way. In this sense, we can develop a "feel" that can be communicated to others with the same intrinsic meaning. We can establish a means to convey to others the quality level of a product without bias of human emotion, costs, advertising, etc. When we can do this, we will be able to do two very important things. First, we will be able to establish a "quality excellence high water mark" with numbers. We will be able to say, very definitively, what quality excellence actually is in and of itself. This will allow others to verify directly any overt or covert references to quality. The second thing we will be able to do is to know how much product quality needs to change in order for that product to be considered excellent.

## THE SIGMA SCALE FOR MEASURING PRODUCT QUALITY

The quality measurement scale that we will consider may be referred to as the "sigma quality index," or just "SQI" for short. This particular concept was first introduced, to this author's knowledge, by W. Smith, Motorola, Inc. (1986). Use of the sigma scale first requires us to reduce quality to nonconformities per million opportunities for nonconformity (NPMO). For the time being, let us just recognize that the NPMO would then be translated into sigma ($\sigma$) units. Now, let us turn our attention to the $\sigma$ scale so that we can start to lay the groundwork for a quantitative definition of quality excellence.

Essentially, a $\sigma$ is a statistical unit of measurement which is kind of like a quality measuring device. It can tell us how "good" a product is. To apply the concept, we must first determine how many opportunities there are for a nonconformity or "defect" to occur, as related to a particular product, or service for that matter. Next, we must count the actual number of defects associated with that product during manufacture. With this information we are now able to determine how many defects there are per million opportunities for a defect. For example, if there are 1,000,000 opportunities for a defect to occur within each of our five previously mentioned radios and we observe five defects (one defect per radio) then there would be one defect per million opportunities or, expressed as a fraction, 0.000001 NPMO. Now, the last thing that we must do is statistically convert the NPMO into "$\sigma$ units." Exactly how this is done will be discussed in detail later on.

When the number of sigma units or "$\sigma$'s" is small, say two, product quality is not very good; i.e., the number of defects per million opportunities for a defect would be intolerable. When the number of $\sigma$'s is large, say six, quality would be excellent; i.e., the number of defects per million opportunities would be extremely small. In general, the bigger the number, the better. In this sense, the quality $\sigma$'s are like water graduations on a glass beaker – like chemists use to measure the volume of a fluid. So think of quality like water in a beaker, the more quality we have in the product, the more fluid there is in the beaker (Exhibit 17). Ideally, the target for quality excellence is $6\sigma$.

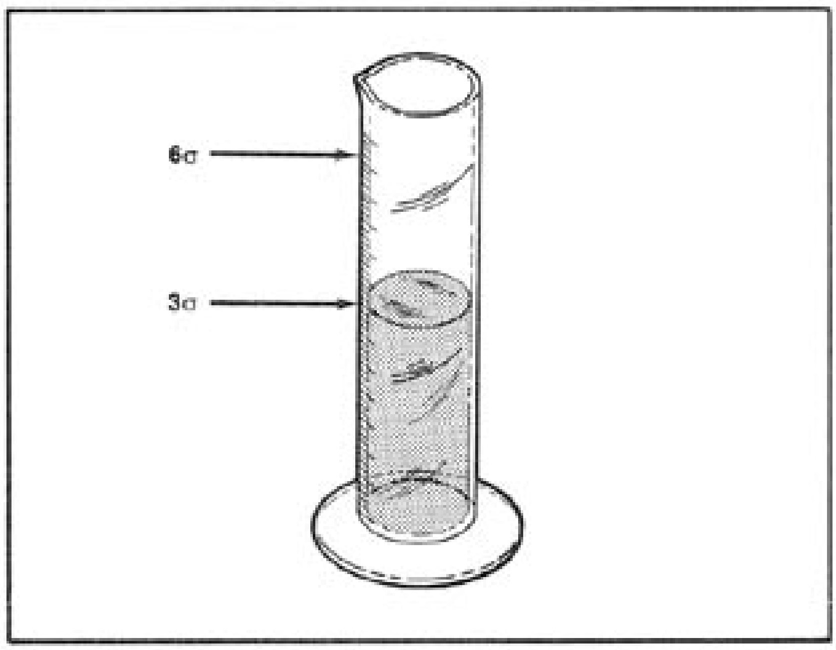


**Exhibit 17. Illustration of the $6\sigma$ Quality Concept**

## THE SIX SIGMA QUALITY PHILOSOPHY

In general, when we say that a product or "logical unit of service" is 6σ, what we are really saying is that it displayed no more than 3.4 nonconformities per million opportunities. This number (3.4 NPMO) takes natural variation into account. That is to say, the 6σ quality philosophy recognizes that a small amount of natural variation (shifting and spread) will be present as result of slight fluctuations in environmental conditions, differences between operators, parts, materials, etc. If the fluctuations in the cause system ($X_1...X_N$) can be sufficiently controlled such that the product characteristic (Y) stays centered on its ideal condition, there would be only 0.002 nonconformities or "defects" per million opportunities (NPMO).

Another way of saying all of this is that the 6σ concept assumes no two product units can be identical – some difference(s) will naturally be present; however, the differences will be so small that they will be negligible, for all practical purposes. This is the key. In practice, the concept recognizes that very slight product variation will be present, but the end result will always be product which displays excellent quality. It positions an organization's products within the marketplace to be "best in class." To help us better understand this concept, let us look at Exhibit 18 to see how many nonconformities or defects per million opportunities there would be for several different σ's with two different "centering" conditions.

| SIGMAS (σ) | NPMO* WITHOUT SHIFT | NPMO* WITH SHIFT |
|---|---|---|
| 1 | 317,400 | 697,700 |
| 2 | 45,400 | 308,733 |
| 3 | 2,700 | 66,803 |
| 4 | 63 | 6,200 |
| 5 | 0.57 | 233 |
| 6 | 0.002 | 3.4 |
| 7 | 0.000003 | 0.019 |

*NONCONFORMITIES PER MILLION OPPORTUNITIES FOR NONCONFORMANCE.

*FOR THE EXPERTS, WITHOUT SHIFT ASSUMES NO CHANGE IN THE UNIVERSE AVERAGE. WITH SHIFT ASSUMES 1.5 SIGMA CHANGE IN THE UNIVERSE AVERAGE. NORMAL DISTRIBUTION ASSUMED (TWO-SIDED).*

**Exhibit 18. Sigma (σ) Quality Levels: Before and After a Shift in the Average**

As you can see from Exhibit 18, a 3σ product quality level (without shift) would give us 2700 NPMO for nonconformance. A 6σ level (without shift) would be 0.002 NPMO.

But exactly how good is an NPMO or ppm of 0.002? What would it be like trying to find a defect in a product or service which exhibits an NPMO of 0.002? Well, if the odds of winning a particular lottery were about 45 in a 1,000,000, the gambling equivalent would be winning this lottery two times in row! As another illustration, consider how many blades of grass are contained within a football field. The equivalent of a 0.002 NPMO would be like trying to find 10 particular blades of grass within the entire field. If you could take the time to inspect each blade of grass on the field, it would take you approximately 70 years working 8 hours per day, 5 days per week, with no vacation, to find the 10 blades of grass. As you can see, an NPMO of 0.002 is an exceptionally high level of product quality – 6σ is the competitive edge.

But how big of a quality difference is there between a 6σ product and, say, a 3σ product? Well, let us consider a 1500 square foot home which has wall-to-wall carpeting. Let us further suppose that we are measuring how much of the carpet has been somehow stained or soiled. If the quality of the carpet, in terms of cleanliness, was at the 0σ level, then 100 percent of the carpet in the house (1500 square feet) would be stained. On the other hand, if the carpet were to be cleaned to the 3σ level, then there would be about 4 square feet of carpet still soiled. This would be approximately equivalent to the carpet area under a typical recliner chair. Now, if the carpet had been cleaned to the 6σ level, there would only be an area the size of a pinhead still soiled. Not a bad cleaning job, huh? If you were paying to have your carpet cleaned, would 3σ be good enough?

We may now continue our carpet example to see what we mean by a "shift in the average" and how it relates to NPMO. In other words, we shall see what happens when our quality changes by 1.5σ; i.e., when it slips a little bit. For the sake of argument, suppose the person cleaning the carpet showed up slightly intoxicated. Image someone weaving around trying to clean the carpet! How much of the carpet do you suppose would not get cleaned because of this? Well let's see. If our carpet cleaner normally performed to 3σ (when sober), we could expect to see about 100 square feet of soiled carpet when he/she finished. This would be an area about the size of a second bedroom. On the other hand, if we hired a carpet cleaner who normally performed to 6σ (sober that is) we could expect to see an area still soiled about the size of the bottom of the cleaner's shot glass – after the contents had been drunk, of course! In this case, 6σ process capability allowed excellent cleaning performance in spite of the fact that the booze was causing the "process" to weave around a little.

As a final illustration, let us consider Exhibit 19. As you can see, the differences between the σ levels is astounding, to say the least. Would you be surprised to know that typical American design philosophy is generally geared around 3σ to 4σ? Furthermore, 3σ is generally accepted as the foundation of process control – as well as the basic expectation of suppliers. Do you suppose this is good enough to stay in business over the long haul? Would you find it interesting to note that the Japanese philosophy is far greater than 3σ? Regardless of who is doing what, the central question is, "How can we make things better?"

**SIGMA (σ) COMPARISONS***

*(WITHOUT SHIFT)*

| SIGMAS | AREA | SPELLING | MONEY | TIME | DISTANCE |
|---|---|---|---|---|---|
| 1σ | Floor space of an average factory | 170 misspelled words per page in a book | $317.4 million indebtedness per $1 billion in assets | 31¾ years per century | From here to the moon |
| 2σ | Floor space of a large supermarket | 25 misspelled words per page in a book | $45.4 million indebtedness per $1 billion in assets | 4½ years per century | 1½ times around the world |
| 3σ | Floor space of a small hardware store | 1.5 misspelled words per page in a book | $2.7 million indebtedness per $1 billion in assets | 3½ months per century | Coast-to-coast trip |
| 4σ | Floor space of a typical living room | 1 misspelled word per 30 pages (about one chapter in a book) | $63,000 indebtedness per $1 billion in assets | 2½ days per century | 45 minutes of freeway driving (in any direction, of course) |
| 5σ | Size of the bottom of your telephone | 1 misspelled word in a set of encyclopedias | $570 indebtedness per $1 billion assets | 30 minutes per century | A trip to the local gas station |
| 6σ | Size of a typical diamond | 1 misspelled word in all of the books contained in a small library | $2 indebtedness per $1 billion of assets | 6 seconds per century | 4 steps in any direction |
| 7σ | Point of a sewing needle | 1 misspelled word in all of the books contained in several large libraries | 3/10¢ indebtedness per $1 billion of assets | One blink of the eye per century | 1/8 of an inch |

**Generating constants approximated on the basis of known proportions, averages, and/or best estimates*

Exhibit 19. Sigma (σ) Comparisons without Shift

## HOW TO ACHIEVE 6σ PRODUCT QUALITY

To help ensure that natural fluctuations in the underlying cause system of a product ($X_1...X_N$) do not cause excessive differences within and between units of product in relation to the customer requirements ($Y_1...Y_N$), there are several things which can be done. First, designers can configure a product in such a manner that its performance is "shielded" against variation. They can stop nonconformities from occurring during the design stage of a product by establishing 6σ requirements on all critical parameters, opening up noncritical specifications, and decreasing the total number of opportunities for creating nonconformities by simplifying the design at every possible point; i.e., reducing part count, materials, and those factors which tend to increase manufacturing difficulties. Whenever designers do these things many other facets of the business are improved such as manufacturing cycle time, inventories, labor costs, product reliability, product serviceability, and warranty costs, just to mention a few. When an organization embodies this philosophy, it can be sure that its products will consistently perform to the specified levels; that is, all of the product will be "on target" with minimum differences within and between units of product. This is often referred to as "designing for producibility."

The second thing which can be done is related to an organization's in-house production process(es) as well as the process(es) of its suppliers. By systematically tracking down, controlling, and ultimately eliminating the root causes of variation through the application of statistical process control (SPC) methods, the "spread" and "centering" of the processes can be significantly improved. When these things are done, and the end result is units of product which display an NPMO of no more than 3.4, we say that the product is 6σ.

## RESULTS ASSOCIATED WITH SIX SIGMA QUALITY PERFORMANCE

People often think that 99.9 percent good product (1000 NPMO) is more than acceptable. As the old saying goes, "We don't build Rolls Royces here." What do you think? Is 99.9 percent really good enough? Well, let's translate what 99.9 percent actually means in the real world.

- 2000 lost articles of mail per hour.
- Unsafe drinking water almost 1 hour each month.
- Nearly 500 incorrect surgical operations per week.
- Two short or long landings at most major airports each day.
- 20,000 wrong drug prescriptions each year.

If you were flying into a major airport, filling a drug prescription, or having surgery, would you say 99.9 percent is good enough? How do you think our customers feel when they receive products that are only 99.9 percent "good stuff." In all of these cases, we would certainly want at least 99.99966 percent good units of product and/or service – the equivalent of an NPMO of 3.4. This level of confidence would certainly give us greater peace of mind – after all, this is a 6σ level of quality with some natural variation. Without natural variation, the confidence would rise to 99.9999998 percent.

To illustrate even further what kind of results we can expect under the concept of the 6σ product quality philosophy, let us consider a typical electronic system that contains 20 printed wiring boards (PWBs) of which each PWB has 500 solder joints. This would make a total of 10,000 solder joints in the system. If only 99.9 percent of the solder joints were good, then we could expect 10 joints within each system to fail. How much of a problem would this create for the end user – particularly in an application where people's well-being might be in the balance? On the other hand, if an absolute minimum of 99.99966 percent of the joints were good (6σ quality with some natural variation), then there would be only 3.4 solder joint failures per 100 systems. Although this is certainly excellent, only zero defects will do. Again, if you were on the airplane in which the PWBs were used, what would you say?

With respect to products and services, we can now easily see why nothing short of quality excellence will do. The attainment of 6σ quality will not only give customers the satisfaction and security they deserve, it will also greatly help to:

- Decrease manufacturing and design cycle time.
- Decrease costs due to inventory, scrap, and rework.
- Increase profitability and market position.
- Cultivate new business and hold on to old business.
- Reduce administrative costs
- Lower labor costs
- Improve pricing accuracy

In the final analysis, we may conclude that the attainment of 6σ quality is not just something nice to do, it is a business necessity – a challenge that we must all rise to, now and long into the future.

## THE ROAD TO SIX SIGMA PRODUCT QUALITY

In order to see how we can get from point A to point B, so to speak, we must first recognize that product variation results from insufficient design margins, inadequate process controls, and less than optimum parts and material. These are the three primary sources of product variation. If we are to achieve 6σ quality in everything we do, including administrative things such as filing, typing, and documentation, as well as activities, services, and output in the areas of accounting, marketing, sales, facilities, etc., we must isolate, control, and ultimately eliminate variation. In this sense, we must view variation as an enemy. It is the enemy of our products, customers, jobs, and even our way of life.

To defeat this enemy, we must all strive to go beyond just "meeting the specs" or "status quo." We must track the enemy down and destroy it by every means available to us. Some of the tools that help us do this include:

- Short Cycle Manufacturing (SCM)
- Design for Producibility
- Statistical Process Control (SPC)
- Participative Management Practices (PMP)
- Supplier SPC (SSPC)
- Part Standardization Initiatives (PSI)
- Technological and Managerial Leadership
- Supplier Qualification Program (SQP)
- Computer Simulation

Not only do these tools, as well as many others, help us remove variation while the product is being built, they help us detect the presence of the enemy before we go into production. In this manner, we are able to prevent product casualties before they happen. We call this "*a priori*" control – control which is gained before the fact, not after something goes wrong. This all translates into working smarter, not harder.

As may be apparent, there are three basic strategies for winning the war on variation. First, we must gain *a priori* control during the product design cycle. To do this, we must: a) define 6σ tolerances on all critical parameters, b) minimize the total number of parts in the product, c) standardize the parts we use, and d) use SPC principles and computer tools during the design and prototype phases. A continuance of this strategy involves using SPC to continually isolate, control, and eliminate variation resulting from: a) people, b) machines, c) material, and d) the environment. And finally, the strategy involves the supplier. Our suppliers must also continually strive to eliminate variation in the parts and materials that we purchase. This is done by: a) instituting a "statistically based" supplier qualification program which is, in part, based on SPC principles, b) requiring process control plans from our suppliers, c) minimizing the total number of suppliers that are used, and d) ensuring a long-term, win-win partnership with the suppliers that are used. These are but a few of the tactics associated with each of the three strategies that will help us defeat the enemy, variation. We must apply all three of these strategies on a continual basis to achieve 6σ quality – the foundation of excellence.

As we have seen, product quality controls costs, manufacturing and engineering cycle times, shipping schedules, and many other facets of a business. In today's highly competitive marketplace, the ability to deal effectively and efficiently with product variation is crucial. It is the only way that 6σ product quality can be achieved.