

The MPCpS[®] Methodology

Process Optimization

A Five-Stage Methodology for Characterizing Processes

Mario Perez-Wilson

**Follow this step-by-step approach
at your own pace, and teach yourself
how to optimize processes.**

**You will be improving processes
right away!**



The M/PCpS[®] Methodology
Stage IV: Optimization

Mario Perez-Wilson

President

Advanced Systems Consultants

"The M/PCpS Methodology - Stage IV: Optimization"

For books, software, public seminars,
in-house training seminars, and
consulting services

please contacts:

**Advanced Systems Consultants
Post Office Box 5257
Scottsdale, Arizona 85261
U.S.A.**

Phone: (480) 423-0081

www.mpcps.com

THE M/PCpS METHODOLOGY - STAGE IV: OPTIMIZATION

First Published	1992
Second Edition	2003
Third Edition	2012
Fourth Edition	2013

Copyright © 1992-2013, by Mario Perez-Wilson.

All Rights Reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in writing from Advanced Systems Consultants.

Current Printing (last digit)
10 9

PRINTED IN THE UNITED STATES OF AMERICA

ISBN 1-883237-21-1

Table of Contents

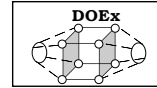
Experimentation	1.1
Why Experimentation?	
When is Statistical Experimentation Important?	
A Methodology - DOEx	
Why Statistically Designed Experiments?	
Experimental Design Funnel	
One-Factor-at-a-Time Strategy of Experimentation	
The M/PCpS Methodology	2.1
The Process Characterization Methodology	
The Seven Steps in Optimization	
Brainstorming Sessions	
Brainstorming Rules	
Cause & Effect Diagrams	
DOE Basic Definitions	3.1
Factors or Independent Variables	
Response or Dependent Variables	
Treatment Combinations	
Sampling Distributions	4.1
Central Limit Theorem	
Consequences of the Central Limit Theorem	
Samples and Populations	
Sampling Error	
Standard Error of the Mean	
Hypothesis Testing	4.13
Statistical Inference	
Hypothesis	
Statistical Testing	
Rejection Region	
Type I and Type II Errors	
One-tailed and Two-tailed Tests	
Power of the Test	
Statistical Assumptions	
Z-Test, One-sample Mean	

Student's t-Distribution	
t-Test, One-sample Mean	
Pooled Variances	
t-Test, Two-sample Mean Equal Standard Deviation	
t-Test, Two-sample Mean Unequal Standard Deviation	
Unbiased Estimate	
X ² Distribution	
One-Sample Variance	
X ² -test, One-Sample Variance	
Degrees of Freedom	
F-Distribution	
F-test, Two-Sample Variance	
Factorial Designs	5.1
Basic Definition	
2 ^k Factorial Designs	
2 ² Full Factorial Design	
Levels	
Yates' Order	
Treatment Combinations	
2² Full Factorial - Hot Dip Zinc Galvanizing Process	5.5
Computing the Main Effects	
Computing the Interactive Effects	
Isolation Plots	
Yates' Algorithm	
Construction of a Yates' Table	
Analysis of Variance	
Sum-of-squares	
Significance	
Selection of Best Factor's Settings	
Accounting for Variation	
2³ Full Factorial - Wire Bonding Process	6.1
Design Matrix	
Table of Replicates	
Table of Yates' Algorithm	
Table of ANOVA	
Main and Interactive Effects	

Isolation Plots	
Normal Plots	6.37
Normal Probability Plot of Effects	
Construction of Normal Plot of Effects	
Modeling	6.41
Determining Mathematical Models	
Linear Regression	
Curvilinear Regression	
Multiple Linear Regression	
Additive Model	
Residuals	6.51
Analysis of Residuals	
Histogram of Residuals	
Plotting Residuals in Time Sequence	
Plotting Residuals Against Predicted Values	
Calculating Residuals	
Reverse Yates' Algorithm	
Normal Plot of Residuals	
Construction of Normal Plot of Residuals	
Contrasts	6.67
Definition	
Construction of the Table of Contrasts	
Fractional Factorials	7.1
Fractional Factorials Designs	
Representation of Fractional Factorials	
Generators and Confounding	
Determining the Generators	
Resolution of the Design	
Full Factorials within Fractional Factorials	
Construction of a Fractional Factorial	
2^{5-1} Fractional Factorial	
Construction of Smaller Fractions of Fractional Factorial	
Designs	
2^{6-2} Fractional Factorial	
Determining all the Defining Contrasts	

Design Generators for Fractional Factorials Resolution and Treatment Combinations	
2⁵⁻¹ Fractional Factorial - High Explosive Bomb Fuze	7.39
Design Matrix	
Table of Replicates	
Table of Yates' Algorithm	
Table of ANOVA	
Main and Interactive Effects	
Isolation Plots	
2⁶⁻² Fractional Factorial - Integrated Circuit Molding	8.1
Process	
Design Matrix	
Table of Replicates	
Table of Yates' Algorithm	
Table of ANOVA	
Main and Interactive Effects	
Normal Probability Plots of Effects	
Isolation Plots	
Table of Regression Coefficients	
Table of Reverse Yates	
Residuals	
Normal Probability Plots of Residuals	
Collapsing Designs	
Blocking	9.1
Definition	
Partitioning a Factorial Design into Blocks	
Blocking Generators for 2 ^k Factorials	
Genichi Taguchi	9.9
Genichi Taguchi's Orthogonal Arrays	
L4 - Orthogonal Arrays	
L8 - Orthogonal Arrays	
L16 - Orthogonal Arrays	
L32 - Orthogonal Arrays	
L9 - Orthogonal Arrays	
L16 - Orthogonal Arrays	

<i>L25</i> - Orthogonal Arrays	.....	9.19
<i>L27</i> - Orthogonal Arrays		
Signal-to-Noise Ratio	.....	9.21
On-Target-Small-Variation is Best		
Smaller is Best		
Larger is Best		
Plackett-Burman Designs	.....	9.23
<i>8-Run</i>		
<i>12-Run</i>		
<i>16-Run</i>		
<i>20-Run</i>		
<i>24-Run</i>		
<i>28-Run</i>		
<i>32-Run</i>		
Saturated Fractional Factorials Designs	.....	9.32
$2^{4-1} - 2^{7-4}$		
$2^{5-1} - 2^{15-11}$		
$2^{6-1} - 2^{31-26}$		
Appendix A	.....	10.1
Tables and Worksheets		
Appendix B	.....	11.1
Analysis of Variance		
References & Bibliography	.....	12.1



When is Statistical Experimentation Important ?

There are many instances when the learning is so important it requires experimentation and the use of statistical methods.

Two important activities in which experimentation is important are:

1. Scientific Research, and
2. **Problem-Solving**

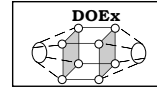
This book deals with the application of experimentation for complex problem-solving.

A Methodology - DOEx

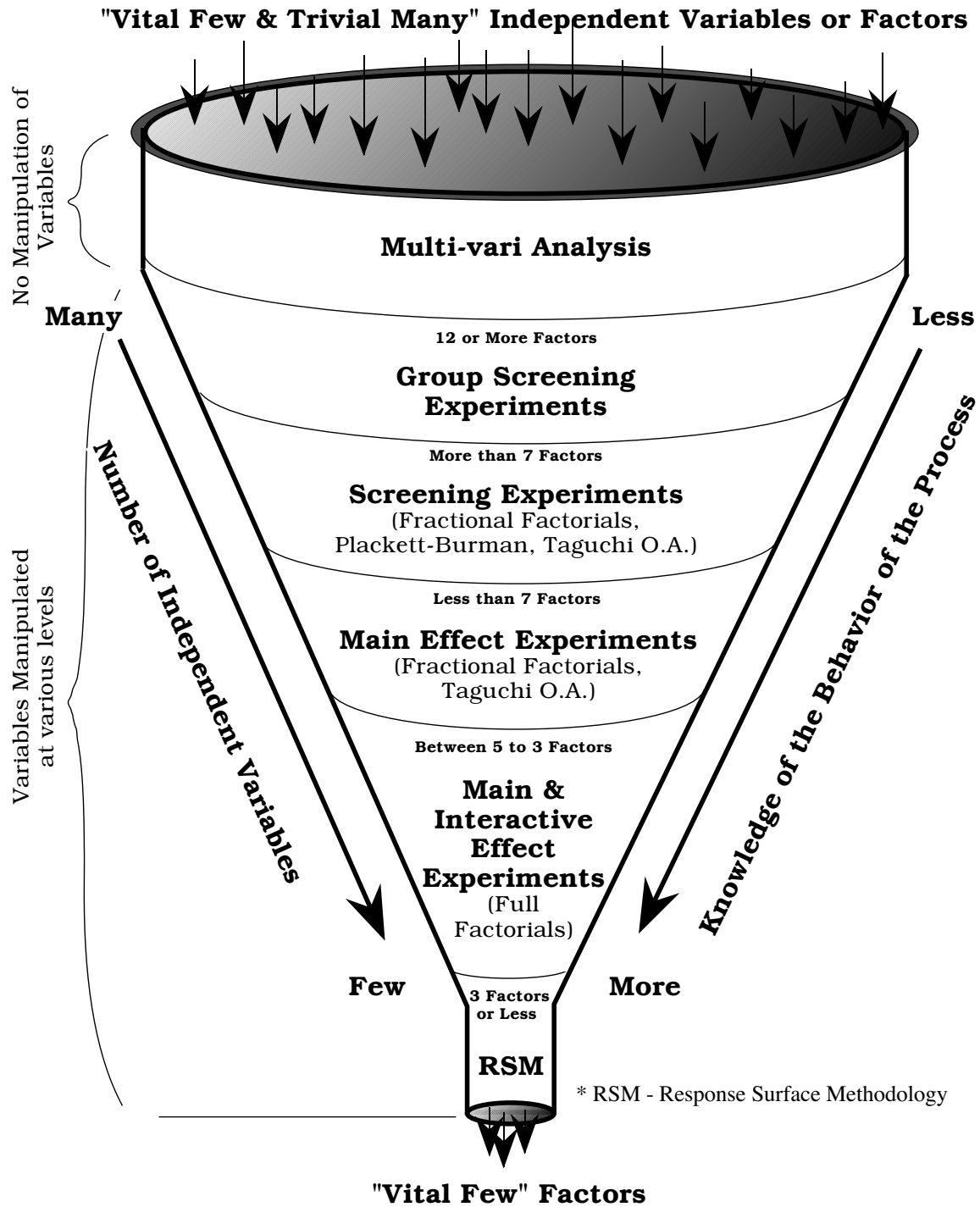
In the process of experimentation for problem-solving, there is no one unique path to obtaining a solution to a problem. Many paths may lead to the solution. However, a strategically designed path comprised of logically selected steps may become a common path or methodology, providing an efficient way of converging to a possible solution every time it is followed. This book attempts to provide such a methodology, and it will be referred to as the DOEx methodology. DOEx stands for the "Design of Experiments - A Methodology".

Qualities Needed For Good Experimentation:

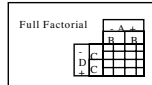
- | | | |
|------------------------------------|---|--|
| 1. Subject-matter Knowledge | { | Knowledge of:
Process
Problem
Physics |
| 2. Intellect | { | Faculty of :
Understanding
Thinking
Acquiring Knowledge |
| 3. Knowledge Of Strategy | { | Statistical Methods
DOEx |



Experimental Design Funnel



* RSM - Response Surface Methodology



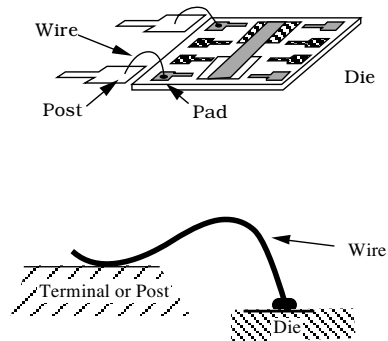
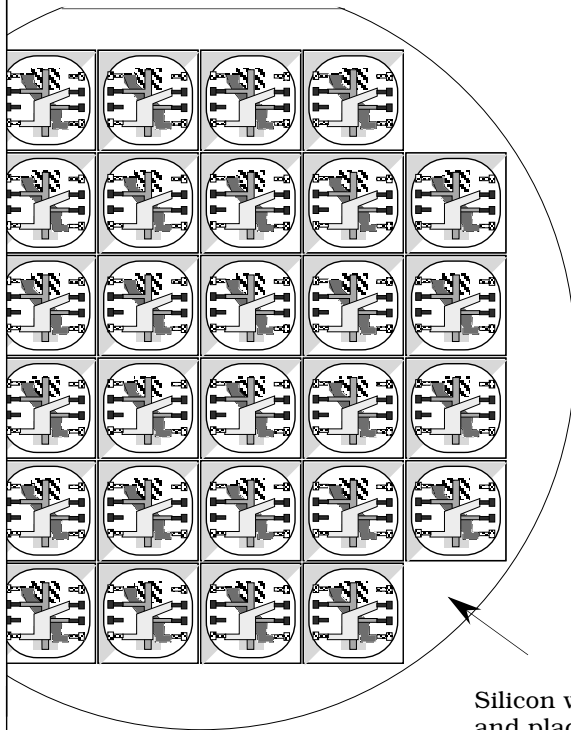
Let's use experimental data collected from a Wire Bonding process to describe the computations of the main and interactive effects in a 2^3 full factorial and to analyze the experiment.

Wire Bonding

An Integrated Circuit (IC) wire bonding process makes wiring connections from wafer die bond pads to the leadframe posts. The bonding is an ultrasonic bonding process.

In a previous process step (die bonding), the die are singly picked from a silicon wafer by a pick-and-place robotic arm and accurately placed in a leadframe. The die are then bonded to the leadframes. Once the die are attached, the wire bonding process uses a gold wire to connect each die bond pad to a leadframe post by bonding the wire from the bond pad to its respective post. The bond on the pad appears as a ball formed by ultrasonic energy, making a good intermetallic formation between the ball-bond and the pad.

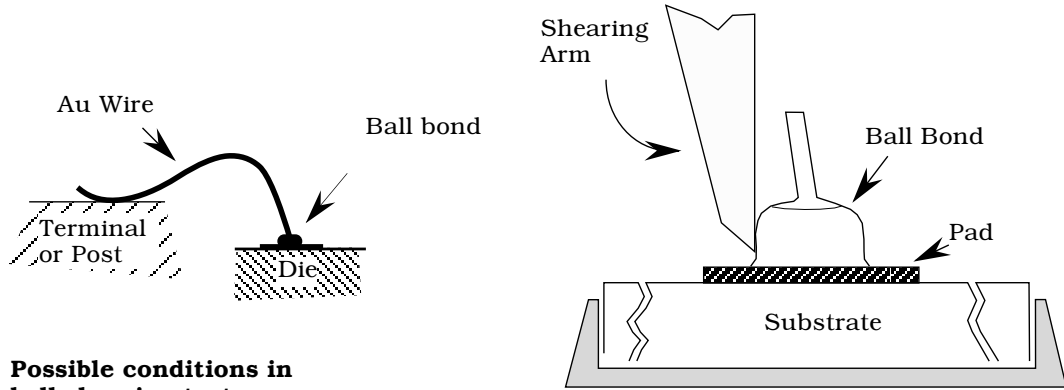
Some typical factors critically important in the wire bonding process are **bond time**, **bond power** and **bond temperature**.



Silicon wafer with die ready to be picked and placed in leadframe for bonding.

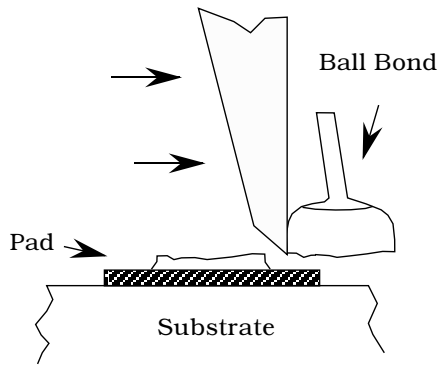
Full Factorial		A	B	C
D	C	B	A	

A shearing arm swivels with an increasing force (grams) to shear the bond ball out of the bonding pad.

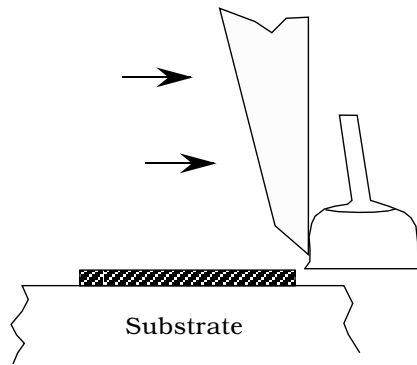


Possible conditions in ball shearing test

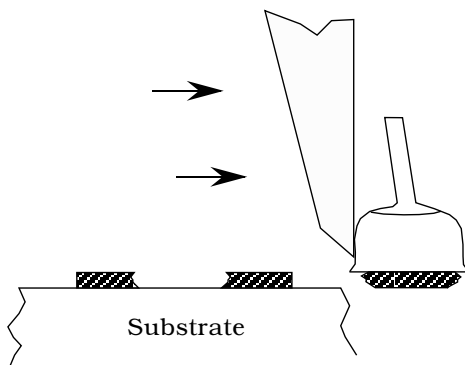
Ball Shear - Bond ball shears, weld area is intact.



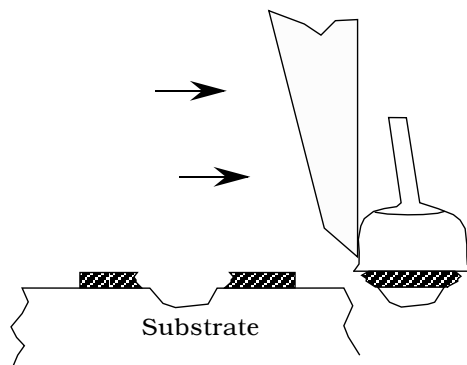
Ball Lifted - Bond ball is fully lifted leaving an imprint on pad.



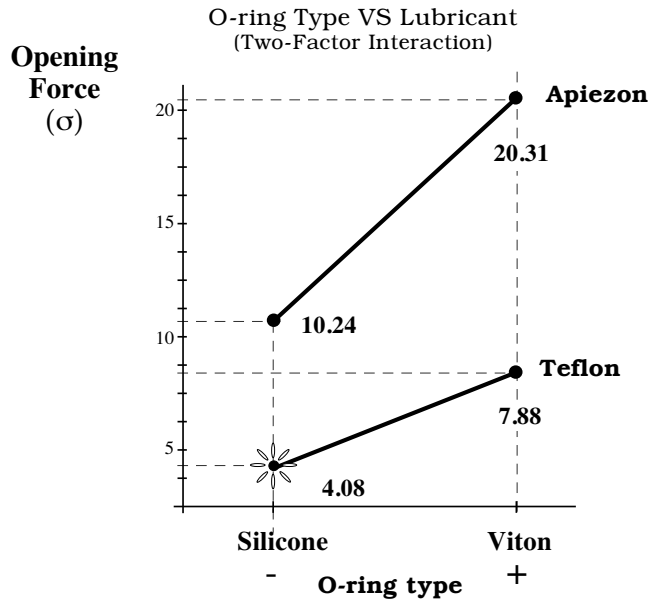
Pad Lifted - There is a residue of pad on the bond ball.



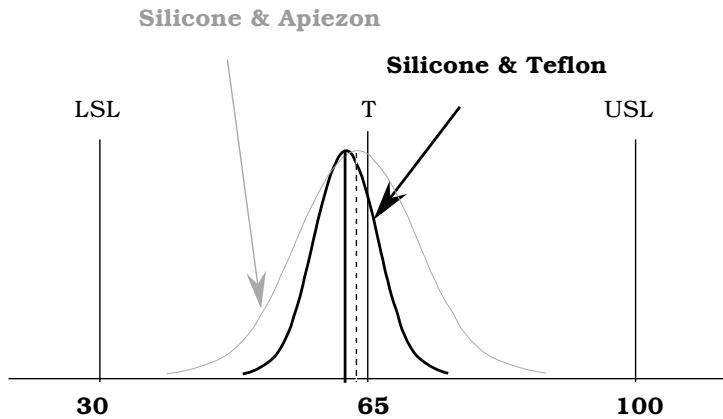
Substrate Lifted - There is a residue of pad and substrate on the bond ball.



Fractional Factorial		-	A	+
		B		B
-	D	C		
		C		

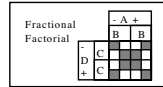


Plotting the standard deviations in an isolation plot, the standard deviation of silicone and teflon is 4.08, and is the lowest of all the other conditions. The apiezon appears to have more variation (standard deviation) than the teflon.



Setting the process with a Silicone o-ring and teflon as a lubricant appears to reduce the opening force average from 101.63 to about 61.5, and reduce the standard deviation from 34.58 to about 4.08. The new setting would improve the Cpk to about 2.57 and make the process ± 8.6 sigma, obviously after testing for normality and stability.





Let's go through an example of conducting a fractional factorial design experiment and of analyzing the data.

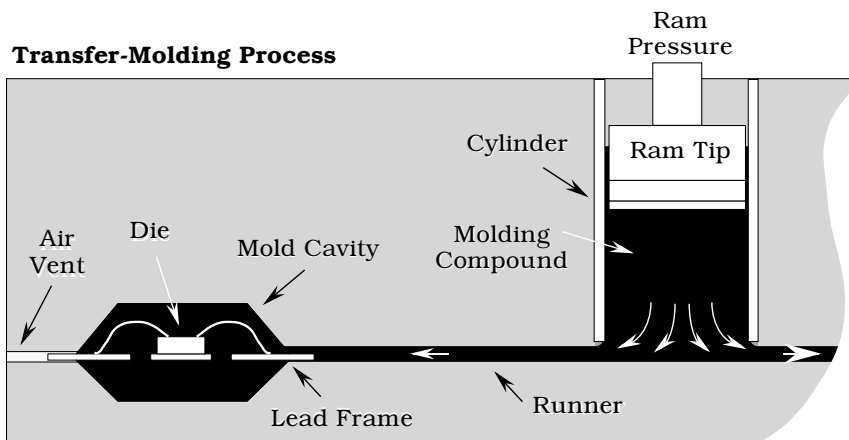
Integrated Circuit Molding Process

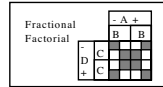
An integrated circuit molding process has been exhibiting some production quality problems and engineering has decided to conduct some experiments to determine the "vital few" independent variables controlling the process. The process has consistently exhibited a high number of voids in the IC components and various process changes have not yielded a stable improvement. Engineering has decided to conduct a screening experiment to determine the main effects of the following variables suspected to be influential in the reduction of voids.

The independent variables determined through a team brainstorming session are:

- [A] **Ram Tip Type**
- [B] **Pellet Preheat Time**
- [C] **Ram Transfer Time**
- [D] **Ram Transfer Pressure**
- [E] **Mold Curing Time**
- [F] **Mold Temperature**

The response variable is percent voids, and the current yield is at about 92%.





Integrated Circuit Molding Process Cont...

***Background:** Prior to the transfer molding process, plastic molding materials are compressed into small pellets of equal size, disk shape, density and weight. In the transfer molding process, molding pellets of 4.0 grams are placed into the pressure transfer chamber where they are later liquefied by heat and pressure. The mold is then closed and clamped by a press platen. The molding compound is then injected into the mold cavities as a hot liquid where the materials will be allowed to cure and harden.*

Molding Pellets

Step 1. Select the factors and levels for those factors.

Factor	Independent Variables	Low (-)	High (+)
A	Ram Tip Type	Taper	Straight
B	Pellet Preheat Time	5 Sec	10 Sec
C	Ram Transfer Time	5 Sec	10 Sec
D	Ram Transfer Pressure	20 Kg/cm ²	40 Kg/cm ²
E	Mold Curing Time	45 Sec	65 Sec
F	Mold Temperature	170 ° C	190 ° C

References & Annotated Bibliography

Addelman, S., "Some Two-level Factorial Plans with Split-plot Confounding". *Technometrics* (1964), 253-258.

Anderson, V.L. and McLean, R.A., **Applied Factorial and Fractional Designs**. Marcel Dekker, Inc. (1984), ISBN 0-.

Anderson, V.L. and McLean, R.A., **Design of Experiments: A Realistic Approach**. Marcel Dekker, Inc. (1974), ISBN 0-.

Barker, T.B., **Engineering Quality by Design**. Marcel Dekker, Inc. (1997), ISBN 0-8246-1.

Barker, T.B., *Quality by Experimental Design*. Marcel Dekker, Inc. (1985), ISBN 0-8247-7451-5.

Bainbridge, T.R., "**Staggered, Nested Designs for Estimating Variance Components**". *Industrial Quality Control* (1965), 12-20.

Box, G.E.P., W.G. Hunter and J.S. Hunter, *Statistics for Experimenters: An Introduction to Design, Data Analysis and Model Building*. John Wiley & Sons, Inc. (1978), ISBN 0-471-09315-7.

• Excellent book, it is written with the non-statistician in mind. •

Box, G.E.P. and Draper, N.R., *Evolutionary Operation: A Statistical Method for Process Improvement*. John Wiley & Sons, Inc. (1969), ISBN 0-471-09305X.

Box, G.E.P. and Draper, N.R., *Empirical Model Building & Response Surfaces*. John Wiley & Sons, Inc. (1987), ISBN 0-471-81033-9.

Box, G.E.P. and Behnken, D.W., "**Some New Three Level Designs for the Study of Quantitative Variables**". *Technometrics* (1960), 455-476.

Box, G. E. P., "**The Exploration and Exploitation of Response Surfaces: Some General Considerations and Examples**". *Biometrics* (1954), 16-60.

Box, G. E. P., "**A Basis for the Selection of a Response Surface Design**". *Journal of the American Statistical Association* (1959), 622-654.

Box, G. E. P. and Draper, N. R., "**The Choice of a Second Order Rotatable Design**". *Biometrika* (1963), 335-352.

Box, G. E. P. and Youle, P. V., "**The Exploration and Exploitation of Response Surfaces: An Example of the Link between the Fitted Surface and the Basic Mechanism of the System**". *Biometrics* (1955), 287-323.

Box, G. E. P., "**The Effects of Errors in the Factor Levels and Experimental Design**". *Technometrics* (1963), 247-262.

Bralcher, T. L., Mason, M. A., and Zimmer, W. J., "**Tables of Samples Sizes in the Analysis of Variance**". *Journal of Quality Technology* (1970), 156- 164.

Cochran, W.G. and Cox, D.R., **Experimental Designs**. John Wiley & Sons, Inc. (1957), ISBN 0-

Cochran, W. G., "**Some Consequences When the Assumptions for the Analysis of Variance are not Satisfied**". *Biometrics* (1947), 22-38.

Cornell, John A., *How to Apply Response Surface Methodology*. ASQC (1990), ISBN 0-87389-092-2 .

- Good introduction to RSM, includes the experimental designs for fitting First-Degree Models as well as Second-Degree Models. Very brief explanation of each of the experimental designs: 2k factorial Designs, Rotatable Designs, 2k-p fractional factorial Designs, Simplex Designs, Plackett-Burman Designs, 3k factorial Designs, Central Composite Design, Orthogonal Blocking of the CCD, Equiradial Designs and Box-Behnken Designs. •

Cornell, John A., *How to Run Mixture Experiments for Product Quality*. ASQC (1990), ISBN 0-87389-021-3.

Cornell, John A., *Experiments with Mixtures: Designs, Models, and the Analysis of Mixture Data*. John Wiley & Sons, Inc. (1981), ISBN 0-471-52221-X.

Cox, D.R., *Planning of Experiments*. John Wiley & Sons, Inc. (1958), ISBN 0-471-57429-5.

Daniel, C., *Applications of Statistics to Industrial Experimentation*. John Wiley & Sons, Inc. (1976), ISBN 0-471-19469-7.

Daniel, C. and Wood, F. S., **Fitting Equations to Data**. John Wiley and Sons, Inc. (1971), ISBN 0-

Davies, Owen L., *The Design and Analysis of Industrial Experiments*. Hafner Publishing Co. (1960), ISBN .

Diamond, W.J., *Practical Experimental Designs*. Van Nostrand Reinhold (1989), ISBN 0-442-31849-9.

• Practical explanation of Plackett-Burman Designs, Jacques Hadamard's Designs, Peter John's three-quarter fractions designs and other fractional designs not presented in other texts. •

Dixon, W. J. and Massey, F. J., **Introduction to Statistical Analysis**. McGraw-Hill, Inc. (1969), ISBN 0-

Draper, N.R. and H. Smith, *Applied Regression Analysis*. John Wiley & Sons, Inc. (1966), ISBN 0-471-02995-5.

Federer, W.T., **Experimental Design: Theory and Application**. The Macmillian Co.(1955), ISBN 0-

Fisher, R.A., *Statistical Methods for Research Workers*. Hafner Publishing Co. (1925).

Fisher, R.A., *The Design of Experiments*. Hafner Publishing Co. (1935).

Fisher, R.A., *Statistical Methods and Scientific Inference*. Hafner Press (1956), ISBN 0-02-844740-9.

Guenther, W. C., **Analysis of Variance**. Prentice-Hall, Inc. (1964), ISBN 0-

Gunst, R. F. and Mason, R. L., **Regression Analysis and Its Application: A Data-Oriented Approach**. Marcel Dekker, Inc. (1980), ISBN 0-

Hicks, C.R., *Fundamental Concepts in the Design of Experiments*. Holt, Rinehart & Winston (1982), ISBN 0-03-061706-5.

Hinkelmann, K. and O. Kempthorne, *Design and Analysis of Experiments*. John Wiley & Sons, Inc. (1994), ISBN 0-471-55178-3.

Hunter, J. S., "**Determination of Optimum Operating Conditions by Experimental Methods**". *Industrial Quality Control*, (1958-1959), Part II- I (Dec.1958), Part 11-2 (Jan.1959),16, Part II-3 (Feb. 1959).

John, P.W.M., **Statistical Design and Analysis of Experiments**. Macmillan (1971), ISBN .

John, P.W.M., **Incomplete Block Designs**. Marcel Dekker, Inc. (1980), ISBN 0-

Johnson, N.L. and Leone, F.C., **Statistics and Experimental Design in Engineering and Physical Sciences**. John Wiley & Sons, Inc. (1977) ISBN 0-

- Good resource for ANOVA calculations. •

Kempthorne, O., **The Design of Experiments**. John Wiley & Sons, Inc. (1952), ISBN 0-

Khuri, A.I. and Cornell, John A., *Response Surfaces Designs and Analyses*. Marcel Dekker, Inc. (1987), ISBN 0-8247-7653-4.

Kirk, R.E., *Experimental Design*. Brooks/Cole (1982), ISBN 0-534-01173-X.

Koons, G. F. and Heasley, R. H., "**Response Surface Contour Plots for Mixture Problems**". Journal of Quality Technology (1981), 207-214.

Kvalseth, T. O., "**Cautionary Note About R²**". The American Statistician, (1985), 279-285.

Lochner, R.H. and J.E. Matar, *Designing For Quality*. ASQC (1990), ISBN 0-527-91633-1.

Mandel, J., *The Statistical Analysis of experimental Data*. Dover Publications Inc. (1964) ISBN 0-486-64666-1.

- Good sections for Method of Least Squares, Fitting of Curves and Surfaces, Fitting of Straight Lines. •

Mason, Robert L., Gunst, Richard F. and Hess, James L., *Statistical Design and Analysis of Experiments*. John Wiley & Sons, Inc. (1989), ISBN 0-471-85364-X.

Milliken, George A. and Johnson, Dallas E., **Analysis of Messy Data: Nonreplicated Experiments**. Nostrand Reinhold (1989), ISBN 0-41206371-9.

Milliken, George A. and Johnson, Dallas E., **Analysis of Messy Data: Design of Experiments**. Nostrand Reinhold (1984), ISBN 0.

- Good resource for ANOVA calculations. •

Montgomery, D.C., *Design and Analysis of Experiments*. Wiley (1976), ISBN 0-471-86812-4.

Montgomery, D.C. and Peck, E.C., **Introduction to Linear Regression Analysis**. John Wiley & Sons, Inc. (1982), ISBN 0-

Myers, R.H., **Response Surface Methodology**. Allyn and Bacon, Inc. (1971), ISBN 0-

Myers, R. H., **Classical and Modern Regression with Applications**. PWS and Kent Publishing Co. (1986), ISBN 0-

Natrella, M.G., **Experimental Statistics**. National Bureau of Standards Handbook 91, Washington, D.C.: US Government Printing Office (Reprinted by John Wiley & Sons, Inc.)

Nelson, L. S., "**Sample Size Tables for Analysis of Variance**". Journal of Quality Technology (1985), 167-169.

Neter, J., Wasserman, W., and Kutner, M. H., **Applied Linear Statistical Models**. Irwin Publishing Co. (1974), ISBN 0-256-08338-X.

Neter, J., Wasserman, W., and Kutner, M. H., **Applied Regression Analysis**. Irwin Publishing Co. (1983), ISBN 0-

Ostle, B. and Malone, L. C., **Statistics in Research**, Fourth Edition. The Iowa State University Press (1988) ISBN 0-

- Good resource for ANOVA. •

Phadke, M.S., *Quality Engineering Using Robust Design*. Prentice Hall (1989), ISBN 0-13-745167-9.

- Good explanation of Nuisance Factors, Blocking and Randomization, Interaction destroying additivity. •

Plackett, R.L. and J.P. Burman, "**The Design of Optimum Multifactorial Experiments**". Biometrika 33 (1946) 305-325.

Schmidt S.R. and R.G. Launsby, *Understanding Industrial Designed Experiments*. Air Academy Press (1988), ISBN N/A.

Searle, S. R., **Linear Models**. John Wiley and Sons, Inc. (1971), ISBN 0-

Seber, G. A. F., **Linear Regression Models**. John Wiley and Sons, Inc. (1977), ISBN 0-

Shapiro, S. S., **How to Test Normality and Other Distributional Assumptions**. ASQC Basic References in Quality Control, Vol 3., (1980)

Shapiro, S. S. and Wilk, M. B., "**An Analysis of Variance Test for Normality (Complete Samples)**". Biometrika (1965), 591 -611.

Smith, J.R. and Beverly, J.M., "**The Use and Analysis of Staggered Nested Factorial Designs**". Journal of Quality Technology (1981), 166-173.

Snedecor, G. W. and Cochran, W. G., **Statistical Methods**. Iowa State University Press (1967), ISBN 0-.

Snee, R.D. and Marquardt, D.W., "**Screening Concepts and Designs for Experiments with Mixtures**". Technometrics (1976), 19-30.

Taguchi, G., System of Experimental Design. American Supplier Institute (1987), ISBN 0-941243-00-1.

Taguchi, G., Introduction of Quality Engineering. Asian Productivity Organization (1987), ISBN 92-833-1084-5.

Taguchi, G., Taguchi Methods - Orthogonal Arrays and Linear Graphs. American Supplier Institute (1987), ISBN 0-941243-01-X.

Wheeler, D.J., Understanding Industrial Experimentation. SPC Inc. (1987), ISBN 0-945320-03-5.

Wheeler, Robert E., "**Portable Power**". Technometrics (1974), 193-201.

Winer, B. J., **Statistical Principles in Experimental Design**. McGraw-Hill, Inc. (1971) ISBN 0-.

Younger, M.S., **A First Course in Linear Regression**, Second Edition. Duxbury Press (1985).