Follow this step-by-step approach at your own pace, and teach yourself how to conduct a Machine and Process Capability Study. You will be improving processes right away!
Machine/Process Capability Study

- A Five Stage Methodology For Characterizing Processes -

Mario Perez-Wilson
President
Advanced Systems Consultants
"Machine/Process Capability Study"

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MACHINE/PROCESS CAPABILITY STUDY

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Foreword

In recent years, American industry has made some progress in product design through techniques such as the design of experiments. Products have been made more "robust" against "noise" and environmental factors through parameter design and tolerance design. Yet, the process that produces the product is often treated as a stepchild. Development engineers do not feel responsible for the process. They relegate that to the process engineer, who, in turn, is heavily dependent on the supplier of the equipment used in the process. And all of them use arbitrary process specifications, antiquated procedures and hit-and-miss experiences in determining process parameters. The result is confusion, finger-pointing, low yields and the high cost of poor quality.

A cooking analogy can be used to describe the chaos in production processes. The task is to bake a cake. But imagine the quality of the cake if the cook had no recipe, no knowledge of the ingredients or their respective quantities! Yet industry moves along blithely with little knowledge of which are the important process variables that must be tightly controlled and which are the unimportant variables where costs can be substantially reduced. In short, poor process characterization and optimization are of epidemic proportions in industry.

To this pall of darkness, Mario Perez-Wilson, with his book on "Machine/Process Capability Study," brings a beacon of light. He carefully orchestrates a step-by-step methodology--process delineation; metrology characterization; process capability determination; optimization; and control. It is a landmark book that fills a gaping void in manufacturing. He utilizes a series of powerful problem-solving tools, spanning different approaches to the design of experiments. He captures the techniques of repeatability and reproducibility in order to assure the accuracy and capability of instrumentation. He marshals the disciplines of statistical experimentation and evolutionary optimization. And he is able to weave these separate and independent strands into a robust cloth that can be used by the novice and the veteran, by the line worker and the professional, by individual contributors and managers.

American industry will do well to pay particular heed to Mario Perez-Wilson's "recipe" in its quest to restore its manufacturing leadership in the world.

Keki R. Bhote
Senior Corporate Consultant
Quality and Productivity Improvement
Motorola Inc.
Preface

The purpose of this book is to serve as a single source of reference to those individuals who are involved in the implementation of statistical methods (Statistical Process Control, and Design of Experiments) in manufacturing. It presents a standard methodology for conducting machine and process capability studies. The methodology has been designed to prove industry with a standard approach for studying processes, and enable them to produce within specifications.

The Machine/Process Capability Study methodology, M/PCpS, presents the steps necessary to achieve process capability in sequential order. It is divided into five progressive stages: 1) Process Delineation, 2) Metrology Characterization, 3) Capability Determination, 4) Optimization, and 5) Control. Prior to introducing each stage, necessary background information is presented. This information usually consists of problem solving tools and/or statistical techniques. Each stage is then thoroughly explained and broken down into further steps. Each step is then defined and described in detail using a "real world" manufacturing process example.

An attempt was made to illustrate the complete methodology using the same manufacturing process example. However, to simplify the explanation of certain steps a different manufacturing process was utilized. The manufacturing process operation selected to demonstrate the methodology is the Wafer Sizing operation done on silicon wafers in the semiconductor industry. Other areas of the methodology have been demonstrated using a Printed Wiring Board (PWB) wave soldering system, a fuze assembly operation, and an electronic component manufacturing process.

The methodology utilizes many techniques and problem solving tools that are usually covered independently. In the methodology, these tools and techniques have been incorporated in sequential order of execution, and integrated into one logical approach for optimizing manufacturing processes and machines. Some of the techniques are: Design of Experiments (Full Factorial Design and Fractional Factorial Designs), Analysis of Variance, Yates Algorithm, Pareto Diagrams, Concentration Diagrams, Ishikawa Diagrams, Control Chart, PosiTrol Plans, Pre-control, etc.

The book is divided into ten sections. The first section describes the author's derivation of the Machine/Process Capability Study methodology. It also suggests how the methodology should be implemented in a manufacturing environment. Sections two through eight present the five stages of the M/PCpS
methodology in order of execution. The basic format is an introduction and a
description of the tools and techniques necessary to understand the section,
followed by a step by step description of the M/PCpS stage, each with an
eexample. Within each section, the pages describing the tools and techniques are
characterized by an icon [ ] at the top right-hand corner of the page. The
pages describing the methodology have "M/PCpS" in its place. Section nine
presents all the standard worksheets (forms) used for guiding the user through
the methodology and for complete documentation of the study. Finally, section
ten contains a complete example of a M/PCpS study.

To the academic reviewers of this book, I must confess that this book is not for
you, but rather for the individuals (engineers, managers and practitioners) in the
manufacturing world struggling to find a method for reducing variation in their
processes.

It has been my intention to provide a standard methodology that industry could
adopt as an operating procedure for studying and optimizing manufacturing
processes. It is my personal belief (as my years of experience in applying this
methodology have proven to me) that this methodology, if followed thoroughly,
will inevitably reduce the major sources of processes variation, increase the
quality of your products, and speed up the successful optimization of your
manufacturing processes. The United States' competitive edge in manufacturing
is currently at a disadvantage against our Asian competitors. We are in an
economic war, and it is time to "buckle up", apply first gear, conduct smart
statistical experimentation and optimization, and win this economic war.

Mario Perez-Wilson
Kowloon, Hong Kong, December 10, 1988
The cumulative normal distribution table gives the area under the curve from minus infinity to the z-score or z value chosen.

Percent of product that falls below the USL = 45 comes from the Table:

0.83147  
100 x 0.83147 = 83.147 %

Percent of product that falls outside the USL = 45 is equal to:

1 - 0.83147 = 0.16853  
100 x 0.16853 = 16.853 %
Machine/Process Potential, (Cp)

The Cp is a process potential index that measures the potential of capability of a machine or process. The Cp is the ratio of the allowable spread over the actual spread. The allowable spread is the range or tolerance of the specification, and is calculated by subtracting the lower specification limit from the upper specification limit. The actual spread is the spread from data collected from the machine or process and is calculated by multiplying 6 times the standard deviation, S, of the data.

A high value of Cp does not guarantee that the process is capable of producing product within specification. Furthermore, the whole distribution of the process, might not overlap with the specification range. The process potential does not measure the location of the average of the actual spread with respect to the center (target) of the allowable spread, it only compares their widths. The capability index, Cpk, measures the degree of centering of the actual process spread with respect to the allowable spread.

The Cp may only be calculated when two sided specifications are available. Numerical properties such as addition and averages, cannot be applied to the Cp because it is a unitless index and would not yield meaningful information.

\[
Cp = \frac{\text{Allowable Spread}}{\text{Actual Spread}}
\]

Engineering Specification or what engineer judgment establishes as allowable for that machine or process.

The spread from the data collected from the machine or process.

What the customer WANTS.

What the customer GETS.

\[
\text{ALLOWABLE SPREAD} = 6 \times S \text{ where } S \text{ is based on a large sample size (Long term study)}
\]

\[
\text{ACTUAL SPREAD} = \left( \bar{x} - \text{LSL} \right) \text{ or } \left( \text{USL} - \bar{x} \right)
\]
Machine or Process Potential

Formula:

\[ Cp = \frac{USL - LSL}{8 \times S} \]  
(Short Term Study)

\[ Cp = \frac{USL - LSL}{6 \times S} \]  
(Long Term Study)

where,

\[ S = \text{standard deviation of the actual process} \]
\[ LSL = \text{lower specification limit} \]
\[ USL = \text{upper specification limit}. \]

Actual Process Data:

Mean, \( \bar{X} \) : 34
Standard Deviation, \( S \) : 3.75

\[ Cp = \frac{45 - 15}{6 \times 3.75} = \frac{30}{22.5} = 1.33 \]

Actual Process Data:

Mean, \( \bar{X} \) : 60
Standard Deviation, \( S \) : 3.75

\[ Cp = \frac{45 - 15}{6 \times 3.75} = \frac{30}{22.5} = 1.33 \]

Defective units: 100%
Machine or Process Capability

Machine or Process Capability, (Cpk)

The Cpk is a machine or process capability index that measures the ability of a machine or process to produce product within specification. The Cpk is the ratio of the distance between the actual process average and the closest specification limit over three times the standard deviation of the actual process. The capability index measures the degree of centering of the actual process spread with respect to the allowable spread. When the actual process average is outside the specification limits, then the Cpk defaults to zero.

\[
Cpk = \left\{ \text{Smallest of: } \frac{\bar{X} - \text{LSL}}{3 \times S} ; \frac{\text{USL} - \bar{X}}{3 \times S} \right\}
\]

A machine or process is referred to as being capable when its Cpk has a minimum value of one, and process stability has been proven. A Cpk equal to one implies that at least 99.73% of the product is within specifications limits, provided that the process is stable. Stability of the process can be proven through the use of a control chart. Once the process data is plotted on a control chart, the process can be regarded as being stable only if it exhibits statistical control. Statistical control is exhibited when the points plotted do not extend beyond the upper and lower control limits, and also by the absence of non-random patterns or trends within the control limits.

The Cpk can be calculated for both single-sided or double-sided specifications. Numerical properties such as addition and averages cannot be applied to the Cpk because it is a unitless index and would not yield meaningful information.
Let's assume that a product characteristic has a specification of $30 \pm 15$. The target of the specification becomes 30 and the tolerance is equal to two times 15 or 30. Let's calculate $C_{pk}$ for different distribution means and standard deviations.

In the example below, the sampling distribution is not centered with the target ($T$) of the specification. The standard deviation is small enough that if the distribution was centered, the process capability, $C_{pk}$, would be equal to the process potential, $C_p$.

In the next example, the sampling distribution is not centered with the target, $T$, of the specification. The standard deviation is very large and even if the distribution were centered, the process would still not be capable. The process potential is less than 1.0, which indicates that centering the distribution would not make the process capable. To make this process capable, the standard deviation has to be reduced.
Machine Capability

Interpretations of the Normal Probability Paper plots.

Capable Machine/Process

Normal Distributed (Symmetrical)

Negatively Skewed

Positively Skewed
Stage 3: Capability Determination

Platykurtic
(Kurtosis << 3.0)

Leptokurtic
(Kurtosis >> 3.0)

Non-Capable Machine/Process
Bimodal

Flat Distribution

Peaked Distribution

Bimodal Distribution
The Taguchi Orthogonal Array L27 (3^{13-11}) design.

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Level for each experimental factor in run # 27.
At the culmination of the stage of Control, the wafer thickness process capability index was Cpk=1.89 and its process potential index was Cp=1.99.

For wafer strength, the process potential index was further improved by experimenting with cutter grit sizes and water flow rates during grinding. The final experimental results lowered the number of cracks/wafer to an average of 0.769 and a standard deviation of 1.107; thus making the wafer very strong.
The specification limits were changed from 30 ± 15 cracks/wafer, to a lower specification limit of 0, and an upper specification limit of 10 cracks/wafer. The standard deviation was reduced from 8.42 to 1.107, far exceeding the ± Six Sigma goal performance capability. The "Guggenheim" wafer grinder achieved best-in-class status, and the wafer breakage yields were improved from 80.8% to 92.7%. An overall savings of $714,000 a year.

Wafer Strength Pre and Post Improvements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before Experimentation (Distribution #1)</th>
<th>After Experimentation (Distribution #2)</th>
<th>Final Results New Spec Limits (Distribution #3)</th>
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<td>( \bar{X} )</td>
<td>0.769</td>
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<td>S</td>
<td>1.10</td>
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<tr>
<td>Cp</td>
<td>1.51</td>
<td>45</td>
<td>1.51</td>
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The specification limits were changed from 30 ± 15 cracks/wafer, to a lower specification limit of 0, and an upper specification limit of 10 cracks/wafer. The standard deviation was reduced from 8.42 to 1.107, far exceeding the ± Six Sigma goal performance capability. The "Guggenheim" wafer grinder achieved best-in-class status, and the wafer breakage yields were improved from 80.8% to 92.7%. An overall savings of $714,000 a year.
### MACHINE/PROCESS CAPABILITY STUDY

**Program:** Bond Pad Corrosion  
**Responsible Person:** Plasma Etch M/PCpS Team

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<th>MACHINE/PROCESS</th>
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<td>$CHF_3$</td>
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<tr>
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<td>18 8 13 3 42</td>
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Within Wafer Thickness Uniformity
(Edge to Center Thickness of Silicone Nitride from Metalization - from 30 Wafers' Average)

Slope = 462 Å

Within Wafer Thickness Uniformity
(Edge to Center Thickness after Plasma Etching - From 30 Wafers' Average)

Slope = 1,278 Å

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MACHINE/PROCESS CAPABILITY STUDY

Study # 012503
Date 5-20-95
Operation Etching
Equip # T-903
Page 25 of 26

Final Results after Characterization

After Characterization and Optimization

- $\bar{X} = 6268.2$
- $R = 230$
- $S = 50.24$
- $Cp = 1.56$
- $Cpk = 1.56$

Before Characterization and Optimization

- $\bar{X} = 6882.73$
- $R = 1209$
- $S = 389.32$
- $Cp = 0.22$
- $Cpk = 0.22$

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Appendix A
  + Six Sigma

Appendix B
  Likert Scale for PWB Solder Deposition

Appendix C
  Nonparametric Statistical Tests

Appendix D
  Relationship Between Average and Sigma

Appendix E
  Charting the Range in a GR&R Study

Appendix F
  Transforming a Normal Distribution to a Standard Normal Distribution

Appendix G
  Fitting a Continuous Curve

Appendix H
  Possibilities of M/PCpS After the Capability Determination Stage
  Objective of M/PCpS Studies

Appendix I
  Cumulative Normal Distribution Table
  Unilateral Normal Distribution Table

Appendix J
  Minitab Instructions for the Capability Determination Stage
Six Sigma or ± Six Sigma

Six Sigma is an optimized level of performance approaching zero-defects in a process producing a product, service or transaction. It indicates achievement and maintenance of world-class performance.

Motorola, on Thursday, January 15, 1987, defined Six Sigma as having plus or minus six sigmas (±6s) or standard deviations within specification limits. In other words, given a particular product characteristic, which has a design specification, that design specification has an upper specification limit, USL, and a lower specification limit, LSL, these two limits demarcated a design tolerance. Motorola held the design tolerance to be such, that it should allow to fit twelve (±6) sigmas or twice the process variation.

Theoretically, under the above stated condition, a process would have Cp=2, Cpk=2, in-process yield around 99.9999998%, and a defective rate below 0.002 parts-per-million (PPM). For all practical purposes, ± Six Sigma implies zero-defects.

What is the objective of ± Six Sigma? To reduce the process variation, such that twelve standard deviations will fit within specification limits, and to center the mean in the middle of the specification limits.

Six Sigma or plus or minus six sigma within specification limits.
Areas under Normal Curve

Sigma Level
(± xσ)

<table>
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<tr>
<th>± 1σ</th>
<th>± 2σ</th>
<th>± 3σ</th>
<th>± 4σ</th>
<th>± 4.5σ</th>
<th>± 5σ</th>
<th>± 6σ</th>
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<tr>
<td>~ One Sigma</td>
<td>~ Two Sigma</td>
<td>~ Three Sigma</td>
<td>~ Four Sigma</td>
<td>~ Four and a half Sigma</td>
<td>~ Five Sigma</td>
<td>~ Six Sigma</td>
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<tr>
<td>0.33</td>
<td>0.67</td>
<td>1.0</td>
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<td>1.50</td>
<td>1.67</td>
<td>2.0</td>
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<tr>
<td>0.33</td>
<td>0.67</td>
<td>1.0</td>
<td>1.33</td>
<td>1.50</td>
<td>1.67</td>
<td>2.0</td>
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<td>317,320</td>
<td>45,500</td>
<td>2,700</td>
<td>63.5</td>
<td>6.9</td>
<td>0.6</td>
<td>0.002</td>
</tr>
</tbody>
</table>

[Yields, sigmas, Cp, Cpk and PPM levels when ± sigmas coincide with specification limits.]
References


American National Standards Institute, (1985), Control Chart Method of Controlling Quality During Production, ANSI Z1.3-1985 (ASQC B3-1985)


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About the Author


Mr. Perez-Wilson has over 23 years of industrial experience in engineering, quality and process improvement and has served at the executive level as Corporate Vice President of Quality for Flextronics International. He holds a B.S. degree in Industrial Engineering from the University of Arizona and Global Leadership from the Thunderbird School of Global Management. He was awarded the "Da N To Tsu" (Japanese for "Best of the Best") award from the Rochester Institute of Technology in the QED 90 Symposium.

One of the original architects of Six Sigma, he served as a Division Statistical Methods Engineering Manager at Motorola. During his tenure, he institutionalized and standardized the application of statistical methods in Motorola's worldwide manufacturing, production and engineering operations. His M/PCpS™ Methodology for characterizing processes has received global recognition and has become the standard in the achievement of Six Sigma.

Mr. Perez-Wilson has conducted seminars for over 18,000 individuals in Brazil, Belgium, People’s Republic of China, Germany, Hong Kong, India, Japan, Korea, Malaysia, Mexico, Philippines, Singapore, Sweden, Taiwan, and the United States, and is currently listed in The International Who's Who in Quality.

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Martin Marietta

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David Butler  
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Olin Interconnect

"An extremely structured and step-by-step methodology - very clear and simplified. A superb book to have for application as well as reference. I strongly recommend all personnel involved in production or manufacturing at all levels to attend this seminar if they are really serious about improving their product quality."

Norman Sim Boon Heng  
SPC Analyst  
Sundstrand Pacific (Atg) P.L.
"M/PCpS methodology is an extremely well planned, step by step course on 'how to' design, plan and complete Machine/Process Capability Studies. Most seminars that I have attended are predominately theory with very little applications. The instructor's experience and knowledge was excellent and made the seminar extremely enjoyable. Probably the BEST seminar I have ever attended - approximately ten in the last three years."

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Arvin NAA

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Quality Engineering Manager  
Allied Signal Inc. Aerospace

"Mario takes a no-nonsense approach to provide designers and manufacturers with what they need to know and use M/PCpS."

W. David Williams  
Quality Assurance Engineering Manager  
Sandia National Labs

"This is a very good course toward 6 Sigma quality. It is a "life statistics", I encourage all manufacturing engineers to attend this class."

Tony C. R. Tsai  
R & QA Manager  
Motorola Electronics, Taiwan

"A very systematic step-by-step approach to understand the behavior of a manufacturing process. This methodology should be made known to all manufacturing operations."

Nakkina VRK  
Process/IE Task Leader  
Motorola (P) Ltd.

"M/PCpS, ... methodology is vital for U.S. to regain status and market share in world economy. This, together with concurrent engineering has potential of reducing many problems of national scope."

R.J. Tockey  
MTS Division Supervisor  
Sandia National Labs

"Mario Perez-Wilson brings complex manufacturing techniques and tools and outlines a simple methodology that engineers can use in their day to day activities to characterize, improve and control both simple and complex manufacturing steps. This methodology can help in the path of continuous quality improvement and in becoming a 'total quality' organization."

Divyesh Shah  
Process & Product Engineering Manager  
Lucas Nova Sensor

"Step by step book clearly moves you through the capability study process. Format is well documented throughout the book."

Scott Schiefer  
Supplier Engineer  
Western Digital

"The course goes to the heart of process improvement. This methodology is as complete as I have seen."

James A. Schue  
Senior SPC Specialist  
Zimmer, Inc

"The Methodology is very well structured and planned. The tools I learned are very powerful!"

Carlos A. Pinheiro  
Site Coordinator (Brazil)  
Multek/ Flextronics

"...Mario Perez-Wilson has significantly added value by organizing these techniques into a workable methodology and demonstration how it can be applied to produce the desired results."

George Melchiorlsen  
Quality Engineer  
Hewlett Packard
TO: Carlos Genardini (RFH920)
FR: Scott Shumway (R75780)
DA: 26 May 88 at 15:29:54
CC: Gordon Chilton (RLWX10)
   Tommy George (RJNN10)
   Jim Norling (RF3500)
RE: SSUP DIVISION SIX SIGMA ROADMAP AND GOALS

I HAVE JUST COMPLETED A REVIEW OF YOUR DIVISION’S SIX SIGMA ROADMAP AND SUPPORTING DETAILED ACTION PLANS AND GOALS — AN OUTSTANDING PACKAGE. YOUR DIVISION, WITH MARIO PEREZ-WILSON’S EFFORTS IN COORDINATING THE TASK, IS TRULY IMPLEMENTING WHAT WE ARE EXPECTING OF ALL DIVISIONS IN THE SECTOR. THAT IS: APPLICATION OF THE SIX SIGMA ROADMAP AS IT APPLIES AT THE DIVISION LEVEL, GENERATION OF THE SPECIFIC ACTION PLANS AND GOALS TO SUPPORT THE STATED OBJECTIVES AND RATES OF IMPROVEMENT, AND INCORPORATION OF THESE INTO THE DIVISION FIVE YEAR PLANS.

THANKS FOR YOUR LEADERSHIP IN OUR SPS QUALITY IMPROVEMENT PROCESS.
SCOTT
ECM

Carlos,
Thanks — good job!

Jan N.
MOTOROLA INC.

SEMICONDUCTOR PRODUCTS SECTOR
INTER-OFFICE CORRESPONDENCE

Date: October 1, 1990

To: Paul Alonas  Theresa Maudie
    Bob Anger  Theresa Monroe
    Rhea Benson  Terry Quah
    John Bliss  Ruth Ruiz
    John Bourn  Nick Schiefer
    Rick Davis  Brooks Scofield
    Mike Finecey  Ora Smith
    Bill Grant  Ray Sura
    Sid Griest  Bob Tucker
    Mark Gabrielle  Art Velanie
    M. K. Hong  Dave Vowles
    Henry Leung  Jack Walker

From: Carlos Genardini  Phone: 244-4573  Mail Drop: Z208

cc: Jerry Baumann  Sandy Johnson
    Gary Beaudin  Tom Marchetti
    Kelvin Blair  Mario Perez-Wilson
    Jim Cryer  Dave Stevenson
    Jim Fogle  John Trice
    Dave Gilbert  Dave Wise

SUBJECT: Machine Process Capability Studies
         A Roadmap to Success

Several of you have completed, or are in the process of completing, work on Machine Process Capability Studies (MPCS). This proven methodology has been accepted by this Division as its approach to Six Sigma engineering of our processes and products. There are other tools that may be added to accelerate our level of accomplishment; however, the fundamental base is this methodology. I expect you to complete the work currently identified, and immediately proceed to identify the next field of study by establishing a new pareto of problems or barriers. Emphasis is to be placed on applying our engineering resources to the area of highest need. During the November Operations Review, I expect to have your management present what you have selected, the timing involved and the resources needed.

Thank you.

Carlos Genardini
Date: 6 February 1990  From: Dick Bond
To: Bob Stuart  Phone: 244-3633  M/O Z308
Gary Thulstedal
Mario Perez Wilson
cc: Carlos Genardini
Don Guthrie
Tim Jones
Paul White
Gordon Chilton

Subj: Allied Signal Customer Visit Presentations on 5 February 1990

Thank you, gentlemen, for your very professional and informative presentations to the Allied Signal management team. The material you presented really helped them get a feel for how we are using SPC and applying our quality improvement principles in the factory to achieve Six Sigma.

Another job well done by three guys who are not only recognized authorities in your respective areas, but who also exhibit a level of confidence and enthusiasm which confirms our commitment to continuous improvement and Total Customer Satisfaction.

Thanks again.

Dick Bond

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☐ Gauge R&R Studies - For Destructive and Non-destructive Testing

☐ Multi-Vari Chart and Analysis - A Pre-Experimentation Technique

☐ Positrol Plans and Logs

☐ Six Sigma - Understanding the Concept, Implications and Challenges

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