

Measurement Systems Analysis

MSA
Fourth Edition



MEASUREMENT SYSTEMS ANALYSIS

Reference Manual **Fourth Edition**

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FOREWORD

This Reference Manual was developed by a Measurement Systems Analysis (MSA) Work Group, sanctioned by the Chrysler Group LLC, Ford Motor Company, and General Motors Corporation Supplier Quality Requirements Task Force, and under the auspices of the Automotive Industry Action Group (AIAG). The Work Group responsible for this Fourth Edition were Michael Down (General Motors Corporation), Frederick Czubak (Chrysler Group LLC), Gregory Gruska (Omnex), Steve Stahley (Cummins, Inc.) and David Benham.

The manual is an introduction to measurement system analysis. *It is not intended to limit evolution of analysis methods suited to particular processes or commodities.* While these guidelines are intended to cover normally occurring measurement system situations, there will be questions that arise. These questions should be directed to your authorized customer representative.

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June 2010

MSA 4th Edition Quick Guide

Type of Measurement System	MSA Methods	Chapter
Basic Variable	Range, Average & Range, ANOVA, Bias, Linearity, Control Charts	III
Basic Attribute	Signal Detection, Hypothesis Test Analyses	III
Non-Replicable (e.g., Destructive Tests)	Alternate Approaches	IV
Complex Variable	Range, Average & Range, ANOVA, Bias Linearity Control Charts	III, IV
Multiple Systems, Gages or Test Stands	Control Charts ANOVA Regression Analysis	III, IV
Miscellaneous	Alternate Approaches	IV
Other	White Papers – available at AIAG website (www.aiag.org)	

NOTE: Regarding the use of the *GRR* standard deviation

Historically, by convention, a 99% spread has been used to represent the “full” spread of measurement error, represented by a 5.15 multiplying factor (where σ_{GRR} is multiplied by 5.15 to represent a total spread of 99%).

A 99.73% spread is represented by a multiplier of 6.0, which is $\pm 3\sigma$ and represents the full spread of a “normal” curve.

If the reader chooses to increase the coverage level, or spread, of the total measurement variation to 99.73%, use 6.0 as a multiplier in place of 5.15 in the calculations.

Note: *The approach used in the 4th Edition is to compare standard deviations. This is equivalent to using the multiplier of 6 in the historical approach.*

Awareness of which multiplying factor is used is crucial to the integrity of the equations and resultant calculations. This is especially important if a comparison is to be made between measurement system variability and the tolerance. Consequently, if an approach other than that described in this manual is used, a statement of such must be stated clearly in any results or summaries (particularly those provided to the customer).

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CHAPTER I

General Measurement System Guidelines

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Chapter I – Section A
Introduction, Purpose and Terminology

Section A

Introduction, Purpose and Terminology

Introduction

Measurement data are used more often and in more ways than ever before. For instance, the decision to adjust a manufacturing process is now commonly based on measurement data. The data, or some statistic calculated from them, are compared with statistical control limits for the process, and if the comparison indicates that the process is out of statistical control, then an adjustment of some kind is made. Otherwise, the process is allowed to run without adjustment. Another use of measurement data is to determine if a significant relationship exists between two or more variables. For example, it may be suspected that a critical dimension on a molded plastic part is related to the temperature of the feed material. That possible relationship could be studied by using a statistical procedure called regression analysis to compare measurements of the critical dimension with measurements of the temperature of the feed material.

Studies that explore such relationships are examples of what Dr. W. E. Deming called *analytic studies*. In general, an analytic study is one that increases knowledge about the system of causes that affect the process. Analytic studies are among the most important uses of measurement data because they lead ultimately to better understanding of processes.

The benefit of using a data-based procedure is largely determined by the quality of the measurement data used. If the data quality is low, the benefit of the procedure is likely to be low. Similarly, if the quality of the data is high, the benefit is likely to be high also.

To ensure that the benefit derived from using measurement data is great enough to warrant the cost of obtaining it, attention needs to be focused on the quality of the data.

Quality of Measurement Data

The quality of measurement data is defined by the statistical properties of multiple measurements obtained from a measurement system operating under stable conditions. For instance, suppose that a measurement system, operating under stable conditions, is used to obtain several measurements of a certain characteristic. If the measurements are all “close” to the master value for the characteristic, then the quality of the data is said to be “high”. Similarly, if some, or all, of the measurements are “far away” from the master value, then the quality of the data is said to be “low”.

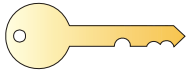
The statistical properties most commonly used to characterize the quality of data are the *bias* and *variance* of the measurement system. The property called bias refers to the location of the data relative to a reference (master) value, and the property called variance refers to the spread of the data.

One of the most common reasons for low-quality data is too much variation. Much of the variation in a set of measurements may be due to the *interaction* between the measurement system and its environment. For instance, a

measurement system used to measure the volume of liquid in a tank may be sensitive to the ambient temperature of the environment in which it is used. In that case, variation in the data may be due either to changes in the volume or to changes in the ambient temperature. That makes interpreting the data more difficult and the measurement system, therefore, less desirable.

If the interaction generates too much variation, then the quality of the data may be so low that the data are not useful. For example, a measurement system with a large amount of variation may not be appropriate for use in analyzing a manufacturing process because the measurement system's variation may mask the variation in the manufacturing process. Much of the work of managing a measurement system is directed at monitoring and controlling variation. Among other things, this means that emphasis needs to be placed on learning how the measurement system interacts with its environment so that only data of acceptable quality are generated.

Purpose



The purpose of this document is to present guidelines for assessing the quality of a measurement system. Although the guidelines are general enough to be used for any measurement system, they are intended primarily for the measurement systems used in the industrial world. This document is not intended to be a compendium of analyses for all measurement systems. Its primary focus is measurement systems where the readings can be replicated on each part. Many of the analyses are useful with other types of measurement systems and the manual does contain references and suggestions. It is recommended that competent statistical resources be consulted for more complex or unusual situations not discussed here. Customer approval is required for measurement systems analysis methods not covered in this manual.

Terminology

The discussion of the analysis of measurement system can become confusing and misleading without an established set of terms to refer to the common statistical properties and related elements of the measurement system. This section provides a summary of such terms which are used in this manual.

In this document, the following terms are used:

- **Measurement** is defined as “the assignment of numbers [or values] to material things to represent the relations among them with respect to particular properties.” This definition was first given by C. Eisenhart (1963). The process of assigning the numbers is defined as the measurement process, and the value assigned is defined as the measurement value.

- **Gage** is any device used to obtain measurements; frequently used to refer specifically to the devices used on the shop floor; includes go/no-go devices (also, see Reference List: ASTM E456-96).
- **Measurement System** is the collection of instruments or gages, standards, operations, methods, fixtures, software, personnel, environment and assumptions used to quantify a unit of measure or fix assessment to the feature characteristic being measured; the complete process used to obtain measurements.

From these definitions it follows that a measurement process may be viewed as a manufacturing process that produces numbers (data) for its output. Viewing a measurement system this way is useful because it allows us to bring to bear all the concepts, philosophy, and tools that have already demonstrated their usefulness in the area of statistical process control.

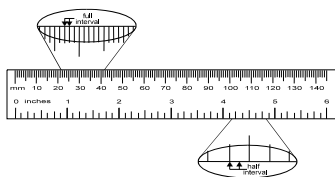
Summary of Terms.¹

Standard

- Accepted basis for comparison
- Criteria for acceptance
- Known value, within stated limits of uncertainty, accepted as a true value
- Reference value

A standard should be an operational definition: a definition which will yield the same results when applied by the supplier or customer, with the same meaning yesterday, today, and tomorrow.

Basic equipment



- **Discrimination, readability, resolution**
 - ✓ Alias: smallest readable unit, measurement resolution, scale limit, or detection limit
 - ✓ An inherent property fixed by design
 - ✓ Smallest scale unit of measure or output for an instrument
 - ✓ Always reported as a unit of measure
 - ✓ 10 to 1 rule of thumb
- **Effective resolution**
 - ✓ The sensitivity of a measurement system to process variation for a particular application

¹ See Chapter I, Section E for terminology definitions and discussion.

- ✓ Smallest input that results in a usable output signal of measurement
- ✓ Always reported as a unit of measure

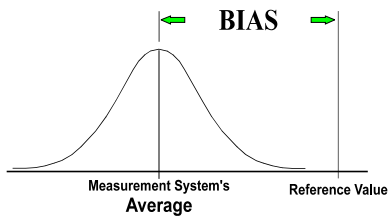
- **Reference value**

- ✓ Accepted value of an artifact
- ✓ Requires an operational definition
- ✓ Used as the surrogate for the true value

- **True value**

- ✓ Actual value of an artifact
- ✓ Unknown and unknowable

Location variation

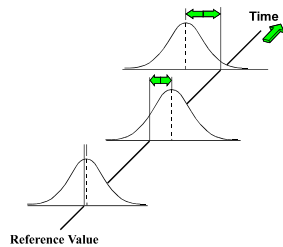


- **Accuracy**

- ✓ “Closeness” to the true value, or to an accepted reference value
- ✓ ASTM includes the effect of location and width errors

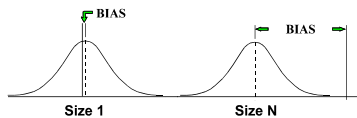
- **Bias**

- ✓ Difference between the observed average of measurements and the reference value
- ✓ A systematic error component of the measurement system



- **Stability**

- ✓ The change in bias over time
- ✓ A stable measurement process is in statistical control with respect to location
- ✓ Alias: Drift

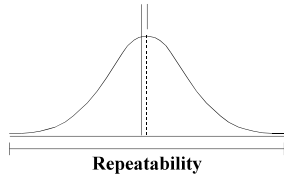


- **Linearity**

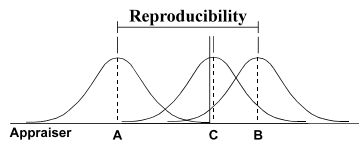
- ✓ The change in bias over the normal operating range
- ✓ The correlation of multiple and independent bias errors over the operating range
- ✓ A systematic error component of the measurement system

Width variation

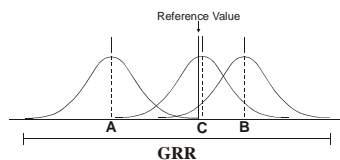
- **Precision²**
 - ✓ “Closeness” of repeated readings to each other
 - ✓ A random error component of the measurement system



- **Repeatability**
 - ✓ Variation in measurements obtained with one measuring instrument when used several times by an appraiser while measuring the identical characteristic on the same part
 - ✓ The variation in successive (short-term) trials under fixed and defined conditions of measurement
 - ✓ Commonly referred to as E.V. – Equipment Variation
 - ✓ Instrument (gage) capability or potential
 - ✓ Within-system variation



- **Reproducibility**
 - ✓ Variation in the average of the measurements made by different appraisers using the same gage when measuring a characteristic on one part
 - ✓ For product and process qualification, error may be appraiser, environment (time), or method
 - ✓ Commonly referred to as A.V. – Appraiser Variation
 - ✓ Between-system (conditions) variation
 - ✓ ASTM E456-96 includes repeatability, laboratory, and environmental effects as well as appraiser effects



- **GRR or Gage R&R**
 - ✓ Gage repeatability and reproducibility: the combined estimate of measurement system repeatability and reproducibility
 - ✓ Measurement system capability; depending on the method used, may or may not include the effects of time
- **Measurement System Capability**
 - ✓ Short-term estimate of measurement system variation (e.g., “GRR” including graphics)

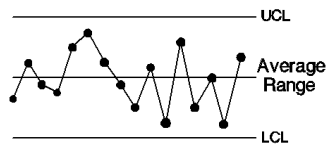
² In ASTM documents, there is no such thing as *the* precision of a measurement system; i.e., *the* precision cannot be represented by a single number.

- **Measurement System Performance**

- ✓ Long-term estimate of measurement system variation (e.g., long-term Control Chart Method)

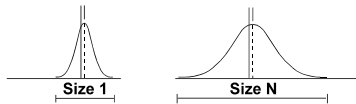
- **Sensitivity**

- ✓ Smallest input that results in a detectable output signal
- ✓ Responsiveness of the measurement system to changes in measured feature
- ✓ Determined by gage design (discrimination), inherent quality (Original Equipment Manufacturer), in-service maintenance, and operating condition of the instrument and standard
- ✓ Always reported as a unit of measure



- **Consistency**

- ✓ The degree of change of repeatability over time
- ✓ A consistent measurement process is in statistical control with respect to width (variability)



- **Uniformity**

- ✓ The change in repeatability over the normal operating range
- ✓ Homogeneity of repeatability

System variation

Measurement system variation can be characterized as:

- **Capability**

- ✓ Variability in readings taken over a short period of time

- **Performance**

- ✓ Variability in readings taken over a long period of time
- ✓ Based on total variation

- **Uncertainty**

- ✓ An estimated range of values about the measured value in which the true value is believed to be contained

The measurement system must be stable and consistent.

All characterizations of the total variation of the measurement system assume that the system is stable and consistent. For example, the components of variation can include any combination of the items shown in I-B 1.

Standards and Traceability

The National Institute of Standards and Technology (NIST) is the principal National Measurements Institute (NMI) in the United States serving under the U.S. Department of Commerce. NIST, formerly the National Bureau of Standards (NBS), serves as the highest level authority for metrology in the U.S. NIST's primary responsibility is to provide measurement services and maintain measurement standards that assist U.S. industry in making traceable measurements which ultimately assist in trade of products and services. NIST provides these services directly to many types of industries, but primarily to those industries that require the highest level of accuracy for their products and that incorporate state-of-the-art measurements in their processes.

National Measurement Institutes

Most of the industrialized countries throughout the world maintain their own NMIs and similar to NIST, they also provide a high level of metrology standards or measurement services for their respective countries. NIST works collaboratively with these other NMIs to assure measurements made in one country do not differ from those made in another. This is accomplished through Mutual Recognition Arrangements (MRAs) and by performing *interlaboratory comparisons* between the NMIs. One thing to note is that the capabilities of these NMIs will vary from country to country and not all types of measurements are compared on a regular basis, so differences can exist. This is why it is important to understand to whom measurements are traceable and how traceable they are.

Traceability

Traceability is an important concept in the trade of goods and services. Measurements that are traceable to the same or similar standards will agree more closely than those that are not traceable. This helps reduce the need for re-test, rejection of good product, and acceptance of bad product.

Traceability is defined by the *ISO International Vocabulary of Basic and General Terms in Metrology* (VIM) as:

“The property of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.”

The traceability of a measurement will typically be established through a chain of comparisons back to the NMI. However, in many instances in industry, the traceability of a measurement may be linked back to an agreed upon reference value or “consensus standard” between a customer and a supplier. The traceability linkage of these consensus standards to the NMI may not always be clearly understood, so ultimately it is critical that the measurements are traceable to the extent that satisfies customer needs. With the advancement in measurement technologies and the usage of state-of-the-art measurement systems in industry, the definition as to where and how a measurement is traceable is an ever-evolving concept.

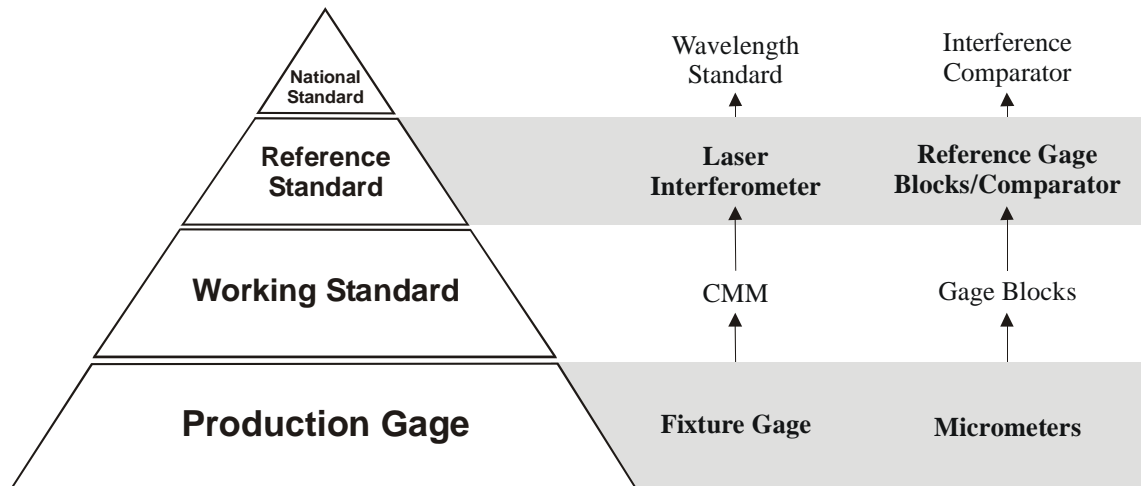


Figure I-A 1: Example of a Traceability Chain for a Length Measurement

NMIs work closely with various national labs, gage suppliers, state-of-the-art manufacturing companies, etc. to assure that their reference standards are properly calibrated and directly traceable to the standards maintained by the NMI. These government and private industry organizations will then use their standards to provide calibration and measurement services to their customers' metrology or gage laboratories, calibrating *working* or other *primary* standards. This linkage or chain of events ultimately finds its way onto the factory floor and then provides the basis for measurement traceability. Measurements that can be connected back to NIST through this unbroken chain of measurements are said to be *traceable to NIST*.

Not all organizations have metrology or gage laboratories within their facilities therefore depend on outside commercial/independent laboratories to provide traceability calibration and measurement services. This is an acceptable and appropriate means of attaining traceability to NIST, provided that the capability of the commercial/independent laboratory can be assured through processes such as laboratory accreditation.

Calibration Systems

A calibration system is a set of operations that establish, under specified conditions, the relationship between a measuring device and a traceable standard of known reference value and uncertainty. Calibration may also include steps to detect, correlate, report, or eliminate by adjustment any discrepancy in accuracy of the measuring device being compared.

The calibration system determines measurement traceability to the measurement systems through the use of calibration methods and standards.

Traceability is the chain of calibration events originating with the calibration standards of appropriate metrological capability or measurement uncertainty. Each calibration event includes all of the elements necessary including standards, measurement and test equipment being verified, calibration methods and procedures, records, and qualified personnel.

An organization may have an internal calibration laboratory or organization which controls and maintains the elements of the calibration events. These internal laboratories will maintain a laboratory scope which lists the specific calibrations they are capable of performing as well as the equipment and methods/procedures used to perform the calibrations.

The calibration system is part of an organization's quality management system and therefore should be included in any internal audit requirements.

Measurement Assurance Programs (MAPs) can be used to verify the acceptability of the measurement processes used throughout the calibration system. Generally MAPs will include verification of a measurement system's results through a secondary independent measurement of the same feature or parameter. Independent measurements imply that the traceability of the secondary measurement process is derived from a separate chain of calibration events from those used for the initial measurement. MAPs may also include the use of statistical process control (SPC) to track the long-term stability of a measurement process.

Note: ANSI/NCSL Z540.3 and ISO 10012 each provide models for many of the elements of a calibration system.

When the calibration event is performed by an external, commercial, or independent calibration service supplier, the service supplier's calibration system can (or may) be verified through accreditation to ISO/IEC 17025. When a qualified laboratory is not available for a given piece of equipment, calibration services may be performed by the equipment manufacturer.

True Value

The measurement process TARGET is the "true" value of the part. It is desired that any individual reading be as close to this value as (economically) possible. Unfortunately, the *true value* can never be known with certainty. However, uncertainty can be minimized by using a *reference value* based on a well defined operational definition of the characteristic, and using the results of a measurement system that has higher order discrimination and traceable to NIST. Because the reference value is used as a surrogate for the true value, these terms are commonly used interchangeably. This usage is not recommended.

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Chapter I – Section A
Introduction, Purpose and Terminology

Section B The Measurement Process³

Measurement Systems

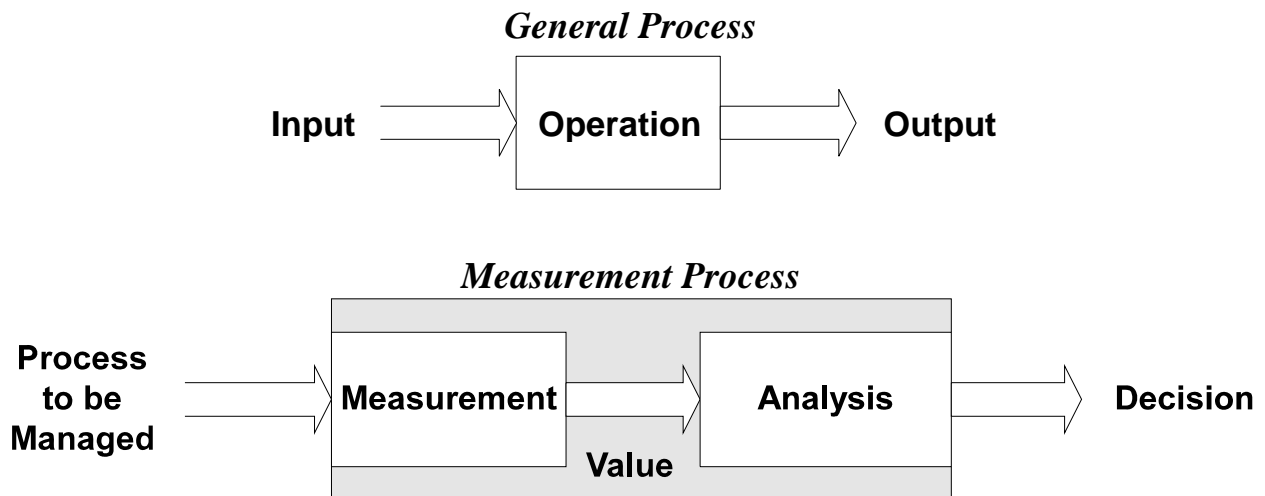
In order to effectively manage variation of any process, there needs to be knowledge of:

- What the process should be doing
- What can go wrong
- What the process is doing

Specifications and engineering requirements define what the process should be doing.

The purpose of a Process Failure Mode Effects Analysis⁴ (PFMEA) is to define the risk associated with potential process failures and to propose corrective action before these failures can occur. The outcome of the PFMEA is transferred to the control plan.

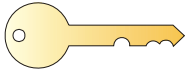
Knowledge is gained of what the process is doing by evaluating the parameters or results of the process. This activity, often called inspection, is the act of examining process parameters, in-process parts, assembled subsystems, or complete end products with the aid of suitable standards and measuring devices which enable the observer to confirm or deny the premise that the process is operating in a stable manner with acceptable variation to a customer designated target. But this examination activity is itself a process.



Unfortunately, industry has traditionally viewed the measurement and analysis activity as a “black box”. Equipment was the major focus – the more “important” the characteristic, the more expensive the gage. The

³ Portions of this chapter adapted with permission from *Measurement Systems Analysis - A Tutorial* by G. F. Gruska and M. S. Heaphy, The Third Generation, 1987, 1998.

⁴ See the *Potential Failure Mode and Effects Analysis (FMEA) Reference Manual – 4th Edition*.



usefulness of the instrument, its compatibility with the process and environment, and its usability was rarely questioned. Consequently these gages were often not used properly or simply not used.

The measurement and analysis activity is a process – a *measurement* process. Any and all of the management, statistical, and logical techniques of process control can be applied to it.

This means that the customers and their needs must first be identified. The customer, the owner of the process, wants to make a correct decision with minimum effort. Management must provide the resources to purchase equipment which is necessary and sufficient to do this. But purchasing the best or the latest measurement technology will not necessarily guarantee correct production process control decisions.

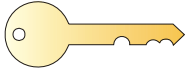
Equipment is only one part of the measurement process. The owner of the process must know how to correctly use this equipment and how to analyze and interpret the results. Management must therefore also provide clear operational definitions and standards as well as training and support. The owner of the process has, in turn, the obligation to monitor and control the measurement process to assure stable and correct results which includes a total measurement systems analysis perspective – the study of the gage, procedure, user, and environment; i.e., normal operating conditions.

Statistical Properties of Measurement Systems

An ideal measurement system would produce only “correct” measurements each time it is used. Each measurement would always agree with a standard.⁵ A measurement system that could produce measurements like that would be said to have the statistical properties of zero variance, zero bias, and zero probability of misclassifying any product it measured. Unfortunately, measurement systems with such desirable statistical properties seldom exist, and so process managers are typically forced to use measurement systems that have less desirable statistical properties. The quality of a measurement system is usually determined solely by the statistical properties of the data it produces over time. Other properties, such as cost, ease of use, etc., are also important in that they contribute to the overall desirability of a measurement system. But it is the *statistical properties* of the data produced that determine the quality of the measurement system.

Statistical properties that are most important for one use are not necessarily the most important properties for another use. For instance, for some uses of a coordinate measuring machine (CMM), the most important statistical properties are “small” bias and variance. A CMM with those properties will generate measurements that are “close” to the certified values of standards that are traceable. Data obtained from such a machine can be very useful for analyzing a manufacturing process. But, no matter how “small” the bias and variance of the CMM may be, the measurement system which uses the CMM may be unable to do an acceptable job of discriminating between good and bad product because of the additional sources of variation introduced by the other elements of the measurement system.

⁵ For a fuller discussion on the matter of standards see *Out of the Crisis*, W. Edwards Deming, 1982, 1986, p. 279-281.



Management has the responsibility for identifying the statistical properties that are the most important for the ultimate use of the data. Management is also responsible for ensuring that those properties are used as the basis for selecting a measurement system. To accomplish this, operational definitions of the statistical properties, as well as acceptable methods of measuring them, are required. Although each measurement system may be required to have different statistical properties, **there are certain fundamental properties that define a “good” measurement system. These include:**

- 1) Adequate discrimination and sensitivity. The increments of measure should be small relative to the process variation or specification limits for the purpose of measurement. The commonly known Rule of Tens, or 10-to-1 Rule, states that instrument discrimination should divide the tolerance (or process variation) into ten parts or more. This rule of thumb was intended as a practical minimum starting point for gage selection.
- 2) The measurement system ought to be in statistical control. This means that under repeatable conditions, the variation in the measurement system is due to common causes only and not due to special causes. This can be referred to as statistical stability and is best evaluated by graphical methods.
- 3) For product control, variability of the measurement system must be small compared to the specification limits. Assess the measurement system to the feature tolerance.
- 4) For process control, the variability of the measurement system ought to demonstrate effective resolution and be small compared to manufacturing process variation. Assess the measurement system to the 6-sigma process variation and/or Total Variation from the MSA study.

The statistical properties of the measurement system may change as the items being measured vary. If so, then the largest (worst) variation of the measurement system is small relative to the smaller of either the process variation or the specification limits.

Sources of Variation

Similar to all processes, the measurement system is impacted by both random and systematic sources of variation. These sources of variation are due to common and special causes. In order to control the measurement system variation:

- 1) Identify the potential sources of variation.
- 2) Eliminate (whenever possible) or monitor these sources of variation.

Although the specific causes will depend on the situation, some typical sources of variation can be identified. There are various methods of

⁶ The measurement analyst must always consider practical and statistical significance.

presenting and categorizing these sources of variation such as cause-effect diagrams, fault tree diagrams, etc., but the guidelines presented here will focus on the major elements of a measuring system.

S	Standard
W	Workpiece (i.e., part)
I	Instrument
P	Person / Procedure
E	Environment

The acronym S.W.I.P.E.⁷ is used to represent the six essential elements of a generalized measuring system to assure attainment of required objectives. S.W.I.P.E. stands for Standard, Workpiece, Instrument, Person and Procedure, and Environment. This may be thought of as an error model for a complete measurement system.⁸

Factors affecting those six areas need to be understood so they can be controlled or eliminated.

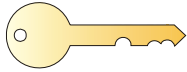


Figure I-B 1 displays a cause and effect diagram showing some of the potential sources of variation. Since the actual sources of variation affecting a specific measurement system will be unique to that system, **this figure is presented as a thought starter for developing a measurement system's sources of variation.**

⁷ This acronym was originally developed by Ms. Mary Hoskins, a metrologist associated with Honeywell, Eli Whitney Metrology Lab and the Bendix Corporation.

⁸ See Appendix F for an alternate error model, P.I.S.M.O.E.A.

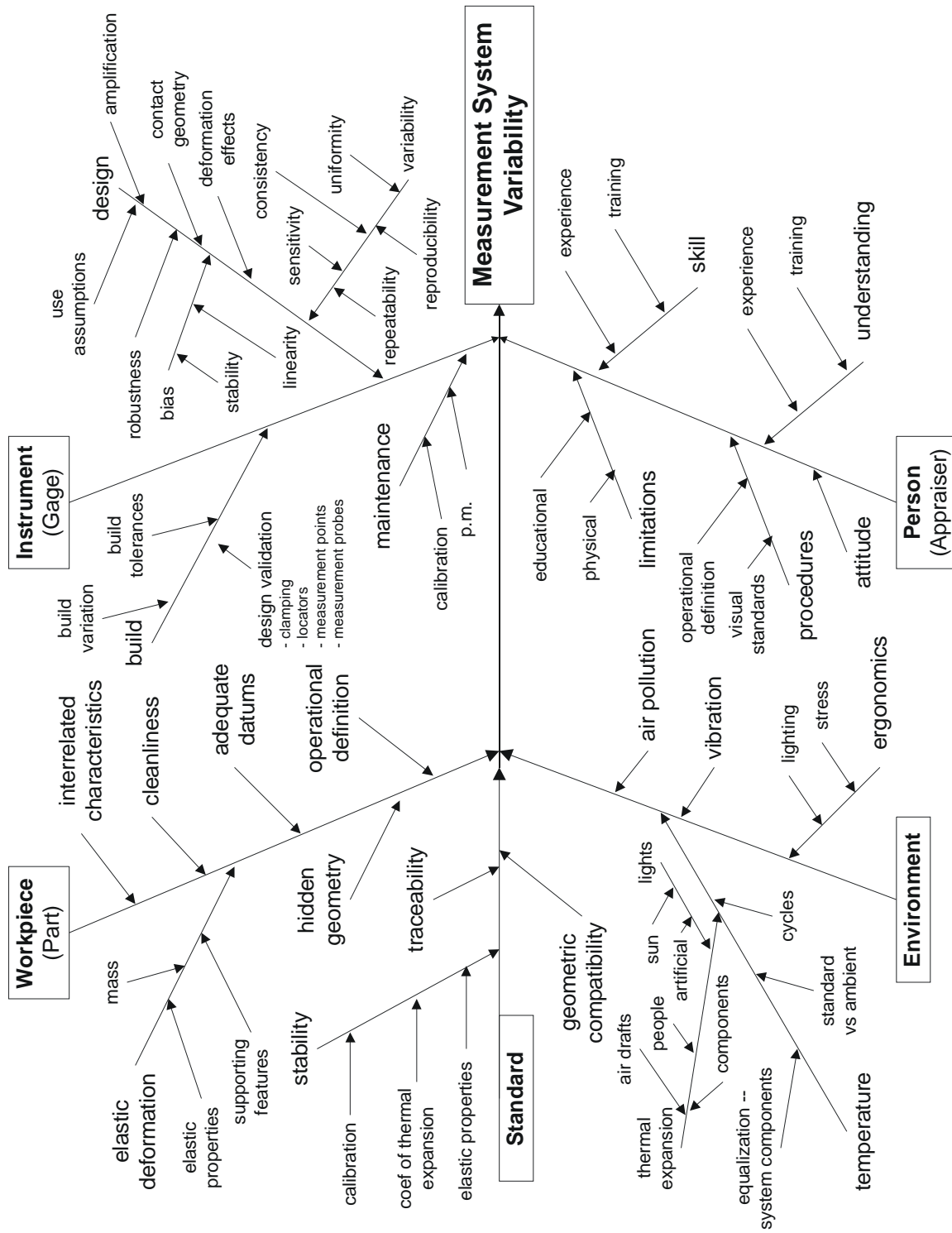


Figure I-B 1: Measurement System Variability Cause and Effect Diagram

The Effects of Measurement System Variability

Because the measurement system can be affected by various sources of variation, repeated readings on the same part do not yield the same, identical result. Readings vary from each other due to common and special causes.

The effects of the various sources of variation on the measurement system should be evaluated over a short and long period of time. The *measurement system capability* is the measurement system (random) error over a short period of time. It is the combination of errors quantified by linearity, uniformity, repeatability and reproducibility. The *measurement system performance*, as with process performance, is the effect of all sources of variation over time. This is accomplished by determining whether our process is in statistical control (i.e., stable and consistent; variation is due only to common causes), on target (no bias), and has acceptable variation (gage repeatability and reproducibility (*GRR*)) over the range of expected results. This adds stability and consistency to the measurement system capability.

Because the output of the measurement system is used in making a decision about the product and the process, the cumulative effect of all the sources of variation is often called *measurement system error*, or sometimes just “error.”

Effect on Decisions

After measuring a part, one of the actions that can be taken is to determine the status of that part. Historically, it would be determined if the part were acceptable (within specification) or unacceptable (outside specification). Another common scenario is the classification of parts into specific categories (e.g., piston sizes).

For the rest of the discussion, as an example, the two category situation will be used: out of specification (“bad”) and in specification (“good”). This does not restrict the application of the discussion to other categorization activities.

Further classifications may be reworkable, salvageable or scrap. Under a *product control philosophy* this classification activity would be the primary reason for measuring a part. But, with a *process control philosophy*, interest is focused on whether the part variation is due to common causes or special causes in the process.

Philosophy	Interest
Product control	Is the part in a specific category?
Process control	Is the process variation stable and acceptable?

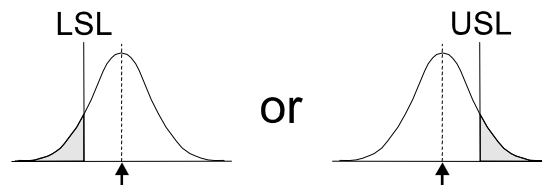
Table I-B1: Control Philosophy and Driving Interest

The next section deals with the effect of the measurement error on the product decision. Following that is a section which addresses its impact on the process decision.

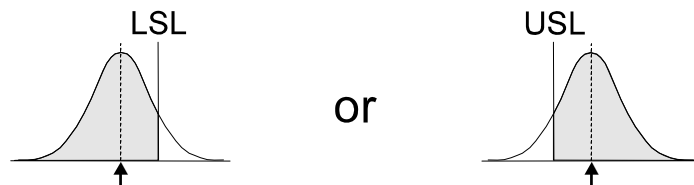
Effect on Product Decisions

In order to better understand the effect of measurement system error on product decisions, consider the case where all of the variability in multiple readings of a single part is due to the gage repeatability and reproducibility. That is, the measurement process is in statistical control and has zero bias.

A wrong decision will sometimes be made whenever any part of the above measurement distribution overlaps a specification limit. For example, a good part will sometimes be called “bad” (type I error, producer’s risk or *false alarm*) if:



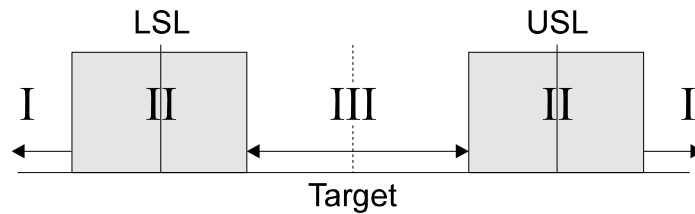
And, a bad part will sometimes be called “good” (type II error, consumer’s risk or *miss rate*) if:



NOTE: False Alarm Rate + Miss Rate = *Error Rate*.

RISK is the chance of making a decision which will be detrimental to an individual or process

That is, with respect to the specification limits, the potential to make the wrong decision about the part exists only when the measurement system error intersects the specification limits. This gives three distinct areas:



where:

- I Bad parts will always be called bad
- II Potential wrong decision can be made
- III Good parts will always be called good

Since the goal is to maximize CORRECT decisions regarding product status, there are two choices:

- 1) Improve the production process: reduce the variability of the process so that no parts will be produced in the II or “shaded” areas of the graphic above.
- 2) Improve the measurement system: reduce the measurement system error to reduce the size of the II areas so that all parts being produced will fall within area III and thus minimize the risk of making a wrong decision.

This discussion assumes that the measurement process is in statistical control and on target. If either of these assumptions is violated then there is little confidence that any observed value would lead to a correct decision.

Effect on Process Decisions

With process control, the following needs to be established:

- Statistical control
- On target
- Acceptable variability

As explained in the previous section, the measurement error can cause incorrect decisions about the product. The impact on process decisions would be as follows:

- Calling a common cause a special cause
- Calling a special cause a common cause

Measurement system variability can affect the decision regarding the stability, target and variation of a process. The basic relationship between the actual and the observed process variation is:

$$\sigma_{obs}^2 = \sigma_{actual}^2 + \sigma_{msa}^2$$

where

$$\sigma_{obs}^2 = \text{observed process variance}$$

$$\sigma_{actual}^2 = \text{actual process variance}$$

$$\sigma_{msa}^2 = \text{variance of the measurement system}$$

The capability index⁹ Cp is defined as

$$Cp = \frac{\textit{ToleranceRange}}{6\sigma}$$

The relationship between the Cp index of the observed process and the Cp indices of the actual process and the measurement system is derived by substituting the equation for Cp into the observed variance equation above:

$$(Cp)_{obs}^{-2} = (Cp)_{actual}^{-2} + (Cp)_{msa}^{-2}$$

Assuming the measurement system is in statistical control and on target, the actual process Cp can be compared graphically to the observed Cp .¹⁰

Therefore the observed process capability is a combination of the actual process capability plus the variation due to the measurement process. To reach a specific process capability goal would require factoring in the measurement variation.

For example, if the measurement system Cp index were 2, the actual process would require a Cp index greater than or equal to 1.79 in order for the calculated (observed) index to be 1.33. If the measurement system Cp index were itself 1.33, the process would require **no** variation at all if the final result were to be 1.33 – clearly an impossible situation.

⁹ Although this discussion is using Cp , the results hold also for the performance index Pp .

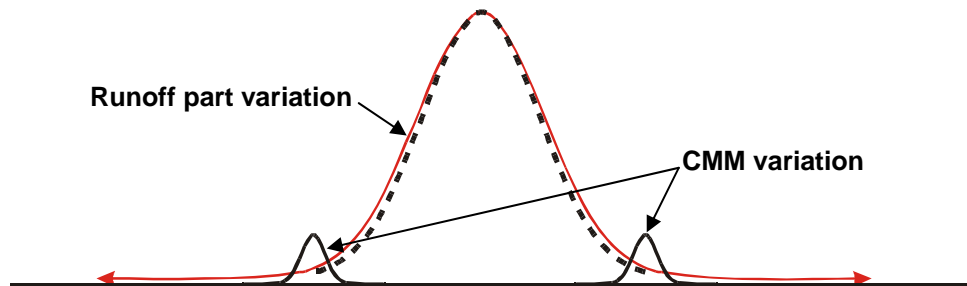
¹⁰ See Appendix B for formulas and graphs.

New Process Acceptance

When a new process such as machining, manufacturing, stamping, material handling, heat treating, or assembly is purchased, there often is a series of steps that are completed as part of the buy-off activity. Oftentimes this involves some studies done on the equipment at the supplier's location and then at the customer's location.

If the measurement system used at either location is not consistent with the measurement system that will be used under normal circumstances then confusion may ensue. The most common situation involving the use of different instruments is the case where the instrument used at the supplier has higher order discrimination than the production instrument (gage). For example, parts measured with a coordinate measuring machine during buy-off and then with a height gage during production; samples measured (weighed) on an electronic scale or laboratory mechanical scale during buy-off and then on a simple mechanical scale during production.

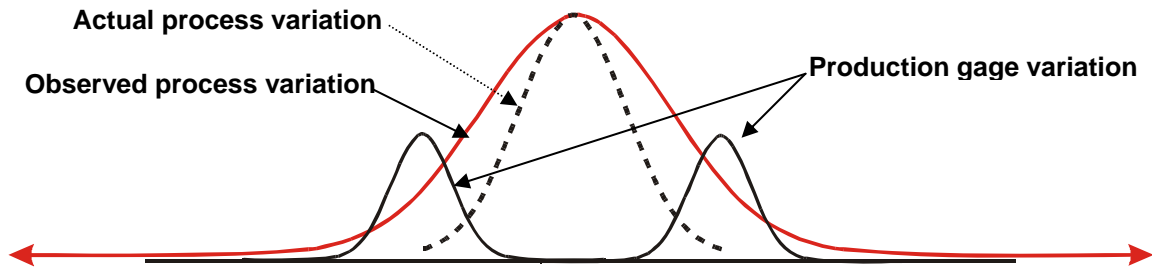
In the case where the (higher order) measurement system used during buy-off has a *GRR* of 10% and the actual process *C_p* is 2.0 the observed process *C_p* during buy-off will be 1.96.¹¹



When this process is studied in production with the production gage, more variation (i.e., a smaller *C_p*) will be observed. For example, if the *GRR* of the production gage is 30% and the actual process *C_p* is still 2.0 then the observed process *C_p* will be 1.71.

A worst case scenario would be if a production gage has not been qualified but is used. If the measurement system *GRR* is actually 60% (but that fact is not known), then the observed *C_p* would be 1.28. The difference in the observed *C_p* of 1.96 versus 1.28 is due to the different measurement system. Without this knowledge, efforts may be spent, in vain, looking to see what went wrong with the new process.

¹¹ For this discussion, assume there is no sampling variation. In reality 1.96 will be the expected value but actual results will vary around it.



Process Setup/ Control (Funnel Experiment)

Often manufacturing operations use a single part at the beginning of the day to verify that the process is targeted. If the part measured is off target, the process is then adjusted. Later, in some cases another part is measured and again the process may be adjusted. Dr. Deming referred to this type of measurement and decision-making as *tampering*.

Consider a situation where the weight of a precious metal coating on a part is being controlled to a target of 5.00 grams. Suppose that the results from the scale used to determine the weight vary ± 0.20 grams but this is not known since the measurement system analysis was never done. The operating instructions require the operator to verify the weight at setup and every hour based on one sample. If the results are beyond the interval 4.90 to 5.10 grams then the operator is to setup the process again.

At setup, suppose the process is operating at 4.95 grams but due to measurement error the operator observes 4.85 grams. According to instructions the operator attempts to adjust the process up by .15 grams. Now the process is running at 5.10 grams for a target. When the operator checks the setup this time, 5.08 grams is observed so the process is allowed to run. Over-adjustment of the process has added variation and will continue to do so.

This is one example of the funnel experiment that Dr. Deming used to describe the effects of tampering.¹² The measurement error just compounds the problem.

Four rules of the funnel experiment are:

- Rule 1: Make no adjustment or take no action unless the process is unstable.
- Rule 2: Adjust the process in an equal amount and in an opposite direction from where the process was last measured to be.
- Rule 3: Reset the process to the target. Then adjust the process in an equal amount and in an opposite direction from the target.
- Rule 4: Adjust the process to the point of the last measurement.

The setup instruction for the precious metal process is an example of Rule 3. Rules 2, 3 and 4 add progressively more variation. Rule 1 is the best choice to produce minimum variation.

¹² Deming, W. Edwards, *Out of the Crisis*, Massachusetts Institute of Technology, 1982, 1986.

Other examples of the funnel experiment are:

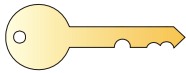
- Recalibration of gages based on arbitrary limits – i.e., limits not reflecting the measurement system’s variability. (Rule 3)
- (Re)mastering the process control measurement system after an arbitrary number of uses without any indication or history of a change (special cause). (Rule 3)
- Autocompensation adjusts the process based on the last part produced. (Rule 2)
- On the job training (OJT) where worker A trains worker B who later trains worker C... without standard training material. Similar to the “post office” game. (Rule 4)
- Parts are measured, found to be off target, but when plotted on a control chart the process is shown to be stable – therefore, no action is taken. (Rule 1)

Section C

Measurement Strategy and Planning

Planning is key before designing and purchase of measurement equipment or systems. Many decisions made during the planning stage could affect the direction and selection of measurement equipment. What is the purpose and how will the measurement result be used? The planning stage will set the course and have a significant effect on how well the measurement process operates and can reduce possible problems and measurement error in the future.

In some cases due to the risk involved in the component being measured or because of the cost and complexity of the measurement device, the OEM customer may use the APQP process and committee to decide on the measurement strategy at the supplier.



Not all product and process characteristics require measurement systems whose development falls under this type of scrutiny. Simple standard measurement tools like micrometers or calipers may not require this in-depth strategy and planning. A basic rule of thumb is whether the characteristic being measured on the component or sub-system has been identified in the control plan or is important in determining the acceptance of the product or process. Another guide would be the level of tolerance assigned to a specific dimension. **Common sense is the guide in any case.**

Complexity

The type, complexity, and purpose of a measurement system may drive various levels of program management, strategic planning, measurement systems analysis, or other special consideration for measurement selection, assessment and control. Simple measuring tools and devices (i.e., scales, measuring tapes, fixed-limit or attribute gages) may not require the level of management, planning, or analysis that more complex or critical measuring systems demand (i.e., master or reference, CMM, test stand, automated on-line gaging, etc.). Any measurement system may require more or less strategic planning and scrutiny depending on a given product or process situation. The decision as to the appropriate level shall be left to the APQP team assigned to the measurement process and customer. The actual degree of involvement or implementation in many of the activities below should be driven by the particular measurement system, consideration of the supporting gage control and calibration system, profound process knowledge, and common sense.

Identify the Purpose of the Measurement Process

The first step is to establish the purpose for the measurement and how the measurement will be utilized. A cross-functional team organized early in the development of the measurement process is critical in accomplishing this task. Specific considerations are made in relation to audit, process control, product and process development and analysis of the “Measurement Life Cycle”.

Measurement Life Cycle

The Measurement Life Cycle concept expresses the belief that the measurement methods may change over time as one learns and improves the process. For example, measurement may start on a product characteristic to establish stability and capability of the process. This may lead to an understanding of critical process control characteristics that directly affect the part characteristics. Dependency on part characteristic information becomes less and the sampling plan may be reduced to signify this understanding (five parts per hour sample reduced to one part per shift). Also, the method of measurement may change from a CMM measurement, to some form of attribute gaging. Eventually it may be found that very little part monitoring may be required as long as the process is maintained or measuring and monitoring the maintenance and tooling may be all that is needed. The level of measurement follows the level of process understanding.

Most of the measuring and monitoring could eventually end up at suppliers of incoming material. The same measurement, on the same characteristic, at the same area of the process, over an extensive period of time is evidence of a lack of learning or a stagnant measurement process.

Criteria for a Measurement Process Design Selection

Before a measurement system can be purchased, a detailed engineering concept of the measurement process is developed. Using the purpose developed above, a cross-functional team of individuals will develop a plan and concept for the measurement system required by the design. Here are some guidelines:

The team needs to evaluate the design of the subsystem or component and identify important characteristics. These are based on customer requirements and the functionality of the subsystem or component to the total system. If the important dimensions have been identified already, evaluate the ability to measure the characteristics. For example, if the important characteristic of a plastic injection molded component was on the mold parting line, the dimensional check would be difficult and measurement variation would be high.

One method to capture issues similar to these would be to use a FMEA process to analyze areas of risk in gage design both from an ability to measure to the part to the functionality gage (Design and Process FMEA). This would aid in the development of the maintenance and calibration plan.

Develop a flow chart showing critical process steps in the manufacturing or assembly of the part or subsystem. Identify key inputs and outputs to each step in the process. This will aid in the development of the measurement criteria and requirements affected by the location in the process.

A measurement plan, a list of measurement types, comes out of this investigation.¹³

For complex measurement systems, a flow chart is made of the measurement process. This would include delivery of the part or sub-system being measured, the measurement itself, and the return of the part or sub-system to the process.

Next use some method of brainstorming with the group to develop general criteria for each measurement required. One of the simple methods to use is a cause and effect diagram.¹⁴ See the example in Figure I-B 1 as a thought starter.

A few additional questions to consider in relation to measurement planning:

- Who ought to be involved in the “needs” analysis? The flow chart and initial discussion will facilitate the identification of the key individuals.
- Why will measurement be taken and how will it be used? Will the data be used for control, sorting, qualification, etc? The way the measurement will be used can change the sensitivity level of the measurement system.
- What level of sensitivity will be required? What is the product specification? What is the expected process variability? How much of a difference between parts will the gage need to detect?
- What type of information will be provided with the gage (e.g., manuals – operating, maintenance, etc.) and what basic operator skills are required? Who will do the training?
- How are measurements taken? Will it be done manually, on a moving conveyor, off-line, automatically, etc? Are the part location and fixturing possible sources of variation? Contact or non-contact?
- How will the measurement be calibrated and will it be compared with other measurement processes? Who will be responsible for the calibration masters?
- When and where will the measurement be taken? Will the part be clean, oily, hot, etc.?

Remember to use data to substantiate common assumptions about the measurement process. It is better to be safe and collect data on the environment, rather than to make decisions based on the wrong information and having a system developed that is not robust to environmental issues.

¹³ This can be considered as a preliminary control plan.

¹⁴ See *Guide to Quality Control*, Kaoru Ishikawa, published by Asian Productivity Organization, 1986.

Research Various Measurement Process Methods

Current measurement methods should be researched prior to investing in new equipment. Proven measurement methods may provide more reliable operation. Where possible, use measurement equipment that has a proven track record.

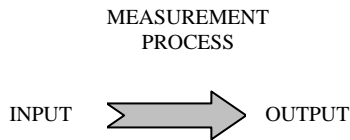
Develop and Design Concepts and Proposals

Refer to “Suggested Elements for a Measurement System Development Checklist” at the end of Chapter I, Section D, when developing and designing concepts and proposals.

During and after the fabrication of the measurement equipment and development of the measurement process (methods, training, documentation, etc.), experimental studies and data collection activities will be performed. These studies and data will be used to understand this measurement process so that this process and future processes may be improved.

Section D Measurement Source Development

This section addresses the quotation/procurement timeframe of the life of a measurement process. It has been constructed to be a self-contained discussion about the process of developing a measurement process quotation package, obtaining responses to that package, awarding the project, completing final design, developing the measurement process, and, finally, marrying that measurement process to the production process for which it was created. It is strongly encouraged that this chapter not be used without reading and understanding the entire discussion about a measurement process. To obtain the most benefit from the measurement process, study and address it **as a process** with inputs and outputs.¹⁵



This chapter was written with the team philosophy in mind. It is not a job description for the buyer or purchasing agent. The activities described here will require team involvement to be completed successfully and it should be administered within the overall framework of an Advanced Product Quality Planning (APQP) team. This can result in healthy interplay between various team functions – concepts arising out of the planning process may be modified before the gage supplier arrives at a final design that satisfies the measurement system requirements.



Generally, the “acquisition process” begins with formal communication between the customer and supplier for a given project. Up-front communication is crucial to the success of the project, since the groundwork necessary for an effective future customer/supplier relationship will be done at this stage. The acquisition process begins with the customer’s formal presentation of the intent of the project in the form of a Request For Quote (RFQ) followed by the supplier’s formal explanation of their proposal to meet this intent (the Quotation). The customer and supplier(s) need to thoroughly understand the project requirements, what the deliverables will be and the methods by which both are to be achieved. This understanding is derived from accurate timely communication between the two parties.

Once a concept has been agreed upon and a customer/supplier relationship has been established for the project at hand, the detailed design, fabrication of the measurement process, and development activities can commence. Communication between the customer and the supplier at this time is especially important. Since there may be several levels of concept approvals to be carried out, and possible environmental changes and the potential of team members changing, the measurement process project could falter or even fail. This risk will be reduced if frequent, detailed communication is maintained and documented between the customer and supplier and formal responsibility (an individual) for maintaining communication is designated

¹⁵ See Chapter I, Section B

by both parties. The ideal forum and format for this activity is the Advanced Product Quality Planning (APQP) process.

After the measurement process has been conceptually designed, the activities surrounding the acquisition of the process/system can begin.

Datum Coordination

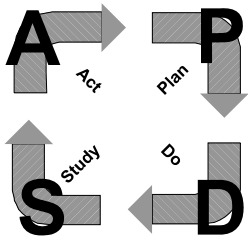
Ideally, with the current prevalence in the use of Geometric Dimensioning & Tolerancing (GD&T), datums need to be coordinated (i.e., made identical) throughout the manufacturing process and the measurement system and this needs to be established very early in the APQP process. Initial responsibility for this may lie with the product design engineer, dimensional control, etc. depending on the specific organization. When datum schemes do not match throughout a manufacturing process, particularly in the measurement systems, this leads to a situation where the wrong things may be measured, and there may be fit problems, etc., leading to ineffective control of the manufacturing process.

There may be times when a datum scheme used in a final assembly cannot possibly match that used in a sub-component manufacturing process. When such is the case, it can be established as early as possible in the APQP process so that all team members understand possible difficulties and conflicts that may lie ahead and have every opportunity to do something about it. During this process, different datum schemes may need to be explored in order to understand the impact of these differences.

Certain commodities present features which can yield more problems than others, such as camshaft centering, or other round, cylindrical or tubular characteristics. For example, a camshaft must be manufactured on centers but the important product features are in its lobes. One method or datum scheme may be required for manufacturing whereas another scheme is required for measurement of the final product measurement.

Prerequisites and Assumptions

Before discussing the development of a gage supplier, it will be assumed that issues such as “correct” engineering product design (GD&T) and “correct” process design (one which allows for measurement at the proper time and location in the process) have been resolved. However this should not detract from consideration of these issues with appropriate team members early in the APQP process.



It is assumed that the gage supplier will be involved with the APQP process, a *team* approach. The gage supplier will develop a clear appreciation of the overall production process and product usage so that his role is understood not only by him but by others on the team (manufacturing, quality, engineering, etc.).

There may be slight overlap in some activities or the order of those activities depending on the particular program/project or other constraints. For instance, the APQP team without much input from a gage source may develop certain gage concepts. Other concepts may require the expertise of the gage source. This may be driven by the complexity of the measurement system and a team decision as to what makes sense.

Gage Source Selection Process

Develop the Quotation Package

Detailed Engineering Concept

Before a measurement process request for quotation package can be supplied to a potential supplier for formal proposals, a detailed engineering concept of the measurement process needs to be developed. The team of individuals that will employ and be responsible for the maintenance and continual improvement of the measurement process have direct responsibility for developing the detailed concept. This can be part of the APQP team. To better develop this concept, several questions need to be answered.



The team may research various issues to help decide which direction or path will be followed for designing the measurement process. Some may be dictated or heavily implied by the product design. Examples of the multitude of possible issues that need to be addressed by the team when developing this detailed concept may be found in the “Suggested Elements for a Measurement System Development Checklist” at the end of this section.

All too often, customers rely too heavily on suppliers for solutions. Before a customer asks a supplier to suggest solutions to process problems, the foundation and intent of the process needs to be thoroughly understood and anticipated by the team that owns that process. Then and only then will the process be properly used, supported and improved upon.

Preventive Maintenance Considerations

What activities should be scheduled for preventive maintenance (e.g., lubrication, vibration analysis, probe integrity, parts replacement, etc.)? Much of these activities will depend on the complexity of the measurement system, device or apparatus. Simpler gages may require only an inspection at regular intervals, whereas more complex systems may require ongoing detailed statistical analyses and a team of engineers to maintain in a predictive fashion.

Planning preventive maintenance activities should coincide with the initiation of the measurement process planning. Many activities, such as draining air filters daily, lubricating bearings after the designated number of operating hours, etc., can be planned before the measurement system is completely built, developed and implemented. In fact this is preferable and improves advanced measurement planning and costs. Data collection methods and maintenance recommendations related to these activities can be obtained from the original manufacturer, or developed by plant engineering, manufacturing and quality personnel. After the measurement process is implemented and in use, data pertaining to the function of the measurement process need to be collected and plotted over time. Simple analytical methods (run charts, trend analysis) can be conducted to determine the stability of the system. Eventually, as the judgment of system stability dictates, preventive maintenance routines can be scheduled accordingly. Conducting preventive maintenance on a stable system, based on time series information, will be less wasteful than conducting preventive maintenance on a system with traditional techniques.

Specifications

Specifications serve as guidelines for both the customer and supplier in the design and build process. These guidelines serve to communicate acceptable standards. Acceptable standards may be considered in two categories:

- Design Standards
- Build Standards

Format of the design standards may be different depending on who is paying for the project. Cost issues may affect the format. Generally, it is a good idea to have sufficient documented design detail that the design may be built or repaired to original intent by any qualified builder – however, this decision

may be driven by cost and criticality. The required format of the final design may be some form of computer assisted design (CAD) or hardcopy engineering drawings. It may involve engineering standards chosen from those of the OEM, SAE, ASTM, or other organization, and the gage supplier must have access to the latest level and understand these standards. The OEM may require the use of particular standards at either the design or build phase and may even require formal approvals before the measurement system may be released for use.

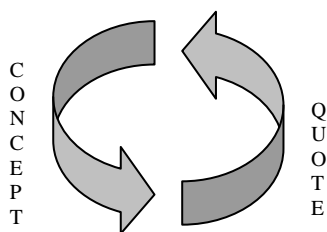
Design standards will detail the method of communicating the design (CAD – e.g., CATIA, Unigraphics, IGES, manual hardcopy, etc.) to the builder. It may also cover performance standards for a more complex measurement system.

Build standards will cover the tolerances to which the measurement system must be built. Build tolerance should be based on a combination of the capabilities of the process used to produce the gage or gage component, and the criticality of the intended measurement. Build tolerance should not be a mere given percent of product tolerance alone.

If duplicate fixtures or systems are required, proper planning and standardizing can lead to interchangeability and flexibility.

Use of standard(ized) components or subassemblies also leads to interchangeability, flexibility, reduced cost and, generally, less long-term measurement error.

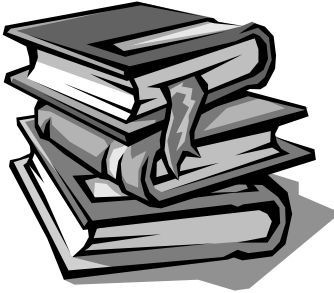
Evaluate the Quotations



As quotations are received, the team ought to assemble to review and evaluate them. Certain items can be noted:

- ✓ Are the basic requirements met?
- ✓ Are there any outstanding concerns?
- ✓ Do any of the suppliers exhibit an exceptional condition and why? *(An exceptional condition could be a significant disparity with regard to price or delivery – this would not necessarily be discounted as a negative factor – one supplier may have discovered an item that others overlooked.)*
- ✓ Do the concepts promote simplicity and maintainability?

Documentation is sometimes overlooked when acquiring a measurement process. The significance that documentation takes with any successful project is often misunderstood. The usual strategy behind documentation is to provide an original set of mechanical and electrical designs (CAD or hardcopy drawings) for the measurement process hardware at the time of delivery. This may satisfy initial implementation requirements, but this documentation does nothing with regard to defining potential wear points, suggesting possible trouble areas or describing how to use the process. Thus,



the required documentation for any process ought to include more than assembly and detailed drawings of the measurement equipment.

Effective documentation for any system serves the same purpose as a good map on a trip. For example, it will suggest to the user how to get from one point to another (user instructions or gage instructions). It provides the user with possible alternative routes to reach the desired destinations (troubleshooting guides or diagnostic trees) if the main route is blocked or closed.

A complete documentation package may include:

- Reproducible set of assembly and detailed mechanical drawings (CAD or hardcopy) (including any required masters)
- Reproducible set of electrical hard-wiring, logic and software
- Suggested spare parts list of heavy use or wear items/details. This list should include items that may require considerable lead-time to acquire
- Maintenance manuals with machine drawing cutaways and steps to properly assemble and disassemble machine components
- Manuals defining utility requirements for setup and operation and machine transport requirements (e.g., load bearing members)
- Diagnostic trees and a troubleshooting guide
- Certification reports (traceable to NIST where applicable)
- Calibration instructions
- User manuals that can be used by the technical support personnel, the system operator and maintenance personnel

The above list can be used as a checklist when organizing the quotation package; however it is not necessarily all-inclusive.

The central theme here is communication. Since documentation is a form of communication, the team and others ought to be involved at every level of the development of the measurement process documentation package.

Qualification at the Supplier

The gage or measurement system should be given a full dimensional layout and functional test, where applicable, at the measurement system supplier before shipment. Obviously, the chosen supplier must have qualified measurement equipment and personnel on site in order to accomplish this. If not, pre-arrangements should have been made to have this work done at an outside independent qualified laboratory. Results of such dimensional layout and/or testing should be done in accordance with customer design and build standards and be fully documented and available for customer review.

After successful dimensional layout, the supplier should perform a preliminary but formal measurement systems analysis. This again pre-requires that the supplier have the personnel, knowledge and experience to accomplish the appropriate analysis. The customer should predetermine with the supplier (and perhaps the OEM) exactly what sort of analysis is required at this point and should be aware of any guidance the supplier might need. Some issues that may need discussion, negotiation or common agreement are:

- Objective of the preliminary MSA study :
 - ✓ Gage repeatability (GR^{16}) versus gage repeatability and reproducibility (GRR)
 - ✓ Assessment of bias and/or linearity
 - ✓ Assessment of the customer purpose for measurement
- Quantity of pieces, trials and operators in study
 - ✓ Acceptance criteria
- Use of supplier personnel vs. customer supplied personnel
- Necessary training for personnel
 - ✓ Are they qualified?
 - ✓ Do they understand intent?
 - ✓ What software might be used? Whatever results are achieved at this point in time, it should be realized that these are merely preliminary and *judgment* may be needed as to the acceptability of the results.

Shipment



CHECKLIST

- When should the equipment be shipped?
- How should it be shipped?
- Who removes equipment from the truck or rail car?
- Is insurance required?
- Should documentation be shipped with the hardware?
- Does the customer have the proper equipment to unload the hardware?
- Where will the system be stored until shipment?

¹⁶ See Appendix D.

- Where will the system be stored until implementation?
- Is the shipping documentation complete and easily understandable for the loader, transporter, unloader and installation crew?

Qualification at the Customer

Generally, what was done to qualify the measurement system above at the supplier before shipment should be repeated in some manner at the customer once delivery is completed. Since this becomes the first real opportunity to study the measurement system in its intended environment, acceptance standards and analysis methods used here should be considered seriously. Attention to detail on the part of all parties involved is paramount to the eventual success of this measurement system and the use of the data it generates.

Before any measurement analysis is begun after receipt, the measurement system should undergo a full dimensional layout to confirm it meets build requirements/standards. The extent of this layout may be balanced against layout work done previously at the measurement system supplier before shipment and confidence in the quality of the layout results done at the supplier as well as the lack of potential shipping damage. When comparing results before and after shipment, be aware that there will likely be some differences in these measurements because of differences in these measurement systems.

Documentation Delivery

The information that is required, at a minimum, to aid implementation and startup of any system is the following: (This information ought to be delivered to the customer prior to delivery.)

- CAD or hardcopy drawings, if required by team
- Process flow diagram of the system, where applicable
- User manuals
 - ✓ Maintenance/service manual
 - ✓ Spare parts list
 - ✓ Troubleshooting guide
- Calibration instructions
- Any special considerations

At the outset, the delivered documentation needs to be noted as preliminary. Original or reproducible documentation does not need to be delivered at this time because potential revision may be necessary after implementation. In fact, it is a wise idea to not have the original documentation package delivered until after the entire system is implemented – suppliers are generally more efficient with updating documentation than customers.

Suggested Elements for a Measurement System Development Checklist

This list should be modified based on the situation and type of measurement system. The development of the final checklist should be the result of collaboration between the customer and supplier.

Measurement System Design and Development Issues:

- ❑ **What is to be measured?** What type of characteristic is it? Is it a mechanical property? Is it dynamic or stationary? Is it an electrical property? Is there significant within-part variation?
- ❑ **For what purpose will the results (output) of the measurement process be used?** Production improvement, production monitoring, laboratory studies, process audits, shipping inspection, receiving inspection, responses to a D.O.E.?
- ❑ **Who will use the process?** Operators, engineers, technicians, inspectors, auditors?
- ❑ **Training required:** Operator, maintenance personnel, engineers; classroom, practical application, OJT, apprenticeship period.
- ❑ **Have the sources of variation been identified?** Build an error model (S.W.I.P.E. or P.I.S.M.O.E.A.) using teams, brainstorming, profound process knowledge, cause & effect diagram or matrix.
- ❑ **Has a FMEA been developed for the measurement system?**
- ❑ **Flexible vs. dedicated measurement systems:** Measurement systems can either be permanent and dedicated or they can be flexible and have the ability to measure different types of parts; e.g., doghouse gages, fixture gaging, coordinate measurement machine, etc. Flexible gaging will be more expensive, but can save money in the long run.
- ❑ **Contact vs. non-contact:** Reliability, type of feature, sample plan, cost, maintenance, calibration, personnel skill required, compatibility, environment, pace, probe types, part deflection, image processing . This may be determined by the control plan requirements and the frequency of the measurement (Full contact gaging may get excessive wear during continuous sampling). Full surface contact probes, probe type, air feedback jets, image processing, CMM vs. optical comparator, etc.
- ❑ **Environment:** Dirt, moisture, humidity, temperature, vibration, noise, electro-magnetic interference (EMI), ambient air movement, air contaminants, etc. Laboratory, shop floor, office, etc? Environment becomes a key issue with low, tight tolerances in the micron level. Also, in cases that CMM, vision systems, ultrasonic, etc. This could be a factor in auto-feedback in-process type measurements. Cutting oils, cutting debris, and extreme temperatures could also become issues. Is a clean room required?
- ❑ **Measurement and location points:** Clearly define, using GD&T, the location of fixturing and clamping points and where on the part the measurements will be taken.
- ❑ **Fixturing method:** Free state versus clamped part holding.
- ❑ **Part orientation:** Body position versus other.
- ❑ **Part preparation:** Should the part be clean, non-oily, temperature stabilized, etc. before measurement?
- ❑ **Transducer location:** Angular orientation, distance from primary locators or nets.

- ❑ **Correlation issue #1 – duplicate gaging:** Are duplicate (or more) gages required within or between plants to support requirements? Building considerations, measurement error considerations, maintenance considerations. Which is considered *the* standard? How will each be qualified?
- ❑ **Correlations issue #2 – methods divergence:** Measurement variation resulting from different measurement system designs performing on the same product/process within accepted practice and operation limits (e.g., CMM versus manual or open-setup measurement results).
- ❑ **Automated vs. manual:** on-line, off-line, operator dependencies.
- ❑ **Destructive versus nondestructive measurement (NDT):** Examples: tensile test, salt spray testing, plating/paint coating thickness, hardness, dimensional measurement, image processing, chemical analysis, stress, durability, impact, torsion, torque, weld strength, electrical properties, etc.
- ❑ **Potential measurement range:** size and expected range of conceivable measurements.
- ❑ **Effective resolution:** Is measurement sensitive to physical change (ability to detect process or product variation) for a particular application acceptable for the application?
- ❑ **Sensitivity:** Is the size of the smallest input signal that results in a detectable (discernable) output signal for this measurement device acceptable for the application? Sensitivity is determined by inherent gage design and quality (OEM), in-service maintenance, and operating condition.

Measurement System Build Issues (equipment, standard, instrument):

- ❑ **Have the sources of variation identified in the system design been addressed?** Design review; verify and validate.
- ❑ **Calibration and control system:** Recommended calibration schedule and audit of equipment and documentation. Frequency, internal or external, parameters, in-process verification checks.
- ❑ **Input requirements:** Mechanical, electrical, hydraulic, pneumatic, surge suppressors, dryers, filters, setup and operation issues, isolation, discrimination and sensitivity.
- ❑ **Output requirements:** Analog or digital, documentation and records, file, storage, retrieval, backup.
- ❑ **Cost:** Budget factors for development, purchase, installation, operation and training.
- ❑ **Preventive maintenance:** Type, schedule, cost, personnel, training, documentation.
- ❑ **Serviceability:** Internal and external, location, support level, response time, availability of service parts, standard parts list.
- ❑ **Ergonomics:** Ability to load and operate the machine without injuries over time. Measurement device discussions need to focus on issues of how the measurement system is interdependent with the operator.
- ❑ **Safety considerations:** Personnel, operation, environmental, lock-out.
- ❑ **Storage and location:** Establish the requirements around the storage and location of the measurement equipment. Enclosures, environment, security, availability (proximity) issues.
- ❑ **Measurement cycle time:** How long will it take to measure one part or characteristic? Measurement cycle integrated to process and product control.
- ❑ **Will there be any disruption to process flow, lot integrity, to capture, measure and return the part?**

- ❑ **Material handling:** Are special racks, holding fixtures, transport equipment or other material handling equipment needed to deal with parts to be measured or the measurement system itself?
- ❑ **Environmental issues:** Are there any special environmental requirements, conditions, limitations, either affecting this measurement process or neighboring processes? Is special exhausting required? Is temperature or humidity control necessary? Humidity, vibration, noise, EMI, cleanliness.
- ❑ **Are there any special reliability requirements or considerations?** Will the equipment hold up over time? Does this need to be verified ahead of production use?
- ❑ **Spare parts:** Common list, adequate supply and ordering system in place, availability, lead-times understood and accounted for. Is adequate and secure storage available? (bearings, hoses, belts, switches, solenoids, valves, etc.)
- ❑ **User instructions:** Clamping sequence, cleaning procedures, data interpretation, graphics, visual aids, comprehensive. Available, appropriately displayed.
- ❑ **Documentation:** Engineering drawings, diagnostic trees, user manuals, language, etc.
- ❑ **Calibration:** Comparison to acceptable standards. Availability and cost of acceptable standards. Recommended frequency, training requirements. Down-time required?
- ❑ **Storage:** Are there any special requirements or considerations regarding the storage of the measurement device? Enclosures, environment, security from damage/theft, etc.
- ❑ **Error/Mistake proofing:** Can known measurement procedure mistakes be corrected easily (too easily?) by the user? Data entry, misuse of equipment, error proofing, mistake proofing.

Measurement System Implementation Issues (process):

- ❑ **Support:** Who will support the measurement process? Lab technicians, engineers, production, maintenance, outside contracted service?
- ❑ **Training:** What training will be needed for operators/inspectors/technicians/engineers to use and maintain this measurement process? Timing, resource and cost issues. Who will train? Where will training be held? Lead-time requirements? Coordinated with actual use of measurement process.
- ❑ **Data management:** How will data output from this measurement process be managed? Manual, computerized, summary methods, summary frequency, review methods, review frequency, customer requirements, internal requirements. Availability, storage, retrieval, backup, security. Data interpretation.
- ❑ **Personnel:** Will personnel need to be hired to support this measurement process? Cost, timing, availability issues. Current or new.
- ❑ **Improvement methods:** Who will improve the measurement process over time? Engineers, production, maintenance, quality personnel? What evaluation methods will be used? Is there a system to identify needed improvements?
- ❑ **Long-term stability:** Assessment methods, format, frequency, and need for long-term studies. Drift, wear, contamination, operational integrity. Can this long-term error be measured, controlled, understood, predicted?
- ❑ **Special considerations:** Inspector attributes, physical limitations or health issues: colorblindness, vision, strength, fatigue, stamina, ergonomics.

Section E

Measurement Issues

Three fundamental issues must be addressed when evaluating a measurement system:

- 1) The measurement system must demonstrate adequate sensitivity.
 - ✓ First, does the instrument (and standard) have adequate discrimination? Discrimination (or class) is fixed by design and serves as the basic starting point for selecting a measurement system. Typically, the Rule of Tens has been applied, which states that instrument discrimination should divide the tolerance (or process variation) into ten parts or more.
 - ✓ Second, does the measurement system demonstrate effective resolution? Related to discrimination, determine if the measurement system has the sensitivity to detect changes in product or process variation for the application and conditions.
- 2) The measurement system must be stable.
 - ✓ Under repeatability conditions, the measurement system variation is due to common causes only and not special (chaotic) causes.
 - ✓ The measurement analyst must always consider practical and statistical significance.
- 3) The statistical properties (errors) are consistent over the expected range and adequate for the purpose of measurement (product control or process control).

The long-standing tradition of reporting measurement error only as a percent of tolerance is inadequate for the challenges of the marketplace that emphasize strategic and continuous process improvement. As processes change and improve, a measurement system must be re-evaluated for its intended purpose. It is essential for the organization (management, measurement planner, production operator, and quality analyst) to understand the purpose of measurement and apply the appropriate evaluation.

Types of Measurement System Variation

It is often assumed that measurements are exact, and frequently the analysis and conclusions are based upon this assumption. An individual may fail to realize there is variation in the measurement system which affects the individual measurements, and subsequently, the decisions based upon the data. Measurement system error can be classified into five categories: bias, repeatability, reproducibility, stability and linearity.

One of the objectives of a measurement system study is to obtain information relative to the amount and types of measurement variation associated with a measurement system when it interacts with its environment. This information is valuable, since for the average production process, it is far more practical to recognize repeatability and calibration bias and establish reasonable limits for these, than to provide extremely accurate gages with very high repeatability. Applications of such a study provide the following:

- A criterion to accept new measuring equipment
- A comparison of one measuring device against another
- A basis for evaluating a gage suspected of being deficient
- A comparison for measuring equipment before and after repair
- A required component for calculating process variation, and the acceptability level for a production process
- Information necessary to develop a Gage Performance Curve (*GPC*),¹⁷ which indicates the probability of accepting a part of some true value

The following definitions help describe the types of error or variation associated with a measurement system, so that each term is clearly understood for subsequent discussion. An illustration is given for each definition which graphically displays the meaning of each term.

¹⁷ See Chapter V, Section C.

Definitions and Potential Sources of Variation

Operational Definition

“An operational definition is one that people can do business with. An operational definition of safe, round, reliable, or any other quality [characteristic] must be communicable, with the same meaning to vendor as to the purchaser, same meaning yesterday and today to the production worker. Example:

- 1) A specific test of a piece of material or an assembly
- 2) A criterion (or criteria) for judgment
- 3) Decision: yes or no, the object or the material did or did not meet the criterion (or criteria)” FP18

Standard

A standard is anything taken by general consent as a basis for comparison; an accepted model. It can be an *artifact* or *ensemble* (instruments, procedures, etc.) set up and established by an authority as a rule for the measure of quantity, weight, extent, value or quality.

The concept of ensemble was formalized in ANSI/ASQC Standard M1-1996.¹⁹ This term was used to stress the fact that all of the influences affecting the measurement uncertainty need to be taken into account; e.g., environment, procedures, personnel, etc. “An example of a simple ensemble would be an ensemble for the calibration of gage blocks consisting of a standard gage block, a comparator, an operator, environment, and the calibration procedure.”

Reference Standards

A standard, generally of the highest metrological quality available at a given location, from which measurements made at that location are derived.

Measurement and Test Equipment (M&TE)

All of the measurement instruments, measurement standards, reference materials, and auxiliary apparatus that are necessary to perform a measurement.

Calibration Standard

A standard that serves as a reference in the performance of routine calibrations. Intended to act as a buffer between the calibration workload and the laboratory’s reference standard(s).

¹⁸ W. E. Deming, *Out of the Crisis* (1982, 1986), p. 277.

¹⁹ This definition was later updated as Measurement and Test Equipment or M&TE by subsequent military standards.