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Environmental Effects on Coordinate Measuring Machine Measurements

AN ASME TECHNICAL REPORT

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 (CMMs). 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, 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 CMMs, 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 ASME B89.4.10360.2. This was, however, contrary to the concept of making the performance evaluation tests quicker and therefore less expensive to run.

When the CMM is used within rated operating conditions, including environmental conditions, as stated by the CMM manufacturer, the performance of the CMM is characterized by its ASME B89.4.10360.2 accuracy specifications. For any combination of environmental conditions that are within the rated operating conditions, the accuracy of the CMM as characterized by ASME B89.4.10360.2 is expressed as a maximum permissible error (MPE) that is assigned by the CMM manufacturer; different MPE values may be assigned to different environmental conditions within the rated conditions. These accuracy specifications apply only to the measurand embodied in the calibrated reference artifact used in the specification, e.g., point-to-point length as measured on gage blocks, step gages, and similar artifacts permitted by the performance testing protocol.

However, if the CMM is used in conditions that are outside its rated environmental conditions, the performance of the CMM is no longer assured. Some guidance for 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 these discussions, it was decided that the best approach would be to develop a reference document that would elucidate the problems and allow the user of the machine to decide what, if anything, to do about it.

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ENVIRONMENTAL EFFECTS ON COORDINATE MEASURING MACHINE MEASUREMENTS

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 also applicable to optical and other noncontact coordinate measurement systems.

2 INTRODUCTION AND BACKGROUND

2.1 Operating Conditions

JCGM 200 (ref. [1]) defines rated operating conditions (4.9) and limiting operating conditions (4.10). Machine specifications, typically stated as maximum permissible errors (MPEs), are intended to be applicable to a CMM that is used within its rated operating conditions. These rated operating conditions are the conditions that must be fulfilled for the machine to perform as designed (i.e., meet the MPEs). These conditions include, but are not limited to, environmental conditions. Limiting operating conditions are the extreme at which a machine can be operated without sustaining damage and without degradation of specifications when subsequently operated within its rated operating conditions.

2.2 Definition of Environment

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

For the purpose of this Technical Report, environments are classified as "laboratory" or "shop." A laboratory environment is controlled in order 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.

2.3 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 para. 2.2, and their influence can vary greatly among different facilities, or even within one facility. Whereas 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 be either 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.

Three main methods are employed to mitigate the influence of the environmental effects, as follows:

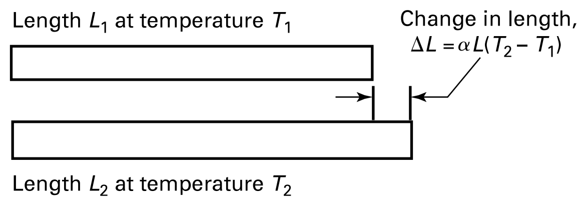
(a) Attempt to Remove the Source of the Influence. This may be done by shutting down or moving equipment causing vibration or removing heat sources from the immediate vicinity of the measuring equipment.

(b) 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.

(c) Compensate for the Influence. 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 environmental influences where these methods are not employed.

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



2.4 Users of This Technical Report

The primary audience for this Technical Report is 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.

The users of this Technical Report fall into the following four general categories (acknowledging that terminology and job classifications vary from company to company and industry to industry):

application engineer (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 (ref. [2]).

operator: an individual who actually prepares workpieces for measurement, places them in fixtures, decides if they have been adequately thermally stabilized, operates the machine, and performs normal daily maintenance.

NOTE: In some companies, the “application engineer” and the “operator” may be the same person.

programmer: an individual whose primary responsibility is creating the necessary code (in the high-level language appropriate to a specific machine) to execute the measurement plan (this may be a separate job classification or its duties may be incorporated within application engineer, operator, or quality engineer).

quality engineer: an engineer that selects, acquires, and installs measuring systems, manages the use of the data coming from the systems, and plans and ensures the proper maintenance of the systems.

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, the change in length due to thermal expansion is calculated as follows:

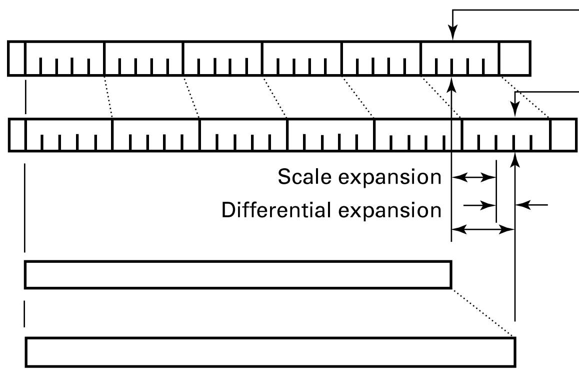
$$\Delta L = L_1 \alpha \Delta T \tag{3-1}$$

where
- α = coefficient of thermal expansion
- ΔL = change in length, $(L_2 - L_1)$
  - L_1 = length at state 1
  - L_2 = length at state 2
- ΔT = change in temperature, $(T_2 - T_1)$
  - T_1 = temperature at state 1
  - T_2 = temperature at state 2

This is shown graphically in Figure 3.1-1 for $T_2 > T_1$. The nominal coefficient of expansion, α, may be negligibly small (e.g., Zerodur) or relatively large (e.g., polymers). Nonmandatory Appendix E gives typical values of some common engineering materials taken from refs. [3], [4], [5], [6], and [7]. The coefficient of expansion may be taken as a constant for the temperatures encountered in industrial length measurements. It does vary at very high or very low temperatures.

Since workpieces expand when their temperatures increase, a dimensional specification is meaningless 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.) and was subsequently adopted by most countries. This

Figure 3.2-1 Effect of Differential Expansion on Length



temperature came into such general use that in 1954, the International Organization for Standardization (ISO) issued a standard, ISO 1 (ref. [8]), promulgating its use among the ISO-participating countries. It is generally accepted that a stated dimension of a body derived from measurement should be the dimension measured if the body is at a uniform 20°C {see ASME Y14.5 (ref. [9]), para. 4.1(m)}.

NOTE: Electrical quantities are specified with a standard reference temperature of 23°C.

3.2 Differential Thermal Expansion

Considering the thermal expansion of all materials, the dimensional measurement process is illustrated in Figure 3.2-1. Both the measuring scale and the workpiece are expanding (or contracting), each according to the temperature and its own coefficient of expansion. 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, differential expansion must be considered.

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 is comprised of a master gage, a comparator, and a workpiece and represents a generalization of the differential expansion concept of para. 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 is 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, through the fixturing to the workpiece, and to the measurement point on the workpiece.

Since coordinate metrology 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 scenarios to be considered, as follows:

(a) 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.

(b) For measurements that involve long measurement times or a 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 para. 3.6 for more information on thermal drift.

3.4 Bimetallic and Gradient Bending

3.4.1 Bimaterial Effects. Materials thermally expand proportionally to their coefficient of thermal expansion (CTE) values. If a workpiece or CMM is composed of materials with different CTEs or of a material with a nonuniform CTE, geometrical distortions may occur as the ambient temperature varies. In the case of CMMs, the CMM manufacturer may provide either mechanical or software means of mitigating or compensating for these expansions. In the case of workpieces, a nonuniform CTE will generally result in bending due to the different coefficients of expansion at different points in the structure.

While this effect can occur when materials with explicitly different CTEs are present, it is less clear for materials with nominally the same CTE. However, even for a single material, the CTE can vary for many reasons, including the following:

(a) stresses induced during the material's fabrication from rolling or forging

(b) metallurgical variations in castings due to nonuniform rates of cooling (many finished metals start out as castings from ingots and can also exhibit these variations)

(c) hardening of surfaces (either by flame or electrically), due to the metallurgical changes that provide the hardness

3.4.2 Gradients. Spatial temperature gradients in CMM components may 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 bimaterial 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. The following three methods are in general use:

(a) 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 the scale's coefficient of expansion. Laser scales fall into this class; the coefficient of expansion is determined from the air index of refraction.

(b) If the scale is rigidly fixed to the machine structure at all points, then scale expansion is determined from the structure's temperature and coefficient of expansion. Scales that are fixed at both ends, e.g., stretched-tape scales, are in this class.

(c) If scale expansion is partially constrained by the structure, e.g., 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 measures the capability of a body to distribute heat throughout its volume. It is formally defined as the ratio of conductivity to heat capacity per unit volume per degree Celsius. Heat capacity is specific heat times the density.

Thermal diffusivity and coefficient of expansion are 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. The rate of change of an object's temperature is related to both the thermal diffusivity within the object and the difference in temperature between the object and its surrounding environment. Time constants are associated with processes that can be described by exponential mathematical functions. Initially, any point in the object will approach its steady-state temperature, quickly at first, and more slowly as the temperature difference diminishes (e.g., a light bulb is turned on near the object). 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 the heat transfer mechanisms of conduction, convection, radiation, and associated boundary conditions. Changing the boundary conditions will change the thermal time constant; e.g., for some workpieces the time constant can be decreased by a factor of 10 by using forced air (i.e., a fan) relative to the time constant for still air. Workpiece soak-out

Table 3.5.2-1 Thermal Step Response Versus Number of Time Constants

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

time is the time required for the workpiece temperature to approach equilibrium so that more accurate measurements can be made. This is discussed further in para. 7.4.2 and Nonmandatory Appendix B.

Time constants are useful to model the change in any length of an object when the object is 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,

$$\Delta L(t) = \Delta L_{ss}\left(1 - e^{-t/\tau}\right) \tag{3-2}$$

where

t = 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)
τ = time constant

When $t = \tau$, the change in length is about 63% of the steady-state change. Table 3.5.2-1 gives this percentage for other times as multiples of the time constant.

$$\frac{\Delta L(t)}{\Delta L_{ss}} \rightarrow 1 \text{ as } t \rightarrow \infty \tag{3-3}$$

A plot of the time response for a body with a time constant of 1 h (3 600 s) is shown in Figure 3.5.2-1. The elapsed times of the first six time constants are shown.

Figure 3.5.2-1 Thermal Step Response

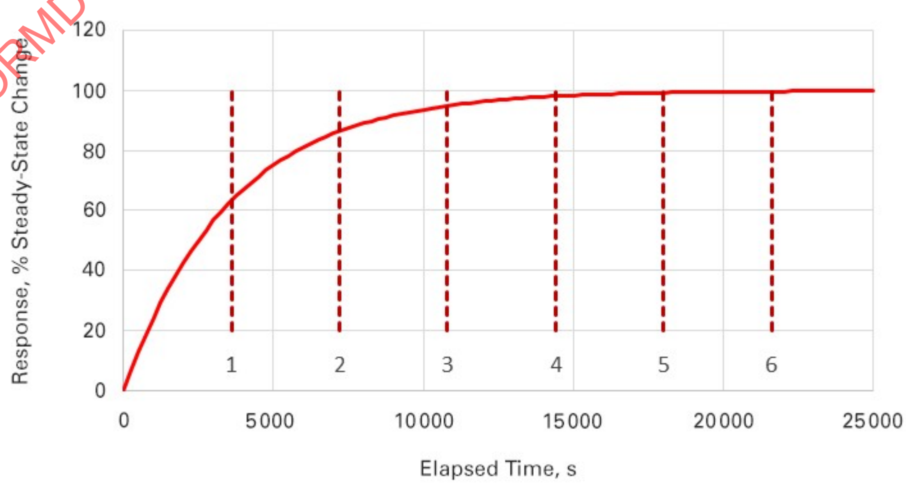
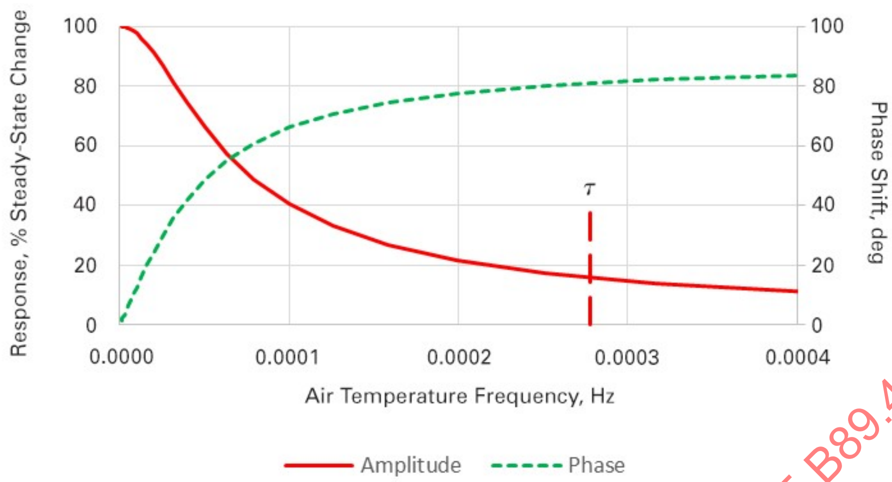


Figure 3.5.2-2 Thermal Response of a Simple Body to Temperature Variation



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. Based on the tolerance, a more efficient soak-out time can be established.

The term "thermal mass" is used to describe the concept of how quickly an object or machine responds to temperature changes in the environment. This is analogous to acceleration of an object under an applied force; the more massive the object, 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, e.g., metals, at frequencies well below the reciprocal of the time constant, the length will track the temperature according to eq. (3-1). 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 h (3 600 s).

NOTE: 1 cycle/min = 0.0167 Hz (16.7 mHz); 1 cycle/h = 0.00028 Hz (0.28 mHz).

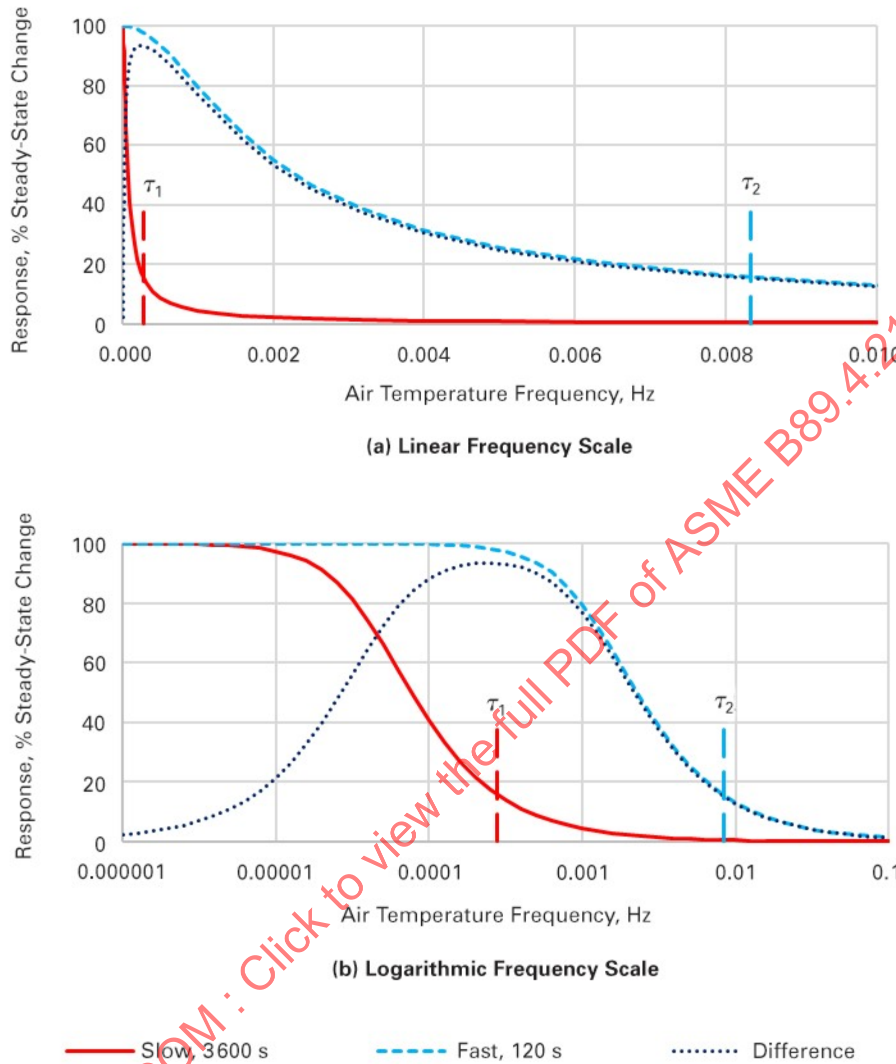
A simple body's thermal response does not have a resonant response like a spring-mass system. That is, the change in length will never exceed the steady-state change predicted by eq. (3-1) for the amplitude of temperature change. However, systems with more than a single thermal element and systems with 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.

Figure 3.2-1 illustrates differential expansion between the workpiece and the measuring scale. In a steady temperature environment at 20°C + ΔT, the differential expansion can be calculated as described in para. 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 changes 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 h (3 600 s) being compared to a thin workpiece with a time constant of 2 min (120 s). The workpiece will have a fast response relative to the scale/beam assembly. The differential response even when they have the same CTE is shown in Figure 3.5.2-3.

The case where thermal resonance may occur deals with a multielement 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

Figure 3.5.2-3 Differential Equation of Measuring System: Two-Element Responses

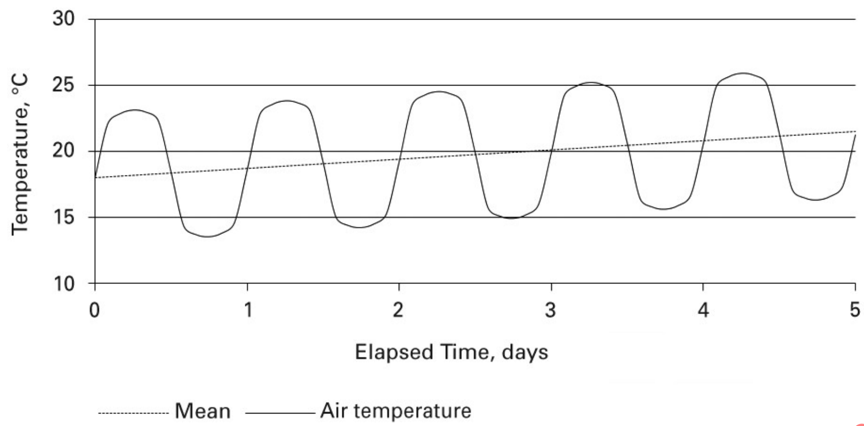


workpiece depends on much more than simply the magnitude of the temperature variation. The three-dimensional displacements are a superposition of linear expansion and bending in all structural elements, each following its own thermal characteristics. The frequency response curve may show a maximum for 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 24 h. See Nonmandatory Appendix B for examples.

3.6 Thermal Environment Characteristics

3.6.1 Temperature Variation Basics. Many dimensional measurement errors are the result of changing temperature rather than 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. To understand these effects, one needs to first review the nature of environmental variation.

Figure 3.6.2-1 Typical Thermal Cycle



Variation in temperature is a significant problem to overcome. Temperature affects material at the microscopic level, causing each small element to change size depending 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 of both the CMM and the workpiece.

In some cases, machine scales are chosen that have CTEs similar to normal workpiece materials applicable to the rated operating conditions. Another method is to use temperature compensation to correct for differences in scale and workpiece CTEs. 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 for aluminum it 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 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 is 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 cycles 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. There are some elements of control since 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 that 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 may not meet specifications in the summer.

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, the ceiling, and the 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 it is typically more pronounced in uncontrolled environments. Stratification is a spatial air temperature variation (or gradient) in the vertical direction, denoted 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 length of time spent in the different vertical temperature regions). Horizontal temperature gradients due to local heat sources can cause similar effects, denoted as $\partial T/\partial x$ and $\partial T/\partial y$ (temperature gradient in the x direction and in the y direction, respectively).

These temperature variations 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 para. 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.

Thermal conditions are a major factor considered in the design of CMMs. For information regarding machine design considerations, see Nonmandatory Appendix F.

3.7 Uncertainty Considerations

When the CMM is used within the 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 (ref. [10]). Measurements outside the rated operating conditions, such as CTEs or measurands not specified in the performance specification, may produce measurement errors not represented by the MPEs. For any combination of environmental conditions that are within the rated operating conditions, the accuracy of the CMM (e.g., as characterized by ASME B89.4.10360.2) is expressed as an MPE that is assigned by the CMM manufacturer. 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, e.g., point-to-point length as measured on gage blocks, step gages, and similar artifacts permitted by the performance testing protocol.

(a) In general, the CMM user is not able 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 its software error correction (i.e., error map) created at 23°C, as this was the ambient temperature when 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 ASME B89.4.10360 specification, is no longer assured. Some guidance for the derating of the CMM performance is discussed in section 5.

(b) The effects of the environment on measurements of production workpieces are 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, or the temperature of the workpiece may be changing with time or may be spatially nonuniform, resulting in geometric distortions. In particular, the workpiece may be secured to the CMM table or other structure in an overconstrained manner, e.g., tightly clamped in several locations. In this case, as the temperatures of the workpiece and of the fixture structure change, 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 reestablish datums 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 addressed in the ASME B89.4.10360.2 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 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.

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

(1) For measurements made within the environmental rated conditions, the point coordinate accuracy of the CMM can be estimated by the ASME B89.4.10360.2 accuracy specifications given in technical literature from the CMM manufacturer.

(2) 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 than 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.

(3) 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, which could involve multiple MPEs such as the length-measuring performance, the probing performance, and the offset probe performance), the effects of the sampling strategy used on the feature, and the effects from the workpiece itself. In this Technical Report, only the effects of the workpiece thermal errors (WTEs) are considered in detail; the uncertainty from the WTE (U_{WTE}) for a feature of size can be estimated from the following equation:

$$U_{\mathrm{WTE}} = 2\sqrt{u_{\mathrm{WTVE}}^2 + L^2(T - 20°\mathrm{C})^2 u^2(\alpha_w) + L^2\,|\alpha_w - \alpha_s|^2 u^2(T)} + \delta \tag{3-4}$$

where

L = length or size of the workpiece being measured
T = temperature of the workpiece, °C
$u(T)$ = uncertainty in the measurement of the temperature of the workpiece
$u(\alpha_w)$ = uncertainty of the nominal coefficient of expansion of the workpiece
u_{WTVE} = standard uncertainty from the workpiece temperature variation error described in para. 5.2
α_s = thermal expansion coefficient of the calibrated test length for which the MPE is stated per ASME B89.4.10360.2; use 11.5×10^{-6}°C^{-1} for normal CTE cases
α_w = thermal expansion coefficient of the workpiece, °C^{-1}
δ = 0 if the CMM has workpiece thermal compensation
= $|L(T - 20°\mathrm{C})\ (\alpha_w - \alpha_s)|$ if the CMM does not have workpiece thermal compensation

4 NONTHERMAL EFFECTS

4.1 Vibration

Vibrations can adversely affect 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 through 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 ideal 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 that 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 that reduces the noise level for the CMM and the operator.

4.2 Illumination

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

(a) adequate visibility so that tasks can be performed with the appropriate speed and accuracy

(b) lighting levels that will permit the operator to work with maximum efficiency

(c) lighting conditions that will result in maximum safety and the absence of factors contributing to visual disability and visual discomfort

Research has shown that lighting intensity levels roughly between 1 000 lx and 1 600 lx are adequate for most applications, although levels as high as 10 000 lx may be required for some specialized measurements. In general, the criteria listed in (a) through (c) 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 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 many cases, they 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, disks, etc. (diametric errors up to 10 μm 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 to 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

IEEE 1159 (ref. [11]) is an accepted standard for defining the types of power phenomena that occur in industrial applications. It provides the user with descriptions relating to nominal operating conditions of electrical power systems and how to properly monitor these systems through the use of power-monitoring devices.

4.4.1 Ground Loops. A frequently overlooked installation detail that can cause operational problems later is the inadvertent creation 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 an instrument to lock up. To eliminate any potential differences, it is best to connect all components to a common ground.

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. CMMs may be adversely affected in environments that have large electromagnetic interference, such as those produced by electric welding.

EMC requirements vary from country to country, as there is not one universally accepted standard. For example, the United States recognizes the UL Certification whereas the European Community has adopted the CE Mark. To comply with these directives, manufacturers must test the product to the emissions and immunity requirements of the appropriate certifying body. If the machine passes, a UL sticker or CE Mark may be applied to the product. If users are concerned about emissions, they should ask the CMM supplier about what EMC standards their product meets.

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). RH 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

Table 4.5-1 Ferrous Corrosion Development

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	This is the effective upper limit of dry air. Usually no ferrous corrosion occurs up to this RH 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 that have been exposed require monitoring and maintenance to avoid corrosion buildup.
50	Continuous attention must be given to corrosion maintenance. Proper maintenance of ferrous surfaces is imperative.
53	Corrosion occurs at a very high rate.

content of air is affected by weather as well as surrounding conditions and activities, and the moisture-holding capacity of air varies with temperature. One way of thinking about RH is as 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.

For example, a volume of air at sea level, at a temperature of 25°C, would be completely saturated if there were 20 g of water vapor in every 1 kg of dry air. If this air actually contained 10 g of water vapor per 1 kg of dry air, the RH would be 10/20 = 50%.

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

Relative humidity is usually a minor problem, but it 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 million for a 100% change in RH at 20°C. Sensitivity to the RH varies as a function of temperature and is significantly larger at 25°C than at 20°C.[1] 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 RH. 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 primary reason that RH needs to be controlled. Table 4.5-1 lists the effects of RH on ferrous material based on a study done by the U.S. Air Force in 1979 (ref. [13]).

ASME B89.6.2 (ref. [14]) recommends 45% RH as the upper limit. NCSLI RP-7 (ref. [15]) and NCSLI RP-14 (ref. [16]) both recommend a maximum of 50% RH be maintained for metrology laboratories. Electrostatic discharge (see also para. 3.4) is also a concern with sensitive instrumentation, such as computer chips, so it is recommended that the lower limit of RH 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, such as the air temperature within the measuring volume and the thermal gradients within that volume. 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, para. 5.1.1. Provided the thermal environment is in compliance with the environmental rated conditions, 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. ASME B89.4.10360.2, para. 5.1.1 lists the requirements of the environmental temperature measurements to fulfill the requirements of the environmental rated conditions. For CMMs equipped with temperature sensors (for measurements of either the CMM structure temperature or the workpiece temperature), the impact of the uncertainty of these sensors is included in the CMM's MPE values. If the CMM requires the user to provide a temperature measurement, of either the thermal environment or the workpiece,

[1] See ASME B89.1.8 (ref. [12]), Table 4.7.2-1, Note (1).

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 item being measured by the coordinate measuring system. Different thermometers or temperature probes are used depending on the temperature measurand selected. Sensor design varies depending on application, such as air temperature, internal material temperature, or surface temperature.

Resistive temperature devices such as platinum resistance thermometers (PRTs) and thermistors are generally preferred for their accuracy. PRTs are very accurate (errors <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 and vibration. Thermistors can be designed to be very accurate (errors <0.5°C) and are not as susceptible to shock and 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). 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, para. 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 measure 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 24 h. 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 (MPE values) are not assured. If the CMM manufacturer agrees to derate the accuracy specifications according to ASME B89.4.10360.2, para. 7.1.3.4.5, the derated MPEs can be used to characterize the point coordinate measurement capability of the CMM and to evaluate the measurement uncertainty of workpieces as described in para. 3.7. The derating should represent the actual environmental conditions during production measurements. If the CMM manufacturer has not agreed to derate the CMM, either because the CMM is not appropriate 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 ASME B89.4.22 (ref. [17])

Coordinate measuring machines available today are capable of obtaining extremely accurate measurements. However, external sources such as vibrations from machine tools, climate control systems, and materials handling systems can significantly degrade both their accuracy and repeatability. Thus, an understanding of the magnitude of external vibration excitation is an important part of the installation site qualification. The biggest contributor to this degradation is vibrations 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) A reputable vendor should be chosen to record the data with the appropriate equipment. The sensors must be responsive to low-frequency vibrations.

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

(c) The vendor should be informed in 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 in use should be operating during any vibration testing. In addition to machines, this includes 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) The vibrations should be recorded in three orthogonal directions and the three rotational modes. Usually the three directions are the vertical and the two horizontal (e.g., east–west, north–south) directions. Vibration testing should have a minimum duration of 30 min.

Following the conclusion of a site survey, evaluate the results against the manufacturer's requirements and determine if the site is suitable for the CMM to operate. If the site is not suitable for CMM operation, then determine either how to improve the CMM performance in a harsh environment or how to improve the environment. If desired, use the manufacturer's expertise to better analyze these results and provide recommendations.

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

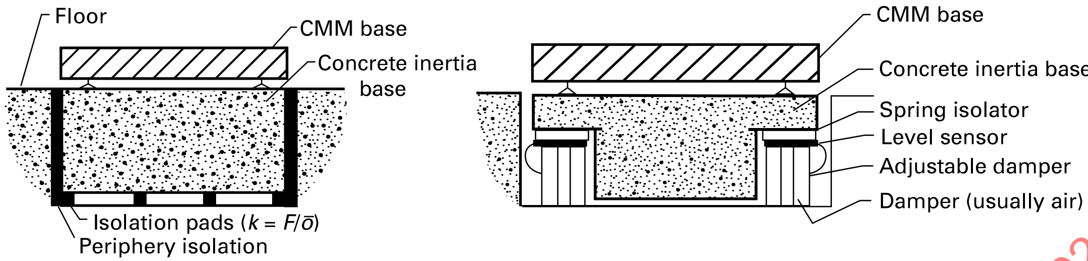
The most common method used is the passive system approach. While there are different configurations for passive systems, they all incorporate the use of springs and an inertial confinement block, typically made from either concrete or steel. Typical configurations are shown in Figure 6.1-1. Note that 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 and 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 effectiveness.

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

Generally, CMM manufacturers offer standard isolators that dampen the floor vibration and are effective for vibrations above 25 Hz. For vibrations between 15 Hz and 25 Hz, medium-cost isolator pads may be available. For vibrations below 15 Hz, 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 may cause repeatability problems for the CMM. To reduce the rocking, damping may be needed or the isolators may need a larger footprint than the CMM base.

An effective method to determine the vibration levels at a proposed CMM site is to place a set of triaxial vibration transducers with suitable calibration and traceability on the floor where the CMM is to be installed or on a common interface. The area monitored is typically about 3 m larger than the footprint of the machine. These transducers produce an output signal proportional to the vibrations at the site. This signal is recorded, analyzed by frequency, and compared

Figure 6.1-1 Passive and Active Isolation Systems



(a) Passive **(b) Active**

with the manufacturer's vibration criteria specification. A review of the data is used to confirm the site suitability and to determine if any vibrational derating is required.

For more information on tests for vibration, see Nonmandatory Appendix G.

6.2 Relative Motion Tests for Vibration

6.2.1 General. Ultimately, the user is concerned with site vibration affecting measurements taken with the CMM. Testing of this influence on performance testing is detailed in paras. 6.2.2 and 6.2.3.

6.2.2 Historical Testing. For older installations, when the machine was originally installed, relative motion tests lasting at least 10 min may have been performed under the same conditions as those during the performance testing. The results of such testing were considered acceptable if the relative amplitude measured between the machine ram and the worktable 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 derated 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 manufacturer (acceptance) and the user (reverification).

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

Repeated measurements of the same artifact yield slightly different results due to such factors as probing noise, vibrations, and backlash. As each calibrated reference length is measured in each location only three times, any statistical analysis is problematic, 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, which 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 of approximately 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 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 the accuracy. The CMM accuracy, as quantified by 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 it 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, in which the CMM will perform to its specified accuracy (i.e., its MPE values). The CMM user is responsible for providing an environment satisfying the rated condition requirements with the CMM, including any necessary auxiliary equipment, operating in the room. 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 performance specifications apply to the results of the particular tests and testing artifacts described in the test protocol. For example, ASME B89.4.10360.2 specifies the CMM length-measuring performance based on a point-to-point length measurement and artifacts that represent calibrated test lengths. In some cases, the test artifact may be required to have a low CTE as part of the rated conditions to achieve test results within the ASME B89 MPE specifications (see ASME B89.4.10360.2, para. 6.3.3.3), and hence such specifications may not reflect the materials used in typical workpieces. Workpieces may present additional uncertainties because their shape and size are different from that of standardized CMM testing artifacts; see para. 3.7.

The test values obtained from a single standardized performance test are a snapshot of the CMM at the particular conditions that prevail at the time of testing, and 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 the thermal and vibrational rated conditions specified by the manufacturer should be carefully considered.

7.2 Thermal and Other Environment Controls

7.2.1 General. Decisions regarding temperature control of CMM inspection operations must often be made. There are often trade-offs 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 sensitivity to environmental temperature, temperature conditions in the area where workpieces are processed, and skill of inspection personnel. This section provides guidance by highlighting 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. Another option is to provide a simple passive enclosure that is relatively inexpensive and provides isolation from the environmental fluctuations of the shop. A third option is a temperature-controlled 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 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 work zone and workpiece maintain a relatively uniform temperature; however, rapidly changing temperatures may cause temperature gradients that are nonlinear, and compensation may not perform as expected. Manufacturer specification and limits for environmental conditions, as stated in rated conditions described in ASME 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.

For more information on the effects of temperature control and the supporting thermal theory, see Nonmandatory Appendices A and D.

7.2.2 Thermal Enclosures. 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 CMM measurements are most accurate. 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, it needs to be protected from these harsher conditions and provided an environment where adequate measuring accuracies can be achieved. Some CMMs are offered with enclosures that protect from the following contaminants found in the shop environment:

(a) dust
(b) coolant mist
(c) changing temperatures
(d) mean temperature other than 20°C
(e) noise or vibration

There are two types of enclosures: passive and active. If the CMM needs additional protection, a passive enclosure may be adequate or a temperature-controlled room may be required.

7.2.2.1 Passive Enclosures. A passive enclosure may provide some damping of high-frequency temperature variation in the vicinity of the CMM but offers 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 buildup 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. A passive enclosure requires little additional space and is easily moved if the CMM is relocated.

7.2.2.2 Active Enclosures. To make more accurate measurements, a temperature-controlled enclosure can be used. This enclosure may cost as much as the CMM itself, depending on size and how accurately the temperature must be maintained. It will maintain the CMM and the workpiece at a more stable temperature and maintain their cleanliness. Thus, the CMM may require less maintenance and less-frequent calibrations, which somewhat offsets the additional cost of the room. This room typically occupies two to four times the floor space of the CMM.

Any enclosure will be ineffective 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 alternative 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 and thus more accurate in laboratory environments near 20°C than in 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 the time constants. The second is to design for very short time constants so that environmental variation periods are long compared with the 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 Compensation. 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 responses of the machine and of the workpiece to environmental temperature may not be the same, and uncertainties of expansion add to the measurement uncertainty. However, such machines can produce accurate results at temperatures near 20°C.

7.3.3 Machines With Linear Thermal Compensation. Linear or first-order thermal compensation is the simplest to implement and thus most common. 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 Compensation. Systems have been developed in which temperature sensors are embedded in the machine frame and are 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 that they make possible in the capital, maintenance, and running costs of the CMM enclosure and temperature control system.

When the change in 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 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.

If a significant temperature change occurs during a measurement, e.g., 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. These shifts in datum can occur due to the differential expansion between the scales and the machine frame including the worktable.

These shifts can be reduced by securing the workpiece near the point on the machine scale where it is secured to the machine structure. Information about the scale's fixed points can be obtained from the manufacturer. The magnitude of measurement variation over time for various locations on the worktable can be experimentally determined. This information can be used to select the location for securing workpieces that minimizes these effects. This experimental information is also useful for approximating the expected relevant measurement error.

7.4 Workpiece Handling

7.4.1 Mounting of Workpieces. Many CMMs are made from a combination of materials, each with a different CTE, such as a combination of granite, steel, aluminum, and ceramic. 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 pinned at the left side and the *Y* scale pinned at the front of the axis, the workpiece 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 overconstrained, which may occur when it is 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. The user should be aware of the workpiece soak-out times and must 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°C of the room temperature.

(a) During the early stages of soak-out time, very large distortions of the workpiece may occur 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. Factors affecting soak-out times are as follows:

(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) As an example, tests were 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 are as follows:

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

(c) ASME B89.6.2, section 10.1.1, Figure 1 presents a coolant effectiveness chart for still and moving air and water on iron and plastic workpieces. From the chart, the following conclusions are made:

(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 Nonmandatory Appendix C.

7.5 Interim Testing

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

7.6 Handling Thermal Influences in Uncertainty Analysis

The following summarizes different approaches to estimation of the contribution to measurement uncertainty caused by the response of CMMs and workpieces to thermal environments:

(a) 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.

(b) A formula for uncertainty contribution is fit 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 in the formula.

(c) 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.

(d) 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.

(e) 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

In the analysis for the purchase of a CMM, it is important to consider cost, speed, and accuracy. A common mistake is to consider the cost of the machine alone without considering the cost of the coordinate measuring system as a whole. Suboptimization on cost, accuracy, or speed typically leads to mistakes. A solution is to design the system first, encompassing all aspects [the scale, the workpiece, the instrument (machine), the operator, and the environmental issues], and then consider the total cost.

8.2 Cost Elements to Consider

8.2.1 General. A generalized complete measurement system may be characterized as the following five basic elements:

(a) a scale
(b) a workpiece
(c) an instrument
(d) a person (the operator)
(e) an environment

These elements are abbreviated as SWIPE. A brief discussion of each component 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 the extra cost 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. Additional costs for thermal compensation for the workpiece should be analyzed carefully. For the beginner it would be beneficial 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. A common mistake in choosing which machine to purchase is to save money by buying a small machine without adequate consideration to required probing clearances, space for work, holding devices, clamps, etc. A rule of thumb is to select the largest component that will be measured, and add 250 mm to 300 mm on all sides that have features to be measured (especially for machines equipped with articulating probe heads). One way to save is to select the appropriate accuracy class of machine. Many CMM models are sold at two or three different accuracy levels. Normally, the highest accuracy is not needed. In fact, depending on the environmental (thermal) situation, this accuracy may not be realized if the machine is not used in the rated operating environment.

8.2.5 Person (Operator). Training operators in how to program and operate the CMM is vital. Therefore, high-quality training is cost effective. In general, learning by reading a manual is difficult, and some software is not intuitive. Note the following about training:

(a) Before an operator or programmer is trained, he or she should have at least some experience in CMM operation working with an experienced operator.

(b) The specific instructor of the class, his or her background, and his or her ability to teach should be known. It is very helpful for trainers to have real-life experience measuring workpieces and programming CMMs to measure 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 temperature range in the enclosure. Providing the recommended level of air cleanliness, lighting intensity, and humidity control are also important considerations. Providing excess control adds little to system performance at high 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, at either the CMM scale temperature or the "shop ambient" temperature (which should be almost the same). This results in a workpiece temperature that can be mathematically corrected.

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

A-1 INTRODUCTION

When the environment is controlled to a steady 20°C, temperature effects are significantly reduced. If the coordinate measuring machine (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.

A-2 TEMPERATURE CONTROL

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 turnover 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°C or more depending on 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 only 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 check 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 between 3 h for thin-walled sections and 24 h for items such as castings with wall thickness up to 20 mm. As discussed in this Technical Report, 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 requalification is greatly reduced. Whenever 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 min before requalification. 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 of 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 it is approximately a degree or less. When neither the CMM nor the workpiece has 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 manufacturer’s recommended practice and rated operating conditions.

NONMANDATORY APPENDIX B
EXAMPLES OF THERMAL TIME CONSTANTS

B-1 INTRODUCTION

As described in para. 3.5 of this Technical Report, thermal time constants are a fundamental concept of temperature effects. Prior to reviewing the examples shown in this Appendix, it is strongly recommended that users review para. 3.5 of this Technical Report and ASME B89.6.2 (ref. [1]), with an emphasis on section 10.

The thermal time constant, τ, may be calculated from eq. (B-1) or eq. (B-2), which are reproduced from ASME B89.6.2.

$$\tau = \frac{CV}{hA} \tag{B-1}$$

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

where

A = surface area, m^2
C = thermal capacitance, $J \cdot m^{-3} \cdot K^{-1}$
c_{pressure} = constant pressure heat capacity, $J \cdot kg^{-1} \cdot K^{-1}$
h = convective heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
V = volume, m^3
ρ = mass density, $kg \cdot m^{-3}$
τ = thermal time constant, s

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

A typical value for a convective heat transfer coefficient, also called convective film coefficient, in slowly moving air over a flat plate is about 5.6 $W \cdot m^{-2} \cdot K^{-1}$. The convective heat transfer coefficient, h, can be increased to about 56 $W \cdot m^{-2} \cdot K^{-1}$ 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 heat transfer coefficient will be much greater than 56 $W \cdot m^{-2} \cdot K^{-1}$.

Table B-1-1 Thermal Capacitance of Common Engineering Materials

Material	Thermal Capacitance, C
Aluminum	660
Beryllium copper	770
Brass	880
Bronze	900
Cast iron	1 030
Copper	920
Granite	600
Invar	1 140
Mild steel	990
Nickel	1 120
Stainless steel	1 100
Titanium	640
Zerodur	550

In most cases, the fluid medium will be slowly moving air. For such a situation, assuming a value of 11.5 $W \cdot m^{-2} \cdot K^{-1}$ 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 ASME B89.6.2 or any textbook on heat transfer.

The examples in paras. B-2 through B-5 illustrate the calculation of thermal soak-out times.

B-2 EXAMPLE 1 — GAGE BLOCK

The thermal time constant of a 250-mm long steel gage block is calculated in this example. 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 calculated as follows:

$$\begin{aligned} A &= 4A_{\text{side}} + 2A_{\text{end cap}} \\ &= 4(250 \times 25) + 2(25 \times 25) \\ &= 26\,250 \text{ mm}^2 \\ &= 0.0263 \text{ m}^2 \end{aligned} \tag{B-3}$$

The volume, V, is calculated as follows:

$$\begin{aligned} V &= L \times W \times H \\ &= 250 \times 25 \times 25 \\ &= 56\,250 \text{ mm}^3 \\ &= 0.000156 \text{ m}^3 \end{aligned} \tag{B-4}$$

where L, W, and H are the length, width, and height, respectively, of the block.

The value of thermal capacitance, C, for steel is 990 $J \cdot m^{-3} \cdot K^{-1}$, and the convective heat transfer coefficient, h, is 11.5 $W \cdot m^{-2} \cdot K^{-1}$.

The thermal time constant, τ, can be estimated as follows:

$$\begin{aligned} \tau &= \frac{CV}{hA} \\ &= \frac{990 \times 0.000156}{11.5 \times 0.0263} \\ &= 0.51 \text{ h or } 31 \text{ min} \end{aligned} \tag{B-5}$$

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 approximately 2 h prior to any measurements being taken.

B-3 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, which has an exponential decay with a thermal time constant, τ, in eq. (B-6).

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

where

T = temperature difference between the bar and the air at time t = 0, °C

t = time, s

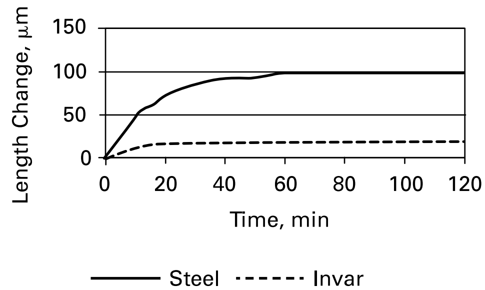
T_{air} = constant temperature of the ambient air, °C

T_{bar} = temperature of the bar at time t, °C

τ = thermal time constant, s

The National Institute of Standards and Technology (NIST) conducted tests 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-3-1. The thermal

Figure B-3-1 Change in Ball Bar Length as a Function of Time



time constant was nearly the same for both the invar and the steel. The time constant was 16 min for these artifacts in still air.

However, the materials have very different coefficients of thermal expansion. The stainless steel ball bar changed 0.100 mm and took 75 min to stabilize within 0.001 mm of its length for a 10°C change. The invar ball bar grew 0.020 mm and took 20 min to stabilize within 0.001 mm of its nominal length. For additional information, see ref. [2].

The following 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-3-1. For a ball bar, the ends of the cylinder are ignored as they are covered by the spheres.

The properties of the spheres will be constant regardless of the length of the bar. Considering a 25-mm diameter sphere and using the value r = 12.5 mm in the equations in Table B-3-1, the surface area is calculated as 0.001963 m^2 and the volume as 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-3-2 shows the surface area and volume for a number of different length ball bars, each with 25-mm diameter spheres attached.

The total surface area and volume are found by simply adding the three elements together as shown in Table B-3-3.

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

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

As shown in Table 3.5.2-1, to provide a result with 98.2% of the initial thermal effects removed, the ball bar should be allowed to soak out in a constant-temperature environment for 4τ, or about 2.4 h, prior to any measurements being taken.

Table B-3-1 Summary of Surface Area and Volume

Element	Surface Area, m^2	Volume, m^3	Ratio, V/A
Sphere	$4\pi r^2$	$4/3\pi r^3$	$r/3$
Cylinder	$2\pi rL$	$\pi r^2 L$	$r/2$

Table B-3-2 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

Table B-3-3 Ratios of Volume/Area as Function of Length

Length, m	Surface Area, m^2	Volume, m^3	Ratio, *V*/*A*, m
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 × 0.00000818) + 0.000479	0.006149
1.200	(2 × 0.00196) + 0.092296	(2 × 0.00000818) + 0.000577	0.006165

B-4 EXAMPLE 3 — CHANNEL SECTION

In this example, the thermal time constant is estimated for a 75-mm aluminum alloy C-channel section that is 1 400 mm 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 calculated as follows:

$$\begin{aligned} A &= (75 \times 1400) + 2[(25 \times 1400) + (6 \times 1400) + (19 \times 1400)] + (63 \times 1400) \\ &= 333\,250 \ \ \mathrm{mm}^2 \\ &= 0.333 \ \ \mathrm{m}^2 \end{aligned} \tag{B-7}$$

The volume, *V*, is calculated as follows:

$$\begin{aligned} V &= [(75 \times 6) + 2(19 \times 6)] \times 1400 \\ &= 949\,200 \ \ \mathrm{mm}^3 \\ &= 0.000949 \ \ \mathrm{m}^3 \end{aligned} \tag{B-8}$$

The value of thermal capacitance, *C*, for aluminum is taken as 660 $\mathrm{J{\cdot}m^{-3}{\cdot}K^{-1}}$ and the convective heat transfer coefficient, *h*, is 11.5 $\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$.

The thermal time constant can be estimated as follows:

$$\begin{aligned} \tau &= \frac{CV}{hA} \\ &= \frac{660 \times 0.000949}{11.5 \times 0.333} \\ &= 0.163 \ \ \mathrm{h} \ \ \text{or} \ \ \text{approximately} \ \ 10 \ \ \mathrm{min} \end{aligned} \tag{B-9}$$

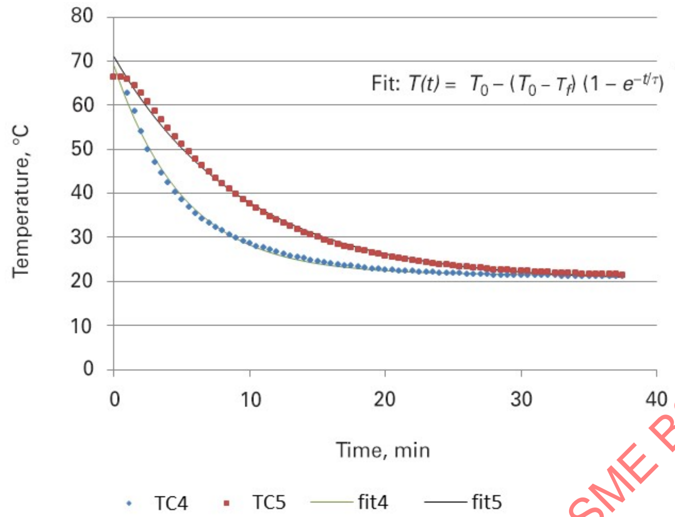
The channel should be allowed to soak out in a constant-temperature environment for 4τ or about 40 min prior to any measurements being taken.

B-5 EXAMPLE 4 — COMPOSITE FAN BLADE

This example uses a different approach from that shown in ASME 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 span-wise from the middle to the 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 is instrumented with thermocouples (TCs) embedded into the center of the thickest cross sections. Another TC is placed in the room air. A low-temperature oven is used to uniformly heat the workpiece to 65°C. The TCs are monitored to ensure stability before the workpiece is removed from the oven and placed on a rack in an air-conditioned room. The monitoring of all TCs continues for 2 h with temperature recordings at 30-s intervals. An example of the measured temperature versus time data is shown in Figure B-5-1, labeled as TC4 and TC5.

Figure B-5-1 Measured Temperature Versus Time With Calculated Values Using the Thermal Time Constant, τ, Obtained From a Least-Squares-Error Fit to the Experimental Data



$$T(t) = T_0 - (T_0 - T_f)(1 - e^{-t/\tau}) \tag{B-10}$$

where

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

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, E, is 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 sum of the squares of errors (SSE) is minimized by adjusting τ:

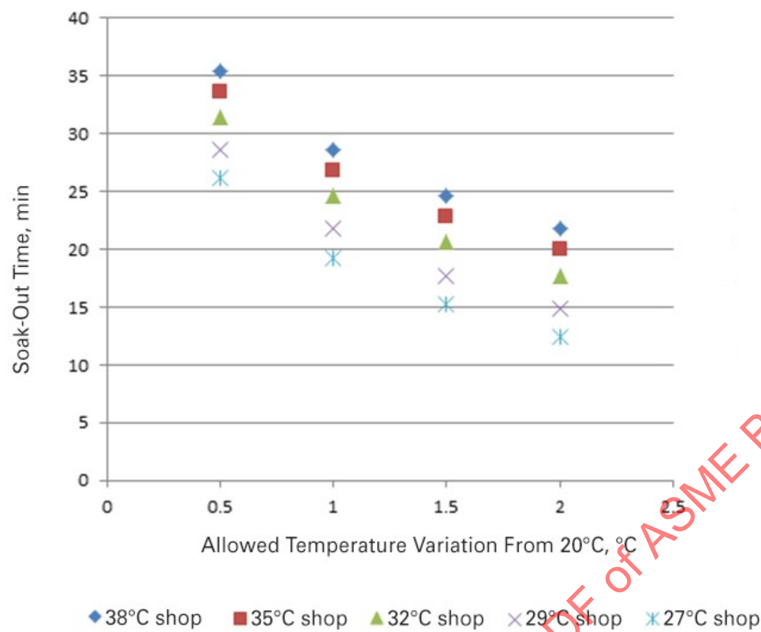
$$\text{SSE} = \sum E^2 \tag{B-12}$$

Minimizing the SSE is a common optimization method; the line labeled fit5 in Figure B-5-1 is produced by Microsoft Excel's built-in solver using this technique. The mathematical description of temperature, derived from basic heat transfer principles, agrees very well with the 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 that is the allowed temperature difference between a CMM and the workpiece; see eq. (B-13). Given an initial temperature and thermal time constant, the temperature versus time equation is rearranged to find the time to get to within X°C of the steady-state temperature beginning at some other temperature as shown in eq. (B-14).

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

Figure B-5-2 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



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

In this example, the following values apply:

T_0 = 35°C (shop)
T_f = 20°C (CMM room)
X = 1°C
τ = 9.9 min

Substituting these values into eq. (B-14) results in the following: t = 26.8 min.

Using eq. (B-14), graphs can also be constructed to predict the soak-out time for different starting temperatures and different final temperature targets as shown in Figure B-5-2. Note that a procedure for finding soak-out time based on workpiece-specific thermal time constants is better than a traditional rule of thumb such as 24 h minimum. A fixed time may unnecessarily affect cycle time for some workpieces or may be insufficient for others. An $N \times \tau$ procedure would be more effective; however, 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-5-2 may be most efficient.

B-6 REFERENCES

[1] ASME B89.6.2-1973 (R2012), Temperature and Humidity Environment for Dimensional Measurement, American Society of Mechanical Engineers (ASME), New York, NY

[2] S. D. Phillips, B. Borchardt, T. Doiron, and J. Henry, "Properties of Free-Standing Ball Bar Systems," *Precision Engineering*, Vol. 15, No. 1, January 1993, National Institute of Standards and Technology (NIST), Gaithersburg, MD

NONMANDATORY APPENDIX C
ILLUMINATION EFFECTS

C-1 APPLICATION TO THE MEASUREMENT TASK

The objective of good lighting is to provide the balanced quantity and quality of light needed for the measurement task. The task may be performed in either a laboratory environment or on the shop floor. Lighting designed specifically for a laboratory environment must meet the requirements of office areas, where mixed visual tasks are often performed. A significant difference is that workpiece 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 workpiece surface illumination.

Determination of proper intensity levels for illumination is necessary to provide for optimal performance of a given measurement task. This includes not only the relationship between performance and illumination, but also such factors as operator fatigue, including physiological and psychological effects, which are not typically considered in economic evaluations.

It is beyond the scope of this Technical Report to discuss the physiological factors that influence visual ability. This Appendix provides a brief discussion of the physical factors that describe certain characteristics of the visual task and the environment in which it is seen.

When a workpiece 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 show that as operators get older both the amplitude of accommodation and visual acuity decrease. This of course must be tempered with the corresponding increase in experience.

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 clear that the luminance in most measurement tasks is not constant, but rather 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.

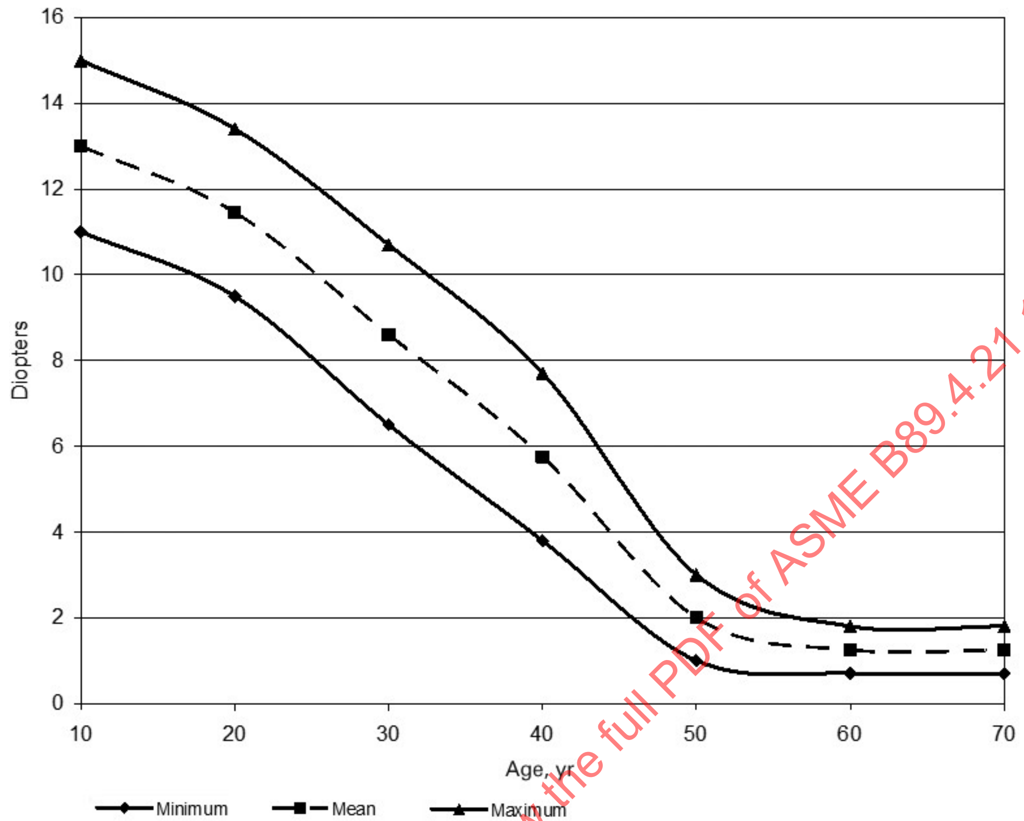
Luminance in the visual field, which surrounds the task, can have different effects depending on the areas involved, their location with respect to the line of sight, and their values compared with that of the task. Since wide variations in luminance can be detrimental to visual ability and/or visual comfort, it is recommended that the whole field of view be as uniform as possible. Thus, in the case of a visual task involving a simple object on a background, the entire surroundings 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 is disability glare, where the 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 irritating reflections of bright areas in specular surfaces.

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



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 in the surroundings 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 lenses, or louvers, as well as 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.

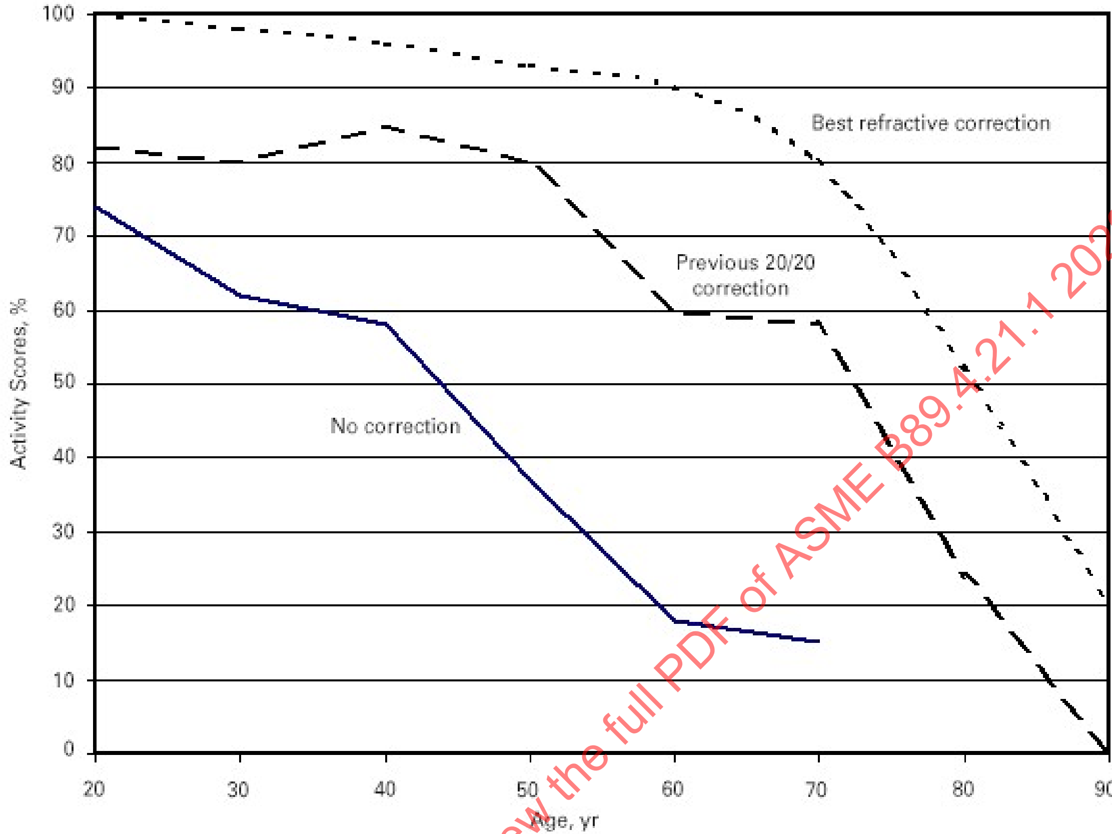
C-2 ADDITIONAL CONSIDERATIONS

Balanced vertical illumination can minimize contrast and thus enhance visual acuity. In a laboratory, this can be achieved using what is called "wall-washing." In this process, lighting is situated toward the edge of the ceiling and pointing down. Typically, the ceiling in a 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, the following three facets of illumination directly affect one or the other and are frequently overlooked:

(a) effect of the lighting on the environmental control
(b) effect of the environment on the lighting
(c) maintenance of the lighting to ensure reasonably constant illumination

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



C-2.1 Effect of Lighting on Environmental Control

To attain uniform shadowless illumination between 1 000 lx and 1 600 lx at 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% of the input energy goes in as light; the other 78% goes in as heat, with about 36% infrared and 42% being dissipated. In terms of illumination, if all of the energy in any light source could be converted into yellow-green light (the theoretical best visible light, with a wavelength of 555 nm), the luminous efficacy of the source would be approximately 680 lumens/W. Unfortunately, due to manufacturing variables, chemical changes, wavelength conversions, etc., the luminous efficacy of a typical cool white fluorescent lamp after its first 100 h of operation is approximately 77 lumens/W. Here again, this luminous efficacy is a function of the arc length of the tube and could be as low as 33 lumens/W for shorter tubes. The energy distribution for a typical cool white fluorescent lamp is shown in Figure C-2.1-1.

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 into the light fixture or either indirectly into the environment by conduction-convection or directly into the environment by radiation.

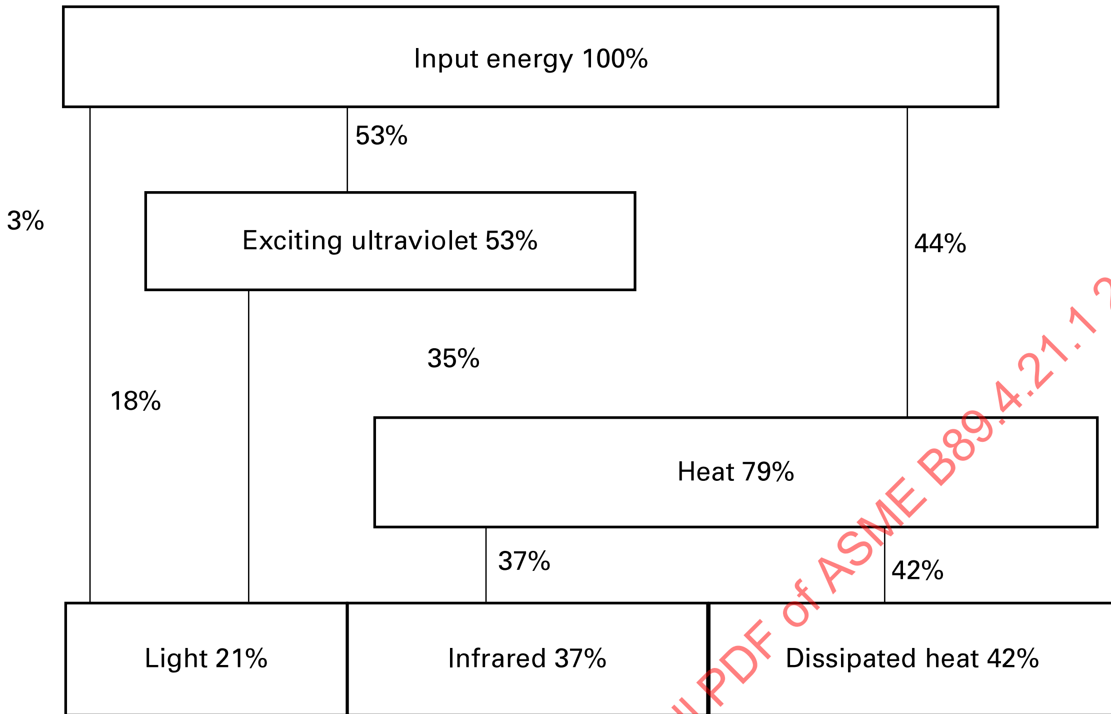
A calculation of the instantaneous rate of heat gain due to the lights can be obtained from eq. (C-1).

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

where

A = total area, m^2
C_u = coefficient of use
E = average illumination, lx
l_m = total lumens per luminaire
M_f = maintenance factor

Figure C-2.1-1 Energy Distribution of Fluorescent Lamp



q_{el} = sensible lighting heat load in conditioned space, W
t_f = thermal factor, ratio of energy in conditioned space to total power input
W = actual wattage per luminaire in service, W

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

The types 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 suspended, surface mounted, or recessed. In some locations, luminous or louvered ceilings may be used. For suspended luminaires, approximately 40% 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 reradiated.

Since nearly all of the input energy remains within the occupied space, the thermal factor is generally taken as unity (a value of 1 with no units). 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 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 higher rate. Unless the ceiling is a good absorber and can reradiate 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 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.

C-2.2 Environmental Effect on Lighting

The heat transferred from the lighting system may be removed by passing air over the luminaires or, in some cases, the airflow 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 that absorbs it. This can become a significant problem in a dimensional measurement process because most objects, e.g., dark surface plates and measuring machines, are better absorbers of light than reflectors of light. 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% at approximately 15°C.

The following six major factors contribute to an overall loss of light in a lighting system:

(a) lamp lumen deterioration
(b) dirt on luminaires
(c) lamp outages
(d) deterioration of luminaire surfaces
(e) dirt on room surfaces
(f) 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% for 10 000 h of operation. As loading increases, however, the decrease in lumen output approaches 40% for the same period of operation. Rated average life for bulbs of this type is typically from 7 500 h to 12 000 h. This is usually based on 3 h of operation per start. Consequently, with normal lumen deterioration, the same lumen output may decrease as much as 40% over the average life of a bulb, which, if operated continuously, could be 1 yr to 2 yr. The type of lighting system maintenance program established will be dictated by the degree of lighting load and illumination required and the economics of operating the program.

C-2.3 Lighting System Maintenance

To maintain the 1 000 lx to 1 600 lx of lighting intensity at each work location, a maintenance program is required that will ensure the light output will not degrade to less than about 66% of the designed initial light output, assuming this designed output would give the 1 600 lx. One way to do this would be to clean the lamps every 18 months and replace 50% of them once every 18 months. Another way would 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 C-2.2(a) and C-2.2(b) are the biggest contributors to loss of light.

NONMANDATORY APPENDIX D THERMAL THEORY

D-1 GENERAL

Coordinate measuring machines (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 accuracy, repeatability, and performance capability needed.

Thus CMMs had to be shop-hardened with temperature-resistant materials, antivibration systems, and protected guideways such as bearing and scale covers and scale systems with thermal compensation and low coefficients of thermal expansion (CTEs). In this Appendix, nomenclature and symbols are as defined in ISO 8000 (ref. [1]).

This Appendix considers the details of heat flow into a body. An initial consideration should address the subtle but distinct difference between heat and temperature.

Heat, Q, is the movement of energy. The 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. Heat is capable of being transmitted through fluids by convection, through solids and fluids by conduction, and through empty space by radiation.

Temperature, T, 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 a substance is, which can lead to an estimate of the direction of heat transfer. The common scale for measuring temperature is the Celsius scale, °C. Note that T is the thermodynamic temperature, which is related to the Celsius temperature, t, as follows:

$$t = T - 273.15 \text{ K}$$

D-2 MECHANISMS FOR HEAT TRANSFER

Heat is always transferred when the temperatures of two bodies are different. The three modes of heat transfer are as follows:

(a) Convection is the transfer of heat by the mixing and motion of macroscopic portions of a fluid.

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

(c) Radiation is the transfer of heat by electromagnetic radiation that arises due to the temperature of a body.

D-3 HEAT TRANSFER RATE

The heat flux, q, which is heat transfer rate per unit area, is determined by dividing the heat transfer rate, ϕ, by the area through which the heat is being transferred, as follows:

$$q = \frac{\Phi}{A} \tag{D-1}$$

where

A = area, m^2

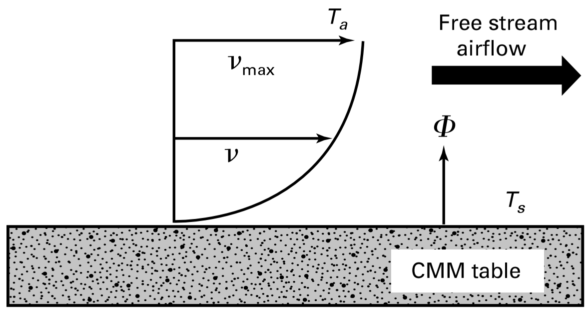
q = heat flux, $W \cdot m^{-2}$

ϕ = heat transfer rate, W

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 is air.

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



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 based on the fluid flow conditions and 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.

The temperature of the CMM table plate is T_s, and the temperature of the airstream is T_a. The arbitrary velocity of the airflow is shown, which is additionally assumed to drop to zero at the tabletop as a result of viscous action. 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 by 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, and the surface roughness. These factors and 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 Newton's law of cooling) as follows:

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

where

A = surface area for heat transfer, m^2
h = convective heat transfer coefficient, W·m^{-2}·°C^{-1}
T_a = air temperature, °C
T_s = surface temperature of the body, °C
ϕ = heat transfer rate, W

For a given set of the physical properties of the fluid and the physical situation, the flow is highly dependent on the convective heat transfer 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.

The convective heat transfer coefficient of air is approximated as follows:

$$h = 12.122 - 1.16v + (11.6 \times \sqrt{v}) \qquad \text{(D-3)}$$

where

v = the relative speed of the air over a workpiece, m/s

NOTE: Equation (D-3) is an empirical equation and is valid for air velocities between 2 m/s and 20 m/s.

Table D-4-1 Typical Values of Convective Heat Transfer Coefficient

Mode of Transfer (in Air)	Heat Transfer Coefficient, *h*, W·m^{-2}·°C^{-1}
Free convection	5–25
Forced convection	10–500

The relationship between the convective heat transfer coefficient and the velocity of the air over the workpiece is shown graphically in Figure D-4-2.

There are two types of convection, natural and forced. Natural convection occurs when 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 heat transfer coefficient and variable air temperature characterize convection.

Forced convection occurs when 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 on 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.

Figure D-4-2 Convective Heat Transfer Coefficient, *h*, as a Function of Velocity

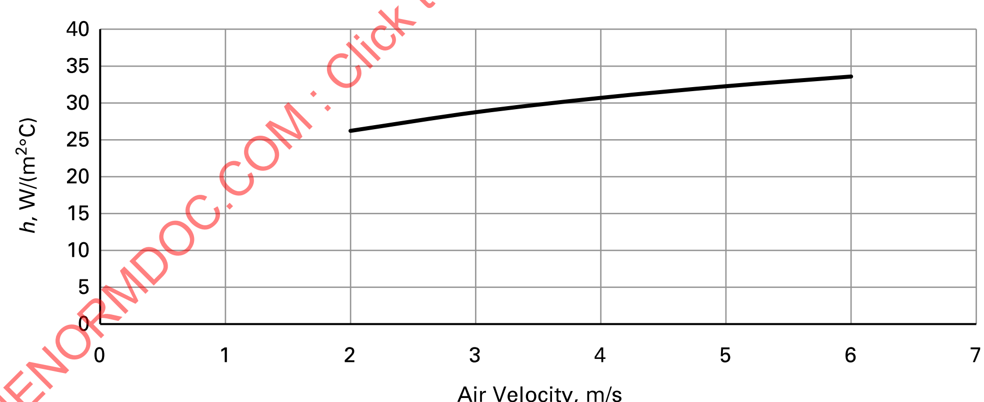
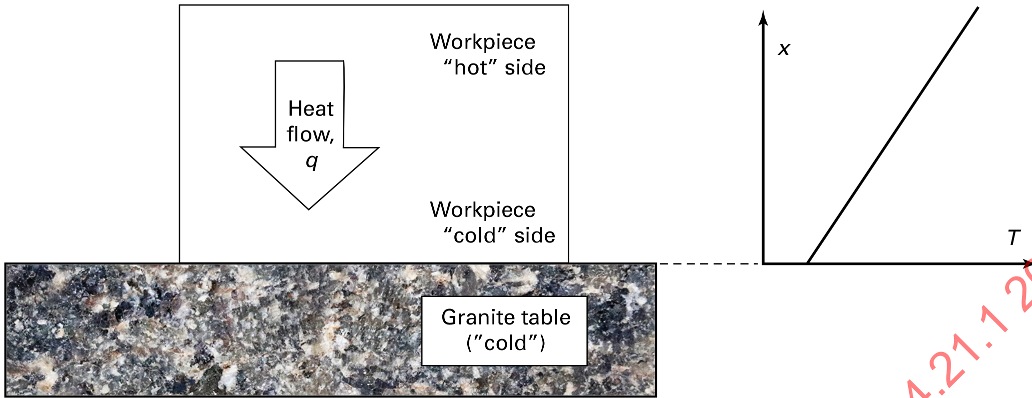


Figure D-5-1 Example of Temperature Profile Within a Workpiece



Legend:
x = location in workpiece
T = internal workpiece temperature

For example, when a workpiece is placed on a granite table at a different temperature, a temperature gradient in the workpiece will develop. When a temperature gradient exists in a workpiece, energy is transferred from the high-temperature region to the low-temperature region. The energy is transferred by conduction, and the heat-transfer rate per unit area is proportional to the normal temperature gradient, which is calculated as follows:

$$\frac{q}{A} \approx \frac{\Delta T}{\Delta x} \tag{D-4}$$

where
A = surface area for heat transfer, m^2
q = rate of heat transfer, W
$\Delta T/\Delta x$ = temperature gradient in the direction of heat flow

When a constant of proportionality is included, the equation becomes

$$q = -\,kA\frac{\Delta T}{\Delta x} \tag{D-5}$$

where
k = thermal conductivity, $W{\cdot}m^{-1}{\cdot}°C^{-1}$

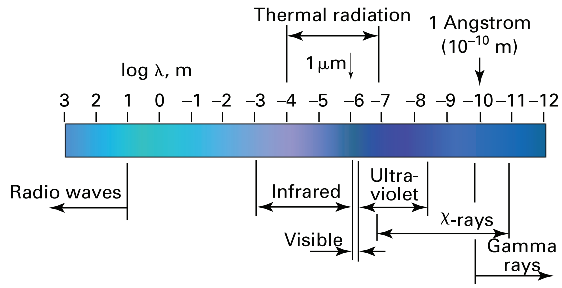
Thermal conductivity, k, is the heat transfer coefficient of a solid material and measures the ability of a material to transfer heat through a solid. For most solid materials, the thermal conductivity is usually a function of temperature.

Note that k is a positive quantity, and the minus sign in eq. (D-5) 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. Representative values of k can be found in Table E-1-1.

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 infrared region of the electromagnetic spectrum, and the term "thermal radiation" is frequently used to distinguish it from other parts of the electromagnetic spectrum that include 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.

Figure D-6-1 Part of the Electromagnetic Spectrum



In contrast to conduction and convection, where any transfer is through a material medium, electromagnetic 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 ultraviolet to far infrared, as shown in the relevant portion of the electromagnetic spectrum in Figure D-6-1.

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

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

$$E = h\nu \tag{D-6}$$

where

h = Planck's constant, 6.626×10^{-34} J·s
ν = frequency, s^{-1}

Making the assumption that each quantum can be considered as a particle having energy, mass, and momentum, then $E = mc^2 = h\nu$ and the momentum $= mc = \frac{ch\nu}{c^2} = h\nu c^{-1}$, 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} $W{\cdot}m^{-2}{\cdot}K^{-4}$.

A "black body" is a theoretical object that absorbs all incident radiation and emits radiation dependent only on its temperature. It will emit energy at a rate proportional to the fourth power of the absolute temperature of the body. The 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 calculated as follows:

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

As noted, eq. (D-7) is for what is considered an ideal black body. In the real world, objects do not radiate as much heat as a black body. To account for this, eq. (D-7) is modified as follows:

$$q = \varepsilon \sigma A T^4 \tag{D-9}$$

where

ε = emissivity of the gray body
σ = Stefan-Boltzmann constant, 5.669×10^{-8} $W{\cdot}m^{-2}{\cdot}K^{-4}$

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 the fraction of energy exiting one surface that directly impinges on a second surface. It is solely dependent on the geometry and is independent of the surface properties and temperature. The view 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

$$q = F_{i-j}\varepsilon\sigma AT^4 \tag{D-10}$$

where

F_{i-j} = 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 lengthy and, in many cases, rather complicated. Therefore, for most practical applications, the geometry is somewhat idealized, and the view factor, rather than being calculated from first principles, is typically estimated using one of the references that have derived and tabulated many geometries and configurations. These view factors are typically presented in the form of a diagram, with appropriate parametric values used to produce a family of curves.

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

Let the ratio Area 2/Area 1 be equal to R. The equation for the view factor is

$$F_{1-2} = \frac{R + 1 - \sqrt{R^2 + 1 - 2R\cos\alpha}}{2} \tag{D-11}$$

where

R = the ratio of Area 2 to Area 1
α = the angle between Area 1 and Area 2

For assumed values of the ratio and different angles, the family of curves shown in Figure D-6-3 can be obtained.

Significant heat flow into a body will occur if there are 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 ref. [2].

D-7 REFERENCES

[1] ISO 80000-5, Quantities and units — Part 5: Thermodynamics, International Organization for Standardization (ISO), Geneva, Switzerland

[2] G. Walton, "Calculation of Obstructed View Factors by Adaptive Integration," *NISTIR 6925*, 2002, National Institute of Standards and Technology (NIST), Gaithersburg, MD

Figure D-6-2 View Factor Between Two Rectangular Faces

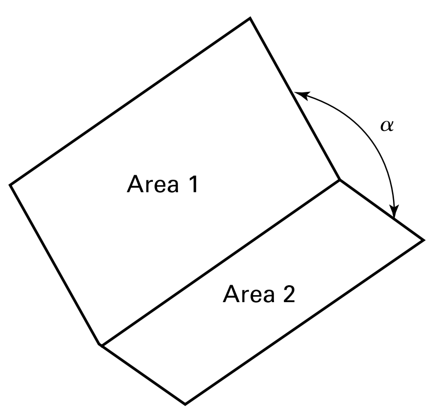
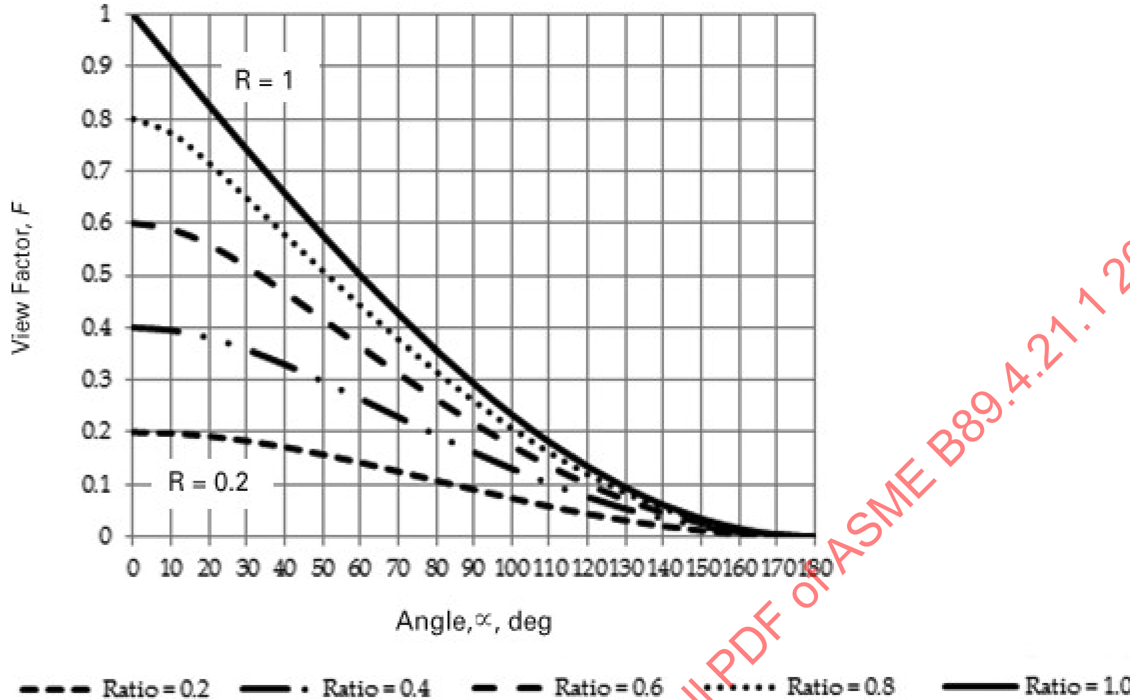


Figure D-6-3 Values of F_{1-2} for Assumed Values of the Ratio and Angle



NONMANDATORY APPENDIX E
USEFUL THERMAL PROPERTIES

E-1 COMMON ENGINEERING MATERIALS

Table E-1-1 emphasizes the following:

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

(b) There is a significant variation of CTE within the same class of 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-1-1 Thermal Properties of Common Engineering Materials

Material	Nominal Coefficient of Expansion, α, μm·m^{-1}·°C^{-1}	Specific Heat, C, J·kg^{-1}·°C^{-1}	Thermal Conductivity, k, W·m^{-1}·°C^{-1}
Acrylics	54–108	1 381–1 464	...
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	1 883	167
Beryllium copper	16.8	2 100	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
Granite	6.0–9.0	790–820	1.6
Invar			
Invar 36	0.64–1.30	515	10.5
Super invar	0.23–0.56	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	1 255–2 092	0.17–0.5
Phenolics	22.0–41.0	1 172–1 674	0.2–0.5
Polytetrafluoroethylene (PTFE)	99	920	...
Silica ceramics	0.5	799	1.4