NISTIR 89-4171

ACCURACY ANALYSIS OF THE SPACE SHUTTLE SOLID ROCKET MOTOR PROFILE MEASURING DEVICE

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Prepared for:
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George C. Marshall Space Flight Center
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Table of Contents

Abstract iii

Introduction 1

Technical Approach 1

Calibration Error. 6

Mechanical Error 9

Thermal Error. 10

Software Error 16

Estimated Total System Error 18

Discussion .19

Appendix A .20

Appendix B .21

ABSTRACT

The Profile Measuring Device (PMD) was developed at the George C. Marshall Space Flight Center following the loss of the Space Shuttle Challenger. It is a rotating gauge used to measure the absolute diameters of mating features of redesigned Solid Rocket Motor (SRM) field joints. Diameter tolerances of these features are typically ±0.005 inches and it is required that the PMD absolute measurement uncertainty be within this tolerance. In this analysis we find the absolute accuracy of these measurements to be ±0.00375 inches, worst case, with a potential accuracy of ±0.0021 inches achievable by improved temperature control.

1. INTRODUCTION

In this document we present error estimates for the absolute accuracy of part diameters measured with the Profile Measuring Device (PMD), developed at the Marshall Space Flight Center (MSFC). The PMD is used to measure the relevant geometry of the mating surfaces of the Space Shuttle Solid Rocket Motors (SRMs). This analysis applies specifically to PMD Serial Numbers 002 and 003, which are mechanically more robust versions of the prototype S/N 001 and which employ an absolute radius mastering fixture of simple geometry. A sketch of the PMD system is shown in Figure 1.

As will be shown, the uncertainties in absolute dimensions determined by the PMD are strongly coupled to the various thermal environments encountered during the calibration and part measurement processes. By international agreement the dimensions of mechanical objects are those which exist at a uniform temperature of 68°F (20°C). Ideally, all precision dimensional metrology should be performed at this temperature. When this is not possible, for reasons of convenience and/or cost, there is a price to be paid in measurement uncertainty. At some point, thermal errors will equal or exceed the entire working tolerance of the part being measured. When this occurs, the only logical choices are to improve the thermal environment or to relax the working tolerances.

As a guide to understanding the effects of temperature variations in dimensional metrology, we include as Appendix A a copy of ANSI Standard B89.6.2-1973, "Temperature and Humidity Environment for Dimensional Measurement."

2. TECHNICAL APPROACH

We have divided the PMD error analysis into a sequence of steps based upon the way the device is used in practice. A typical part measurement cycle proceeds as follows:

1) CALIBRATION

The absolute radius of the PMD radial arm is determined by comparison with a wavelength-compensated laser interferometer system. This mastering is performed for each of the interchangeable measuring tips and occurs in some approximately known set of environmental conditions. In particular, the average temperature of the radial arm during calibration is estimated to be T_{AC}, based upon measurement at one radial location.

2) MEASUREMENT

SRM tang and/or clevis features are measured. During this process, the PMD tips are changed in order to access all of the relevant features. These measurements are performed in

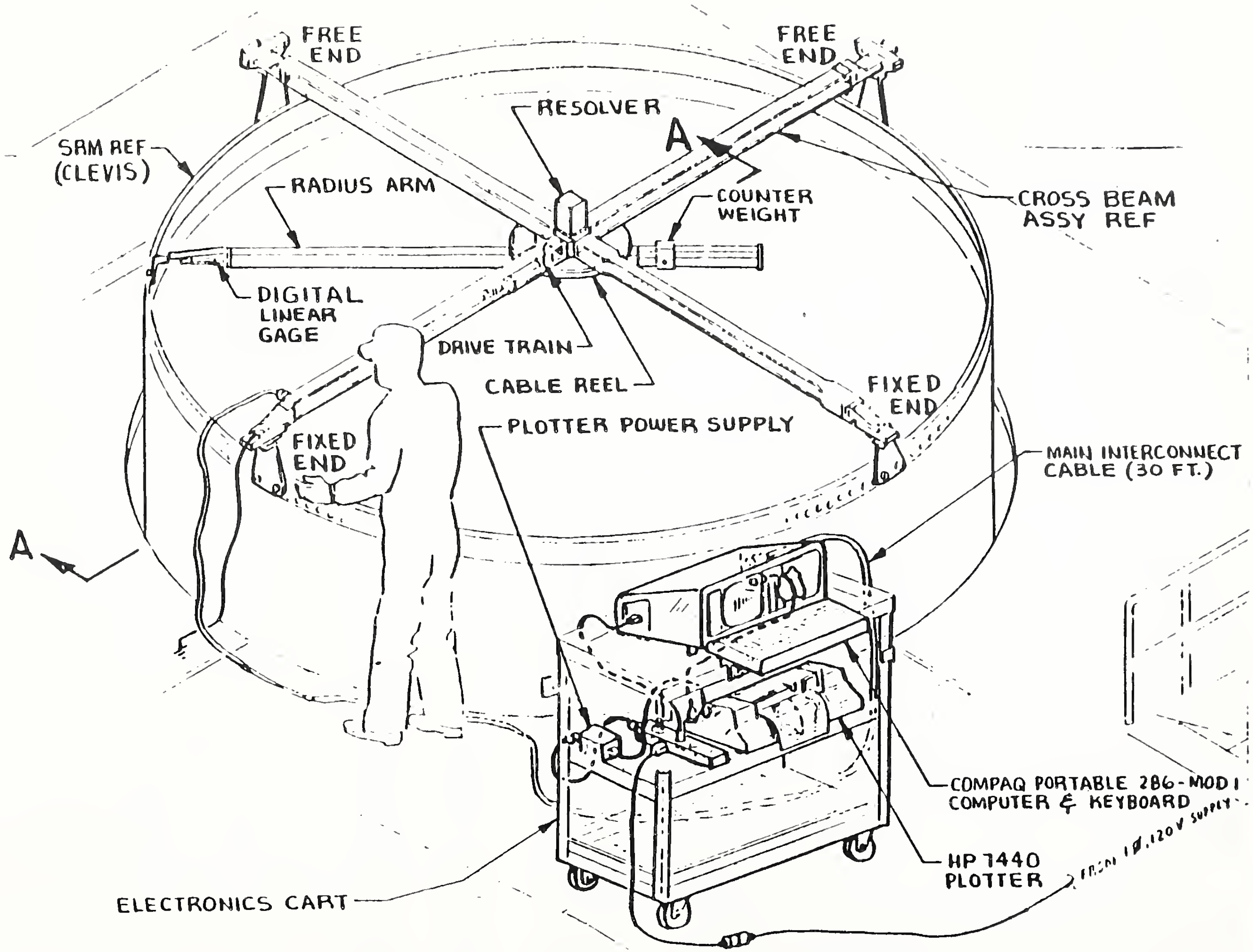

Figure 1. SRM Measuring Tool Assembly, P/N 97M50225

some (generally different) set of approximately known environmental conditions. The part temperature is measured at four circumferential locations, and the average part temperature is assigned an estimated value of T_{PM}. The average temperature of the radial arm is estimated to be T_{AM}, based upon measurement at one radial location. The difference $T_{AM}-T_{AC}$ is used to correct the radial data for thermal expansion of the radial arm.

3) ANALYSIS

The measured set of polar coordinate data pairs (r_i, θ_i) is reduced by a software analysis routine to yield the part dimensions of interest. The routine proceeds by first removing the PMD centering error using a least-squares fit to a circle. Then, the feature perimeter is estimated by summing the chords connecting adjacent points and multiplying the sum by a constant. This constant (1.000012693) is the ratio of the circumference of a circle to the perimeter of a 360-sided inscribed polygon. Finally, the feature diameter is calculated by dividing the perimeter by π.

4) EXTRAPOLATION TO 68°F

Part feature dimensions are extrapolated to 68°F using a thermal expansion calculation and the temperature difference T_{PM}-68°F.

An examination of this measurement sequence suggests a way to decompose the PMD error analysis into a set of plausibly uncorrelated components which can be individually estimated and then combined in quadrature. We have chosen the following error components:

1) <u>CALIBRATION ERROR</u>

Error associated with the mastering process.
Diameter error = ΔD_{CAL}.

2) <u>MECHANICAL ERROR</u>

Error contribution from the geometry and moving elements of the PMD.
Diameter error = ΔD_{MECH}.

3) <u>THERMAL ERROR</u>

Errors in thermal expansion calculations.
Diameter error = ΔD_{THERM}.

4) <u>SOFTWARE ERROR</u>

Error introduced in the analysis algorithms.
Diameter error = ΔD_{SOFT}.

In estimating the contributions to the total PMD measurement error from the individual error sources, we are guided by the work of R.R. Donaldson, who first developed a systematic approach to error budgeting for precision machines (see Appendix B).

The first step involves estimating the peak-to-valley (PV) error amplitudes associated with each individual error source. In some instances this can be done by a reasonably straightforward calculation. In most cases, however, these error amplitudes are plausible estimates guided by experience and by comparison with the known behavior of other precision machines. The most important requirement in this process is to analyze the system at a sufficient level of detail so that potentially significant sources of error are not inadvertently omitted.

Once the error amplitudes are assigned, they must be combined to yield a composite error using a combinatorial rule. There is no known rigorously correct way to do this for mechanical systems since the detailed contributions and correlations of the individual errors are not known <u>a priori</u>. A worst-case estimate can be arrived at by simply adding all PV amplitudes together, but this is conservative in the extreme since it is highly unlikely that all sources of error will be simultaneously at a maximum and in the same direction.

Another method of error combination, as suggested by Donaldson, is to compute a total RMS error from individual RMS contributions according to:

$$RMS_{TOTAL} = \left[\sum_{i=1}^{N} (RMS_i)^2 \right]^{1/2} \quad (1)$$

where the relation

$$PV_i = K \cdot RMS_i \quad (2)$$

relates the RMS amplitudes to the corresponding PV values. The constant K depends upon the probability distribution of the individual errors which, again, is not generally known. A reasonably conservative approach is to use a uniform distribution of the individual errors, in which case

$K = 2\sqrt{3} = 3.46$ and Equation (1) becomes

$$RMS_{TOTAL} = \frac{1}{2\sqrt{3}} \left[\sum_{i=1}^{N} (PV_i)^2 \right]^{1/2} \tag{3}$$

Because Equation (3) neglects any possible error correlations, there will be a tendency to underestimate the total error.

In light of these observations, we have adopted an approach which has recently been used in the Precision Engineering Program at Lawrence Livermore National Laboratory in the design error budget for a new, high-accuracy measuring machine for the Department of Energy. Here, we estimate the composite error by averaging the (over-conservative) sum of PV errors and the (under-conservative) RMS result:

$$\Delta D = \frac{1}{2} \left[RMS_{TOTAL} + PV_{TOTAL} \right] \tag{4}$$

where

$$PV_{TOTAL} = \sum_{i=1}^{N} PV_i \tag{5}$$

Lacking any more rigorous theoretical guidance, we believe that this approach will yield a plausible estimate of PMD absolute accuracy.

The estimated diameter errors are then calculated for each of the four error components: calibration, mechanical, thermal, and software. Since we believe these components to be uncorrelated, the estimated system error is then calculated by quadrature:

$$\Delta D_{TOTAL} = \left[(\Delta D_{CAL})^2 + (\Delta D_{MECH})^2 + (\Delta D_{THERM})^2 + (\Delta D_{SOFT})^2 \right]^{1/2} \tag{6}$$

Equation (6) represents the central result of our estimation procedure. We now proceed to develop the detailed error components.

3. CALIBRATION ERROR

The absolute radius of the PMD is determined using a calibration fixture consisting of a laser interferometer system and a precision inspection block. The vacuum wavelength of the laser is measured by the manufacturer by frequency comparison with an iodine-stabilized He-Ne laser. The latter is an internationally recognized transfer standard of length which realizes the definition of the meter with an uncertainty of approximately 1 part in 10^{10}.

Measurement errors associated with the calibration process consist of interferometer errors and mechanical errors. Interferometer errors are length-dependent and are calculated assuming a nominal measured displacement of 144 inches.

The vacuum wavelength of the metrology laser is known, by frequency comparison, to 1 part in 10^7 or better [displacement uncertainty = 0.1 parts per million (ppm)]. It is necessary to correct the vacuum wavelength for the refractive index of air during calibration. This correction is primarily determined by air pressure, temperature, and relative humidity. Based upon witnessed calibrations and an examination of the methods used to determine the environmental variables, we estimate the following systematic errors: (a) pressure uncertainty = 0.1 in Hg; (b) temperature uncertainty = 2°F; (c) humidity uncertainty = 10% RH. The respective error contributions are 1 ppm (pressure), 1 ppm (temperature), and 0.1 ppm (humidity).

The refractive index of air is also affected by changes in composition, particularly those due to carbon dioxide and organic solvents. We conservatively estimate an error of 1 ppm associated with composition uncertainty in the current calibration environment at Clearfield.

If the metrology laser beam is not aligned with the axis of travel of the calibration fixture slider, the measured travel will be too small by an amount proportional to the cosine of the angular misalignment. The resultant error is called cosine error. By careful alignment, cosine error can be made as small as desired. A worst-case estimate for the PMD calibration fixture, corresponding to 1/16 inch beam offset in 144 inches of travel results in 0.1 ppm cosine error.

We now turn to calibration-related mechanical errors, beginning with the PMD rotation axis. The radial arm is mounted to a central shaft guided by a pair of annular contact bearings. The two bearings are pre-loaded and separated by approximately 4 inches. Any radial motion, or "runout," of this bearing system will cause a one-for-one error in radius calibration. We have estimated this radial error motion to be 20 microinches PV, which is the range of errors observed in precision machine spindles using ball bearings. The worst-case diameter error is then 40 microinches.

If the radial errors of the spindle bearings are not in phase, then there will be a tilt error motion inversely proportional to the bearing separation. Assuming a 20 microinch radial motion for each bearing and a 4 inch separation yields a tilt motion of 10 microradians or about 2 arc-seconds. The actual radial error at the measuring tip depends upon the axial offset of the tip from the center of rotation of the bearing system. Taking 6 inches as a typical offset yields a radial error due to tilt motion of 6 inches x 10 microinches/inch = 60 microinches, or a diameter error of 120 microinches.

We estimate a diametral error of 40 microinches due to radial motion and shape error of the measuring tip contact bearing. Length calibration data for the inspection block, according to MSFC personnel, show a length uncertainty of -0/+200 microinches. We assume a least-count error in reading the digital linear gauge at each end of the calibration process, yielding a diameter error of 200 microinches.

In this analysis we have assumed that the horizontal and vertical ball slides at the end of the PMD radial arm are in the same locations at each end of travel in the calibration process. Should this not be the case, errors contributed by these slides would have to be included in the calibration error budget. These errors are discussed in the section on mechanical errors.

We have also assumed negligible error due to lack of squareness between the spindle rotation axis and the line of motion of the calibration fixture slider. The fixture is carefully adjusted during calibration so that the tip contacts the inspection block at the same height at both ends of travel. if these heights were to differ by 0.05 inches, the resultant diameter error would be about 10 microinches.

Finally, we assume here that the tip contact forces during calibration are negligibly different from those encountered during part measurement, so that tip deflections are constant and are included in the values of the calibrated radii.

The PMD measuring tips are bolted into place, with no attempt to make their locations kinematically determinate. Furthermore, we are not aware of any torque specifications in the tip mounting procedures. We estimate that each tip can be removed and re-mounted with a radial uncertainty of 100 microinches, leading to a diameter error of 200 microinches.

The calibration error budget is shown in Table 1. Combining the individual errors according to Equation (4) yields $\Delta D_{CAL} = \pm 702$ microinches.

TABLE 1.

CALIBRATION ERROR BUDGET

Error Source	Peak-to-Valley Diameter Error (microinches)
1. <u>Laser Interferometer</u>	
a. Vacuum Wavelength (0.1 ppm)	14.4
b. Pressure Error (1 ppm)	144.0
c. Temperature Error (1 ppm)	144.0
d. Humidity Error (0.1 ppm)	14.4
e. Air Composition (1 ppm)	144.0
f. Cosine Error (0.1 ppm)	14.4
2. <u>Mechanical Factors</u>	
a. Spindle radial motion	40.0
b. Spindle tilt motion	120.0
c. Tip bearing errors	40.0
d. Tip mounting repeatability	200.0
e. Inspection block calibration	200.0
f. Linear gauge least count	200.0
PV_{TOTAL} = 1275 μin.	RMS_{TOTAL} (Eq. 3) = 129 μin.

$$\boxed{\Delta D_{CAL} = \pm 702\ \mu\text{in.}}$$

4. MECHANICAL ERROR

The mechanical error budget includes those error components associated with the geometry and moving elements of the PMD. Spindle errors, tip bearing errors, and tip mounting repeatability have been discussed in the context of calibration errors and they also contribute to errors during measurement.

Radial deviations are measured using a digital linear gauge with 100 microinch resolution. Specifications provided by MSFC do not state the accuracy of this gauge, but experience with similar devices at the National Institute of Standards and Technology (NIST) suggests an absolute accuracy of approximately 200 microinches per inch of travel. With this estimate of gauge accuracy the diameter error is 400 microinches, assuming a total travel of one inch during part measurement.

The linear gauge/ball slide/measuring tip assembly of the PMD is characterized by what is called an Abbé offset. This means that the linear gauge is not in line with the displacement to be measured, i.e., the radial motion of the measuring tip. Because of this offset, any angular motion (pitch) of the horizontal ball slide as it translates will cause a radial error. The magnitude of the error is simply the offset distance times the slide pitch error motion. The offset distance depends upon which tip is being used, with a maximum value of about 8 inches. The pitch motion of the horizontal slide is not specified in the data sheet supplied by MSFC but may be estimated to be 5 arc-seconds in one inch of travel, a value typical of precision ball slides. Using these values, we estimate the radial error contribution to be 8 inches x 5 arc-seconds x 5 microinches/inch/arc-second or 200 microinches, with a corresponding diameter error of 400 microinches.

Straightness error motions of the vertical ball slide cause one-for-one errors in radial data. The data sheets for this slide specify a straight line accuracy of 500 microinches per inch of travel. Assuming 1/2 inch of travel during a part measurement implies a possible radial error of 250 microinches or 500 microinches diameter error.

If the vertical ball slide is not mounted orthogonally to the horizontal slide, then motion of the vertical slide will contain a component in the radial direction. Estimating a squareness error of 20 arc-seconds and 1/2 inch of travel yields a radial error of 1/2 inch x 20 arc-seconds x 5 microinches/inch/arc-second = 50 microinches radial error, 100 microinches on diameter.

PMD radial error is also sensitive to angular motion of the vertical ball slide. If the slide rotates, or pitches, the measuring tip will move radially by an amount equal to the tip length times the pitch angle. For a pitch of 2.5 arc-seconds in 1/2 inch of travel, and a 6 inch tip, the error is 6 inches x 2.5 arc-seconds x 5 microinches/inch/arc-second = 45 microinches radial error, 90 microinches on diameter.

The estimated mechanical error budget is shown in Table 2. Combining the individual errors according to Equation (4) yields $\Delta D_{MECH} = \pm 1061$ microinches.

5. THERMAL ERROR

The coefficient of thermal expansion of an engineering material is defined by

$$\alpha(T) = \frac{dL/L}{dT} \quad , \tag{7}$$

where dL/L is the fractional change in a characteristic linear dimension and dT is the change in temperature. If a sample has length L_0 at temperature T_0, then the length L at the temperature T is found by integrating Equation (7):

$$L = L_0 \exp \left[\int_{T_0}^{T} \alpha(T)dT \right] \quad . \tag{8}$$

In common engineering practice $\alpha(T)$ is approximated by its average value $\bar{\alpha}$ over the temperature range $T-T_0$, so that Equation (8) becomes

$$L = L_0 \exp \left[\bar{\alpha}(T-T_0) \right] \quad . \tag{9}$$

The range of temperatures encountered in dimensional metrology is nearly always such that $\bar{\alpha}(T-T_0)<<1$, so that Equation (9) may be written

$$L = L_0 \left[1 + \alpha(T-T_0) \right] \quad . \tag{10}$$

Equation (10) is the standard expression used to correct dimensional measurements for the effects of thermal expansion. [Note: we have replaced $\bar{\alpha}$ by α for simplicity.]

TABLE 2.

MECHANICAL ERROR BUDGET

Error Source	Peak-to-Valley Diameter Error (microinches)
1. Spindle radial motion	40.0
2. Spindle tilt motion	120.0
3. Linear gauge accuracy	400.0
4. Horizontal slide pitch	400.0
5. Vertical slide straightness	500.0
6. Vertical slide pitch	90.0
7. H-V slide squareness	100.0
8. Tip bearing errors	40.0
9. Tip mounting repeatability	200.0

PV_{TOTAL} = 1890 μin. RMS_{TOTAL} (Eq. 3) = 232 μin.

$\boxed{\Delta D_{MECH} = \pm 1061\ \mu\text{in.}}$

For measurements that demand a very high degree of accuracy, it is important to realize that the arguments of Equation (10) may not be known exactly. Taking the differential of both sides yields

$$\delta L = \alpha L_0 \delta(T-T_0) + L_0(T-T_0)\delta\alpha$$

$$= \alpha L_0 \left[\delta(T-T_0) + (\delta\alpha/\alpha)(T-T_0) \right]$$

$$= \alpha L_0 \left[\delta T - \delta T_0 + (\delta\alpha/\alpha)(T-T_0) \right] \quad . \tag{11}$$

Here, δT and δT_0 are temperature uncertainties and $\delta\alpha$ is the uncertainty in the coefficient of thermal expansion. Since the signs of the uncertainties are generally unknown, the maximum error in estimated length is found by re-writing Equation (11) using absolute values:

$$\delta L_{MAX} = \alpha L_0 \left[|\delta T| + |\delta T_0| + (\delta\alpha/\alpha)|T-T_0| \right] \quad . \tag{12}$$

The quantity $\delta\alpha/\alpha$ is the fractional uncertainty in the nominal coefficient of thermal expansion. It is rarely encountered in dimensional metrology but it becomes significantly important for large parts (large αL_0) and for large temperature extrapolations (large $|T-T_0|$). The consequences of this uncertainty are emphasized in Section 20.2 of ANSI Standard B89.6.2 (Appendix A).

Thermal expansion corrections for PMD measurement data employ two coefficients: (a) for the radial arm, α_{ARM} = 13 ppm/°F (6061-T6 aluminum alloy) and (b) for the part, α_{PART} = 6.8 ppm/°F (steel). The uncertainties in these coefficients are not known; they are estimated here to be 5% of the nominal values. That is

$$\delta\alpha_{ARM}/\alpha_{ARM} = \delta\alpha_{PART}/\alpha_{PART} = 0.05. \tag{13}$$

Based upon ANSI B89.6.2 these estimates are reasonable, and, in the case of the radial arm, may be somewhat optimistic. A brief survey of engineering material reference data on 6061-T6 wrought aluminum alloy found values of the expansion coefficient ranging from 12 ppm/°F [ALCOA Structural Handbook] to 13.5 ppm/°F [Standard Handbook for Mechanical Engineers]. Perhaps the definitive reference work is Volume 12 of the Thermophysical Properties of Matter, "Thermal Expansion of Metallic Elements and Alloys," which gives a value of α for 6061-T6 alloy of 12.5 ppm/°F at 20°C (68°F), with an explicit statement of a ±7% uncertainty in thermal expansion data on this alloy.

Case diameter data from the PMD involves two thermal expansion calculations. Radial data is corrected for expansion (or contraction) of the radial arm between the calibration temperature (T_{AC}) and the arm temperature during measurement (T_{AM}). Then, the part dimensional data is extrapolated from the part temperature during measurement (T_{PM}) to 68°F. These calculations employ the standard expression, Equation (10), using nominal values for the expansion coefficients. The uncertainties in the calculations can now be estimated using Equation (12) and Equation (13). We write for the two uncertainties:

ΔD^T_{ARM} = diameter error due to arm thermal expansion uncertainty

ΔD^T_{PART} = diameter error due to part thermal expansion uncertainty.

Using Equations (12) and (13) gives

$$\Delta D^T_{ARM} = \alpha_{ARM} D_{NOM} \left[|\delta T_{AC}| + |\delta T_{AM}| + 0.05\ |T_{AM} - T_{AC}| \right] \tag{14a}$$

and

$$\Delta D^T_{PART} = \alpha_{PART} D_{NOM} \left[|\delta T_{PM}| + 0.05 |T_{PM} - 68| \right] \quad . \tag{14b}$$

Here, D_{NOM} is a nominal part feature diameter, taken to be 144 inches. Using the nominal values of α_{ARM} (13 ppm/°F) and α_{PART} (6.8 ppm/°F), we have

$$\Delta D^T_{ARM} = 1872 \left[|\delta T_{AC}| + |\delta T_{AM}| + 0.05\ |T_{AM} - T_{AC}| \right] \quad , \tag{15a}$$

$$\Delta D^T_{PART} = 979 \left[|\delta T_{PM}| + 0.05\ |T_{PM} - 68| \right] \quad . \tag{15b}$$

In these expressions the temperature units are°F and the diameter errors are given in microinches.

Once the various thermal environments are known (or at least estimated), the total system error due to thermal effects can be calculated from Equations (15a-b). The two expressions are PV estimates of separate thermal error components. The total thermal error ΔD_{THERM} is then calculated using Equations (4) and (5).

Because of the very wide range of thermal environments found at Clearfield, there is clearly no unique value for the measurement thermal error. We therefore proceed to calculate the thermal error for a range of temperatures typical of the current environment. We will also analyze a "best-case" situation assuming that the entire PMD measurement process takes place in a thermal environment similar to that found in a standards laboratory.

We first consider three thermal environments at nominal average temperatures of 68, 78, and 88°F. The 20°F range of temperatures is representative of the range actually experienced at Clearfield during PMD measurement testing. The PMD radial arm and the measured parts have temperature sensors used for data correction during calibration and measurement. While these sensors have been calibrated at MSFC, in order to account for calibration errors, drift, linearity errors, and unknown temperature gradients, we assume an uncertainty δT of 1°F (PV) for the average arm and part temperatures. That is:

$$\delta T_{AC} = \delta T_{AM} = \delta T_{PM} = \pm 0.5°F$$

We now proceed to calculate the thermal error estimates. Recall that the PMD is calibrated at a nominal temperature of T_{AC} and that the part is measured with the arm at temperature T_{AM} and the part at temperature T_{PM}. The quantities T_{AC}, T_{AM}, and T_{PM} can assume any of the three chosen temperature values, although we expect that the PMD and the part are in thermal equilibrium during a measurement, so that $T_{AM} = T_{PM}$. There are three special cases to consider:

(a) $T_{AC} = T_{AM}$. If the temperature is nominally unchanged through a calibration/measurement cycle, then no thermal expansion correction is applied to the PMD radial arm. Because of the ±0.5°F temperature tolerance, however, the two temperatures may differ by as much as 1°F. In this case ΔD_{ARM} is calculated using Equation (10) with $T\text{-}T_0 = 1°F$, $\alpha = \alpha_{ARM}$, and $L_0 = D_{NOM} = 144$ inches.

(b) $T_{PM} = 68°F$. If the part is measured at a nominal temperature of 68°F, then no part temperature correction is applied. Because of the ±0.5°F temperature tolerance, however, the actual part temperature may differ from 68°F by as much as 0.5°F. In this case ΔD_{PART} is calculated using Equation (10) with $T\text{-}T_0 = 0.5°F$, $\alpha = \alpha_{PART}$, and $L_0 = D_{NOM} = 144$ inches.

(c) In all other situations the thermal errors are calculated using Equations (15a-b).

Table 3 displays, in matrix form, the range of estimated total thermal error. We see that this error can be less than 0.0015 inches when gauge calibration and part measurement are carried out at 68°F with reasonable control (±0.5°F). On the other hand, the error is more than 0.003 inches if the gauge is calibrated at 68°F and the measurement is done at 88°F.

As a "best-case" scenario, if the calibration and measurement process could be performed in a thermal environment of 68±0.2°F (typical of a dimensional metrology laboratory), then the system thermal error would be less than 0.0007 inches.

TABLE 3

THERMAL ERROR MATRIX

Calibration Temperature, T_{AC} (°F)

Measurement Temperature T_{AM}, T_{PM} (°F)

	68±0.5	78±0.5	88±0.5
68±0.5	±1461	±2061	±2663
78±0.5	±2323	±1730	±2323
88±0.5	±3188	±2597	±2104

Table entries are estimated thermal error ΔD_{THERM} in units of microinches. The method of calculation is explained in the text.

NOTE: If $T_{AC} = T_{AM} = T_{PM} = 68 \pm 0.2$°F, then $\Delta D_{THERM} = 693$ microinches.

6. SOFTWARE ERROR

The PMD analysis software uses a simple chord algorithm to compute the perimeters of measured SRM features. The input data set of polar coordinate data pairs is first fit to a least-squares circle and the points re-expressed in a polar coordinate system with its origin at the center of this circle. This is mathematically equivalent to removing the first harmonic term in a Fourier series and has the effect of removing the PMD centering error.

It should be noted that the data centering fit is performed independently for each measured feature, so that the PMD does not measure the complete joint geometry in a fixed coordinate system. If two SRM joint features were perfectly circular but eccentric, the eccentricity would not be detected. Because of the way in which the SRM cases are manufactured this is probably not a problem, but the effect should be recognized.

Part diameters computed using the MSFC algorithm have been shown to be insensitive to PMD gauge centering. In one witnessed test, the gauge was deliberately de-centered by 0.25 inches and the measured feature diameter repeated to 100 microinches.

We have performed extensive testing of the MSFC chord algorithm, using computer-generated simulated case data as well as actual hardware measurement data supplied by MSFC personnel. Computed diameters using the chord algorithm were also compared with those determined by a variety of other curve fitting algorithms, including least-squares circles, linear arcs, blended smoothing polynomials, cubic B-splines, and global fitting to Fourier series up to the 16th harmonic in θ. In addition to these tests we also examined the effects of resolver angular errors and radial noise (random radial errors) on the fit results. We summarize these tests below.

We first tested the chord algorithm using computer-generated data representing an ellipse with a semi-major axis of 74 inches and a semi-minor axis of 70 inches. The perimeter of this simulated case can be calculated to any required precision using high-accuracy numerical integration. The test data set had 3600 points, so that the numerical correction factor of 1.000012693 was changed to 1.00000012693. In this test, the chord algorithm yielded the perimeter with an error of less than 1 microinch. The actual numbers are (a) exact result (to 9 significant figures): 452.476613 inches; (b) MSFC chord algorithm: 452.4766124 inches. For comparison purposes we note that the perimeter of the best-fit circle is 452.563841 inches, which is too large by 0.087 inches. The diameter of this circle is approximately 0.014 inches larger than that of the circle obtained by "rounding" the elliptical case.

We then compared the chord algorithm with a range of other techniques for perimeter estimation, using actual SRM case measurement data (MSFC data file 07248709.49). This was a clevis feature using PMD tip #5. In our opinion, the most accurate of these algorithms is a global Fourier series fit to the data with terms included up to the 16th harmonic. The results of this comparison are as follows:

Algorithm	Perimeter (inches)	Diameter (inches)
16th-harmonic Fourier	454.242822	144.589981
MSFC chord summation	454.242851	144.589990
B-spline smoothing	454.242839	144.589986
Linear arcs	454.242795	144.589972
Least-squares circle	454.240667	144.589295

The difference in mean diameter between the MSFC algorithm and the Fourier expansion fit is seen to be only 9 microinches. We also note that the least-squares circle result, while reasonably good in absolute terms, is the least accurate of the algorithms. This has been found to be generally true, particularly as actual case features depart substantially from circular, because of the averaging nature of the circular fit.

The next test was designed to examine the effects of random radial errors on the calculated feature diameters. The size and distribution of random errors in real PMD data is not known, but an examination of the raw data from repeated runs suggests a level of 200-300 microinches. For this numerical experiment the PMD data from the previous comparison was artificially corrupted by the addition of a uniform distribution of random "noise" to the radial data. We then computed the mean feature diameter using the chord algorithm. The results, for various levels of noise, are as follows (average of 10 trials for each noise level):

Radial Noise (inches)	Mean Diameter (inches)	Delta Diameter (inches)
0	144.589990	0
±0.001	144.590039	+0.000049
±0.002	144.590070	+0.000080
±0.003	144.590251	+0.000261
±0.004	144.590515	+0.000525

It is clear from these results that the MSFC chord algorithm is insensitive to any plausible level of random radial error in the PMD data.

As a final test of the analysis software, we examined the effects of angular errors in the data. The existence of such errors was suggested by calibration data on the resolver of PMD S/N 002. This data showed a second-harmonic angle error with an amplitude of approximately ±0.25 degrees. We do not know the accuracy of this data, which was taken using radial case pin holes as angle reference locations. Clearly, the effects of angular errors will depend on the actual shape of the measured case features. A perfectly circular case, for example, would look circular regardless of the angular locations of the measured radii.

We modelled a set of angle errors approximating the calibration data and used this computer-generated error set to corrupt the part measurement data from MSFC data file 07248709.49. The angular error function was the second harmonic form

$$\phi = \phi_{MAX} \sin(2\theta), \qquad (16)$$

where $\phi(\theta)$ is the angle error at a nominal angle θ and ϕ_{MAX} is the maximum error. At each nominal angle the error ϕ was added to θ to yield the angle used in the fitting algorithm. The results of this procedure are as follows:

ϕ_{MAX} (deg)	Mean Diameter (inches)	Delta Diameter (inches)
0	144.5900	0
+0.1	144.5905	+0.0005
+0.2	144.5910	+0.0010
+0.3	144.5916	+0.0016
+0.4	144.5921	+0.0021
+0.5	144.5926	+0.0026

The results for negative values of ϕ_{MAX} show diameter changes of equal magnitude and opposite sign to those above. We see here that resolver errors can affect the measurement results at the level of 0.001 inches if the measured errors are accurate. This suggests that the PMD resolver systems be more accurately calibrated or be replaced by more accurate angle transducers.

Based upon these studies and numerical experiments, we estimate that the maximum diameter error due to the MSFC analysis software is $\Delta D_{SOFT} = \pm 1500$ microinches. We note that the contribution of resolver error is not really a software error but we have included it here since the effects of such error are not readily apparent until the PMD data has been reduced and analyzed.

7. ESTIMATED TOTAL SYSTEM ERROR

The PMD measurement accuracy can now be estimated by combining the separate diameter error estimates according to Equation (6). As explained in Section 5, the wide range of thermal environments encountered during calibration and measurement precludes any unique value for the system accuracy. Accordingly we present three estimates: a worst case, a best case (given the current state of temperature control), and a potential accuracy achieved by better temperature control.

A. WORST CASE ESTIMATE

PMD calibrated at 68±0.5°F, part measured at 88±0.5°F.
From Equation (6):

$$\Delta D_{TOTAL} = \pm \left[(702)^2 + (1061)^2 + (3188)^2 + (1500)^2 \right]^{\frac{1}{2}}$$

$$= \underline{\pm 3746 \text{ microinches}}$$

B. BEST CASE ESTIMATE

PMD calibrated and part measured at 68±0.5°F.
From Equation (6):

$$\Delta D_{TOTAL} = \pm \left[(702)^2 + (1061)^2 + (1461)^2 + (1500)^2 \right]^{\frac{1}{2}}$$

$$= \underline{\pm 2450 \text{ microinches}}$$

C. POTENTIAL ACCURACY

PMD calibrated and part measured at 68±0.2°F.
From Equation (6):

$$\Delta D_{TOTAL} = \pm \left[(635)^2 + (1061)^2 + (693)^2 + (1500)^2 \right]^{\frac{1}{2}}$$

$$= \underline{\pm 2064 \text{ microinches}}$$

8. DISCUSSION

The error budget formalism used in this analysis can serve as a valuable tool for potential PMD accuracy enhancement. Many of the individual error components could be measured and the error estimates re-calculated based on the measurement results. One clear example of this procedure is the angle measuring resolver system. This system could be accurately calibrated and an error map created. This map would then provide a look-up table for data correction. Alternatively, the resolver could be replaced by a high-accuracy absolute optical encoder so that angular error would be negligible. The important point is that a means exists for a quantitative analysis of PMD error reduction as more information becomes available.

APPENDIX A

ANSI Standard B89.6.2 - 1973

Temperature and Humidity Environment for Dimensional Measurement

AMERICAN NATIONAL STANDARD

Temperature and Humidity Environment for Dimensional Measurement

ANSI B89.6.2 - 1973

SECRETARIAT

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

PUBLISHED BY

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

United Engineering Center 345 East 47th Street New York, N. Y. 10017

Printed in U.S.A.

FOREWORD

American National Standards Committee B89 on Dimensional Metrology, organized under the procedures of the American National Standards Institute, was formed to develop certain minimum standards for the various parameters in metrology and represents the consensus of United States industry. The various subcommittees of Committee B89 deal with the different parameters, i.e., environment, angle, length, geometry, etc. Subcommittee B89.6 is assigned the task of developing standards in physical environment and the effects of this environment and other extraneous influences on accuracy and precision of dimensional measurements. This standard for temperature and humidity is the work of the ANSI B89.6.2 Working Group. The results of its cooperative efforts are expressed in this document.

The effect of heat flow and resulting temperature gradients, differences and variation from measurement to measurement can result in errors of dimensional measurement because of the thermal expansion properties of materials. By international agreement the true size and shape of an object is that which exists at a uniform temperature of 68° F (20° C). The purpose of this standard is to provide American industry with practical requirements, procedures, and methods by which the intent of the international agreement can be satisfied without compromise to economical operation.

In discharging its responsibilities, the Working Group has recognized two basic needs of industry. First, it recognizes the need for standard approaches to the buying and selling of artificially controlled environments. Second, it recognizes the need for the qualification of individual measurements regarding errors induced by non-ideal temperature conditions.

Standard specifications for artificially controlled environments, in terms of the quality of temperature control, are especially necessary as a means of communicating metrological requirements to construction agencies such as heating and air-conditioning contractors. In specific instances, sufficient experience has been obtained such that required dimensional accuracies can be translated directly into temperature control specifications. However, the Working Group has concluded that no general set of temperature control specifications can be stated that will simultaneously assure levels of measurement accuracy and avoid the risk of overdesign or underdesign. Indeed, no recommendation can be made on which type of artificial environment, or even whether one is necessary or not, that would represent the most satisfactory engineering for every application. Consequently, the Working Group has chosen to list those properties of an artificially controlled environment that must be specified for an adequate description, to specify standard procedures for the administration of the required specifications, and to provide advisory information in the form of guidelines that the users of this standard may find helpful in the development of specifications adapted to individual needs.

The metrologist, his management, or a potential customer of a metrological service has, each for his own purpose, a need and a right to know the magnitude of measurement errors induced by the thermal environment. Therefore, this standard includes a description of procedures for the estimation of the error contributions caused by various defects of the thermal environment. Further, there is a need for a convenient means of communication between these parties. For this purpose, the Working Group has provided a standard figure of merit, the Thermal Error Index. Because this document, for the first time, presents the Thermal Error Index for use by industry at large, the methods for its determination and use are carefully developed in an appendix.

Recommendations for the control of humidity in metrological environments are included in this document, because it is often directly affected by and related to the control of temperature, especially in the design of room enclosures.

After approval by the B89 National Standards Committee and submittal to public review the Standard was approved by ANSI as a National Standard on October 30, 1973.

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DIMENSIONAL METROLOGY

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AMERICAN NATIONAL STANDARD

TEMPERATURE AND HUMIDITY ENVIRONMENT FOR DIMENSIONAL MEASUREMENT

1. SCOPE AND INTENT

This standard is intended to fill industry's need for standardized methods of:

a. Describing and testing temperature-controlled environments for dimensional measurements, and

b. Assuring itself that temperature control is adequate for the calibration of measuring equipment, as well as the manufacture and acceptance of work-pieces.

2. REFERENCED DOCUMENTS

2.1 Standards and Specifications

This standard has been coordinated insofar as possible with the following standards and specifications. Unless stated otherwise, the latest issue is implied.

2.1.1 Governmental

a. MIL-C-45662A–Calibration System Requirements

b. MIL-HDBK-52–Evaluation of Contractor's Calibration System

c. MIL-Q-9858A–Quality Program Requirements

d. Fed. Std. #209–Clean Room and Work Station Requirements, Controlled Environment.

2.1.2 Non-governmental

a. Standards of the American National Standards Institute (ANSI), formerly United States of America Standards Institute (USASI),

b. Standards of the American Society for Testing and Materials (ASTM),

c. Standards of the Society of Automotive Engineers, Inc. (SAE),

d. Recommendation R1–Standard Reference Temperature for Industrial Length Measurements, International Organization for Standardization (ISO).

2.2 Other Publications

a. ASHRAE–Handbook of Fundamentals published by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 345 East 47th Street, New York, New York 10017

3. DEFINITIONS

3.1 Average Coefficient of Expansion

The average coefficient of expansion of a body over the range of temperature from 68° F (20° C) to t is defined as the ratio of the fractional change of length of the body to the change in temperature.

Fractional change of length is based on the length of the body at 68° F (20° C).

$$\alpha(68, t) = \frac{L_t - L_{68}}{L_{68}\,(t - 68)} \tag{1}$$

Hereinafter the term "coefficient of expansion" shall refer only to the average value over a range from 68 F (20 C) to another temperature, t.

3.2 Coefficient of Expansion

The true coefficient of expansion, α, at a temperature, t, of a body is the rate of change of length of the body with respect to temperature at the given temperature divided by the length at the given temperature.

$$\alpha = \frac{1}{L_t}\left(\frac{dL}{dt}\right)_t \tag{2}$$

3.3 Comparator

Any device used to perform the comparison of the part and the master is called a comparator.

3.4 Differential Expansion

Differential expansion is defined as the difference between the expansion of the part and the expansion of the master from 68° F (20° C) to their time-mean temperatures at the time of the measurement.

3.5 Differential Response

Differential response is defined as the relative length variation between any two objects per unit sinusoidal environment temperature oscillation as a function of frequency of temperature oscillation.

3.6 Full-Scale Dilatometry

Full-scale dilatometry is a procedure for determining the average true coefficient of expansion of a workpiece.

3.7 Dimensional Response

Dimensional response is defined as the amplitude of absolute length variation of an object per unit of sinusoidal environment temperature oscillation as a function of the frequency of temperature oscillation.

3.8 Drift Test

An experiment conducted to determine the actual drift inherent in a measurement system under normal operating conditions is called a drift test. Since the usual method of monitoring the environment (see Definition 3.13) involves the correlation of one or more temperature recordings with drift, the test will usually consist of simultaneous recordings of drift and environmental temperatures. The recommended procedure for the conduct of a drift test is given in 20.3.1.

3.9 Master

The standard against which the desired dimension of the part is compared is called the master. The standard may be in the form of the wavelength of light, the length of a gage block, line standard, lead screw, etc.

3.10 Mastering

The action of nulling or setting a comparator with a master is called mastering.

3.11 Mastering Cycle Time

The time between successive masterings of the process is called the mastering cycle time of the process.

3.12 Measurement Cycle Time

The time between measuring and the previous mastering is called measurement cycle time.

3.13 Monitoring

To ensure the constancy of the Thermal Error Index (see 3.22), it will be necessary to monitor the process in such a way that significant changes in operating conditions are recognizable.

The recommended procedure is to establish a particular temperature recording station or stations which have a demonstrable correlation with the magnitude of the drift.

The temperature of the selected station should be recorded continuously during any measurement process to which the index is to be applied. If the recording shows a significant change of conditions, the index is null and void for that process, and a re-evaluation of the index should be conducted, or the conditions corrected to those for which the index applies.

In addition to continuous monitoring of environmental conditions, it is recommended that efforts be made to establish that the process is properly soaked out. This may be done by checking the temperature of all elements before and after the execution of the measurements.

3.14 Nominal Coefficient of Expansion

The estimate of the coefficient of expansion of a body shall be called the nominal coefficient of expansion. To distinguish this value from the average coefficient of expansion $\alpha\ (68, t)$ it shall be denoted by the symbol κ.

3.15 Nominal Differential Expansion*

The difference between the Nominal Expansion of the part and of the master is called the Nominal Differential Expansion:

$$NDE = (NE)_{part} - (NE)_{master} \,. \tag{3}$$

3.16 Nominal Expansion*

The estimate of the expansion of an object from 68° F to its time-mean temperature shall be called the Nominal Expansion, and it shall be determined from the following relationship:

$$NE = \kappa\ (L)\ (t - 68)\,. \tag{4}$$

3.17 Part or Workpiece

In every dimensional or geometric measurement process, there is usually some physical object for which a dimension is to be determined. This object is called the part or workpiece.

3.18 Soak Out

One of the characteristics of an object is that it has a thermal "memory". When a change in environment is experienced, such as occurs when an object is transported from one room to another, there will be some period of time before the object completely "forgets" about its previous environment and exhibits a response dependent only on its current environment. The time elapsed following a change in environment until the object is influenced only by the new environment is called soak out time. After soak

*These concepts are used in determining the Thermal Error Index in Section 6.

out, the object is said to be in equilibrium with the new environment. In cases where an environment is time variant, the response of the object is also a variable in time.

3.19 Temperature of a Body

3.19.1 Temperature at a Point. When discussing a body which does not have a single uniform temperature, it is necessary to refer in some manner to the distribution of temperature throughout the body. Temperature at a point in a body is assumed to be the temperature of a very small volume of the body centered at that point. The material of which the body is composed is assumed to form a continuum.

3.19.2 The Temperature of a Body. When the differences between the temperatures at all points in a body are negligible, the body is said to be at a uniform temperature. This temperature is then the temperature of the body.

3.19.3 Instantaneous Average Temperature of a Body. When the body is not at a uniform temperature at all points, but it is desirable to identify the thermal state of the body by a single temperature, the temperature which represents the total heat stored in the body may be used. When the body is homogeneous, this is called the average temperature of the body (This temperature is the average, over the volume of the body, of all point temperatures.).

3.19.4 Time-Mean Temperature of a Body. The average of the average temperature of a body, over a fixed period of time, is called the time-mean temperature of the body. The fixed period is selected as appropriate to the measurement problem.

3.20 Temperature Variation Error, TVE

An estimate of the maximum possible measurement error induced solely by deviation of the environment from average conditions is called the Temperature Variation Error. TVE is determined from the results of two drift tests, one of the master and comparator and the other of the part and the comparator.

3.21 Thermal Conductivity

Thermal conductivity is normally defined as the time rate of heat flow through unit area and unit thickness of a homogeneous material under steady conditions when a unit temperature gradient is maintained in the direction perpendicular to area. In this standard it is designated by K and has the units of BTU/hr ft^2 °F.

3.22 Thermal Error Index

The summation, without regard to sign, of the estimates of all thermally induced measurement errors, expressed as a percentage of the working tolerance (or total permissible error).

3.23 Thermal Expansion

The difference between the length (or volume) of a body at one temperature and its length (or volume) at another temperature is called the linear (or volumetric) thermal expansion of the body.

3.24 Thermally Induced Drift

Drift is defined as the differential movement of the part or the master and the comparator caused by the time variations in the thermal environment.

3.25 Time Constant of a Body

The time required for a physical quantity to change its initial (zero-time) magnitude by the factor $(1 - 1/e)$ when the physical quantity is varying as a function of time, $f(t)$ according to either the decreasing exponential function,

$$f(t) = e^{-kt},$$

or the increasing exponential function,

$$f(t) = 1 - e^{-kt},$$

when $k = 1/t$, it is called the time constant of the physical quantity. In this standard it is designated by τ.

Since e has the numeric value 2.71828—, the change in magnitude $(1 - 1/e)$ has the fractional value 0.63212—. Thus, after a time lapse of one time constant, starting at zero-time, the magnitude of the physical quantity will have changed approximately 63.2 percent.

The time constant of a body can be used as a measure of the response of the body to environmental temperature changes. It is the time required for a body to achieve approximately 63.2 percent of its total change after a sudden change to a new level in its environment.

3.26 Transducer Drift Check

An experiment conducted to determine the drift in a displacement transducer and its associated amplifiers and recorders when it is subjected to a thermal environment similar to that being evaluated by the drift test itself. The transducer drift is the sum of the "pure" amplifier drift and the effect of the environment on the transducer, amplifier, and so on. The transducer drift check is performed by blocking the transducer and observing the output over a period of time at least as long as the duration of the drift test to be performed. Blocking a transducer involves making a transducer effectively indicate on its own frame, base, or cartridge. In the case of a cartridge-type gage head, this is accomplished by mounting a small cap over the end of the cartridge so the plunger registers against the inside of the cap. Finger-type gage heads can be blocked with similar devices. Care must be exercised to see that the blocking is done in such a manner that the influence of temperature on the blocking device is negligible.

3.27 Uncertainty of Nominal Coefficient of Expansion

The maximum possible percentage difference between the true coefficient of expansion, α, and the nominal coefficient of expansion shall be denoted by the symbol δ.

$$\delta = 100 \frac{\alpha - \kappa}{\alpha} \% \qquad (5)$$

This value, like that of κ itself, must be an estimate. Various methods can be used to make this estimate. For example,

(a) The estimate may be based on the dispersion found among results of actual experiments conducted on a number of like objects;

(b) The estimate may be based on the dispersion found among published data.

Of the two possibilities given above, (a) is the recommended procedure.

Because the effects of inaccuracy of the estimate of the uncertainty are of second order, it is considered sufficient that good judgment be used.

3.28 Uncertainty of Nominal Differential Expansion

The sum of Uncertainties of Nominal Expansion of the part and master is called the Uncertainty of Nominal Differential Expansion.

$$\text{UNDE} = (\text{UNE})_{\text{part}} + (\text{UNE})_{\text{master}} \qquad (6)$$

3.29 Uncertainty of Nominal Expansion

The maximum difference between the true thermal expansion and the nominal expansion is called the Uncertainty of Nominal Expansion. It is determined from

$$\text{UNE} = \kappa L\,(t - 68)\left(\frac{\delta}{100}\right)\% \,{}^{*}. \qquad (7)$$

*See Equation 23, Paragraph 20.2 for possible revision.

4. GENERAL REQUIREMENTS

4.1 The methods of describing and testing temperature-controlled environments shall be in accordance with Section 5.

4.2 A calibration, part manufacture, or part acceptance procedure complies with this standard if it is carried out with all pertinent components of the measurement system at 68° F; or if it can be shown that the Thermal Error Index (as defined in Section 6) is a reasonable and acceptable percentage of the working tolerance.

5. DESCRIPTION AND TESTING OF ENVIRONMENT

In this section an environment is to be understood as a room, box or other enclosure through which a temperature-controlled fluid (liquid or gaseous) is circulated and which is intended to contain dimensional measurement apparatus.

5.1 Description of Environment

In the following paragraphs the essential properties of an environment are listed. These characteristics must be unequivocally specified.

5.1.1 Thermal Specifications. The following properties of a controlled environment must be specified.

5.1.1.1 Cooling Medium. The type of cooling medium is to be described in terms of its chemical composition and physical properties of viscosity, density, specific heat and thermal conductivity. When common substances such as ambient air or water are to be used, unless otherwise specified, their properties are to be assumed those given in standard tables.

Commercial fluids such as oils may be specified by manufacturer and type.

5.1.1.2 Flow Rate and Velocity. The flow rate of the cooling medium shall be specified in units of weight per unit time, volume per unit time, or changes per unit time. Velocity shall be specified in feet per unit time.

5.1.1.3 Ranges of Frequencies of Temperature Variation and Limit from Mean Temperature. These two properties are interrelated and cannot be specified separately. For example, in general, the higher the frequency the wider the permissible temperature excursions from the mean temperature in the cooling medium (see Section 10). Frequencies are to be specified in cycles per unit time, and limits from mean temperature in plus or minus (±) units Fahrenheit (units Celsius). Separate limit specifications may be applied to a number of frequency ranges.

5.1.1.4 Mean Temperature. The mean temperature shall be the time average temperature at a specified point (or time average of the average of temperatures at more than one specified point) within the boundaries of the environment. A period of time over which the time average is to be computed shall be specified.

5.1.1.5 Gradients. Within the working volume of the environment, maximum steady-state temperature differences are to be specified. The specification can take one or both of two forms:

(a) "Worst case" maximum temperature difference in the cooling medium between any two points within the specified boundaries of the environment;

(b) Maximum rate of change of temperature along one or more specified directions within the specified boundaries.

Specifications can be applied to sub-boundaries, or volumes within volumes.

Each such specification should be qualified as to the conditions of acceptance testing, e.g., whether or not equipment and/or personnel are to be within the boundaries during the testing.

5.1.2 Humidity. Requirements for humidity control arise from desires to provide human comfort, to prevent deleterious effects of moisture such as corrosion of workpieces and measurement apparatus, and to maintain measurement accuracy of workpieces that are dimensionally sensitive to moisture (for example, certain hygroscopic materials). Specifications for humidity control shall be consistent with the practices established by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE).

5.1.3 Maintainability. Requirements shall be specified governing the maintenance of performance in accordance with the above requirements in order that deterioration of the environment with time, due to the reduction of control efficiency, can be held within acceptable limits by implementation of established operating and maintenance procedures.

5.2 Testing of Environments

5.2.1 Thermal Specifications

5.2.1.1 Cooling Medium. When a cooling medium other than air or water is to be supplied as a part of the environment, its thermal properties must be qualified. The standard test methods listed here may be used to determine the required properties. The list is not intended to be exhaustive, but is only representative of the many standard procedures available.

5.2.1.1.1 Viscosity

ASTM D445-65 – Viscosity of Transparent and Opaque Liquids

ASTM D1545-63 – Viscosity of Transparent Liquids by Bubble Time Method

5.2.1.1.2 Density (Specific Gravity)

ASTM D941-55 (Reapproved 1968)–Density and Specific Gravity of Liquids by Lipkin Bicapillary Pycnometer

ASTM D1298-67 – Density, Specific Gravity or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method

5.2.1.1.3 Thermal Conductivity

ASTM D2717-68T–Thermal Conductivity of Liquids

5.2.1.2 Flow Rate and Velocity

5.2.1.2.1 Flow Rate

ASTM D2458-69 – Flow Measurement of Water by the Venturi Meter Tube

ISO R541-1967 – Measurement of Fluid Flow by Means of Orifice Plates and Nozzles

5.2.1.2.2 Velocity

ASHRAE Handbook lists several accepted test methods.

5.2.1.3 Ranges of Frequencies of Temperature Variation and Limits from Mean Temperature. Limits of variation from mean temperature in the cooling medium at any specified point or points within the specified boundaries is to be determined by use of a sensitive recording thermometer. The time constant of this instrument is to be no more than one-fifth (1/5) of the period of the shortest cycle period (highest frequency) of interest; and its resolution is to be at least one-tenth (1/10) of the smallest amplitude of specified temperature variation.

The temperature recording duration shall be a minimum of 24 hours and should be as long as the representative work cycle (e.g., a week). The test should be performed under worst-case conditions (i.e., hottest day of year and coldest day of year).

The maximum peak-to-valley temperature variation is to be determined from the recorded data for every discernible frequency component. Isolated disturbances, i.e., single "spikes", are to be regarded as a component of the appropriate frequency.

Limits from mean for each frequency component are to be calculated as one-half (½) of the observed peak-to-valley excursion.

5.2.1.4 Mean Temperatures. A thermometer that has been calibrated by comparison with a standard platinum-resistance thermometer in the specified cooling medium is to be used to determine mean temperature. A recording thermometer whose output is averaged over the test period is preferred. However, a thermometer with a large time constant can be used if it is read at a frequency corresponding to one-half (½) of its time constant over the test period and all such readings averaged.

The resolution of the test thermometer shall be one-tenth (1/10) of the specified tolerance for the mean temperature. Also, the test thermometer should be standardized or calibrated so that in use it would indicate temperatures with an inaccuracy no worse than one-fourth (¼) of the specified tolerance for the mean temperature.

5.2.1.5 Gradients. If a "worst case" specification is to be administered, the locations of the temperature sensors are to be clearly specified.

If a maximum rate of change of temperature per unit length in a given direction or directions is to be administered, a grid pattern shall be established to define the locations of temperature sensors. In the case of room, box, and tank enclosures, that fraction of the total volume immediately adjacent to the enclosure walls is to be excluded from the grid pattern. Unless otherwise specified, for an enclosure that is empty, does not contain furniture, personnel, and equipment other than that used in the performance of the test, the excepted volumes shall be those obtained by reducing each dimension by 10 percent. For example, a 10′ x 10′ x 10′ room shall be reduced to 9′ x 9′ x 9′, the excluded volume being that contained within 6″ from the walls, ceiling, and floor.

If the specification calls for testing with equipment or personnel in the enclosure, the specification shall include a description of excluded areas or volumes adjacent to such personnel or objects.

Testing shall be performed over a representative work period.

5.2.2 Humidity. Humidity in the controlled environment is to be measured by any means having sufficient accuracy to satisfy the design specifications.

A sling psychrometer provides an economical and convenient way to monitor humidity on a periodic basis.

6. ASSURANCE OF ADEQUACY OF ENVIRONMENTAL CONTROL—THERMAL ERROR INDEX

In the buying and selling of goods and services, it is common practice that the buyer requests the seller to produce evidence of his ability to satisfy specifications. Most questions of metrological capability can be satisfied by means of available certification services, e.g., gage block calibration by a competent agency. In the special case of thermal effects errors, it is sometimes possible for the seller to meet the buyer's requirements by showing that work is to be done in an environment of a description acceptable to the buyer. In general, however, the variety of gages, workpieces, and measurement procedures that is found in practice precludes having all requirements met by even a small choice of standard environment descriptions.

The purpose of this section of the standard is to set forth a procedure for the assessment of the maximum possible measurement error due to all thermal effects. Basically, this procedure consists of computing estimates of possible error, taking into account uncertainties involved in the computations, and experimentally determining other error components. Summing all component error estimations gives an estimate of the over-all maximum possible error. Dividing this number by the total permissible error from all sources (working tolerance) gives an index of merit (Thermal Error Index) that can be used for the administration of environment quality control requirements.

In the following paragraphs, the standard procedure for computing the Thermal Error Index is described. Only the most significant components of error are considered. Approximate methods of error estimation are used. Section 20 of the Appendix includes a more thorough discussion of the methods of error estimation and possible means of improving the accuracy of the estimates. However, the following are the standard procedures.

6.1 Consequences of Environment Mean Temperature Other than 68° F (20° C)

6.1.1 Length Measurements

6.1.1.1 Nominal Expansion, NE. Assuming that an object in a convective environment has a uniform temperature equal to the environment mean temperature in its immediate vicinity, its Nominal Expansion is estimated by

$$NE = \kappa\,(L)\,(t - 68). \qquad (8)$$

6.1.1.2 Nominal Differential Expansion, NDE. The difference between the Nominal Expansion of the part and the master is called the Nominal Differential Expansion.

$$\mathrm{NDE} = (\mathrm{NE})_{part} - (\mathrm{NE})_{master} \qquad (9)$$

6.1.2 **Measurements Other than Length.** In cases of measurements other than length, where a standard computational method is not given, the estimation of the consequences of environment mean temperatures other than 68° F (20° C) shall be made according to formulae appropriate to the specific case, if possible. An example is given in Section 20 of the Appendix.

Satisfactory formulae with which to carry out the intent of this section are not always available because of insufficient technical knowledge of each specific case.

6.2 Consequences of Uncertainties of Error Computations

6.2.1 Length Measurement

6.2.1.1 Uncertainty of Nominal Expansion, UNE. The Uncertainty of Nominal Expansion is

$$\mathrm{UNE} = \kappa\,(\delta)\,(L)\,(t - 68)/100\%^{*} \qquad (10)$$

where t is the worst-case (greatest difference from 68) measured temperature of the object (part or master).

*Rearrangement of Equation 7, Paragraph 3.29.

The fact that it is mandatory to make use of directly measured temperatures in the calculation of Uncertainty of Nominal Expansion means that the intent of Section 6.4 is automatically satisfied for the case of length measurements.

6.2.1.2 Uncertainty of Nominal Differential Expansion, UNDE. The sum of the Uncertainties of Nominal Expansion of the part and master is called the Uncertainty of Nominal Differential Expansion.

6.2.2 **Measurements Other than Length.** In cases of measurements other than length, where a standard computational method is not given, an estimation of the possible consequences of the uncertainties of coefficients of expansion and temperature measurements shall be made according to formulae appropriate to the specific case if possible. An example is given in Section 20 of the Appendix.

Satisfactory formulae with which to carry out the intent of this section are not always available because of insufficient technical knowledge of each specific case.

6.3 Consequences of Time Variation of Temperature Length Measurements, Temperature Variation Error, TVE

The maximum observed or recorded thermal drift during either part/comparator or master/comparator drift test (see Appendix), whichever gives the larger value, during a period of time corresponding to the measurement cycle is called the Temperature Variation Error.

6.4 Consequences of Gradients in Environment Temperature

In some measurements, gradients in environment temperature have a resultant error effect that is distinct from those described in the preceding paragraphs and which is significant enough to be given special consideration. For example, in the use of surface plates the consequences of an environment mean temperature other than 68° F (20° C) are insignificant provided the material of the surface plate is sufficiently homogeneous with respect to thermal expansion properties. However, the control of temperature differences between the top and bottom of the surface plate is of prime importance.

No general formulae can be given for the estimation of gradient temperature effects.

6.5 Thermal Error Index, TEI

The sum of all the approximate thermal effects error components from Paragraphs 6.1, 6.2, 6.3, and 6.4, where such paragraphs apply, expressed as a percentage of the total permissible error from all sources is called the Thermal Error Index.

For length measurements,

$$\mathrm{TEI} = \frac{\mathrm{NDE} + \mathrm{UNDE} + \mathrm{TVE}}{\text{Total permissible error}} \times 100\% \qquad (11)$$

if no correction for differential expansion is attempted, and

$$\mathrm{TEI} = \frac{\mathrm{UNDE} + \mathrm{TVE}}{\text{Total permissible error}} \times 100\% \qquad (12)$$

if a correction for differential expansion is computed and applied in the measurement procedure.

APPENDIX

Historical Background of Standard Temperatures for Dimensional Standards[1]

The presently recognized standard temperature of 20° Celsius (68° Fahrenheit) was preceded by at least two others; namely, 0° Celsius (32° Fahrenheit), the temperature of melting ice, and 16-2/3° Celsius (62° Fahrenheit) which historically, at least, appears to have been the earliest.

Zero Celsius was the temperature adopted by the International Congress for Weights and Measures at Paris in 1889 at which the platinum-iridium bar, maintained at the International Bureau of Weights and Measures at Sevres, France, represented the meter exactly. However, its length at 20° Celsius had been carefully determined and for many years the comparisons of the various national standard meter bars with the international standard bar were made at 20° Celsius.

France, however, continued to use 0° Celsius as the standard temperature for length standards and gages until 1931, when 20° Celsius was adopted internationally.

Sixteen two-thirds° Celsius (62° Fahrenheit) was long recognized as the standard temperature for dimensional standards in Great Britain, dating back to at least 1831. Like France, Great Britain switched to 20° Celsius in 1931.

As early as 1898-99, C. E. Johansson of Sweden considered that the measurements given for his measuring instruments should apply at 19 or 20° Celsius. Since he found the usual temperature was between 15 and 25° Celsius, he took the mean value, 20° Celsius, as the temperature easiest to maintain and generally prevailing in daily workshop practice.

About 1903, Johansson had a nominally 100-millimeter rod measured by the International Bureau, which stated that the rod was 100 millimeters at 20.63° Celsius. With this information, Johansson made a new rod 0.0007 millimeters longer than the first so that it would be of correct length at 20° Celsius. This rod was then used in subdividing lengths to produce a set of gage blocks in various series.

From this beginning, the use of 20° Celsius as a standard temperature grew until in April 1931 the International Committee of Weights and Measures adopted a resolution that, in the future, the temperature of 20° Celsius (68° Fahrenheit) should be universally adopted as the normal temperature of adjustment for all industrial standards of length. Consequently, most of the nations of the world adopted this temperature as their standard for length adjustments. Thereafter, standards of length were adjusted to be nominally correct at 20° Celsius and manufacturers of gage blocks, end standards, scales, tapes, fixed dimensional gages, lead screws, etc. adjusted their manufacturing methods so these devices would be nominally correct at 20° Celsius.

In an article by Peters and Boyd of the National Bureau of Standards published in 1920[2] we find the statement, "The temperature at which the actual length of the gage equals the nominal length must, therefore, be specified and is usually taken as 20°C or 68°F."

The National Bureau of Standards installed its first constant-temperature (20° Celsius) room for calibrating gage blocks and other dimensional standards in 1924. Johansson, himself, was responsible for the first industrial room, at the Ford Motor Company, in 1926.

Twenty Celsius thereafter became so generally used that Recommendation No. 1 of the International Organization for Standardization, issued in 1954 promulgated its use among the 40 participating countries.

Therefore, since at least as far back as 1912 when it was recorded that Johansson was making his gage blocks for America on the basis of 1 inch equals 25.4 millimeters and at a temperature of 20° Celsius, millions of items such as gage blocks, end standards, micrometers, dimensional gages and products off of machines having lead screws, have been manufactured to be nominally correct at 20° Celsius.

[1] This information was taken, in part, from unpublished notes of Irvin H. Fullmer, former Chief of the Engineering Metrology Section, The National Bureau of Standards.

[2] "The Calibration and Dimensional Changes of Precision Gage Blocks," C. G. Peters and H. S. Boyd, American Machinist, September 30 and October 7, 1920.

The argument frequently advanced that measurements can be made at any temperature and corrected to 20° C (68° F) by applying corrections based on the various coefficients of thermal expansions is valid only if the coefficients are known with sufficient accuracy. The importance of this was known at least forty years ago when, in the paper by Peters and Boyd of the NBS, referenced above, this statement was made.

> "Another property which must be recognized when considering true accurate length of gages is the thermal expansion of the material. A 1-inch steel gage (block) increases in length about 0.000 013 inches for every degree C (Celsius) rise in temperature. The temperature at which the actual length of the gage equals the nominal length must therefore be specified and is usually taken as 20°C or 68°F. At 25°C the length of a gage which is one inch at 20°C is about 1.000 065 inches. If a gage be measured at the higher temperature its length at 20°C may be computed if the expansion coefficient is known. If higher precision is desired, it is not good policy to use expansion coefficients given in tables because our measurements show that the expansion coefficients of steel may vary from 0.000 0105 to 0.000 0135 depending on its hardness and composition.
>
> This variation would permit an unknown steel gage that agrees exactly with a standard at 25°C to differ from it by more than 0.000 01 inch at 20°C. If the unknown piece that is being measured is brass or some other material having an expansion coefficient that differs greatly from that of the standard the effect of temperature change is augmented. From these considerations it is evident that to measure or use gages with an accuracy in the millionth place, the coefficient of expansion of the material must be accurately known, and also temperature controlled and measured to at least 0.1°C."

A 1-inch micrometer caliper is required to have a maximum error in indicated reading not exceeding 0.000 1 inch and a 12-inch micrometer caliper not exceeding 0.000 3 inch. If the standard temperature were 23° C (73.4° F), the existing 1-inch micrometers would be in error by about one-third of their tolerance while the 12-inch micrometers would be in error by about one and one-third times the tolerance.

An indication of the impact on the users of the thousands of precision machine tools using lead screws presently in existence can be made by considering the case of the standard leading screw lathe in use at the National Physical Laboratory in Great Britain. The 60 inch traverse of its lead screw is correct to within 0.000 10 inches at 68° F. At 73.4° F an additional error of 0.000 21 inches would be introduced, for a total error of about 0.000 31 inches.

In 1952, Dr. F. H. Rolt, Superintendent of Metrology at the National Physical Laboratory had this to say about Great Britain's change from 16-2/3° C to 20° in 1931:

> "Previous to 1931, the standard temperature for engineering measurements (the temperature at which standard length gages and other gages are adjusted to size) was 62°F (16-2/3°C) in Great Britain, 0°C in France and 20°C in some other European countries and the United States. This confused state of affairs was abolished in April 1931 when the International Committee of Weights and Measures adopted a resolution that, in future, the temperature of 20°C (68°F) should be universally adopted as the normal temperature of adjustment for all industrial standards of length. This change was supported by the British Standards Institution and put into effect by the National Physical Laboratory at the beginning of 1932. It amounted to a change of approximately four and a half ten-thousandths in the length of a 12-inch gage and pro-rata for other lengths. In other words, a 12-inch gage which had been true to size at the old temperature of 62°F had to be actually shortened by closely 0.000 45 inches to bring it true to size at the new temperature of 20°C.
>
> British industry weathered this change without much trouble 20 years ago, but with the general all-round improvement in accuracy in latter years, to effect a change of that magnitude today would bring quite a number of difficulties in its train."[3]

For many years, "°C" has stood for "degrees centigrade," the well established temperature scale devised by the Swedish Astronomer Anders Celsius, 1701 to 1744. In keeping with the practice of honoring certain individuals who have made significant contributions to our scientific knowledge and development, by renaming units after them (e.g., "Hertz" for "cycles per second"), the use of the word "Celsius" over "centigrade" is now to be preferred. It is a fortunate coincidence that both begin with the letter "C".

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[3] "The Development of Engineering Metrology," by F. H. Rolt, Institute of Production Engineers, 1, 1952.

10. ADVISORY INFORMATION PERTAINING TO DESCRIPTION OF ENVIRONMENTS

10.1 Description of Environments

10.1.1 Thermal Guidelines

10.1.1.1 Cooling Medium. For most conventional metrology work, the appropriate cooling medium will be air and the enclosure will be a room, in a building, in which human beings are occupied in daily tasks. However, in some cases it is advisable to consider fluids other than air for the cooling medium.

Considerations that may have influence in choosing a fluid other than air for the cooling medium are

(a) Greater heat removal capacity,

(b) More accurate temperature sensing and control,

(c) Avoidance of contamination of parts, especially from oxidation.

Both (a) and (b) can result from using a liquid that has the greater effectiveness as a coolant. The effectiveness of a coolant is measured in terms of a film coefficient (*h*; Btu/hr-ft^2-°F). In a specific case of heat flow from a surface into a fluid, the film coefficient is a rather complicated function of fluid properties, flow velocity, and geometry. To simplify estimating the relative effectiveness, air and water have been chosen in Figure 1 as representative of all gaseous and liquid coolants respectively. Rough boundaries can be established for the film coefficients attainable for each of these coolants for natural and forced convection, as is shown by the vertical lines in Figure 1.

The expected film coefficient in slowly moving room air is about 1.0. This can be increased by increasing the velocity of the air up to a limit at about h = 10.0, which is approximately the lowest limit for

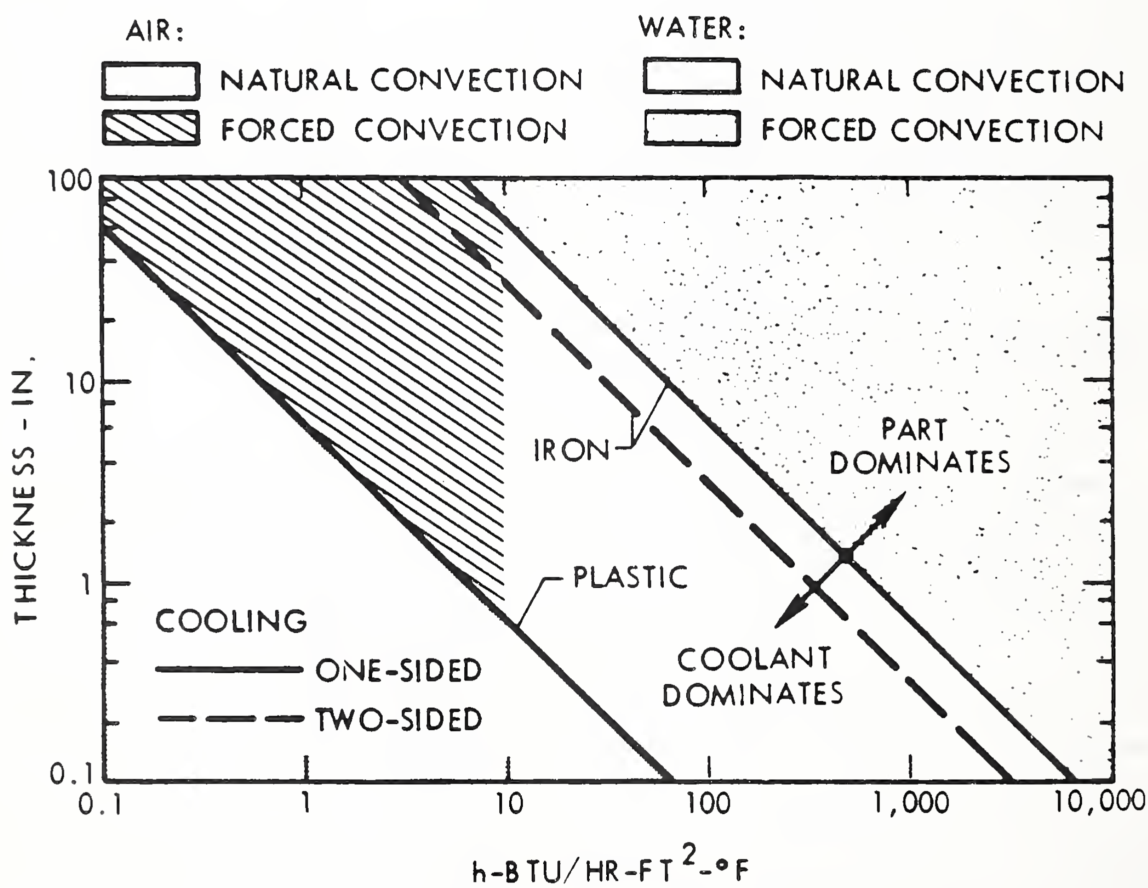


FIG. 1 Coolant-effectiveness chart for air versus water in natural and forced convection for material thickness varying from 0.1 to 100 in. The solid lines separate regions of part and coolant dominance for iron and a typical plastic. A condition within the area of coolant dominance indicates that improvement in the control of the part temperature can be achieved by increasing the flow or changing the coolant.

water in natural convection. Water in forced convection has a potential film coefficient of several hundred times that of room air.

The total resistance to heat flow from a solid wall into a fluid coolant includes the thermal resistance of the wall material:

$$R = \frac{1}{A}\frac{1}{h} + \frac{t}{2K} \tag{13}$$

for a wall cooled on both sides and heated at midplane; and

$$R = \frac{1}{A}\frac{1}{h} + \frac{t}{K} \tag{14}$$

for a wall heated on one surface and cooled on the other.

The point at which an increase in the film coefficient begins to produce diminishing returns, is where the internal and external resistances are equal. The diagonal lines on the chart show the boundaries of this effect for different wall materials and one-sided and two-sided cooling. The chart shows that for one-sided cooling of iron, the forced water convection is fully effective for wall thicknesses well over 1 inch; while, for plastics, forced water convection is less effective because of the dominance of internal resistance for much thinner sections.

10.1.1.2 Flow Rate and Velocity. The flow rate of the cooling medium is of prime importance in the control of frequency of temperature variation, and temperature gradients. Frequency of temperature variation in an artificially controlled environment is related to lags and delays in the feedback control system and, thus, to flow rate and the distance between temperature sensor and the heating and cooling surfaces. Gradients are related to the flow rate, the specific heat of the cooling medium and the magnitude of heat loads, as well as the distribution of the heat sources in contact with the flow.

In general, the higher the flow rate the higher the frequency of temperature variation and the smaller the temperature gradients. In addition, the higher the flow rate the higher the velocity of the cooling medium. This can have both beneficial and detrimental effects.

The beneficial effect of higher velocity is higher film coefficients. With higher film coefficients, a smaller temperature difference is required to remove heat from the surface of an object. This means that objects, with either internal heat sources (e.g., motors inside machine frames) or receiving heat by radiation (e.g., from electrical lights) will have temperatures more nearly equal to that of the cooling medium if the velocity is increased.

The detrimental effect is a tendency to discomfort human personnel. Where human operators are expected to work in rapidly moving air, the permissible velocity is limited because the human response to a given dry-bulb temperature depends on the air velocity and the relative humidity. At a dry-bulb temperature of 68° F, a relative humidity of 50 percent, and a velocity of 100 fpm, the temperature is felt as 63° F, and as 58° F for 400 fpm (see Figures 2 and 3). The maximum permissible velocity for human comfort in a 68° F, 50 percent R.H., room is about 25 fpm.

High precision metrology laboratory air velocities range from 6 to 20 fpm.

10.1.1.3 Ranges of Frequencies of Temperature Variation and Limits from Mean. The dimensional response of an object to ambient temperature variation depends on its length, coefficient of expansion, and time constant (see 3.2.5). The time constant of an object can be estimated from

$$\text{time constant} = \tau = \frac{CV}{hA} \tag{15}$$

where

V = volume, cu. ft.

A = surface area, sq. ft.

h = film coefficient, Btu/hr. ft.^{2}°F

C = thermal capacitance, Btu/°F ft^3.

Values for C are approximate

Iron, Steel ~ 54

Aluminum ~ 36

Brass ~ 48.

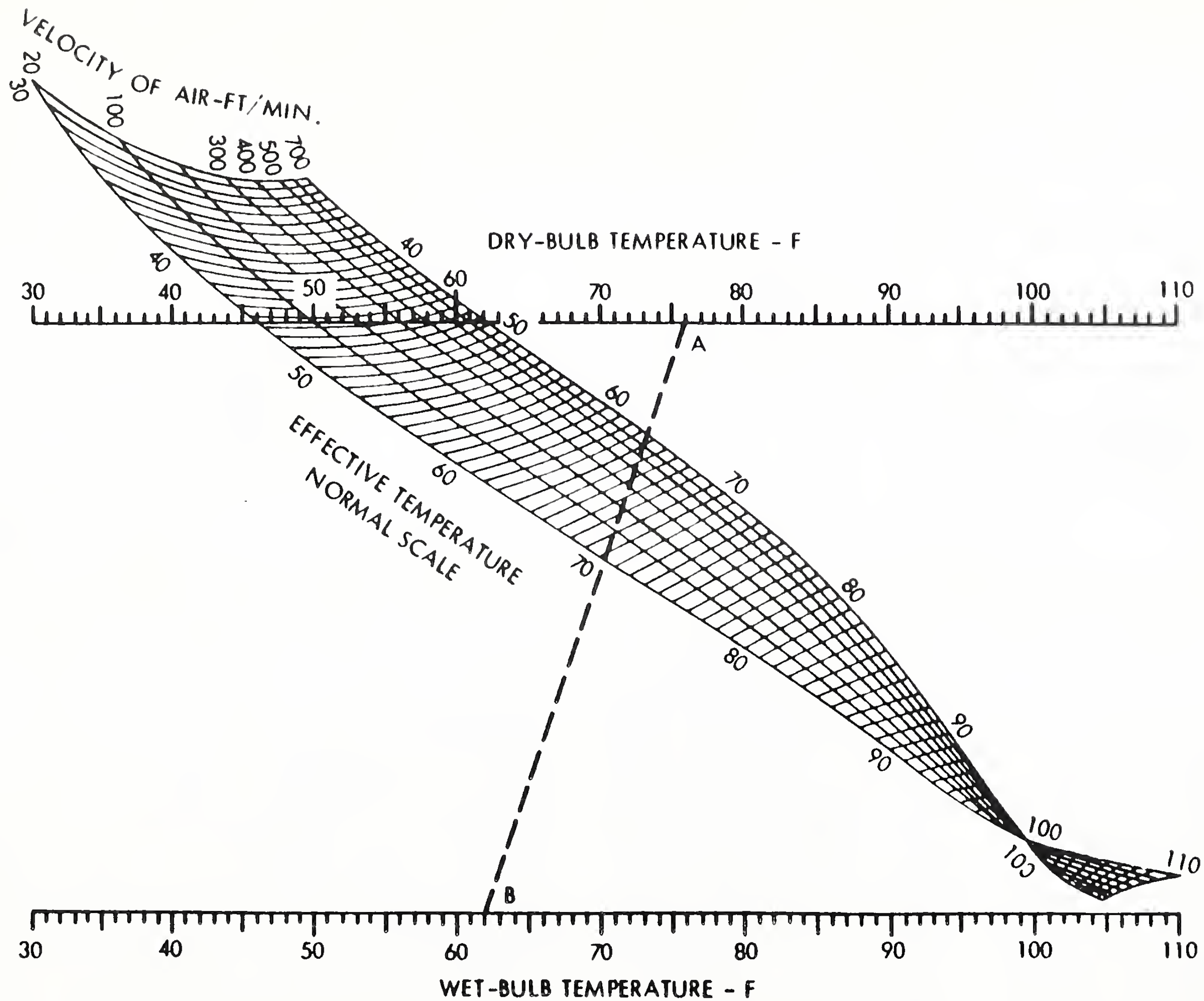
Example:

A steel gage block 1 inch square in cross-section and 10 inches long, in natural convection (estimate $h = 2$)

$$\tau = \frac{54\,(10)}{2\,(42)\,(12)} = 0.53 \text{ hr.}$$

This time constant is the time the gage block would take to reach 63.2 percent of its total change (see 3.2.5). For example, it would be the time required for the object to change temperature 0.632 degrees after a step change in environment temperature of one degree.

For a 1-degree step in temperature in the air around the gage block of the above example, the gage eventually changes length approximately 60



HOW TO USE THE CHART: Draw line A-B through measured dry-bulb and wet-bulb temperature. Read effective temperature or velocity at desired intersections with line A-B. EXAMPLE: Given 76 F db and 62 F wb, read: 69 ET at 100 fpm velocity, or 340 fpm required for 66 ET.

FIG. 2 Chart for determining effective temperature for sedentary individuals, normally clothed, from measurements of dry-bulb temperature, wet-bulb temperature and velocity of air

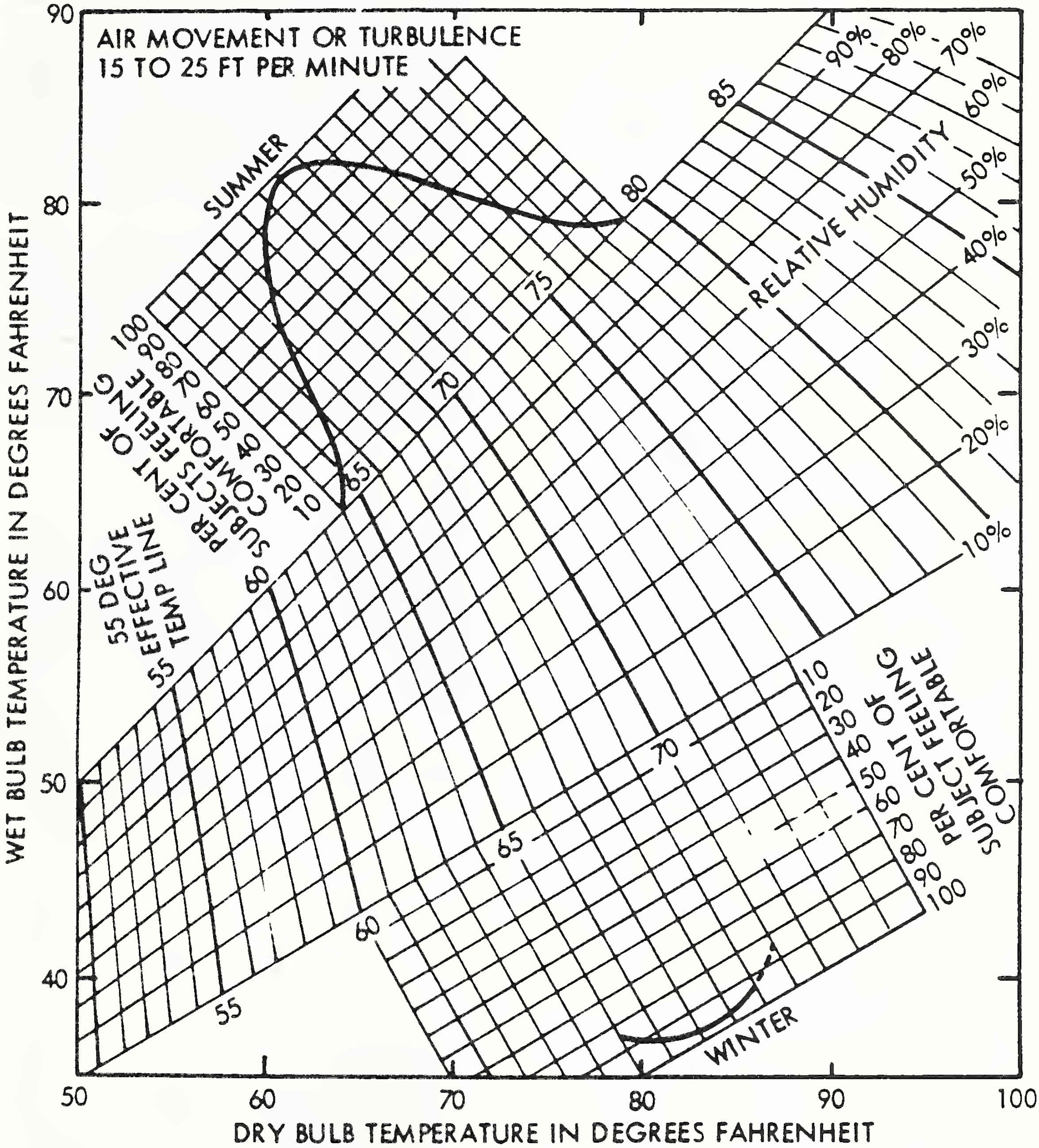


FIG. 3 Still-air comfort chart of the American Society of Heating, Refrigerating and Air-Conditioning Engineers

microinches. But it takes 0.53 hour (32 minutes) to change 38 microinches. This slowness of response, or thermal inertia, is important to the specification of environments, because it means that high frequency temperature variation is tolerable. The higher the frequency, the more tolerable it is.

Experience shows that most machinery, instrument stands, etc., have a limited range of volume to surface area ratio. Quite good results are often achieved with a frequency of temperature variation (in air) of 15 to 60 cycles per hour and an amplitude of 1 degree Fahrenheit. For the gage block in the above example, this temperature variation would cause a length variation of less than 1 microinch.

Like those of high frequency temperature variations, the effects of very low frequency temperature variations are not significant when the part and master have closely similar dimensional response.

The most fortunate case possible is that in which the part, master, and comparator (see Section 20) all have the same dimensional response characteristics. Then no temperature variation effect is significant. In general, however, there exists an upper and lower limit of frequency between which is a frequency of maximum differential response. Unfortunately, it is not uncommon that gaging systems have their maximum differential response at a frequency close to the natural 24-hour day/night cycle period.

Consequently, it is usually advisable to specify the tolerance-to-temperature variation in terms of allowable deviations from mean temperature which vary according to the frequency. Closer limits should be applied to low frequency components, and wider limits may be permitted for high frequency components.

10.1.1.4 Mean Temperature. Selection of a mean environmental temperature affects the cost of refrigeration and heating equipment, insulation, and flow distribution.

Operation at a temperature other than 68° F (20° C) entails consequences in the form of potential errors of measurement that must be carefully evaluated. Evaluation procedures are described in Section 20.

The most common objection to operating a room enclosure at 68° F, other than the cost of the air conditioning system, is a possible discomfort to personnel. As discussed in Section 10.1.1.2, a high air velocity can cause a sensation of much lower temperatures and result in complaints. In order to maintain human comfort without a requirement for special clothing, the velocities to which personnel are subjected should be less than 20 fpm to avoid the sensation of drafts. Conventional registers, at which the velocities may be 800 fpm or more are not satisfactory. Large inlet and outflow areas are recommended. Full-flow ceilings are used successfully to simultaneously provide high flow rate and low velocity.

In cases where the needs of measuring equipment (68° F) and human personnel (low velocity) cannot be satisfied simultaneously, it is recommended that the equipment environment and human environment be separated. Use of special air-flow boxes, liquid baths, or localized high-velocity air showers have been used successfully for this purpose.

10.1.1.5 Gradients. Gradients are the most difficult of all non-ideal temperature conditions to assess for possible error effects. The existence of gradients, of course, implies that portions of the environment will not be at the same mean temperature so that the consequences of mean temperatures other than 68° F (20° C) will be different in different locations in a room. Movement of equipment or workpieces from one area to another will result in a change in the error pattern.

Machinery is affected by gradients in a variety of ways. For example, a machine with a high vertical column (z-motion) where the z-motion is controlled by a lead screw will have a progressive error if there is a high vertical temperature gradient. In addition, if the vertical slide carries a long cantilever arm, the arm will undergo a transient change of length when raised or lowered.

Surface plates are affected by vertical gradients in that a temperature difference between the top and bottom of the plate will cause the plate to bend. For solid surface plates, the amount of bending or out-of-flatness, δ, is calculated by using the following formula:

$$\delta \cong \frac{L^2}{8R} = \frac{L^2 \kappa \Delta T}{H\left(1 - \kappa \frac{\Delta T}{2}\right)} \quad \ldots . \qquad (16)$$

where

L = length of the surface plate
H = height or thickness of the surface plate
T_u = upper surface temperature
T_1 = lower surface temperature
$\left.\right\} \Delta T = T_u - T_1$
κ = coefficient of linear thermal expansion
R = radius of curvature of the plate.

Machine bedways are similarly affected by both vertical and horizontal gradients which cause angular motions (pitch, roll and yaw).

Gradients occur because of heat sources that exist within the boundaries of the environment. For this reason, it is difficult to administer meaningful requirements by testing in the absence of equipment and personnel that shall exist under normal working conditions. The main sources of heat are the electrical lighting fixtures, electrical and electronic equipment, motors, and people. Room enclosures with only the electrical lighting fixtures present and operating have been tested with an observed gradient of less than 0.1° F per foot in any direction. However, the same room with equipment installed normally has gradients of over 0.2° F per foot and high gradients of several degrees per foot near the surfaces of surface plates, electronic cabinets, etc.

As mentioned in Section 10.1.1.2, increasing the flow rate will decrease the gradients. For example, surface plates are observed to have temperatures on the upper surfaces of 2° F or more above the local mean in a flow rate of 10 to 15 changes per hour and a 0.5° F or less in 100 changes per hour.

10.1.2 Humidity. In certain measurement systems, a significant error can occur if an incorrect value for humidity is used in computing a dimension. For example, in the measurement of the length of gage blocks by interferometry, a 10 percent relative humidity uncertainty will introduce an error of 0.1 microinch per inch of length. Therefore, in laboratories where these kinds of measurements are to be made, it is desirable to control (and measure) the humidity within close limits to keep this uncertainty small.

There are three basic requirements for humidity control:

(a) To provide human comfort;

(b) To prevent deleterious effects of moisture such as corrosion of workpieces and measurement apparatus, and;

(c) To maintain measurement accuracy of workpieces that are dimensionally sensitive to moisture.

A discussion of the latter requirement is felt to be beyond the scope of this standard since it would deal with parameters of materials that are not directly correlative with the guidelines for environmental control of dimensional metrology laboratories.

Requirements 1 and 2 are related, but are almost diametrically opposed. Consequently, there have been many suggestions given as to what limits, if any, should be placed on the range of relative humidities to be permitted in dimensional metrology enclosures.

For maximum protection against corrosion of ferrous components of measuring instruments, humidity should be maintained at very low levels. However, for the maximum comfort of personnel in a laboratory where the dry bulb temperature is maintained at 68° F, the humidity should be kept at a high level. The relative humidity recommended is a reasonable compromise between these two extremes.

Probably, the most frequently heard value for the upper limit is 45 percent relative humidity. A lower limit is then selected that is high enough to afford a certain degree of personal comfort, but low enough to not economically compromise the 45 percent upper limit.

What is frequently overlooked, however, is that relative humidity, in itself, is just one of the contributing factors to corrosion. Of almost equal importance are the constituents of the atmosphere, or cooling medium, in which the workpiece and measuring apparatus are placed. For example, the presence of certain hygroscopic salts in the air will either cause or accelerate the corrosion of iron exposed to the air even though the relative humidity is relatively low. A saturated solution of lithium chloride will stand in equilibrium with air having only a 12 percent relative humidity. Similarly, saturated solutions of either calcium chloride or magnesium chloride will stand in equilibrium with air having a relative humidity of 31 or 33 percent relatively. Yet iron exposed to air containing any of these salt solutions will corrode more rapidly than if they were not present. Again, iron exposed to air containing ordinary solutions of sea salts shows little corrosion at a relative humidity of 30 percent, but fairly rapid corrosion if the air has a relative humidity of 35 percent. Salts are not the only corrosion-accelerating agent in air, so far as iron is concerned. Small traces of sulphur dioxide (a common constituent of industrial and urban air) will accelerate corrosion in iron at ordinary temperatures and humidities.

Probably one of the greatest accelerators of corrosion in dimensional metrology laboratories is the perspiration residue deposited during handling. The chloride ion in the residue is probably the main accelerating agent, although the fatty acids will also be a factor.

Since iron, in some form, is the most common material found in the workpieces and measuring equipment in a dimensional metrology laboratory, the rest of this section will deal briefly with the role humidity plays in its corrosion.

Probably the most exhaustive and definitive laboratory studies on the atmospheric corrosion of metals were those reported by W. H. J. Vernon in England shortly after World War I. Briefly stated, these studies showed that the rusting of iron in air was not necessarily associated with the dew-point as had been supposed; but instead, a profound increase in the rate of attack was identified with a critical humidity very considerably below saturation. In an ordinary room atmosphere of low relative humidity, the process of rusting is influenced entirely by the suspended particulate impurities in the atmosphere. Consequently, screening or protection of the surface from such matter could arrest, or even prevent rust. However, even in the case of screened or filtered air, a primary oxide film will form even with relatively low humidities. The so-called "critical humidity" values for iron are approximately 62 percent and 82 percent. These are the relative humidity values at which profound increases in corrosion occur. Vernon's studies showed a gradual increase in corrosion with increases in relative humidity from 0 percent to 99 percent.

Based on Vernon's studies of the atmospheric corrosion of metals and the studies conducted by, or for, the U.S. Navy on the long-term preservation of materials (Operation Mothball), it is generally accepted that there will be little or no destructive corrosion of metals if they are held at 30 percent relative humidity in a reasonably pure atmosphere, i.e., free of harmful particulate matter such as salts and sulphur dioxide. By using protective oils or greases on the base surfaces, iron can exist without further corrosion at a relative humidity of 45 percent, provided the surfaces to be protected are cleaned as thoroughly as possible to eliminate possible hygroscopic dirt particles before the protective coating is applied.

To reiterate, the presence of moisture is essential for natural corrosion to take place at normal temperatures; presence of hygroscopic matter on the surfaces can accelerate the normal rate of corrosion; and the presence of certain materials, such as salts, chloride ions, and fatty acids can precipitate corrosion at relative humidity levels well below saturation.

An upper limit of 45 percent relative humidity has been suggested for dimensional metrology laboratories provided, of course, that normally bare iron surfaces are clean and protected with some type of coating.

10.1.3 Maintainability. Operating and maintenance procedures must be promulgated that, if followed, will ensure maintaining the performance of the dimensional metrology enclosure within its specified design limits.

10.2 Testing

The purpose of this section is to give users of this standard some understanding of the practical problems that exist in the administration of the requirements outlined in Section 5. Wherever possible, specific procedural suggestions are made. However, a thorough discussion of every possible instrument or procedure that is available for the administration of each requirement is beyond the scope of this document.

It is strongly recommended that every specification include a description of the test procedure or instrument that is intended for the administration of each requirement. Section 2 of this document contains some of the more common sources of information on practical procedures and instrumentation.

10.2.1 Thermal Guidelines

10.2.1.1 Cooling Medium. Because this standard has been deliberately kept as general as possible in order to permit the use of a variety of cooling media, there is little that can be discussed here beyond that already presented in Section 5. The user of this standard is cautioned that the properties listed in Section 5 are only those that pertain to the thermal behavior of the cooling medium. For specific cases, other properties such as color, opacity, odor, toxicity, acidity, lubricity, etc. may be very important.

10.2.1.2 Flow Rate and Velocity. As mentioned in Section 10.1.1, air is the most widely used cooling medium in dimensional metrology laboratories or enclosures, although the possible use of a fluid medium in some enclosures cannot be overlooked.

When air is used as the cooling medium, there is a tendency to have it flow at relatively low rates to provide as high an effective temperature as possible for the occupants of the laboratory consistent with the 68° F design specification. This tendency, aside from the effect on the film coefficients discussed in Section 10.1.1.1 and 10.1.1.2, creates problems when measuring the air velocity. At velocities of 0 to 100 fpm, the flow pattern is frequently very unstable. As a result, the mass turbulence level may be of the same magnitude as the velocity. Consequently, it becomes imperative that any instrument used be properly calibrated, and the using personnel be aware of both the limitations of the instruments, and their operation. For example, several types of thermal anemometers (so-called hot-wire types) can be used in this range; but the accuracy of the measurements at the lower end could be questionable, even though the precision of the measurements is quite good. Another example, non-directional instruments are usually unable to distinguish between large-scale turbulence and the mass velocity of air. Tables 1 and 2 list various types of instruments commercially available to measure either flow rate or velocity.

Table 1 Measurement of Velocity

No. Measurement Means	Application	Range, fpm	Precision	Limitations
1. Hot-wire anemometer	(a) Low air velocities; directional and non-directional available	5–1,000	1–20%	Accuracy of some types not good at lower end of range
	(b) High air velocities	up to 60,000	1–10%	
2. Kata thermometer	Low air velocities in rooms; non-directional	5–300	5–15%	Awkward to use; affected by radiation
3. Smoke puff or airborne solid	Low air velocities in rooms; highly directional	5–50	10–20%	Awkward to use but valuable in tracing air movement
4. Deflecting-vane type anemometer	Air velocities in rooms, at outlets, etc.; directional	30–24,000	5%	Not well suited for duct readings; needs periodic check calibration
5. Venturi-type multiplying Pitot tube	Low air velocities in rooms and ducts; directional	100–2,000 with micromanometer; 180–2,000 with draft gages	1–5%	Accuracy falls off at low end of range
6. Revolving-vane type anemometer	Moderate air velocities in ducts and rooms; somewhat directional	100–2,000	5–20%	Extremely subject to error with variations in velocities with space or time; easily damaged; needs periodic calibration
7. Cup Anemometer				
8. Pitot tube	Standard instrument for measurement of duct velocities and pressures	180–10,000 with micromanometer; 600–10,000 with draft gages; 10,000 up with manometer	1–5%	Accuracy falls off at low end of range
9. Impact tube and side-wall or other static tap	High velocities, small tubes and where air direction may be variable	120–10,000 with micromanometer; 600–10,000 with draft gages; 10,000 up with manometer	1–5%	Accuracy depends upon constancy of static pressure across stream section

Table 2 Measurement of Volume or Mass Flow Rate

No.	Measurement Means	Application	Range	Precision	Limitations
1.	Orifice and manometer	Flow through pipes, ducts and plenums—all fluids	Above Reynolds number of 5,000	1%	Coefficient and accuracy influenced by approach conditions
2.	Nozzle and Manometer	Flow through pipes, ducts and plenums—all fluids	Above Reynolds number of 5,000	1%	Coefficient and accuracy influenced by approach conditions
3.	Venturi tube and manometer	Same as 1 and 2 above but used where permissible pressure drop is limited	Above Reynolds number of 5,000	1%	Coefficient and accuracy influenced by approach conditions
4.	Rotameters	Normally used for liquids	Any	1%	Must be calibrated for the liquid with which used
5.	Turbine	Normally used for liquids	Any	0.5%	Utilizes electronic readout
6.	Timing a given weight flow	Liquids only—used for calibrating other flow means	Any	0.1%	–
7.	Displacement meter	Relatively small volume flow at high pressure drop	Relatively small volume flow at high pressure drop	0.2–2.0% depending on type	Some types require calibration
8.	Gasometer or volume displacement	Short duration tests; used for calibrating other flow means	Total flow limited by available volume of containers	0.5–1.0%	–
9.	Element of resistance to flow and manometer	Used for check where there is calibrated resistance element in the system	Lower limit set by readable pressure drop	1–5%	Secondary reading depends on accuracy of calibration
10.	Thomas meter (temperature rise of steam due to electrical heating)	Where elaborate setup is justified by need for good accuracy	Any	1%	Uniform velocity, usually used with gases
11.	Heat input and temperature change with steam or water coil	Check value in heater or cooler tests	Any	1–3%	–
12.	Instrument for measuring point velocity	Primarily used in installed systems where no special provision for flow measurements have been made	Lower limit set by accuracy of velocity measurement	2–4%	Accuracy depends upon uniformity of flow and completeness of traverse

The Reynold's number referred to in Table 2 is a dimensionless parameter used to designate the ratio of the inertia forces to the viscous forces in a fluid motion that occurs at the transition from laminar to turbulent flow.

Measurements made using the kinds of instruments shown in Tables 1 and 2 are frequently made either in the ducts conveying the air, or in close proximity to such ducts. It should be recognized, however, that this may not give a complete picture of the actual air changes in the room since the air leakage into the laboratory caused by wind or temperature differences are not indicated by these means. Consequently, if a more accurate determination of the total change time is required, it might be necessary to go to a measurement system employing a thermal conductivity comparator and a tracer gas. In this system, a known amount of a tracer gas (usually some percent of the total air volume) is released into the room and allowed to thoroughly mix with the air. As the release occurs, this mixture becomes diluted. The conductivity comparator is then used to measure the decrease in concentration at regular time intervals.

The infiltration can then be calculated from

$$C = C_0 e^{-kt/v} \tag{17}$$

where

C = concentration after t minutes, percent
C_0 = initial tracer gas concentration, percent
k = infiltration rate, cubic feet per minute
v = volume of room, cubic feet
e = 2.718.

This infiltration rate can then be used to correct the flow rate yielded by using the more conventional instruments.

10.2.1.3 Ranges of Frequencies of Temperature Variation and Limits from Mean. The main factors to be considered in choosing an instrument or instruments with which to administer temperature variation requirements are the frequencies of interest and the cooling medium. The instrument chosen must have a sensing element with a time constant small enough that the highest frequency of interest is detected and displayed without significant attenuation or distortion.

One point frequently overlooked is that a sensing element may have a different time constant for each medium it is in.

Example:

Bare Thermistor
Time constant in air–3 minutes
Time constant in liquid–3 seconds

10.2.1.4 Mean Temperature. Mean temperature is not measured directly (see 5.1.1.4). However, the temperature sensor-recorder system used to measure the temperatures from which the mean temperature is calculated must have adequate sensitivity, precision, and accuracy and must be used properly so that the calculated mean temperature will fall within acceptable confidence limits.

10.2.1.5 Gradients. The effect of thermal gradients can best be measured by closely monitoring the temperature of the master, the part, and the comparator during the actual measurement and applying the necessary thermal differential corrections to the measurement results.

The composition and flow rate of the cooling medium should be monitored for continued conformance to design specifications.

10.2.2 Humidity. Humidity is to be measured by any method having sufficient sensitivity and accuracy to assure the basic design specifications are met.

10.3 Operation and Maintenance

10.3.1 Thermal Guidelines

10.3.1.1 Once the heat transfer into an enclosure has been established, it should hold fairly constant as long as the physical integrity of the enclosure is not disturbed. Some long-term shifts due to aging of the materials, such as the wall insulation, may be expected. Normally, however, this should not pose a serious threat.

Installation of heat-producing sources adjacent to the controlled enclosure should be avoided if at all possible because of the possible effect on the heat transfer. If a recalculation of the heat transfer should show a significant change that could affect the thermal stability in the enclosure, additional insulation may be required.

If the integrity of the enclosure is maintained and the condition of the filters, the lighting system, and the air-conditioning system is maintained at a sufficiently high level to minimize deviations in temperature, cooling medium flow and velocity, little else should be required.

10.3.1.2 Flow Rate and Velocity. Periodic maintenance of the cooling medium distribution system is normally sufficient to maintain the established cooling medium flow rates and velocities provided the layout of equipment in the enclosure has not been sufficiently rearranged, or new instruments have been added that could disrupt the initial cooling medium flow patterns.

10.3.1.3 Ranges of Frequencies of Temperature and Variations and Limits from Mean. The only way for the accuracy and precision of the temperature sensing system to remain within the suggested limits is for a regularly scheduled standardization and/or calibration program to be established and followed.

A periodic maintenance program is recommended for the temperature control system for the enclosure to assure that the design criteria are satisfied.

10.3.1.4 Mean Temperature. If the procedures given in the other sections of 10.3.1 are followed, the established mean temperature should be maintained.

10.3.1.5 Gradients. Because of the difficulties encountered in establishing and maintaining thermal stability in a dimensional standards laboratory, a program of continued vigilance to ferret out causes of instability is strongly recommended. This is particularly important during the periods when measurements are actually being made.

10.3.2 Humidity. The specified humidity limits should be maintained by any suitable means.

20. ADVISORY INFORMATION PERTAINING TO THE ASSURANCE OF ADEQUACY OF ENVIRONMENTAL CONTROL

In this section it is assumed that the measuring equipment and the thermal environment exist, and that normal or expected operating conditions are in force. The object of the discussion is to describe the manner in which one goes about determining the extent of measurement errors resulting from non-ideal temperature conditions.

The ideas and methods described are those found in fairly common usage by metrologists everywhere. But, for the first time, these ideas and methods are unified and formally presented. Some of the concepts presented may at first appear strange and unrelated to previous experience. The 3-element system concept, for example, will probably fall in this category. However, with a little patient study, the concept will be seen to correspond to common notions, and its utility in a disciplined investigation will become clear.

The other notion that may appear to be new is that of the uncertainty of the coefficient of expansion.

Each of these concepts is examined and reduced to a practical procedure in the first four of the following paragraphs.

The last paragraph of this section is devoted to explaining the Thermal Error Index and its use.

20.1 Estimation of Consequences of Mean Environmental Temperatures Other than 68° F (20° C)

20.1.1 Length Measurements. The assessment of the consequences of temperatures other than 68° F (20° C) are easily obtained by means of equations that give the Nominal Differential Expansion in terms of the Nominal Expansions of the part and master.

$$NDE = (NE)_p - (NE)_m \qquad (18)$$

and

$$NE = \kappa L\,(T - T_s). \qquad (19)$$

Combining these equations, we get

$$\begin{aligned} NDE &= \kappa_p L\,(T_p - T_s) - \kappa_m L\,(T_m - T_s) \\ &= L\,[\kappa_p\,(T_p - T_s) - \kappa_m\,(T_m - T_s)] \ \ldots \end{aligned} \qquad (20)$$

Assuming that the part and master both are at the mean temperature, $T_p = T_m = T_{me}$ (the only reasonable assumption unless thermometers are attached to both the part and master), we see that the error is reduced to insignificance if the coefficients of thermal expansion approach equality. And this is true even with a large deviation of the mean environmental temperature from 68° F (20° C).

Because the great majority of manufactured parts and gages are of ferrous materials having similar coefficients of expansion, many industries, particularly those where tolerances are in tens of thousandths of inches, have successfully functioned without concern over the effect of mean environmental temperature on manufacturing accuracy. In many such situations, an arbitrary insistence on 68° F (20° C) temperature control leads to unjustified increased cost of manufacture.

As tolerances become tighter, as the parts become bigger, and as the materials of parts and masters become more dissimilar, the consequences of mean environmental temperatures other than 68° F (20° C) become correspondingly greater. Here it is to be noted that in recognition of the possible consequences of mean environmental temperatures other than 68° F (20° C), it is not uncommon to find the following actions in use:

(a) Special gaging or masters made of nominally the same material as the parts;

(b) Computation of corrections which are applied to the indicated values of length. The required computation method is derived from Equation 23. The correction is set equal to the negative of the Nominal Differential Expansion.

$$\text{Correction} = -NDE \qquad (21)$$

$$\text{Corrected Length} = \text{As-read Length} + \text{Correction}. \qquad (22)$$

As the working tolerance decreases, both of these procedures fail to be satisfactory because of the magnitude of the Uncertainty of Nominal Differential Expansion (see 20.2).

20.1.2 Measurements Other than Length. Procedures and formulae for the assessment of the effects of mean environmental temperatures other than 68° F (20° C) as simple and straightforward as those presented in the preceding paragraph are not usually possible in cases other than length measurements.

For example, consider the case of an iron bedway casting of a machine. Because the casting may have both thick- and thin-walled sections, the physical composition of the material may not be homogeneous, resulting in a non-uniform coefficient of thermal expansion. The magnitude of such a variation in expansion coefficient may be as much as 5 percent. If the non-uniformity is distributed as a vertical gradient, raising or lowering the mean temperature will result in a bending like that produced by a vertical temperature gradient.

This effect is the same as that observed in the well-known bimetal strip, and can be called a "bimetal effect".

The bimetal effect in structures of nominally one material is relatively small compared with the effect of temperature gradients. For example, a base casting like that mentioned above would have to be subjected to a temperature offset of 20° F before the bending approaches that induced by an upper and lower surface temperature difference of only 1° F. However, in structures composed of two or more greatly dissimilar materials that are assembled at 68° F (20° C), the bimetal effect can be quite significant. In such cases the effect of mean temperatures other than 68° F (20° C) can be properly estimated only by taking into account the thermal stresses that exist.

Existence of severe bimetal effect can be avoided only by strict control at 68° F.

Evaluation of the effects of mean temperatures other than 68° F requires that the net effect of the distortions of both master and part be determined.

20.2 Consequences of Uncertainties of Computations

There are two kinds of systematic errors that occur when the effects of mean temperatures other than 68° F (20° C) are computed. They are the errors in the values of the temperatures and in the coefficients of thermal expansion that are used in the computations.

Values of temperatures used in computations can be in error because of defects in the instruments used in making the measurements or because of the location at which the measurement is made. For example, the thermometer used may be inaccurately calibrated or have a built-in source of error such as the self-heating effect found in resistance-bulb thermometers. Because of the self-heating effect, resistance-bulb thermometers can be very precisely calibrated in liquid baths and give erroneous readings on metal surfaces or in air because the heat transfer process is quite different in the different cases.

Location of the temperature-measuring probe is of significance because of the possible gradients. Use of room air temperature values may introduce errors of a degree or more. Readings of direct-contact probes are more reliable but are still subject to error because of gradients within the object whose temperature is being measured. An effective means of assessing the validity of a given location is to compare effects of several locations.

The approach taken in formulating the standard procedure for estimating the effects of Uncertainty of Nominal Differential Expansion is to require that part and master temperatures be measured to determine worst-case deviations from 68° F. This procedure, as noted in 6.2.1, for length measurements, takes into account the effects of gradients in the apparatus, as well as in the room in which it is located.

If part and master temperatures are not measured, the estimation of the consequences of uncertainties of computations must include consideration of the uncertainties in the temperatures used in computing the estimation of the effects of temperatures other than 68° F. Equation 7 is modified as follows:

$$\mathrm{UNE} = (\delta + \theta)\,(L)\,(t - 68)/100\% \qquad (23)$$

where $\theta = \Delta t/t - 68 \times 100$, or the possible percentage error in the estimated difference between the part or master and 68° F. Δt is the estimated possible error in temperature difference.

With proper attention to the simple, well-established rules of precision thermometry, the uncertainties due to temperature measurement can be easily reduced. In the usual case, however, the effects of uncertainties of coefficient of thermal expansion values are much more difficult to overcome.

Coefficient of thermal expansion data are published in tables in many handbooks and other sources. These values cannot be used without consideration of their applicability, i.e., their uncertainty. Uncertainties in the published data arise because

(a) The material of the elements of the measurement system–part or master or both–differ from the material for which the data are given. The differences may be in chemical composition, physical composition, or both.

(b) The published values are usually the result of averaging data from several experiments and from several experimenters. Consequently, the data reflect the effect of experimental bias.

(c) The published values are valid only for temperatures other than 68° F or for a range of temperature other than that of the computation.

The National Bureau of Standards, in calibrating steel gage blocks, assumes an uncertainty of the coefficients of expansion of ±5 percent when the heat and mechanical treatment of the steel is known. The precision of the coefficient is (1) about ±3 percent among many heats of steel of nominally the same chemical content, (2) about ±10 percent among several heat treatments of the same steel, and (3) about ±2 percent among samples cut from different locations in a large part of steel that has been fully annealed. Hot or cold rolling will cause a difference of about ±5 percent.

Other materials have their own susceptibility to uncertainty of coefficient of thermal expansion, depending on the effects of chemical contaminant or physical structure. Some materials have grain structure effects in terms of expansion coefficients that vary with direction.

The typical thermal expansion measurement is conducted with an apparatus called a dilatometer in which a specimen, usually rod shaped, is heated and its change of length measured. Another form of dilatometer measures change of volume by Archimedes' principle, resulting in a coefficient of cubical expansion. For homogeneous (nondirectionally sensitive) materials, the coefficient of cubical expansion has a value three times that of the coefficient of linear expansion.

The fact that the typical test specimen bears little resemblance to real parts, with consequent uncertainties in composition and treatment not reflected in experimental data scatter, suggests that decreased uncertainties can be obtained by direct measurement of each specific object, or full-scale dilatometry.

Figures 4 and 5 represent two possible ways one may find thermal expansion data presented in the literature. Figure 4 is a synthetic case deliberately oversimplified for the purposes of this discussion. Figure 5 is an actual case.[4] Note that Figure 4 is a plot of change of length, ΔL, as a function of temperature where ΔL is defined as zero when the temperature is 68° F. This is the usual form of raw data from dilatomer experiments.

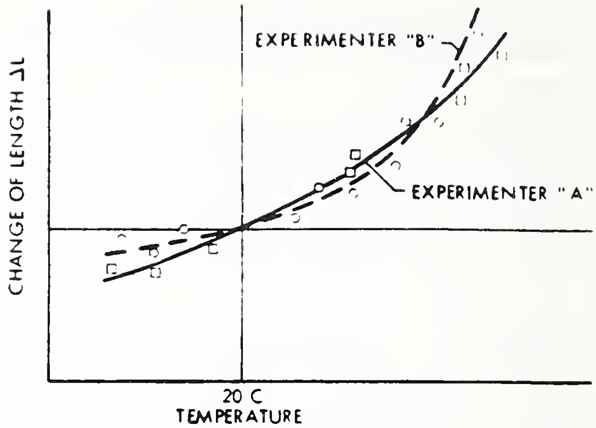


FIG. 4 Synthetic Experimental Results of Thermal Expansion Measurements

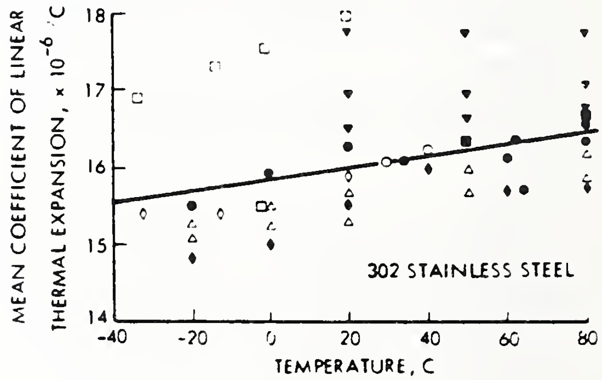


FIG. 5

Figure 5 on the other hand is a plot of the mean (or average) coefficient of expansion from 20° C,

$$\alpha_m = \frac{L_t - L_{20}}{L_{20}\,(t - 20)} \tag{24}$$

plotted at t. The data for t = 20° C are derived from the slope of the thermal expansion, $d\,\Delta L/dt$, at that special temperature.

Figure 5 gives results from several investigators. Figure 4 shows how two investigators may obtain differing results that are reflected in Figure 5. Both Figures show (1) the scatter of experimental data, and (2) the nonlinear nature of expansion relative to temperature. Data of this type are the source of all

[4] Data courtesy of Richard K. Kirby, U.S.N.B.S., Thermal Expansion Laboratory

tabulated coefficient of expansion data. The published value, however, varies according to how the experimental data are interpreted. For a single investigation, the value depends on how the trend is interpreted, i.e., how the average curve is fitted. For multiple investigations, the value depends on how the data is averaged.

For example, published values for pure or element aluminum is reported as 23.6/° C at 20° C in Metals Handbook and 22.4/° C at 20° C in Machinery's Handbook.* Also, in Metals Reference Book, Table 2, the average from 20° C to 100° C is given as 23.9/° C; and in Metals Reference Book, Table 1, the average from 0° C to 100° C is given as 23.5/° C.

20.3 Estimation of the Consequences of Temperature Variation

An estimation of the consequences of temperature variation can very seldom be obtained by direct calculation. Therefore, the procedures described in this section are based on an experimental approach to the estimation.

The basic experimental procedure used in the estimation of the consequences of temperature variation is the drift test which is described in 20.3.1. Drift test results can be interpreted in a variety of ways to obtain an estimation of Temperature Variation Error. One method is described more fully in 20.3.2 along with other methods of interpreting drift test results that are not standard, but may be useful because they are less conservative and may provide development of concrete grounds for negotiating the acceptability of thermal effects errors in special cases.

The rationale for both the drift test and the estimation of Temperature Variation Error is given in 20.3.3 in an explanation of the concept of the 3-element system.

20.3.1 Drift Test Procedure

20.3.1.1 Equipment. The object of a drift test is to record relative displacement in a 2-element system (see Section 20.3.3). The most direct method utilizes electronic indicators whose output is recorded on a strip-chart recorder. Some measurement processes, such as the measurement of flatness with an optical flat and monochromatic light or an indicating micrometer do not lend themselves to the use of automatic recording. Therefore, in some cases it will be necessary for a human operator to observe the drift and record numerical values and corresponding clock time. These data can be subsequently hand plotted.

It is strongly urged, however, that wherever possible sensitive electronic indicators and strip-chart recorders be used.

Though a drift test can be performed without any necessity for knowledge of temperature variation, it is often advisable to record one or more temperatures either for use in later correlation of two drift tests or for reference if temperature variation is to be later accepted as a method of monitoring the process for validation of the Temperature Variation Error estimate.

Just as in the case of displacement measurements, it is strongly urged that all temperatures be automatically recorded. For this purpose, recording resistance element thermometers, especially those with thermistor sensors, are recommended.

20.3.1.2 Equipment Testing

20.3.1.2.1 Displacement Transducers. Aside from the usual calibration checks, electronic indicators should be checked for possible sensitivity to the thermal environment in which the drift test is to be performed. An "electronics drift check" should be conducted by blocking the transducer and recording the output for at least the same period of time as that of the drift check to be performed. "Blocking" a transducer is to make it effectively indicate on its own frame, base, or cartridge. Figure 7 shows a cartridge-type linear variable differential transformer blocked by means of a cap or capture device which holds the indicator armature in a fixed position relative to the cartridge.

During the electronics drift check, the entire displacement recording system should be located as nearly as possible as it will be during the drift test.

Electronics drift tests have been useful in proving that, in many cases where electronic indicators have been the suspected source of drift, they were innocent and the real cause was thermal drift. The commercially available cartridge-type LVDT gage heads have been proven many times to be especially free from drift.

20.3.1.2.2 Temperature Recording Systems. The temperature-measuring and recording apparatus should be thoroughly tested for calibration, response, and drift.

Resolution of at least 0.1° F is recommended. Time constants of sensing elements of about 3 minutes are recommended for air temperature sensors, 30 seconds for liquid and surface temperature sensors. Air probes must be shielded from possible radiation effects.

20.3.1.3 Preparation of System for Test. An essential feature of the feature of the drift test is that

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*Calculated from 12.44 μin/in/° F at 68° F

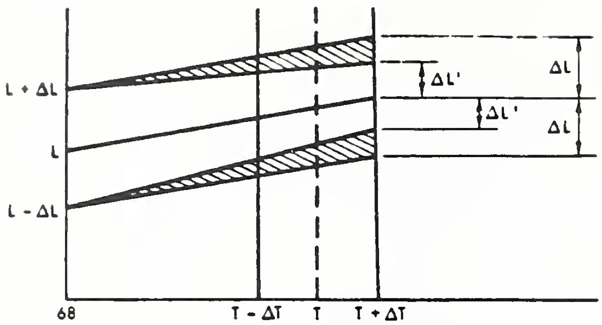


FIG. 6 Effect of uncertainties of coefficients of expansion on permissible tolerances. Part nominal size of L with tolerance ±ΔL. Tolerance is reduced to ±ΔL' when mean temperature is T ± ΔT.

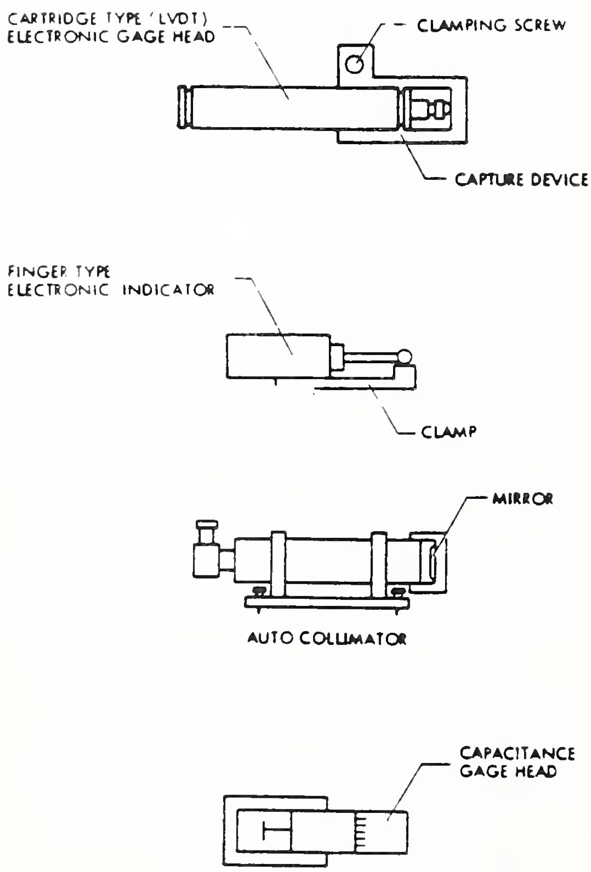


FIG. 7

conditions during the test must duplicate the normal conditions for the process as closely as possible. Therefore, before the test is started, normal conditions must be determined. The step-by-step procedure followed in the subject process must be followed in the same sequence and with the same timing in the drift test. This is especially important in terms of the actions of human operators in mastering and all preliminary setup steps. With as little deviation from normal procedure as possible, the displacement transducers should be introduced between the part (or master, depending on the type of drift check) and the rest of the C-frame such that it measures relative displacement along the line of action of the subject measurement process.

The temperature-sensing pickup must be placed so as to measure a temperature which is correlatable with the drift. Some trial and error may be necessary. In the extreme case, temperature pickups may have to be placed to measure the temperatures of all of the active elements of the measurement loop.

20.3.1.4 Representative Time Period for a Drift Test. Once set up, the drift test should be allowed to continue as long as possible, with a minimum of deviation from normal operating conditions. In situations where a set pattern of activity is observed, its duration should be over some period of time during which most events are repeated. When a 7-day work week is observed in the area, and each day is much like any other, a 24-hour duration is recommended. If a 5-day work week is observed, then either a full-week cycle should be used or checks performed during the first and last days of the week.

20.3.1.5 Postcheck Procedure. After the drift test, the displacement transducers and the temperature recording apparatus should be restandardized.

20.3.1.6 Example Drift Test Results. Figures 8 and 9 are results from drift tests conducted on a measuring machine/gage. Figure 8 is the drift recorded over a 24-hour period for a system consisting of the master and comparator. Figure 9 is the drift recorded over the succeeding 24-hour period for a system consisting of the part to be measured and the comparator. In both cases, ambient temperature at a point near the gage was recorded and is plotted in the corresponding figures.

20.3.2 Temperature Variation Error. Figure 10 shows the results of both part/comparator and master/comparator drift tests for a real measurement process. In this case, ambient temperature readings were obtained simultaneously with each drift test for the purpose of approximating the proper phase relationship.

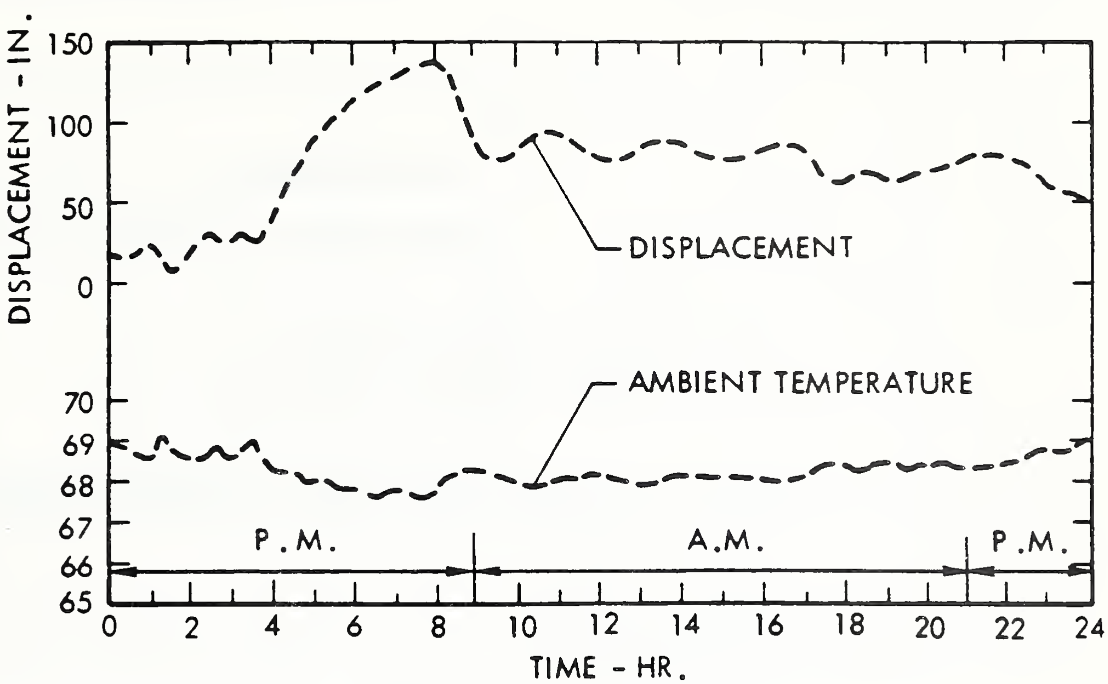
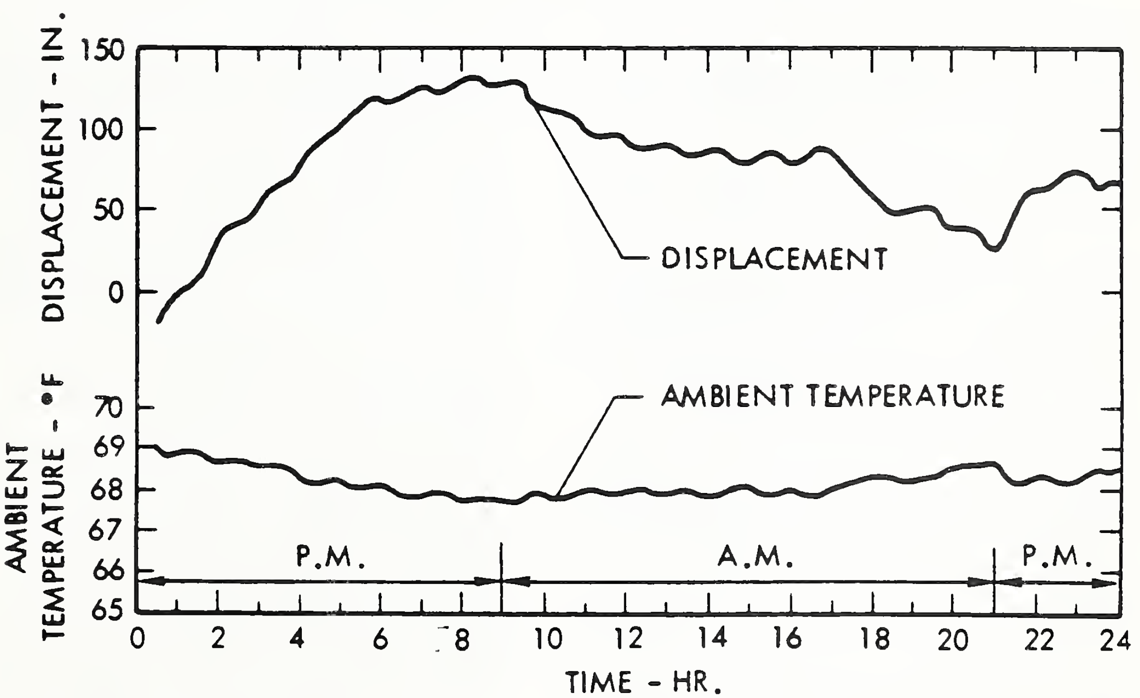

DISPLACEMENT - IN.
150
100
50
0
70
69
68
67
66
65
DISPLACEMENT
AMBIENT TEMPERATURE
P.M.
A.M.
P.M.
0
2
4
6
8
10
12
14
16
18
20
22
24
TIME - HR.

FIG. 8


DISPLACEMENT - IN.
AMBIENT TEMPERATURE - °F
150
100
50
0
70
69
68
67
66
65
DISPLACEMENT
AMBIENT TEMPERATURE
P.M.
A.M.
P.M.
0
2
4
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8
10
12
14
16
18
20
22
24
TIME - HR.

FIG. 9

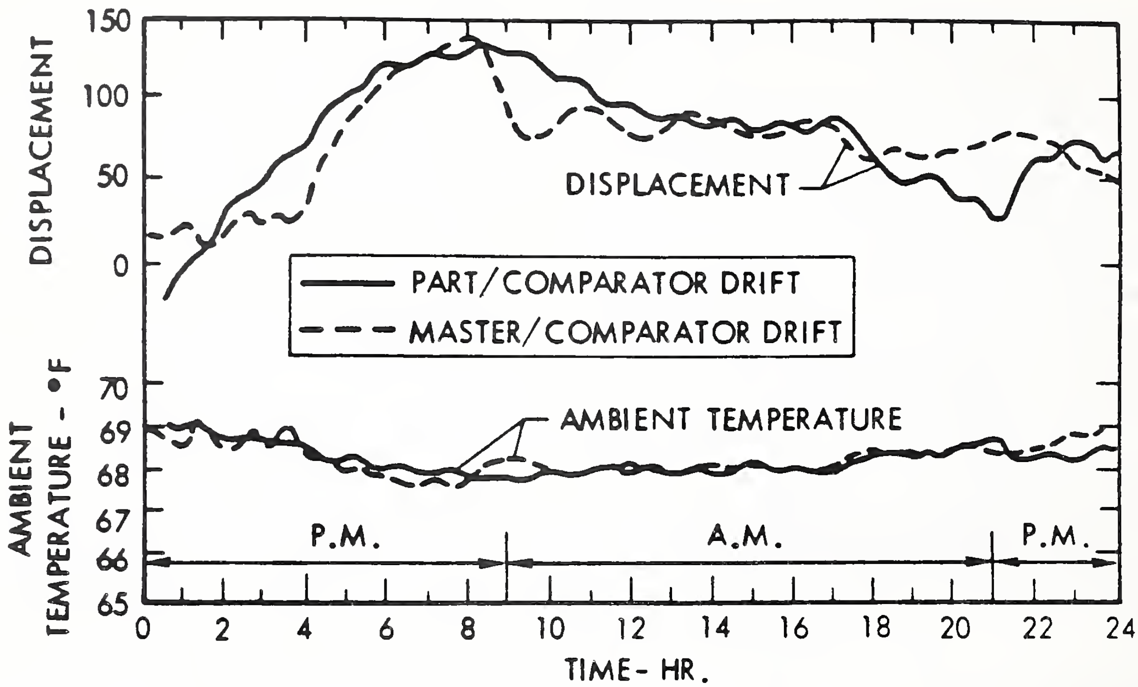

FIG. 10 Results of part/comparator and master/comparator drift tests of a gage in an Inspection Shop. Tests were conducted on successive days. The data are superimposed on clock time

The two sets of data were superimposed on a basis of clock time, which appears to give a good overall agreement in ambient temperature variation.

The ambient temperature variation on the two successive days has a well-defined 24-hour component with an amplitude of about 1.5 F. Superimposed on this are higher frequency components with periods of from ½ to 1½ hours. From these data it is possible to compare the 24-hour cycle characteristics because of the repeatability of the environment at this frequency; but phase relationships at the higher frequencies are not discernible because of nonrepeatability.

At the 24-hour frequency, the master/comparator and part/comparator drift curves are in phase and have very nearly the same amplitude. This is a classic example that shows the importance of measuring cycle time because the larger amplitudes of drift are associated with the low frequency, whereas the smaller amplitudes of drift are associated with the higher frequencies.

For short measurement cycle times, say 1 hour, the procedure for evaluating Temperature Variation Error given in Section 20.3.1 results in a TVE = 60μin. For measurement cycle times of 12 hours or more the TVE = 120μin.

When the quality of the drift data permits, it is sometimes possible to apply the more precise evaluation methods discussed in Section 20.3.3 which are less conservative. In the example of Figure 10, little is gained by this procedure because the maximum difference between the two drift curves, which corresponds to the possible error for short measurement cycle times is still about 60 microinches. This is probably because of nonrepeatable components of temperature variation in the two days testing. The day on which the master/comparator drift test was performed appears to have had more severe high frequency temperature components. This discrepancy appears to exaggerate the true part/master relative drift. Further drift tests to obtain results for more consistent temperature variations would be advisable in this case if Temperature Variation Error is the major thermal effect in this measurement process.

20.3.3 The 3-Element System Concept. The magnitudes of the effects of temperature variation are dependent on the structure of the measurement apparatus and not only on the size and composition of the part and master as was true in the previous sections. Also unlike the other components of thermal error, Temperature Variation Error depends on the work habits of the person making the measurements.

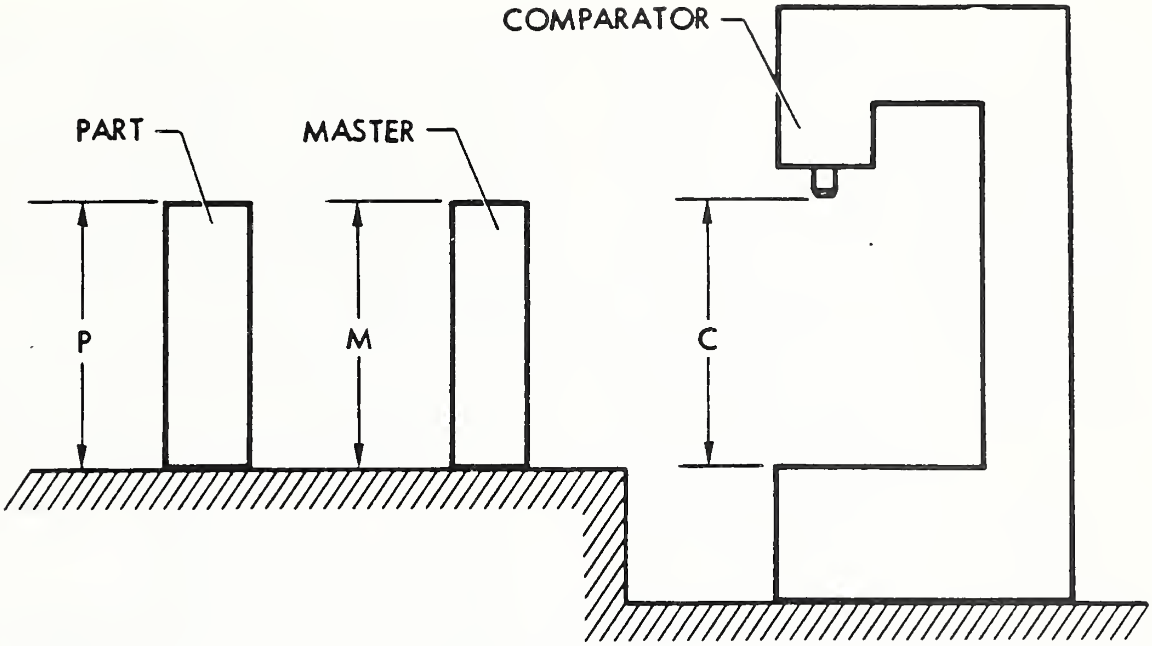

FIG. 11 The three elements of a length-measuring system.

One of the simplest structures is that encountered in the measurement of the length of an object with a gage block and a column comparator. Figure 11 shows a schematic representative of such a system. As can be seen, it consists of a part, a master (the gage block) and a comparator. Thus, the system consists of three elements.

In Figure 11, each element is shown to have a characteristic length; P = part length, M = master length, and C = comparator length. In the measurement process, C is first set equal to M, then P is checked to see if $P = C$.

If there were no temperature variations, the measurement process could be straightforward. However, because of temperature variations, heat is constantly being exchanged between the three elements and the ever-changing environment.

If the time constants of all three elements are not the same, they will respond to temperature variations such that it would be possible that all three elements will never simultaneously have the same temperature. And even if the time constants were all the same, and their temperatures always equal, they may not have the same length, except when all are at 68° F (20° C), because of different coefficients of expansion.

For each element, its time constant, length and coefficient of expansion defines its dimensional response to temperature variation.

Figure 12 shows the dimensional response of the three elements of Figure 11 for an assumed sinusoidal ambient temperature variation. For simplicity, the hypothetical system consists of three elements of the same material but different time constants, the largest being that of the master, the smallest being that of the part with the time constant of the comparator between those of the other elements.

As can be seen, the result is that the 3-dimensional responses differ in amplitude and phase. It should be noted that dimensional response data in this form is rarely obtainable, because it requires the use of an independent apparatus that must itself be unaffected by temperature variation.

The data of Figure 12, if it were obtainable, can easily be interpreted for an estimate of the Temperature Variation Error. It is only necessary to consider the effect of the measurement cycle as follows.

Suppose that at time T_{m1} the comparator is mastered. The act of making C and M equal causes the dimensional response curve of the comparator to be shifted parallel to itself (the comparator is "zero shifted") as shown by the dashed curve. If the part is checked without delay after mastering, it is found to be too large by the amount q. If, instead, the part is checked much later, say at time T_{m2}, the part will be

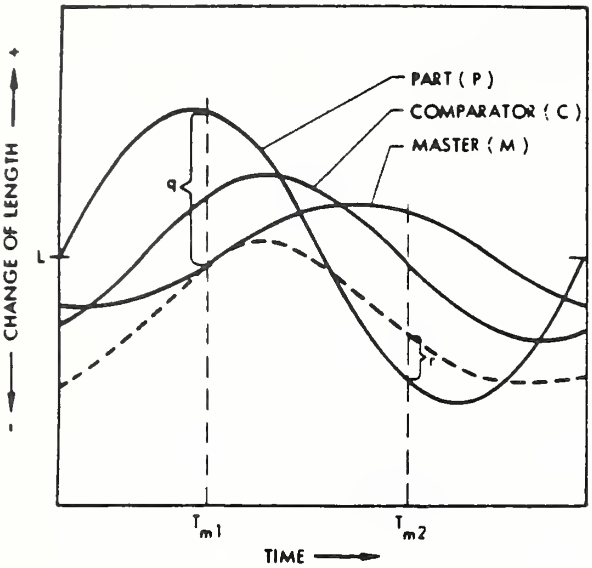

FIG. 12 Sample steady-state dimensional response of a 3-element system to a sinusoidal ambient-temperature variation

found to be too small by the amount r. If the comparator is remastered at time T_{m2}, the comparator curve is again shifted, resulting in new magnitudes of possible error.

Because Temperature Variation Error results from the variation of the differences of the characteristic lengths, it is possible to separate the 3-element system into two 2-element subsystems. For example, Figure 13 shows the two curves that result when the comparator variations (c) are subtracted from the part and master dimensional responses (P-C and M-C). These data might have been obtained by recording the output of an electronic indicator, such as is found used on modern column comparators, when the part and master are, successively, in the comparator with the indicator contacting the part and master, respectively. Data such as this are the result of drift tests. In the next section detailed procedures will be given for the conduct of drift tests followed by a discussion of methods of interpreting drift test data to obtain an estimate of Temperature Variation Error.

The main problem in interpreting such data results from the fact that it is not possible to conduct simultaneous part comparator and master/comparator drift tests. Consequently, additional data is required to determine the proper phase relationship between the two recorded drift curves; or the possible consequences of unknown phase relationship must be considered in the estimate of Temperature Variation Error.

Because the data of Figure 13 have been constructed from the data of Figure 12, no phase uncertainty exists and the Temperature Variation Error can be extracted easily. For example, for a mastering cycle occurring between times T_{m1} and T_{m2} and a measurement of the part without delay, the possible error q is simply the difference between the two curves.

The effect of mastering is to establish a new baseline for the part/comparator drift curve (P-C). This new baseline is shown in Figure 13 as the line (O-O). If the measurement of the part takes place at time T_{m2}, the resultant error is r as determined previously.

If a series of like parts are inspected between times T_{m1} and T_{m2}, the consequences of Temperature Variation Error range from $+q$ to r.

In the case that the clock times at which mastering occurs are unknown and unpredictable and the measurement cycle time is very short (mastering with each measurement and negligible delay before the part is inspected), the possible Temperature Variation Error is $\pm x$, or the maximum difference between the two drift curves at any given time. Because of the short

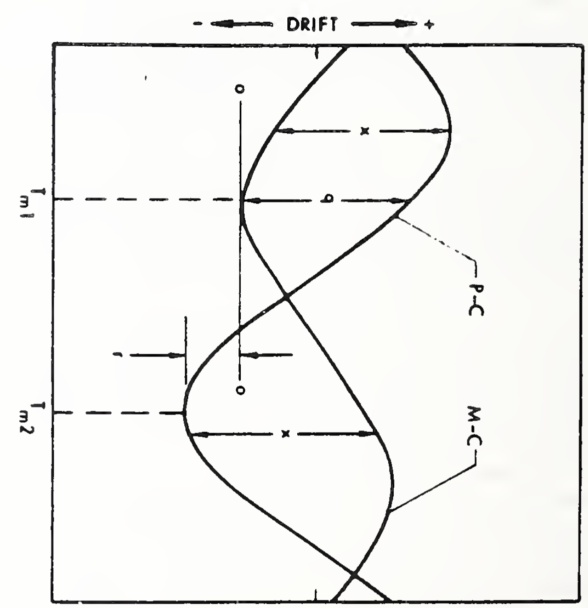

FIG. 13 Relative drift components for a 3-element system (same example as in Figure 11). P-C is the relative drift between the part and the comparator, and M-C is the relative drift between the master and the comparator.

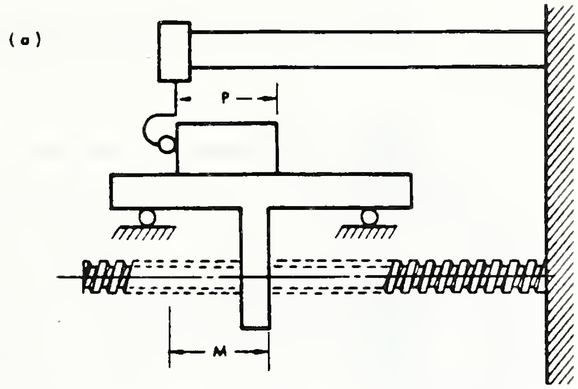

FIG. 14 Schematic of setup used to measure part on a gage with a lead-screw master.

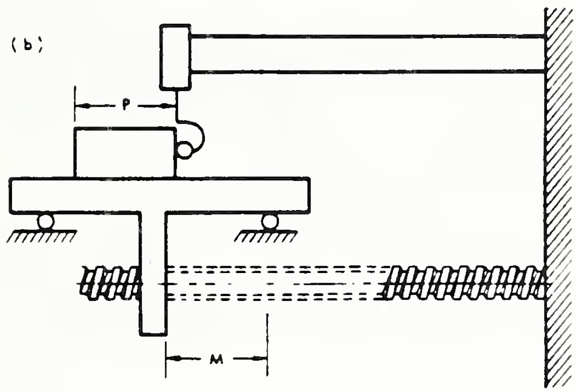

FIG. 15 Schematic of setup used to measure part on a gage with a lead-screw master. The measuring sequence is a change from (a) to (b).

measuring cycle time the comparator is slaved to the master so that the comparator contributes nothing to the error. The error, therefore, is

$$(P\text{-}C) - (M\text{-}C) = P - M.$$

This error is dependent only on the difference between the master/comparator drift and the part/comparator drift and the clock time at which the measurement is made. If the measurement cycle time is longer than the period of the temperature oscillation, the maximum possible error is $\pm y$, or the maximum difference between the two drift curves regardless of time.

Note that y is slightly larger than x.

In some dimensional measurement processes the 3-element system reduces to a 2-element system. For example, the process of measuring flatness with an optical flat under monochromatic light, is a case of a 2-element system. The comparator here is the human eye which is assumed to have no effective dimensional response to ambient temperature variation.

In length-measuring processes, however, a 3-element system is always found. For example, consider the cases shown in Figures 14 and 15. The former is the case of a measuring machine or machine tool with a leadscrew serving as master. In Figure 15, the measurement process is shown to consist of changing from position (a) to position (b). The analogy between this case and the simple 3-element system of Figure 11 is seen if it is realized that in the two configurations, the comparator is composed of a portion of the leadscrew, the nut and table support for the part. These elements, though appearing to change, remain in a structural loop, while the part and master exchange places as members of the loop.

The case shown in Figure 16 is that of a 1-inch indicating micrometer used as a comparator. The master is a gage block. Figure 17 shows the same micrometer used to measure the part without checking zero. In this case, the micrometer frame plus screw, opened to the size of the part, constitutes the master. The same structure also fulfills the function of comparator.

In Figure 18 still the same micrometer is brought to its null position and a zero correction is made before the part is measured. In this case the master is that portion of the screw that is withdrawn to make room for the part. The rest of the micrometer forms the comparator.

Consider now a 2-inch indicating micrometer and the following case. The part is 1½ inches in diameter.

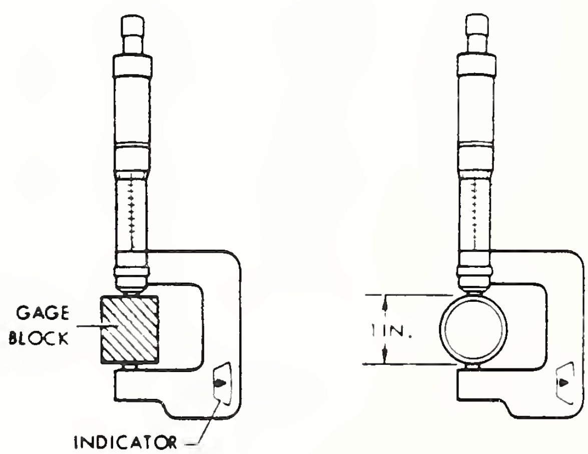

FIG. 16

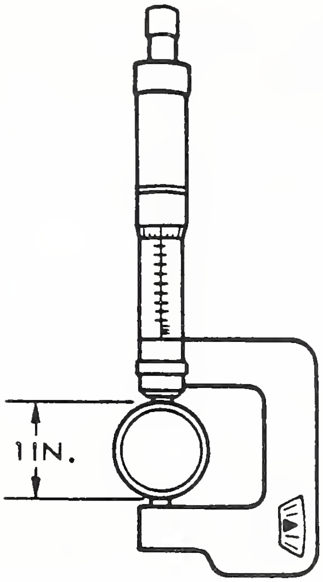

FIG. 17

A 1-inch gage block is used to master the micrometer. The master in this case is the gage block plus that portion of the screw, approximately ½-inch long, which is withdrawn to make room for the part (see Figure 19).

The last four cases show how the master and comparator can be changed by changes in the operating procedure.

20.4 Consequences of Temperature Gradients

Effects of gradients in mean environmental temperature are usually accounted for in the case of length measurements under effects of temperatures other than 68° F or under considerations of uncertainties of temperature measurements. Consequently, the main concern here is the effect on measurements other than length such as a measurement of flatness. An example of the estimation of the effect of temperature gradient on a measurement of flatness is given in Section 10.1.

To satisfy the intent of the Thermal Error Index, computation of an estimate of the consequences of uncertainties of computations as discussed in Section 20.2 must be performed and added to the estimation of the consequences of temperature gradient and the consequences of temperature variation (Section 20.3).

20.5 Thermal Error Index

This standard does not recommend values for the Thermal Error Index. Such values cannot be stated without regard to other sources of error in the measurement process. For example, a Thermal Error Index of 10 percent assigns to thermal effects that fraction

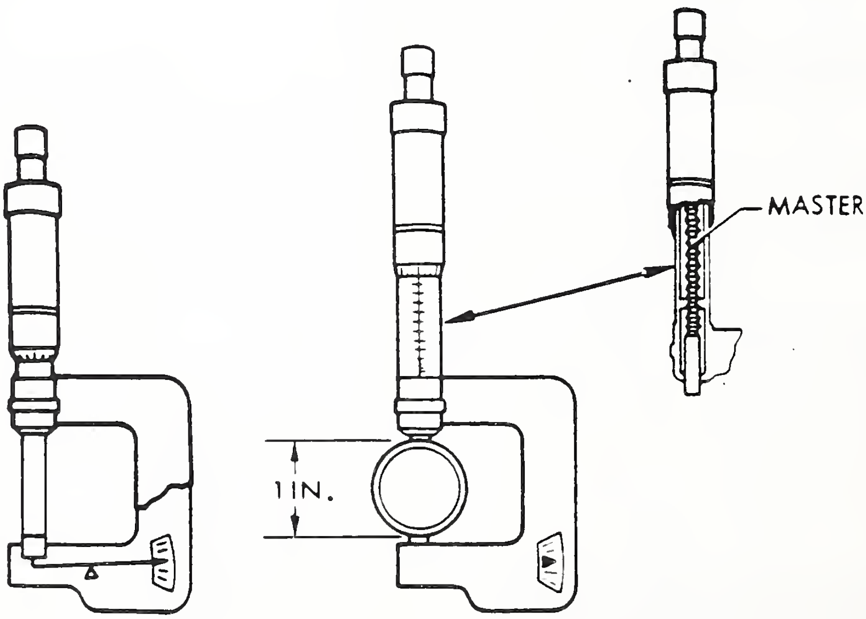

FIG. 18

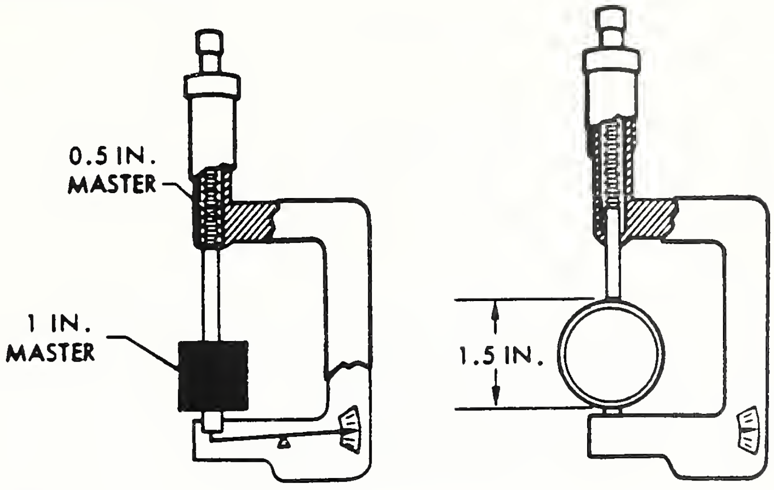

FIG. 19

of the working tolerance that is usually considered to include the composite effects of all error sources. In given cases, the permissible values depend on the degree of control that is maintained over all aspects of the measurement process, including the skill level of personnel. In a machine shop, a value of 0.1 may be justifiable while in a metrology laboratory it may be possible to increase the value to 0.2.

The main objective of the Thermal Error Index is to convey the quality of a measurement process with respect to thermal effect. As such, it is mainly an administrative tool.

It is to be noted that one way to reduce a Thermal Error Index is to increase the working tolerance. Consequently, it serves as a feedback device to inform management and designers of the degree of absurdity of a specified tolerance. The Thermal Error Index does nothing more than estimate the maximum possible error caused by thermal environment conditions affecting a particular measurement process. It does not establish the true magnitude of error in any measurement. It serves to remove doubt about the existence of errors and to establish a system of rewards and penalties to processes that are combinations of techniques and conditions, some good and some bad.

A Thermal Error Index evaluation penalizes a measurement process on three counts.

(a) Existence of temperatures other than 68° F

(b) Existence of temperature variations

(c) Existence of temperature gradients

The same evaluation rewards good techniques by decreasing the Thermal Error Index for (1) attempting a correction for the consequences of temperatures other than 68° F, (2) keeping environmental variations to a minimum, and (3) maintaining acceptable temperature gradients. The act of performing the evaluation results in the knowledge of what techniques or conditions can be changed to achieve the greatest improvement with the least effort. For example, if Temperature Variation Error is found to be the greatest source of error, the measurement cycle time may be reduced such that the Thermal Error Index is reduced to an acceptable value. Thus, by more frequent mastering, at some nominal increase in operating expense, possible misapplication of capital to improve temperature control is avoided.

AMERICAN NATIONAL STANDARDS RELATED TO DIMENSIONAL METROLOGY

Precision Inch Gage Blocks for Length Measurement (thru 20 Inches) B89.1.9–1973
Measurement of Out-of-Roundness B89.3.1–1972
Temperature and Humidity Environment for Dimensional Measurement B89.6.2–1973
Gages and Gaging for Unified Screw Threads B1.2–1966
American Gaging Practice for Metric Screw Threads B1.16–1972
Preferred Limits and Fits for Cylindrical Parts B4.1–1967
Surface Texture B46.1–1962 (R1971)

APPENDIX B

Error Budgets

by R. R. Donaldson

Reprinted from: Technology of Machine Tools
Volume 5
Machine Tool Accuracy
Lawrence Livermore National Laboratory
UCRL-52960-5

9.14 ERROR BUDGETS

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INTRODUCTION

Generally speaking, an error budget is a systems analysis tool, used for prediction and control of the total error of a system at the design stage for systems where accuracy is an important measure of performance. Given a system-error goal, an error budget can be used in a control mode to set individual subsystem error limits, while also making trade-offs that balance the level of difficulty among the subsystems. In a predictive mode, proposed subsystem design can be assessed for error contributions, leading to a predicted overall system error. Typically the predictive and control modes are iterated repeatedly.

A significant break-point occurs when the required subsystem error limits exceed the state of the art. Within the state of the art, the error budget can be used as an aid in minimizing the overall system cost. Beyond the state of the art, the trade-off alternatives are those of accepting a less stringent system-error goal or accepting the time and cost required for the necessary improvements in the state of the art. Obviously the larger the required improvements the more speculative the development process becomes, but the error budget remains useful as an assessment tool.

To the author's knowledge, error budgets have not been used in the design of machine tools beyond the example to be presented later in this article, and hence the subject is not well developed. The following section contains the general approach applied to the example; suggested areas for further development are given at the end of the article.

MACHINE TOOL ERROR BUDGETS

BASIC ASSUMPTIONS

Two basic assumptions underlie the use of an error budget for a machine tool. The first is that the instantaneous value of the total error in a specified direction is the sum of all the individual error components in that direction (i.e., linear superposition is valid). The second is that the individual error components have physical causes that can be isolated and controlled or measured to allow reduction or prediction of the error magnitude. Both assumptions are supported by the discipline of machine tool metrology, which provides methods for the measurement of individual errors, as discussed in Sec. 7.0.

ERROR BUDGET FLOW CHART

Figure 9.14-1 shows the overall process of generating an error budget, illustrated for a two-axis lathe, from the physical sources of error at the

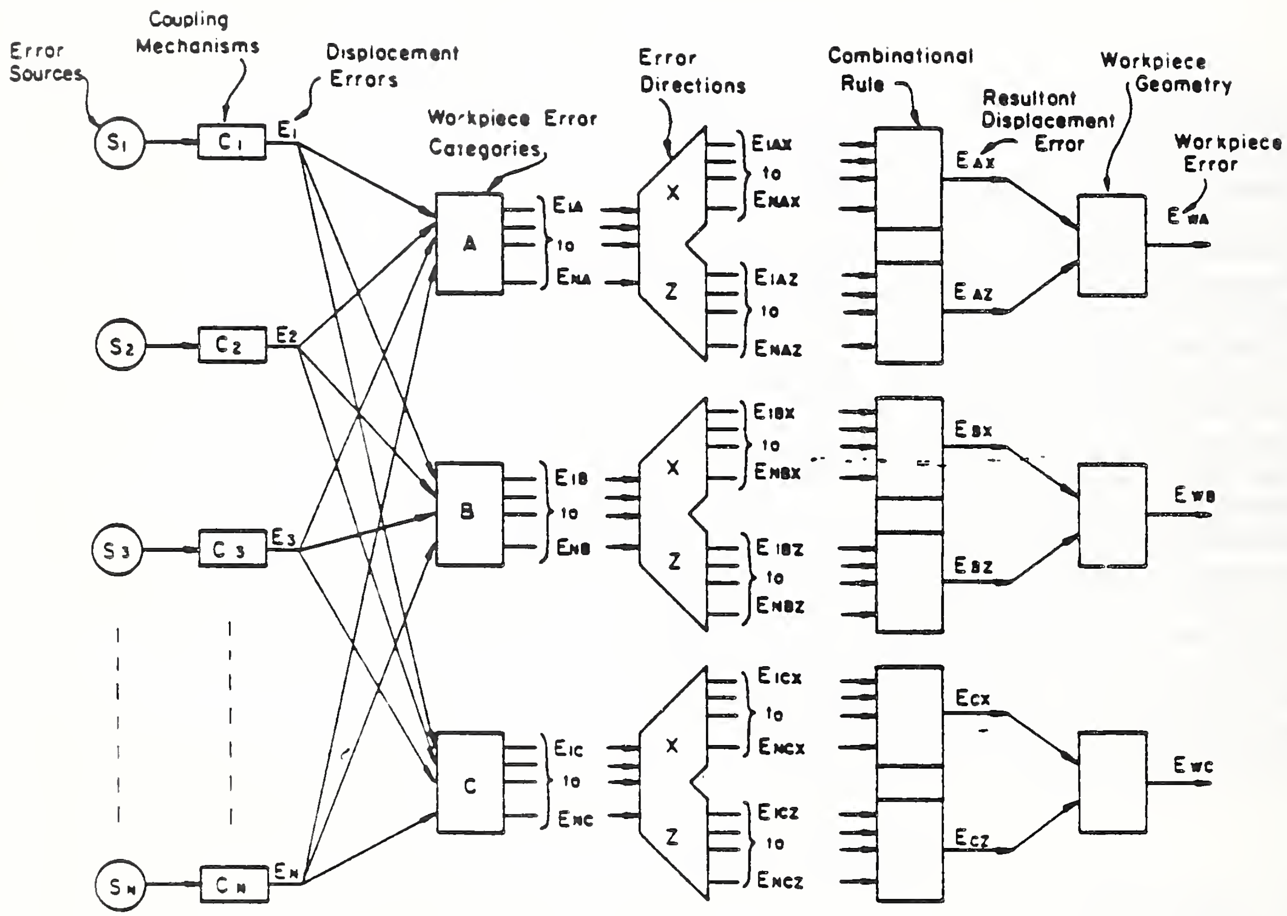

FIG. 9.14-1 Flow chart for generating an error budget for a two-axis lathe.

left to the errors of the workpiece at the right. The following paragraphs will elaborate on the various stages; underlined terms are defined in the sentences in which they first appear.

ERROR SOURCES, COUPLING MECHANISMS AND DISPLACEMENT ERRORS

The displacement errors are the distances between the surfaces of an actual and an ideal (perfect) workpiece. The displacement errors are always measured in the sensitive direction, i.e., normal to the ideal workpiece surface. It is useful to note that even for a general-purpose machine tool intended for many part shapes, the sensitive directions may be restricted--e.g., for a lathe, the X-Z (slide axis) plane containing the spindle centerline is the plane of all sensitive directions during cutting, and hence comparable displacement errors in the Y direction are nonsensitive, being tangent to the workpiece surface.

An error source is the physical cause of a displacement error, and a coupling mechanism is the physical factor that connects the two. Error sources need only be as fundamental as is useful, i.e., surface finish can be degraded by seismic ground motions which can be further explained by study of the earth sciences, but some knowledge of the amplitude and frequency of the seismic motions is sufficient. In this example, reducing the resulting displacement error to an acceptable level depends entirely on the design or selection of adequate vibration isolators for the coupling mechanism. This example also illustrates that the coupling mechanism is in general a transfer function in the dynamic system sense. The transfer function may range from elementary to very complex. For example, slideway positioning error due to Abbe offset (perpendicular distance from the cutting tool to the line of action of the position measuring system) has angular motion of the slideway as the error source and the offset distance as the coupling mechanism, making the transfer function a simple multiplier. At the other extreme, room-temperature variations as an error source have a complicated time-history effect on tool-to-workpiece displacement errors.

There are two difficult points in dealing with the error sources in an error-budget analysis. The first is generating a complete list that does not omit any significant sources. Here the past experience of those compiling the list is the primary factor; there is no known test for completeness. The second area of difficulty is in assessing magnitudes, both for the error source and for the displacement error resulting from the source and the coupling mechanism. Ideally one would prefer to have complete detail on the displacement errors E_i, including their variation within the machine work zone and with time. However, it is unreasonable at the design stage to expect more than a peak-to-valley envelope bound on E_i, together with some approximate knowledge of the frequency of variation (temporal or spatial) within the envelope. Magnitude estimates should be supported by calculations wherever possible; these may range from simple order-of-magnitude estimates (e.g., temperature stability of 0.01°C means a steel bar ($\alpha = 11.5 \times 10^{-6}$ per °C) of 1 m length will change in length by 0.115 µm, to computer-based finite-element calculations of structural deformations under load. Some magnitudes can only be estimated, such as the deformation of the workpiece by the clamping fixtures or the wear of the cutting tool.

It is worth noting that the machine tool designer is usually faced with a problem of divided responsibility in constructing an error budget, unless a complete turnkey facility is being provided for machining specified workpieces. If the user locates the machine in a poorly controlled thermal environment, or if the machine tool is general purpose, and hence to be used with a wide variety of workpiece shapes, materials, fixtures, and cutting tools, the error estimation process becomes more difficult. Nevertheless, it is recommended that all error sources be included that influence the final workpiece accuracy. If desired, the final result can be recomputed with various assumptions regarding those error sources having divided responsibility, to determine the sensitivity of the total error to these assumptions.

WORKPIECE ERROR CATEGORIES

Considering a circular cylinder as a simple but specific example of a workpiece, it is clear that there can be several workpiece error categories, such as:

- Size (diameter, length).
- Form (roundness, straightness, end flatness).
- Surface Finish (side or end, with or across lay).

Since different error sources S_i may produce displacement errors E_i that fall into different workpiece error categories, A, B or C, in Fig. 9.14-1, it is important to choose categories that are meaningful for the intended end use of the workpieces if possible (again raising the problem of divided responsibility). Note that the categories given can be separated according to the spatial frequency of variation along the workpiece surface, with average size error being a "dc" (zero frequency) term, surface finish having the most rapidly varying spatial frequency and form errors being in between. When dealing with error sources having a temporal frequency, it is necessary to determine the spatial frequency that will result on the workpiece surface by use of typical machining parameters. For example, a lathe spindle turning at 1200 rpm (20 rps) with a feedrate of 0.15 mm/rev will yield a feed speed of 3 mm/s. If surface finish is considered to consist of wavelengths shorter than 0.75 mm along the workpiece surface, then the temporal frequency in the surface-finish category will be higher than (3 mm/sec)/(0.75 mm), or 4 Hz; lower frequencies will contribute to form errors. Increasing (or decreasing) the spindle speed or feedrate per revolution will increase (or decrease) the transition frequency of 4 Hz. Since any given source S_i may cause a displacement error E_i in more than one workpiece error category, each possibility should be examined.

ERROR DIRECTIONS

After generation of a list of displacement errors in each category, it is preferable to separate these into error directions along the machine tool axes (X and Z for a lathe, Fig. 9.14-1). In the surface-finish category, this may not be feasible, since many of the sources are vibrational, and it is difficult to predict the direction of vibration in a complex machine tool structure. The recommended method is to estimate a maximum amplitude and assume it to be omnidirectional.

COMBINATORIAL RULE

Given the displacement errors by category and direction, the next question is what combinatorial rule to use in combining them into a single displacement error. If the set of errors had complete detail, direct addition could be used to generate a map of the resultant displacement error as a function of slideway position, time, etc. In the more probable case of no detail except an upper bound for the magnitude of each error, the selection of a combinatorial rule is more difficult. The end use of the workpiece is also a factor in the selection process. In some applications an averaging process occurs, making an rms error amplitude meaningful, while in others, the largest isolated error peak is crucial, regardless of the perfection of the remaining surface. In the first case a statistical treatment is obviously indicated. In the latter extreme, a conservative approach is to sum the individual displacement-error amplitudes arithmetically. However, this approach may be extremely conservative, due to the very low probability of all N errors being at a maximum simultaneously; statistics can also aid in assessing the probability of exceeding some submaximum amplitude.

The rms error amplitude RMS_{tot} for N individual errors of varying rms amplitudes RMS_i, providing the individual errors are uncorrelated, is simply

$$RMS_{tot} = \left[\sum_{i=1}^{N} (RMS_i)^2 \right]^{1/2} \quad . \tag{1}$$

Use of Eq. (1) requires an rms amplitude for each displacement error, whereas the preceding discussion has used a total or peak-to-valley amplitude PV_i (separation of two parallel lines containing the error signal). The two amplitudes are connected by an equation of the form

$$PV_i = K \cdot RMS_i \quad , \tag{2}$$

where K is a numerical factor depending on the probability distribution of the error signal between the bounding lines. The values of K for three distributions—a pure sinusoid, a signal with uniform probability density, and ±2-sigma Gaussian—are 2.83, 3.46 and 4.0 respectively. Unless more detailed information is available, the middle case is recommended (K = 3.46). Individual error traces are typically not Gaussian, although they may show some central tendency, causing the uniform density assumption to be somewhat conservative; in any case the other two values of K differ only by about ±20%. The result is then

$$RMS_{tot} = \frac{1}{2\sqrt{3}} \left[\sum_{i=1}^{N} (PV_i)^2 \right]^{1/2} \quad . \tag{3}$$

Eq. (3) can be applied in Fig. 9.14-1 to error amplitudes E_{1AX} to E_{NAX} to yield E_{AX}, and so on for E_{AZ}, etc.

WORKPIECE ERROR

Given the resultant displacement error by direction for each workpiece error category, the workpiece error of Fig. 9.14-1 can be predicted in each category from knowledge of the workpiece geometry, i.e., the size and shape as shown on an engineering drawing. For workpiece surfaces having a slope angle ϕ with respect to the X axis, the formula for the error normal to the surface in category A is

$$E_{A\phi} = \left[(E_{AX} \cos \phi)^2 + (E_{AZ} \sin \phi)^2\right]^{1/2} \quad , \tag{4}$$

and similarly for other categories. Eq. (4) describes an ellipse with major and minor values of E_{AX} and E_{AZ}. If E_{AX} and E_{AZ} are equal, the ellipse is a circle and the error is omnidirectional. If the error is not omnidirectional and the workpiece contains a continuously varying contour, Eq. (4) can be used to calculate the error at selected points along the contour for the purpose of estimating an average error. For cases where the workpiece geometry is unknown, this section can be omitted.

ERROR BUDGET FOR THE LARGE OPTICS DIAMOND TURNING MACHINE

BACKGROUND

A properly sharpened natural diamond cutting tool will cut in exact accordance with its edge location and can produce a mirror finish on a variety of materials if the machine tool has a sufficiently low vibration level. This has created interest in the use of machine tools to fabricate reflective metal optics. While it offers the possibility of radically aspheric shapes that are not reasonable to produce by conventional optical figuring and polishing methods, it also requires accuracies that are 10-100 times more stringent than those usually expected of precise machine tools. Efforts in this direction have progressed to the point that diameters below 0.5 m can be diamond-turned to figure accuracies of the order of 100 nm (4 μin.) rms and diameters up to 2 m done for accuracies of the order of 250 nm (20 μin.) rms. Interest in accuracies down to 13 nm (0.5 μin.) in sizes up to 1.5 m led to a study for a new machine, known as the Large Optics Diamond Turning Machine. Because the achievement of these goals would require a major effort, development of an error budget was made a part of a preliminary design study. Due to time constraints on subsequent design and construction, improvements in the state of the art were limited to moderate extensions by methods reasonably well-defined at the outset.

An overall view of the above machine is shown in Fig. 9.14-2. The design and the error budget evolved by mutual interaction; space does not permit a full description of the process or of the resulting design. However, Fig. 9.14-2 illustrates several features:

- Use of symmetry, such as a vertical spindle axis (gravity along workpiece centerline) and a bridge design for increased rigidity. Symmetry causes several error sources to be self-cancelling (zero coupling).
- Interferometric tool-path measurement, with interferometer beams contained in evacuated telescoping tubes.
- Metrology frame, a structure kept free of variable loads to serve as a measurement reference datum.

Other features will be noted in discussing the various error-budget entries.

Two workpiece error categories will be presented, surface finish and radial figure error. A wavelength of 0.1 mm (0.004 in.) was chosen as the transition between the two. For a finishing cut feedrate of 4 μm/rev and 100 rpm, the associated time is 15 s. For the optical systems in question, an

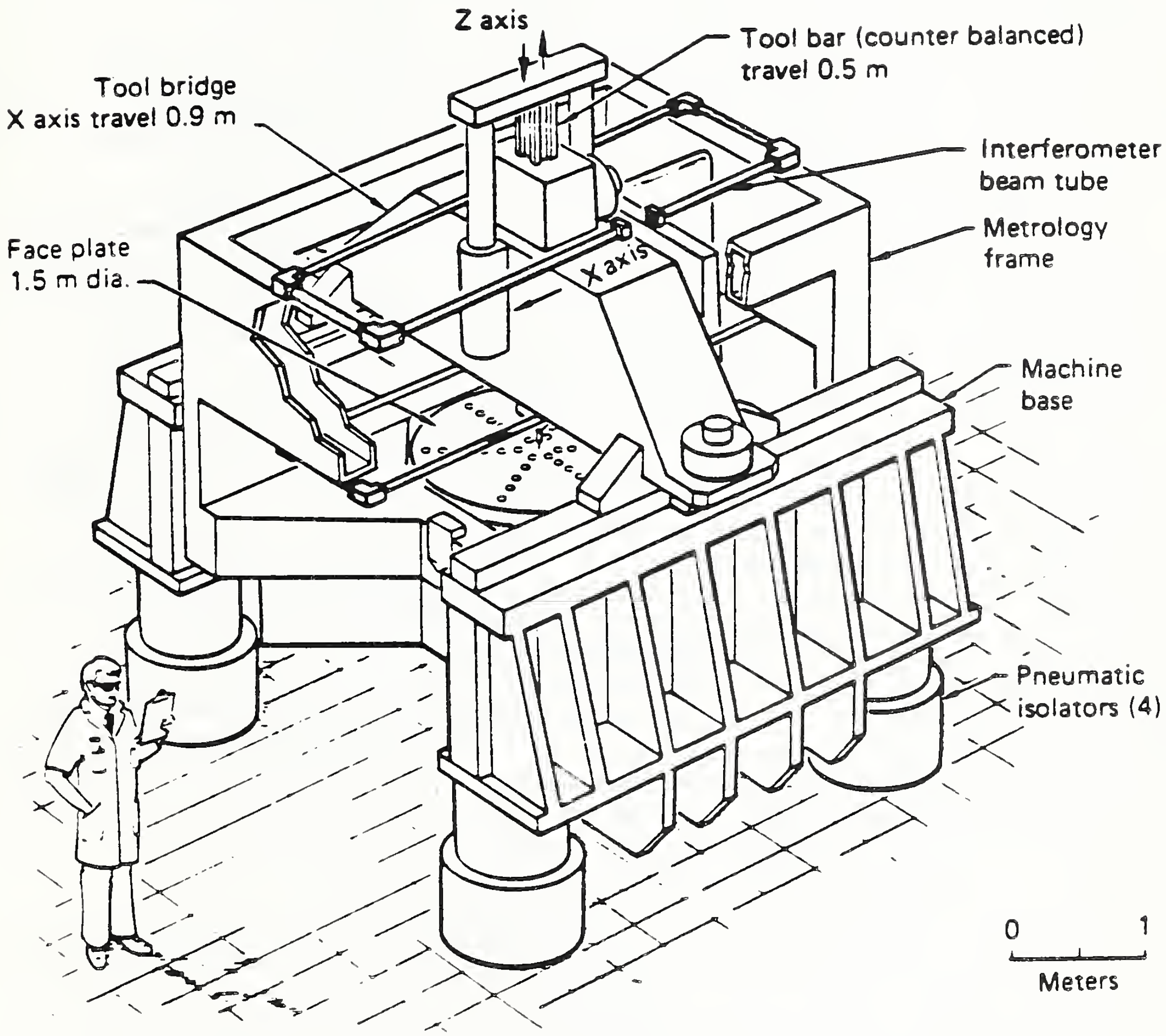

FIG. 9.14-2 Artist's concept of Large Optics Diamond Turning Machine.

rms error amplitude is meaningful and was used in both categories. Displacement errors were estimated as peak-to-valley amplitudes and the uniform probability density assumption leading to Eq. (3) was employed.

SURFACE-FINISH ERROR BUDGET

Surface finish is degraded by a variety of sources, many of which are difficult to quantify. For this reason the entries in Table 9.14-1 are largely derived from experience and are treated as omnidirectional.

The first four error sources in Table 9.14-1 are sources of vibration excitation. External mechanical disturbances come from the fact that the pneumatic isolators transmit some fraction of seismic disturbances and building vibrations to the machine, as do various electric and fluid power lines. Room noise is also an excitation source; a machine room with sound-insulated walls is required. Hydraulic vibration refers to noise created by flow of temperature-controlled liquids through or over the machine to maintain a stable temperature field. The spindle drive entry is similar to the first category, but refers to excitation from the floor-mounted motor being transmitted by a low-influence drive coupling. Imperfect spindle air-pressure regulation will cause the spindle faceplate to rise and fall; the entry shown corresponds to 0.03% change in gage pressure for time periods shorter than 15 s. Theoretical finish is the height of the scallop-shaped cuts caused by the finite advance per revolution of a round-nosed cutting tool and is one of the few entries that can be calculated. In fact, the magnitude was chosen to be equal to the other smaller entries, leading to the feedrate quoted in the earlier calculation of the 15 s transition time (assuming a 0.75-mm (0.30-in.) tool radius). The estimate for imperfections from the tool edge and the cutting mechanics is based on experimental data from the literature. The resolution of the control system becomes significant when approaching tangency to one axis. The servo-controlled tool mount is a low-amplitude, high-bandwidth position servo mounted on the lower end of the tool bar, driven by the position-loop error signals of the main slideways; the entry represents a combination of the tool mount resolution and the accuracy of its position measurement sensors. The last two entries in Table 9.14-1 are associated with the interferometers. The first applies to the distance interferometers, and is a consequence of imperfect beam-splitting of the two-frequency laser beam, causing a cyclic displacement error once per wavelength (633 nm). The last applies to the straightness interferometers, which operate in still air at 1 atm and are subject to any difference in index of refraction caused by pressure or temperature differences between the two equal-length measurement arms; the estimate is based on experimental data.

Performing the root-sum-square operation of Eq. (3), the rms value is found to be 4.2 nm or 42 Å (0.17 μin). This result is somewhat smaller than is typically observed on existing diamond turning machines, especially larger machines, but is larger than the best achievements on smaller machines, which approach 10 Å rms; hence the result is achievable in principle.

The numerical results of Table 9.14-1 can be used to illustrate a feature of rms error amplitude when the individual amplitudes are comparable, that the total increases approximately as $N^{1/2}$ (exactly, if all amplitudes are equal). Adding another entry of average size 4 nm (0.16 μin.) increases the calculated result by about 4% to 44 Å, as does multiplying by $(12/11)^{1/2} = 1.04$. Thus the consequence of overlooking an independent error of a typical magnitude is not serious if N is reasonably large. Another feature of rms

TABLE 9.14-1 Surface-finish error budget.

Error source	Peak-to-Valley amplitude nm (μin.)
1. External mechanical disturbances	5.0 (0.20)
2. Airborne noise	2.5 (0.10)
3. Hydraulic vibration	2.5 (0.10)
4. Spindle drive	2.5 (0.10)
5. Spindle air pressure	2.5 (0.10)
6. Theoretical finish	2.5 (0.10)
7. Tool-edge/cutting mechanics	4.0 (0.16)
8. MCU resolution	5.0 (0.20)
9. Servo-controlled tool mount	10.0 (0.40)
10. Interferometer phase distortion	2.5 (0.10)
11. Index difference-straightness interferometer	3.5 (0.14)
Sum of squares =	215.75 (0.3452)
rms value (Eq. 3) =	4.2 nm (0.17 μin.) or 42 Å rms

errors, the tendency of the larger entries to dominate the results, can also be shown from Table 9.14-1. If entry 9 (10 nm) had been omitted, the result would drop by about 25% to 31 Å; if entry 9 were increased to 20 nm, the new result would become 66 Å, over 50% larger.

RADIAL FIGURE-ERROR BUDGET

Figure error along a radial path is distinguished from azimuthal figure error (along a circular path around the axis), the latter being caused, for example, by errors in the spindle truth of rotation. Figure errors are distinguished from surface-finish errors by spatial wavelengths longer than 0.1 mm (0.004 in.) or temporal frequencies lower than 1/15 Hz.

Table 9.14-2 shows the various sources of radial figure error and the associated amplitudes in the X and Z directions, which will be discussed in turn.

The interferometric measurement of position is fundamentally limited by the stability of the laser frequency. The error magnitude corresponds to a

TABLE 9.14-2 Radial figure error budget.

Error source	Peak-to-valley magnitudes X-direction nm (μin.)	Peak-to-valley magnitudes Z-direction nm (μin.)
Position interferometers		
Laser central frequency	3.0 (0.12)	5.5 (0.22)
Index of refraction	3.0 (0.12)	5.5 (0.22)
Optical, electronic factors	5.0 (0.20)	5.0 (0.20)
Straightness interferometers		
Path length difference	3.7 (0.15)	3.7 (0.15)
Optical flat difference	15.0 (0.60)	15.0 (0.60)
Index difference	3.5 (0.14)	3.5 (0.14)
Resolution–metrology frame drift	—	6.3 (0.25)
Control system		
Servo-controlled tool mount	10.0 (0.40)	10.0 (0.40)
Temperature control		
Metrology structural loop	10.0 (0.40)	7.5 (0.30)
Spindle growth	—	40.0 (1.60)
Workpiece thermal boundary layer	30.4 (1.22)	34.4 (1.38)
Spindle air supply pressure	—	7.5 (0.30)
Gravitational loading	5.0 (0.20)	—
Barometric pressure	4.0 (0.16)	5.0 (0.20)
Nonmachine factors		
Tool nose roundness	13.0 (0.50)	13.0 (0.50)
Workpiece fixture distortion	75.0 (3.00)	60.0 (2.40)
Workpiece body forces	25.0 (1.00)	20.0 (0.80)
Workpiece internal unbalance	25.0 (1.00)	20.0 (0.80)
Workpiece residual stress	25.0 (1.00)	20.0 (0.80)
Sum of squares	9128 (14.60)	8207 (13.13)
rms values (Eq. 1-2)	27.6 nm (1.10 μin.)	26.1 nm (1.05 μin.)

drift of 5 parts in 10^9; this value is well within the state of the art for laboratory lasers using iodine-cell stabilization, but is more stringent than the 3 parts in 10^8 for commercially available heterodyne lasers and hence assumes either further local development or a reduction to commercial practice. The difference in the numerical values for X and Z come from the maximum difference in arm lengths, which is smaller for X even though it has a larger travel, because of the symmetric arrangement of beam paths. The variation of the index of refraction within the beam path, also 5 parts in 10^9, can be achieved by maintaining a vacuum in the beam tubes between 1 and 15 millitorr. The optical and electric factors include items such as beam collimation and spatial filtering, mirror scatter and non-flatness, etc., which tend to produce poorly defined fringes, plus detector noise, amplitude sensitivity and electronic jitter; the amplitudes are estimates.

Figure 9.14-3 shows a schematic diagram of the straightness interferometer for the X axis. As noted earlier, the straightness interferometers operate in a still-air enclosure with arm lengths that are nominally equal; errors can be caused by actual differences in arm length due to inaccurate system setup, or by air currents, etc., that cause index differences between the two arms. Since the beams traverse the two optical flats as the X-position changes, differences in flatness cause errors. This error is very sensitive; the amplitudes given correspond to measurement of the flatness differences to about 4 nm (1/6 μin.), with storage and subsequent recall from a microprocessor memory. The geometry of the arrangement shown in Fig. 9.14-3 is also sensitive to slight rotations of the metrology frame; a scheme for measuring such rotations using the difference of the upper and lower interferometer readings is resolution-limited by the amount shown.

The only long-term control-system error is the residual error of the servo-controlled tool mount, which as noted earlier is driven by the error signals of the main axis drives. The error magnitudes shown are based on resolution and linearity error of the tool mount displacement sensors.

The metrology structural loop will be temperature stabilized by a large flow of water within an enclosing shroud (not shown in Fig. 9.14-2); the magnitudes shown are calculated from an ability to measure and control the incoming water temperature to 1.1×10^{-3}°C (2×10^{-3}°F) and a possible temperature gain or loss of half this amount from inlet to outlet. These two error sources may be correlated and hence are assumed to be additive rather than independent. The estimated value for spindle growth, due to heat generated during operation, is based on extensive computer calculations of an internal forced-air cooling system. The workpiece thermal boundary layer arises from the fact that most of the energy expended in rotating the workpiece in the sea of air around the machine is dissipated in a thin layer at the workpiece surface, which becomes significant for the case shown of a 1.5-m diameter rotating at 100 rpm.

The source of error associated with the spindle air supply is the same as in the preceding section except that the present estimate is for long-term drift. Gravitational loading is due to small tilt errors in the self-leveling system of the pneumatic isolators, causing a distortion of the metrology frame in the X direction. Barometric pressure effects arise because of the evacuated beam tubes; the tube area times the extremes of atmospheric pressure amount to force variations of a few pounds on the metrology structure. Both this and the gravitational load displacement were calculated from finite-element models of the proposed design.

The final category of nonmachine errors represents the area of divided responsibility for this example. One is the out-of-roundness of the diamond-tool nose; the error amplitude represents an accuracy of measuring the

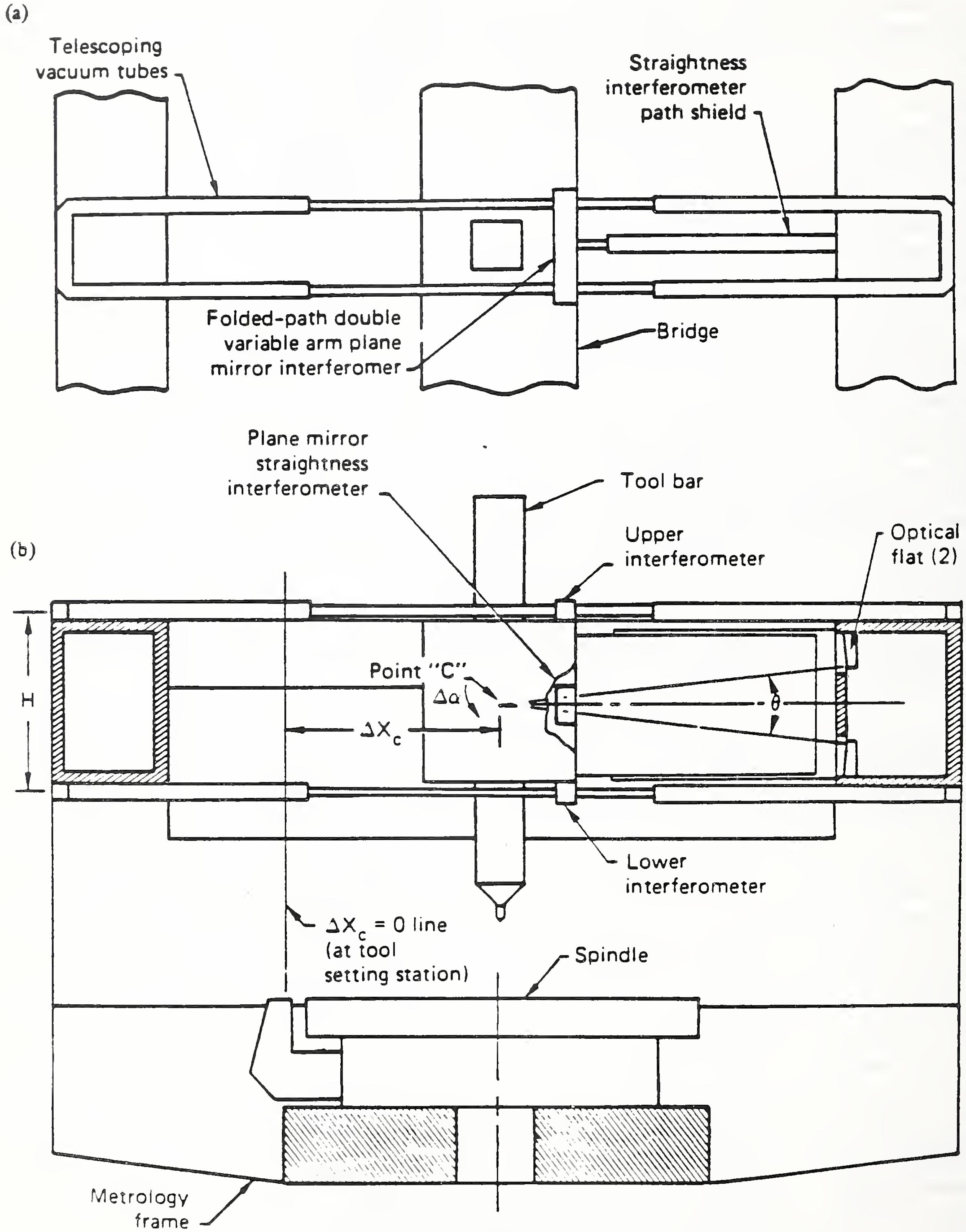

FIG. 9.14-3 X-axis measuring system, (a) plan view and (b) side view.

tool nonroundness and programming the tool path to compensate. The remaining errors arise from fixturing distortion and other forces associated with rotating and cutting an unknown workpiece. While the estimates for the workpiece factors are the largest in the error budget, they are also considerably smaller than is presently achieved in diamond turning practice.

Applying Eq. (3) to the X and Z error magnitudes yields the values shown of about 27 nm (1.1 μin.) for both axes. Since the two values are nearly equal, the resultant error is omnidirectional despite the variations of the individual axis components.

It can be noted that the most stringent goal of 13 nm (0.5 μin.) rms was not achieved. The dominant factors in the error budget are the final group of non-machine factors; the goal could be reached in the X direction if all factors in the group were reduced to about 10 nm (0.4 μin). However, the goal could not be reached in the Z direction even if all of the nonmachine factors were zero; further reduction in the spindle growth and the workpiece thermal boundary layer (e.g., by operating at very low spindle rpm) would be necessary.

As a final observation, it should be noted that several error sources were excluded from Table 9.14-2, as shown in Table 9.14-3. The first two are axis-alignment errors that are angles rather than displacements and hence dependent on the radial width of the workpiece surface of interest. The second two can be shown to cause a curvature error. For optical components these errors were judged worthy of special treatment; in a more general case they would be included in Table 9.14-2.

TABLE 9.14-3 Special figure errors.

Error source	Peak-to-valley amplitude
X-axis squareness to spindle	0.1 μrad
Z-axis parallelism to spindle	0.1 μrad
Tool setting-X direction	50 nm (2 μin.)
Tool nose radius size	13 nm (0.5 μin.)

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

An error budget for machine tool accuracy subdivides the overall problem into a number of smaller steps, thereby providing a more systematic approach as well as a greater degree of scrutiny of the various details.

The example cited in this paper is clearly esoteric; a valuable step would be the development of a checklist of error sources for more common levels of accuracy.

Implicit in the discussion of errors is an assumed ability to measure them; hence a given firm interested in designing to increased accuracy may have to begin by improving their capability in machine tool metrology.

The development presented herein assumes an rms combinational rule as suitable. This work could be extended toward applications concerned with the worst peak-to-valley error by presenting a method for calculating the probability of reaching increasingly larger fractions of the maximum amplitude.

Another possible extension of the error-budget concept is to aid in the writing of specifications between buyer and seller for the acquisition of machine tools. A typical position taken by the buyer is to require that the seller provide a machine tool capable of producing one or more workpieces within the tolerances of the workpiece drawing, placing the full burden of Fig. 9.14-1 on the seller. The seller is more inclined to agree to a performance specification that sets limits on errors by category and direction, nearer the center of Fig. 9.14-1 (positioning accuracy, straightness, squareness, etc.). Through an understanding of what accuracy is required for his particular class of workpieces, and application of the error-budget approach to the seller's performance specifications, it should be possible for the buyer to connect the two views quantitatively. This approach should also allow a rational comparison between the performance specifications of competing sellers.

It should be emphasized that significant reductions in the requirements for machine tool accuracy can arise from examining the geometry of the class of workpieces to be machined. For example, in machining optical components (such as parabolic mirrors), two factors are significant. First, the sensitivity to errors in the radial (X) direction is proportional to the "speed" of the optic, and is an order of magnitude smaller than the axial (Z) sensitivity at the outer edge of a moderately fast f/2.5 optic. Secondly, a number of sources lead to Z errors that vary linearly with X (spindle squareness to X, Z lead error in positioning, radial toolsetting error (to first order), the linear portion of axial spindle growth with time (if constant rpm and feedrate are used)). For optical components, the effect of linear error terms can be significantly reduced by selecting another best-fit curvature and making a small compensating adjustment in the axial mounting position. Since the commercialization of machined optics in the infrared region is underway, a study which quantifies these reduced error sensitivities for optical workpieces would be valuable.

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NISTIR 89-4171	2. Performing Organ. Report No.	3. Publication Date NOVEMBER 1989

4. TITLE AND SUBTITLE

Accuracy Analysis of the Space Shuttle Solid Rocket Motor Profile Measuring Device

5. AUTHOR(S)

W. Tyler Estler

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, AL 35812

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The Profile Measuring Device (PMD) was developed at the George C. Marshall Space Flight Center following the loss of the Space Shuttle Challenger. It is a rotating gauge used to measure the absolute diameters of mating features of redesigned Solid Rocket Motor (SRM) field joints. Diameter tolerances of these features are typically ±0.005 inches and it is required that the PMD absolute measurement uncertainty be within this tolerance. In this analysis we find the absolute accuracy of these measurements to be ±0.00375 inches, worst case, with a potential accuracy of ±0.0021 inches achievable by improved temperature control.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

dimensional metrology, error budget, roundness, Space Shuttle

13. AVAILABILITY

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14. NO. OF PRINTED PAGES

78

15. Price

A05