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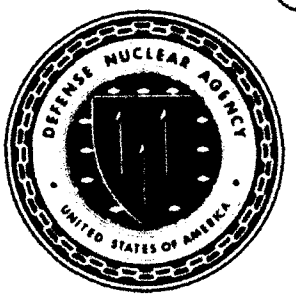

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# Statistics of Mass Production

R. Larry Williams
Wilson Y. Gateley
Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, CO 80933-7463



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R. Larry Williams and Wilson Y. Gateley

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This paper summarizes the statistical quality control methods and procedures that can be employed in mass producing electronic parts (integrated circuits, buffers, capacitors, connectors) to reduce variability and ensure performance to specified radiation, current, voltage, temperature, shock, and vibration levels. Producing such quality parts reduces uncertainties in performance and will aid materially in validating the survivability of components, subsystems, and systems to specified threats.

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## SUMMARY

Statistical Quality Control (SQC) is a broad term defining procedures that can be employed during production to insure that parts are produced having specified characteristics and performance. In developing complex systems of systems whose performance cannot be tested as entities, methods exist to identify components and subsystems whose failures, degradations, and variations most severely affect system level performance. Once identified, two methods may be employed to reduce or eliminate the system effects caused by such critical components - (1) design change employing such techniques as redundancy, proliferation, and spatial separation, and (2) component quality improvement.

This paper summarizes the SQC methods and procedures that can be employed in mass producing electronic parts - ICs, SRAMs, buffers, capacitors, connectors - to reduce variability and insure performance to specified radiation, current, voltage, temperature, shock, and vibration levels. Producing such quality parts reduces uncertainties in performance and will aid materially in validating the survivability of components, subsystems, and systems to specified threats.

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## SECTION 1

## CONTROLLING QUALITY TO INSURE SURVIVABILITY

### 1.1 TOP LEVEL STATEMENT OF THE PROBLEM.

The companion paper The Meaning and Utility of Confidence (See References) shows how system models can be created and employed to develop system-level survivability distributions and confidence intervals from quantitative information about piece parts, components, and systems. A major contributor to uncertainty in the survivability of components and piece parts is performance variability inherent from the production process. The discipline of statistical quality control provides numerous techniques for ferreting out the causes of variation and controlling or eliminating them during the production process. Applying such procedures during mass production of piece parts (e.g., silicon chips, integrated circuits) could provide significant reductions in overall uncertainties in the survivabilities of all components and subsystems of large complex systems of systems (e.g., GPALS).

Important contributors to survivability uncertainties of components and subsystems are variations in the quality of ubiquitous mass-produced electronic piece parts - microchips, integrated circuits, PC boards, switches, cables, connectors, etc. Instituting statistical quality control techniques and procedures during the production of these parts to reduce variations in parameters having the most important effects upon performance is a significant way to reduce uncertainties in survivability estimates. Consequently, SQC may be a principal tool in validating survivability at all levels of integration.

A nuclear detonation is probably the most severe conceived threat against a complex system. Such detonations can produce several types of stresses upon systems - energy coupling, airblast, dynamic loads, thermal radiation, EMP, and electro-optic disturbances. A range of such threats exist definable by hostile system capabilities and locations of detonations from specific equipment. Each postulated detonation can be specified as a point environment - an x-ray fluence, spectrum, and time waveform, a total dose, a neutron fluence, a blast overpressure, and an IR irradiance. These can be characterized as prompt (x-rays, prompt gammas, neutrons and EMP) and persistent (IR, debris gammas, betas) environments. For a system to survive and function during and after being exposed to such environments, provision must be made to withstand their effects.

Electron emission drives currents which may burnout or upset electronics. Debris gammas cause noise spikes in focal plane arrays and may affect Signal-to-Noise ratios in equipment. Induced currents due to the prompt environment and performance degradation from total dose radiation are effects that concern system developers. These effects, and those of most other nuclear environments, can be mitigated by good design and shielding. If, in the absence of other survivability measures, the survivability of various vulnerable components to specified environmental levels or current thresholds can be assured by SQC, then it appears feasible that a combination of demonstrated capability and additional hardening and shielding features will insure survivability to all but a limited set of proximate nuclear environments.

A recent paper entitled Statistical Process Control for Qualified Manufacturer's Line (QML) Radiation Hardness Assurance by P. S. Winokur, et al, at Sandia National

Laboratories (SAND-90-0368C) states that a quantitative understanding of two relationships is essential to establishing a QML to produce macrocells (1K SRAMs, random logic, buffers) and capacitors. A Qualified Manufacturer's Line is one which has been certified to meet quality standards such that additional sampling and testing of products from that line are not necessary. All parts produced meet required quality levels.

The necessary relationships are the capability to extrapolate the radiation response of an IC in actual threat scenarios from controlled laboratory measurements (e.g., total-dose "rebound" testing of hardened ICs) and the capability to correlate responses of test structures with the responses of ICs fabricated on the line. As the authors show, threshold voltage shifts due to oxide-trapped charge (DVot) and interface traps (DVit) caused by irradiation can be measured, extrapolated, and correlated. By identifying the production parameters and IC characteristics that induce the most significant effects in radiation hardness, production processes can be fine-tuned to reduce variations in these important characteristics, produce quality parts, and thus insure radiation hardness to specified levels.

## 1.2 STATISTICAL QUALITY CONTROL.

Statistical quality control is the application of statistical techniques to control the quality of manufactured products. While certain principal features of SQC - control charts, acceptance sampling - have been extant for many decades, newer techniques can also be employed. These include Taguchi methods, design of experiments, computer analysis software and process control that employ sophisticated orthogonal testing to determine the relationships of product characteristics to process parameters. The specified quality can be built into mass-produced parts by using automated processing of such data to focus on parameters having greatest effects on product performance and variability. Properly employed, these tools provide the mechanism to produce quality parts that will insure and validate survivability. Consequently, this paper summarizes and reviews pertinent SQC techniques and shows their application to reduce product variabilities that affect survivability in nuclear environments.

## SECTION 2

## IDENTIFYING CRITICAL ITEMS AND THE EFFECTS OF UNCERTAINTIES

### 2.1 SYSTEM MODELS FOR ANALYSIS.

Early in the conceptual design phase of developing a complex system of systems, system level models (e.g., system GO models as discussed in The Meaning and Utility of Confidence) should be constructed to the subsystem and component levels. Using such models with performance distributions defined as accurately as possible, sensitivity runs can be made to identify individual components and classes of components whose performance and performance uncertainties most degrade or cause variation in system survivability. Once identified, and degradation and variation quantified, appropriate measures can be taken to mitigate such effects. These include design tradeoffs, redundancy, proliferation, spatial separation, and statistical quality control.

### 2.2 FMEAS AND FMECAS TO IDENTIFY CRITICAL COMPONENTS.

Another fruitful approach for identifying critical components is to perform Failure Modes and Effects Analyses (FMEAs) and Failure Modes and Effects Criticality Analyses (FMECAs). Such analyses identify which components and which failure modes of these components can cause system failures. These components and failure modes can then be rank ordered by probability of occurrence and steps taken to eliminate failures by design alterations and quality improvements.

FMEAs and FMECAs are systematic and detailed analyses down to root cause levels of component and piece part failures. Results are usually presented in tabular form. Such studies become even more meaningful if probabilities of occurrence of the various failure modes can be determined, because, if the probabilities of occurrence of failures in specified environments can be specified, then the quantitative effects upon system performance can be determined and ordered. This provides a prioritized list of which components force design changes or quality improvement, and quantifies the potential benefits of effecting such changes or improvements.

#### *2.2.1 GO Fault Finder and Fault Trees.*

To perform FMEAs and FMECAs low-order fault sets causing system failure must be identified. Systematic procedures to identify low-order fault sets, the combinations of failed components that cause system failure, include developing Fault Trees (FT) and using FT software, or developing a system GO model and exercising the GO Fault Finder software, to identify the fault sets causing system-level failures. A nice feature of the GO Fault Finder capability is that no additional modeling is required to employ it for any anomalous system events once the system model has been developed. The software automatically identifies fault sets for specified system-level failure events. Identifying low-order fault sets using either technique is an integral part of an FMEA or an FMECA to find those components whose failures most effect system performance. Once identified, their possible failure modes and causes are comprehensively examined.

### *2.2.2 Common Cause Failures.*

Of special interest in such studies is the examination of common cause failures. That is, the common environment or cause that can simultaneously fail numerous components all susceptible to the same stimulus (e.g., temperature, moisture, radiation, excessive currents, etc.).

## 2.3 BENEFITS OF ANALYSIS.

Performing these types of system and component assessments early in the design process will produce the biggest performance increases for the least cost. An additional benefit is that when the design is finalized, the system models can be updated to provide current performance estimates throughout system life based upon operating experience and data.

## SECTION 3

## SOME BASIC IDEAS OF SQC

Producing a product involves the transformation of one or more inputs (materials, components, subsystems, etc.) into an output (the product). Mass production involves many repetitions of a particular transformation, and we call this set -- conceptually extended to an infinite number of repetitions -- a process.

The concept of a process is very general and includes everything from an employee marking his timecard to NASA producing a space shuttle. The latter, of course, involves thousands of subprocesses, each of which can be studied by itself.

The four words "quality," "control," "process," and "statistical" are used in various combinations such as "quality control," "process control," "statistical quality control," and "statistical process control" to describe the efforts to deliver an acceptable product to a customer. These four phrases are frequently used interchangeably, and so careful definitions are academic for the most part. However, a phrase involving "process" usually refers to the process which produces a product, whereas if "process" is missing, the reference is usually to the product itself. The word "statistical" suggests that formal statistical methods of one kind or another are involved in the control of the quality of the product.

By using thorough sampling procedures it is possible that acceptable products may be obtained from a low quality process -- this is defect detection. It is generally a costly procedure and represents a last-ditch defense against an inferior production process. Defect prevention is the preferable course of action, and this means designing and controlling the process so that high quality products are consistently created. For this reason, our principal concern in this paper is with process control and, in particular, because of the need for, and efficiency of, statistical methods, statistical process control (SPC).

## SECTION 4

## QUALITY CONTROL CHRONOLOGY

A brief chronology of some of the highpoints of manufacturing quality control is given in this section:

*Pre-Industrial Revolution:*
Master-apprentice system; everyone a craftsman; small organizations; close producer-customer contact; careful inspection of products; good quality control.

*18th & 19th centuries -- Industrial Revolution:*
Factory system; skilled, semi-skilled, and unskilled workers; some quality control by inspection.

*1890s:*
F. W. Taylor develops his "scientific management system" in which planning is separated from production (the "brains" from the "brawn"). This contributed to large increases in productivity, but at the expense of decreases in human relations and product quality. Inspection departments flourished, and they -- rather than the production departments -- were usually blamed for the faulty products sent to customers.

*Early 1900s:*
More and more, science and technology replace empiricism in the development of new materials and the designs of new products and production processes. Low quality products are prevalent and quality control remains in the hands of the inspectors.

*1924:*
Walter A. Shewhart proposed the use of control charts to his superiors at Western Electric. Shewhart's books Economic Control of Quality of Manufactured Product (1931) and Statistical Method from the Viewpoint of Quality Control were the foundations of much current quality control theory and practice.

*1930s:*
The Dodge-Romig Sampling Inspection Tables were developed by Harold Dodge and Harry Romig at the Bell Telephone Laboratories.

*World War II:*
Quantity rather than quality was the name of the game. The use of sampling was expanded and this effort was aided by the use of MIL-STD-105 which was based on the Dodge-Romig tables and which continues to be used in both military and nonmilitary contracts to this day. In addition, a department was set up by the War Production Board to help companies meet quality standards. Two professors of statistics were appointed to lead that department, and they developed a series of eight-day courses based upon probability theory, sampling theory, and the Shewhart control chart. These courses were instrumental in spreading the news about statistical quality control and led to the formation of the American Society for Quality Control in 1946.

*Post-World War II:*
The pent-up demand for consumer goods encouraged manufacturers to continue to emphasize quantity rather than quality, and quality control efforts generally dwindled.

*1950:*
W. Edwards Deming spoke to Japan's leading industrialists at the request of JUSE (the Union of Japanese Scientists and Engineers) in their search for ways to rebuild the Japanese manufacturing industry at a high quality level.

*1951:*
Total Quality Control by Armand V. Feigenbaum was published. In this book, Feigenbaum espoused the concept of quality control in all areas of business from design to sales and emphasized the desirability of defect prevention rather than defect detection.

*1957:*
Genichi Taguchi's book Design of Experiments Method was published. (See Section 8 herein.)

*1982:*
W. Edwards Deming's book Out of the Crisis published. This book is an exposition of the author's thoughts on how the transformation of American management can and should take place.

*1987:*
ISO 9000 series of standards published by the International Standards Organization. (See Section 10 herein.)

## SECTION 5

## THE PROCESS

Broadly speaking, a process is a transformation which changes something (the process input) into something else (the process output) -- there, of course, may be multiple inputs and outputs.

Although the change is usually thought to be in the form of the input (manufacturing a VCR), it may involve a change in location (sending a letter to your congressman) or a change in time (getting to the church on time). We are involved throughout our lives with processes of all kinds, frequently worry about many of them, and occasionally take positive action to improve some of them. However, the use of statistical methods for measuring, analyzing, improving, and finally controlling them is seldom encountered outside large-scale production facilities.

Generally, the processes of interest are those which are repeatable over time because that gives us the possibility of improving them so that the cost of operation is reduced, the quality of the output is increased, or, preferably, both.

A simple process example which we will refer to several times below is the following: A golfer -- let's call him "Gus" -- hits a golf ball. The inputs of interest might include the ball, the club used to hit the ball, the weather conditions (precipitation, temperature, wind), and many aspects of Gus himself. The outputs might include how long the ball was in the air, the direction and speed with which it was hit, and where it came to rest. For our example we will let the only output of interest be the distance between the starting point of the ball and the point where it finally stopped. We will call this the Golf Ball Process (GBP).

The ultimate interest in a process is with its output, and this interest usually involves both its cost and its quality (which refers to how well the output compares with some conceptual ideal, the nominal specification).

GBP: Gus wishes to learn how to hit the ball some particular distance and is trying for 100 yards at the moment. Thus the GBP output nominal specification is 100 yards.

The evaluation of an output will be done using either attribute data or variables data. Attribute data is usually based on good/bad (acceptable/unacceptable, go/no-go) information -- that is, does a specific output possess a certain attribute or not? The resulting numerical information for evaluating the process might then be the number or the proportion of good outputs produced over a certain time. Variables data consist of measurements (length, weight, etc.) and consequently provide more information than attribute data. Thus, if the output of a process is a metal plate in which a hole has been drilled, the use of a caliper to measure the diameter of the hole is preferable (at least for process control purposes) to the use of a go/no-go gage.

GBP: The output is evaluated by variables data -- the measured distance from where the ball was when it was hit to where it stopped. (Note that the measuring of this distance is another process in itself; we will assume that any errors made by this process are insignificant compared to those of the GBP.)

The outputs from several repetitions of a process almost always exhibit variation. Thus some drilled holes will be acceptable and some will not be; the golf ball distance will be 101 yards on the first try and 95 on the second. Such variation, besides being the bane of everyone concerned with the process or its outputs, is the major raison d'etre of probability and statistics. This rightly suggests that statistical methods can be valuable tools for studying the performance of a process.

## 5.1 PROCESS PARAMETERS AND STATISTICS.

The most important numerical measures of the performance of a process are those which define the average of the values of an output characteristic and those which define the variation of those values.

For variables data, averages include the mean (the most commonly used), the median, and the mode, while measures of variation include the variance and the standard deviation (the square root of the variance). These and other process-related measures are called process parameters.

Conceptually, any process may go on forever -- that is, there may be an unlimited (infinite) number of repetitions of the process operation. This suggests that it is impossible to ever know the exact value of these performance measures, except, of course, for theoretical studies in which the values are postulated. However, by sampling the process outputs -- looking at some of them -- over a period of time and computing appropriate sample statistics corresponding to the process parameters, estimates of the parameter values may be obtained. Thus the process mean (denoted by $\mu$) can be estimated by the sample mean (denoted by xbar), the process variance ($\sigma^2$) can be estimated by the sample variance ($s^2$), and the process standard deviation ($\sigma$) by the sample standard deviation (s) or the sample range (r). The formulas for these statistics, given a sample of n measurements of the process output (x1, x2, ..., xn), are:

$$\text{xbar} = (x1 + x2 + \ldots + xn) / n$$
$$s^2 = [(x1 - \text{xbar})^2 + (x2 - \text{xbar})^2 + \ldots + (xn - \text{xbar})^2] / (n-1)$$
$$s = \sqrt{s^2}$$
$$r = \text{largest xi} - \text{smallest xi}$$

GBP: Gus hits ten balls and measures the start-to-finish distance of each. The ten sample values and the calculation of the sample statistics are shown in Figure 5-1.

If additional samples of size n are taken from the process, we would expect to get for each sample somewhat different sample values and, consequently, different values for the sample statistics. For each statistic we could make a graph (a control chart) by plotting the several values of the statistics versus the sample number (or possibly the time at which the sample was taken).

GBP: Gus hit 15 buckets each containing 10 balls. He calculated the sample mean (xbar) for the balls from each bucket and plotted them in an x-bar chart (Figure 5-2).

How would the graph in Figure 5-2 change if Gus had used buckets containing 40 rather than 10 balls? Probability theory tells the answer: the spread in the resulting xbar values would be cut in half -- that is, the xbar values would tend to fall between 99 and 101 instead of between 98 and 102. More generally, the spread in xbar

| x | xi | xi-xbar | $(xi-xbar)^2$ |
|---|---|---|---|
| 1 | 102 | 3.1 | 9.61 |
| 2 | 105 | 6.1 | 37.21 |
| 3 | 96 | 2.9 | 8.41 |
| 4 | 101 | 2.1 | 4.41 |
| 5 | 99 | 0.1 | 0.01 |
| 6 | 98 | 0.9 | 0.81 |
| 7 | 92 | 6.9 | 47.61 |
| 8 | 101 | 2.1 | 8.41 |
| 9 | 100 | 1.1 | 1.21 |
| 10 | 95 | 3.9 | 15.21 |
| **Total** | **989** | | **128.90** |

xbar = 989 / 10 = 98.9
$s^2$ = 128.90 / 9 = 14.32
s = $\sqrt{14.32}$ = 3.78
r = 105 - 92 = 13

**Figure 5-1. GBP statistics.**

values (and s values as well) is inversely proportional to the square root of the sample size.

Even further, probability theory tells us, for example, that about 99% of the xbar values will lie between $\mu-3\sigma/\sqrt{n}$ and $\mu+3\sigma/\sqrt{n}$, which not only says that as n increases the spread in the xbar values decreases towards zero, but also that the value about which the xbar values cluster is $\mu$, the process mean. A similar statement can be made about s -- that is, as n increases, the spread in the values of s will shrink towards zero, and the value about which they cluster will be $\sigma$, the process standard deviation.

Now imagine that we were able to take an extremely large sample at frequent intervals (Gus hits a bucket of one million balls every minute). What would the resulting x-bar chart look like? Assuming no distorting influence occurring to the process, we would expect all of the xbar values to be very close to the process mean, and so the plotted points would lie along a straight horizontal line. Ignoring the points but keeping the line, we can think of the chart as representing the process mean itself rather than the sample means -- that is, we would have a Process Mean chart rather than an x-bar chart. Similarly, we can imagine constructing a Process

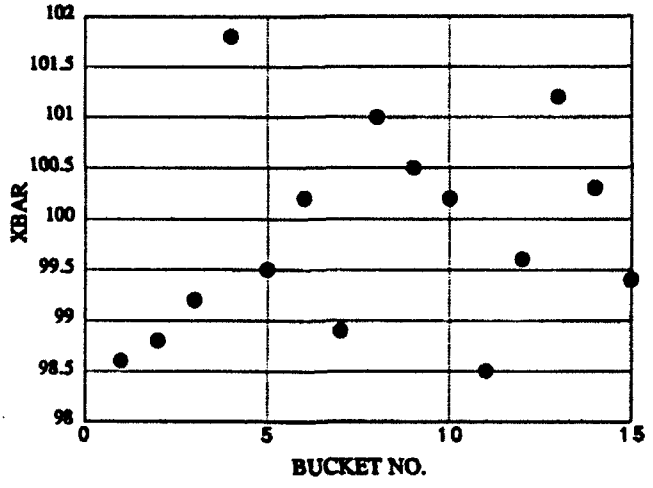



**Figure 5-2. X-bar chart.**

Standard Deviation chart. In both cases we can think of the horizontal axis as representing time. Figure 5-3 shows the resulting charts (combined into one).

The horizontal lines for $\mu$ and $\sigma$ tell us that at least over the time interval covered by the chart, both $\mu$ and $\sigma$ remained constant, and consequently, we say that the process was stable or in-control.

An unstable or out-of-control process is then one characterized by a nonconstant mean and/or standard deviation.

GBP: If Gus became tired, he might tend to hit the balls with less force (which would cause the process mean curve to dip downwards) and, possibly, more erratically (which would cause the process standard deviation curve to rise). Consequently, if both of those effects occurred, the points on a sample s chart would tend to move higher and those on a sample x-bar chart would move higher, and would also spread more because of the increase in $\sigma$.

An unstable process is inherently an unpredictable one. Consequently, because of the interest in producing high quality products in the future, the top priority activity is to create and maintain stable processes. Unfortunately, neither the detection of process instability nor its removal once it is detected is a simple or straightforward task.

To start with, there is not a practical sharp boundary between stability and instability -- that is, a few wiggles in a process chart curve are probably of no great consequence for the process output and would be ignored even if they were discovered.

Secondly, finding small instabilities in a process is extremely difficult. Detection is accomplished by searching for unusual events in the behavior of one or more of the sample statistics. However, even a stable process has some inherent variability which causes variation in the values of a sample statistic, and so small changes due to

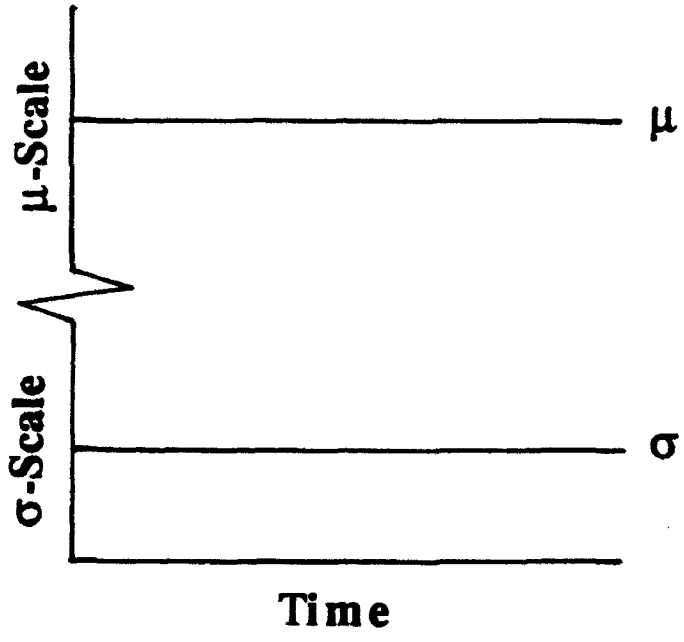



**Figure 5-3. Process mean and standard deviation chart.**

changes in the process can easily be missed. As a result of this, a process is considered to be stable unless and until an indication of instability is found.

Process variations are divided into two classifications, the first containing those which are present in a stable process and the second containing those which cause instability. The stable process variations (or causes of such variations) are referred to as common, chance, random, or inherent, while the others are called special, assignable, non-random, or non-inherent. The distinction between common and special causes is not always clear-cut, and one which is common today may be special tomorrow if it becomes prominent after other causes have been removed.

GBP: A spectator coughing and upsetting Gus is a special cause of variation, while minor fluctuations in the wind speed is probably considered a common cause if Gus is a duffer, but may be special if he is Jack Nicklaus.

## 5.2 PROCESS PROBABILITY DISTRIBUTIONS.

A process probability distribution is a mathematical function which describes the manner in which the output measurements of a stable process are distributed. In particular -- and of prime importance for the purpose of process control -- it provides a way to calculate the (approximate) proportion of output measurements falling in any specified interval (this is usually stated as the probability that a measurement

will fall in the interval). The world "approximate" is important because the probability distribution of a process can never be known exactly except by assumption or in theoretical studies.

Fortunately, for our purposes, approximations give sufficient information for most purposes.

All of the parameters of a process are implicitly defined by its probability distribution -- that is, if we know the distribution, the values of all of the parameters, as well as the probability behavior of the process can be found. Because of this, it is preferable to define process stability as an unchanging distribution rather than just one with a constant mean and standard deviation. Changes in the distribution almost always show up as changes in either the mean or standard deviation, and the changes in these are relatively easy to detect.

When discussing a process probability distribution, the term random variable is frequently used as a synonym for "output measurement". The adjective "random" basically means "coming from a distribution according only to its probability law" -- that is, nothing other than the process itself determines the value of a random variable. A set containing one or more values of a random variable is called a random sample.

The manner of defining a probability distribution depends upon whether the distribution is discrete or continuous. A discrete distribution is one for which the random variable is discrete -- that is, takes on only "separated" values such 1, 2, and 3, but not 1.5 -- and is generally associated with attribute data, such as the number of acceptable items in a sample or the number of telephone calls received per day. A continuous distribution is associated with variables data and is one for which the random variable can take on any value in an interval such as 0 to 100 or even $-\infty$ to $\infty$ (where, $\infty$ is the infinity symbol) and the interval includes all real numbers.

A distribution function is a formula and, in addition to the usual "dummy variable" (which we will always denote by "x"), will usually contain one or more parameters which permits the formula to define a family of similar distributions which differ by having different specific values for each of the parameters. In most cases, the mean and standard deviation are given by simple formulas involving the parameters.

## 5.3 DISCRETE DISTRIBUTIONS.

For each possible value of the dummy variable, the formula for a discrete distribution gives the probability that the random variable will have that value. Among the important discrete distributions are the binomial, the Poisson, and the hypergeometric.

The binomial distribution gives the probabilities of obtaining a certain number of "good" items when a sample of size n is taken from a stable process which produces a certain proportion of such items. The number of good items in the sample must, of course, be an integer between zero and n.

GBP: If a "good" shot is one which stops between 98 and 102 yards and, if experience shows that 95% of all shots are good, then the binomial distribution can be used to find, for example, the probability that if a bucket of ten balls is shot, at least eight of them will be good. The answer is 0.988 -- the reader may consult an

elementary probability book or the local statistician for computational details. We also find the mean number of good shots (over an assumed unlimited number of ten-ball buckets) is 9.5 and the standard deviation is 0.69.

The Poisson distribution gives, for example, the probabilities of the number of events occurring over some time interval when the average rate of occurrence is known. Thus, if an office receives an average of ten telephone calls per hour, the Poisson distribution says that the probability of 15 or more calls in an hour is 0.0835.

The hypergeometric distribution provides probabilities associated with acceptance sampling schemes.

## 5.4 CONTINUOUS DISTRIBUTIONS.

A continuous distribution is defined in a manner different from a discrete one. The graph of the distribution function (usually called a density function) is a non-negative curve having the property that the area between the curve, the x-axis, and the vertical lines at two points on the x-axis gives the probability that the random variable lies between those two points. The total area between the curve and the x-axis must be 1.0 because the total probability of any distribution is always 1.0.

The simplest continuous distribution (and of no particular importance to us except as an example) is the uniform distribution defined on the unit interval (between $x = 0$ and $x = 1$). Its graph is shown in Figure 5-4. The area under the "curve" between $x = 0$ and $x = 1$ is clearly 1.0. The probability that the random variable lies between 0.2 and 0.6 is 0.4; ((0.6-0.2) x 1.0).

Unfortunately, probabilities for most continuous distributions are not as simple to find, and, generally, we must rely upon published tables or appropriate computer programs to obtain them.

Because of its overriding importance, the only other continuous distribution we will mention is the normal (or Gaussian). The normal distribution function contains two parameters which happen to be the mean $\mu$ and the standard deviation $\sigma$. Its graph is the familiar bell-shaped curve which is symmetric about the vertical line at the mean. Figure 5-5 shows the graphs of several normal distributions which illustrate the influence of the parameters $\mu$ and $\sigma$.

It turns out that probabilities for a normal distribution with any specified values for $\mu$ and $\sigma$ can be obtained from a table for the standard normal for which $\mu = 0$ and $\sigma = 1$. Such a table can be found in almost any probability or statistics book, but we will not discuss its use in this paper.

The reason normal distributions play such an important role lies in the remarkable Central Limit Theorem which, in essence, says that if the total variation (the deviations from the mean) of a stable process is the sum of many small deviations coming from independent random causes, then the process distribution will be approximately normal and the approximation will improve if the number of causes increases.

GBP: There are undoubtedly many reasons why a golf ball fails to stop at exactly the 100 yard mark: the ball has a small defect or two; the wind has a slight change in direction or speed; the grass on which the ball rolls after landing differs from shot-to-shot; etc. Consequently, we would expect the process distribution to be

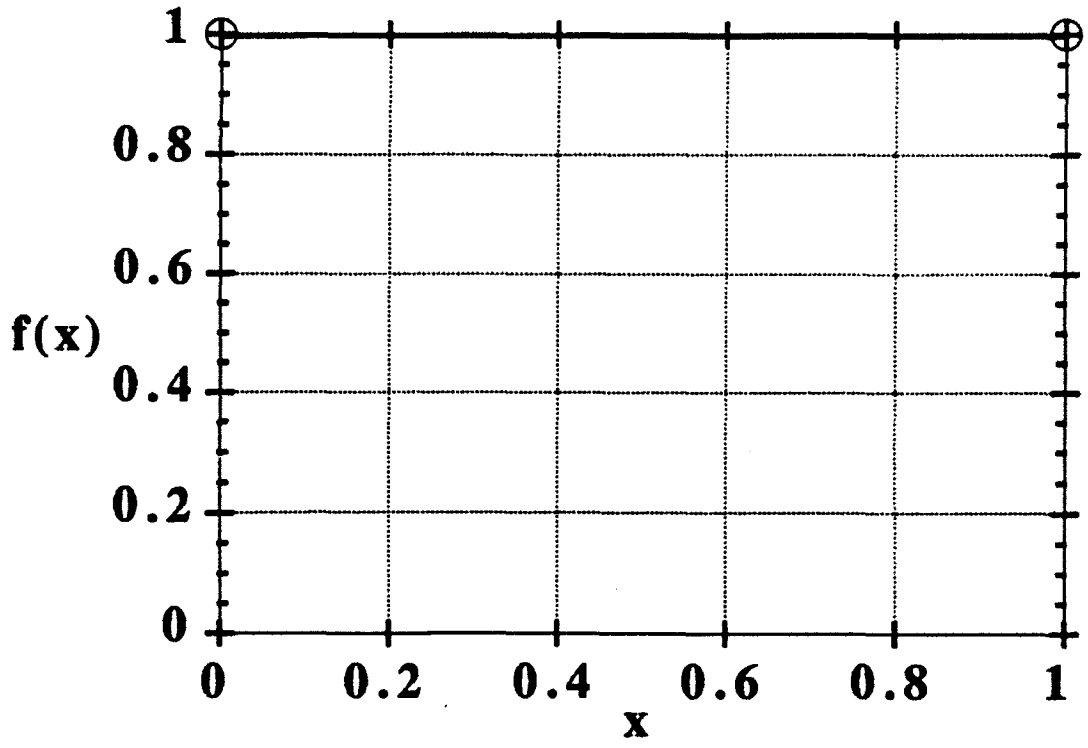



**Figure 5-4. Uniform distribution (density) function.**

approximately normal once the process has been stabilized -- that is, the major and erratic causes of variation have been eliminated.

As a result of the Central Limit Theorem and the ease of finding probabilities of a normal distribution, we are able to find approximate values for the probabilities of most stable processes.

The Central Limit Theorem also plays an important role when samples of a process are used, because, for example, if a sample of size ten is taken, the number of small variations is ten-fold greater than that of a single observation. Consequently, the probabilistic behavior of the values of the sample mean (which are essentially sums of individual values) is approximately normal. Even if the process distribution itself is far from normal, sample sizes as small as four produce distributions quite close to normal.

It must be stressed that "approximate" means exactly that, and it is a mistake to believe strongly in approximate probabilities calculated to several decimal places. This caution applies particularly to probabilities associated with the "tails" of the distribution -- that is, with those points more than two or so standard deviations from the mean.

If a distribution cannot safely be normally approximated, there are other approximations which can be used. One of these involves Chebyshev's inequality and applies to any distribution; another involves the Camp-Meidell inequality and applies to any distribution which has a single mode -- that is, the graph has a single

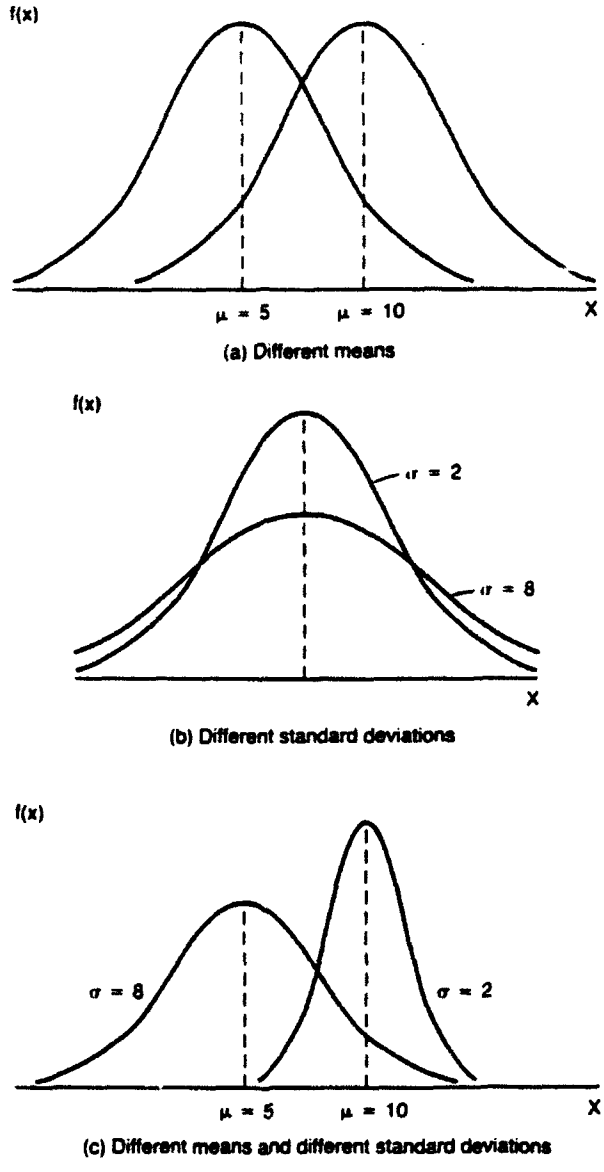



**Figure 5-5. Normal distributions.**

high point. Table 5-1 shows some statements which can be made about the probability of a random variable lying in an interval centered at its mean, depending upon whether an assumption of normality, a single mode, or nothing is made about the distribution.

Table 5-1. Probabilities of a random variable being in the interval $\mu - n\sigma$ to $\mu + n\sigma$.

| n | Normal Distribution | Unimodal Distribution | Any Distribution |
|---|---|---|---|
| 2 | 0.954 | at least 0.889 | at least 0.750 |
| 3 | 0.997 | at least 0.951 | at least 0.889 |
| 4 | 0.99994 | at least 0.972 | at least 0.938 |
| 5 | 0.9999994 | at least 0.982 | at least 0.960 |

## 5.5 TESTING FOR NORMALITY.

The determination of whether or not a distribution is approximately normal or not is subjective for the most part, but can be guided by some graphical tools. In any case, a sample of the process output is needed, and the larger the better (probably in the range from 100 to 1000).

The first -- and relatively crude -- tool is a histogram of the data. This involves dividing the range of the sample values into several subintervals (maybe 8 to 10), counting the number of sample values which lie in each subinterval, and drawing a bar chart as shown in Figure 5-6 where the height of each bar is the number of values in that subinterval. The figure shows several common histogram patterns of which only the Bell-Shaped one suggests a normal distribution.

A much better procedure is to arrange the sample values in ascending order and plot them on normal probability graph paper whose vertical axis has a nonlinear scale constructed so that the points on a plot of a sample from a normal distribution will fall very close to a straight inclined line. Systematic deviations from a straight line indicate non-normality. Figure 5-7 shows a plot which clearly suggests normality. (Computer programs are available to do all of the manipulations of the data and the drawing of the graphs.)

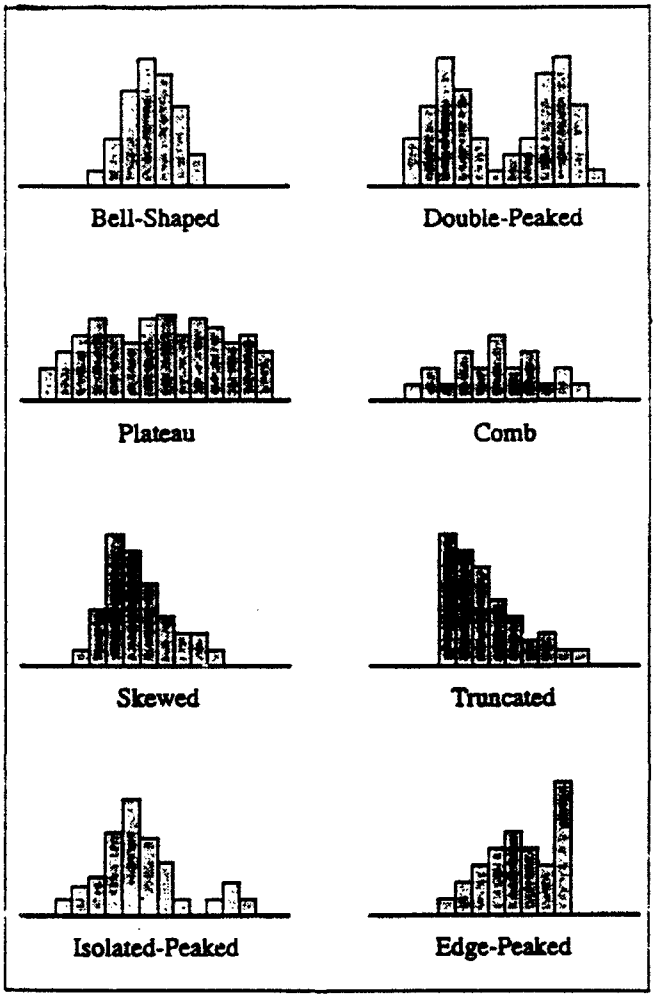



**Figure 5-6. Common histogram patterns.**

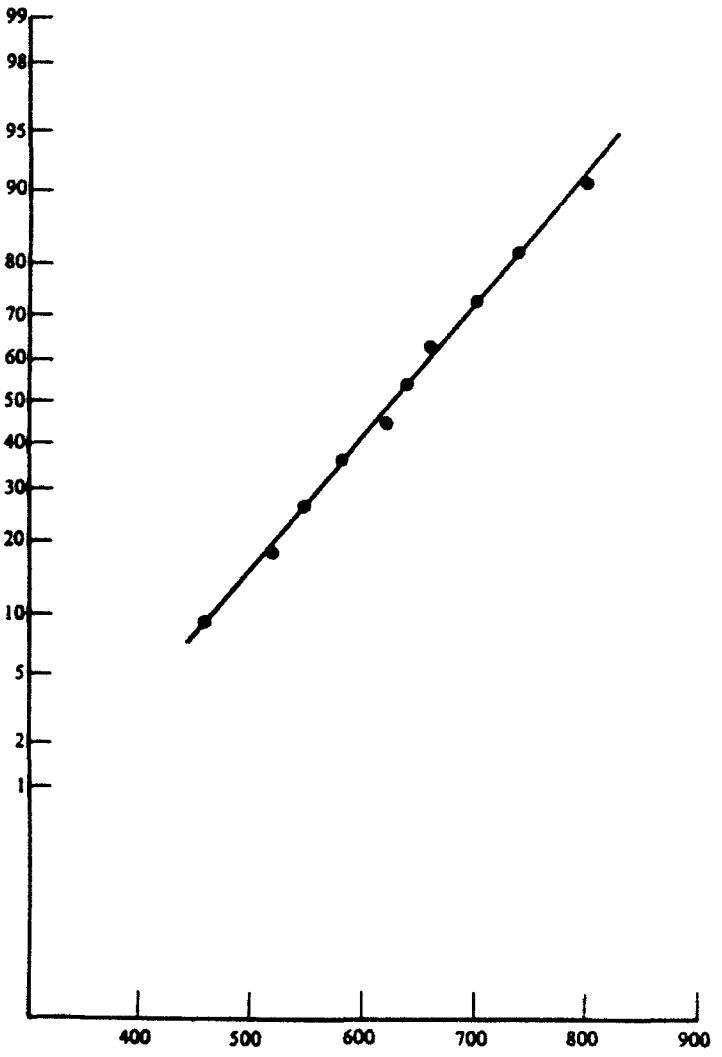



**Figure 5-7. Normal probability plot.**

## SECTION 6

## PROCESS CONTROL

The purpose of process control is to manipulate the process so that almost all of its products meet or exceed the requirements of the customer ("the almost" is due to the fact that even the best regulated process will occasionally turn out a lemon).

A briefer statement might simply say that the purpose is to produce a high-quality product, but generally the meaning of "quality" is both vague and subjective. However, a reasonably good definition can be obtained by converting the "almost" in the previous paragraph to a number which is the percentage of acceptable products produced. Thus, a process for which 95% of its products are acceptable has a quality of 95% (in the sense that the quality of a product actually refers to the quality of the process which created the product). Process control consists of those procedures which

- create a stable process.
- adjust a stable process so that a product of an acceptable quality level is produced.
- continue to monitor, adjust, and improve the process so that the product quality is at least maintained and preferably improved.

### 6.1 COLLECTING DATA.

The first step in the creation of a stable process is to learn as much as possible about the design and operation of the current process and the nature of its outputs. Most of this study will be non-statistical and might involve process flowcharts of various kinds, blueprints, layout diagrams, conversations with people at all levels who are involved, either directly or indirectly, with the process, etc.

The sources and nature of the inputs to the process should be investigated, and, in particular, the quality of the inputs must be determined.

The use of the process products by a customer should be studied, because the customer is the one who, by his use of the product, ultimately defines and determines its quality.

The analysis of the process output involves taking random samples of the output and using them to investigate the probability behavior of the process. This investigation might involve the calculation of sample statistics, constructing process control charts to see if any obvious abnormalities are present, drawing a histogram to see the general shape of the distribution, and, generally, using all graphical or analytical tools which might shed some light on the process and help detect and uncover the causes of instabilities.

Discussions with those workers most closely associated with the process are particularly valuable here because these people can often pinpoint the cause of observed irregularities.

## 6.2 CONTROL CHARTS.

Control charts are probably the major analytical tool used to create and maintain a stable process. Such charts consist of nothing more than graphs of consecutive values of some sample statistic on which certain horizontal lines are drawn. Charts may be constructed for any sample statistic or even for individual measurements (really just a sample of size 1). Table 6-1 lists most of the common charts.

**Table 6-1. Control chart types.**

| Data Type | Statistic | Chart Name |
|---|---|---|
| Variables | mean<br>standard deviation<br>range<br>individual<br>individual | x-Bar<br>s<br>r<br>x<br>moving range |
| Attribute | proportion defective<br>number defective<br>number of defects | P<br>np<br>c or u |
| Either | any | cumulative sum (cusum) |

We will not discuss any particular type of chart, but simply note that the principles of constructing and using any of them are similar. Variables charts are the most common and are preferred over attribute charts because a measurement provides more information than a good/bad determination. Attribute charts are usually "one-sided" in the sense that the number of defective items in a sample or the number of defects occurring with a single item can never be less than zero, and zero is always the desired goal.

For variables data at least two charts are used: one for a measure of the sample average (usually an x-Bar chart for the sample means) and another for a measure of the sample variability (either an s chart for the sample standard deviations or an r chart for the sample ranges). S charts are preferable to r charts because, in a statistical sense, a sample standard deviation is a better estimator than a sample range of the process standard deviation. The range has been used in the past, at least for small sample sizes (less than ten or so) because of the relative simplicity of calculating a range compared to that for a standard deviation. With the ready and inexpensive availability of electronic calculators and computers to do the arithmetic, the objection to using a standard deviation has much less force today.

The control chart on which the values of a sample statistic are plotted is completed by adding a horizontal line at the best available estimate of the unknown and unknowable mean of the theoretical population of sample statistic values and two other horizontal lines, one a certain distance above the mean line and the other below. These two lines are called control lines -- upper (UCL) and lower (LCL) -- and are positioned so that almost all possible sample statistic values will fall between them if the process is stable. In most cases the lines are so-called 3-sigma lines which means that they are placed a distance from the mean line of 3 times the estimated standard deviation of the sample statistic population. The idea is that if the

distribution of the statistic were normal and the exact values of the population mean and standard deviation were known, the probability would be exactly 0.997 (99.7%) that any sample statistic value would fall in the band between the control limits.

Consequently, a value falling outside the band would say that either a very unlikely event occurred (probability = 0.3%) if the process is stable, or an unlikely event has not occurred because the process is out-of-control (not stable) and needs some attention. Unfortunately, except in theoretical studies, we do not know either the population mean or standard deviation or whether or not the distribution is normal. As a result, the probability associated with the control band is almost certainly not 99.7%.

Table 5-1 above indicates that the probability associated with a 3-sigma band is at least 89% for any distribution and at least 95% if the distribution is unimodal. In short, the probability is almost certainly greater than 0.3% that a statistic value will fall outside the control band, and so we may expect more false alarms than we had hoped for. We might, of course, use 4-sigma limits to reduce the number of such alarms, but this would also increase the risk of not detecting instability. The moral here is that use of a control chart should always be tempered by the wisdom and intuition provided by a well-trained person with considerable process control knowledge and experience.

Some statistics, unlike the sample mean, do not have symmetrical probability distributions, and so the two control limits are set at different distances from the mean line in such a manner that the probability associated with the part of the band above the mean line is the same as that below. (Actually, regardless of the form of the distribution, there may be situations in which unequal probabilities are desired, but such cases are unusual.) Doing all this sounds a bit forbidding, but almost any process control textbook or manual contains tables of theoretically-derived constant coefficients which can be easily used to set the limits for any type of chart.

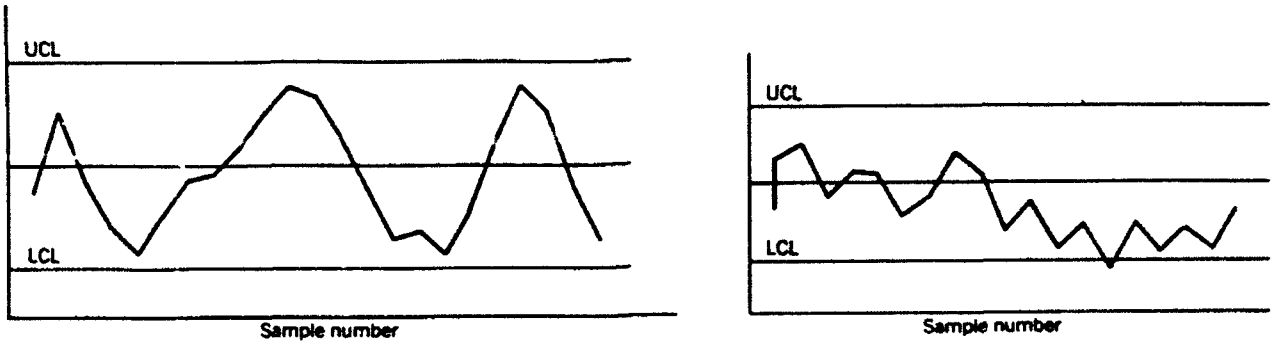
There are many ways by which a process instability can reveal itself other than a sample statistic value falling outside the control band.

These include a substantial change in the level of the observed values, a drift upwards or downwards, a cyclical pattern, and generally any pattern which has a low probability of occurring if the process is indeed in-control. Figure 6-1 shows some typical charts for out-of-control processes. There are a number of specific rules available, but their application should always be used with some degree of caution.

## 6.3 CREATING STABILITY.

Once instability is detected or suspected in a process, the question of how to isolate the cause arises. There are no magic tools to use for this, but the possibilities include:

- Create and use a Cause-and-Effect diagram. This is a diagram showing all of the possible causes which can be thought of which might lead to an effect (in this case, the instability). This is usually a group effort and has proved to be quite successful in many cases. A Cause-and-Effect diagram is also called a fishbone or an Ishikawa diagram, the first because of the form it frequently takes as possible causes are broken down into smaller ones, and the second after Kaoru Ishikawa who developed it in 1943.




CYCLES ON A CONTROL CHART A SHIFT IN PROCESS LEVEL

**Figure 6-1. Some charts of out-of-control processes.**

- Create a Pareto chart for the more promising causes. A Pareto chart is just a bar chart in which the height of each bar represents a measure of how much of the effect is due to the cause associated with that bar (the bars are usually placed in descending order of height). The Pareto principle states that in many situations almost all of an effect (80% or so) is due to only a few of the possible causes (20% or so). Thus a Pareto chart, even though the numbers involved are crude, may indicate which causes are the most promising candidates for attention.

- Investigate possible process mixtures. The output of a process may involve a mixture of two or more subprocesses -- for example, a night shift and a day shift, several machines or people whose outputs are combined before sampling occurs, process inputs from different sources, etc. Measuring the output due to each component of a mixture may reveal significant differences.

The Shewhart Cycle -- renamed the Deming Cycle by the Japanese and commonly referred to as the Plan-Do-Check-Act (PDCA) Cycle -- is a general four-step method which can aid management in stabilizing a process as well as in other quality improvement efforts:

1. Plan: A plan to effect improvement is developed.

2. Do: The plan is carried out, preferably on a small scale.

3. Check: The effects of the plan are observed.

4. Act: If the results are favorable, the plan can be implemented on a large scale; otherwise, go back to step 1.

## 6.4 MEETING THE CUSTOMER'S SPECIFICATIONS.

The goal of controlling a process is to produce a product which makes the customer happy. Usually "what makes the customer happy" is expressed in the form of product specifications. In most cases, the specifications for each of the possible measurements of the product are given numerically and define a band of values within which the measurement must fall in order that the product be acceptable (conformable). This band is commonly defined by a nominal (target) value and a tolerance, so that the band extends from "nominal - tolerance" to "nominal + tolerance" (there may be separate tolerances for below and above). The resulting two numbers are called the Lower Specification Limit (LSL) and the Upper Specification Limit (USL) respectively.

The ability of a process to satisfy product specifications depends upon two attributes of its distribution: accuracy and precision. Accuracy pertains to the distance between the process mean $\mu$ and the corresponding nominal specification (this distance is called the bias of the process), while precision pertains to the variation of the process about that mean and is measured by the process standard deviation $\sigma$ (the larger the standard deviation, the smaller the precision). Accuracy and precision are frequently used in a relative manner -- for example, process A is more accurate than process B, or process C is not precise (presumably relative to some other process). The two attributes are independent of each other, precision being an inherent property of the process and accuracy depending upon the process behavior with respect to an external standard.

GBP: Figure 6-2, in which each dot represents one golf ball, shows the results of a sample for each of the four possible combinations of accuracy and precision combinations. The nominal specification is 100 yards, but no tolerance is indicated.

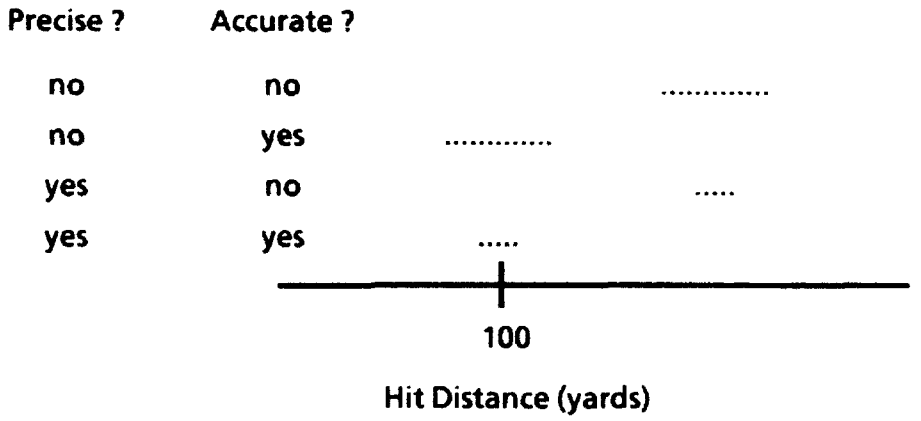



**Figure 6-2. GBP accuracy and precision.**

It is desirable to have a measure of the ability of a process to satisfy the product specifications. Such a measure (capability index) -- which is meaningful only for a stable process -- should involve both the accuracy and precision of the process and the specification limits. Some commonly used indices include:

- $C_p = (USL - LSL) / (6\sigma)$
- $CPU = (USL - \mu) / (3\sigma)$
- $CPL = (\mu - LSL) / (3\sigma)$
- $C_{pk}$ = minimum of CPU and CPL

GBP: Gus wants to have the balls stop within four yards (the tolerance) of the nominal value of 100 yards. Therefore, LSL = 96 and USL = 104. If $\mu = 99$ and $\sigma = 1$, then;

$$C_p \ (104 - 96) / 6 = 1.33$$

$$CPU = (104 - 99) / 3 = 1.67$$

$$CPL = (99 - 96) / 3 = 1.00$$

$$C_{pk} = \min(1.67, 1.00) = 1.00$$

These indices are not altogether satisfactory, because, for them to be meaningful, it is necessary to have a normally distributed process ($C_p$ also requires that the process be unbiased). There is considerable debate in the quality control community about their worth, and care must be taken with their use.

If the $C_p$ of a stable, normally distributed, and unbiased process is equal to unity, then the probability of producing a conformable product is 99.7% -- a defect rate of about three per thousand. If the $C_p$ were 1.67, each specification limit would be $5\sigma$ from the process mean, and the defect rate would be only about one per million. A defect rate -- or, equivalently, the percent conformable -- is what the above indices are attempting to express and is a much more understandable measure. In addition, it can be applied to any biased or non-normal distribution as long as the distribution can be adequately estimated.

In the above discussion it was tacitly assumed that, as far as the customer is concerned, a product whose value falls at or near one of the specification limits is just as good as one falling exactly at the nominal value. Although this is certainly true in many cases, it seems unreasonable that the worth of a product suddenly jumps from totally satisfactory to worthless as its value crosses a specification limit. Taguchi (and others before him) has suggested that the worth of a particular product item be degraded as a function of the distance between the product value and the specification target and, in particular, that a quadratic loss function be used -- that is, the loss in worth be proportional to that distance. Even though this form of the loss function is not always appropriate, the idea that getting product values closer and closer to the target value is a worthwhile goal for both the producer and the customer can do and has done much to promote high quality in production processes.

## 6.5 MAINTAINING AND IMPROVING A STABLE PROCESS.

Once a stable process has been created, the stability must be maintained and continuing effort made to reduce the common variation. Reducing the common variation is beneficial to both producer and customer, primarily by the reduction or elimination of defective products. Whether a defective item is found by the producer or by the customer, it must be fixed or replaced, and this creates a direct and/or indirect cost to both parties.

The maintenance of the stability of a process uses the same tools as those for the creation of the stability in the first place. Instability might occur for any of several reasons -- wearout of the machinery, changes in personnel, changes in the nature of an input material, complacency setting in after initial stability has been achieved, environmental changes, etc. The possibility of instability returning is lessened if common variation reduction is pursued, because of the required active surveillance of the process.

One of the major pitfalls to be avoided with a stable process is an overzealous attempt to reduce the variability by frequent process adjustments. If the process is truly stable, this action -- called tampering -- is guaranteed to produce just the opposite effect and increase rather than decrease the variability. Such an effect is convincingly demonstrated by the funnel experiment -- popularized by Deming -- in which marbles are dropped one at a time through an elevated funnel onto a flat surface and the stopping locations of the marbles marked. If the location of the funnel remains fixed, the experiment will be a stable process and will produce a well-defined pattern of dispersion of the marked points. If the funnel's position is changed after each marble in an attempt to obtain more uniformity in the stopping positions (a fairly natural impulse), the variation will inevitable increase, possibly without bound, depending on the nature of the tampering rule used.

GBP: If Gus has developed a stable process, his attempts to adjust it by hitting the ball softer or harder, changing his stance, and so forth will almost certainly increase rather than decrease the variation in the stopping distance of a ball.

The total common variation of a process is almost always due to several sources. Reduction of that variation first requires identifying some of these sources and then estimating the variation produced by each of them. This program sounds similar to that employed for changing an unstable process to a stable one, but a major difference is that common causes of variation do not produce distinctive patterns in control charts, whereas special causes usually do. Consequently, the identification of common causes and the measurement of their effects usually requires experiments with the process in which one or more of the process variables (input materials, operators, machines, etc.) are altered in a systematic manner, and the results analyzed. Although studying one cause at a time can lead to improvements in many cases, the possibility of interaction between causes, and the desire to obtain optimum results over several causes without excessive experimental costs, point to the need for statistically designed experiments. The father of such experiments was R. A. Fisher, whose work in the 1920s and 1930s laid both the theoretical and practical foundations of these experimental methods. Over the past twenty years or so, the name of Genichi Taguchi has become well-known largely because of his work in this area.

GBP: In his efforts to reduce the variation in his golf game (which has become stable), Gus has identified several possible sources of variation, including golf ball

brand, club design, air temperature and humidity, and the color of his socks. Without going into technical detail, we suggest that he visit his neighborhood statistician to help set up a suitable experimental design which will permit Gus to investigate the effects of all of these factors simultaneously. This will minimize the time and cost of the experiment and still produce results which include the effects for both the individual factors and their interactions, consequently guiding Gus towards an optimized game.

## 6.6 ACCEPTANCE SAMPLING.

Goods or services enter an organization from a vendor or are passed along internally from department to department and may be subjected to inspection procedures in an effort to both receive and produce high quality goods and thus reduce total production costs. Three alternatives for inspection exist: (1) no inspection; (2) 100% inspection (inspect everything with the goal of weeding out all defective items); and (3) acceptance sampling (inspect a sample of the goods to determine if the remainder should be accepted, rejected, or screened). Historically, acceptance sampling has been used if the inspection test is destructive or the cost of 100% inspection is excessive.

The purpose of acceptance sampling is to determine the disposition of goods or services (accept, reject, or screen). This is accomplished by selecting that disposition which minimizes the cost of inspection to achieve a desired level of quality (% acceptable). Although acceptance sampling has a long history, its use has come under attack in recent years by Deming and others, the argument being that if the production process is stable, both a sample and the remainder of the sampled group of products are independent random samples of the process, and, consequently, the number of defects in the sample indicates nothing about the number in the remainder; consequently, the only reasonable sampling procedures are either 0% or 100%.

Whether or not this view will prevail remains to be seen, but it is unlikely that acceptance sampling will totally vanish from the scene.

To choose between the two alternatives of 0% and 100%, Deming has proposed using the kp rule. If we let p be the proportion of defects produced by the process, k1 be the cost to initially inspect one item, and k2 be the cost to dismantle, repair, and reassemble a good or service that fails because a defective item was used in its production, then the inspection rules are:

1. If k1/k2 is greater than p, then use 0% inspection. There is little risk associated with a defective item.

2. If k1/k2 is less than p, then use 100% inspection. There is great risk associated with a defective item.

3. If k1/k2 equals p, choose either 0% or 100% inspection, but if there is any serious doubt, for safety's sake choose 100%.

A major problem in applying the kp rule is the difficulty of determining values for k1 and k2, but even rough estimates may be sufficient to choose an appropriate course of action.

It is important to note that 0% inspection does not mean that no information is available about the process, because small samples should always be taken to provide data for maintaining control charts.

## 6.7 IN-PROCESS MEASUREMENT AND CONTROL.

Inspection, including dimensional inspection, has commonly been an activity performed after, rather than during, a manufacturing step or process. In many instances, several steps may be performed before a part is measured. If a part is found to deviate from the manufacturing tolerances, it must be either reworked or rejected at a point where considerable value has been added to it, but in either case, the manufacturing cost is boosted.

Because of increasing competitive pressures, the American industrial community is turning to means of reducing manufacturing costs while improving quality. In addition to such approaches, such as increased automation and the use of robots, more subtle methods that work hand in hand with automation are being implemented. One such approach is the combination of in-process measurement and control. In-process measurement is significant in that it ultimately allows a manufacturer to achieve a goal of zero scrap, since deviations in the manufacturing process which are measured by sensors can be used in a corrective manner to control the process before tolerances are exceeded. (Note that this is not tampering because the corrections are made to insure that the current item is satisfactory rather than to hope that the next one will be.) Advances in sensor technology and digital computers and controllers are permitting a dramatic increase in the implementation of these ideas.

## SECTION 7

## TOTAL QUALITY CONTROL

Total Quality Control (TQC) is essentially a philosophy of production management which espouses the involvement of management at all levels in the task of quality control. Names of prominent people involved in the practice and/or teaching of TQC include Phillip Crosby, W. Edwards Deming, Armand Feigenbaum, Kaoru Ishikawa, and Joseph Juran.

As an example of the ideas, the well-known 14 points of Deming (taken from the 1986 edition of his book Out of the Crisis) are:

1. Create constancy of purpose toward improvement of product and service, with the aim to become competitive and to stay in business and to provide jobs.

2. Adopt the new philosophy. We are in a new economic age. Western management must awaken to the challenge, must learn their responsibilities, and take on leadership for change.

3. Cease dependence on inspection to achieve quality. Eliminate the need for inspection on a mass basis by building quality into the product in the first place.

4. End the practice of awarding business on the basis of price tag. Instead, minimize total cost. Move toward a single supplier for any one item, on a long-term relationship of loyalty and trust.

5. Improve constantly and forever the system of production and service, to improve quality and productivity, and thus constantly decrease costs.

6. Institute training on the job.

7. Institute leadership. The aim of supervision should be to help people, machines, and gadgets to do a better job. Supervision of management is in need of overhaul as well as supervision of production workers.

8. Drive out fear, so that everyone may work effectively for the company.

9. Break down barriers between departments. People in research, design, sales, and production must work as a team to foresee problems of production and in use that may be encountered with the product or service.

10. Eliminate slogans, exhortations, and targets for the work force asking for zero defects and new levels of productivity. Such exhortations only create adversarial relationships, as the bulk of the causes of low quality and low productivity belong to the system and thus lie beyond the power of the work force.

11a. Eliminate work standards (quotas) on the factory floor. Substitute leadership.

11b. Eliminate management by objective. Eliminate management by numbers, numerical goals. Substitute leadership.

12a. Remove barriers that rob the hourly worker of his right to pride of workmanship. The responsibility of supervisors must be changed from sheer numbers to quality.

12b. Remove barriers that rob people in management and in engineering their right to pride of workmanship. This means, inter alia, abolishment of the annual or merit rating and of management by objective.

13. Institute a vigorous program of education and self-improvement.

14. Put everybody in the company to work to accomplish the transformation. The transformation is everybody's job.

## SECTION 8

## TAGUCHI METHODS

Genichi Taguchi is a Japanese engineer who has been active in the improvement of Japan's industrial products and processes since the late 1940s. He has developed both a philosophy and a methodology for the process of quality improvement that depends heavily upon statistical concepts and tools, especially statistically designed experiments. Many Japanese firms have achieved great success by applying his methods, and it has been reported that thousands of engineers have performed tens of thousands of experiments based on his teaching.

Although he has given seminars in the U.S. since the early 1970s, it wasn't until about 1980 that American companies (including AT&T, Ford, and Xerox) actively began applying his ideas. While much attention has focused on Taguchi's statistical methods, the heart of his message has more to do with his conceptual framework for the process of quality improvement. The following seven points summarize the elements of this message:

1. An important dimension of the quality of a manufactured product is the total loss to society generated by that product.

2. In a competitive economy, continuous quality improvement and cost reduction are necessary for staying in business.

3. A continuous quality improvement program includes incessant reduction in the variation of product performance characteristics about their target values.

4. The customer's loss due to a product's performance variation is often approximately proportional to the square of the distance of the performance characteristic from its target value.

5. The final quality and cost of a manufactured product are determined to a large extent by the engineering designs of the products and its manufacturing process.

6. A product's (or process') performance variation can be reduced by exploiting the nonlinear effects of the product (or process) parameters on the performance characteristics.

7. Statistically designed experiments can be used to identify the settings of product (and process) parameters that reduce performance variation.

Most of these points have been made by others in the past, but Taguchi has been particularly successful in integrating them and demonstrating their effectiveness.

## SECTION 9

## COMPUTER USE

There are several ways in which computers are involved in process control, and their use is becoming more and more significant as an increasingly large number of commercial computer programs become available. The list below shows in parentheses the number of these programs which are appropriate for each of the listed categories and which were included in the 1991 yearly summary of computer programs in Quality Progress, a publication of the American Association for Quality Control. (Many of the individual programs are included in more than one category):

Calibration (34)
Capability Studies (85)
Data Acquisition and Reporting (71)
Design of Experiments (51)
Gage Repeatability and Reproducibility (39)
Inspection (60)
Management (74)
Measurement (74)
Problem Solving (64)
Quality Assurance for Software Development (11)
Quality Costs (39)
Quality Function Deployment (5)
Reliability (47)
Sampling (49)
Simulation (14)
Statistical Methods (82)
Statistical Process Control (103)
Supplier Quality Assurance (49)
Taguchi Techniques (24)
Training (52)
Other (40)

## SECTION 10

## STANDARDS

Companies in the United States have long had standards to describe what a quality system should be. Some of these have been regulatory standards such as the Good Manufacturing Practices for the Food and Drug Administration and military standards such as MIL-Q-9858A (quality program requirements), MIL-STD-45662A (creating and maintaining a calibration system for measurement and test equipment), MIL-STD-414 (controlling the fraction of incoming material that does not conform to specifications for variable data), and MIL-STD-105E (lot-by-lot acceptance sampling plans). In recent years, the International Standards Organization (ISO) -- a specialized international agency for standardization composed of the national standards bodies of 91 countries -- has developed the ISO 9000 series of international standards.

The standards in the ISO 9000 series were developed by Technical Committee 176 of the ISO and approved in their present form in 1987.

Concurrently, the American Society for Quality Control cooperated in adopting the ISO 9000 series for use in the United States, and this resulted in the Q90 series.

There are five standards in the ISO 9000 series:

The ISO 9000 standard provides some basic definitions and concepts and summarizes how to select and use the other standards in the series.

The ISO 9001, 9002, and 9003 standards are for use in external quality assurance purposes for contractual situations:

ISO 9001 is to be used to ensure conformance to specified requirements during design and development, production, installation, and servicing.

ISO 9002 is used when only production and installation conformance is to be ensured.

ISO 9003 is the least detailed standard and requires only that conformance in final test and inspection be ensured.

ISO 9004 contains guidance on the technical, administrative, and human factors affecting the quality of products and services. This standard is for internal use only and is not to be used in contractual situations. The standard lists the essential elements that make up a quality system in some detail, starting with the responsibilities of management. Whole sections are devoted to each aspect of the quality system: marketing, design, procurement, production, measurement, post production, materials control, documentation, safety, and use of statistical methods. This standard could be used to evaluate a company's progress toward a fully implemented quality system.

The ISO 9000 series of standards has been adopted by British companies as a tool to establish whether their suppliers have been and are using a quality system that will ensure their ability to meet their product and service requirements. This requires that the supplier be audited and then registered (if it passes the audit) as an

ISO 9000 supplier. All other companies will accept this registration with little or no further auditing. Companies wishing to be suppliers to British companies are being required to become registered under the appropriate ISO standard. By 1990, more than 30 U.S. companies were registered by the British Standards Institute or other accredited registration agencies. Starting in 1992, companies in the integrated European Community will require their suppliers to be audited and registered under the British EN 29000 series of standards. These, like the Q90 series, are technically identical to the ISO 9000 series.

## SECTION 11

## LIST OF REFERENCES

The references list below is not intended to be exhaustive, but includes those books and articles that have been consulted in the preparation of this paper or have been particularly recommended.


TEXTS:

AT&T, Statistical Quality Control Handbook. Indianapolis, Ind.: AT&T, 1956.

Box, G.E.P., J. S. Hunter, and W. G. Hunter, Statistics for Experimenters. New York: John Wiley & Sons, 1978.

Deming, W. Edwards, Out of the Crisis. Cambridge, Mass.: MIT Center for Advanced Engineering Study, 1986.

Feigenbaum, A. V., Total Quality Control. New York: McGraw-Hill, 1980.

Gitlow, H., S. Gitlow, A. Oppenheim, and R. Oppenheim, Tools and Methods for the Improvement of Quality, Boston, Mass.: Richard D. Irwin, Inc., 1989.

Hart, M. K., and R. F. Hart, Quantitative Methods for Quality and Productivity Improvement. Milwaukee, Wis.: ASQC Quality Press, 1989.

Ishikawa, K., Guide to Quality Control. Tokyo, Japan: Asian Productivity Organization, 1976.

Juran, J., Quality Control Handbook. New York: McGraw-Hill, 1979.

Montgomery, D.C., Introduction to Quality Control. New York: John Wiley & Sons, 1985.

Murphy, S. D. (editor), In-Process Measurement and Control. New York: Marcel Decker, Inc., 1990.

Oakland, J. S., Statistical Process Control. New York: John Wiley & Sons, 1988.

Ott, E. R., Process Quality Control. New York: McGraw-Hill, 1975.

Taguchi, G. and Y. Wu, Introduction to Off-Line Quality Control. Nagoya, Japan: Central Japan Quality Control Association, 1980.

Williams, R. L. and Gateley, W. Y., The Meaning and Utility of Confidence. Colorado Springs: Kaman Sciences Corporation, 1992.

Winokur, P. S., et al, Statistical Process Control for QML Radiation Hardness Assurance. Albuquerque: Sandia National Laboratories, 1990.

PERIODICALS:

Journal of Quality Technology (formerly Industrial Quality Control), published by the American Society for Quality Control.

Quality Engineering, published by the American Society for Quality Control.

Quality Progress, published by the American Society for Quality Control.

Technometrics, published jointly by the American Statistical Association and the American Society for Quality Control.

## APPENDIX A

## GLOSSARY OF ACRONYMS, TERMS, AND DEFINITIONS

Acceptable Quality Level - When a continuing series of lots is considered, a quality level that, for the purposes of sampling inspection, is the limit of a satisfactory process average.

Acceptance Sampling - Inspection of a sample from a lot to decide whether to accept or not accept that lot. There are two types: attributes sampling and variables sampling. In attributes sampling, the presence or absence of a characteristic is noted in each of the units inspected. In variables sampling the numerical magnitude of a characteristic is measured and recorded for each inspected unit; this involves reference to a continuous scale of some kind.

Acceptance Sampling Plan - A specific plan that indicates the sampling sizes and the associated acceptance or non-acceptance criteria to be used. In attributes sampling, for example, there are single, double, multiple, sequential, chain, and skip-lot sampling plans. In variables sampling, there are single, double, and sequential sampling plans.

Accreditation - Certification by a duly recognized body of the facilities, capability, objectivity, competence, and integrity of an agency, service, or operational group or individual to provide the specific service or operation needed. The Registration Accreditation Board accredits those organizations that register companies to the ISO 9000 series standards.

American Quality Foundation - An independent, nonprofit entity formed under the auspices of the American Society for Quality Control (ASQC). Its mission is to involve business leaders and public policy analysts in strengthening the future of quality. Acting as a research and development function of ASQC, the foundation develops programs to promote and support efforts that improve U.S. business's ability to compete.

American Society for Quality Control - A professional, not-for-profit association that develops, promotes, and applies quality-related information and technology for the private sector, government, and academia. The Society serves more than 96,000 individual and 700 corporate members in the United States and 63 other countries.

Analysis of Means (ANOM) - A statistical procedure for troubleshooting industrial processes and analyzing the results of experimental designs with factors at fixed levels. It provides a graphical display of data. Ellis R. Ott developed the procedure in 1967 because he observed that nonstatisticians had difficulty understanding analysis of variance. Analysis of means is easier for quality practitioners to use because it is an extension of the control chart. In 1973, Edward G. Schilling further extended the concept, enabling analysis of means to be used with non-normal distributions and attributes data where the normal approximation to the binomial distribution does not apply. This is referred to as analysis of means for treatment effects.

Analysis of Variance (ANOVA) - A basic statistical technique for analyzing experimental data. It subdivides the total variation of a data set into meaningful component parts associated with specific sources of variation in order to test a

hypothesis on the parameters of the model or to estimate variance components. There are three models: fixed, random, and mixed.

ANOM - Analysis of Means

ANOVA - Analysis of Variance

AOQ - Average Outgoing Quality

AOQL - Average Outgoing Quality Limit

ASQC - American Society for Quality Control

Attribute Data - Go/no-go information. The control charts based on attribute data include percent chart, number of affected units chart, count chart, count-per-unit chart, quality score chart, and demerit chart.

Availability - The ability of a product to be in a state to perform its designated function under stated conditions at a given time. Availability can be expressed by the ratio uptime/(uptime + downtime), uptime being when the product is operative (in active use and in standby state) and downtime being when the product is inoperative (while under repair, awaiting spare parts, etc.).

Average Chart - A control chart in which the subgroup average, X-bar, is used to evaluate the stability of the process level.

Average Outgoing Quality - The expected average quality level of outgoing quality over all possible levels of incoming quality for a given acceptance sampling plan and disposal specification.

Benchmarking - An improvement process in which a company measures its performance against that of best-in-class companies, determines how those companies achieved their performance levels, and uses the information to improve its own performance. The subjects that can be benchmarked include strategies, operations, processes, and procedures.

Big Q, Little Q - A term used to contrast the difference between managing for quality in all business processes and products (big Q) and managing for quality in a limited capacity - traditionally in only factory products and processes (little Q).

Blemish - An imperfection that is severe enough to be noticed but should not cause any real impairment with respect to intended normal or reasonably foreseeable use. (See also defect, imperfection, and nonconformity.)

Block Diagram - A diagram that shows the operation, interrelationships, and interdependencies of components in a system. Boxes, or blocks (hence the name), represent the components; connecting lines between the blocks represent interfaces. There are two types of block diagrams: a functional block diagram, which shows a system's subsystems and lower-level products, their interrelationships, and interfaces with other systems; and a reliability block diagram, which is similar to the functional block diagram except that it is modified to emphasize those aspects influencing reliability.

Brainstorming - A technique that teams use to generate ideas on a particular subject. Each person in the team is asked to think creatively and write down as many ideas as possible. The ideas are not discussed or reviewed until after the brainstorming session.

C Chart - Count Chart

Calibration - The comparison of a measurement instrument or system of unverified accuracy to a measurement instrument or system of a known accuracy to detect any variation from the required performance specification.

Cause-And-Effect Diagram - A tool for analyzing process dispersion. It is also referred to as the Ishikawa diagram, because Kaoru Ishikawa developed it, and the fishbone diagram, because the complete diagram resembles a fish skeleton. The diagram illustrates the main causes and subcauses leading to an effect (symptom). The cause-and-effect diagram is one of the seven tools of quality.

Check Sheet - A simple data-recording device. The check sheet is custom-designed by the user, which allows him or her to readily interpret the results. The check sheet is one of the seven tools of quality. Check sheets are often confused with data sheets and checklists.

Checklist - A tool used to ensure that all important steps or actions in an operation have been taken. Checklists contain items that are important or relevant to an issue or situation. Checklists are often confused with check sheets and data sheets.

Common Causes - Causes of variation that are inherent in a process over time. They affect every outcome of the process and everyone working in the process.

Company Culture - A system of values, beliefs, and behaviors inherent in a company. To optimize business performance, top management must define and create the necessary culture.

Conformance - An affirmative indication or judgment that a product or service has met the requirements of a relevant specification, contract, or regulation.

Continuous Improvement - The ongoing improvement of products, services, or processes through incremental and breakthrough improvements.

Control Chart - A chart with upper and lower control limits on which values of some statistical measure for a series of samples or subgroups are plotted. The chart frequently shows a central line to help detect a trend of plotted values toward either control limit.

Corrective Action - The implementation of solutions resulting in the reduction or elimination of an identified problem.

Cost of Poor Quality - The costs associated with providing poor-quality products or services. There are four categories of costs: internal failure costs (costs associated with defects found before the customer receives the product or service), external failure costs (costs associated with defects found after the customer receives the product or service), appraisal costs (costs incurred to determine the degree of

conformance to quality requirements), and prevention costs (costs incurred to keep failure and appraisal costs to a minimum).

Cost of Quality - A term coined by Philip Crosby referring to the cost of poor quality.

Count Chart - A control chart for evaluating the stability of a process in terms of the count of events of a given classification occurring in a sample.

Count-Per-Unit Chart - A control chart for evaluating the stability of a process in terms of the average count of events of a given classification per unit occurring in a sample.

$C_p$ - A widely used process capability index. It is expressed as (upper control limit - lower control limit)/(6σ).

$C_{pk}$ - A widely used process capability index. It is expressed as $|\mu$ - nearer spec$|$/(3σ).

Cross Plot - See Scatter Diagram.

Cumulative Sum Control Chart - A control chart on which the plotted value is the cumulative sum of deviations of successive samples from a target value. The ordinate of each plotted point represents the algebraic sum of the previous ordinate and the most recent deviations from the target.

Customer - See External Customer and Internal Customer.

Customer Delight - The result of delivering a product or service that exceeds customer expectations.

Customer Satisfaction - The result of delivering a product or service that meets customer requirements.

Customer-Supplier Partnership - A long-term relationship between a buyer and a supplier characterized by teamwork and mutual confidence. The supplier is considered an extension of the buyer's organization. The partnership is based on several commitments. The buyer provides long-term contracts and uses fewer suppliers. The supplier implements quality assurance processes so that incoming inspection can be minimized. The supplier also helps the buyer reduce costs and improve product and process designs.

D Chart - Demerit Chart

Decision Matrix - A matrix used by teams to evaluate problems or possible solutions. After a matrix is drawn to evaluate possible solutions, for example, the team lists them in the far-left vertical column. Next, the team selects criteria to rate the possible solutions, writing them across the top row. Third, each possible solution is rated on a scale of 1 to 5 for each criterion and the rating recorded in the corresponding grid. Finally, the ratings of all the criteria for each possible solution are added to determine its total score. The total score is then used to help decide which solution deserves the most attention.

Defect - A product's or service's nonfulfillment of an intended requirement or reasonable expectation for use, including safety considerations. There are four classes of defects: Class 1, Very Serious, leads directly to severe injury or catastrophic economic loss; Class 2, Serious, leads directly to significant injury or significant economic loss; Class 3, Major, is related to major problems with respect to intended normal or reasonably foreseeable use; and Class 4, Minor, is related to minor problems with respect to intended normal or reasonably foreseeable use.

Demerit Chart - A control chart for evaluating a process in terms of a demerit (or quality score), i.e., a weighted sum of counts of various classified nonconformities.

Deming Cycle - See Plan-Do-Check-Act Cycle.

Dependability - The degree to which a product is operable and capable of performing its required function at any randomly chosen time during its specified operating time, provided that the product is available at the start of that period. (Nonoperation-related influences are not included.) Dependability can be expressed by the ratio (time available)/(time available + time required).

Design of Experiments - A branch of applied statistics dealing with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters.

Designing In Quality Vs. Inspecting In Quality - A two-phase investigation used by teams to solve chronic quality problems. In the first phase - the diagnostic journey - the team journeys from the symptom of a chronic problem to its cause. In the second phase - the remedial journey - the team journeys from the cause to its remedy.

Dodge-Romig Sampling Plans - Plans for acceptance sampling developed by Harold F. Dodge and Harry G. Romig. Four sets of tables were published in 1940: single-sampling lot tolerance tables, double-sampling lot tolerance tables, single-sampling average outgoing quality limit tables, and double-sampling average outgoing quality limit tables.

DOE - Design of Experiments

80-20 - A term referring to the Pareto principle, which was first defined by J.M. Juran in 1950. The principle suggests that most effects come from relatively few causes; that is, 80% of the effects come from 20% of the possible causes.

Employee Involvement - A practice within an organization whereby employees regularly participate in making decisions on how their work areas operate, including making suggestions for improvement, planning, goal setting, and monitoring performance.

Empowerment - A condition whereby employees have the authority to make decisions and take action in their work areas without prior approval. For example, an operator can stop a production process if he detects a problem or a customer service representative can send out a replacement product if a customer calls with a problem.

Experimental Design - A formal plan that details the specifics for conducting an experiment, such as which responses, factors, levels, blocks, treatments, and tools are to be used.

External Customer - A person or organization who receives a product, a service, or information but is not part of the organization supplying it.

Failure Mode Analysis - A procedure to determine which malfunction symptoms appear immediately before or after a failure of a critical parameter in a system. After all the possible causes are listed for each symptom, the product is designed to eliminate the problems.

Failure Mode Effects Analysis - A procedure in which each potential failure mode in every sub-item of an item is analyzed to determine its effect on other sub-items and on the required function of the item.

Failure Mode Effects And Criticality Analysis - A procedure that is performed after a failure mode effects analysis to classify each potential failure effect according to its severity and probability of occurrence.

Fishbone Diagram - See Cause-And-Effect Diagram

Fitness For Use - A term used to indicate that a product or service fits the customer's defined purpose for that product or service.

Flowchart - A graphical representation of the steps in a process. Flowcharts are drawn to better understand processes. The flowchart is one of the seven tools of quality.

FMA - Failure Mode Analysis

FMEA - Failure Mode Effects Analysis

FMECA - Failure Mode Effects And Criticality Analysis

Force Field Analysis - A technique for analyzing the forces that will aid or hinder an organization in reaching an objective. An arrow pointing to an objective is drawn down the middle of a piece of paper. The factors that will aid the objective's achievement (called the driving forces) are listed on the left side of the arrow; the factors that will hinder its achievement (called the restraining forces) are listed on the right side of the arrow.

14 Points - W. Edwards Deming's 14 management practices to help companies increase their quality and productivity: 1) create constancy of purpose for improving products and services, 2) adopt the new philosophy, 3) cease dependence on inspection to achieve quality, 4) end the practice of awarding business on price alone; instead, minimize total cost by working with a single supplier, 5) improve constantly and forever every process for planning, production, and service, 6) institute training on the job, 7) adopt and institute leadership, 8) drive out fear, 9) break down barriers between staff areas, 10) eliminate slogans, exhortations, and targets for the work force, 11) eliminate numerical quotas for the work force and numerical goals for management, 12) remove barriers that rob people of pride of workmanship and eliminate the annual rating or merit system, 13) institute a vigorous program of education and self-improvement for everyone, and 14) put everybody in the company to work to accomplish the transformation.

Funnel Experiment - An experiment that demonstrates the effects of tampering. Marbles are dropped through a funnel in an attempt to hit a flat-surfaced target below. The experiment shows that adjusting a stable process to compensate for an undesirable result or an extraordinarily good result will produce output that is worse than if the process had been left alone.

Gantt Chart - A type of bar chart used in process planning and control to display planned work and finished work in relation to time.

Gauge Repeatability and Reproducibility - The evaluation of a gauging instrument's accuracy by determining whether the measurements taken with it are repeatable (i.e., there is close agreement among a number of consecutive measurements of the output for the same value of the input under the same operating conditions) and reproducible (i.e., there is close agreement among repeated measurements of the output for the same value of input made under the same operating conditions over a period of time).

GDT - Geometric Dimensioning and Tolerancing

Geometric Dimensioning and Tolerancing - A method to minimize production costs by showing the dimension and tolerancing on a drawing while considering the functions or relationships of part features.

GO/NO-GO - State of a unit or product. Two parameters are possible: go (conforms to specification) and no-go (does not conform to specification).

GR&R - Gauge Repeatability And Reproducibility

Histogram - A graphic summary of variation in a set of data. The pictorial nature of the histogram lets people see patterns that are difficult to see in the simple table of numbers. The histogram is one of the seven tools of quality.

Hoshin Planning - Breakthrough planning. A Japanese strategic planning process in which a company develops up to four vision statements that indicate where the company should be in the next five years. Company goals and work plans are developed based on the vision statements. Periodic audits are then conducted to monitor progress.

Imperfection - A quality characteristic's departure from its intended level or state without any association to conformance to specification requirements or to the usability of a product or service.

In-Control Process - A process in which the statistical measure being evaluated is in a state of statistical control (i.e., the variations among the observed sampling results can be attributed to a constant system of chance causes).

Inspection - Measuring, examining, testing, or gauging one or more characteristics of a product or service and comparing the results with specified requirements to determine whether conformity is achieved to each characteristic.

Instant Pudding - A term used to illustrate an obstacle to achieving quality; the supposition that quality and productivity improvement is achieved quickly through an affirmation of faith rather than through sufficient effort and education.

W. Edwards Deming used this term - which was initially coined by James Bakken of the Ford Motor Co. - in his book Out of the Crisis.

Internal Customer - The recipient (person or department) of another person's or department's output (product, service, or information) within an organization.

Ishikawa Diagram - See Cause-And-Effect Diagram

ISO 9000 Series Standards - A set of five individual but related international standards on quality management and quality assurance developed to help companies effectively document the quality system elements to be implemented to maintain an efficient quality system. The standards, initially published in 1987, are not specific to any particular industry, product, or service. The standards were developed by the International Organization for Standardization (ISO), a specialized international agency for standardization composed of the national standards bodies of 91 countries.

JIT Manufacturing - Just-In-Time Manufacturing

Just-In-Time Manufacturing - An optimal material requirement planning system for a manufacturing process in which there is little or no manufacturing material inventory on hand at the manufacturing site and little or no incoming inspection.

Kaizen - A Japanese term that means gradual unending improvement by doing little things better and setting and achieving increasingly higher standards. The term was made famous by Masaaki Imai in his book Kaizen: The Key to Japan's Competitive Success.

LCL - Lower Control Limit

Leadership - An essential part of a quality improvement effort. Organization leaders must establish a vision, communicate that vision to those in the organization, and provide the tools and knowledge necessary to accomplish the vision.

Lot - A defined quantity of product accumulated under conditions that are considered uniform for sampling purposes.

Lower Control Limit - Control limit for points below the central line in a control chart.

Maintainability - The probability that a given maintenance action for an item under given usage conditions can be performed within a stated time interval when the maintenance is performed under stated conditions using stated procedures and resources. Maintainability has two categories: serviceability (the ease of conducting scheduled inspections and servicing) and repairability (the ease of restoring service after a failure).

Mean Time Between Failures - The average time interval between failures for repairable product for a defined unit of measure (e.g., operating hours, cycles, miles)

MIL-Q-9858A - A military standard that describes quality program requirements.

MIL-STD-105E - A military standard that describes the sampling procedures and tables for inspection by attributes.

MIL-STD-45662A - A military standard that describes the requirements for creating and maintaining a calibration system for measurement and test equipment.

MTBF - Mean Time Between Failures

Multivariate Control Chart - A control chart for evaluating the stability of a process in terms of the levels of two or more variables or characteristics.

n - Sample size (the number of units in a sample).

NDE - Nondestructive Evaluation

NDT - Nondestructive Testing

Nominal Group Technique - A technique, similar to brainstorming, used by teams to generate ideas on a particular subject. Team members are asked to silently come up with as many ideas as possible, writing them down. Each member is then asked to share one idea, which is recorded. After all the ideas are recorded, they are discussed and prioritized by the group.

Nonconformity - The nonfulfillment of a specified requirement.

Nondestructive Testing and Evaluation - Testing and Evaluation methods that do not damage or destroy the product being tested.

np Chart - Number of Affected Units Chart

Number of Affected Units Chart - A control chart for evaluation the stability of a process in terms of the total number of units in a sample in which an event of a given classification occurs.

OC Curve - Operating Characteristic Curve

Operating Characteristic Curve - A graph used to determine the probability of accepting lots as a function of the lots' or processes' quality level when using various sampling plans. There are three types: Type A curves, which give the probability of acceptance for an individual lot coming from finite production (will not continue in the future); Type B curves, which give the probability of acceptance for lots coming from a continuous process; and Type C curves, which, for a continuous sampling plan, give the long-run percentage of product accepted during the sampling phase.

Out-Of-Control Process - A process in which the statistical measure being evaluated is not in a state of statistical control (i.e., the variations among the observed sampling results can be attributed to a constant system of chance causes).

Out of Spec - A term used to indicate that a unit does not meet a given specification.

p Chart - Percent Chart

Pareto Chart - A graphical tool for ranking causes from most significant to least significant. It is based on the Pareto principle, which was first defined by J.M. Juran in 1950. The principle, named after 19th-century economist Vilfredo Pareto,

suggests that most effects come from relatively few causes; that is, 80% of the effects come from 20% of the possible causes. The Pareto chart is one of the seven tools of quality.

PDCA Cycle - Plan-Do-Check-Act Cycle

Percent Chart - A control chart for evaluating the stability of a process in terms of the percent of the total number of units in a sample in which an event of a given classification occurs. The percent chart is also referred to as a proportion chart.

Plan-Do-Check-Act Cycle - A four-step process for quality improvement. In the first step (plan), a plan to effect improvement is developed. In the second step (do), the plan is carried out, preferably on a small scale. In the third step (check), the effects of the plan are observed. In the last step (act), the results are studied to determine what was learned and what can be predicted. The plan-do-check-act cycle is sometimes referred to as the Shewhart cycle (because Walter A. Shewhart discussed the concept in his book Statistical Method From the Viewpoint of Quality Control) and as the Deming cycle (because W. Edwards Deming introduced the concept in Japan; the Japanese subsequently called it the Deming cycle).

Prevention Vs. Detection - A term used to contrast two types of quality activities. Prevention refers to those activities designed to prevent nonconformances in products and services. Detection refers to those activities designed to detect nonconformances already in products and services. Another term used to describe this distinction is "designing in quality vs. inspecting in quality."

Process Capability - A statistical measure of the inherent process variability for a given characteristic. The most widely accepted formula for process capability is $6\sigma$.

Process Capability Index - The value of the tolerance specified for the characteristic divided by the process capability. There are several types of process capability indexes, including the widely used $C_p$ and $C_{pk}$.

Product Or Service Liability - The obligation of a company to make restitution for loss related to personal injury, property damage, or other harm caused by its product or service.

Q Chart - Quality Score Chart

QFD - Quality Function Deployment

QML - Qualified Manufacturer's Line

Q90 Series - Refers to ANSI/AXQC Q90 series of standards, which is the Americanized version of the ISO 9000 series standards. The United States adopted the ISO 9000 series as the ANSI/ASQC Q90 series in 1987.

Qualified Manufacturer's Line - A Qualified Manufacturer's Line is one which has been certified to meet quality standards such that additional sampling and testing of products from that line are not necessary. All parts produced meet required quality levels.

Quality - A subjective term for which each person has his or her own definition. In technical usage, quality can have two meanings: 1) the characteristics of a product

or service that bear on its ability to satisfy stated or implied needs and 2) a product or service free of deficiencies.

Quality Assurance/Quality Control - Two terms that have many interpretations because of the multiple definitions for the words "assurance" and "control." For example, "assurance" can mean the act of making certain; "control" can mean an evaluation to indicate needed corrective responses, the act of guiding, or the state of a process in which the variability is attributable to a constant system of chance causes. (For a detailed discussion on the multiple definitions, see ANSI/ASQC Standard A3-1987, Definitions, Symbols, Formulas, and Tables for Control Charts.") One definition of quality assurance is: all the planned and systematic activities implemented within the quality system that can be demonstrated to provide confidence that a product or service will fulfill requirements for quality. One definition for quality control is: the operational techniques and activities used to fulfill requirements for quality. Often, however, "quality assurance" and "quality control" are used interchangeably, referring to the actions performed to ensure the quality of a product, service, or process.

Quality Audit - A systematic, independent examination and review to determine whether quality activities and related results comply with planned arrangements and whether these arrangements are implemented effectively and are suitable to achieve the objectives.

Quality Circles - Quality improvement or self-improvement study groups composed of a small number of employees (10 or fewer) and their supervisor. Quality circles originated in Japan, where they are called quality control circles.

Quality Control - See Quality Assurance/Quality Control

Quality Costs - See Cost of Poor Quality

Quality Engineering - The analysis of a manufacturing system at all stages to maximize the quality of the process itself and the products it produces.

Quality Function Deployment - A structured method in which customer requirements are translated into appropriate technical requirements for each stage of product development and production. The QFD process is often referred to as listening to the voice of the customer.

Quality Loss Function - A parabolic approximation of the quality loss that occurs when a quality characteristic deviates from its target value. The quality loss function is expressed in monetary units: the cost of deviating from the target increases quadratically the farther the quality characteristic moves from the target. The formula used to compute the quality loss function depends on the type of quality characteristic being used. The quality loss function was first introduced in this form by Genichi Taguchi.

Quality Score Chart - A control chart for evaluating the stability of a process in terms of a quality score. The quality score is the weighted sum of the count of events of various classifications where each classification is assigned a weight.

Quality Trilogy - A three-pronged approach to managing for quality. The three legs are quality planning (developing the products and processes required to meet

customer needs), quality control (meeting product and process goals), and quality improvement (achieving unprecented levels of performance).

Quincunx - A tool that creates frequency distributions. Beads tumble over numerous horizontal rows of pins, which force the beads to the right or left. After a random journey, the beads drop into vertical slots. After many beads are dropped, a frequency distribution results. In the classroom, quincunxes are often used to simulate a manufacturing process. The quincunx was invented by English scientist Francis Galton in the 1890s.

R Chart - Range Chart

RAB - Registrar Accreditation Board

RAM - Reliability/Availability/Maintainability

Random Sampling - A commonly used sampling technique in which sample units are selected in such a manner that all combination of n units under consideration have an equal chance of being selected as the sample.

Range Chart - A control chart in which the sub-group range, R, is used to evaluate the stability of the variability within a process.

Red Bead Experiment - An experiment developed by W. Edwards Deming to illustrate that it is impossible to put employees in rank order of performance for the coming year based on their performance during the past year because performance differences must be attributed to the system, not to employees. Four thousand red and white beads (20% red) in a jar and six people are needed for the experiment. The participants' goal is to produce white beads, because the customer will not accept red beads. One person begins by stirring the beads and then, blindfolded, selects a sample of 50 beads. That person hands the jar to the next person, who repeats the process, and so on. When everyone has his or her sample, the number of red beads for each is counted. The limits of variation between employees that can be attributed to the system are calculated. Everyone will fall within the calculated limits of variation that could arise from the system. The calculations will show that there is no evidence one person will be a better performer than another in the future. The experiment shows that it would be a waste of management's time to try to find out why, say, John produced four red beads and Jane produced 15; instead, management should improve the system, making it possible for everyone to produce more white beads.

Registrar Accreditation Board - A board that evaluates the competency and reliability of registrars (organizations that assess and register companies to the appropriate ISO 9000 series standards). The Registrar Accreditation Board, formed in 1989 by ASQC, is governed by a board of directors from industry, academia, and quality management consulting firms.

Registration To Standards - A process in which an accredited, independent third-party organization conducts on on-site audit of a company's operations against the requirements of the standard to which the company wants to be registered. Upon successful completion of the audit, the company receives a certificate indicating that it has met the standard requirements.

Regression Analysis - A statistical technique for determining the best mathematical expression describing the functional relationship between one response and one or more independent variables.

Reliability - The probability of a product performing its intended function under stated conditions without failure for a given period of time.

Right The First Time - A term used to convey the concept that it is beneficial and more cost-effective to take the necessary steps up front to ensure a product or service meets its requirements than to provide a product or service that will need rework or not meet customers' needs. In other words, an organization would engage in defect prevention rather than defect detection.

Robustness - The condition of a product or process design that remains relatively stable with a minimum of variation even though factors that influence operations or usage, such as environment and wear, are constantly changing.

s Chart - Sample Standard Deviation Chart

Sample Standard Deviation Chart - A control chart in which the subgroup standard deviation, s, is used to evaluate the stability of the variability within a process.

Scatter Diagram - A graphical technique to analyze the relationship between two variables. Two sets of data are plotted on a graph, with the y axis being used for the variable to be predicted and the x axis being used for the variable to make the prediction. The graph will show possible relationships (although two variables might appear to be related, they might not be - those who know most about the variables must make that evaluation). The scatter diagram is one of the seven tools of quality.

Seven Tools of Quality - Tools that help organizations understand their processes in order to improve them. The tools are the cause-and-effect diagram, check sheet, control chart, flowchart, histogram, Pareto chart, and scatter diagram.

Shewhart Cycle - See Plan-Do-Check-Act Cycle

Signal-To-Noise Ratio - A mathematical equation that indicates the magnitude of an experimental effect above the effect of experimental error due to chance fluctuations.

Six-Sigma Quality - A term used generally to indicate that a process is well-controlled, i.e., + -3 sigma from the centerline in a control chart. The term is usually associated with Motorola, which named one of its key operational initiatives "Six Sigma Quality."

S/N Ration - Signal-To-Noise Ratio

SPC - Statistical Process Control

Special Causes - Causes of variation that arise because of special circumstances. They are not an inherent part of a process. Special causes are also referred to as assignable causes.

Specification - A document that states the requirements to which a given product or service must conform.

SQC - Statistical Quality Control

Statistical Process Control - The application of statistical techniques to control a process. Often the term "statistical quality control" is used interchangeably with "statistical process control."

Statistical Quality Control - The application of statistical techniques to control quality. Often the term "statistical process control" is used interchangeably with "statistical quality control," although statistical quality control includes acceptance sampling as well as statistical process control.

Structural Variation - Variation caused by regular, systematic changes in output, such as seasonal patterns and long-term trends.

Supplier Quality Assurance - Confidence that a supplier's product or service will fulfill its customers' needs. This confidence is achieved by creating a relationship between the customer and supplier that ensures the product will be fit for use with minimal corrective action and inspection. According to J.M. Juran, there are nine primary activities needed: 1) define product and program quality requirements, 2) evaluate alternative suppliers, 3) select suppliers, 4) conduct joint quality planning, 5) cooperate with the supplier during the execution of the contract, 6) obtain proof of conformance to requirements, 7) certify qualified suppliers, 8) conduct quality improvement programs as required, and 9) create and use supplier quality ratings.

Taguchi Methods - The American Supplier Institute's trademarked term for the quality engineering methodology developed by Genichi Taguchi. In this engineering approach to quality control, Taguchi calls for off-line quality control, on-line quality control, and a system of experimental design to improve quality and reduce costs.

Tampering - Action taken to compensate for variation within the control limits of a stable system. Tampering increases rather than decreases variation, as evidenced in the funnel experiment.

Top-Management Commitment - Participation of the highest-level officials in their organization's quality improvement efforts. Their participation includes establishing and serving on a quality committee, establishing quality policies and goals, deploying those goals to lower levels of the organization, providing the resources and training that the lower levels need to achieve the goals, participating in quality improvement teams, reviewing progress organization-wide; recognizing those who have performed well, and revising the current reward system to reflect the importance of achieving the quality goals.

Total Quality Management - A term initially coined in 1985 by the Naval Air Systems Command to describe its Japanese-style management approach to quality improvement. Since then, total quality management (TQM) has taken on many meanings. Simply put, TQM is a management approach to long-term success through customer satisfaction. TQM is based on the participation of all members of an organization in improving processes, products, services, and the culture in which they work. TQM benefits all organization members and society. The methods for implementing this approach are found in the teaching of such quality leader as

Philip B. Crosby, W. Edwards Deming, Armand V. Feigenbaum, Kaoru Ishikawa, and J.M. Juran.

TQM - Total Quality Management

Trend Control Chart - A control chart in which the deviation of the subgroup average, X-bar, from an expected trend in the process level is used to evaluate the stability of a process.

Type I Error - An incorrect decision to reject something (such as a statistical hypothesis or a lot of products) when it is acceptable.

Type II Error - An incorrect decision to accept something when it is unacceptable.

u Chart - Count Per Unit Chart

UCL - Upper Control Limit

Upper Control Limit - Control limit for points above the central line in a control chart.

Value-Adding Process - Those activities that transform an input into a customer-usable output. The customer can be internal or external to the organization.

Variables Data - Measurement information. Control charts based on variables data include average (X-bar) chart, range (R) chart, and sample standard deviation (s) chart.

Variation - A change in data, a characteristic, or a function that is caused by one of four factors: special case, common cases, tampering, or structural variation.

Vital Few, Useful Many - A term used by J.M. Duran to describe his use of the Pareto principle, which he first defined in 1950. (The principle was used much earlier in economics and inventory control methodologies.) The principle suggests that most effects come from relatively few causes; that is, 80% of the effects come from 20% of the possible causes. The 20% of the possible causes are referred to as the "vital few"; the remaining causes are referred to as the "useful many." When Juran first defined this principle, he referred to the remaining causes as the "trivial many," but realizing that no problems are trivial in quality assurance, he changed it to "useful many."

World-Class Quality - A term used to indicate a standard of excellence: the best of the best.

x-bar Chart - Average Chart

Zero Defects - A performance standard developed by Philip B. Crosby to address a dual attitude in the workplace; people are willing to accept imperfection in some areas, while, in other areas, they expect the number of defects to be zero. This dual attitude had developed because of the conditioning that people are human and humans make mistakes. However, the zero defect methodology states that, if people commit themselves to watching details and avoiding errors, they can move closer to the goal of zero defects. The performance standard that must be set is "zero defects," not "close enough."

## APPENDIX B

## QUALITY CONTROL PERSONALITIES

Brumbaugh, Martin A. (Deceased) - The founder and first editor of Industrial Quality Control magazine. A former professor of statistics at the University of Buffalo, Brumbaugh's writings on applied statistics were regularly published. Brumbaugh was instrumental in getting two separate quality organizations - the Federated Societies and the Society for Quality Control - merged into one national organization: ASQC.

Collier, Simon (Deceased) - An ASQC president who led the Society during a critical growth period in 1952-53. His term was marked by numerous milestone events, including a membership increase of 22% and the formation of 11 new sections and the first divisions. Collier was a chemist who began his career at the National Bureau of Standards (now the National Institute of Standards and Technology). Later he worked at Johns-Manville Corporation, where he produced a quality training film used by more than 300 companies.

Crosby, Philip - The founder and chairman of the board of Career IV, an executive management consulting firm. Crosby also founded Philip Crosby Associates Inc. and the Quality College. He has authored many books, including Quality is Free, Quality Without Tears, Let's Talk Quality, and Leading: the Art of Becoming an Executive. Crosby originated the zero defect concept.

Deming, W. Edwards - A prominent consultant, teacher, and author on the subject of quality. After sharing his expertise in statistical quality control to help the U.S. war effort during World War II, the War Department sent Deming to Japan in 1946 to help that nation recover from its wartime losses. Deming has published more than 200 works, including the well-known books Quality, Productivity, and Competitive Position and Out of the Crisis.

Dodge, Harold F. (Deceased) - An ASQC founder. His work with acceptance sampling plans scientifically standardized inspection operations and provided controllable risks. Although he usually is remembered for the Dodge-Romig sampling plans he developed with Harry G. Romig, Dodge also helped develop other basic acceptance sampling concepts (e.g., consumer's risk, producer's risk, average outgoing quality level) and several acceptance sampling schemes.

Edwards, George D. (Deceased) - First president of ASQC. Edwards was noted for his administrative skills in forming and preserving the Society. He was the head of the inspection engineering department and the director of quality assurance at Bell Telephone Laboratories. He also served as a consultant to the Army Ordnance Department and the War Production Board during World War II.

Feigenbaum, Armand V. - The founder and president of General Systems Co., an international engineering company that designs and implements total quality systems. Feigenbaum originated the concept of total quality control in his book Total Quality Control, which was published 1951. The book has been translated into many languages, including Japanese, Chinese, French, and Spanish.

Grant, Eugene L. - Professor Emeritus of economics engineering at Stanford University. Grant was part of a small team of professors assigned during World War

II to introduce statistical quality control concepts to improve manufacturing production. He has written many textbooks, including Principles of Engineering Economy and Statistical Quality Control, editions of which he co-authored with W. Grant Ireson and Richard S. Leavenworth.

Ishikawa, Kaoru (Deceased) - A pioneer in quality control activities in Japan. In 1943, he developed the cause-and-effect diagram. Ishikawa published many works, including What Is Total Quality Control? The Japanese Way, Quality Control Circles at work, and guide to Quality Control. He was a member of the quality control research group of the Union of Japanese Scientists and Engineers while also working as an assistant professor at the University of Tokyo.

Juran, Joseph M. - The chairman emeritus of the Juran Institute. Since 1924, Juran has pursued a varied career in management as an engineer, executive, government administrator, university professor, labor arbitrator, corporate director, and consultant. Specializing in managing for quality, he has authored hundreds of papers and 12 books, including Juran's Quality Control Handbook, Quality Planning and Analysis (with F.M. Gryna), and Juran On Leadership For Quality.

Ott, Ellis R. (Deceased) - An educator who devoted his career to providing U.S. industry with statistical quality control professionals. In 1946, Ott became the chairman of the mathematics department at Rutgers University's University College with one condition: that he could also consult on and teach quality control. His influence led the university to establish the Rutgers Statistics Center. Ott developed the analysis of means procedure and published many papers.

Romig, Harry G. (Deceased) - An ASQC founder who was most widely known for his contributions in sampling. At AT&T Bell Laboratories, Romig and Harold F. Dodge developed the Dodge-Romig sampling tables, operating characteristics for sampling plans, and other fundamentals. Romig alone developed the first sampling plans using variables data and the concept of average outgoing quality limit. Later in his life, Romig was a consultant and taught quality-related courses at several universities.

Shewhart, Walter A. (Deceased) - Referred to as the father of statistical quality control because he brought together the discipline of statistics, engineering, and economics. He described the basic principles of this new discipline in his book Economic Control of Quality of Manufactured Product. Shewhart, ASQC's first Honorary member, was best known for creating the control chart. Shewhart worked for Western Electric and AT&T Bell Telephone Laboratories in addition to lecturing and consulting on quality control.

Taguchi, Genichi - The executive director of the American Supplier Institute, the director of the Japan Industrial Technology Institute, and an honorary professor at Nanjing Institute of Technology in China. Taguchi is well-known for developing a methodology to improve quality and reduce costs, which, in the United States, is referred to as the Taguchi Methods. He also developed the quality loss function.

Wescott, Mason E. - A professor emeritus at the Rochester Institute of Technology (RIT), Wescott has been teaching mathematics and statistics since 1925. He taught at Northwestern University, Rutgers University, and RIT, where the Wescott Statistics Laboratory was dedicated in his honor in 1984. Wescott succeeded Martin A. Brumbaugh as editor of Industrial Quality Control in 1947, a position he held until 1961.

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