force of gravity acting on an object.

winter solstice
Shortest day of the year. It usually falls on December 21st in the northern hemisphere. The sun casts its longest shadows in the winter solstice.

work
That which is accomplished when a force acts on matter and moves it. (ft/lb, in/oz, etc...)

X

Y

Z

Zener point
See avalanche breakdown

zenith
The point of the celestial sphere that is directly opposite the nadir and vertically above the observer.