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Environmental Effects on Coordinate Measuring Machine Measurements

Technical Report

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The American Society of Mechanical Engineers
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FOREWORD

This Technical Report addresses the environmental effects on measurements taken when using coordinate measuring machines. In this Report, the considered effects are those due solely to environmental effects, such as temperature and vibration. Operational effects, including items such as fixturing, materials, probe considerations and the workpiece itself etc. are not addressed in this document.

The intent of this document, is not to provide detailed solutions to specific applications, but rather to address and highlight some items to consider when making measurements on coordinate measuring machines, with the ultimate objective of reducing the uncertainty in the measurement.

The subject matter itself is extremely broad and complex, making standardized solutions very difficult. As such, how to deal with environmental issues is highly user dependent and difficult to standardize. The initial concept was to try to develop a standard test, similar to those currently documented in B89.4.10360.2. This was however contrary to the concept of making the performance evaluation tests quicker (and hopefully less expensive) to run.

In the first case, the CMM is used within rated environmental conditions as stated by the CMM manufacturer. In this situation, the performance of the CMM is characterized by its ASME B89.4.10360 accuracy specifications. For any combination of environmental conditions that are within the rated conditions, the accuracy of the CMM as characterized by the ASME B89.4.10360 Standards, is expressed as a maximum permissible error (MPE) that is assigned by the CMM manufacture and different MPE values may be assigned to different environmental conditions that are within the rated conditions. These accuracy specifications apply only to the measurand embodied in the calibrated reference artifact used in the B89 specification, for example point-to-point length as measured on gage blocks, step gages and similar artifacts permitted by the performance testing protocol.

In the second case the CMM might be used in conditions that are outside its rated environmental conditions. In this case the performance of the CMM, as characterized by its B89.4.10360 specifications, is no longer assured. Some guidance of the derating of the CMM performance is given in ASME B89.4.10360.2, however, unless the CMM manufacturer has agreed to a derating method, there is no applicable accuracy specification.

From the above discussions, it was decided that perhaps the best approach would be to develop a reference document that would elucidate the problems, but allow the user of the machine to decide what (if anything) they would do about it.

Comments and suggestions for improvement of this Technical Report are welcomed. They should be addressed to The American Society of Mechanical Engineers, Secretary, B89 Main Committee, Two Park Avenue, New York, NY 10016-5990.

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Dimensional Metrology

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ENVIONMENTAL EFFECTS ON COORDINATE MEASURING MACHINE MEASUREMENT

1 Scope

This Technical Report discusses important influences of the environment on dimensional and geometric measurements, performed using coordinate measuring machines (CMMs), including influences on both the machine and the workpieces to be measured. This report discusses the thermal effects related to the use of tactile CMMs but many of these effects are applicable to optical and other non-contact Coordinate Measurement Systems.

2 Introduction and Background

2.1 Operating Conditions

The JCGM 200 (4.9 and 4.10) (Reference 1) defines rated operating conditions and limiting operating conditions. Machine specifications, typically stated as MPE's, are intended to be applicable to a CMM which is used within its rated operating conditions. These rated operating conditions include but are not limited to environmental conditions. Limiting operating conditions are the extreme that a machine can be operated at without sustaining damage and without degradation of specifications when subsequently operated within its rated operating conditions.

2.2 Definition of an Environment

For the purposes of this Technical Report, the CMM environment includes those elements in the machine surroundings, other than machine operators, which affect CMM system performance (effects of operators are not addressed in this report). The effects are temperature and humidity, illumination, vibration, electrical and contamination. These effects are caused or transmitted by surrounding air, building structure, other equipment, supply air and the electrical system.

2.3 Classification of Environments

For the purpose of this Technical Report, environments are classified as *laboratory* and *shop.* A laboratory environment is controlled in an attempt to perform measurements at an acceptable accuracy level. A shop environment is controlled only to the level required to produce acceptable workpieces. A shop environment may not be acceptable for performing measurement tasks.

2.4 Overview of Environmental Effects

The influence of environmental variables on the measurement results obtained using the CMM are classified as environmental effects. The variables are identified in section 2.2 above, and their influence can be vastly different between different facilities, or even within one facility. Where temperature and humidity may vary depending on the time of day or season of the year, influences such as illumination, electrical noise, and vibration may be fairly constant for a given CMM installation. Contamination, either airborne or on the CMM and workpieces, may either be a steady state or varying condition. The ability to manage contamination will depend on the nature of the installation and the perceived impact of the contamination on measurement results.

2.5 Treatment of Environmental Effects

There are three main methods employed to mitigate the influence of the environmental effects described above. The first is to attempt to remove the source of the influence: this may be to shut down or move equipment causing vibration, or remove heat sources from the immediate vicinity of the measuring equipment. The second method is to attenuate the effects of the influence: vibration isolators may be used between the factory or laboratory floor and the

CMM, or baffles may be installed to block radiation from a heat source that cannot be moved. The third method is compensation: by using knowledge about how a particular influence effects the measurement and sensors to quantify the environmental state, the measurement results can be adjusted to compensate for the environment. After mitigation, simply evaluate the influence: the uncertainty of measurement can be increased to accommodate the effect of environment influences where the previous three methods are not employed.

2.6 Anticipated Users of This Document

The primary audiences for this Technical Report are buyers and users of CMMs who need to choose machines and levels of environmental control necessary for the anticipated measurement tasks, wherever they may be performed, as well as those who are responsible for using the CMM to make measurements.

It is anticipated that the users of this Technical Report, fall into the following four broad categories, accepting that terminology and job classification vary considerably from company to company and industry to industry.

Quality Engineers –those who select measuring systems, acquire them, install them, manage the use of the data coming from the systems, and plan and ensure their proper maintenance.

Application Engineers (Measurement Planner) – typically the person who designs fixtures, plans the measurement strategy, purchases probe equipment, determines probe calibration frequency, and at times writes the application programs. For additional information on Measurement Planners, see ASME B89.7.2-2014, *Dimensional Measurement Planning*. (Reference 2)

Programmers – this category may be a separate job classification or its duties incorporated within one of the other identified categories. A programmer's primary responsibility is creating the necessary code (in the high level language appropriate to a specific machine) necessary to execute the measurement plan.

Operators – those who actually prepare workpieces for measurement, place them in fixtures, decide if they have been adequately thermally stabilized, operate the machine, and perform normal daily maintenance. (Note: in some companies the "application engineer" and the "operator" may be the same person).

3 Thermal Effects

3.1 Thermal Expansion of Materials

An unrestrained body will expand if its temperature is increased. For a uniform temperature within a body

$$\Delta L = L_1 \alpha \Delta T \quad (1)$$

Where

ΔL = change in length = $(L_2 - L_1)$
L_1 = original length
ΔT = change in temperature = $(T_2 - T_1)$
α = coefficient of Thermal Expansion

This is shown graphically in Figure 3.1-1 for $T_2 > T_1$. The nominal coefficient of expansion (α) may be negligibly small (Zerodur) or relatively large (polymers). Appendix E gives typical values of some of the more common engineering materials, taken from References 3, 4, 5, 6, and 7.

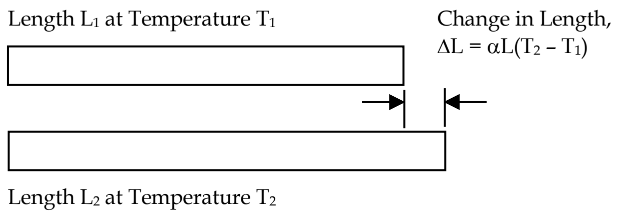

Figure 3.1-1: The Effect of Increase in Temperature on Length

The coefficient of expansion may be taken as a constant for the temperatures encountered in industrial length measurements. It does vary at significantly different temperatures.

Since workpieces expand when their temperatures increase, a dimensional specification has no exact meaning unless the temperature at which the specification must be met is also specified. At a meeting of the International Committee of Weights and Measures in Paris in 1931, it was resolved that, 20 °C would be universally adopted as the standard reference temperature for calibration of length standards (gage blocks, etc.). Subsequently most of the nations of the world adopted 20 °C as the standard reference temperature for defining the lengths of gages. This temperature came into such general use that in 1954 ISO issued a standard, ISO 1 (Reference 8), promulgating its use among the ISO-participating countries. It is now generally accepted that a stated dimension of a body derived from measurement should be the dimension that would be measured if the body was at a uniform 20 °C. Paragraph 1.4*(l)* of ASME Y14.5-2009 (Reference 9) states, "*Unless otherwise specified, all dimensions are applicable at 20 °C (68°F).*" It must be noted that electrical quantities are specified with a standard reference temperature of 23 °C.

3.2 Differential Thermal Expansion

In view of the thermal expansion of all materials, consider the dimensional measurement process as illustrated below. Both the measuring scale and the workpiece are expanding (or contracting), each according to its own coefficient of expansion and temperature. A measurement on the workpiece that is not corrected for thermal expansion will be the length of the workpiece as indicated on the scale. This is the length of the workpiece at 20 °C plus the *difference* between the expansion of the workpiece and the scale. Thus, when discussing thermal effects in dimensional metrology, one will always need to consider the *differential expansion*.

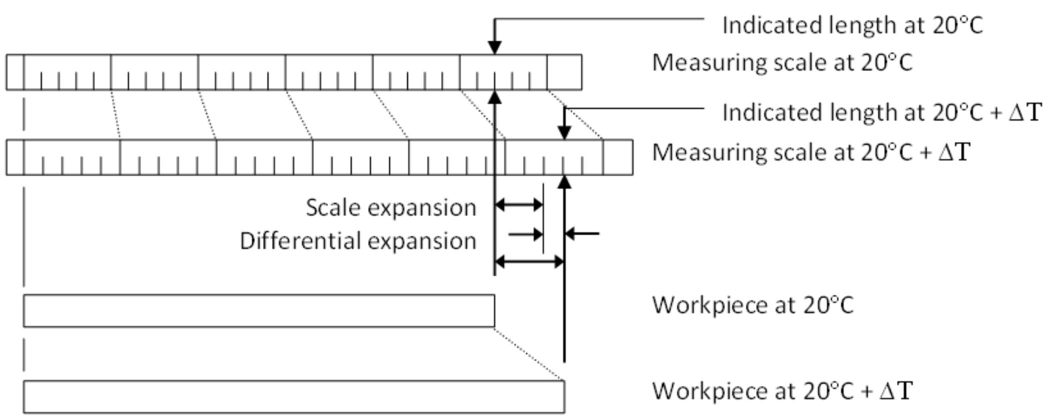

Figure 3.2-1 – The Effect of Differential Expansion on Length

3.3 The Metrology Loop: A Three Element System in Coordinate Metrology

A more sophisticated view of the measurement process in a varying thermal environment involves analyzing dimensional measurement instruments using the *three-element* concept of length measurement: this includes a master gage, a comparator and a workpiece and represents a generalization of the differential expansion concept of section 3.2. The prototypical example is a gage block comparator, however for coordinate metrology the situation is more complex. The master gage for a CMM are the calibrated scales affixed to each coordinate axis and the comparator represents the entire machine structure including workpiece fixturing. The three elements form a loop, known as the metrology loop which is the path from the CMM probe tip, through the machine structure to the scale reading, to the point where the scale is fixed to the machine structure, through the machine structure to the CMM table, and through the fixturing to the workpiece, and to the measurement point on the workpiece.

Since coordinate metrology always involves the calculation of one set of coordinate points relative to another set of coordinates (e.g. a feature relative to a datum), each set of coordinates involves the metrology loop. There are two general measurement cases of interest. If all of the coordinates are measured in quick succession so that thermal expansions and distortions of the metrology loop do not change during the measurement, then the thermal effects in the loop are static to all coordinates and dynamic thermal effects, e.g. thermal drift, can be neglected when evaluating the dimensional measurement uncertainty. For measurements that involve long measurement times or significant change in temperature, thermal expansions and distortions of the metrology loop may evolve and hence the measurement coordinates become increasingly shifted relative to their coordinate system and to each other. In this case, thermal drift within the metrology loop is significant. Frequently reestablishing the workpiece coordinate system can partially mitigate this effect but a careful analysis of the thermal behavior of the metrology loop is needed to evaluate the impact of thermally induced measurement uncertainty; see section 3.6 for more information on thermal drift.

3.4 Bi-metallic and Gradient Bending

3.4.1 Bi-Material Effects

Because materials thermally expand proportionally to their CTE values, if a workpiece or CMM is composed of materials with different CTEs, or a material with a non-uniform CTE, geometrical distortions, may occur as the ambient temperature varies. In the case of CMMs, the CMM manufacturer may have provided either mechanical or software means of mitigating or compensating for these expansions. In the case of workpieces, a non-uniform CTE will generally result in bending due to the different coefficients of expansion at different points in the structure.

While it is obvious that this effect can occur when materials with explicitly different CTEs are present, it is less obvious for materials with nominally the same CTE. However, even for a single material, the CTE can vary for many reasons including: (1) stresses induced during its fabrication from rolling or forging; (2) metallurgical variations in castings due to variations in the rate of change of cooling (since most materials start out as casting from ingots this can also arise in many finished metals); (3) Hardening of surfaces (either by flame or electrically) can change the CTE value due to the metallurgical changes that provide the hardness.

3.4.2 Gradients

Spatial temperature gradients in CMM components also cause bending. In particular, beams bend if heat inputs or time constants at opposite faces are unequal. Joints between beams are a particular problem due to uneven wall thicknesses. Generally, gradient and bi-material effects cause changes in machine squareness. The squareness changes are caused by thermal distortion of the joints between structural members and by distortion in the movable carriages that interconnect the machine guideways. There is an additional thermal error caused by distortion of the structure between the primary guideway (the guideway that is fixed relative to the workpiece) and the workpiece mounting point. Workpiece distortion causes movement of the workpiece measurement points. These movements must be determined relative to the point on the workpiece that is fixed relative to the machine.

Scales are a major factor in machine response to the thermal environment. The nature of the effect depends on how the scales are mounted. There are three methods in general use: I. If the scale is fixed to the machine structure at one point and floats at all other points, then scale expansion is determined from scale temperature and scale's coefficient of expansion. Laser scales fall into this class; the coefficient of expansion is determined from the air index of refraction. II. If the scale is rigidly fixed to the machine structure at all points then scale expansion is determined from the structure temperature and coefficient of expansion. Scales that are fixed at both ends, for example stretched-tape scales, are in this method. III. If scale expansion is partially constrained by the structure, for example by means of a layer of elastomer between the scale and structure, then a more complicated situation occurs. If the scale and structure have different coefficients of expansion, then shear forces set up in the elastomer affect scale expansion. The shear forces, and consequently the scale expansion, vary along the scale length.

3.5 Thermal Response Times

3.5.1 Thermal Diffusivity

When heat flows into a body due to an environmental temperature increase, the lag of body temperature relative to environmental temperature and the magnitude of spatial temperature gradients in the body both depend on thermal diffusivity. Thermal diffusivity is a measure of capability of a body to distribute heat throughout its volume. It is the reciprocal of the compound constant in equation (8) and is formally defined as the ratio of conductivity to heat capacity per unit volume per °C. Heat capacity is specific heat times the density.

Thermal diffusivity, together with coefficient of expansion, is a characteristic that is useful for determining suitability of a material for a thermally sensitive application. Thermal diffusivity can also be used to determine an effective depth to which temperature from a cyclic environmental temperature variation will penetrate into bodies.

3.5.2 Thermal Time Constants

Time constants are associated with processes that can be described by exponential mathematical functions. A rate of change of an object's temperature is related to the difference in temperature between the object and its surrounding environment. From an initial condition, (for example, a light bulb is turned on near the object) any point in the object will approach its steady-state temperature; quickly at first, then more slowly as the temperature difference diminishes. Theoretically, it takes forever to reach steady-state. However, the difference becomes negligible after a period of 2, 3, or 4 times the time constant, depending on what is considered negligible. The time constant depends on several factors including material properties, geometry of the object, and heat transfer mechanisms of conduction, convection, radiation, and associated boundary conditions. By changing the boundary conditions, the thermal time constant will also change, for example, for some workpieces the time constant can be decreased by a factor of ten by using forced air (i.e. a fan) relative to the time constant for still air. This topic is discussed further in Appendix B, workpiece soak out time.

Time constants are useful to model the change in any length of an object when subjected to a sudden change in temperature. When a machined component is transferred from a warm shop to a metrology laboratory at 20 °C and placed on a table, there is a question of how long to wait before the component can be inspected with negligible temperature error. For any length of interest on the component,

$$\Delta L(t) = \Delta L_{ss}\left(1 - e^{-t/\tau}\right) \tag{2}$$

Where

t = the time from the sudden change
$\Delta L(t)$ = change in length at any time, t
ΔL_{ss} = equilibrium change in length (steady-state, or t = infinity)
T = time constant

One can calculate easily from this model that when t = τ, the change in length is about 63% of the steady-state change. The following table gives this percentage for other times as multiples of the time constant.

$$\frac{\Delta L(t)}{\Delta L_{ss}} \longrightarrow 1 \; as \; t \rightarrow \infty \quad (3)$$

t/τ	1	2	3	4	5	6
$\Delta L(t)/\Delta L_{ss}$	0.63	0.86	0.95	0.982	0.993	0.998

A plot of the time response for a body with a time constant of 1 hour (3600 s) is shown in Figure 3.5.2-1. The elapsed times of the first 6 time constants are shown.

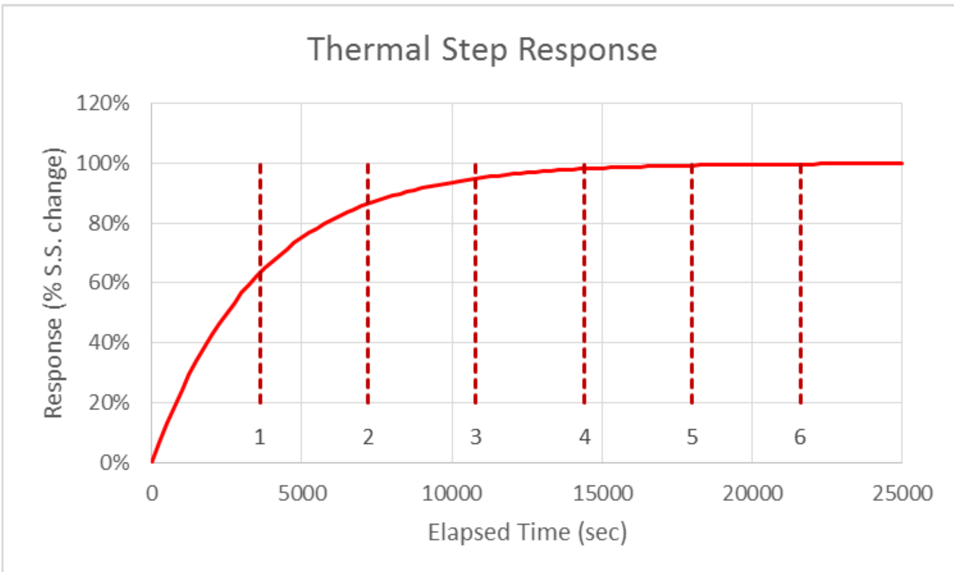

Figure 3.5.2-1: Thermal Step Response

This model can be used to estimate "soak out time" for a specific component. Typically, a few measurements within the first hour provide enough information to perform a regression analysis on the two unknown variables, ΔL_{ss} and τ. Then, based on the tolerance, a more efficient soak out time can be established.

The term, "thermal mass," is sometimes used to describe the concept of how quickly an object or machine responds to temperature changes in the environment. This is somewhat analogous to acceleration of an object under an applied force; the more massive, the slower its response.

If a sinusoidal environmental temperature variation is applied to a simple body, its length variation is also sinusoidal. For materials with relatively high diffusivities (like metals), at frequencies well below the reciprocal of the time constant, the length will track the temperature according to Equation 1. However, as the frequency increases, the length response is attenuated as the body's temperature is unable to keep up with the environmental variation. This also leads to an increasing phase shift between the environmental temperature and the body's length. A plot of a simple body's response to an external sinusoidal temperature variation is shown in Figure 3.5.2-2. The time constant is 1 hour (3600 seconds.) Note that 1 cycle/minute is 0.0167 Hz (16.7 mHz) and 1 cycle/hour is 0.00028 Hz (0.28 mHz.)

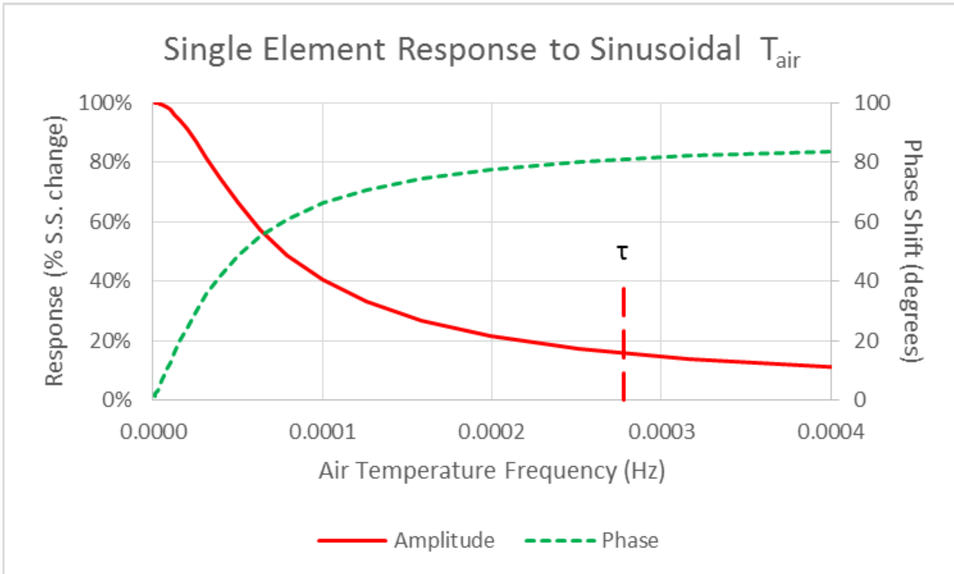

Figure 3.5.2-2: Thermal Response of a Simple Body to Temperature Variation

A simple body's thermal response does not have a resonant response like a spring-mass system. That is, the change in length will never exceed the steady state change predicted by Equation 1 for the amplitude of temperature change. However, systems with more than a single thermal element and systems with significant gradients do show a frequency dependent maximum in their thermal responses that may exceed their steady state responses. By analogy with the spring-mass resonance, this phenomenon is called *thermal resonance*, whether or not the response exceeds 1.0.

Returning to Figure 3.2-1 and differential expansion, one can imagine a CMM with the measuring scale along a measuring axis and a workpiece to be measured. In a steady temperature environment at 20 °C + ΔT, the differential expansion can be calculated as described in section 3.2. However, when both are subjected to fluctuating air temperature, the workpiece and scale will respond according to their individual thermal time constants and their heat transfer situations. In general, they will have different length change and different phase lags in response to the fluctuating temperature.

Consider a simple example with a scale attached to an axis beam having a time constant of 1 hour (3600 s) being compared to a thin workpiece with a time constant of 2 minutes (120 s). The workpiece will have a fast response relative to the scale/beam assembly. The differential response even when they have the same coefficient of thermal expansion is shown in Figure 3.5.2-3 below.

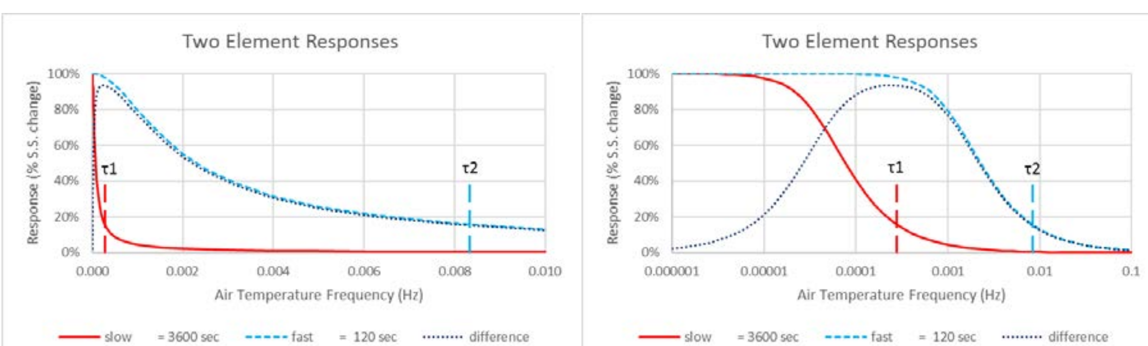

Figure 3.5.2-3: Differential Equation of Measuring System (a) Linear freq. Scale (b) Logarithmic freq. Scale

The second case where thermal resonance may occur deals with a multi-element structure such as a CMM and the effects of thermal gradients on the elements. Each mechanical component of a CMM in the structural loop from workpiece to sensor has its own, unique response to temperature change. Because heat transfer boundary conditions are often not symmetric surrounding these components, temperature gradients occur within and among the structural components causing the structure to bend. Therefore, displacements occur that are tangential, or normal, to the direction of the elements' simple, linear thermal expansion. The magnitudes of these displacements are complicated to predict as they depend on the magnitude and frequency of the temperature fluctuations and the thermal response characteristics of each component. When multiple components are connected, the final displacement in any direction of the CMM sensor relative to the workpiece depends on much more than simply the magnitude of the temperature variation. The 3-dimensional displacements are a superposition of linear expansion and bending in all structural elements, each following its own thermal characteristics. The frequency response curve may show a maximum for some frequency of temperature variation. This is another example of thermal resonance. Again, the displacements may exceed the steady state value calculated from length, temperature, and CTE. The temperature variation frequency that causes this to occur may be considered a characteristic of a particular CMM. Machines may be designed to be insensitive to the most common cyclic periods such as 24h.

See Appendix B for some worked examples.

3.6 Thermal Environment Characteristics

3.6.1 Temperature Variation Basics

Many dimensional measurement errors are the result of changing temperature rather than just a very stable offset from 20°C. The primary consequence of most of these problems is that the temperature within the machine structure or the workpiece is not uniform. In order to understand these effects, one will need to first review the nature of environmental variation.

Variation in temperature is a significant problem to overcome. Temperature affects material at the microscopic level causing each small element to change size dependent on the local temperature. The cumulative effect can cause structural changes in both the CMM and the workpieces being measured. Objects have their size and shape specified at 20°C. The extent of the measured size and shape change depends on the material, both of the CMM, as well as the workpiece.

It is important for potential users to know the CMM rated operating conditions. In some cases, machine scales are chosen that have CTE similar to normal workpiece materials applicable to the rated conditions. Another method is to use temperature compensation to correct for differences in scale and workpiece CTE. The materials used to construct the CMM may have various CTEs. For instance, the CTE for steel is approximately 11.5 $\mu m \cdot m^{-1} \cdot °C^{-1}$ and aluminum is approximately 23 $\mu m \cdot m^{-1} \cdot °C^{-1}$. However, when materials with significant differences in CTE are used in the CMM structure or scales, the design of the CMM and assembly methods should take into account the differential thermal expansion of materials. One method typically used is to allow for unconstrained thermal expansion such that a machine scale fixed at one point is free to expand with changes in temperature. The design should account for differential thermal expansion in CMM materials such that undesirable deformation of the machine structure that would result in changes in straightness, pitch, yaw, roll, or squareness of the axes are minimized.

Most typical environments have cyclical variations about some mean temperature. They are normally characterized by describing the frequency of the dominant temperature cycles, as well as the range (or amplitude) of the variation at each frequency. Since recent history is the most important, analysis is based on the current (most recent) cycle, and modest differences between the current and preceding cycle do not strongly affect results.

Usually, the major components of a cycle are daily day-night (diurnal) variation and air-conditioning variation. These components may be evaluated separately and the results superimposed.

3.6.2 Classification of Environments – Uncontrolled or Controlled.

An uncontrolled environment is dominated by weather and nearby heat sources. Uncontrolled environments are generally found in manufacturing areas. They have some elements of control because temperature cycles tend to repeat, buildings have thermal inertia, and some level of air-conditioning is often required for worker comfort. Typically, uncontrolled environments can be characterized by a strong day-night variation which varies somewhat from cycle to cycle. An example cycle is shown in Figure 3.6.2-1. Seasonal cycles must also be considered. For example, a CMM that is adjusted for optimum performance in a winter environment might not meet specifications in the summer.

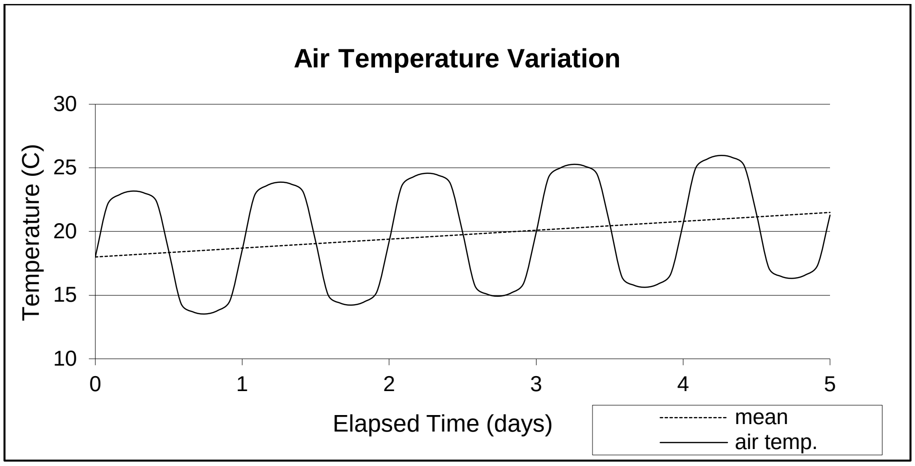

Figure 3.4.2-1: Typical Thermal Cycle

Temperature variation in a controlled environment is typically dominated by the performance characteristics of an air-conditioning system. Controlled environments of various qualities are found in inspection departments and laboratories. They are never perfectly controlled because the amount of heat that must be pumped in or out by the air conditioning system depends on outside influences such as weather. Since weather conditions are variable, so is the air-conditioning cycle. Weather affects the amount of heat that flows through room walls, ceiling and floor to room air, and the amount of radiant energy reaching the CMM. Weak and variable day-night temperature variations with a strong and reasonably repeatable superimposed air-conditioning variation typically characterize temperature-controlled rooms. The quality of control is reduced by the opening and closing of doors to admit workpieces and people, and by intermittent heat sources in the room such as computers and people.

3.6.3 Stratification

Stratification is a concern in most environments, though typically worse in uncontrolled environments. Stratification is a spatial air temperature variation (or gradient) in the vertical direction, usually reported as $\partial T/\partial z$. A first effect is that temperature differences in the upper and lower portions of horizontal guideways cause bending. A second effect is that machine members that move vertically change size as a function of the measurement routine (i.e., depending on how much time they spend in the different vertical temperature regions). Horizontal temperature gradients due to local heat sources can also cause similar effects, usually reported as $\partial T/\partial x$ and $\partial T/\partial y$.

The temperature variations described above affect measuring instruments and workpieces by creating temperature differences between them and temperature gradients within them. The most common effect of gradients is some form of bending within one of the objects. This is discussed in more detail in Section 3.4. To achieve the CMM manufacturer’s stated accuracy, the MPE, it is necessary for the user to supply an environment that satisfies all rated operating conditions, especially the thermal conditions.

3.7 Uncertainty Considerations

When the CMM is used within rated operating conditions as stated by the CMM manufacturer the performance of the CMM is characterized by its accuracy specifications, e.g. as given by ASME B89.4.10360.2 (Reference 10).

Measurements outside the rated operating conditions, such as CTEs or measurands not specified in the performance specification, the measurement errors may not be represented by the MPEs. For any combination of environmental conditions that are within the rated conditions, the accuracy of the CMM (for example as characterized by the ASME B89.4.10360.2 Standard) is expressed as a maximum permissible error (MPE) that is assigned by the CMM manufactures and different MPE values may be assigned to different rated environmental conditions. These accuracy specifications apply only to the measurand embodied in the calibrated reference artifact used in the specification, for example point-to-point length as measured on gage blocks, step gages and similar artifacts permitted by the performance testing protocol.

In general, it is not possible for the CMM user to predict the thermal behavior of a CMM. Consequently, the user should rely on the CMM manufacturer's performance specifications and the associated rated conditions for guidance. For example, a particular CMM may have had its software error correction (i.e. error map) created at 23 °C, as this happened to be the ambient temperature at the time the correction map was created. Consequently, the thermally induced errors in the CMM, including both simple homogenous thermal expansion (e.g. of the scales) and thermally induced distortions in the CMM structure, are (ideally) completely compensated for at this temperature. So, for this example, as the CMM ambient temperature shifts away from its error correction mapping temperature of 23°C, thermally induced (uncompensated) errors emerge, e.g., the CMM may be less accurate at 20°C than at 23°C. Even for CMMs that do not have error correction software, when the CMM is installed (or annually "recalibrated") it is typically mechanically adjusted to minimize the CMM errors, including thermally induced errors, and this minimization occurs at whatever temperature happens to prevail at the time of adjustment. So even in the case of a CMM without software error correction it is not always true that the CMM will be in its most accurate state at 20 °C. When the CMM is used in conditions that are outside its rated environmental conditions the performance of the CMM, as characterized by its B89.4.10360 specifications, is no longer assured. Some guidance of the derating of the CMM performance is discussed in Section 5 of this document.

The effects of the environment on measurements of production workpieces is typically more complicated than the effect on the dimensional gages used in the CMM performance testing. For example, the surfaces of workpieces may be rough or contaminated with particulates; the temperature of the workpiece might be changing with time or may be spatially non-uniform resulting in geometric distortions. In particular, the workpiece might be secured to the CMM table or other structure in an over constrained manner, e.g. tightly clamped in several locations. In this case, as the temperature of the workpiece and fixture structure changes the different thermally induced dimensional changes will be competing with each other and unpredictable effects will occur. For example, if the clamping is very tight and the fixture structure very rigid, the workpiece will geometrically distort; if the clamping is less secure the workpiece may shift about in an erratic manner as thermally induced forces stick-slip on the fixturing structure. If this occurs during a measurement, then workpiece features, including datum features, will be shifting about in an uncorrected manner during a CMM measurement cycle. One method of mitigation is to frequently redatum on the workpiece thus bringing the CMM coordinate system and the coordinate system of the physical workpiece back into coincidence.

These previously described effects on production workpieces are not significantly included in the ASME B89.4.10360 CMM accuracy specifications. This is because the dimensional gages used in the characterization of the CMM have simple designs (e.g. rods and bars), excellent physical geometry (e.g. flatness of surfaces), minimal surface roughness, near-homogenous and well known CTEs, and excellent fixturing (minimizing distortions). Additionally, the measurands on of the dimensional gages are elementary (e.g. point-to-point length) whereas the measurands of production workpieces are often much more complex, hence the duration of the measurement and the sensitivity to the environment can be significantly larger on workpieces than on the dimensional gages used in CMM testing.

When estimating the uncertainty of measured features on production workpieces, at least three categories of uncertainty sources must be considered:

(a) First is the point coordinate accuracy of the CMM; for measurements made within the environmental rated conditions this can be estimated by the ASME B89.4.10360 accuracy specifications given in technical literature from the CMM manufacturer.

(b) Secondly, the sampling strategy (the number and location of CMM probing points on the surface of a workpiece) must be taken into account for the actual measurand of the workpiece feature. For example, it is well-known that the uncertainty of the diameter of a ring gage measured with several points spread over a small angular region is much greater that the uncertainty of the diameter of the ring gage when the same number of points are spread over the entire circumference. This effect can be evaluated using technical references or by computer simulations.

(c) Thirdly, the effects of actual production workpieces (as opposed to idealized dimensional gages) must be taken into account as described below.

The evaluation of the measurement uncertainty of a workpiece feature measured within the rated operating conditions of a CMM involves the MPEs of the CMM (evaluated at the conditions of the measurement and this could involve multiple MPEs such as the length measuring performance, the probing performance, the offset probe performance etc.), the effects of the sampling strategy used on the feature, and the effects from the workpiece itself. In this document, only the effects of the workpiece thermal errors (WTE) are considered in detail; the U_{WTE} for a feature of size can be estimated from the following equation,

$$U_{WTE} = 2\sqrt{u_{WTVE}^2 + L^2(T\text{-}20)^2|u^2(\alpha_w)\text{-}u^2(\alpha_s)| + L^2|\alpha_w\text{-}\alpha_s|u^2(T)} + \delta \tag{4}$$

Where

u_{WTVE} = the standard uncertainty from the workpiece temperature variation error described in section 5.2,
L = the length or size of the workpiece being measured,
$u(\alpha_w)$ = the uncertainty of the nominal coefficient of expansion of the workpiece,
α_w = the thermal expansion coefficient of the workpiece,
$u(\alpha_s)$ = the uncertainty in the nominal coefficient of expansion of the standard used in the ASME B89.4.10360.2 test,
α_s = the thermal expansion coefficient of the standard used in the ASME B89.4.10360 test; use 11.5×10^{-6} /°C if α_s is not known,
$u(T)$ = the uncertainty in the measurement of the temperature of the workpiece,
T = temperature of the workpiece,
$\delta = 0$ if the CMM has workpiece thermal compensation, and
$\delta = |L(T - 20)(\alpha_w - \alpha_s)|$ if the CMM does not have workpiece thermal compensation.

4 Non-Thermal Effects

4.1 Vibration

Vibrations can adversely impact the accuracy of CMM measurements. Vibrations transmitted through the CMM structure can result in small but significant motion of the sensor relative to the workpiece that is not accurately detected by the machine scales or sensor. These errors are often the result of vibration induced elastic deformations in the CMM structure. External vibrations may be transmitted though the structure supporting the CMM which is typically the floor, or through the air. The CMM can also be the source of vibrations resulting from such items as motors, fans, air bearings, and inertial effects.

One symptom of floor vibrations is degraded repeatability of measurements made on the CMM. In many instances, it is better to eliminate the source of the vibration; this will eliminate the problem for other machines in the area as well. If the intended environment does not meet the vibration requirements specified by the manufacturer, alternatives such as removing the source of vibration, selecting a better environment, or acquiring passive or active vibration isolation should be considered.

Audible noise is an airborne vibration which may cause problems for CMMs. The noise may cause the covers or panels on the CMM to vibrate which excites the CMM structure. This may negatively impact measurement repeatability or may trigger the more sensitive touch probes unexpectedly. Absorption barriers may be used to reduce the noise level at the CMM. Adding damping material on the covers or panels of the CMM can reduce their resonance amplitudes. If the audible noise level is very high in the environment, a room for the CMM should be considered which reduces the noise level for the CMM and operator.

4.2 Illumination

Illumination in the area where measurements are being taken must be of sufficient intensity to:

(a) provide adequate visibility so that tasks can be performed with the appropriate speed and accuracy
(b) provide lighting levels that will permit the operator to work with maximum efficiency.
(c) provide lighting conditions that will result in maximum safety and absence of factors contributing to visual disability and visual discomfort.

Research has shown that intensity levels roughly between 1,000 and 1,600 lux (lx) are usually adequate for most applications, although levels as high as 10,000 lux may be required for some specialized measurements. In general, the criteria listed above can be met if shadowless, uniform lighting is maintained at each work location. For additional information, see Nonmandatory Appendix C.

4.3 Particulate Contamination

Contaminants normally consist of dirt, coolant, and residual oil/grease used in the machining process. Depending on the level of accuracy required in the measurement task, it is normally critical that dirt and coolant be completely removed from the workpiece machined surfaces before measurement. The highest level of accuracy also requires the removal of oil films and residual grease from the measurement surfaces.

It is noteworthy that in some cases the oil films are nearly transparent, they are not easily seen and readily removed – and in fact, in many cases are left on components that are measured. However, tests have shown that these effects can add or subtract significantly on measurements of bores, master rings, discs etc. (diametric errors up to 10 micrometers have been observed). This problem is especially common in gage labs that receive masters used in very harsh operational environments that have the opportunity to accumulate contaminants over long periods of time.

Contaminants in normal shop environments can also have adverse effects directly on the performance of measuring systems. Because of the growing trend to locate CMMs close to the production processes, it is important to be aware of the effects of dirt and take preventive measures to mitigate them. Dust and dirt from air and surrounding activities can quickly build up on bearing and way surfaces causing significant error in motions. In addition, these particles can cause premature and rapid wear of components which further contributes to axis motion error and measurement errors. When CMMs are operated in production environments, routine cleaning procedures should be implemented within the normal calibration interval.

4.4 Electrical Supply

The IEEE Standard entitled 1159-2009 **–** *IEEE Recommended Practice for Monitoring Electric Power Quality* (Reference 11), is an accepted standard for defining the types of power phenomena that occur in industrial applications.

4.4.1 Ground Loops

It is assumed that the machine has been installed in accordance with the requirements and recommendations indicated in paragraph 4.4 and Appendix D of ASME B89.4.1-1997. A frequently over looked installation detail which can cause operational problems later on, is the issue of ground loops. A ground loop is when two or more electrically grounded points are at different potentials. Ideally, and in theory, all grounds are at zero potential volts. However, in reality, potential differences exist between different “grounds” resulting in a small current flow. This current flow may cause erroneous readings on instruments, or even cause the instrument to lock up.

4.4.2 Electromagnetic Compatibility

Electromagnetic Compatibility (EMC) is defined as the combination of electromagnetic emissions and immunity. It affects all electronic devices. Emission is the electromagnetic energy emitted by the device. Immunity is the ability to not be influenced by the application of electromagnetic energy from external sources.

The European Community has adopted the CE Mark. As part of the requirements to comply with these directives the manufacturer must test the product to the emissions and immunity requirements. If the machine passes, a CE Mark sticker may be applied to the product. If users are concerned about emissions, they should ask the CMM supplier if it meets the CE Mark New Approach Directives. These requirements have been in effect since 1997 in the European Community. CMMs may be adversely affected in environments that have large electromagnetic interference such as produced by electric welding.

4.5 Humidity

Humidity is the amount of water in the air and can be described in a number of different ways, perhaps the most common being “relative humidity (RH).” Relative humidity is defined as the amount of water vapor in the air compared with the amount of vapor needed to make the air saturated at the air’s current temperature, usually stated as a percentage. The moisture content of air is affected by weather as well as conditions and activities, while the moisture holding capacity of air varies with temperature. One way of thinking about RH is that it is a measure of air’s tendency to absorb or release moisture to its surroundings. Thus, when the RH of air in a room increases, moisture will tend to transfer from the air. When the RH of air decreases, moisture will transfer into the air. The RH of the atmosphere is always changing by the hour, and more dramatically, with the seasons. As previously stated, relative humidity is given as a percentage: the amount of water vapor is expressed as a percent of saturation.

For example, a volume of air at sea level, at a temperature of 25 °C, would be completely saturated if there were 20 grams of water vapor in every kilogram of dry air. If this air actually contained 10 grams of water vapor per kilogram of dry air, one would say that the relative humidity would be 10/20 = 50%.

Since RH depends upon the temperature and moisture content of the air, it is not possible to maintain a constant RH by controlling room temperature alone. In fact, maintaining an even temperature while moisture content varies will actually cause a change in the RH.

Table 1: Ferrous Corrosion Development

Percent (%) Relative Humidity	Ferrous Corrosion Development
0	Usually no moisture is present on ferrous surfaces and therefore no corrosion occurs since hydrous solutions do not develop.
38	Effective upper limit of dry air. Usually no ferrous corrosion occurs up to this relative humidity value.
42	Microscopic moisture begins to condense. Ferrous corrosion may begin, but the rate of development would be slow.
45	The condensation of moisture has increased somewhat over that at 42, but the rate permits productive use of ferrous materials with precision surfaces. Proper care is important with cleaning and oiling at the end of the usage is appropriate.
48	Moisture condensation occurs enough to intensify corrosion. Proper care is imperative. The surfaces, which have been exposed, will require monitoring and maintenance to avoid corrosion build-up.
50	Continuous attention must be given to corrosion maintenance. Proper maintenance of ferrous surfaces is imperative.
53	Corrosion occurs at a very high rate.

Relative Humidity is usually a minor problem but needs to be monitored. If the CMM uses laser interferometer scales or if the machine is calibrated with a laser interferometer, the index of refraction of air is affected by humidity. This error is approximately 1 part per a million for every 30% change in relative humidity. Most laser interferometers have readily available compensation techniques. Granite is a hygroscopic material that will distort when subjected to liquids or a long-term high relative humidity. Since the reaction time of granite is very long if the granite does distort it will require a very long soak out time to stabilize. The oxidation or rust of steel surfaces is the prime reason that relative humidity needs to be controlled. The table above demonstrates the effects of relative humidity on ferrous material based upon a study done by the US Air Force in 1979 (Reference 12).

B89.6.2 (Reference 13) recommends 45% RH as the upper limit. Both National Conference for Standards Laboratories International documents NCSLI RP-7 (Reference 14) and NCSLI RP-14 (Reference 15) recommend a maximum of 50% RH be maintained for metrology laboratories. Electrostatic Discharge (see also Paragraph 3.4) is also a concern with sensitive instrumentation, such as computer chips so it is recommended that the lower limit of relative humidity be 20%.

5 Assessing Thermal Effects

5.1 Temperature Measurement

Temperature measurement is an important ancillary measurement in dimensional measurement. Coordinate measuring systems must account for several effects due to temperature. The air temperature within the measuring volume and the thermal gradients within that volume are but one aspect. The details of the CMM thermal environment rated conditions and the instructions on the temperature measurements needed to verify the environment are given in ASME B89.4.10360.2 § 5.1.1. Provided the thermal environment is in compliance with the environmental rated conditions then no derating of the CMM is allowed and the MPE specifications describe the accuracy of the CMM (as described by the testing protocol) for all combinations of conditions that are within the rated conditions. To fulfill the requirements of the environmental rated conditions, ASME B89.4.10360.2 § 5.1.1 also provides information describing the requirements of the environmental temperature measurements. For CMMs equipped with temperature sensors (either for measurements of the CMM structure temperature or for the workpiece temperature), the impact of the uncertainty of these sensors is included in the CMM's accuracy specifications and there are no changes to the MPE values. If the CMM requires the user to provide a temperature measurement, of either the thermal environment or of the workpiece temperature, and the user satisfies the temperature accuracy (as stated by the CMM manufacturer) then the impact of the uncertainty of these sensors is included in the CMM's accuracy specifications and there are no changes to the MPE values. If the CMM manufacturer does not specify the allowed error of the temperature measurements, or the error of temperature measurements exceeds the allowed error, then this additional source of uncertainty must be considered in addition to the MPE of the CMM.

Appropriate temperature measuring instruments are selected to ensure the accuracy is sufficient for the target temperature, the sensitivity is adequate for the measurement, and the response time is fast enough to detect changes during the measurement process. All temperature measuring instruments should have appropriate traceability with sufficiently low uncertainties.

Temperature measuring instrument selection should also take into account whether the instrument is measuring the temperature of the air, the machine, the measuring surface, or the temperature of the item being measured by the coordinate measuring system. Different thermometers or temperature probes are selected for the temperature measurand selected. Sensor design vary dependent upon application, such as air temperature, internal material temperature, or surface temperature.

Resistive temperature devices such as Platinum Resistance Thermometers (PRT) and Thermistors are generally preferred for their accuracy. PRTs are very accurate (<0.1°C) but are susceptible to shock and vibration. Thin-film PRTs are useful for air or surface temperature measurements and are less susceptible to shock or vibration. Thermistors can be designed to be very accurate (<0.5°C) and are not as susceptible to shock or vibration. Several sensor designs are available for a variety of applications.

Thermocouple-type thermometers are typically accurate to within ±2°C and can be calibrated with uncertainties around ±0.6°C. Several sensor designs are available for a variety of applications.

Infrared (radiation) thermometers are not recommended as these instruments display an average temperature of the heat radiated by a surface and are generally not very accurate (±2% of reading) and the measurement uncertainties associated with their traceability are relatively high. Surface emissivity is a factor with radiation thermometry measurements as emissivity is not usually well known and items being measured are not always uniform in material content or surface finish.

5.2 Drift Testing

The manifestation of a changing thermal environment can often be evaluated by a drift test. A drift test assessing the effect of the thermal environment on the CMM structure is described in ASME B89.4.10360.2 § 7.1.3.4.3. This drift test evaluates the changes in the CMM but does not appreciably assess the impact of the changing thermal environment on the workpiece. The uncertainty introduced on a workpiece measurement due to changing thermal conditions can be evaluated by the workpiece thermal variation error (WTVE) drift test as follows. Fixture the workpiece in a manner similar to that of production measurements. Create a CMM measurement program that includes each feature of interest and measured in a manner similar to that of an actual production measurement, including datuming on workpiece features and CMM probe requalifications (if they occur during actual production measurements). Loop the measurement program so that approximately six full measurement cycles occur per hour and conduct the test for as long as practical, preferably for 24 hours. The WTVE standard uncertainty associated with each workpiece feature, u_{WTVE}, is given by the standard deviation of all the measured values for that feature; a u_{WTVE} value is computed for each feature of interest on the workpiece.

5.3 Thermal Derating

If the user’s thermal environment is outside the CMM’s rated conditions, then the CMM’s accuracy specifications (the MPE values) are not assured. If the CMM manufacturer agrees to derate the accuracy specifications according to ASME B89.4.10360.2 § 7.1.3.4.5 then the derated MPEs can be used to characterized the point coordinate measurement capability of the CMM and employed in evaluating the measurement uncertainty of workpieces as described in section 3.7. The derating should represent the actual environmental conditions present during production measurements. If the CMM manufacturer has not agreed to derate the CMM, either because the CMM is very inappropriate for that environment or because the user has subsequently changed the environment of an established CMM, then the derating process is speculative and should only be considered as general guidance.

6 Assessing Vibration Effects

6.1 Foundation Vibration Testing (Based on B89.4.22)

Coordinate measuring machines available today are capable of obtaining extremely accurate measurements. However, external sources such as vibrations from machine tools, climate control systems, materials handling systems, etc., can significantly degrade both the accuracy and repeatability. Thus, an understanding of the magnitude of external vibration excitation is an important part of the installation site qualification. By far the biggest contributor to this degradation is vibrations that are transmitted through the floor, having a particularly negative impact on the repeatability. Vibration limits are usually defined in the manufacturer’s specification.

It is good practice to locate the CMM in an area where vibrations are minimal or less than the CMM manufacturer’s specification. If this is not possible, site surveys should be performed to determine the vibration’s magnitude and frequency orientation of the foundation. The following should be considered when a site survey is made:

(a) Choose a reputable vendor to record the data with the appropriate equipment. The sensors must be responsive to the low frequency vibrations.

(b) Discuss with the vendor the frequency range that is important to their machine and what data is to be recorded. Normally the CMMs are most affected by vibrations in the 10-30 Hz range but data should be recorded through the 5-60 Hz range.

(c) Tell the vendor what format the analysis and output should be. Usually the CMM supplier wants the data in amplitude versus frequency or acceleration versus frequency.

(d) When the data is recorded, it is highly recommended that any adjacent equipment that may be running when the CMM is expected to be in use should be operating during any vibration testing. This includes not only machines but cranes, tow motors, and air compressors. If rail tracks are in the vicinity, record the data when a train is passing by. Record the data when all individual elements are operational. In some cases it is easier to identify and isolate the source of the vibration than to isolate the CMM.

(e) Record the vibrations in three orthogonal directions and the three rotational modes. Usually the three directions are the vertical, and the two horizontal (east- west, north- south for example) directions. Vibration testing should typically have a minimum duration of 30 minutes.

The effect of vibrations, typically characterized by amplitude versus time or frequency, is usually minimized by the use of either an active or passive isolation system. Installing the most appropriate isolation system depends upon the specific engineering requirements of the application and the desired vibration characteristics and is usually best left to a site vibration specialist.

Evaluate the results of the site survey against the manufacturer's requirements and determine if the site is suitable for the CMM to operate. Use the manufacturer's expertise to better analyze these results and then consider the recommendations before making a decision on how to improve the performance in a harsh environment.

The most common method used is the passive system approach. While there are different configurations for passive systems, they all incorporate the use of springs and an inertial confinement block, typically made from either concrete or steel. Typical configurations are as shown. Note that the springs may not actually be springs, (in some cases isolation pads are used) but can be modeled as a spring with certain stiffness. Typical pad materials include neoprene, felt, fiberglass, or other similar compressive material. Their natural frequencies are generally between 5 Hz to 30 Hz. Pad stability can be an important consideration. Some material properties change as a function of time, i.e. many get harder, and thus the natural frequency of the pad increases, resulting in a decrease in their effectiveness.

An active control system uses a series of transducers that produce a force that is equal in frequency and amplitude to the vibration present, but is 180 degrees out-of-phase with the input, with the net effect that the two forcing sources cancel each other out.

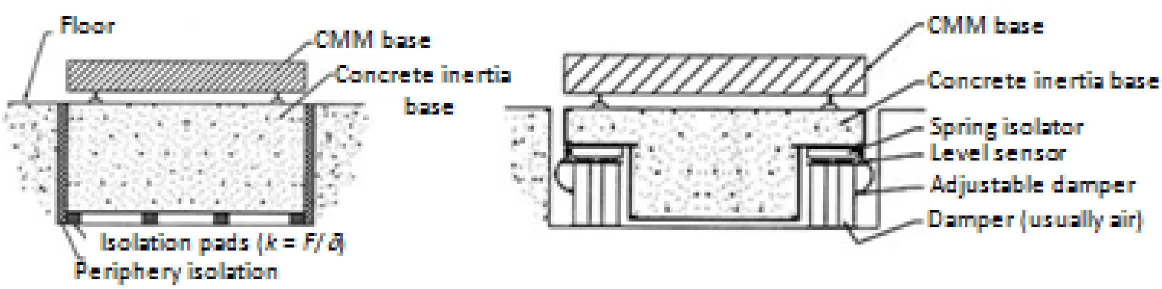

Figure 6.1-1: Passive and Active Isolation Systems

Generally, CMM manufacturer's offer standard isolators which dampen the floor vibration and are effective for vibrations above 25 hertz. For vibrations between 15 to 25 hertz medium cost isolator pads may be available. For vibrations below 15 hertz, air vibration isolation systems are available. When isolating the CMM, no isolation occurs until the floor vibration frequency is above 1.5 times the natural frequency of the isolation system. The lower the natural frequency of the isolator system the more it will reduce the floor vibration. As the natural frequency is lowered, the system becomes less stiff. This allows the CMM to rock when the axes accelerate or decelerate. The rocking can cause repeatability problems for the CMM. To reduce the rocking damping may be needed or the isolators may need a larger foot print than the CMM base.

An effective method to determine the vibration levels at a proposed CMM site is to place a set of tri-axial vibration transducers (with suitable calibration and traceability) on the floor where the CMM is to be installed, or installed on a common interface. The area monitored is typically about 3 meters larger than the footprint of the machine. These transducers produce an output signal that is proportional to the vibrations at the site. This signal is recorded, analyzed by frequency, and compared with the manufacturer's vibration criteria specification. A review of the data is used to confirm the site suitability and determine if any vibrational derating is required.

6.2 Relative Motion Tests for Vibration

6.2.1 General

Ultimately, the user is concerned with the influence of site vibration on the measurements taken with the CMM. Testing of these influences, and their effect on performance testing, are detailed in the sections that follow.

6.2.2 Historical testing

For older installations, when the machine was originally installed, relative motion tests, lasting at least 10 minutes, may have been performed under the same conditions as existing during the performance testing. The results of such testing were considered acceptable if the relative amplitude measured between the machine ram and the work table was less than 50% of the machine working tolerance for repeatability. In the event that the test specification was not met, the machine specification was de-rated such, that the required repeatability was equal to the measured repeatability on an axis-by-axis basis.

6.2.3 Recent Methodology

From the latest standards on acceptance and reverification tests, allowable limits for permissible environmental conditions such as temperature conditions, air humidity and vibration at the site of installation that influence the measurements shall be specified by the manufacture (acceptance) and the user (reverification).

For newer installations, testing is performed in an environment that complies with the CMM manufacturers specifications, usually expressed as ranges of thermal parameters. In practice, the actual test is performed in a particular condition only, as it is usually impossible for time and cost reasons, to repeat the test many times while varying temperatures, gradients, vibrations, etc. The strong sensitivity of CMM performance to the environmental conditions is well known; as a result, the environment may significantly affect the test result.

The repeated measurements of the same artifact yield slightly different results due to such factors as probing noise, vibrations, backlash, etc. As each calibrated reference length is measured in each location only three times, any statistical analysis is problematical, giving potentially different errors of indication. The problem results from the stipulated test procedure, which specifies the number of repeated measurements, and allows the test to be performed just once if the manufacturer's environmental specifications are met. The rationale for this is a trade-off in the interest of economic feasibility, based on educated experience that most CMM behavior is captured by this test and with the awareness that more extensive coverage could only be achieved at an unacceptable cost.

6.3 Instrument Internal Sources

Motion of the CMM carriages during measurements can excite vibrations within the CMM structure. The forces necessary to move the probe to the measurement position can induce oscillatory motions in the CMM structure and this can result in a stylus tip's location that is not fully accounted for by the CMM scale readings. Large CMMs with long rams typically have low frequency oscillations (e.g. 1 Hz) while smaller CMMs may have oscillations in the range of 10 Hz. CMM manufacturers carefully tune the drive systems of the CMM to minimize these effects. Another mitigation strategy may include settling times after a high speed motion in order to allow oscillations to die out; these effects are particularly relevant for larger CMMs. The CMM user should be aware that changing the probe tip approach velocity, acceleration, settling time, or approach (also called standoff) distance can affect the vibrational excitation spectrum and hence affect the accuracy. The CMM accuracy, as quantified by B89 performance specification values, is only assured when the CMM is operated within the rated conditions for probing velocity, acceleration, settling time, and approach distance as specified in the CMM user manual (or similar specification documents). Additionally, the CMM manufacturer may require that the probe be requalified if any of these parameters are changed; failure to do so may result in the CMM operating outside its rated conditions and hence may have degraded accuracy.

7 Managing Thermal and Vibration Effects

7.1 Instrument Specifications

The CMM manufacturer is responsible for stating the required conditions, including the thermal and vibrational conditions, within which the CMM will perform to its specified accuracy (the MPE values). The CMM user is responsible for providing an environment satisfying the rated condition requirements with the CMM operating in the room including any necessary auxiliary equipment. The user can expect that the CMM will perform within its specified accuracy under any combination of conditions that are within the rated condition requirements. However, the ASME B89 performance specifications apply to the results of the particular tests and testing artifacts described in the B89 Standard. For example, the Standard specifies the CMM length measuring performance based on a point-to-point length measurement. In some cases, the test artifact may be required to have a low thermal expansion coefficient as part of the rated conditions to achieve test results that are within the B89 MPE specifications (see ASME B89.4.10360.2 § 6.3.3.3) and hence such specifications may not reflect the materials used in typical workpieces. Additionally, workpieces may present additional uncertainties because their shape and size are different from that of standardized CMM testing artifacts; see the discussion in section 3.7 of this document.

The test values obtained from a single standardized performance test are just a snapshot of the CMM at the particular conditions that prevail at the time of testing and that changes in the thermal conditions and vibrational environment (that are within the rated conditions) will likely change the values obtained in any future performance tests. Consequently, any comparison of different CMMs should be based on the manufacturer’s specifications (MPE values) and carefully consider the thermal and vibrational rated conditions specified by the manufacturer.

7.2 Thermal and Other Environment Control

7.2.1 General

Decisions regarding temperature control of CMM inspection operations must often be made. There are often tradeoffs between the quality of the inspections and costs of time and capital. The relevant information for the appropriate decision includes feature tolerances, workpiece size and thermal response, workpiece material, CMM accuracy and its sensitivity to environmental temperature, temperature conditions in the area where workpieces are processed, skill of inspection personnel, etc. This section provides guidance by pointing out some of the advantages and disadvantages for the progressive levels of temperature control that may be considered. Some CMMs are designed to operate in a shop environment with no additional control. This may be appropriate. Another option is to provide a simple “passive enclosure” which is relatively inexpensive and provides some isolation from the environmental fluctuations of the shop. A third option is a temperature controlled enclosure, “active enclosure,” which generally provides more temperature stability but may be considerably more expensive. When more than one CMM operation is to be controlled, it may be most cost effective to enclose them all within a single temperature controlled room.

The use of a “factory floor” CMM may be appropriate. In addition to thermal compensation, these systems often employ air bearing systems with “double sweep” technology. A supply of pressurized air clears the path for the bearings to sweep on a clean table, therefore any dust or debris located on the pathway is swept clear, prior to the lift being made for the bearing itself.

Thermal compensation is imperfect. The accuracy of compensation depends on predictions of machine behavior based on temperature information at the location of temperature sensors. Many systems apply only linear approximations for compensation. There may be sensors mounted at the extremes of the working volume with compensation for each direction coming from a linear interpolation. This may be adequate when temperature changes slowly and the workzone and workpiece maintain a relatively uniform temperature, However, rapidly changing temperatures may cause temperature gradients which are nonlinear and compensation may not perform as expected. Manufacturer specification and limits for environmental conditions, as stated in rated conditions described by B89.4.10360.2, should be examined carefully in comparison to the expected operating environment. When workpiece tolerances and other factors do not allow the use of a "factory floor" CMM, some type of enclosure should be considered.

7.2.2 Thermal Enclosures

There are two types of enclosures: passive and active.

Ideally the CMM is located inside a climate controlled lab at 20 °C and the workpiece temperature is stabilized at 20 °C. This is when the CMM measurements are the most accurate. However, as the CMMs are used for process control, they need to be nearer the manufacturing process. If the CMM is located near the manufacturing process some decisions need to be made about how to best protect it from these harsher conditions and provide an environment where adequate measuring accuracies can be achieved. Some CMMs are offered with enclosures to protect them from the contaminants found in the shop environment:

(a) Dust
(b) Coolant mist
(c) Changing temperatures
(d) Mean temperature other than 20 °C.
(e) Noise/vibration

7.2.3 Passive Enclosures

If the CMM needs some additional protection one must decide if a passive enclosure is adequate or if a temperature controlled room is required. Passive enclosures may provide some damping of high frequency temperature variation in the vicinity of the CMM, but offer little control against low frequency oscillations in temperature. Consequently, a passive enclosure may be an economical solution to mitigate high frequency temperature variations. A fan should be provided to prevent hot spots inside the enclosure. An external fan with a filter on the enclosure may be provided which will additionally provide a slight positive pressure with filtered air to minimize dust build up on the CMM. Both the workpiece and the CMM will be buffered from quick thermal changes. Temperature compensation will aid in correcting for workpiece and CMM thermal expansions to report measured dimensions corresponding to their 20 °C value. They require little additional space and are easily moved if the CMM is relocated.

7.2.4 Active Enclosures

To make more accurate measurements a temperature controlled enclosure can be used. These enclosures may cost as much as the CMM itself, depending on size and how accurately the temperature must be maintained. They will maintain the CMM and the workpiece at a more stable temperature and keep them clean. Thus, the CMM may require less maintenance and less frequent calibrations, which somewhat offsets the additional cost of the room. These rooms typically occupy two to four times the floor space of the CMM.

The results from any enclosures will be disappointing unless steps are taken to stabilize the workpiece at 20 °C before measurement. To ensure the workpiece is at a constant temperature during measurement, the workpiece must be brought into the room already at the room's temperature or adequate soak out time and workpiece storage space must be provided in the room. A workpiece washer with the wash fluid temperature set to the room temperature will quickly stabilize the workpiece temperature. These workpieces can then be brought into the air-conditioned room.

An alternate active approach is an air curtain at 20°C that blows upward from the floor.

7.3 Thermal Compensation

7.3.1 General

There are additional sources of uncertainty of measurement that must be considered when taking measurements on the shop floor versus in a lab at 20 °C. The accuracy of the CMM, as specified by its MPE, is valid only when the CMM is within its rated operating conditions. Measurements made outside the rated operating conditions do not have assured accuracy. In some cases, the CMM manufacturer may specify the MPE as a function of environmental conditions. In general, the specified MPE will be smaller (more accurate) in laboratory environments near 20 °C than on shop floor conditions.

The specified MPE refers to the measurands measured during standardized testing, e.g., point-to-point length measurements, and to specific materials, e.g. steel gages. Additional workpiece uncertainties depend on the workpiece material, the measurand, the sampling strategy (number and locations of the measurement points), and workpiece fixturing (particularly in a changing thermal environment).

Based on "thermal resonance" there are two approaches to CMM or CMM component design. The first is to design for very long time constants so that environmental variation periods are short compared with these time constants. The second is to design for very short time constants so that environmental variation periods are long compared with time constants. Both approaches avoid "thermal resonance." Both approaches are often found in the design of the same machine.

7.3.2 Machines without Thermal Correction

If a CMM and workpiece are at a constant homogeneous temperature other than 20 °C, an additional induced measurement error is the differential thermal expansion. Thus, in theory the thermal error is close to zero if the two CTEs are equal. Some CMMs are designed to this principle. Drawbacks to the approach are that such a CMM is designed to measure workpieces of a particular material (usually steel), the time response of the machine and the workpiece to environmental temperature may not be the same, and uncertainties of expansion add to the measurement uncertainty. However, such machines can give excellent results at temperatures near 20°C.

7.3.3 Machines with Linear Thermal Correction

Linear or "first order" thermal correction is the most common because it is the simplest to implement. The concept of linear correction is that measurements reported are corrected for linear homogenous expansion of both the workpiece and machine scales. Temperature sensors on the machine scales and workpiece are typically used and highly recommended. Issues of implementation of thermal compensation for the workpiece include uncertainty of the temperature values, and uncertainty of how well temperatures represent bulk temperatures of the workpiece. However, the main part of the nominal differential expansion (NDE) error is eliminated.

7.3.4 Machines with Geometric Thermal Corrections

Systems have been developed where temperature sensors are embedded in the machine frame and used to estimate temperature distribution. A finite element analysis (FEA) model can be used to estimate the CMM distortions, which are used to calculate measurement corrections. The workpiece is modeled at a uniform temperature. Such systems can correct most of the thermal errors except for distortion and uncertainty of expansion of the workpiece. These systems are limited by how well the model represents the actual machine, and are also impacted by the temperature history prior to the measurement. The capital and maintenance costs of such sensors should be compared with the savings, which they make possible in the capital, maintenance and running costs of the CMM enclosure and temperature control system.

When the change of temperature during a measurement is small, the major thermal error source is the relevant differential expansion between the workpiece and scale. Such may be the case in a stable environment that is not at

20°C or when the distance between two points is measured within a short time relative to the rate of change of temperature. The correction to be applied is then straightforward.

However, if a significant temperature change occurs during a measurement, for example during the time taken to measure the distances from a datum to a large number of features, apparent shifts of the datum can be an important error source even after applying the above correction for the differential expansion. The shifts can be significantly reduced by fixing both the scale and the workpiece in the same axial plane, and by installing the scale reader in the same axial plane as the probe.

Since the positioning of workpiece clamps is variable, a good design would use a scale fixed at all points relative to the workpiece support surface. Unfortunately, this solution is only practical for the table axis.

7.4 Workpiece Handling

7.4.1 Mounting of Workpieces

Many CMMs are made from a combination of materials each with a different coefficient of thermal expansion. There may be a combination of granite, steel, aluminum and ceramic on the machine. On some CMMs the scale is allowed to freely expand or contract from the axis structure. Typically, the scale will be pinned at some location to the axis structural element and allowed to expand or contract from this point. The scale may be attached with foam tape, which holds the scale normal to the axis but the low shear rate of the tape allows the scale to expand freely at a rate equal to the scale material. This known rate is used in temperature compensation algorithms.

When measuring workpieces with a CMM that does not have thermal compensation for the workpiece and scale, and where the temperature is changing the operator should be aware of this technique. Ideally it would be best to have the workpiece datum references coincide with the scale pinned locations. For example, with the X scale is pinned at the left side and the Y scale pinned at the front of the axis, the work piece should be secured to the table on the left side and front allowing the workpiece to expand to the right and the rear at its nominal rate of expansion. If the workpiece is over-constrained, e.g. which may occur when secured on multiple sides, then it will expand or distort at some combination of the table and workpiece expansion characteristics, resulting in additional measurement uncertainty.

7.4.2 Workpiece Soak Out Time

This section is to make the reader aware of the workpiece soak out times so they allow adequate time for the workpiece to stabilize so that more accurate measurements can be made. If measurement results are not needed immediately, the workpieces can thermally normalize to the ambient room temperature, after they are brought into the room. When a workpiece is moved into a different temperature, its temperature changes rapidly at first and then slows down as the workpiece temperature approaches the room temperature as in an exponential decay. The thermal time constant of a workpiece is the time for the workpiece temperature to be within approximately 63% of its final value if placed in a constant temperature. For a 20 °C change it takes 5 time constants for the workpiece to be within 0.1 degree of the room temperature. This period of time when the workpiece temperature is reaching equilibrium with the room temperature is called the “soak out time.”

(a) During the first stages of this time very large distortions of the workpiece may occur as well if the temperature differential is large. Workpieces should not be measured during this period. Soak out times will vary depending on the workpiece and its environment. Items effecting soak out times are:

(1) Workpiece Material
(2) Workpiece shape
(3) Surface texture
(4) Specific heat of the material
(5) Conduction coefficient
(6) Convection coefficient
(7) Temperature differential

(8) Ambient environment around workpiece

(b) Tests have been conducted on a 25 mm thick by 200 mm steel roller bearing cup to determine the soak out time for a 19°C change. The time was determined for the workpiece temperature to reach equilibrium with the room within 0.1°C (5 time constants). The soak out times were:

(1) 6 hours in still air
(2) 25 minutes with 600 m/min air blowing across workpiece
(3) 2 minutes if the workpiece is placed into a fluid bath at the room temperature.

(c) ASME B89.6.2 (pages 10 and 11) includes a coolant effectiveness chart for still and moving air and water on iron and plastic workpieces. From the chart one can conclude the following:

(1) Moving air versus still air reduces the soak out time by an order of magnitude.
(2) Using water instead of air reduces the soak out time by an order of magnitude.
(3) Agitating the water further reduces the soak out time by 3 orders of magnitude.
(4) Plastic workpieces take 2 orders of magnitude longer to soak out than metal workpieces.

Tests or analysis should be performed on actual workpieces if more accurate estimates are needed. For a more detailed discussion with examples, see Annex C.

7.5 Interim Testing

Interim testing is important and should be run to maintain confidence in the accuracy of the CMM as appropriate for the type of measurements and the risk associated by those measurements. The frequency and complexity of these tests will depend on the risk of an incorrect measurement and should be based on your quality management system. For a thorough discussion of this topic, refer to B89.4.10360.2, informative Annex H, Interim Testing of CMM Systems.

7.6 Handling Thermal Influences in Uncertainty Analysis

This section summarizes approaches to estimation of the contribution to measurement uncertainty caused by the response of CMMs and workpieces to thermal environments.

The uncertainty budget approach is to list all the significant sources of thermal uncertainty, estimate the magnitude of each contributor, combine the estimates, and expand the result to a suitable confidence level.

Another approach is to fit a formula for uncertainty contribution to the results of an analysis or test. The formula is used to estimate the effect of thermal environment over a range of conditions. Generally, the analysis or test is used to determine the values of coefficients it the formula.

In stimulated response testing the mechanisms causing thermal errors are identified, and tests are performed to determine the relationship of output to input for each mechanism.

In the FEA approach, the temperature distribution in each machine or workpiece element is estimated, and FEA is used to estimate distortions. Distortions are then used to estimate maximum workpiece measurement errors, which are taken as uncertainty contributions. Uncertainties estimated from models should have the model experimentally verified.

In a results-oriented approach, measurements are classified by type, and multiple measurements for each type are performed in the real CMM environment and in a controlled laboratory. Average differences are taken as thermal biases and distribution widths are taken as uncertainties.

8 Economic Considerations

8.1 General

As one analyzes the purchase of a coordinate measuring machine, cost is one important element to be considered, along with others such as speed and accuracy. One of the most frequently made mistakes is to consider the cost of the machine alone, and to not consider the cost of the coordinate measuring system as a whole. Sub optimization on cost, or accuracy, or speed typically leads to mistakes. A solution to this problem is to design the system first, including all aspects (the scale, the workpiece, the instrument (machine), the person, and the environmental issues) – then consider the total cost.

8.2 Cost Elements to Consider

8.2.1 General

A generalized complete measurement system may be characterized as five basic elements: a scale, a workpiece, an instrument, a person, and an environment (SWIPE). A brief discussion of each of these system components follows.

8.2.2 Scale

Some machines have optional higher resolution or low expansion scales (at additional cost). Depending on the material of the component being measured, the temperature control in the measuring area (lab or shop floor), and the accuracy required, it is likely that paying extra for low expansion scales will not significantly improve measuring accuracy.

Higher resolution scales may improve the repeatability of measurements, however once the scale resolution is significantly less than the machine accuracy, further improvement in measurement accuracy is unlikely.

8.2.3 Workpiece

Paying additional cost for thermal compensation for the workpiece should be analyzed carefully. For the beginner it would be good to seek advice from an experienced system designer in the process of making such investment decisions. Investing in equipment to quickly bring the workpiece to a stable temperature (without internal thermal gradients) that is as close as possible to the CMM scale temperature may be a better investment.

8.2.4 Instrument

One of the most frequent mistakes on choosing which machine to purchase is to try and save money by buying a small machine – and to not give adequate consideration to required probing clearances, space for work holding devices, clamps, etc. do not save money on the size of the measuring cube. A rule of thumb is to select the largest component that will be measured, and add 250 to 300mm on all sides that have features to be measured (especially for machines equipped with articulating probe heads). A good place to save is by selecting the correct accuracy class of machine. Many CMM models are sold at 2 or 3 different accuracy levels. Normally, the highest accuracy is not needed – and in fact, depending on the environmental (thermal) situation, this accuracy may not be realized if not used in the rated operating environment.

8.2.5 Person

Buy the most and highest quality training available. Training in how to program and operate CMMs is vital. In general many things are hard to learn by reading a manual, and most software is not intuitive. Two important points about training:

(a) before sending an operator or programmer to training class make sure they have at least some exposure to an existing CMM installation by letting them work with someone who is running the machine. Going into a class “cold” is extremely difficult and there will be others in the class who will push the instructor to move faster resulting in the beginner quickly becoming lost.

(b) ensure that you know the specific instructor of the class, their background, and ability to teach. It is very helpful if they have had “real” experience programming and measuring workpieces.

8.2.6 Environment

When purchasing environmental enclosures ensure that the temperature control provided is in accordance with the manufacturer’s recommendations for vertical and horizontal gradients, rate of change per time, and range of the temperature in the enclosure. Providing the recommended level of air cleanliness, lighting intensity, and humidity control are also important considerations. However, providing excess control adds little to system performance, and much to system cost. In the event that the machine is designed for installation in a “factory” environment – the most important consideration is to provide a method to quickly bring the workpiece to a stable temperature – either at the CMM scale temperature, or at the “shop ambient” (which should be close to the same). This results in a workpiece temperature that can be mathematically corrected.

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NONMANDATORY APPENDIX A
OVERVIEW IN THE USE OF TEMPERATURE CONTROL FOR METROLOGY OF WORKPIECES

When the environment is controlled to a steady 20 °C, temperature effects are significantly reduced. If the CMM has stabilized to 20 °C, the scales do not need to be compensated for temperature. Assuming the workpiece to be measured has adequate time to soak out and stabilize to 20 °C its size as measured does not have to be compensated. A common method to minimize temperature variation is to provide an enclosed area in which the temperature is controlled.

The enclosed area should be temperature controlled independently of the temperature outside of the room and be heated and air conditioned as the temperature outside of the room changes. In addition, the air inside the room must have frequent turnovers so it does not stratify. Caution should be exercised when using a typical air conditioner as these units typically cycle on and off, and can induce local thermal gradients. These units operate by bringing in outside air and the compressor cycles on and off depending on the thermostat on the wall. Also, the temperature on the wall is typically not the same as the temperature surrounding the CMM. The air coming out of the air conditioner typically changes 5 degrees C or more depending whether the compressor is on or off. If the air blows directly on the CMM, the CMM and workpiece are exposed to an air temperature change every cycle. This may be worse than no air conditioning and using temperature compensation on the CMM.

The CMM internal temperature may be subject to some thermal instability from non-steady state internal heat sources such as motors, even though the room temperature is constant. One way of testing this is to measure the temperature inside the covers of the CMM near the encoder or scale area when it is idle and again after the CMM has inspected workpieces for an hour to see if heat is being trapped inside the covers. The workpiece temperature may also be influenced by heat sources internal to the CMM. If the temperature does change slowly and is homogeneous, temperature compensation can effectively be used to correct for this temperature growth.

In a well-controlled room, workpieces need time for their temperature to reach that of the room. This is the soak out time. This can be three hours for thin walled sections to 24 hours for items such as castings with wall thickness up to 20 mm. As discussed in other sections of this document, a movement of air from a fan across these workpieces will reduce the soak out time by an order of magnitude.

By working in a temperature-controlled environment, the temperature of the probe styli is constant and the need for tip re-qualification is greatly reduced. Anytime the stylus is changed manually, the stylus will heat and expand due to hand contact. Styli should be requalified after changing by hand, and on aluminum or steel extensions one should wait approximately 15 minutes before re-qualification. If cotton gloves are used when changing styli, this will greatly reduce the heat transfer and the wait time can be reduced to a few minutes.

Therefore, the ideal condition is to measure the workpieces that have had adequate time to soak out in an air-conditioned room at 20 °C. Use temperature compensation to reduce the effects of machine temperature warm up inside the covers and workpiece temperature that has not completely soaked out. By controlling the environment close to 20 °C, this will greatly reduce the error caused by the Uncertainty of Nominal Differential Expansion (UNDE) because the temperature difference from 20 °C is a small number, when approximately a degree or less. When both the CMM and workpiece do not have distortions from large changes in temperature, these effects are greatly reduced. A CMM with temperature compensation will correct for these small expansions or contractions from items not being at exactly 20 °C at the time of the compensation and the temperature sensors can monitor any abnormal temperature changes during the measurement process. If the temperature of either the CMM or the workpiece is changing, the thermal compensation should be updated frequently – consult the manufactures recommend practice and rated operating conditions.

NONMANDATORY APPENDIX B
THERMAL TIME CONSTANTS, SOME WORKED EXAMPLES

Prior to reviewing the examples shown in this Appendix, it is strongly recommended that users review Section 3.5 of this Technical Report and ANSI B89.6.2, with an emphasis on Section 10.

The thermal time constant (τ) may be calculated from equations (B-1) or (B-2) below which are reproduced from ANSI B89.6.2.

$$\tau = \frac{CV}{hA} \quad \text{(B-1)}$$

Where

V = volume, m^3
A = surface area, m^2
h = convective film coefficient, W m^{-2} K^{-1}
C = thermal capacitance, J m^{-3} K^{-1}

The thermal time constant may also be expressed as:

$$\tau = \rho c_{pressure} \frac{V}{hA} \quad \text{(B-2)}$$

Where

ρ = the mass density, kg m^{-3}
$c_{pressure}$ = the constant pressure heat capacity, J kg^{-1} K^{-1}

and *V*, *h* and *A* are as previously defined.

Typical values for the thermal capacitance for a number of common materials are shown in Table B-1.

Table B-1: Thermal Capacitance of Common Engineering Materials

Material	*C*	Material	*C*	Material	*C*
Aluminum	660	Copper	920	Stainless Steel	1,100
Beryllium Copper	770	Granite	600	Titanium	640
Brass	880	Invar	1,140	Zerodur	550
Bronze	900	Mild Steel	990	-	-
Cast Iron	1,030	Nickel	1,120	-	-

A typical value for a convective film coefficient in slowly moving air over a flat plate is about 5.6 W m^{-2} K^{-1}. The convective film coefficient (*h*) can be increased to about 56 W m^{-2} K^{-1} by increasing air velocity over the plate. If the geometry of the item is changed from a flat plate to a group of thin, parallel fins and the air flows parallel to (along) the fins, then the convective film coefficient will be much greater than 56 W m^{-2} K^{-1}.

In most cases, the fluid medium will be slowly moving air. For such a situation, assuming a value of 11.5 W m^{-2} K^{-1} for the convection film coefficient is usually adequate. For additional information on estimating thermal time constants, thermal soak out times or fluid heat transfer properties, see ANSI B89.6.2 - *Temperature and Humidity Environment for Dimensional Measurement* or any text book on heat transfer.

The following examples illustrate the calculation of thermal soak out times.

Example 1 - Gage block

It is required to estimate the thermal time constant of a 250 mm long steel gage block. The block has a cross section of 25 mm by 25 mm. The assumed environment is slowly moving air.

The surface area (*A*) of the block is found from

$$(250 \times 25 \times 4) + (25 \times 25 \times 2) = 26{,}250\ mm^2\ or\ 0.0263\ m^2 \qquad \text{(B-3)}$$

The volume (*V*) is found from

$$(250 \times 25 \times 25) = 156{,}250\ mm^3\ or\ 0.000156\ m^3 \qquad \text{(B-4)}$$

The value of thermal capacitance (*C*) for steel is taken 990 J m^{-3} K^{-1} and the convective film coefficient (*h*) is 11.5 W m^{-2} K^{-1}.

The thermal time constant can now be estimated from,

$$\tau = \frac{CV}{hA} = \frac{[990 \times 0.000156]}{[11.5 \times 0.0263]} \qquad \text{(B-5)}$$

$$= 0.51\ hours\ or\ 31\ minutes$$

The soak out time depends on an acceptable uncertainty and the magnitude of Δt, but a commonly applied rule of thumb is for the workpiece to be allowed to soak out in a constant temperature environment for 4τ, in this example for about two hours prior to any measurements being taken.

Example 2 - Ball Bar

For environments with small temperature differences between the ball bar and the environment, the heat flow is proportional to the difference between the temperature of the ball bar and the surrounding air and has an exponential decay with a thermal time constant τ in the equation

$$T_{bar} - T_{air} = Te^{-t/\tau} \qquad \text{(B-6)}$$

Tests were conducted at NIST to determine thermal time constants and their effects on the measurement of ball bars. Two 900 mm ball bars made of stainless steel and invar were used as the artifacts. The rod between the two balls was a hollow tube of 25 mm outside diameter with an internal diameter of 18 mm. The ball bar was placed into a refrigerator and the temperature lowered to 10 °C. The ball bar was then removed from the refrigerator and placed on the CMM table in a 20 °C environment. Measurements of the ball bar length and its temperature were made as the ball bar warmed in the 20 °C ambient environment. The results are shown in Figure B-1. The thermal time constant was nearly the same for both the invar and the steel. The time constant was 16 minutes for these artifacts in still air.

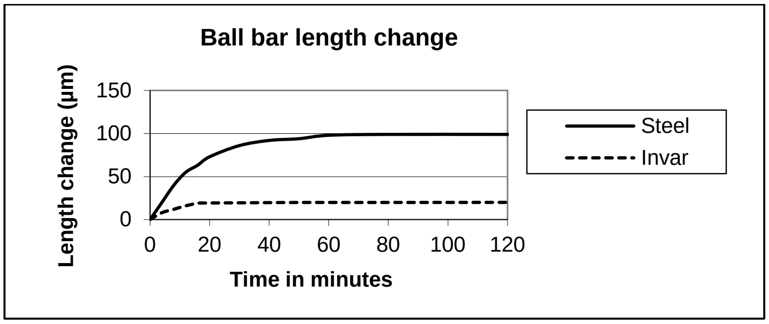

Figure B-1: Change in Ball Bar Length as a Function of Time

However, the materials have much different coefficients of thermal expansion. The stainless steel ball bar changed 0.100 mm and took 75 minutes to stabilize within 0.001 mm of its length for a 10 degree change. The invar ball bar grew 0.020 mm and took 20 minutes to stabilize within 0.001 mm of its nominal length.

For additional information, see Reference 16.

The following example illustrates the calculation of a thermal soak out time for a ball bar. The ball bar can be considered as being made up of three elements, two spheres and a cylinder. The surface area and volume for the elements are shown in Table B-2. For a ball bar, the ends of the cylinder are ignored as they are covered by the spheres.

Table B-2: Summary of Surface Areas and Volumes

Element	Surface area (m^2)	Volume (m^3)	Ratio (V/A)
Sphere	$4\pi r^2$	$\frac{4}{3}\pi r^3$	$\frac{r}{3}$
Cylinder	$2\pi rL$	$\pi r^2 L$	$\frac{r}{2}$

The properties of the spheres will be constant regardless of the length of the bar. Considering a 25 mm diameter sphere, then substituting the value of r = 12.5 mm into the equations for the sphere gives the surface area as 0.001963 m^2 and the volume of 0.000008181 m^3.

The length of the ball bar is from the center of one sphere to the center of the other. The length of the cylinder can then be found by subtracting 25 mm, i.e. two radii.

Ball bars are usually manufactured in millimeter lengths. Table B-3 shows the surface area and volume for a number of different length ball bars, each with 25 mm diameter spheres attached.

Table B-3: Surface Area and Volume as a Function of Length

Length (m)	Length of cylinder (m)	Surface Area (m^2)	Volume (m^3)
0.300	0.275	0.021601	0.000135
0.500	0.475	0.037311	0.000233
0.700	0.675	0.053021	0.000331
0.900	0.875	0.068731	0.00043
1.000	0.975	0.076586	0.000479
1.200	1.175	0.092296	0.000577

The total surface area and volume can now be found by simply adding the three elements together as shown in Table B-4.

Table B-4: Ratios of Volume/Area as Function of length

Length (m)	Surface Area (m^2)	Volume (m^3)	Ratio of V/A
0.300	(2 × 0.00196) + 0.021601	(2 × 0.00000818) + 0.000135	0.005931
0.500	(2 × 0.00196) + 0.037311	(2 × 0.00000818) + 0.000233	0.006053
0.700	(2 × 0.00196) + 0.053021	(2 × 0.00000818) + 0.000331	0.006107
0.900	(2 × 0.00196) + 0.068731	(2 × 0.00000818) + 0.000430	0.006138
1.000	(2 × 0.00196) + 0.076586	(2 × 0.00080018) + 0.000479	0.006149
1.200	(2 × 0.00196) + 0.092296	(2 × 0.00000818) + 0.000577	0.006165

So, the ratios are almost constant, as one would expect because the volume/area for the cylinder is constant at $r/2$ and the contribution of the spheres is very small.

From Equation B-2, using the values of volume/area from Table B-4 and taking the value of thermal capacitance C for stainless steel as 1,100 J $m^{-3} \cdot K^{-1}$ and the convective film coefficient (h) as 11.5 W $m^{-2} \cdot K^{-1}$, the thermal time constant = [1,100 × 0.00609]/[11.5] = 0.582 hours or about 35 minutes, where 0.00609 is the average value of V/A.

Using the rule of thumb, the ball bar should be allowed to soak out in a constant temperature environment for 4τ for about 2.4 hours prior to any measurements being taken.

Example 3 - Channel Section

It is required to estimate the thermal time constant for a 75 mm aluminum alloy channel section that is 1.4 m long. Ignoring the radii, the channel is assumed to have a flange length of 25 mm and a constant thickness of 6 mm. The assumed environment is slowly moving air.

Ignoring the ends, the surface area (A) of the channel is found from

$$\{(75 \times 1{,}400) + 2[(25 \times 1{,}400) + (6 \times 1{,}400) + (19 \times 1{,}400)] + (63 \times 1{,}400)\}$$
$$= 333{,}250\ mm^2\ or\ 0.333\ m^2 \qquad \text{(B-7)}$$

The volume (V) is found from

$$[(75 \times 6) + 2(19 \times 6)] \times 1{,}400 = 949{,}200\ mm^2\ or\ 0.000949\ m^3 \qquad \text{(B-8)}$$

The value of thermal capacitance (C) for aluminum is taken 660 J m^{-3} K^{-1} and the convective film coefficient (h) is 11.5 W m^{-2} K^{-1}.

The thermal time constant can now be estimated from,

$$\tau = \frac{CV}{hA} = \frac{[660 \times 0.000949]}{[11.5 \times 0.333]} \quad \text{(B-9)}$$

= 0.163 hours or approximately 10 minutes

The channel should be allowed to soak out in a constant temperature environment for 4τ or about 40 minutes prior to any measurements being taken.

Example 4 – Composite Fan Blade

The final example uses a different approach from that presented in ANSI B89.6.2, but is reflective of many real-world examples. A composite fan blade has complex geometry and material properties that are difficult to analyze accurately to establish the thermal time constant. The cross-sectional thickness varies widely from root to tip as well as spanwise from the middle to leading and trailing edges. Additionally, any cross-section may be composed of materials ranging in conductivity. Therefore, the rate of temperature change varies by location, and temperature gradients exist during transient conditions. Most manufactured workpieces or assemblies have similar characteristics. For purposes of establishing an adequate "soak out time" for inspection of these workpieces, it may be most efficient and effective to find the thermal time constant experimentally.

Such a workpiece was instrumented with thermocouples (TCs) embedded into the center of the thickest cross-sections. Another TC was placed in the room air. A low temperature oven was used to uniformly heat the workpiece to 65 °C. The TCs were monitored to ensure stability before the workpiece was removed from the oven and placed on a rack in an air-conditioned room. The monitoring of all TCs continued for two hours with temperature recordings at 30s intervals. An example of the measured temperature data vs. time is shown in Figure B-2, labeled as TC4 and TC5.

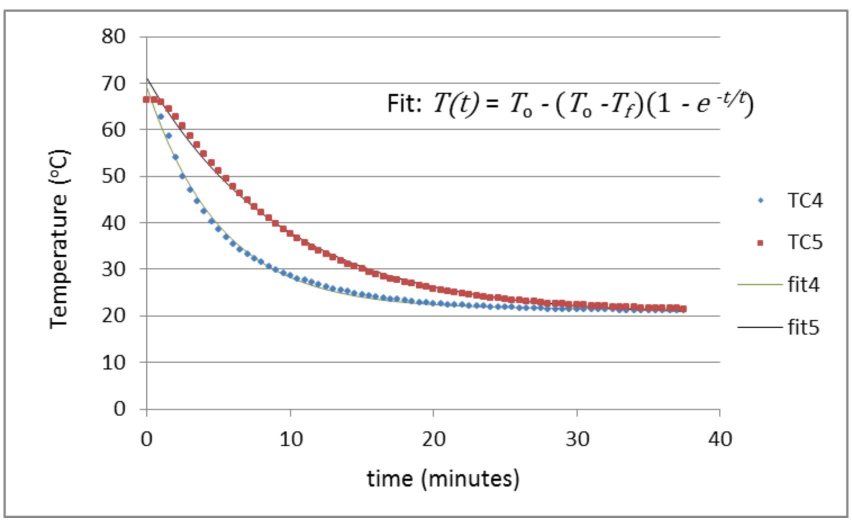

Figure B-2: Measured temperature vs. time together with calculated values using the thermal time constant, τ, obtained from a least-squares-error fit to the experimental data

$$T(t) = T_0 - (T_0 - T_f)\left(1 - e^{-t/\tau}\right) \quad \text{(B-10)}$$

Where

$T(t)$ = temperature at time, t
t = time
T_0 = initial uniform temperature
T_f = room temperature (final)

The value of each thermal time constant, τ, can be found by any number of fitting methods. For a least-squares-error solution, the error function is written as the difference between measured temperature and calculated temperature.

$$E = T(t) - \{T_0 - (T_0 - T_f)\left(1 - e^{-t/\tau}\right)\} \tag{B-11}$$

Then for all data points available the following value is minimized by adjusting τ.

$$\sum E^2 \tag{B-12}$$

The solver function in Microsoft Excel works well, for example. The line labeled fit5 in
Figure B-2 is the result of this procedure. The mathematical description of temperature, derived from basic heat transfer principles, agrees very well with measurements. For a given set of heat transfer conditions, the thermal time constant can be considered to be a characteristic of a specific workpiece. That is, the temperature at any time after a step change in environmental temperature is predictable regardless of initial and final temperatures. This is used to establish a soak out time.

Based on workpiece tolerance and required measurement accuracy, a value can be established which is the allowed temperature difference between a CMM and the workpiece. Given an initial temperature and thermal time constant, we can rearrange the temperature vs. time equation to find the time it takes to get to within X degrees of the steady-state temperature beginning at some other temperature.

$$T(t) = (T_f + X) = T_0 - (T_0 - T_f)\left(1 - e^{-t/\tau}\right) \tag{B-13}$$

$$t = -\tau \ln\left[1 - \frac{(T_0 - T_f - X)}{(T_0 - T_f)}\right] \text{ or simply, } t = -\tau \ln\left[\frac{X}{(T_0 - T_f)}\right] \tag{B-14}$$

Example: the values

T_0 = 35 (shop)
T_f = 20 (CMM room)
X = 1 ^{o}C
τ = 9.9 minutes

result in

t = 26.8 minutes

Using this version of the equation, graphs can also be constructed to predict the “soak out time” for different starting temperatures and different targets for final temperature. One is shown here as Figure B-3. Note that a procedure for “soak out time” based on workpiece-specific thermal time constants is better than a traditional “rule of thumb” such as 24hr minimum. A fixed time may unnecessarily affect cycle time for some workpieces while it may be insufficient for others. An “N × τ” procedure would be better. But this allows the temperature during measurement to vary depending on the starting temperature. If an acceptable allowed temperature difference from 20 °C can be established based on workpiece tolerances, then the use of a chart such as Figure B-3 may be most efficient.

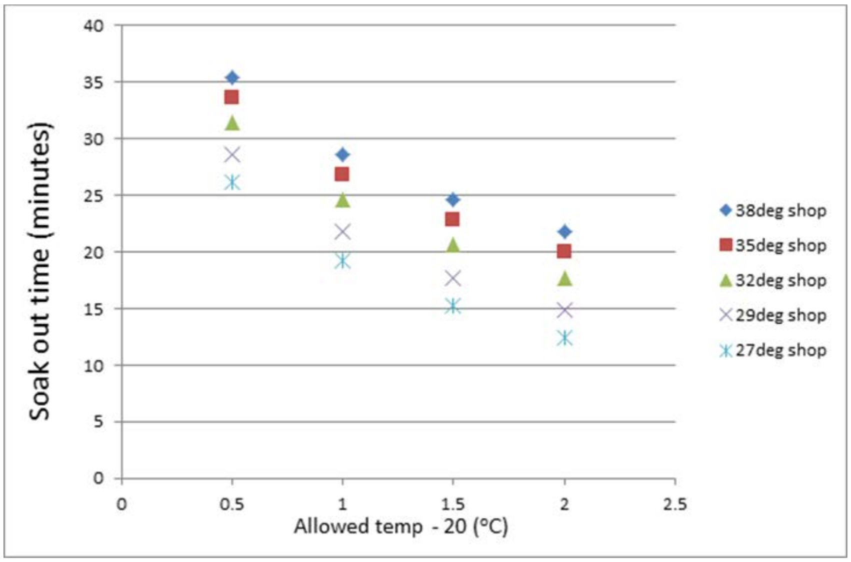

Figure B-3: Estimated soak out time for a workpiece coming from a shop area at some temperature into a CMM room with a nominal temperature of 20 °C

NONMANDATORY APPENDIX C
ILLUMINATION EFFECTS

C-1 Application to the Measurement Task

The objective of good lighting is a design that provides the balanced quantity and quality of light needed for the measurement task. The task may be performed in either a laboratory environment, or in many cases, out on the shop floor. Lighting designed specifically for a laboratory environment must meet the requirements of offices areas, where mixed visual tasks are often performed. A significant difference is that work piece surfaces in the measurement environment, simply due to the size of the workpiece, are typically at different heights. Hence many measurement tasks can be considered three-dimensional in nature, involving surfaces and planes at different elevations and even in vertical orientations. Thus, for good visual acuity, a balance should be obtained between horizontal and vertical work piece surface illumination.

Determination of proper intensity levels for illumination is to provide for optimal performance of a given measurement task. This includes not only the proper relationship between performance and illumination, but also such factors as avoidance of fatigue, physiological and psychological costs not reflected in the evaluation of performance, economics, and the cultural or emotional effects of light.

It is beyond the scope of this Technical Report to discuss the physiological factors that influence visual ability. A brief discussion of the physical factors that describe certain characteristics of the visual task and the environment in which it is seen appears to be in order, however.

When a work piece is viewed during the measurement task, there is a resultant subjective visual sensation that represents the completion of the ocular part of the visual activity at the moment. The seeing of all the things that have to be seen at that moment constitutes the visual part of any task, and the term visual task conventionally designates the sum total of all the things that have to be seen at the given moment. The data shown in Figures C-1-1 and C-1-2 generally shows that as operators get older both the amplitude of accommodation and the visual acuity decrease. This of course must be tempered with the corresponding increase in experience.

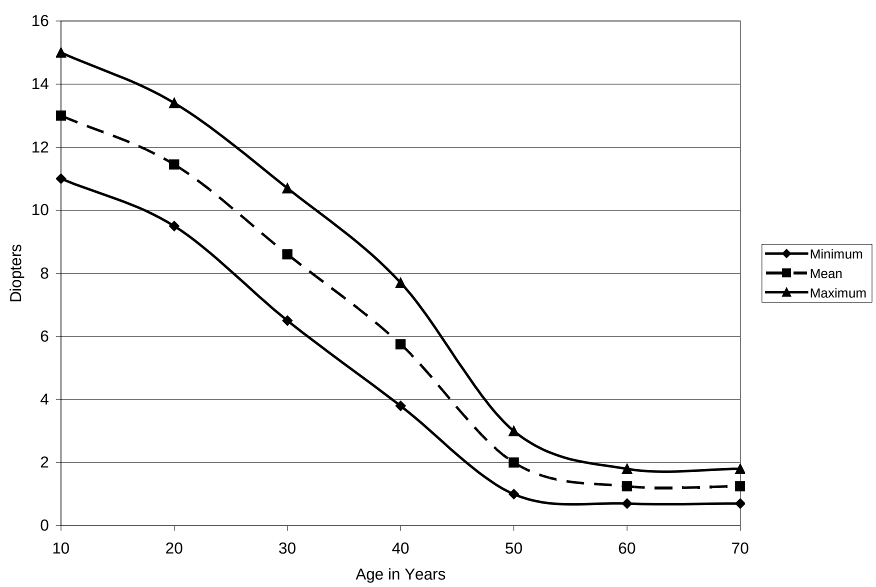

Figure C-1-1: Diopters as a Function of Age

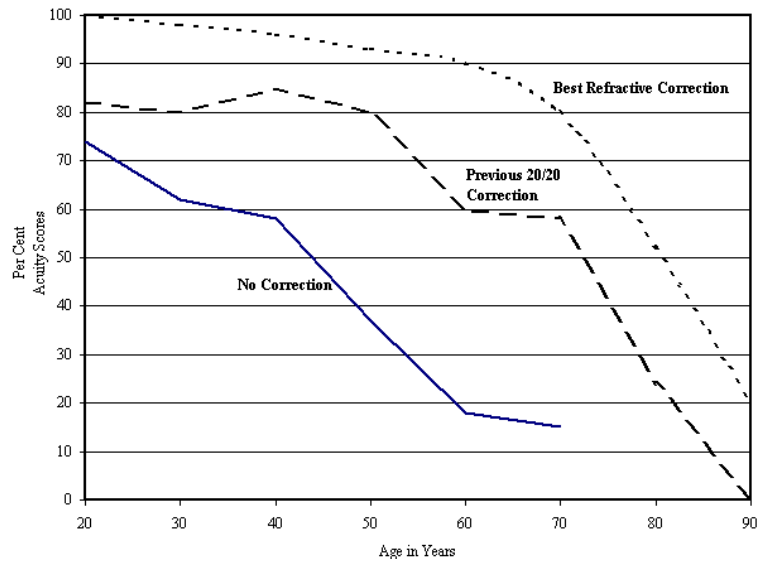

Figure C-1-2: Percent Acuity as a Function of Age

Obviously, the characteristics of the visual task change as a function of time. Consequently, in determining the adequacy of the illumination, these changes must be considered. A visual task can be described in terms of its size, contrast, luminance, and color. It may also be necessary to consider the length of time available to see the task.

It is obvious that the luminance in most measurement tasks is not constant, but consists of variations between objects and backgrounds. These luminance variations manifest themselves in the form of gradients or abrupt transitions, which are commonly termed contrast borders. The minimum perceptible contrast that can be seen is a function of the luminance of the background against which the object is seen. As the contrast increases, necessary luminance can decrease. One way to increase the contrast would be to use higher reflectance backgrounds.

Luminances in the visual field, which surrounds the task, can have different effects depending upon the areas involved, their location with respect to the line of sight and their values compared with that of the task. Since wide variations in these luminance's can be detrimental to visual ability and/or visual comfort, it is recommended that the whole field of view be as uniform as possible. This means that in the case of a visual task involving a simple object on a background, the entire surround should have the same luminance as the immediate background of the object. Since this is not readily available, it would be sufficient to have the field surrounding the task as uniform as possible with a luminance equal to the average of the central portion of the field in which the task is located.

Superposition of glare sources or stray light from glare sources on the otherwise approximately uniform luminance should be avoided since they may reduce visual ability, and could cause actual visual discomfort and fatigue.

When luminances and their relationship in the field of view cause visual discomfort but do not necessarily interfere with seeing, the sensation experienced by the observer is usually referred to as a discomfort glare. Discomfort glare is likely to be more of a problem during the measurement process than disability glare, where ability to see is actually impaired.

Discomfort glare is usually caused by direct glare from light sources or luminaires that are too bright, inadequately shielded, or of too great an area. It can also be caused by reflected glare from annoying reflections of bright areas in specular surfaces.

Proper positioning of light sources, work positions, position of the operator with respect to the task, elimination of shadows in the immediate area of the task and uniformity of luminance's in the surround will eliminate most causes of discomfort glare.

Reduction of visual ability due to veiling reflections can be minimized by controlling the amount of direct light that can be reflected into the eyes of the operator. Consideration should be given to the type of lighting used. Use of luminaire covers such as diffusers, prismatic lens, louvers, etc.; and proper orientation of the worker, the task, and the light source, can reduce the direct reflected glare of the incident light into the eyes of the operator from the visual task area.

C-2 Additional Considerations

Balanced vertical illumination can minimize contrast and thus enhance visual acuity. In a laboratory this can readily be achieved using what is called "wall-washing." As the name suggests, in this process, lighting is situated towards the edge of the ceiling and pointing down. Typically, a ceiling in any room will contribute more to the distribution of light than any other surface. To maximize this, if possible, a white or nearly white ceiling is highly desirable, resulting in reflectance values between 0.80 and 0.85.

With the degree of environmental control required in a dimensional measurement laboratory, as well as the requisite accuracy of the work performed there, there are three facets of illumination that directly affect one or the other that are frequently overlooked. These are the effect of the lighting on the environmental control, the effect of the environment on the lighting, and the maintenance of the lighting to assure reasonably constant illumination.

To attain uniform shadow less illumination between 1,000 and 1,600 lux of each work position, the total input energy pumped into the lighting system may be quite high. However, for a typical cool white fluorescent lamp only approximately 22 percent of the input energy goes into light, the other 78 percent as heat with about 36 percent infrared and 42 percent being dissipated. Or, in terms of illumination, if all of the energy in any light source could be converted into yellow-green light, (555 nanometers) the theoretical best visible light, the luminous efficacy of the source would be approximately 680 lumens per watt. Unfortunately, due to manufacturing variables, chemical changes, wavelength conversions etc., the luminous efficacy of a typical cool white fluorescent lamp after its first 100 hours of operation is approximately 77 lumens per watt. Here again, this luminous efficacy is also a function of the arc length of the tube, and could be as low as 33 lumens per watt for the shorter tubes. The energy distribution for a typical cool white fluorescent lamp is shown in Figure C-2-1.

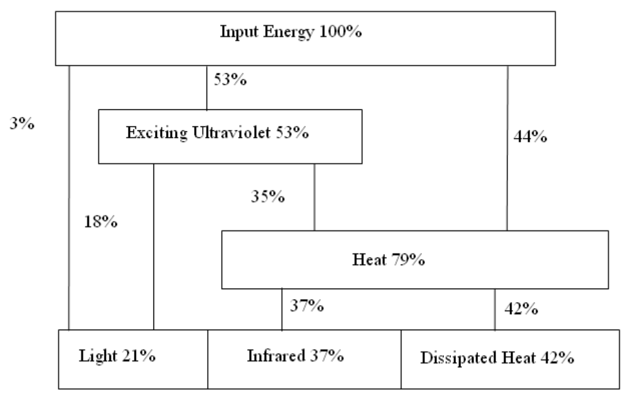

Figure C-2-1: Energy Distribution of Fluorescent Lamp

It is obvious then, that to overcome the low efficiency of this type of lamp, considerable energy must be pumped in and as stated above, the majority of this energy appears as heat. This heat, therefore, must be dissipated either into the light fixture or indirectly into the environment by conduction-convection or directly into the environment by radiation.

A calculation of the instantaneous rate of heat gain due to the lights can be obtained from the relationship shown in equation (C-1).

$$q_{el} = \frac{11.66\ AEWt_f}{l_m C_u M_f} \tag{C-1}$$

Where

q_{el} = sensible lighting heat load in conditioned space in watts
A = total area in square meters
E = average illumination in lux
l_m = total lumens per luminaire
C_u = coefficient of utilization
M_f = maintenance factor
W = actual wattage per luminaire in service watts
t_f = thermal factor, ratio of energy in conditioned space to total power input

Although actual coefficients of utilization and maintenance factors should be calculated for each location, typical numbers used are about 0.4 and 0.7, respectively.

The type of ceiling and method of luminaire mounting are significant factors in the distribution of the thermal energy developed in the lighting system. In dimensional measurement, the usual type of luminaire mounting is either suspended, surface mounted, or recessed. In some locations, luminous or louvered ceilings may be used. Briefly, for suspended luminaires, approximately 40 percent of the total energy is dissipated to convective air currents in the room. The input balance is indicated in all directions to be reflected or absorbed and re-radiated.

Since nearly all of the input energy remains within the occupied space, the thermal factor is generally taken as unity. On the other hand, for surface mounted luminaires, the heat is transferred by radiation, convection, and conduction. Upper surfaces of the luminaire absorb energy and transfer it by conduction into the ceiling. Since many of the ceilings are made of acoustical materials and hence are insulators, the temperatures within the luminaire will be elevated. Consequently, the lower surfaces will radiate and convect to the space below at a somewhat higher rate. Unless the ceiling is a good absorber and can re-radiate into space above it, essentially all of the input energy will remain in the occupied space. Recessed luminaires will distribute some portion of the input wattage above the suspended ceiling.

As a result, the energy actually transferred to the room is less than the total and this results in a lower thermal factor for the room. The energy transferred to the space above the ceiling may contribute to the overall problem, however, since many times this space is part of the air system for the laboratory. Luminous or louvered ceiling type lighting systems behave very much like a suspended luminaire in their transfer of energy since most of the plastics or glasses used in this type of ceiling are good absorbers of infrared.

The heat transferred from the lighting system may be removed by passing air over the luminaries, or in some cases, the air flow may be supplemented by the use of a circulating water system. This may be particularly advantageous when infrared filters are used on the luminaires to reduce the total energy because of the greater amounts of heat retained in the luminaire.

The light from the luminaires in itself is a heat producer. Not by heating the air as convection sources do, but by raising the temperature of any surface which absorbs it. This can become significant problem in a dimensional measurement process. This is because most objects are better absorbers of light than reflectors, i.e., dark surface plates, measuring machines, etc. In many cases, this can cause a degree or more temperature differential between the air and the object.

It is recommended that the general lighting system in a dimensional measurements location be left on at all times to stabilize the heat load in the occupied space from this source. This is also important because of the possible detrimental effect the lower air temperature may have on the lighting system, particularly if fluorescent lamps are used.

Light output and luminous efficiency of a fluorescent lamp normally reach optimum values when the coolest point on the bulb is about 38°C. The light output drops off sharply as the coolest point temperature drops, becoming approximately 50 percent about 15°C.

It is generally accepted that there are six major factors contributing to an overall loss of light in a lighting system

(1) Lamp lumen deterioration;
(2) Dirt on luminaires;
(3) Lamp outages;
(4) Deterioration of luminaire surfaces;
(5) Dirt on room surfaces;
(6) Temperature and voltage variation.

As in any light source, the lumen output of fluorescent lamps decreases as the hours of operation increase. For medium loaded lamps, this decrease runs about 20 percent for 10,000 hours of operation. As loading increases, however, the decrease in lumen output approaches 40 percent for the same period of operation. Rated average life for bulbs of this type are typically from 7,500 to 12,000 hours. This is usually based on three hours of operation per start. Consequently, with normal lumen deterioration, the same lumen output may decrease as much as 40 percent over the average life of a bulb which, if operated continuously, could be from one to two years. The type of lighting system maintenance program to be established will be dictated by the degree of lighting load and illumination required and the economics of operating the program.

To maintain the 1,000 to 1,600 lux of lighting intensity at each work location, a maintenance program is required that will insure the light output will not degrade to less than about 66% of the designed initial light output, assuming this designed output would give the 1600 lux. One possible way to do this would be to clean the lamps every 18 months and replacing 50% of them once every 18 months. Another way might be to clean the lamps and replace 33% of them every 12 months. Obviously, if the measurement operation requires that the lighting load and illumination be held to tighter tolerances, then the maintenance program would have to be more exacting. This would result in considerably shorter cleaning and replacement intervals, since of the six factors listed above, lamp lumen deterioration and dirt on the luminaires are the biggest contributors to loss of light.

NONMANDATORY APPENDIX D
THERMAL THEORY

D-1 General

CMMs were introduced in the early 1960s, but it was not until the 1990s that they really started to emerge from the clean, temperature-stable environment of the laboratory. As workpiece measurements increasingly moved from the laboratory to the shop floor, CMM manufacturers realized that their products had to be tough enough to take their place near the machine tools and still provide the kind of accuracy, repeatability, and performance capability needed.

That meant that CMMs had to be shop-hardened with temperature-resistant materials, anti-vibration systems, protected guideways such as bearing and scale covers and scale systems that have thermal compensation and may also have low coefficients of thermal expansion (CTE). In this Annex, nomenclature and symbols are as defined in ISO 80000-5 (2007) - Quantities and units - Part 5: Thermodynamics.

The following discussion considers the details of heat flow into a body. An initial consideration should address the subtle, but distinct difference between heat and temperature.

Heat is the movement of energy. This transfer of energy as heat occurs at the molecular level as a result of a temperature difference. Various mechanisms, to be discussed in some detail, allow heat to be transmitted through different media. If all cases the symbol for heat is Q. Heat is capable of being transmitted through fluids by convection, through solids and fluids by conduction and through empty space by radiation.

On the other hand, *temperature* is the amount of energy possessed by the molecules of a substance and can be thought of as a relative measure of how hot or cold substance are, which can also lead to an estimate of the direction of heat transfer. The symbol for temperature is T. The common scale for measuring temperature is the Celsius scale, denoted by °C. Note that in the above, T is the thermodynamic temperature which is related to the degree Celsius (t) by $t = T – T_0$, where T_0 = 273.15 K. where K represents the temperature in Kelvin.

D-2 Mechanisms for heat transfer

Heat is always transferred when the temperature between two bodies is different. The three modes of heat transfer:

Convection involves the transfer of heat by the mixing and motion of macroscopic portions of a fluid.

Conduction involves the transfer of heat by the interactions of atoms or molecules of a material through which the heat is being transferred.

Radiation involves the transfer of heat by electromagnetic radiation that arises due to the temperature of a body.

D-3 Heat transfer rate

The rate at which heat is transferred is represented by the symbol Φ. The unit for heat transfer rate is W (watts). Sometimes it is also useful to know the heat transfer rate per unit area, or *heat flux*, which has the symbol q. Units for heat flux are W m^2. The heat flux is determined by dividing the heat transfer rate by the area through which the heat is being transferred, as given by

$$q = \frac{\Phi}{A} \qquad \text{(D-1)}$$

Where

q = heat flux (W m^2)
Φ = heat transfer rate (W)
A = area (m^2)

D-4 Convection heat transfer

In convection, heat is transferred by means of the motion and mixing of molecules in a moving fluid or gas. For almost all CMMs and their workpieces the fluid in question is air.

Heat transfer by convection is difficult to analyze because no single property of the heat transfer medium, such as thermal conductivity, can be explicitly defined. Heat transfer by convection varies upon the fluid flow conditions and it is frequently coupled with the mode of fluid flow. Consider a situation where an arbitrary profile of air is flowing over a CMM table that has a thermal history. This is shown in Figure D-4-1.

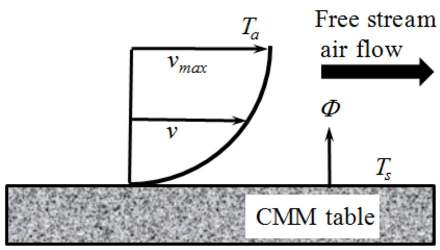

Figure D-4-1: Heat Transfer by Convection Showing Air Velocity Profile

The temperature of the CMM table plate is T_s, and the temperature of the air stream is T_a. The arbitrary velocity of the air flow is shown, which is additionally assumed to drop to zero at the tabletop as a result of viscous action. It should be noted, that as the velocity of the air at the table is zero, the heat can only be transferred by conduction on the table. Due to this condition, it may be assumed that the heat transfer can be found from using the thermal conductivity of the air and the temperature gradient at the table. If it is erroneously assumed that the heat flow is by conduction, the effect of the velocity of the air will be ignored. This cannot be done as the thermal gradient is dependent on the rate at which the heat is dissipated by the air. Therefore, the analysis of convection must include the relationship between the two effects, i.e. the temperature gradient and the flow.

Convection heat transfer is usually assessed experimentally due to a number of factors including, but not limited to, heat flux, fluid velocity and viscosity, as well as the surface roughness. These factors, plus others typically affect the stagnant film thickness.

The convective heat transfer coefficient (h), defines, in part, the heat transfer due to convection. The convective heat transfer coefficient is sometimes referred to as a film coefficient and represents the thermal resistance of the relatively stagnant layer of fluid between a heat transfer surface and the fluid medium.

The equation for heat flow into a body is expressed (by the somewhat confusing name of Newton’s law of cooling) as

$$\Phi = hA(T_a - T_s) \tag{D-2}$$

Where

Φ = rate of heat transfer rate (W)
h = convective heat transfer coefficient ($W \cdot m^{-2} \cdot °C^{-1}$)
A = surface area for heat transfer (m^2)
T_a = air temperature (°C)
T_s = surface temperature of the body (°C)

For a given set of the physical properties of the fluid and the physical situation, the flow is highly dependent on the convective film coefficient, *h*, which has a strong correlation between the airflow rates over the surface. Typically, the convective heat transfer coefficient for laminar flow (natural) is relatively low compared to the convective heat transfer coefficient for turbulent (forced) flow. Values of *h* have been measured and tabulated for the commonly encountered fluids and flow situations occurring during heat transfer by convection. Typical examples in air are shown in Table D-4-1.

Table D-4-1: Typical Values of convective heat transfer coefficient (*h*)

Mode (in air)	h (W· m^{-2}· °C^{-1})
Free convection	5-25
Forced convection	10-500

The convective heat transfer coefficient of air is can be found approximately from

$$h_c = 10.45 - v + \left(10 \times \sqrt{v}\right) \quad \text{(D-3)}$$

where v = *the relative speed of the air over a workpiece between 1* to *5 m/s*. (Note: 5m/s is approximately 10 miles per hour). This is shown graphically in Figure D-4-2.

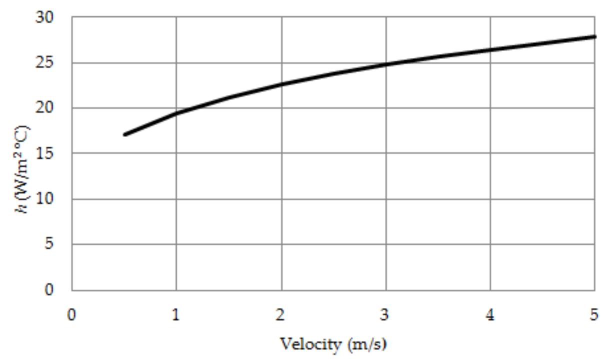

Figure D-4-2: Convective heat transfer coefficient (*h*) as a function of velocity

There are two types of convection, namely, natural and forced. The term natural convection is used if the air is moved by variations in air density, which is caused by temperature gradients created in the air by heat sources. The transfer of heat from a hot water radiator to a room is an example of heat transfer by natural convection. It is usually the predominant type of convection in shop environments. A low convective film coefficient and variable air temperature characterize convection.

The term forced convection is used if the mixing is created by an external force, such as a fan. The transfer of heat from the surface of a heat exchanger to the bulk of a fluid being pumped through the heat exchanger is an example of forced convection.

D-5 Conduction heat transfer

In conduction, heat is transferred by means of the molecular interaction between adjacent molecules. This interaction is primarily dependent on the temperature difference and the resistance of the material to heat transfer. The resistance to heat transfer is dependent upon the nature and dimensions of the heat transfer medium. While all heat transfer problems are dependent on the difference in temperature, the geometry, and the physical properties of the object being measured, in conduction heat transfer, the object being measured is in almost all cases a solid. There are several ways to correlate the geometry, physical properties, and temperature difference of an object with the rate of heat transfer through the object. In conduction heat transfer, the most common means of correlation is through Fourier's law of heat conduction.

When a temperature gradient exists in a work piece, energy is transferred from the high-temperature region, such as the work piece to the low-temperature region, for example a granite table. The energy is transferred by conduction and the heat-transfer rate per unit area is proportional to the normal temperature gradient, such that

$$\frac{q}{A} \approx \frac{\Delta T}{\Delta x} \quad \text{(D-4)}$$

When a constant of proportionality is included, the equation becomes

$$q = -kA\frac{\Delta T}{\Delta x} \quad \text{(D-5)}$$

Where

q = rate of heat transfer (W)
k = thermal conductivity ($W \cdot m^{-1} \cdot °C^{-1}$)
A = surface area for heat transfer (m^2)
$\Delta T/\Delta x$ = temperature gradient in the direction of heat flow

The heat transfer coefficient of a solid material is called the thermal conductivity (*k*) and is measured in $W\ m^{-1}\ °C^{-1}$. It is a measure of the ability of a material to transfer heat through a solid. For most solid materials, the thermal conductivity is usually a function of temperature.

Note that *k* is a positive quantity, and the minus sign is included to ensure that the second principle of thermodynamics will be satisfied, i.e., heat must flow downhill on the temperature scale, as indicated in Figure D-5-1.

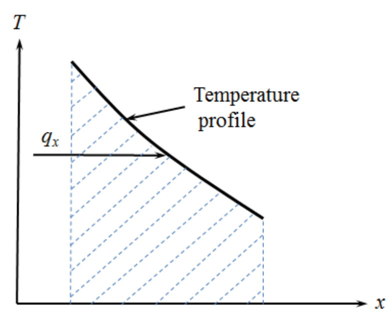

Figure D-5-1: Temperature Profile within a Solid

Representative values of *k* can be found in Table E-1.

D.6 Radiant heat transfer

Radiant heat transfer is the transfer of heat by electromagnetic radiation that arises due to the temperature of a body. This mode of heat transfer most commonly occurs in the infra-red region of the electromagnetic spectrum and the term thermal radiation is frequently used to distinguish it from other parts of electromagnetic spectrum that include, for example, radio waves, x-rays and gamma rays. In this Technical Report, the discussion of thermal radiation is limited to electromagnetic radiation which is propagated as a result of a temperature difference.

It should be noted that, in contrast to conduction and convection, where any transfer is through a material medium, electro-magnetic radiation may also be transferred through a vacuum. Any material that has a temperature above absolute zero gives off some radiant energy.

Thermal radiation includes light, and certain other radiations similar to light but outside the visible range. The bandwidth for thermal radiation is from near ultra-violet to far infrared, as shown in the relevant portion of the electromagnetic spectrum below (Figure D-6-1).

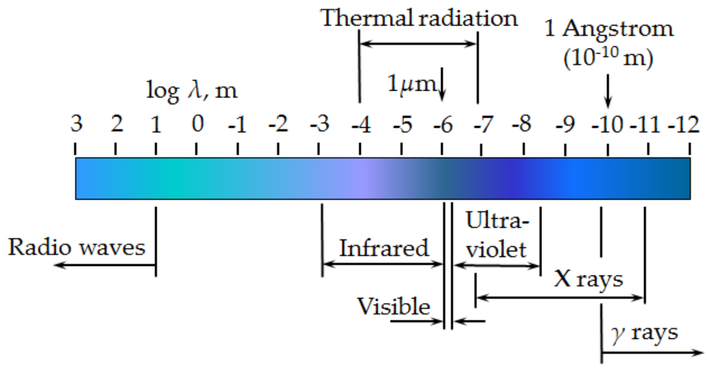

Figure D-6-1: Part of the Electromagnetic Spectrum

The limits of the thermal radiation currently discussed, lies between about 10^{-4} to about 10^{-7}m. The visible-light range is fairly small, covering the range between about 0.38×10^{-6} to about 0.75×10^{-6} m.

Thermal radiation propagates in the discrete quanta, each quantum having energy of

$$E = hv \tag{D-6}$$

where h is Planck's constant, having a value of 6.625×10^{-34} J s.

Making the assumption that each quantum can be considered as a particle having energy, mass and momentum, then $E = mc^2 = hv$ and the momentum $= mc = \frac{chv}{(c^2)^{-1}} = hvc^{-1}$, from which the total emitted energy is proportional to the absolute temperature to the fourth power. Then $E = \sigma T^4$, where σ is the Stefan-Boltzmann constant, having a value of 5.669×10^{-8} W m^{-2} k^{-4} and the temperature is in K.

As briefly discussed above, an ideal radiator, which is usually referred to as "blackbody", will emit energy at a rate proportional to the fourth power of the absolute temperature of the body.

Radiant heat transfer rate from a black body to its surroundings can be expressed by the following equation.

$$q = \sigma A T^4 \tag{D-7}$$

When two bodies exchange heat by radiation, the net heat exchange is then proportional to the difference in T^4. This is usually written as

$$q = \sigma A(T_1^4 - T_2^4) \tag{D-8}$$

As noted, the above is for what is considered an ideal blackbody. In the real world, objects do not radiate as much heat as a black body. To account for this, Equation D-7 is modified to become

$$q = \varepsilon \sigma A T^4 \quad \text{(D-9)}$$

Where

ε = emissivity of the gray body

The emissivity factor simply accounts for real world objects. Thus, emissivity is a dimensionless number between 0 and 1.

When the radiative heat transfer rate between two gray bodies is considered, a “view” factor must also be included. It is sometimes called a “shape factor” or “configuration factor.” The view factor is solely dependent upon the geometry and is independent of the surface properties and temperature. The factor is required to account for the fact that not all the radiation leaving one surface will reach the other surface since electromagnetic radiation travels in straight lines and some will be lost to the surroundings.

The equation for radiation then becomes

$$q = F_{i-j} \varepsilon \sigma A T^4 \quad \text{(D-10)}$$

where:

$F_{i\text{-}j}$ = is the view factor, which depends on the spatial arrangement of the two objects and is a dimensionless factor between 0 and 1.

For most practical geometric shapes, the mathematical expressions for the view factors can become rather lengthy and in many cases, rather complicated. Therefore, for most practical application, the geometry is somewhat idealized and the view factor found from previously publish data, which is typically presented in the form of a diagram, with appropriate parametric values used to produce a family of curves.

Consider a fairly simple example of a part shown in Figure D-6-2.

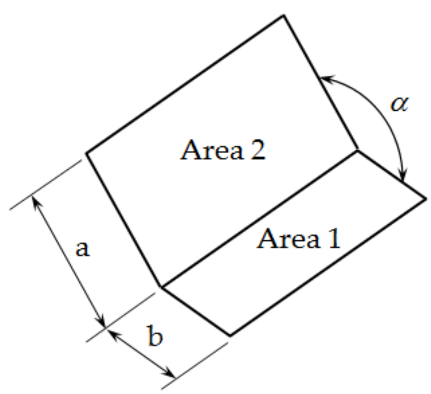

Figure D-6-2: View Factor between Two Rectangular Faces

Let the ratio a/b be equal to R. Then the required equation is

$$F_{1-2} = \frac{R + 1 - \sqrt{R^2 + 1 - 2R\cos\alpha}}{2} \quad \text{(D-11)}$$

For assumed values of the ratio and different angles, the following family of curves can be obtained.

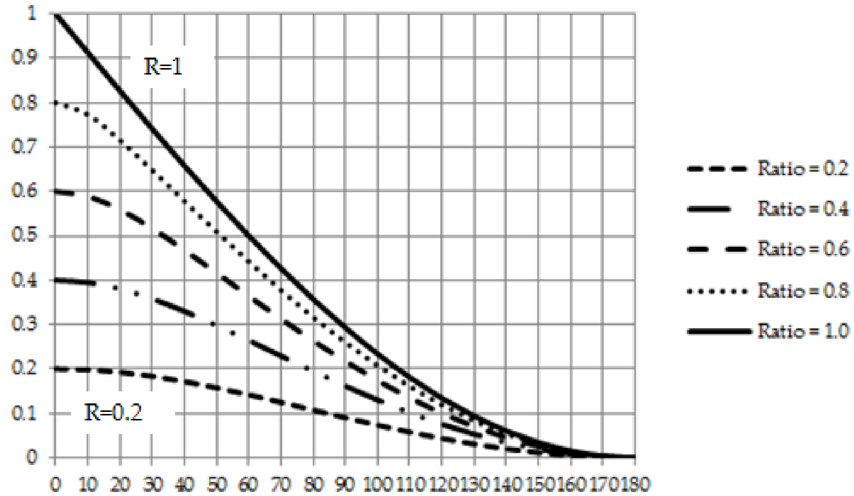

Figure D-3-3: Values of F_{1-2} for Assumed Values of the Ratio and Angle

Significant heat flow into a body will occur if there are significant surrounding heat sources such as lighting, the sun, room surfaces and machines at a higher temperature than the body, if a significant portion of the radiant energy reaches the body and if energy reaching the body is absorbed rather than reflected.

Additional information on view factors can be found in (Reference 17).

NONMANDATORY APPENDIX E
USEFUL THERMAL PROPERTIES

E-1 Common Engineering Materials

The table included in this section emphasizes at least two important points:

(a) That there is a significant variation of coefficient of thermal expansion (CTE) between different materials.

(b) That there is a significant variation of CTE within the same class of materials.

Table E-1-1: Thermal Properties of Common Engineering Materials

Material	Nominal Coefficient of Expansion (μm · m^{-1} · $°C^{-1}$) {α}	Specific Heat (J · kg^{-1} · $°C^{-1}$) {C_p}	Thermal Conductivity (W · m^{-1} · $°C^{-1}$) {k}
Acrylics	54-108	1381-1464	
Cast Aluminum alloys			
356	21.4		159
520	24.5		88
Wrought Aluminum alloys	22.1-23.9	900-962	117-240
2000 series	23.2	921	189
4000 series			
6000 series	23.4	963	180
7000 series	23.6	963	121
Beryllium alloys	11.5-16.2	1883	167
Beryllium Copper	16.8	2100	193
Brass	17.2-21.0	380	29-234
Bronze	17.2-19.4	376-418	35-208
Cast Copper	14.9-21.2	380-390	194-393
Cast Iron	13.0	460-525	46
class 40	10.8	544	48-52
Ductile	11.9	544	33
Grey	11.5	544	47
Malleable	13.5		51
Duralumin	19.3	900	150
Glass - soda lime	9.0	840-883	1.0
Material	Nominal Coefficient of Expansion ((μm · m^{-1} · $°C^{-1}$) {α}	Specific Heat (J · kg^{-1} · $°C^{-1}$) {C_p}	Thermal Conductivity (W · m^{-1} · $°C^{-1}$) {k}
Granite	6.0-9.0	790-820	1.6
Invar			
Invar 36	.64-1.30	515	10.5
Super Invar	.23-.56	510	10.5
Lead alloys	23.2-26.9	128-134	28-34
Nickel alloys	11.6-17.8	372-837	9.8-85.8
Nylons	22.0-45.0	1255-2092	0.17-0.5
Phenolics	22.0-41.0	1172-1674	0.2-0.5
PTFE	99	920	
Silica Ceramics	.5	799	1.4
Silver	16.9-19.3	233-234	419
Steels			
cast	14.7	440	46.7
hard	11.2	413	375
mild	11.2	413	525

Material	Nominal Coefficient of Expansion ($\mu m \cdot m^{-1} \cdot °C^{-1}$) $\{\alpha\}$	Specific Heat ($J \cdot kg^{-1} \cdot °C^{-1}$) $\{C_p\}$	Thermal Conductivity ($W \cdot m^{-1} \cdot °C^{-1}$) $\{k\}$
spring	11.2	413	525
wrought	9.4-12.1		
carbon, A1040-60	8.3		
carbon, AISI 1020	11.7-15.1	419	46.7
Stainless 304	17.3	502	16.3
Stainless 440C	10.1	460	24.2
Stainless Steels	12.2-18.7	460	
Austenitic			
Cast			
Martensitic	9.9-11.2	460	20.2-36.7
Tin alloys	16.2-21.6	210-226	64
Titanium alloys	8.1-10.8	460-648	
Tungsten alloys	4.5-7.2	201-230	10.8
Zerodur	.05	821	1.6
Zinc alloys	14-27	387-523	105-108

Note that the uncertainty of CTE can be commonly estimated as 10% even for well characterized materials.

E-2 Conversion Factors

The conversion factors found in Table E-2-1 may be used for most engineering applications, without significant errors.

Table E-2-1: Useful Conversion Factors for Thermal Properties

For:	**To Convert From:**	**To:**	**Multiply by:**
CTE			
	$\mu in \cdot in^{-1} \cdot °F^{-1}$	$\mu m \cdot m^{-1} \cdot °C^{-1}$	1.8 $°F \cdot °C^{-1}$
	$\mu m \cdot m^{-1} \cdot °C^{-1}$	$\mu in \cdot in^{-1} \cdot °F^{-1}$	0.55556 $°C \cdot °F^{-1}$
Specific heat capacity			
	$BTU \cdot lb^{-1} \cdot °F^{-1}$	$kJ \cdot kg^{-1} \cdot °C^{-1}$	4.1868
	$kJ \cdot kg^{-1} \cdot °C^{-1}$	$BTU \cdot lb^{-1} \cdot °F^{-1}$	0.23885
Thermal Conductivity			
	$BTU \cdot hr^{-1} \cdot ft^{-1} \cdot °F^{-1}$	$W \cdot m^{-1} \cdot °C^{-1}$	1.7307
	$W \cdot m^{-1} \cdot °C^{-1}$	$BTU \cdot hr^{-1} \cdot ft^{-1} \cdot °F^{-1}$	0.57779

NONMANDATORY APPENDIX F
MACHINE DESIGN CONSIDERATIONS

F-1 General

In practice, many factors in addition to environmental concerns are considered in the design of a CMM, including repeatability, motion errors, transport speed and accelerations, compensation methods, material costs, and assembly time. In the selection of materials, factors to be considered include cost, material availability, density, machining characteristics, bending modulus, strength, thermal diffusivity, vibration damping characteristics, etc. The structure of a CMM influences its response to environmental conditions that impact measurement uncertainty. The various materials, geometry, and assembly constraints used for the CMM's structure, scales, sensors, and covers influence its response to environmental factors. In practice, many factors should be considered in the design of a CMM, including repeatability, motion errors, transport speed and accelerations, compensation methods, material costs, assemble time and the intended environment for use. In the selection of materials, factors to be considered include cost, material availability, density, machining characteristics, bending modulus, strength, thermal diffusivity, vibration damping characteristics, etc. Many of these factors compete against each other in the design of CMMs. CMM designs should attempt to minimize the adverse influences from the environmental while attempting to meet other design constraints.

F-2 CMM Design Components

F-2.1 Covers

Covers may be used for a variety of reasons including shielding the machine from short term thermal effects, contamination from dirt, providing EMI shielding, providing safety shielding, styling, cosmetic impact, etc. If the environment contains airborne particulates, protected guideways (bearing and scale covers) may be beneficial. Covers may be beneficial in shielding the machine structure from cyclic temperature fluctuations in the machines environment. However, if there are components under the covers that generate heat, this internally generated heat inside the CMM, could be trapped under the covers potentially increasing the thermal resonance of the machine, To the extent that these internal heat source have a constant power dissipation, the influence of the covers may lengthen the time required for the CMM to warm-up prior to measuring workpieces. If the CMM was sitting idle and then turned on and immediately started taking measurements, the measurement results would be slightly different than if the CMM were exercised for 30 minutes and then the measurements taken. The structures under the covers may have changed by one to two degrees during the warm up and measurement process. If a steel scale had heated 2°C, the scale length would change about 23 μm over a one meter length. Additionally, bending may occur if a temperature gradient is induced in the machine structure. Machines with active temperature compensation would compensate for this change in length. Internal components that dissipate variable energy, such as servo motors or linear actuators dissipate heat as a function of the measurement duty cycle. For example, if a measurement cycle has a series of Y axis moves with little or no X and Z axis motion, the heat dissipation from the Y axis actuator may influence one or more machine scales and could induce a thermal gradient in the machine structure. Therefore, the influence of internally generated variable heat dissipation may be more difficult to correct for than constant heat sources that may equilibrate during a warm up cycle.

On some machines, there are fewer covers and the structural elements may not be covered at all. This design reduces the entrapment of heat, but the machine may be more susceptible to external influences such as direct heating or heating and air conditioning vents blowing directly on the machine.

F-2.2 Structural Materials

A CMM installed on the shop floor should be resistant to environmental influences. Resistance to thermal influence can be improved by matching the machines CTE, thermal diffusivity, and effective time constant to that of typical workpieces being measured. If the environment is subject to high levels of vibration, the CMM should be constructed of materials with favorable damping characteristics, or have integrated anti-vibration systems. Use of scale systems with a very low coefficient of thermal expansion can also aid in reduction of thermal influences when used in conjunction with temperature compensation.

With regards to thermal expansion problems on coordinate measuring machines, the following machine design philosophies exist:

(a) *Prevention:* Restrict the rated environment to limit thermal influence

(b) *Minimize impact:* Design the critical machine structure to minimize thermal influences.

(c) *Compensation*: Compensate for error through adjustments or control program changes.

The machine's basic design is critical because it determines, to a great extent, how much heat will be introduced and absorbed. It is best if the design directs any heat away from the machine structure. Heat sources should be kept away from the machine structure, and components and materials that will minimize heat generation should be used. Given the fact that some heat will always be present, the next item to review is thermal stability. Large and thermally inert structures respond slowly to heat, however may be subject to internal thermal gradients resulting in bending. Sometimes a built-in cooling system is used to remove heat or more evenly distribute heat. Isolation of scales and encoders from heat sources can help to minimize their temperature changes.

The ideal material for a CMM structure should minimize distortions caused by temperature changes and gradients. Its characteristics are high thermal diffusivity and a low coefficient of expansion. Reasonable cost, manufacturable materials with this combination of characteristics are not available. Thus, opinions on the best practical material vary from aluminum, which has high diffusivity and a high coefficient of expansion to ceramics, which have low diffusivity and low coefficient of expansion.

Care should be used in designing structural elements with materials that change characteristics as they age. Examples are elastomers and glass.

F-2.3 Structural Design Details

Beams are commonly used elements in many CMM designs where they serve as guideways and/or supports for guideways. In addition to bending from external loading, beams can bend due to bi-material effects or due to temperature differences between opposite faces in low diffusivity materials.

Bi-material effects can occur due to nominal differential expansion or variations represented by the uncertainty of nominal expansion. Nominal differential expansion will occur if, for example, a steel guideway is rigidly attached to a granite beam. Differential expansion due to uncertainty might occur where a beam is fabricated from sheet material having a non-uniform coefficient of expansion throughout the sheet, or material from different sheets is used in the same beam.

Temperature differences between opposite beam faces may occur if the convective film coefficients are different, for example due to different air velocities, if more radiant energy reaches one wall then the other, if wall thicknesses are unequal, or if more heat is conducted away from one wall than the other.

If opposite faces of a beam have different expansions, the amount of bending is inversely proportional to the distance between the faces. Thus, beams can be desensitized to bi-material or gradient bending by increasing the distance between the faces. This effect is shown in Figure F-2.3-1. However, increasing the distance can adversely impact the temperature gradient across the beam.

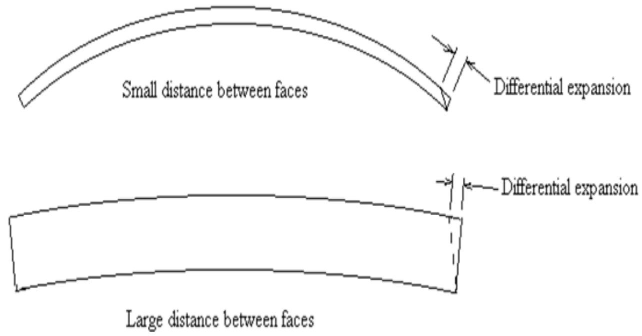

Figure F-2.3-1: Effect of Differential Expansion Relative to Distance between Beam Faces

Beams can also be desensitized to temperature bending by improving heat flow from one face to the other and by using materials with low CTE.

Joints between beams should be carefully analyzed because they usually have non-uniform contact area and also may impede heat flow resulting in thermal gradients.

An alternative to minimizing thermal growth through the use of low CTE materials, is to allow for thermal growth to occur along axes, where compensation is easier. Symmetry is an important consideration because elongation (or contraction) is more predictable. The materials from which the machine is made also play a part. Distortion may be minimized when all structural parts are from the same material, and of equal thickness. However, this may not be practical or in conflict with other desirable material properties for various elements of the machine. Uneven structural ribbing or unequal wall thickness may increase thermal distortion.

Symmetry is often a characteristic of good thermal design, either for beams or for structures. For example, if the legs of a bridge structure have equal time constants, the bridge cross member will not tilt as a result of the legs, so long as they are being uniformly subjected to a change of temperature. The effects of internal heat sources such as motors should be carefully considered.

F-2.4 Composite Assemblies

In some cases, a body is made up of several components having different coefficients of expansion. An example is a scale assembly in which a glass scale is secured to an aluminum frame through an intermediate layer of elastomer. For such bodies an effective coefficient of expansion is determined such that expansion of the assembly is the same as expansion of a body with a coefficient expansion equal to the effective coefficient. Note that, for the scale example, the effective coefficient of expansion can change with time due to hardening of the elastomer, and that creep of the elastomer can change length of the scale.

A structure made of two or more materials that are rigidly constrained relative to each other and having different CTEs, are subject to distortions such as bending when subjected to changes in temperature. One method that can effectively minimize thermal distortions is to constrain the different materials in a way that allows them to freely expand relative to each other effectively not over constraining the assemble. One example of this is when a steel scale or spar is attached to a granite or aluminum structure where it is rigidly attached at a single point and constrained such that it can freely expand independently of the base structure.

If a body subjected to a temperature increase is mechanically prevented from expanding, it will develop internal stresses. The approach to determining these stresses is to determine how much the part would expand if it were unconfined, determine what forces would be required to return it to its confined dimensions, and determine what stresses these forces would cause. Note that forces that cause linear compression can also cause bending. A related case is an unconfined body with a non-uniform temperature distribution. A similar analytical approach is used. If either the body or the temperature distribution is not symmetrical, it is likely that bending will occur.

A body can bend when its temperature increases when the coefficient of expansion is not uniform throughout the body. This topic is discussed in the appendix to ANSI B89.6.2 with respect to castings. When an instrument is made of a combination of materials with differing coefficients of expansion, even a constant temperature different from its calibration temperature can cause bending via the so-called bi-material effect.

F-2.5 Compensation Design Details

When measuring away from 20 °C, and there is differential CTE between the workpiece and the machine scales, active compensation of the machines scales and the workpiece can be beneficial. Resistance to thermal influences can be facilitated by active temperature compensation. Typically, each scale temperature should be measured and corrected independently, as well as the temperature of the workpiece.

NONMANDATORY APPENDIX G
SEISMIC VIBRATION VERIFICATION TESTS

G-1 SCOPE

The purpose of this Appendix is to recommend vibration measurement instrumentation and procedures for measuring vibration at machine installation sites. Vibration levels shall be measured at the proposed machine site(s) to compare to allowable site vibration limits established by the machine supplier. This document also defines the instrumentation and measurement procedures to establish vibration on the machine for additional analysis. This Appendix does not address the determination of vibration sources or reduction of vibration levels. This task is usually involved and requires the knowledge of vibration specialists.

G-2 DEFINITIONS

To the extent possible, this document is intended to be self-defining. It is written for individuals with an engineering background. Definitions for specific vibration terminology may be found in the Institute of Environmental Sciences and Technology document IEST-RP-CC024.1, Measuring and Reporting Vibration in Microelectronics Facilities.

G-3 VIBRATION ACCEPTANCE CRITERIA

The machine supplier is to provide site vibration criteria of acceptability. Below these levels, the machine can operate successfully, and above these levels, problems may occur. Each machine supplier has different formats and levels of acceptance. The type of vibration measurements to be taken will depend on format and vibration units specified by the machine supplier. Based on the type of criteria, the vibration specialist should determine the necessary measurement units, frequency range, measurement locations, and instrumentation.

G-3.1 Criteria Units

Vibration is characterized by amplitude versus time or frequency. The amplitude can be defined in displacement, velocity, acceleration, or power spectral density. Depending on the type of criteria, the amplitude ordinate can be defined in either the time domain or frequency domain.

G-3.1.1 Amplitude Units

Since the machine is a measurement tool, units of displacement are most useful in relation to machine performance. However, velocity and acceleration are more appropriate parameters for measuring machine site vibration. Displacement may be suitable for specific situations, but it is not recommended for general vibration measurements. However, velocity and acceleration are more appropriate parameters for measuring machine site vibration. Displacement may be suitable for specific situations, but it is not recommended for general vibration measurements.

G-3.1.2 Ordinate Units

The use of time or frequency for the ordinate will depend on the acceptance criteria format of the machine supplier. Time-based criteria are referred to as a time history that provides measurement of transient or very low-frequency vibratory events, such as beat signals. The frequency domain allows measurement over a very short time range that provides ability to diagnose many dynamic events.

G-3.2 Criteria Format

The supplier shall provide, as part of the machine specification, a statement of acceptable vibration. The criteria should be provided by the supplier or listed as part of the machine specification form, if used. At least two criteria format options may be used: (frequency) response function and time history. The supplied acceptance criteria will define the format to present the vibration data for ease of comparison.

G-3.2.1 Frequency Response Function Criteria

These types of criteria are specified as a vibration amplitude as a function at specific frequencies. The criteria are usually presented as allowable vibration amplitude versus frequency, in hertz. The frequency range may vary from supplier to supplier. In general, seismic vibrations are applicable over a range of 0 (DC) to 100 Hz. Vibration levels have large dynamic range, and it is sometimes helpful to present amplitude data in logarithmic scale. If decibels are used, the standard reference values must be used.

G-3.2.2 Time History

These measurements represent the vibration during the time period of interest. The supplier should specify a maximum peak-to-peak acceptable vibration level and a time period over which it applies. The vibration amplitude could be in units of velocity or acceleration.

G-4 INSTRUMENTATION

This paragraph describes various instruments required to perform on-site vibration measurements. Various types of sensors, signal conditioners, recorders, computer programs, and signal analyzers are available that will acquire these data. It is not intended to single out any particular equipment manufacturer, but to recommend types of equipment that meet the requirements of this Standard.

G-4.1 Transducers

Many types of transducers exist for various types of vibration measurements. The measurements specified in this document require a seismic accelerometer or a specific type of velocity transducer.

G-4.1.1 Seismic Accelerometers

The two most important requirements for the accelerometer are frequency response and sensitivity. Site vibration measurements generally require low frequency and high sensitivity. The minimum frequency response linearity should be less than 1 Hz, preferably 0.5 Hz. The frequency response should be greater than 100 Hz. The sensitivity of the accelerometer should be 10 V/g or greater, where g is equal to 9.8 m/s2**.**

G-4.1.2 Velocity Transducers

These sensors are also referred to as geophones. The sensitivity of the geophone should be 4 V/cm/s. The frequency response linearity requirement of the velocity transducer is the same as the accelerometer, 0.5 Hz to 100 Hz.

G-4.2 Amplifiers and Signal Conditioners

The transducers require amplifiers and signal conditioners. Most seismic accelerometers require an amplifier, but some models may have built-in electronics that do not require signal conditioning. Velocity transducers may require amplification and signal conditioning, depending upon the sensitivity and signal-to-noise ratio. It is the responsibility of the vibration specialist to use the proper signal conditioners.

G-4.3 Signal Recording/Analysis Instruments

The type of instrumentation to use will depend on the type of criteria and format that have been provided by the machine supplier. The frequency response criteria require a Fast Fourier Transform (FFT) dynamic signal analyzer or digital recorder. Time history data can be acquired with an oscilloscope, a digital recorder, or an FFT analyzer.

G-4.3.1 FFT Signal Analyzers

This type of analyzer is the most sophisticated means of measuring vibration, by providing the greatest amount of information about the vibration signal. In most cases this additional information is necessary to understand the vibration environment. Many types of FFT analyzers exist, from many different manufacturers. One- and two-channel units, hand-held, and PC-based are formats readily available.
It should be noted that using a data recorder, as specified below, will require the use of an FFT analyzer after the

data are acquired. It is the user's responsibility to understand the instrument, its capabilities, and its limitations. The following list offers guidelines for FFT analysis configuration and specifications:

(*a*) *Noise Floor.* 100 dB/Hz.
(*b*) *A/D Resolution.* The resolution of the analog-to-digital converter should be at least 12 bits. The better analyzers will have a 16 bit A/D resolution.
(*c*) *Dynamic Range.* The dynamic range should be at least 70 dB. Better spectrum analyzers will have a higher dynamic range.
(*d*) *Frequency Resolution.* This parameter, as it applies to the analyzer, is denoted in number of lines over which the analysis range is divided. Most analyzers can have selectable resolution from 100 lines to 1600 lines. The resolution is calculated by dividing the frequency range by the number of lines. For example, a 0–100 Hz frequency range acquired with a 400 line analysis will have 0.25 Hz (100/400) resolution. The frequency resolution used must be compatible with the resolution of the frequency response criteria. If the criteria are defined at every 1 Hz, the data must be acquired with a 1 Hz resolution. For example, 0–100 Hz criteria defined every 1/2 Hz would need to be acquired with 200 lines of resolution. This document recommends that 0–100 Hz data be acquired with 400 lines of resolution, producing 0.25 Hz resolution data. The overall frequency resolution will also be dependent on the transducer frequency response. The procedure above should be followed and modified only when the machine supplier's specification requests otherwise.
(*e*) *Anti-Aliasing Filter.* This filter prevents incorrect reporting of frequency components due to under-sampling of higher frequency signals. This filter is found on most (if not all) FFT analyzers. It should always be used.
(*f*) *Averaging.* Most analyzers have this feature. It is used to reduce the effects of transient events such as personnel or vehicular activity. It is recommended that ten averages be taken for all measurements. Some spectrum analyzers have various types of averaging functions, such as linear, rms, peak hold, or exponential. Linear or summation averaging should be used.
(*g*) *Window Functions.* This feature is used to force a generalized vibration signal into discrete time domain periods. When window functions are not used, the frequency response of the vibratory signal is incorrectly distributed throughout the frequency range. There are many types of window functions. The most popular are Hanning, flat top, and uniform. Other windows provide excellent amplitude accuracy and poor frequency accuracy, and vice versa. The Hanning should be used for all measurements specified in this Appendix.

G-4.3.2 Data Recorders

For ease of gathering vibration data in the field, the use of a multichannel data recorder is found to be useful and convenient. Such an instrument allows for three or more channels of data to be recorded simultaneously, while providing a permanent record for archives and verbal data annotation during specific events. Additionally, the recorder allows a record of the real-time response, which can be most useful. The data can then be processed at a later date using in-house data reduction techniques such as FFT analyzers specified in the paragraph above. The recorder format must be digital and use digital audio tape (DAT) because of its excellent signal-to-noise ratio and dynamic range, as compared to analog tape.

G-4.3.3 Oscilloscopes

This piece of general laboratory equipment may be easily obtained to make an initial set of time history readings. Most facilities have an oscilloscope and personnel who can operate the equipment, which allows a user to take baseline readings. The oscilloscope is also useful for viewing beat signals, transient events, and hourly and daily vibratory changes. The oscilloscope should be set to AC-coupled and free-run triggering. Viewing the signal, determining the peak-to-peak voltage amplitude, and using the transducer sensitivity for converting to appropriate amplitude units, determine the vibration amplitude.

G-5 TEST PROCEDURES

The procedures for making vibration measurements are fairly simple, once the appropriate analysis equipment is selected and configured as required.

G-5.1 Calibration

At a minimum, a qualified lab, traceable to NIST, should have calibrated the vibration measurement equipment in the past 12 months. Site calibration of the transducers at the start of the testing is required.

G-5.2 Transducer Mounting

For all measurements, the transducers should be mounted directly and firmly to the floor or a common interface for measuring three mutually orthogonal axes. Such mounting arrangements are referred to as *triaxial*. Some accelerometers incorporate three triaxial transducers in one device. When this mounting arrangement is used, all three channels should be acquired simultaneously. Time-independent triaxial measurements should not be performed.

G-5.3 Measurement Location

In general, the transducers should be mounted in the general area where the machine will rest. This area should encompass the outer envelope of the machine plus 3 m (approximately 10 ft) beyond this footprint.

G-5.4 Acquiring/Recording Data

Vibration measurements should be made during normal operations of the facility. Nearby equipment that will be operating when the machine is expected to be used should be running during the vibration testing. A written test log or voice channel on a data recorder should be maintained by the individual performing the test so that any abnormal events during the test may be recorded. A test should be repeated if abnormal events occur. Normal vehicular traffic should not be excluded. When the environmental conditions are satisfactory, the data should be recorded on tape, saved to memory, and printed or manually recorded.

G-5.4.1 Time History

For time history criteria, simply compare the measured peak-to-peak vibration levels to the permissible level. The machine supplier may provide vertical and horizontal criteria. It is important to compare the acquired data to the criteria in the appropriate direction.

G-5.4.2 Frequency Response Function

Comparison of frequency response function criteria to frequency domain vibration data can require more effort than taking the data. If the criteria have the same level at all frequencies (straight line) or little changes in amplitude, it will be easy enough to draw the criteria over the printed vibration levels. If the criteria are not constant or uniform, it may be easier to compare data and criteria with various software programs. This involves digitizing the criteria, which in some cases requires entering levels at 1 Hz increments. The vibration data stored on the FFT analyzer must be downloaded into a PC. This requires different steps, depending on the analyzer manufacturer. Using a spreadsheet, math, graphing, or special program, the vibration data and criteria are combined into a single graph. Once the data are in a software format, they can be manipulated, graphed, and analyzed in a usable format.

G-6 CRITERIA ASSESSMENT

G-6.1 Measured Vibration below Criteria

If the vibration levels measured by the procedure above are within the supplier's criteria, no additional work is required. It is the sole responsibility of the supplier to maintain the performance of the machine in order to meet specifications.

G-6.2 Measured Vibration above Criteria

If the vibration levels exceed the supplier's specifications, it is the responsibility of the user to isolate the vibration in order to conform to the specification, or else accept a performance derating. Again, this Appendix does not provide information on how to reduce excessive vibration levels, but vibration isolation will reduce the levels. Before the vibration levels can be reduced, the source of the vibration must be determined. It may be easy to do this with the above equipment. Shock and vibration isolator suppliers who specialize in low frequency vibration attenuation should be contacted if vibration isolation or a vibration survey is required.

G-7 REPORT

A report shall be issued by the vibration specialist and shall include all backup information and analyzed data with a comparison to the machine specification. The report shall include the following as a minimum:

(*a*) title
(*b*) dates (issued and when data were taken)
(*c*) calibration information
(*d*) description and diagram of test setup
(*e*) procedure
(*f*) analysis
(*g*) summary

It is important to note that the report should serve to archive the baseline vibration data for later review, if problems arise after machine installation.

G-8 FIELD INSTRUMENTATION DIAGRAM

A diagram of the instrumentation is given in Figure G-8-1.

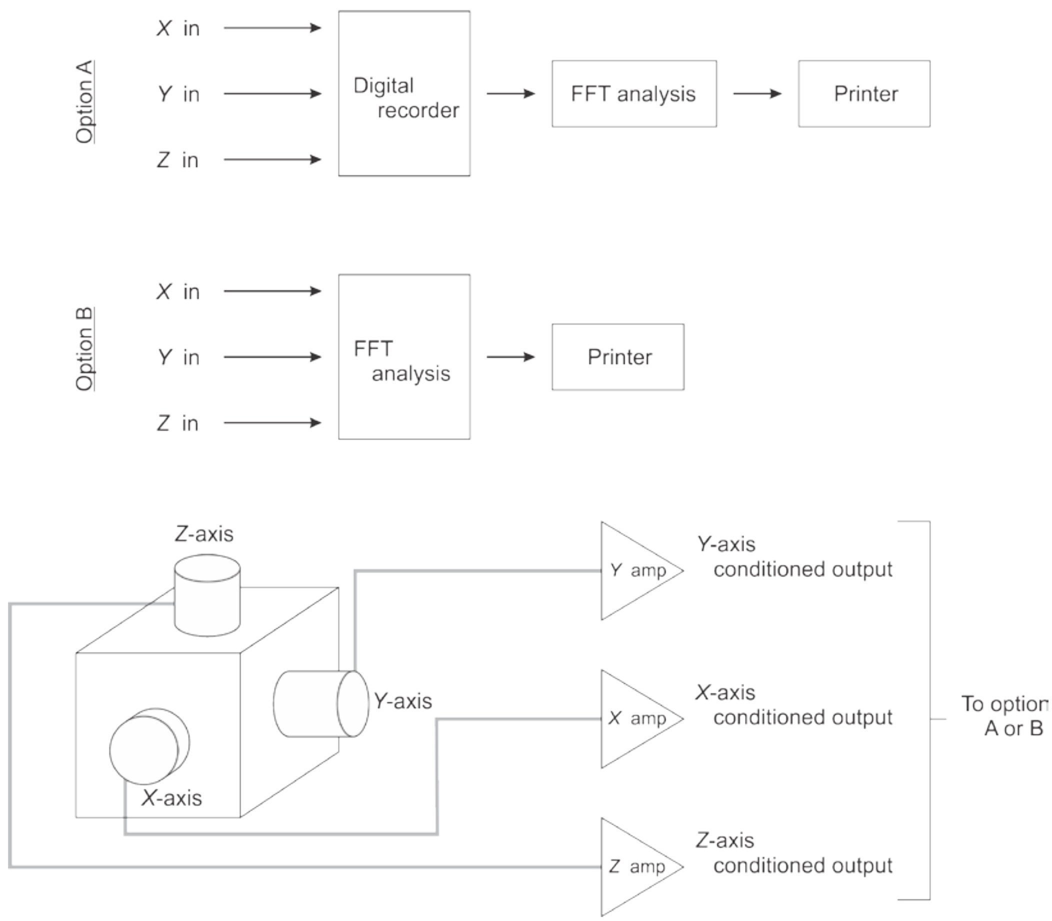

Figure G-8-1: Diagram of Sensor Arrangement and Instrumentation Configuration