An Analysis of Experiments for Determining Optimal Operating Conditions of a Wire Bonder.

By

Mr. Charin Chaonatong

A Final Report of the Three - Credit Course
CE 6998 Project

Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science
in Computer and Engineering Management
Assumption University

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The Graduate School of Assumption University has approved this final report of the three-credit course, CE 6998 PROJECT, submitted in partial fulfillment of the requirements for the degree of Master of Science in Computer and Engineering Management.

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ABSTRACT

This project report optimizes the wire bonding factor in Magnetic Resistive Recording Head Stack Assembly Process through Analysis of Variance (ANOVA) method. In the process, most of the defects that we found are poor bonding. Poor bonding has been important and affected product quality and the company credits. So the factors which are concerned with in the wire bonding process are the power of wire bonder machine, the bonding tip force, the bonding time, type of bonding tip length, and type of wires. The experiment treats the factors with an experimental design with Full Factorial method to find the optimize value. We use statistics to generate the treatment combination and analyse the result.

The result of the measurable data analysis reveals that the type of bonding tip length has a significant effect on the wire bonding performance. Therefore we separated the results of optimized analysis referring to the bonding tip length. The result shows that for a 10 Mil. tip length the bonding performance is higher than that of 7 Mil. tip length in terms of wire pull strength. The factors that significantly affect the bonding performance of both the bonding tip length are the bonding tip force, the power of wire bonder machine, the color of wires, and the interaction of the force and power. The optimized value of 10 Mil. tip length is the force at 170 grams, the power at 280 mW. and the Gold color of the wire. And the optimize value of 7 Mil. tip length is the force at 170 grams, the power at 270 mW. and the Green color of the wire. After we implement the optimize value of 7 Mil. tip length wire, the pull strength average increases from 17 grams to 20 grams and the Cpk increases from 0.7 to 1.0. For 10 Mil. tip, we can get the wire pull strength to 22 grams and Cpk 1.2. The 10 Mil. tip length is a good choice to improve the wire bonding performance.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Chamnong Jungthirapanich who spent his time on advising, and correcting my project. His constant encouragement has led me to complete my project. Also I would like to express appreciation to my Advisory Committee members: Prof Dr. Srisakdi Charmonman, Dr. Chamnong Jungthirapanich, and Assoc. Prof Somchai Thayarnyong for their constructive comments and advice throughout the project.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure		Page

LIST OF TABLES

I. INTRODUCTION

1.1 General Background

For Hard Disk Drive manufacturing companies these are very high competitions and product changes when compared also to the fast new technology development. The manufacturers need to improve their process capability for high volume market demand. [as shown in Figure 1.1]

Figure **1.1.** The Supply Chain of Personal Computer Businesses.

The Head Stack Assembly manufacturing process is a part of Hard Disk Drive Assembly manufacturing process that includes many component parts, and long processes for assembling in the production line. Therefore the process includes many raw materials and tools or equipment concerned with volume building of the production line and the quality of the product.

In the process of head stack assembly, one of the operation is bonding recording head wire. The flex circuit at the bonding area is called 'bonding pads' and uses Ultrasonic bonding system called 'Head 's Wire Bonding Machine'. Ultrasonic bonding system and wire bonder send ultrasonic wave at high constancy frequency and transfer to the bonding tip for bonding the wires. The next process is conformal coating, covering bonded area by adhesive and then cures the adhesive by using UV oven.

One process that contributes to a lot of failure is the head wire bonding and concerns with many factors from the process and environment. Process engineer tries to segregate the problem such as shown in Figure 1.2 cause-effect diagram;

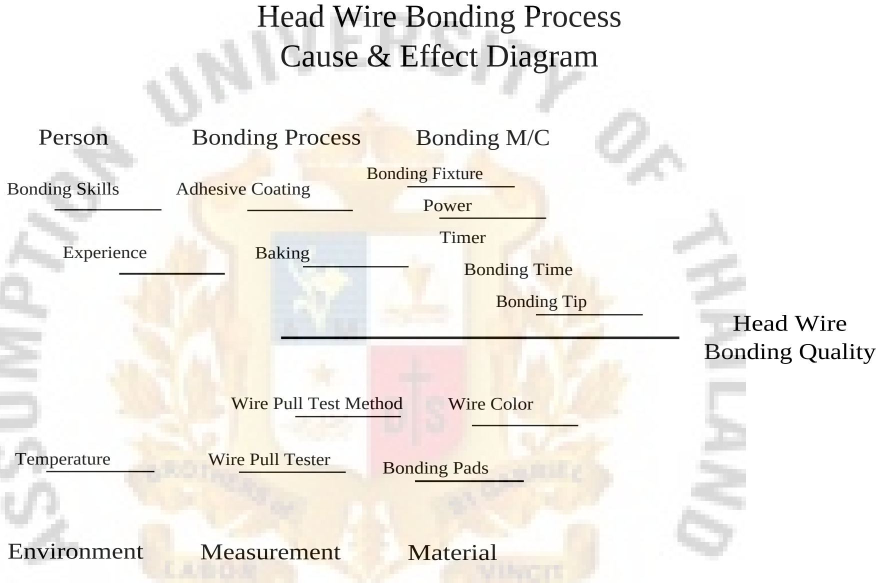

Figure 1.2. A Cause-Effect Diagram of Head Wire Bonding Quality.

The project will separate all factors into 2 groups. The first is controllable factor such as power of the machine, bonding time, machine model and bonding tip. The second is uncontrollable factors such as room temperature, operator's skill or electricity potential for supplying the machine.

The design of experiments is part of the systematic, structured development strategy for product/process design in order to understand and optimize the products we produce with a minimal waste. The study will focus on controllable factors especially the wire bonding machine's parameters set up as follows:

(a) Power of wire bonder Machine

(b) Bonding Time

(c) Bonding Tip Force

The study is using Factorial Design method to help in term of experimental design. Factorial designs are Orthogonal Arrays where the number of treatment combinations equals the number of levels raised to a power of the number of factors.

Example

$Tc = 2^3$

Where 3 is the number of factors and 2 is the number of levels in the design.

1.2 Statement of Problems

The focusing is on head wire bonding failure and the problem related to the wire bonding issues. The following problems currently exists:

(a) Poor head wire bonding integrity.

(b) Head wire lifted from the bonding pad.

(c) Reduced capacity of the machine or units per hour (UPH) because of time for complete bonding.

(d) Increasing down time related to poor bonding.

(e) Reduced bonding tip usage compared with volume built.

(f) Loss opportunity for reworking the part because of wire bonding pads' limitation.

1.3 Objectives

The study will give the optimum value of the machine's parameters to achieve our target as follows:

(a) Increase head wire bonding strength.

(b) Improve head wire bonding yield.

(c) Reduce cost for the equipment maintenance.

(d) Improve product quality in terms of head performance.

1.4 Scope and Limitation

For the study, we are focusing on the wire bonding operation then we narrow down the process parameters as follows:

(a) Find out the optimized parameters of head wire bonded machine conditions.

(b) Find out the parameter for controlling.

(c) Implement the machine.

(d) Exclude machine and fixture design, operator skill and head different.

1.5 Deliverables

This study will provide the solution of head wire bonding failure and the problem related to the bonding performance. The output of the project will give the benefit as follows:

(a) To get the right way for solving the problem of head wire bonding failure.

(b) To clarify and avoid the problem which may occur with head stack assembly process.

(c) To increase capacity or units per hour (UPH) of the machine.

(d) To help process engineer as process tools for solving similar problems in head stack assembly (HSA) process.

1.6 Plan and Development of the Project

For understanding and clarifying the project information to be in the same direction, we go through the study of the process step by step as shown in Figure 1.3 Framework of project. And the framework of the project will be as follows:

(1) Literature Review of Experimental Design

This chapter mentions most of the experimental design methods that are being used in electronic company or in assembly manufacturing.

(2) Research Methodology

We show the experimental design method in this project. The method that we selected involves consideration of the response or output that we are focused about including data analysis, statistical methods use to analyze the data so that results and conclusion are objective to the decision making process in the future.

(3) Experimental Process and Data Collection

By the experiment concept in selecting the design, we use JMP software to generate treatment combination and the software provides a table of treatment combination.

(4) Experimental Result and Discussion

From the printout of the software shows in terms of data analysis to follow the statistical methods, the result of the experiment will show what the input or factors affect our response or objective.

(5) Conclusion and Recommendation

What we get from the experimental result and discussion, we can give the recommendation to guide the process engineer as to how to get improvement from the process. And this chapter has some suggestions for solving some problems when we found it in the experiment.

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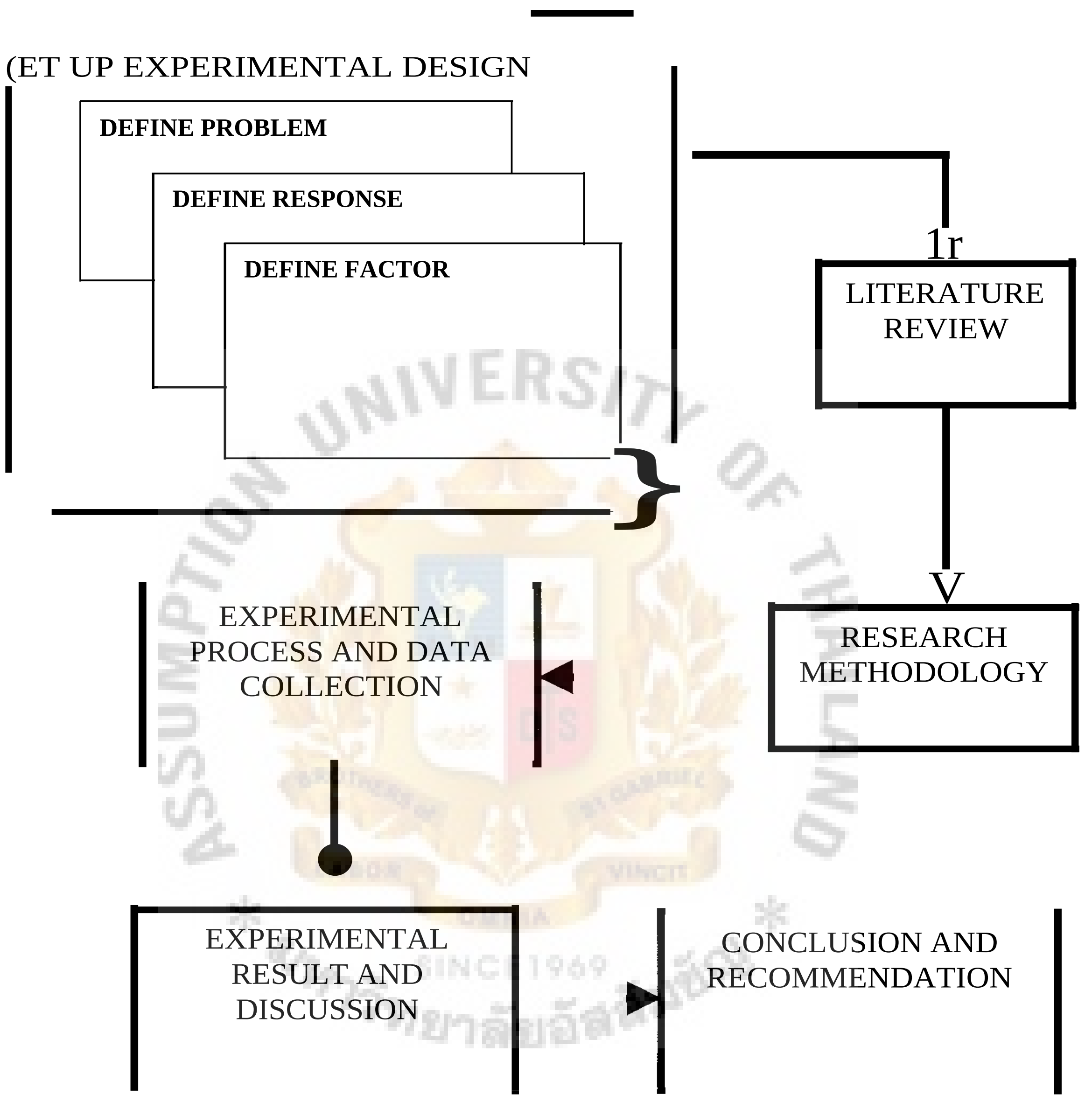

Figure 1.3. The Project Framework.

II. LITERATURE REVIEW

2.1 The Basic Concept of Experimental Design

A designed experiment is a test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes in the output response.

The model as shown in Figure 2.1 can represent the process under study. Our process has a combination of machines, methods, people, and others resources that transform some input into an output that has one or more observable responses. Some of the process variables xi, , x_p are controllable, other variables z_1, z2, , z_p are uncontrollable.

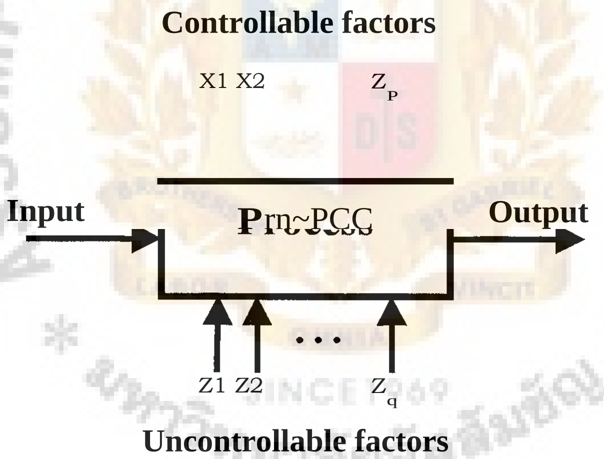

Figure 2.1. The General Model of a Process.

Experimental design methods play an important role in process development and process troubleshooting to improve performance. The objective in many cases may be to develop a robust process, that is, a process affected minimally by external sources of variability (the z's).

2.2 Application of Experimental Design

Experimental design is as important tool in engineering for improving the performance of a manufacturing process. It has extensive application in the development of new processes. The application of experimental design techniques early in process development can result in:

(a) Improved process yields.

(b) Reduced variability and closer conformance to nominal or target requirements.

(c) Reduced development time.

(d) Reduced overall costs.

In engineering design activities, new products are developed and existing ones improved. Some applications of experimental design in engineering design include:

(1) Evaluation and comparison of basic design configurations.

(2) Evaluation of material alterations.

(3) Selection of design parameters so that the product will work well under a wide variety of field conditions, that is so that the product is robust.

(4) Determination of key product designs parameters that impact product performance.

We can separate the applications of experimental design to different target response as follows:

2.2.1 Process Characterization

We would use designed experiment to determine which parameters of our process are influential in the occurrence of defects of our product and which adjustments should be made to those variables to reduce the defects. In this situation we are interested in characterizing the process and we want to determine which factors (both controllable and uncontrollable) affect the occurrence of defects on the product. To accomplish this, we can design an experiment that will enable us to estimate the magnitude and direction of the factor effects. That is, how much does the response variable change when each factor is changed, and does changing the factors together produce different results than are obtained from individual adjustments. Sometimes we call an experiment such as this a screening experiment.

The screening or characterization experiment will be used to identify the critical process factors and to determine the direction of adjustment for these factors to reduce further the number of defects per unit.

2.2.2 Process Optimization

Optimization, if the response yields, we would look for region of maximum yield, whereas if the response is variability in a critical production dimension, we would seek a region of minimum variability. We know from the result of a characterization experiment, which factors have major concern with process variables that influence the yield. So experimental methods will be required to optimize the yield with respect to the factor.

To locate the optimum, it is necessary to perform an experiment that varies factor value. This type of experiment is called a factorial experiment.

2.2.3 Product Design

Experimental design methods can often be applied in the design process. When we want to design the product we need to consider that quality characteristic of interest is a function of usage of the product and ability of the product. We can build the prototype in which all of the factors can be varied over certain ranges. Once appropriate levels for factor ranges have been identified, an experiment can be designed consisting of various combinations of factor levels and the prototype can be tested at these combinations.

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2.2.4 Determining System and Component Tolerances

Our tester, is good if the overall gage capability is good. That is, the standard deviation of measurement error is small. We have decided the factor values are the best choices for the design parameters so far as gaging capability is concerned, but the overall measurement error is still too height. This is likely due to the tolerances that have been specified on the components. The tolerance bands can be used to define high and low factor levels, and an experiment can be preformed to determine which components have the most critical tolerances. The minimum amount possible is consistent with the desired measurement capability. Consequently, a lower-cost design that is easier to manufacture will result.

2.3 Basic Principles

There are three basic principles of experimental design, the first is replication, by which we mean a repetition of the basic experiment. Replication has two important properties. First, it allows the experimenter to obtain an estimate of the experimental error. This estimate of error becomes a basic unit of measurement for determining whether observed differences in the data are really statistically different. Second, if sample mean (e.g., y) is used to estimate the effect of the factor in the experiment, then replication permits the experimenter to obtain a more precise estimate of this effect.

The second, randomization is the cornerstone underlying the use of statistical methods in experimental design. By randomization we mean that both the allocation of the experimental material and the order in which the individual runs or trials of the experiment are to be performed are randomly determined. Statistical methods require that the observations (or errors) be indecently distributed random variables. Randomization usually makes this assumption valid. By properly randomizing the

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experiment, we also assist in "averaging out" the effect of extraneous factors that may be present.

The third, blocking, is a technique used to increase the precision of an experiment. A block is a portion of the experimental material that should be more homogeneous than the entire set of material. Blocking involves making comparisons among the conditions of interest in the experiment within each block.

We are focusing on the process optimization so we conduct to experimental design methods that are related to factorial experiment as follows:

(1) Factorial Design

(2) Fractional Factorial Design

(3) Taguchi's Methods

2.3.1 Factorial Design

By Factorial design we mean that in each complete trial or replication of the experiment all possible combinations of the levels of the factors are investigated. For example, if there are levels of factor A and b levels of factor B, then each replicate contains all ab treatment combinations. When factors are arranged in a factorial design, they are often said to be crossed.

The effect of a factor is defined to be the change in response produced by a change in the level of the factor. This frequency is called a main effect because it refers to the primary factors of interest in the experiment. We may find that the difference in response between the levels of one factor is not the same as all levels of the other factors. There is an interaction between the factors.

The Advantage of Factorial.

Factorial designs have several advantages. They are more efficient than one-factor-at-a-time experiment. Furthermore, a factorial design is necessary when interactions may be present to avoid misleading conclusions. So factor designs allow the effects of a factor to be estimated at several levels of the factors, yielding conclusions that are valid over a range of experiment conditions.

General Term

The general type of design is;

$tc = n^k$

Where ;

tc = number of treatment combinations

n = number of levels

k = number of factors

The most important of these special cases is that of k factors, each at two levels. A complete replicate of such a design requires 2 x 2 x • • • x 2 = 2^k observations and this is called $2''$ factorial design (Montgomery 1991).

2.3.2 Fractional Factorial Design

As the number of factors in a 2^k factorial design increases, the number of runs required for a complete replicate of the design rapidly outgrows the resources of most experimenters. If we can reasonably assume that certain high-order interactions are negligible, then information on the main effects and low-order interactions may be obtained by running only a fraction of the complete factorial experiment. These fractional factorial designs are among the most widely used types of designs for product and process design and for process trouble shooting.

The Advantage of Fractional Factorials.

A major use of fractional factorial designs is in screening experiments. There are experiments in which many factors are considered with the purpose of identifying those factors that have large effects. Screening experiments are usually performed in the early stages of a project when it is likely that many of the factors initially considered have little or no effect on the response. The factors that are identified as important are then investigated more thoroughly in subsequent experiments.

The successful use of fractional factorial designs is based on three key ideas;

(1) The sparsity of effects principle. When there are several variables, the system or process is likely to be driven primarily by some of the main effects and low-order interactions.

(2) The projective property. Fractional factorial designs can be projected into stronger (larger) designs in the subset of significant factors.

(3) Sequential experimentation. It is possible to combine the runs of two (or more) fractional factorials to assemble sequentially a larger design to estimate the factor effects and interactions of interest.

General Term

The general type of design at two levels is;

$tc = n^{k-p}$

Where ;

tc = number of treatment combinations

n = number of levels under study

k = number of factors under study

p = fractionalizing element of the design

(Montgomery 1991)

2.3.3 Taguchi's Methods

Taguchi Philosophy

In the early 1980s, Professor Genechi Taguchi started to develop new methods to optimize the process of engineering experimentation. He developed techniques which are now known as the Taguchi Methods. A key component of Taguchi's philosophy is the reduction of variability which involves three central ideas;

(a) Products and processes should be designed so that they are robust to external sources of variability.

(b) Experimental design methods are an engineering tool to help accomplish this objective.

(c) Operation on-target is more important than conformance to specifications.

The full factorial design will identify all possible combination for a given set of factors. Since most industrial experiments usually involve a significant number of factors, a full factorial design results in a large number of experiments. Taguchi's approach complements these two important areas.

First, he clearly defines a set of Orthogonal Arrays (OA), each of which can be used for many experimental situations. Second, he devised a standard method for analysis of the results. The combination of standard experimental design techniques and analysis methods in the Taguchi approach, produces consistency and reproducibility rarely found in any other statistical method.

The Advantage of Taguchi's Methods.

The Taguchi method offers two new powerful elements. First, it is a declined way of developing a product or investigating complex problems. Second, it provides a means to cost effectively investigate the available alternatives. Although Taguchi's method was built upon well developed concepts of optimization through the design of experiments, his philosophy regarding the value of quality and the procedure for carrying out experiments were new. The power and popularity of the method lie in the discipline rather than the technique itself.

The technique is applied in four steps.

(1) Brainstorm the quality characteristics and design parameters important to the product/process.

(2) Design and conduct the experiments.

(3) Analyze the results to determine the optimum conditions.

(4) Run a confirmatory test(s) using the optimum conditions.

Basic Methodology

The factorial design will generate treatment combination by follow the formula Il^{k}, at n level and k factor, and the corresponding suggested Taguchi number of experiments as shown in Table 2.1.

A factorial experiment of 7 factors, at 2 levels each, with 128 possible combinations is represented by Table 2.2. The letters A, B, C, D, E, F, and G represent the factors. The subscripts 1 and 2 (Table 2.3) represent the value of a factor at level 1 and 2 respectively. Each of the 128 cells corresponds to a unique combination of the factors. Cells T-1 through T-8 indicated the 8 trial numbers defined by Taguchi's partial factorial OA (Table 2.3).

Table 2.1. Comparison of Factorial Design and Taguchi Design.

Factors	Level	Factorial	Taguchi
		Total Number of Experiment	
2	2	4 (2^2)	4
3	2	8 (2^3)	4
4	2	16 (2^4)	8
7	2	128 (2^7)	8
15	2	32,768 (2^{15})	16
4	3	81 (3^4)	9

Table 2.2. Experiment Structure, Using L8 Array.

Full Factorial Experiments				Al				A2			
				B1		B2		B1		B2	
				C1	C2	C2	C2	C1	C2	C1	C2
D1	Ei	F1	G1	T-1							
			G2								
		F2	G1								
			G2				T-3				
	E2	F1	G1								
			G2						T-5		
		F2	G1							T-7	
			G2								
D2	Ei	F1	G1								
			G2							T-8	
		F2	G1						T-6		
			G2								
	E2	F1	G1				T-4				
			G2								
		F2	G1								
			G2	T-2							

Table 2.3. Trial Runs and Conditions, Using L8 Array.

Column / Trial No.	1	2	3	4	5	6	7
	A	B	C	D	E	F	G
H H 1-e H 1-3 H H 173 OOv VI tJ,-11(4,t() :,	1	1	1	1	1	1	1
	1	1	1	2	2	2	2
	1	2	2	1	1	2	2
	1	2	2	2	2	1	1
	2	1	2	1	2	1	2
	2	1	2	2	1	2	1
	2	2	1	1	2	2	1
	2	2	1	2	1	1	2

Taguchi has established OAs to describe a large number of experimental situations. The symbolic designation for these arrays carries the key information on the size of the experiment. The array of Table 2.3 is designated as L-8 or L_8. The number 8 indicates 8 trials are required. The next lower size of the OA is ***L4.*** An ***L4*** experiment requires 4 trial runs. The array handles up to 3 factors at 2 levels each. To fit a situation with factors between 4 to 7, all at 2 levels, an ***L8*** will be used.

Experiment designs by OAs are attractive because of experimental efficiency, but there are some potential tradeoffs. OAs experiment work well when there is minimal interaction among factors. The factor influencing on the measured quality objectives are independent of each other and are linear. In other words, when the outcome is directly proportional to the linear combination of individual main effects factor, OA design identifies the optimum condition and accurately estimates performance at this condition. If however, the factors interact with each other and influence the outcome in a nonlinear manner, there is still a good chance that the optimum condition will be accurately identified. However the estimate of optimum performance can be significantly off The degree of inaccuracy in performance estimates will depend on the degree of complexity of interactions among all the factors(Ross 1988).

III. RESEARCH METHODOLOGY

When we start to set an experiment for studying any factors that concern with our response related to the process, it is necessary that everyone involved in the experiment have a clear idea in advance of exactly what is to be studied. We may proceed as follows:

3.1 Recognition and Statement of the Problem

In terms of Head Stack Assembly process, we always found head's wire poor bonding problem. The problem will affect hard disk drive assembly process which considers to functional working. Although the HSA process has been detected by head wires bonding pull strength testing, we still have the problem of the unstable pull strength value because this operation has many factors concerning the bonding performance.

3.2 Choice of Factors and Levels

We must select the factors following the cause-effect diagram as we mention in chapter 1, Introduction. The factors that be selected will be decided on a region of interest for each variable. The level of factors has to cover a range of current process specification.

3.3 Selection of the Response Variable

In selecting the response variable, we should be certain that this variable really provides useful information about the process under study. So we set the output of head's wires bonding operation as wire pull strength value. Because the pull strength will figure exactly the wire bonder machine performance.

3.4 Choice of Experiment Design

Factorial Design

For 1 Factor 1 Level Testing

Pre-Experiment Designs

X = treatment

O = observation

R = randomization

(1) One shot case study

X O

(2) One group Pretest Posttest

O X O

(3) Static group comparison

X O

O

True Experiment

(4) Pretest — Posttest Control Group Design

R O X O

R O O

(5) Solomon Four-Group Design

R O X O

R O O

R X O

R O

(6) Posttest Only Control Group Design

R X O

R O

(7) Factorial Designs

Factorial designs are Orthogonal Arrays where the number of treatment combinations equals the number of levels raised to a power of the number of factors.

$$tc = n^k$$

Where :

tc = number of treatment combinations

n = number of levels

k = number of factors

Example ; 1 F.A.T. — one factor at a time manipulation

	Low	High
Pressure (P)	100 psi (Po)	200 psi (Pi)
Temp. (T)	70° (To)	90° (Ti)
Time (t)	10 min (t_o)	20 min (ti)

Objective : Test of the idea that % contamination is a function of time, pressure, and temperature.

$$tc = 2^3$$

tc = 8 runs

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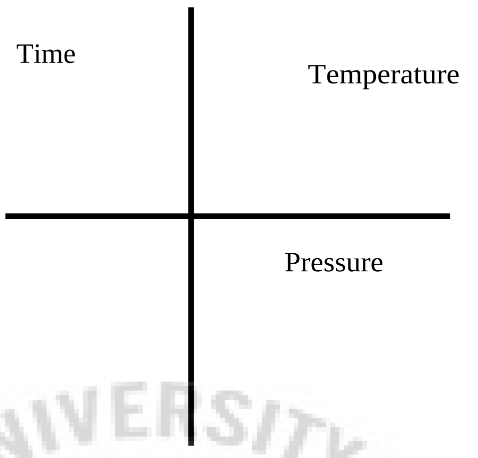
(a)



Goal : The independent assessment of the effect of each factor.

(h)

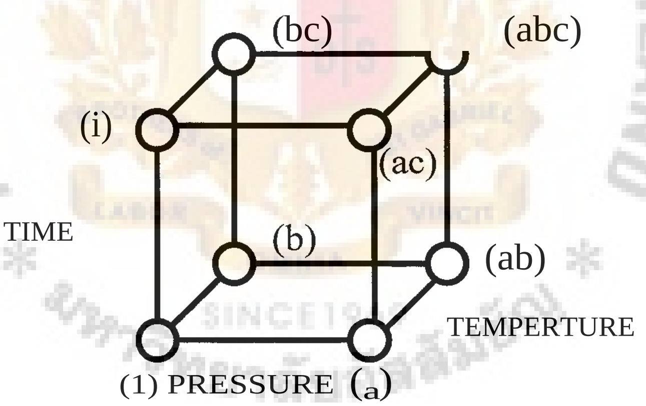


Figure 3.1. Structure of Orthogonal Arrays.

Factorial Array

Factors A

Pressure Time Temperature

Runs	tc			
1	1			
2	a	+		
3	b	-	+	
4	ab	+	+	
5	c		-	+
6	ac	+	-	+
7	be		+	+
8	abc	+	+	+

The order of treatment combinations is known as Yates Order (AKA — Standard Order)

3.5 Data Analysis

3.5.1 Hypothesis Testing

A statistical hypothesis is a statement about the parameter of a probability distribution. In simple experiments, hypotheses are stated as the differences between means and variation. If we are optimistic about the appearance of the data we will say there is no difference between the sample and the population. The statement as we call <u>null hypothesis</u> is as follows:

$$H_o : \mu = [to$$

Where :

H_o is the hypothesis under the test.

μ is the average from the sample.

llo is the mean of the population.

The alternative hypothesis is there is a difference between the means or the variation.

HA : μ # tto

If the sample mean is far from the population mean, we have little difficulty in choosing. If the sample mean is very close to the population mean we also have no problem in choosing or if the sample mean is in the middle ground we need statistics to help judge.

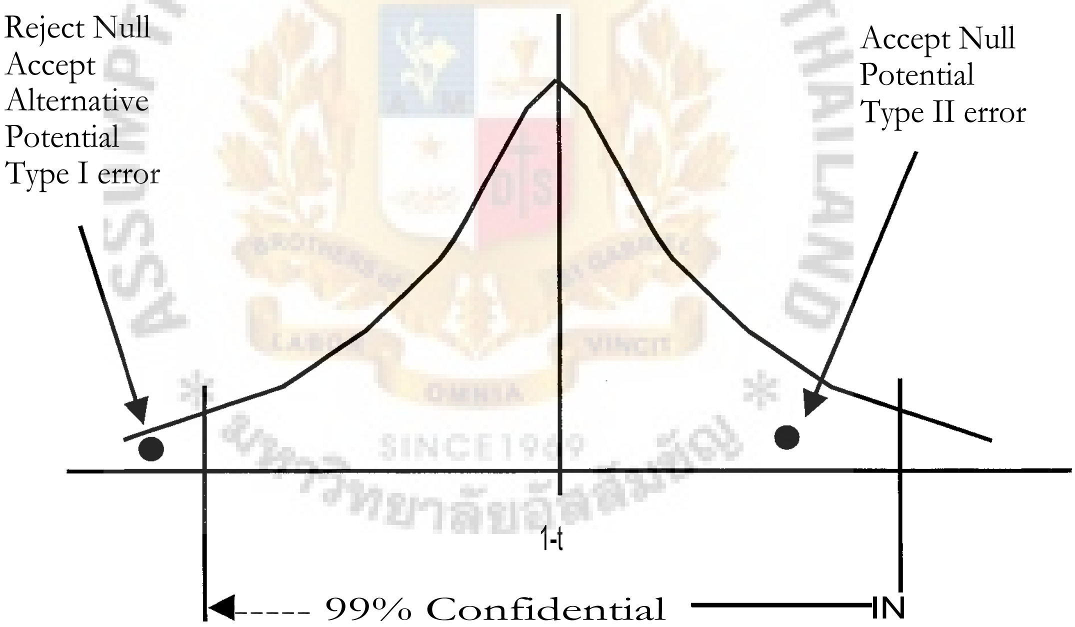


Figure 3.2. Type I and Type II Error.

Two kinds of error may be committed when testing hypothesis. Type I error can only happen when we reject the null, type II error can only happen when we accept the null, as shown in Figure 3.2. The probabilities of these two errors are given special symbols;

a = P (Type I error) = P (Reject Ho I Ho is true)

13 = P (Type II error) = P (Fail to reject Ho I Ho is false)

Sometimes it is more convenient to work with the power of the test, where;

Power = 143 = P (Reject Ho I Ho is false)

The general procedure in hypothesis testing is to specify a value of the probability of type I error a, often called the significance level of the test, and then design the test procedure so that probability of type II error r3 has a suitably small value.

Common value for a,

0.01 99% Confidential

0.05 95% Confidential

0.10 90% Confidential

3.5.2 Data Analysis

The analysis of data including interactions follows the same steps as are taken when there is no interaction. The objectives are as shown below:

(a) Determine the optimum condition.

(b) Identify the individual influence of each factor.

(c) Estimate the performance at the optimum condition.

Analysis Of Variance (ANOVA)

There is standard statistical technique which is routinely used to provide a measure of confidence. The technique does not directly analyze the data, but rather determines the variability (variance) of the data. Confidence is measured from the variance.

ANOVA Terms

Definitions:

C.F. = Correction Factor | n = Number of trials

e = Error (experimental) | r = Number of repetitions

F = Variance ratio | P = Percent Contribution

df = Degree of freedom | T = Total (of results)

df_e = Degree of freedom of error | SS = Sum of squares

df_T = Total degree of freedom | SS' = Pure sum of squares

MS = Mean squares (variance)

Total Number of Trials

In experimental design to determine the effect of factor A on response Y, factor A is to be tested at L levels. Assume n_1 repetitions of each trial that includes A_1 Similarly at level $A_1$the trial is to be repeated n_2 times. The total number of trials is the sum of the number of trials at each level, i.e.,

$$n = n_1 + n_2 + \cdots + n_L$$

Degree of Freedom (DOF)

DOF is an important and useful concept that is difficult to define. It is a measure of the amount of information that can be uniquely determined from a given set of data. DOF for data concerning factor equals one less than the number of levels. For a factor A with four levels, A_1 data can be compared with A2, A3, and A4 data and not with itself. Thus a four level factor has 3 DOF.

The concept of DOF can be extended to the experiment. An experiment with n trial and r repetitions of each trial has n x r trial runs. The total DOF becomes;

$$df_T = n \times r - 1$$

Similarly, the DOF for a sum of squares term is equal to the number of terms used to compute the sum of squares and the DOF of the error term df_e is given by;

$$df_e = df_T - df_A - df_B - df_C$$

Sum of Squares

The sum of squares is a measure of the deviation of the experimental data from the mean value of the data. Summing each squared deviation emphasizes the total deviation. Thus

$$ss_T = \sum^{n} (Y_; - Y)2$$

Where Y is the average value of Yi .

Similarly the sum of squares of deviations SS_T, from a target Yo , is given by;

$$SS_T = \sum_{i=1}^{n} (Y_i - Y)^2 + n(\quad yo)^2 \qquad (3\text{-}1\text{-}1)$$

Variance measures the distribution of the data about the mean of the data. Since the data is representative of only a part of all possible data, DOF rather than the number of observations is used in the calculation.

$$\text{Variance} = \frac{\text{Sum of Squares}}{\text{Degree of Freedom}}$$

Or $MS = SST \quad df$

When the average sum of squares is calculated about the mean, it is called the general variance. The general variance $\bar{o}^2$ is defined as;

$$6^2 — \quad \sum_{i=1} \qquad (3\text{-}1\text{-}2)$$

Let m represent the deviation of the mean Y from the target value SS_T, i.e.,

$$m = (Y - Y_0) \qquad (3\text{-}1\text{-}3)$$

Substitution Eqs. (3-1-2) and (3-1-3) into Eq. (3-1-1),

$$SST = no^2 \quad nm^2 \quad n(zT^2 + m^2) \qquad (3\text{-}1\text{-}4)$$

Thus the total sum of squares of deviations (SST) from the target value Yo is the sum of variance about the mean, and the square of the deviation of the mean from the target value multiplied by the total number of observations made in the experiment.

SS_T of Eq. (3-1-4) also represents the expected statistical value of SS_T. The symbol, SS_T is used for both the expected value and the computed value. The total sum of squares SS_T (Eq. 3-1-4) gives estimate of the sum of the variations of the individual observations about the mean Y of the experimental data and the variation of the mean about the target value *Yo*.

Mean Sum (of Deviations) Squared

Let $T = E_{i=i} (Y1 - Y_o)$ the sum of all deviations from the target value. Then, the mean sum of squares of the deviation is;

$$SS = T^2/n = [E_i (Yi - Yo)]^2 \text{ in} \qquad (3\text{-}2)$$

Eq. (3-2-1) can thus be written as ;

$$SS_m = nm^2$$

It is important to note that even though from an over-simplistic derivation of the value of $SS_m = nm^2$, its statistic estimate or the expected value, includes one part of the general variance. Therefore representing the statistically expected value by $E(SS_m)$;

$$E(SS_m) = SS_m = \ ^2 + nm^2 \qquad (3\text{-}3)$$

The term ($SS_T - SS_m$) is usually referred to as the error sum of squares and can be obtained from Eqs. (3-1-4) and (3-3).

Therefore,

$SS, = SS_T -$ $= (n - 1)\ a^{2}$

Rewriting,

$SS_T = SS, + SS.$

Thus the total effect of variance SS_T can be decomposed into the mean deviation SS_m and the deviation SS_e about the mean.

Degree of Freedom (DOF)

The DOF df_e ,dfT and df_m of the sum of squares SS_e, SST, and SS_m are as follows:

$df_T = n$ = number of data points

$df_m = 1$ (always for the mean)

$df, = df_T - df_m = (n - 1)$

As pointed out earlier, the DOF df_T is equal to n because there are n independent values of $(Y, - Y_o)^2$. For investigating the effect of factors at different levels, the DOF are usually one less than the number of observation.

To summarize;

$SS_T = na^{2} + nm^{2}$ (3-4)

$SS. = a^{2} + nm^{2}$ (3-5)

$SS, = SS_T - SS. = (n - 1)\ a^{2}$ (3-6)

Also as stated earier, variance MS, is

$MS = SS / df$

Therefore;

$MST = MST / dfT = CT\ 2 \quad + m\ 2$ (3-4)

$MS. = MS. / df. = a^2 + nm^2$ (3-5)

$MS_e = (SST — SS.) / df, = a^2$ (3-6)

Variance Ratio

The variance ratio, commonly called the F statistic, is the ratio of variance due to the effect of a factor and variance due to the error term. (The F statistic is named after Sir Ronald A. Fisher.) This ratio is used to measure the significance of the factor under investigation with respect to the variance of all the factors included in the error term. The F value obtained in the analysis is compared with a value from standard F-Tables for a given statistical level of significance. The tables for various significance levels and different degrees of freedom are available in most handbooks of statistics.

When the computed F value is less than the value determined from the F tables at the selected level of significance, factors does not contribute to the sum of the squares within the confidence level.

The F values are calculated by;

$F. = MS. / MS_e$

$F, = MS, / MS, = 1$ (3-7)

And for a factor A it is given by;

$FA = MSA / MS_e$ (3-8)

Pure Sum of Squares

In Equations (3-4), (3-5), and (3-6) for each of the sum of squares, there is general variance a ^{2} term expressed as $(DOF)^2$ x a ^{2} . When this term is subtracted from the sum of squares expression, the remainder is called the pure sum of squares. Since SS_m has only one degree of freedom, it therefore contains only one a ^{2} i.e., MS, . thus the pure sum of square for SS. is;

$$SS'_m = SS. — MS, = o^2 + nni^2 .. cy\ 2 = nm^2$$

The portion of error variance subtracted from the sum of squares for SS_m is added to the error term. Therefore,

$$SS', = SS, + MS, \quad (3\text{-}9)$$

If factors A, B, and C, having DOF dfA , df_B ,and dfc, are included in an experiment, their pure sum of squares are determined by;

$$SS'A = SSA — dfA \times MSe \quad (3\text{-}10)$$

$$SS'_B — SS_B — df_B \times MS,$$

$$SS'_C = SS_C — dfc \times MS,$$

$$SS'_e = SS, + (dfA + df_B + df_C) \times MS, \quad (3\text{-}11)$$

Percent Contribution

The percent contribution for any factor is obtained by dividing the pure sum of squares for that factor by SS_T and multiplying the result by 100. The percent contribution is denoted by P and can be calculated using the following equation.

$$P. = SS'_m \times 100 / SS_T$$

$$PA = SS'A \times 100 / SST$$

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$$PB = SS'B \times 100 / SST$$

$$P_c = SS'c \times 100 / SST$$

$$Pe = SS'e \times 100 / SST \qquad (3\text{-}12)$$

ONE WAY ANOVA

When one-dimensional experimental data are analyzed using ANOVA, the procedure is termed a one way analysis of variance. And for one factor and two levels, the value of SS_m for the effect of factor A (sources) is obtained as:

SS_m = Squares of sum for source A_1

+ Squares of sum for source A_2

- Correction factor

Thus, the correction factor, C.F.,can be written as:

$$C.F. = T^2 / n$$

Table 3.1 presents the format of analysis F, SS, and P term as printed out of the software.

Table 3.1. ANOVA Summary Table (ONE WAY ANOVA).

Source Of Variation	Sum Of Square SS	Degree Of Freedom df	Mean Square MS	Variance Ratio F	Pure Sum Of Square SS'	Percent Contribution P/100
Mean (m)	SS_m	df.,	SS_m / df_m	$MS. / MS_e$	$SS_m - MS_e$	$SS',,, / SS_T$
Error (e)	SS_e	df_e	SS_e / df_e		SS_m + MS,	SS'_e / SS_T
Total	SS_T	df_T				

TWO WAY ANOVA

We can extend ANOVA to the experimental data of two or more factors with two or more levels.

The total contribution of each factor is calculated as shown below:

$$SS_A = A_1^2 / N_{AI} + A2^2 / NA2 - C.F.$$

$$SS_B = B_1^2 / NBI + B2^2 / NB2 - C.F.$$

$$SSAB = \sum_{i=1}^{2} \sum_{j=1}^{2} (A, Bi)^2 / - C.F.$$

$$SSAxB = SSAB - SS_A - SS_B$$

$$SST = SS_e + SSA + SSB + SSA_xB$$

Where NA1 NA2 etc., refer to the number of trial runs included in the sums A_1, A2 etc. A, B_J is the total experimental response for factor A at level I and the factor B at level j whereas rj is the number of replications (observations) for the cell ij. The term SSAxB represents the interaction sum of squares.

Table 3.2 presents the format of analysis F, SS, and P terms so we can calculate the data back and to get more understanding when we read the print out from the software.

Table 3.2. ANOVA Summary Table (TWO WAY ANOVA).

Source Of Variation	Sum Of Square SS	Degree Of Freedom df	Mean Square MS	Variance Ratio F	Pure Sum Of Square SS'	Percent Contribution P/100
Factor A	SS_A	dfA	SSA / dfA	MSb / MS_e	SSA – (dfA MS_e)	SS'A / SST
Factor B	SSB	dfB	SSB / dfB	MSb / MS_e	SSB – (dfB MS_e)	SS'g / SST
Interactio n AxB	SS_{AxB}	df_A x dfB	SSA_xB / dfA_xB	MSA_xg / MSe	SSAxB – (dfAxB MS_e)	SS'AxB / SST
Error (e)	SS_e	df_e	SS_e / df_e		SS, + (df_A + df_B + dfAxB)MSe	SS', / SS_T
Total	SS_T	dfT				

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IV. EXPERIMENTAL PROCESS AND DATA COLLECTION

Experiment Design Process

The experiment design steps will be as follows:

(1) Define response of product.

(2) Define parameters.

(3) Design level of parameters configuration.

(4) Design table of treatment combinations.

(5) Define steps and process of experiment.

4.1 Define Response of Product

We consider the Pull Strength value of wire bonding for wire bonding operation. Because in our process, we have two responses on our report, wire pull strength and visual inspection report, we have not found problems for visual inspection defects. So the response in the experiment is the wire pull strength value only.

4.2 Define Parameters

We define parameters of the experiment as follows:

(a) Force of bonding tip

(b) Power of wire bonder machine

(c) Timer of wire bonding machine

(d) Bonding tip length

(e) Color of Wire

4.3 Design Level of Parameters Configuration

(1) Force of bonding tip , we define 4 levels at 150 grams, 160 grams, 170 grams ,and 180 grams to cover the force that we are using in the current value. (The current value is 160 grams)

(2) Power of wire bonder machine, we define to 4 levels at 270 mW, 280 mW, 290 mW ,and 300 mW to cover the power that we are using in the current value. (The current value is 280 mW.)

(3) Timer of wire bonding machine, we define to 4 levels at 320 msec., 325 msec., 330 msec. ,and 335 msec. to cover the force that we are using in the current value. (The current value is 325 msec.)

(4) Bonding tip length, we are using 7MIL tip for the existing tip and we want to try to use 10 MIL tip so we define them for 2 levels.

(5) Color of wire, we define to 4 levels because we have 4 colors of wire of our product, BLACK, GOLD, GREEN and RED.

The parameters that we fixed in the experiment process are as follows:

(a) Wire bonder machine is Anza Ultrasonic Bonder Machine model 74000A, that is only one model which we are using in the production line.

(b) Flex circuit concerns with bonding pads, we have only one supplier which is Mektek FCBA.

(c) Bonding fixture

4.4 Design Table of Treatment Combinations

Table 4.1 represent a summary of all the input in our wire bonding process.

Table **4.1.** Levels of Parameters.

Parameter	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Force	150	160	170	180
Power	270	280	290	300
Timer	320	325	330	335
Tip	7MIL.	10MIL.		
Wire Color	BLACK	GOLD	GREEN	RED

We designed our experiment by using statistical software called JMP Statistics and Graphics, version 3.2.2, that is developed by SAS Institute Inc., Cary NC.We selected *General Factorial mode* to generate model of experiment as Full Factorial Model for multilevel factors as show in Figure 4.1. After that we defined factors and level values in dialog panel of the mode which refers to the design levels of parameter configuration.

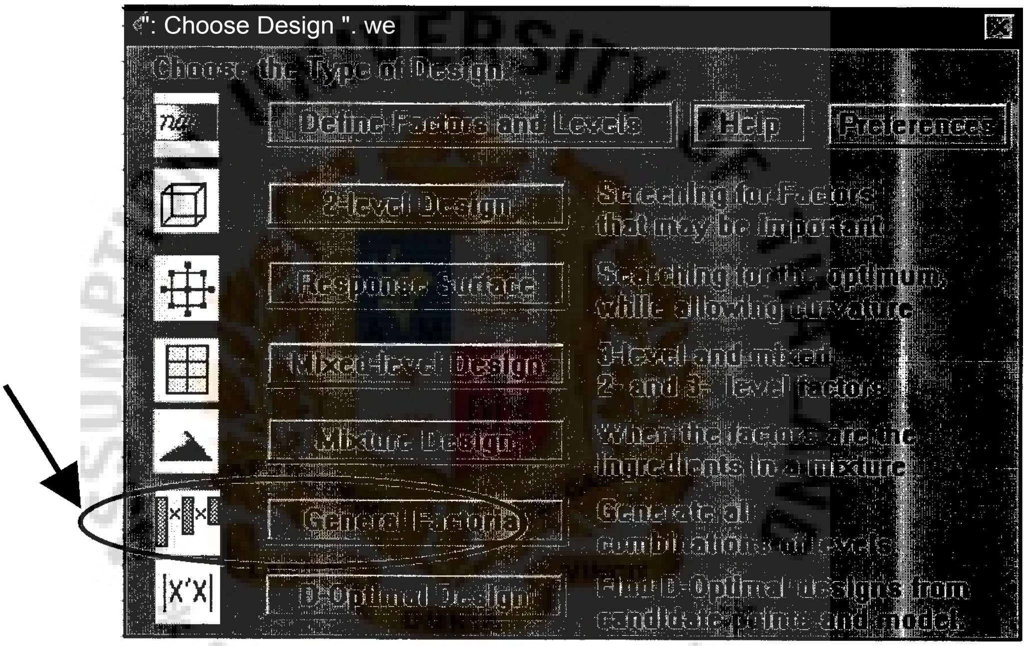

Figure 4.1. The Choose Design Type Panel.

The software generated a table of treatment of a combination of 512 runs and we got the table as a sample as shown in the Table 4.2 below. However, the complete table can be seen in Table A.1, Appendix A. We set the response to 5 samples for each of the combination.

Refer to the printout of JMP software;

Table 4.2. Treatment Combination Design.

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
1	11111	150	270	320	BLACK	7MIL						
2	11112	150	270	320	BLACK	10MIL						
3	11121	150	270	320	GOLD	7MIL						
4	11122	150	270	320	GOLD	1OMIL						
5	11131	150	270	320	GREEN	7MIL						
6	11132	150	270	320	GREEN	10MIL						
7	11141	150	270	320	RED	7MIL						
8	11142	150	270	320	RED	10MIL						
9	11211	150	270	325	BLACK	7MIL						
10	11212	150	270	325	BLACK	10MIL						
11	11221	150	270	325	GOLD	7MIL						
12	11222	150	270	325	GOLD	10MIL						
13	11231	150	270	325	GREEN	7MIL						
14	11232	150	270	325	GREEN	10MIL						
15	11241	150	270	325	RED	7MIL						
16	11242	150	270	325	RED	10MIL						
17	11311	150	270	330	BLACK	7MIL						
18	11312	150	270	330	BLACK	IOMIL						
19	11321	150	270	330	GOLD	7MIL						
20	11322	150	270	330	GOLD	1OMIL						
21	11331	150	270	330	GREEN	7MIL						
22	11332	150	270	330	GREEN	IOMIL						
23	11341	150	270	330	RED	7MIL						
.	.	.	.	.								
.	.	.	.	.	.	.						
.	.	.	.	.								
500	44322	180	300	330	GOLD	1OMIL						
501	44331	180	300	330	GREEN	7MIL						
502	44332	180	300	330	GREEN	10MIL						
503	44341	180	300	330	RED	7MIL						
504	44342	180	300	330	RED	10Mu,						
505	44411	180	300	335	BLACK	7MIL						
506	44412	180	300	335	BLACK	1OMIL						
507	44421	180	300	335	GOLD	7MIL						
508	44422	180	300	335	GOLD	1OMIL						
509	44431	180	300	335	GREEN	7MIL						
510	44432	180	300	335	GREEN	1OMIL						
511	44441	180	300	335	RED	7MIL						
512	44442	180	300	335	RED	10MIL						

4.5 Define Steps and Process of Experiment

(1) Prepare wire bonder machine

Tooling /Equipment

(a) Anza Ultrasonic Wire Bonder (USWB)Model #251

(b) Gaiser USWB Tips 7 mil. And **10 mil.**

(c) USWB Bonding Tip Gage

(d) USWB Bonding Fixture

(e) Tool Height Block

(f) Pull strength Gage

(g) Stainless steel Tweezers

Before we started to run the experiment, we must set up the wire bonder machine as the standard setting parameters.

(2) Prepare Material

(a) Wires as Black, Gold, Green and Red color

(b) Flex circuit

(c) Actuator Model

We built a model such as when we run the operation.

(3) Run the experiments

4.6 Data Collection

We run the experiment by following the table of treatment combination as shown in Table 4.2 and obtained the response result, wire pull strength as presented in Table A.1. We run 5 samples for each of the combinations and calculated the average value of the response, wire pull strength value. The completed table of the experimental results is shown in Table A.1, Appendix A.

From the results of the experiment we also used JMP software to analyse what we will discuss in Chapter 5.

Table A.1. The Experiment Results.

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
1	11111	150	270	320	BLACK	7MIL	13.0	13.0	16.0	23.0	18.0	**16.6**
2	11112	150	270	320	BLACK	10MIL	20.0	21.0	19.0	21.0	19.0	**20.0**
3	11121	150	270	320	GOLD	7MIL	16.0	19.0	13.0	13.0	18.0	**15.8**
4	11122	150	270	320	GOLD	10MIL	22.0	16.0	23.0	26.0	23.0	**22.0**
5	11131	150	270	320	GREEN	7MIL	19.0	21.0	23.0	24.0	21.0	**21.6**
6	11132	150	270	320	GREEN	10MIL	24.0	29.0	23.0	24.0	24.0	**24.8**
7	11141	150	270	320	RED	7MIL	18.0	18.0	18.0	16.0	11.0	**16.2**
8	11142	150	270	320	RED	iomm	21.0	28.0	21.0	24.0	26.0	**24.0**
9	11211	150	270	325	BLACK	7MIL	21.0	14.0	14.0	14.0	16.0	**15.8**
10	11212	150	270	325	BLACK	10MIL	19.0	26.0	19.0	24.0	21.0	**21.8**
11	11221	150	270	325	GOLD	7MIL	13.0	18.0	18.0	14.0	16.0	**15.8**
12	11222	150	270	325	GOLD	10MIL	21.0	24.0	24.0	23.0	21.0	**22.6**
13	11231	150	270	325	GREEN	7MIL	23.0	21.0	18.0	19.0	23.0	**20.8**
14	11232	150	270	325	GREEN	lomm	23.0	24.0	29.0	21.0	19.0	**23.2**
15	11241	150	270	325	RED	7MIL	21.0	16.0	19.0	18.0	19.0	**18.6**
16	11242	150	270	325	RED	10MIL	21.0	24.0	26.0	23.0	26.0	**24.0**
17	11311	150	270	330	BLACK	7MIL	8.0	14.0	16.0	19.0	14.0	**14.2**
18	11312	150	270	330	BLACK	lomm	16.0	19.0	21.0	21.0	19.0	**19.2**
19	11321	150	270	330	GOLD	7MIL	21.0	14.0	18.0	16.0	21.0	**18.0**
20	11322	150	270	330	GOLD	10MIL	21.0	24.0	23.0	24.0	23.0	**23.0**
21	11331	150	270	330	GREEN	7MIL	23.0	24.0	21.0	23.0	19.0	**22.0**
22	11332	150	270	330	GREEN	10MIL	24.0	21.0	19.0	21.0	26.0	**22.2**
23	11341	150	270	330	RED	7MIL	18.0	11.0	16.0	16.0	19.0	**16.0**
24	11342	150	270	330	RED	10MIL	21.0	28.0	21.0	26.0	21.0	**23.0**
25	11411	150	270	335	BLACK	7MIL	19.0	11.0	19.0	9.0	18.0	**15.2**
26	11412	150	270	335	BLACK	iomm	18.0	22.0	21.0	19.0	21.0	**20.2**
27	11421	150	270	335	GOLD	7MIL	24.0	23.0	31.0	28.0	23.0	**25.8**
28	11422	150	270	335	GOLD	10MIL	23.0	19.0	18.0	21.0	22.0	**20.6**
29	11431	150	270	335	GREEN	7MIL	21.0	13.0	23.0	24.0	21.0	**20.4**
30	11432	150	270	335	GREEN	10MIL	21.0	21.0	21.0	19.0	24.0	**21.2**
31	11441	150	270	335	RED	7MIL	18.0	13.0	19.0	18.0	18.0	**17.2**
32	11442	150	270	335	RED	lomm	26.0	19.0	21.0	21.0	18.0	**21.0**
33	12111	150	280	320	BLACK	7MIL	11.0	13.0	18.0	16.0	16.0	**14.8**
34	12112	150	280	320	BLACK	10MIL	21.0	21.0	22.0	23.0	21.0	**21.6**
35	12121	150	280	320	GOLD	7MIL	13.0	13.0	16.0	19.0	16.0	**15.4**
36	12122	150	280	320	GOLD	iomm	21.0	28.0	23.0	21.0	25.0	**23.6**
37	12131	150	280	320	GREEN	7MIL	23.0	21.0	18.0	23.0	19.0	**20.8**
38	12132	150	280	320	GREEN	10MIL	28.0	26.0	24.0	18.0	24.0	**24.0**
39	12141	150	280	320	RED	7MIL	16.0	16.0	11.0	19.0	16.0	**15.6**

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

Analysis of Results

From the data of Table A.1 result of the experiments, we used to make a model option of data analysis which refers to the JMP software. We opened the Fit Model Dialog window as shown in Figure 5.1.

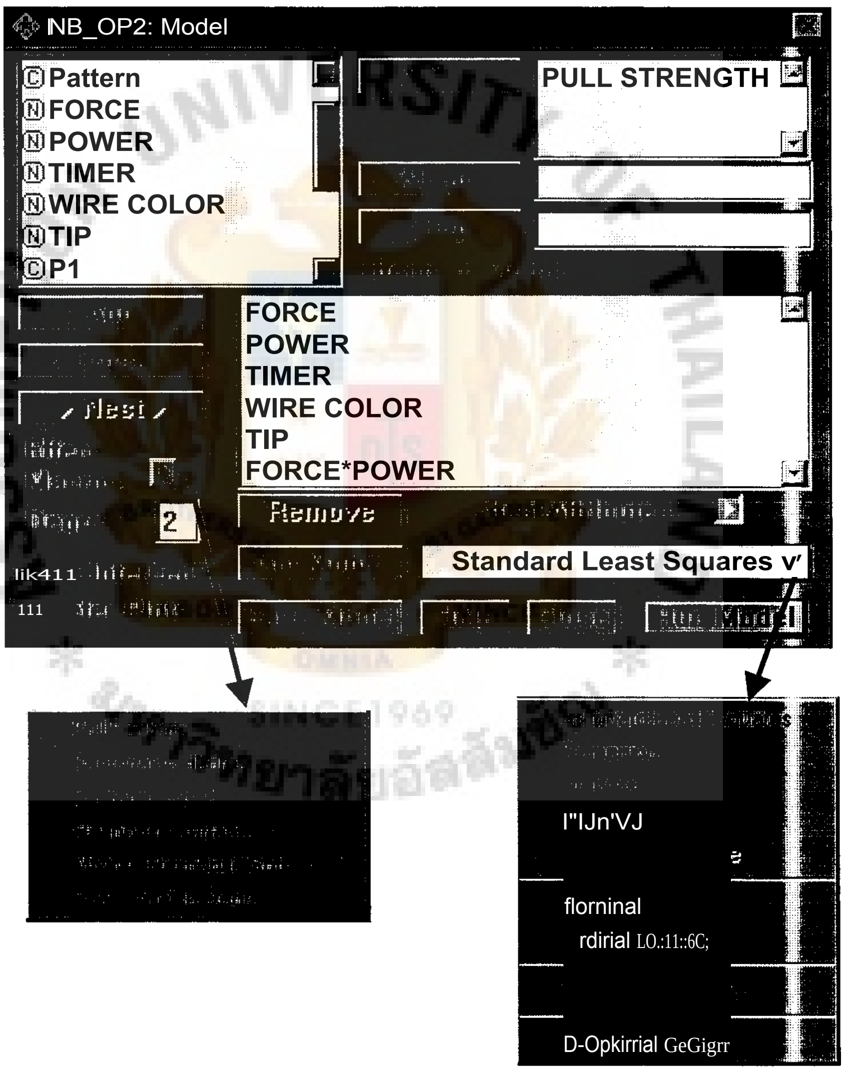

Figure 5.1. Fit Model Dialog for Full Factorial Analysis.

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We selected Full Factorial option from lists of the appropriate effects for the model. These become effective comments that are carried through to the analysis reports.

Refer to the print out of JMP software, where confidential level is 0.95 and Alpha is 0.05.

5.1 Whole the Experiments

Table 5.1. The Summary of Fit Response, Pull Strength Average.

Summary of Fit	
RSquare	0.777489
Rsquare Adj.	0.554106
Root Mean Square Error	2.332316
Mean of Response	19.5293
Observations	512

Table 5.2. The Effect Test Table.

Effect Test					
Source	Nparm	DF	Sum Of Squares	F Ratio	Prob>F
Force	3	3	243.2965	14.9087	<0.0001
Power	3	3	91.8227	5.6267	0.0009
Timer	3	3	15.2246	0.9329	0.4253
Color of Wire	3	3	297.2965	18.2177	<0.0001
Tip	1	1	2975.0907	546.9232	<0.0001
Force x Timer	9	9	19.7282	0.4030	0.9329
Force x Power	9	9	38.0401	0.8032	0.6135
Power x Timer	9	9	32.8395	0.6738	0.7351
Force x Power xTimer	27	27	91.1540	0.6206	0.9308
Force x Color of Wire	9	9	64.2988	1.3134	0.2300
Power x Color of Wire	9	9	81.8576	1.6720	0.0960
Timer x Color of Wire	9	9	42.6807	0.8718	0.5510
Force x Power x Color of Wire	27	27	207.0334	1.4096	0.0918
Force x Timer x Color of Wire	27	27	62.6602	0.4266	0.9950
Power x Timer x Color of Wire	27	27	174.0640	1.1851	0.2474
Force x Power x Timer x Color of Wire	81	81	409.7438	0.9299	0.6437

Table 5.3. Analysis of Variance for the Whole Model.

Analysis of Variance				
Source	**DF**	**Sum Of Squares**	**Mean Square**	**F Ratio**
Model	256	4846.8375	18.9330	3.4805
Error	255	1387.1230	5.4397	Prob>F
C Total	511	6233.9605		<0.0001

Interpretation of the Finding.

The whole experiment means all the data concerned to fit the full factorial analysis model. The data in Tables 5.1, 5.2 and 5.3 can be interpreted by considering F ratio value, the bonding tip parameter showed the highest. This means that the bonding tip has significant effects on the wire pull strength value. The color of wires and bonding tip force are also significant and affect the wire pull strength value and then we looked into the probability of obtaining Prob>F value or P value. For the analysis of variance result of the whole model, we accept the null hypothesis referred to P value of less than 0.0001 at a significance probability of 0.05.

From the analysis, the table gives us a guideline as to how to concentrate on the bonding tip parameter and we can see more clearly in Figure 5.2 that shows the scatter plot between wire pull strength value and the bonding tip length. On the graph, we can say that the 10 mil. bonding tip length give us a higher wire pull strength value than as a 7 mil. bonding tip length.

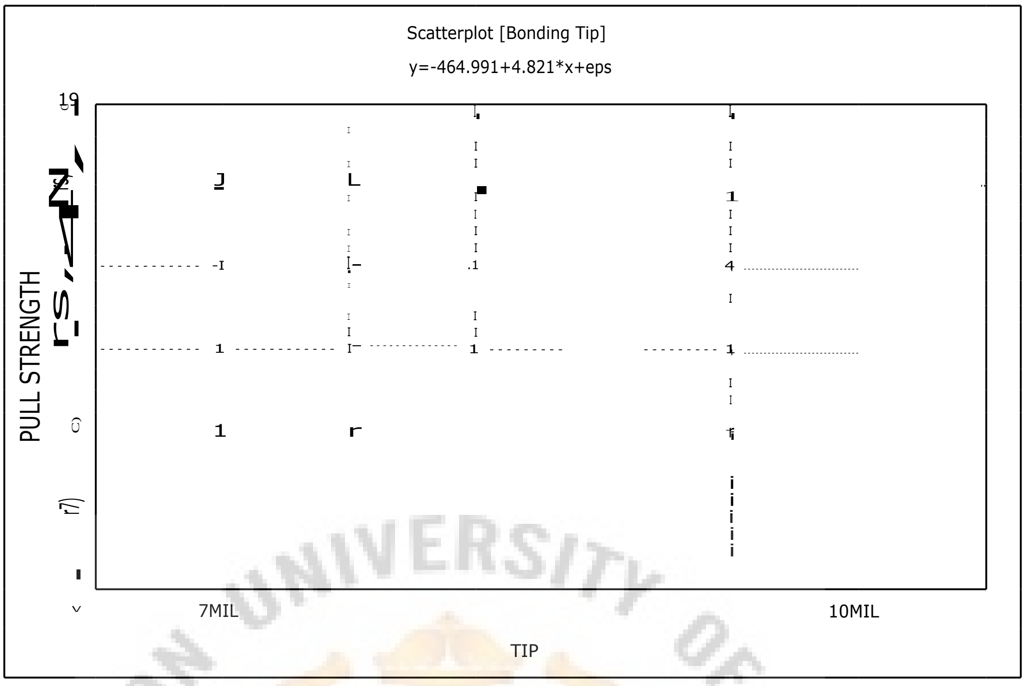

Figure 5.2. Scatter Plot Pull Strength versus Bonding Tip.

So we separate the data into two groups. The bonding tip length is different because the data analysis result will show the bonding tip length performance for each group and Table 5.2 shows F Ratio value of the tip to be higher than that of the rest of the sources so we should separate the data into two groups by bonding tip length. (7Mil. Tip and 10Mil. Tip). First is the data of 7Mil. Tip and the second is data of 10Mil. Tip.

The next analysis will show the summary of each group:

5.2 Group I 7MIL. Tip

Table 5.4. The summary of Fit Response for 7 mil. Tip Length.

Summary of Fit	
RSquare	0.52011
Rsquare Adj.	0.35253
Root Mean Square Error	2.34756
Mean of Response	17.11875
Observations	256

Table 5.5. The Effect Test for Bonding Tip 7Mil.

Effect Test					
Source	**Nparm**	**DF**	**Sum Of Squares**	**F Ratio**	**Prob>F**
Force	3	3	302.14125	19.0697	<0.0001
Power	3	3	129.14875	8.1512	<0.0001
Timer	3	3	4.01625	0.2535	0.8588
Color of Wire	3	3	451.79375	28.5150	<0.0001
Force x Timer	9	9	72.94000	1.4706	0.1614
Force x Power	9	9	21.85750	0.4407	0.9116
Power x Timer	9	9	31.49500	0.6350	0.7662
Force x Power x Timer	27	27	115.49125	0.7762	0.7787

Table 5.6. Analysis of Variance for Bonding Tip 7Mil.

Analysis of Variance				
Source	**DF**	**Sum Of Squares**	**Mean Square**	**F Ratio**
Model	12	1128.8837	17.1043	3.1036
Error	243	1041.5862	5.5110	Prob>F
C Total	255	2170.4700		<0.0001

Interpretation of the Finding.

From the results of the analysis as shown in Tables 5.4, 5.5 and 5.6 for 7 mil. bonding tip length, we also found the same as for the whole experiment that has the color of wires, bonding tip force and the power significance effects to the wire pull strength value based on F ratio value. For the interaction of the parameter that only has the bonding tip force and the timer affecting the wire pull strength value, but the rest does not affect the response value.

So for 7mil. bonding tip length should be considered for the color of the wires, the bonding tip force, the power and the interaction between the bonding tip force and the timer. In Tables 5.4, 5.5 and 5.6, we found the 7 mil. model which seems like the model performing non-linear regression as sown in Table 5.1 in which, R-square is low.

We discuss the result for each parameter as shown below:

(1) The Bonding Tip Force

We found the bonding tip force, in terms of the least square means value, 170 grams obtained from the optimum value of the response value, as shown in Table 5.7. The Table 5.7 will show the bonding tip force significance to the effect of the wire pull strength value.

Table 5.7. Effect Test for Bonding Tip Force (7mil).

Effect Test			
Sum Of Squares	**F Ratio**	**DF**	**Prob>F**
302.14125	18.2749	3	<0.0001

Table 5.8. Least Square Means Summary Table for Bonding Tip Force 7mil.

Least Squares Means			
Level	**Least Sq. Mean**	**Std Error**	**Mean**
150	17.91250000	0.2934450108	17.9125
160	15.96250000	0.2934450108	15.9625
170	18.45937500	0.2934450108	18.4594
180	16.14062500	0.2934450108	16.1406

We can plot the bonding tip force in relation to the wire pull strength value based on the least square means as show in Figure 5.3. The graph shows the optimum point of the parameter as the bonding tip force, 170 grams, and gives the wire pull strength value of 18.459 grams.

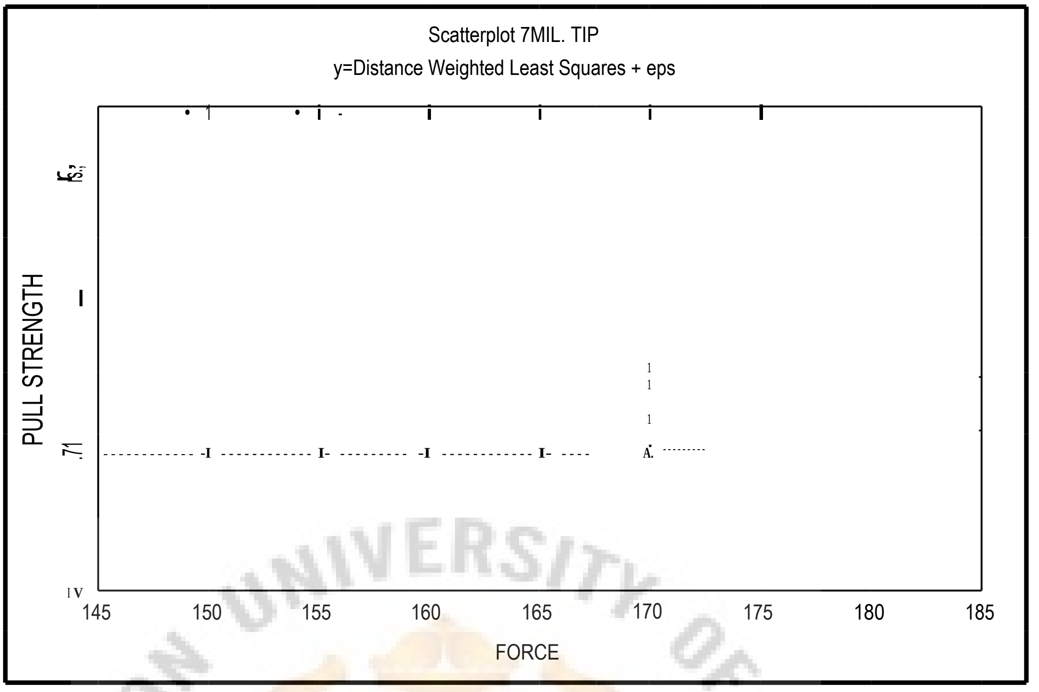

Figure 5.3. Scatter Plot Pull Strength versus Force of Bonding Tip.

(2) The Power of Wire Bonder Machine

Table 5.9. Effect Test for the Power (7mil).

Effect Test			
Sum Of Squares	**F Ratio**	**DF**	**Prob>F**
129.14875	7.8115	3	<0.0001

Table 5.10. Least Square Means Summary for the Power (7mil).

Least Squares Means			
Level	**Least Sq. Mean**	**Std Error**	**Mean**
270	18.32187500	0.2934450108	18.3219
280	16.56250000	0.2934450108	16.5625
290	16.95625000	0.2934450108	16.9563
300	16.63437500	0.2934450108	16.6344

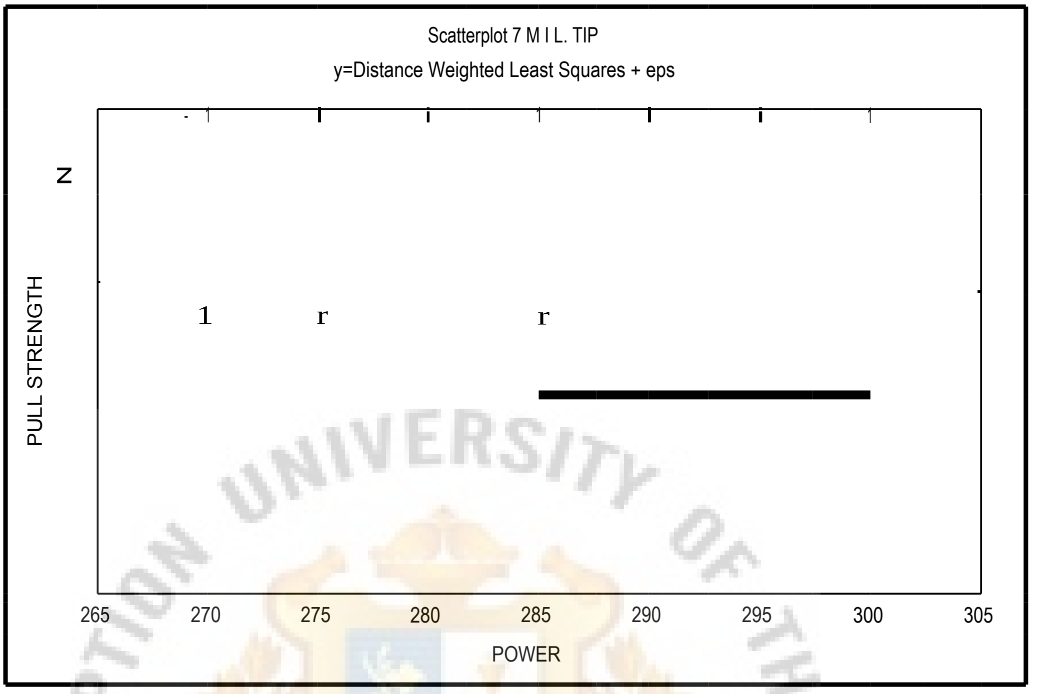

Figure 5.4. Scatter Plot Pull Strength versus Power of Wire Bonder M/C.

Tables 5.9 and 5.10, show the power of wire bonder machine's significance effect to the wire pull strength. The power at 270 mW. gives the highest of the wire pull strength value, at 18.322 grams.

Figure5.4 represents the scattering plot between the wire pull strength value and the power based on the least square means calculation and the optimum point is the power at 270mW.

(3) The Timer (Bonding Time)

Table 5.11. Effect Test for the Timer (7mil).

Effect Test			
Sum Of Squares	**F Ratio**	**DF**	**Prob>F**
4.0162500	0.2429	3	0.8663

Table 5.12. Least Square Means Summary Table for the Timer (7mil).

Least Squares Means			
Level	**Least Sq. Mean**	**Std Error**	**Mean**
320	17.10625000	0.2934450108	17.1063
325	17.22812500	0.2934450108	17.2281
330	17.22187500	0.2934450108	17.2219
335	16.91875000	0.2934450108	16.9188

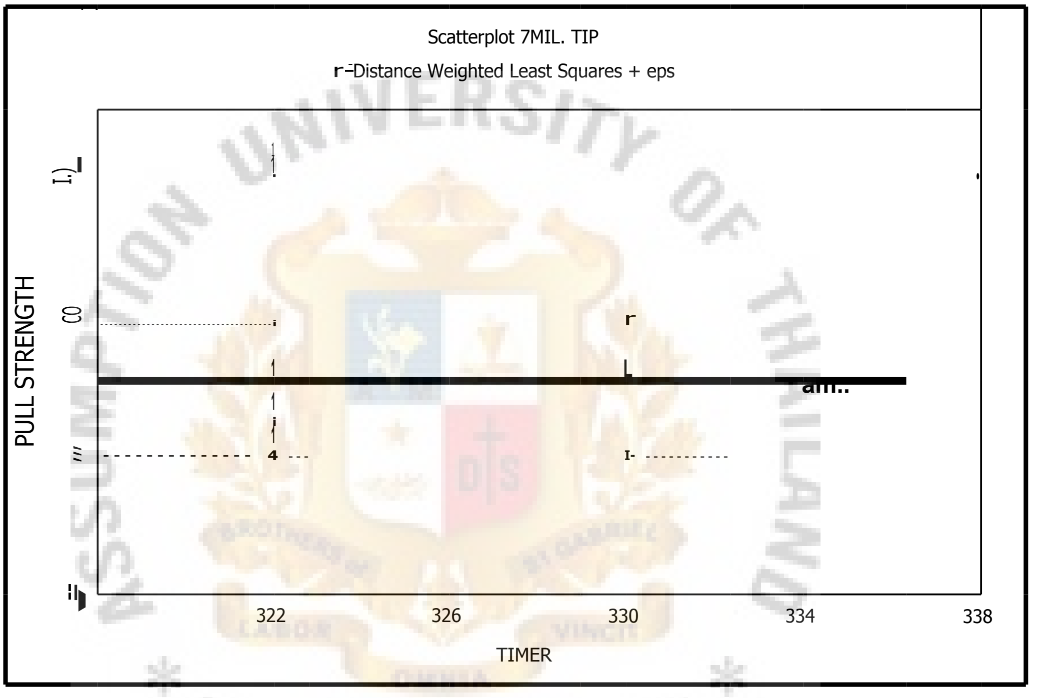

Figure 5.5. Scatter Plot Pull Strength versus Timer.

The timer or bonding time has not any significant effects on the response referred to in the results in shown Tables 5.11 and 5.12. The wire pull strength value does not change when we vary the timer.

Figure 5.5 also shows a straight line and can not find the optimum point.

(4) The Color of Wires

Table 5.13. Effect Test for the Color of Wires (7mil).

Effect Test			
Sum Of Squares	**F Ratio**	**OF**	**Prob>F**
451.79375	27.3266	3	<0.0001

Table 5.14. Least Square Means Summary Table for the Color of Wire (7mil).

Least Squares Means			
Level	**Least Sq. Mean**	**Std Error**	**Mean**
BLACK	15.41250000	0.2934450108	15.4125
GOLD	17.30937500	0.2934450108	17.3094
GREEN	19.09375000	0.2934450108	19.0938
RED	16.65937500	0.2934450108	16.6594

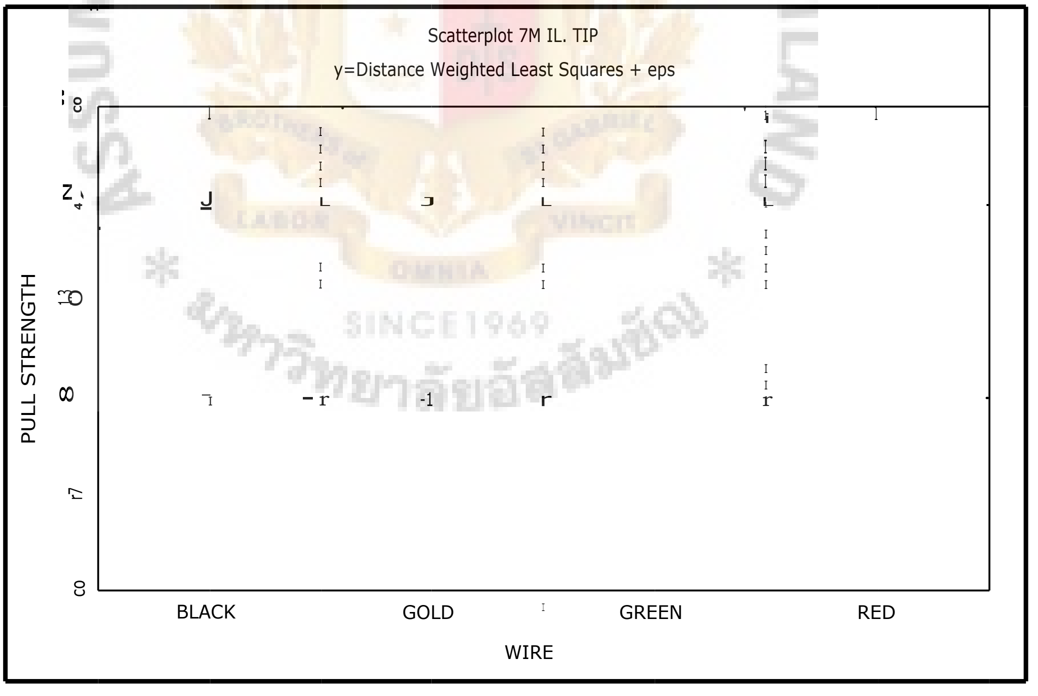

Figure 5.6. Scatter Plot Pull Strength versus Color of Wires.

The bonding tip length 7 mil. has high performance in terms of the wire pull strength value with green color of wire as shown in Table 5.14 and the result of the analysis will show the color of wires parameter's significance effect on the response.

Figure5.6 illustrates the green color of wire which will give the highest wire pull strength value, 19.094 grams. The black color of wire will give the least of the pull strength value, 15.413 grams.

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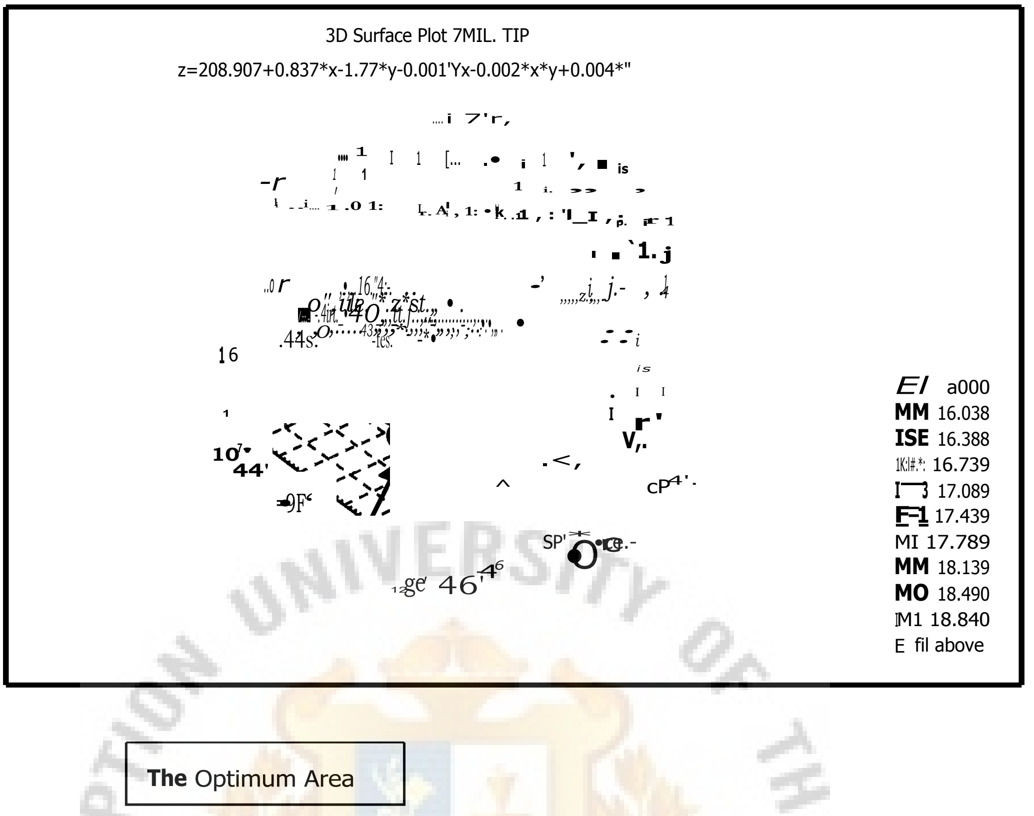


Figure 5.7. 3D Plot of the Bonding Tip Force, the Power and the Pull Strength Value for 7 Mil. Tip.

The optimum area is shown in Figure 5.7. We combined the power and the bonding tip force related to the wire pull strength. It shows that the optimum area is at high the force and low the power.

5.3 Group II 10MIL. Tip

Table 5.15. The Summary of Fit Response for 10 mil. Tip Length.

Summary of Fit	
RSquare	0.284289
Rsquare Adj.	0.034358
Root Mean Square Error	2.030164
Mean of Response	21.93984
Observations	256

Table 5.16. Effect Test Summary for 10 mil. Tip Length.

Effect Test					
Source	**Nparm**	**DF**	**Sum Of Squares**	**F Ratio**	**Prob>F**
Force	3	3	23.859219	1.9538	0.1216
Power	3	3	36.669219	3.0027	0.0312
Timer	3	3	13.320469	1.0908	0.3537
Color of Wire	3	3	25.374219	2.0778	0.1037
Force x Timer	9	9	48.632656	1.3111	0.2334
Force x Power	9	9	62.891406	1.6955	0.0925
Power x Timer	9	9	31.881406	0.8595	0.5625
Force x Power x Timer	27	27	66.789219	0.6002	0.9415

Table 5.17. Analysis of Variance for 10 mil. Tip Length.

Analysis of Variance				
Source	**DF**	**Sum Of Squares**	**Mean Square**	**F Ratio**
Model	66	309.4178	4.68815	1.1375
Error	189	778.9758	4.12156	Prob>F
C Total	255	1088.3936		0.2500

Interpretation of the Finding.

The results of the analysis are shown in Tables 5.15, 5.16 and 5.17 for 10 mil. bonding tip length. We also found the difference from the whole experiment and the 7 mil. tip, that has the power, the color of wire, and the force effect on the wire pull strength value based on F ratio value, especially the power that is higher than the color of wires. For the interaction of the parameter that has the bonding tip force with the power, the power with the timer affect the wire pull strength value, but the rest does not affect the response value.

So a 10mil. bonding tip length, should consider many parameters that relate to the response referred to F ratio from the table. In Tables 5.15, 5.16 and 5.17, the 10 mil. model seems like the model performing non-linear regression as shown in Table 5.15, R-square is low.

We discuss the result for each parameters as shown below:

(1) The Bonding Tip Force

We found the bonding tip force, in terms of the least square means of the value, 170 grams got the optimum value of the response value, as shown in Table 5.19. And Table 5.18 will show the bonding tip force significance effect on the wire pull strength value.

Table 5.18. Effect Test for Bonding Tip Force (10mil).

Effect Test			
Sum Of Squares	**F Ratio**	**DF**	**Prob>F**
23.859219	1.9296	3	0.1216

Table 5.19. Least Square Means for Bonding Tip Force (10mil).

Least Squares Means			
Level	**Least Sq. Mean**	**Std Error**	**Mean**
150	22.05937500	0.2537704727	22.0594
160	21.75000000	0.2537704727	21.7500
170	22.37500000	0.2537704727	22.3750
180	21.57500000	0.2537704727	21.5750

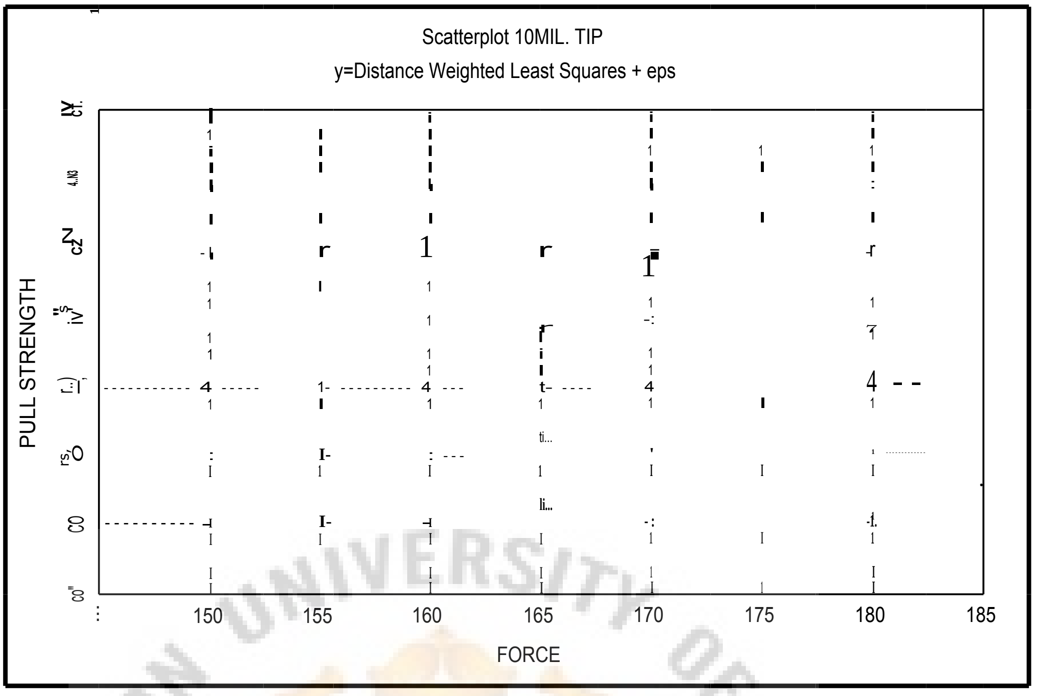


Figure 5.8. Scatter Plot Pull Strength versus Force of Bonding Tip.

The optimum point of the force that affect the pull strength is 170 grams and gives higher pull strength at 22.375 grams. Figure5.8 represents the trend of the pull strength based on the least square mean plot.

(2) The Power of Wire Bonder Machine

The 10mil tip length has a significant effect on the wire pull strength referring to Tables 5.20 and 5.21. The power at 280 mW. is the optimum point the gives the higher pull strength value, 22.472 grams.

Table 5.20. Effect Test for Power of Wire Bonder Machine (10mil).

Effect Test			
Sum Of Squares	**F Ratio**	**DF**	**Prob>F**
36.669219	2.9656	3	0.0333

Table 5.21. Least Square Means for the Power Wire Bonder Machine (10mil).

Least Squares Means			
Level	**Least Sq. Mean**	**Std Error**	**Mean**
270	22.08125000	0.2537704727	22.0812
280	22.47177500	0.2537704727	22.4719
290	21.75000000	0.2537704727	21.7500
300	21.45625000	0.2537704727	21.4562

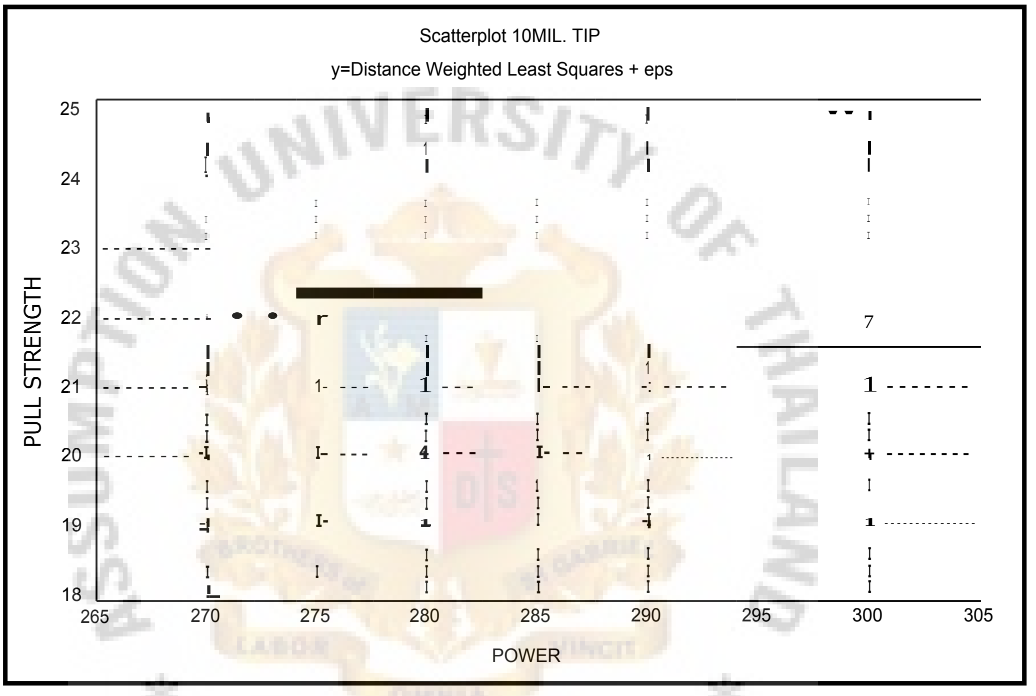


Figure 5.9. Scatter Plot Pull Strength versus Power of Wire Bonder M/C.

Figure 5.9 shows trends of the optimum point of the power at low power and the higher power will give the low pull strength based on the least square mean plot.

(3) The Timer (Bonding Time)

Table 5.22. Effect Test for the Timer (10mil).

Effect Test			
Sum Of Squares	**F Ratio**	**DF**	**Prob>F**
13.3204649	1.0773	3	0.3599

Table 5.23. Least Square Means for the Timer (10mil).

Least Squares Means			
Level	**Least Sq. Mean**	**Std Error**	**Mean**
320	21.89687500	0.2537704727	21.8969
325	22.26562500	0.2537704727	22.2656
330	21.97187500	0.2537704727	21.9719
335	21.62500000	0.2537704727	21.6250

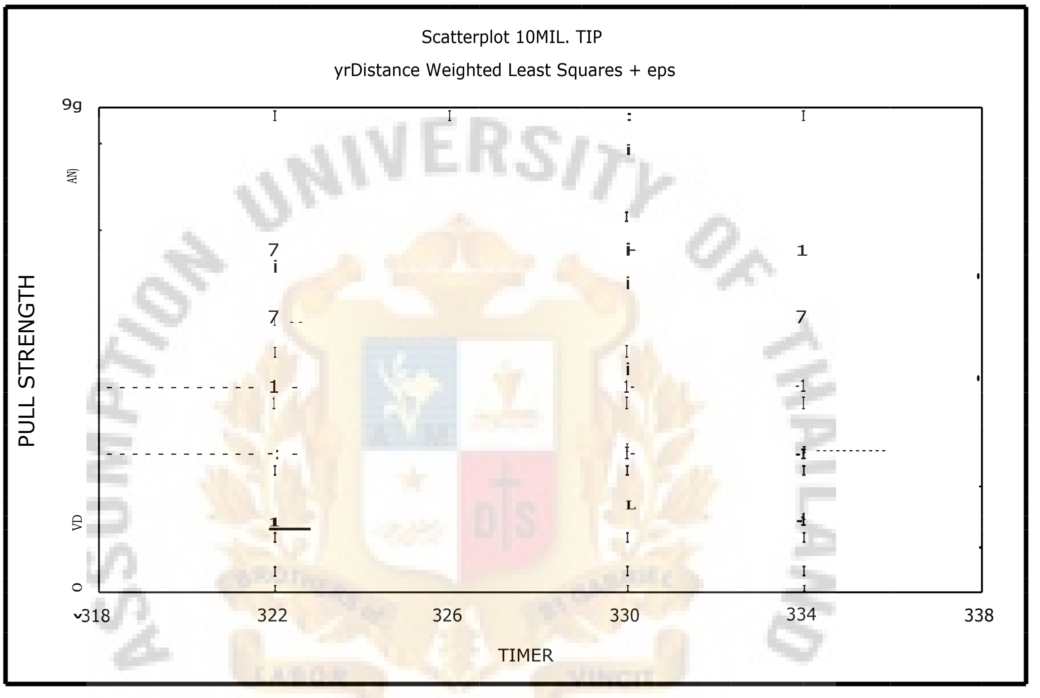


Figure 5.10. Scatter Plot Pull Strength versus Timer.

The timer has no significant effect on the response so we may not see the difference between the pull strengths when we varied the timer. The results of the analyse show the same as for the whole model and the 7mil. tip length.

Tables 5.22 and 5.23 show the pull strength value which is not quite the variation in terms of the timer variation.

Also Figure 5.10 represents the trend of the pull strength value related to the timer based on the least square mean plot, the average about 21 grams of the pull strength value.

(4) The Color of Wires

Table 5.24. Effect Test for the Color of Wires (10mil).

Effect Test			
Sum Of Squares	**F Ratio**	**DF**	**Prob>F**
25.374219	2.0522	3	0.1081

Table 5.25. Least Square Means for the Color of Wires (10mil).

Least Squares Means			
Level	**Least Sq. Mean**	**Std Error**	**Mean**
BLACK	21.50000000	0.2537704727	21.5000
GOLD	22.38750000	0.2537704727	22.3875
GREEN	21.97187500	0.2537704727	21.9719
RED	21.90000000	0.2537704727	21.9000

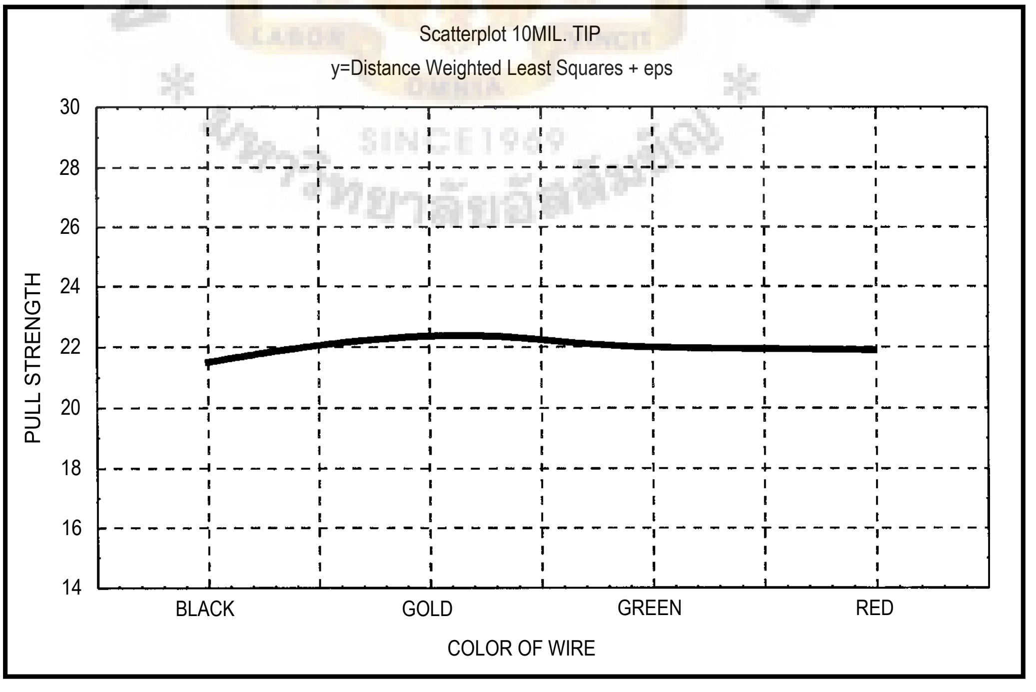
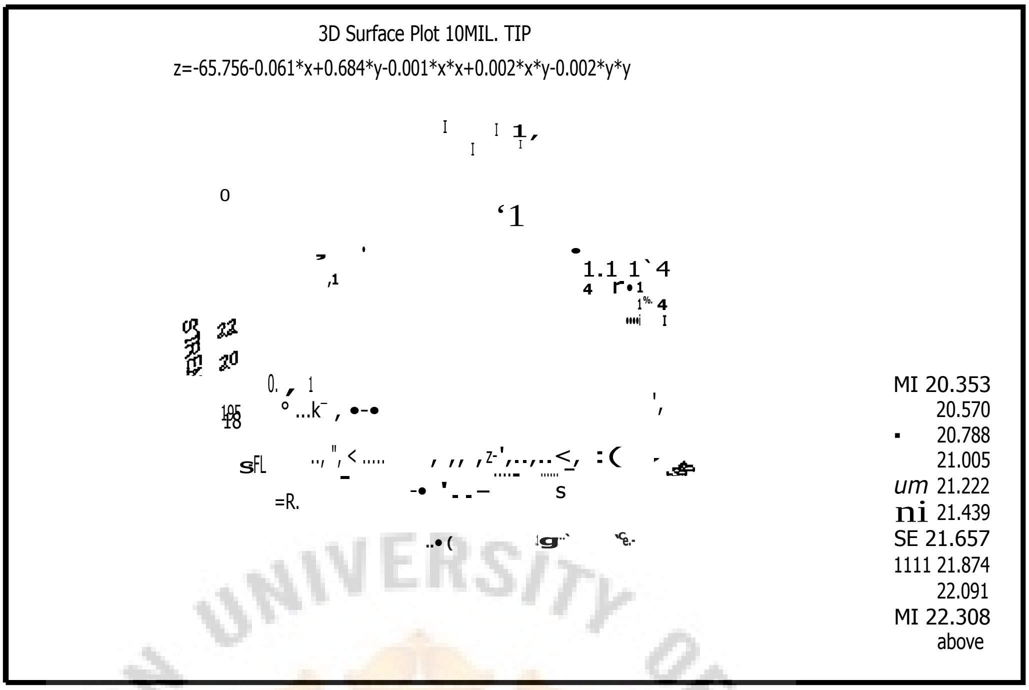


Figure 5.11. Scatter Plot Pull Strength versus Color of Wires.

Tables 5.24 and 5.25 show the color of wires effect on pull strength and the Gold color of wire gives high performance in terms of pull strength value, 22.388 grams and Black color of wire gives low performance in terms of pull strength value, 21.5 grams.

And the result of analysis of the color of wires shows difference from the 7mil tip length.

Figure 5.11 illustrates the scattering plot between force, power and pull strength. The optimum point is Gold color of wire based on least square mean plot.



The Optimum Area

Figure 5.12. 3D Plot of the Bonding Tip Force, the Power and the Wire Pull Strength Value for 10 Mil. Tip.

For the optimum area as shown in Figure 5.12, we combined the power and the bonding tip force related to the wire pull strength. It shows the optimum area (the wire pull strength), the force is high and the power is low same as the result of 7mil tip length.

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VI. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Referring to the analysis of the result of the experiment that we consider to wire pull strength value and separate the data into two groups by bonding tip length.

Because we look at the whole result of the experiment, Effect Test, Table 6.1 shows the factors which are concerned with response, pull strength, and the bonding tip length. And in the process, we prefer to reduce the tooling types because of the process variation reduction.

Parameters that have effected the pull strength value are as follows:

(1) Bonding tip length

(2) Force of bonding tip

(3) Power of wire bonding machine

(4) Colors of wire

The parameter that has not affected the pull strength value is Timer or bonding time.

Table 6.1. Group I (7 Mil. Tip) & Group II (10 Mil. Tip) Optimized Value.

Parameter	Bonding tip	Optimum Value	Pull Strength
Force	7 Mil.	170	18.4594
	10 Mil.	170	22.3750
Power	7 Mil.	270	18.3219
	10 Mil.	280	22.4719
Timer	7 Mil.	325	17.2281
	10 Mil.	325	22.2656
Color Of Wire	7 Mil.	GREEN	19.0938
	10 Mil.	GOLD	22.3875

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From the result of experiment, we can compare the pull strength value between the bonding tip 7Mil. and 10Mil. under the optimum value of parameters. We can see the significant difference from Figures 6.1, 6.2, 6.3 and 6.4 as shown by the scatter plot comparison between 7Mil. & 10Mil and parameters. We found in terms of the pull strength value that the 10Mil. tip length has higher performance than 7Mil. tip length of all the parameters.

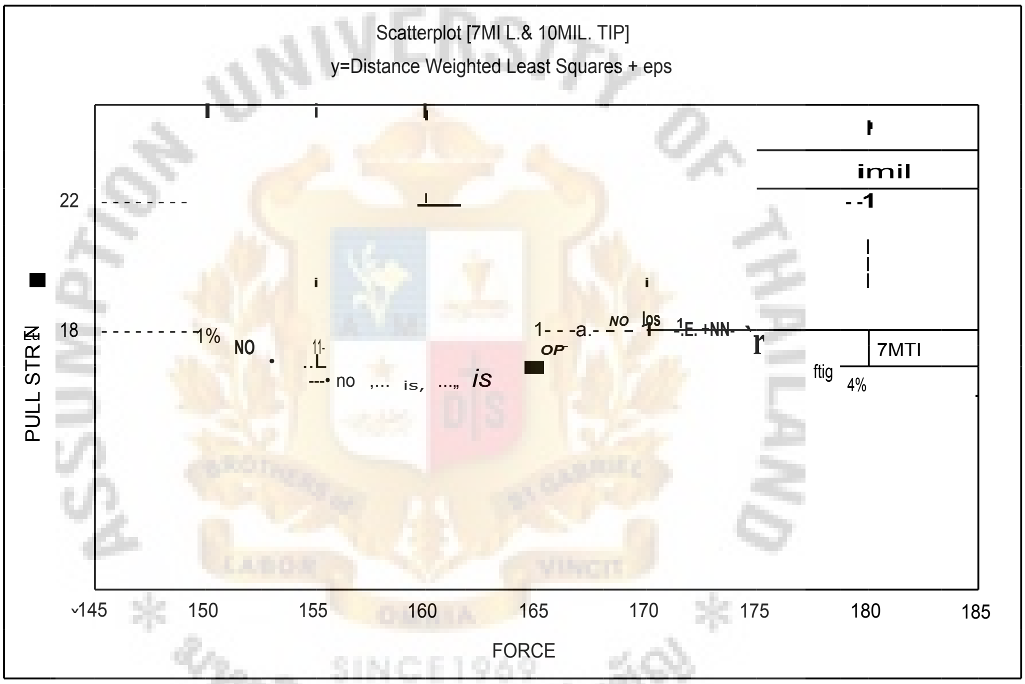

Figure 6.1. Bonding Tip Comparison with Force.

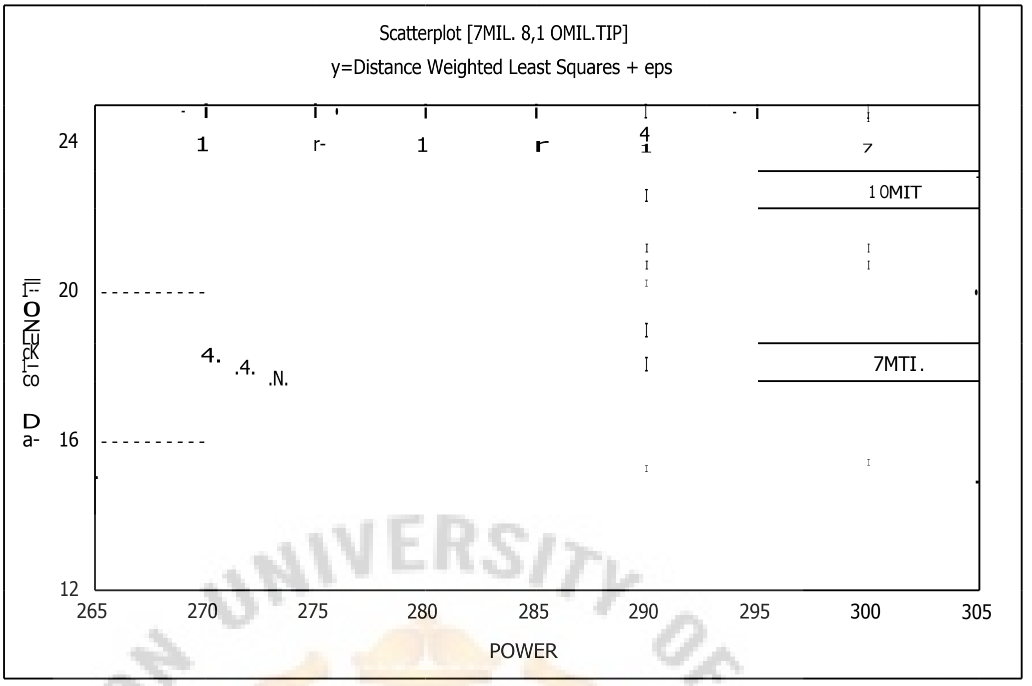

Figure 6.2. Bonding Tip Comparison with Power.

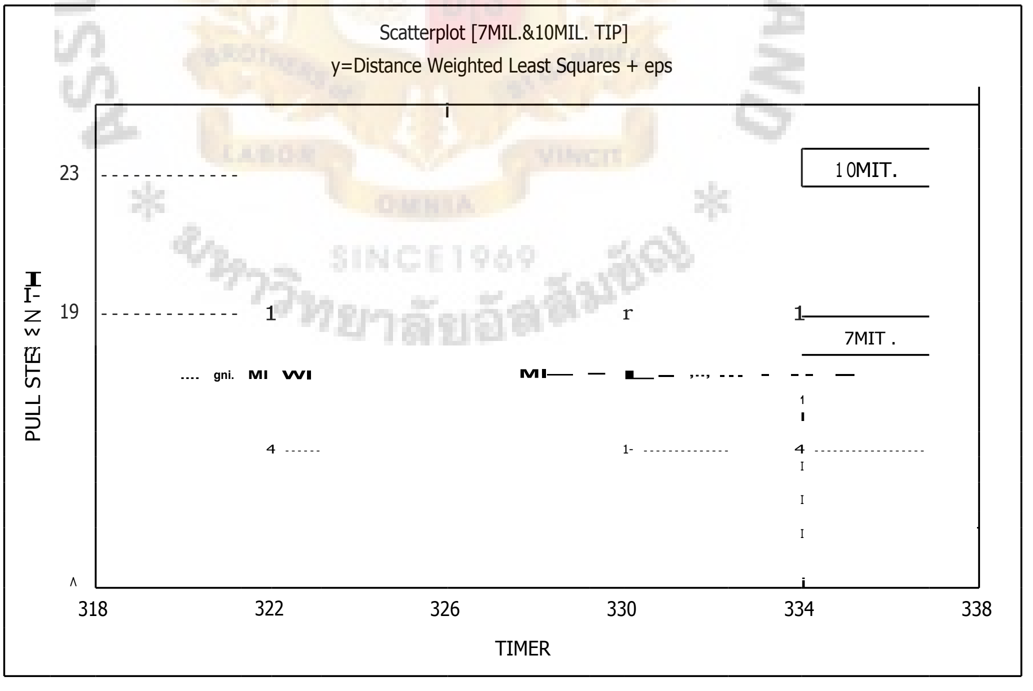

Figure 6.3. Bonding Tip Comparison with Timer.

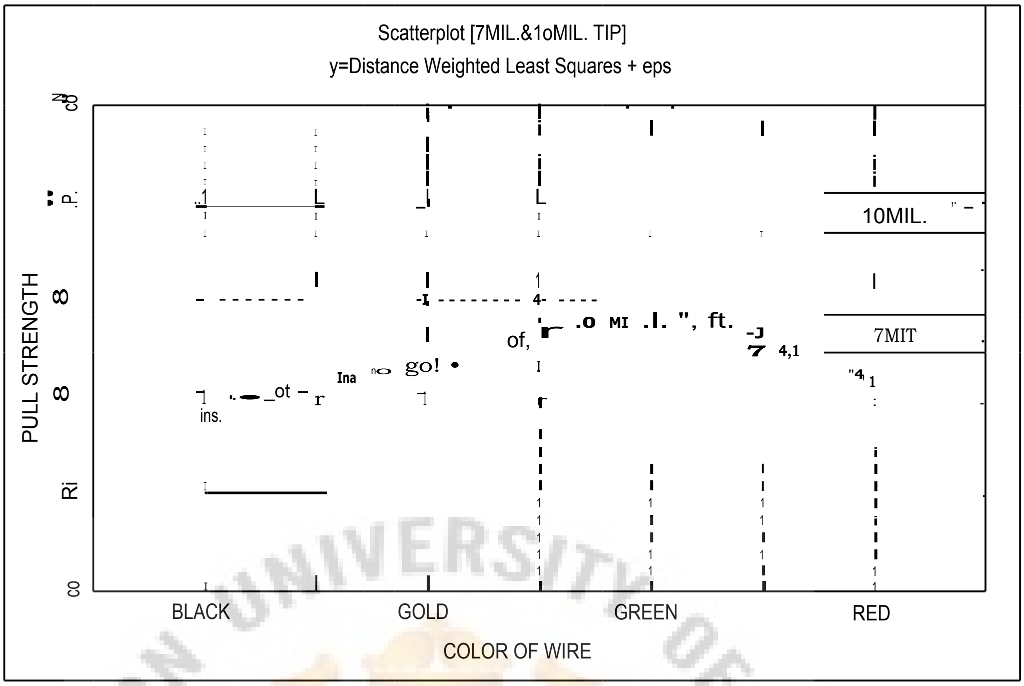

Figure 6.4. Bonding Tip Comparison with Color of Wire.

6.2 Recommendations

In the production process, we used 7Mil. tip length in production lines. We can improve the wire bonding operation performance by changing the bonding tip length to 10Mil., because we proved it by the experiment result. However we can improve the wire bonding operation performance by using 7Mil. tip length by setting up the optimized value of the parameters. Refer to Table 6.1.

The parameters that significantly affected the wire pull strength of the 10Mil. tip length are the power and bonding tip force so when we use the 10Mil. tip we would consider both parameters. For the color of wires, we can say for 10Mil. tip length also has a significant effect on the pull strength but the wires are materials so we will use the experiment result feedback to head's wire vendor to reduce the variance in terms of material. For 7Mil. tip length, Green color has higher the pull strength than the others and Black color has poor performance compared with the others.

We can use the parameter setting of value of the wire bonder machine as shown in Table 6.1 as a guideline and we must send the wire bonder machine to calibrate all the critical functions of the machine such as frequency output, or bonding tip height bonding fixture.

After we implemented the optimized value on work-week 34 (WW34) we found Cpk improvement of quality-bonding performance as shown in Table 6.2 for Cpk improvement before and after implementation of 7 Mil. tip increased from around 0.6 to around 0.9. For 10 Mil. as shown in Table 6.3, we have not the historical background because we never use 10 Mil. tip before so we just have the data after implemented only and there are Cpk 1.2 to 1.3. We can see clearly in Figure 6.5 when we implemented the value Cpk's the trend will go up compared with before and after implementation of 7 Mil. tip but 10 Mil. tip just showed Cpk's the trend to be higher than 7 Mil. tip.

Table 6.2. Cpk Ultrasonic Wire Bonding by Weekly (7 Mil.Tip).

Data	WW30	WW31	WW32	WW33	WW34	WW35	WW36	WW37	WW38
Mean	16.95	17.28	17.09	16.42	17.75	18.54	18.50	18.22	17.70
Stdev	4.19	3.91	3.94	3.38	2.75	2.95	2.81	2.96	3.17
Cpk	0.553	0.621	0.600	0.633	0.939	0.965	1.008	0.926	0.810

Table 6.3. Cpk Ultrasonic Wire Bonding by Weekly (10 Mil.Tip).

Data	WW34	WW35	WW36	WW37	WW38
Mean	22.23	21.35	22.12	21.97	22.15
Stdev	2.98	3.01	3.11	2.96	3.17
Cpk	1.368	1.257	1.299	1.348	1.278

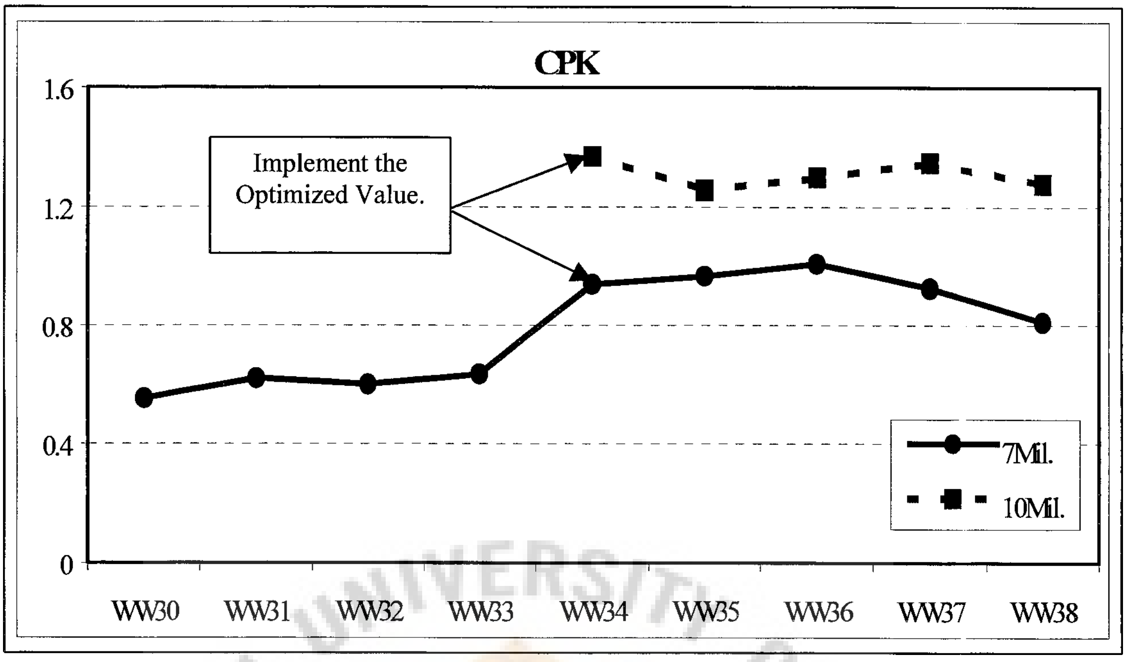

Figure 6.5. Cpk Trend after Implemented the Optimized Value.

The experimental result shows that the bigger area of the bonding tip will give higher bonding performance. It seems that if we use a bigger bonding tip such as 12 Mil. tip we should get a higher the bonding performance than from 10 Mil. tip. But in fact we can not use 12 Mil. tip because we have to concentrate on rework times also. Normally, we have limited bonding pads area for 7 Mil. tip and 10 Mil. tip. We can do rework 3 times. It means we can do re-bonding 3 times in the same bonding pad but we can not do so with 12 Mil. tip because it uses more using area of bonding pad so the rework times will be reduced to 2 times. In terms of scrap cost, it will increase when rework opportunity decreases. That is the reason why we do not use 12 Mil. tip for our process.

The Experimental Problems

We need to control the other parameters that are concerned with our output such as bonding tip height, bonding fixture or bonding tip force setting. We take a long time to run the experiment and we need to keep all the conditions the same as when we run at any time. So we run the experiment at the extra bonder machine and we use the optimized value to implement the production's machines. We may not get the same results as we run the experiment because the machines have different conditions. So before we implement the optimized value to the other machines, we must send their machines back to re-calibrate to get all conditions of the machines to be nearly the same as the machine that we used for the experiment. We are lucky that all machines in our production lines, are of one model only otherwise we will get another input from different machine models.

In this study, we do not have to concentrate on the color of wires although the result will have significance differences on the different colors. Because the wire came from vendor where there are many levels in the supply chain, we need to deeply in their process and kinds of chemical that they are using. So there is a need to take more details and study their processes otherwise we will gain more bonding performance.

APPENDIX A

THE EXPERIMENTAL RESULTS

The Experiment Results

Table A.1. The Experiment Results.

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
1	11111	150	270	320	BLACK	7MIL	13	13	16	23	18	16.60
2	11112	150	270	320	BLACK	10MIL	20	21	19	21	19	20.00
3	11121	150	270	320	GOLD	7MIL	16	19	13	13	18	15.80
4	11122	150	270	320	GOLD	10MIL	22	16	23	26	23	22.00
5	11131	150	270	320	GREEN	7MIL	19	21	23	24	21	21.60
6	11132	150	270	320	GREEN	10MIL	24	29	23	24	24	24.80
7	11141	150	270	320	RED	7MIL	18	18	18	16	11	16.20
8	11142	150	270	320	RED	10MIL	21	28	20	24	26	24.00
9	11211	150	270	325	BLACK	7MIL	21	14	14	14	16	15.80
10	11212	150	270	325	BLACK	10MIL	19	26	19	24	21	21.80
11	11221	150	270	325	GOLD	7MIL	13	18	18	14	16	15.80
12	11222	150	270	325	GOLD	10MIL	21	24	24	23	21	22.60
13	11231	150	270	325	GREEN	7MIL	23	21	18	19	23	20.80
14	11232	150	270	325	GREEN	10MIL	23	24	29	21	19	23.20
15	11241	150	270	325	RED	7MIL	21	16	19	18	19	18.60
16	11242	150	270	325	RED	10MIL	21	24	26	23	26	24.00
17	11311	150	270	330	BLACK	7MIL	8	14	16	19	14	14.20
18	11312	150	270	330	BLACK	10MIL	16	19	21	21	19	19.20
19	11321	150	270	330	GOLD	7MIL	21	14	18	16	21	18.00
20	11322	150	270	330	GOLD	iomIL	21	24	23	24	23	23.00
21	11331	150	270	330	GREEN	7MIL	23	24	21	23	19	22.00
22	11332	150	270	330	GREEN	10MIL	24	21	19	21	26	22.20
23	11341	150	270	330	RED	7MIL	18	11	16	16	19	16.00
24	11342	150	270	330	RED	10MIL	21	28	21	26	21	23.40
25	11411	150	270	335	BLACK	7MIL	19	11	19	9	18	15.20
26	11412	150	270	335	BLACK	10MIL	18	22	21	19	21	20.20
27	11421	150	270	335	GOLD	7MIL	24	23	31	28	23	25.80
28	11422	150	270	335	GOLD	10MIL	23	19	18	21	22	20.60
29	11431	150	270	335	GREEN	7MIL	21	13	23	24	21	20.40
30	11432	150	270	335	GREEN	10MIL	21	21	21	19	24	21.20
31	11441	150	270	335	RED	7MIL	18	13	19	18	18	17.20
32	11442	150	270	335	RED	10MIL	26	19	21	21	18	21.00
33	12111	150	280	320	BLACK	7MIL	11	13	18	16	16	14.80
34	12112	150	280	320	BLACK	10MIL	21	21	22	23	21	21.60
35	12121	150	280	320	GOLD	7MIL	13	13	16	19	16	15.40
36	12122	150	280	320	GOLD	1omIL	21	28	23	21	25	23.60
37	12131	150	280	320	GREEN	7MIL	23	21	18	23	19	20.80
38	12132	150	280	320	GREEN	10MIL	28	26	24	18	24	24.00
39	12141	150	280	320	RED	7MIL	16	16	11	19	16	15.60

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
40	12142	150	280	320	RED	10mIL	28	21	28	26	21	24.80
41	12211	150	280	325	BLACK	7MIL	21	18	11	13	26	17.80
42	12212	150	280	325	BLACK	10MIL	21	19	21	21	23	21.00
43	12221	150	280	325	GOLD	7MIL	23	13	23	19	23	20.20
44	12222	150	280	325	GOLD	1OMIL	21	26	20	24	23	22.80
45	12231	150	280	325	GREEN	7MIL	19	24	16	16	14	17.80
46	12232	150	280	325	GREEN	10MIL	33	33	18	21	21	25.20
47	12241	150	280	325	RED	7MIL	13	21	18	14	16	16.40
48	12242	150	280	325	RED	1OMIL	21	26	24	21	31	24.60
49	12311	150	280	330	BLACK	7MIL	19	14	14	14	11	14.40
50	12312	150	280	330	BLACK	10MIL	21	22	21	20	23	21.40
51	12321	150	280	330	GOLD	7MIL	23	18	13	16	16	17.20
52	12322	150	280	330	GOLD	10MIL	16	14	18	21	22	18.20
53	12331	150	280	330	GREEN	7MIL	26	23	21	19	14	20.60
54	12332	150	280	330	GREEN	IOMIL	19	26	24	26	24	23.80
55	12341	150	280	330	RED	7MIL	13	11	13	13	14	12.80
56	12342	150	280	330	RED	1 omIL	23	31	21	31	26	26.40
57	12411	150	280	335	BLACK	7MIL	23	13	16	13	16	16.20
58	12412	150	280	335	BLACK	10mIL	19	19	18	14	14	16.80
59	12421	150	280	335	GOLD	7MIL	19	18	13	24	11	17.00
60	12422	150	280	335	GOLD	10MIL	18	26	21	19	18	20.40
61	12431	150	280	335	GREEN	7MIL	18	23	23	24	21	21.80
62	12432	150	280	335	GREEN	10MIL	16	24	18	33	18	21.80
63	12441	150	280	335	RED	7MIL	18	18	19	14	13	16.40
64	12442	150	280	335	RED	IOMIL	21	21	18	16	18	18.80
65	13111	150	290	320	BLACK	7MIL	18	11	16	18	16	15.80
66	13112	150	290	320	BLACK	ioMIL	16	21	16	18	19	18.00
67	13121	150	290	320	GOLD	7MIL	16	28	18	21	19	20.40
68	13122	150	290	320	GOLD	1OMIL	20	21	22	23	24	22.00
69	13131	150	290	320	GREEN	7MIL	23	24	14	24	24	21.80
70	13132	150	290	320	GREEN	10MIL	26	18	23	23	26	23.20
71	13141	150	290	320	RED	7MIL	18	26	13	21	19	19.40
72	13142	150	290	320	RED	10mIL	21	18	19	18	19	19.00
73	13211	150	290	325	BLACK	7MIL	16	11	14	16	18	15.00
74	13212	150	290	325	BLACK	10mIL	19	21	20	21	19	20.00
75	13221	150	290	325	GOLD	7MIL	16	13	18	16	13	15.20
76	13222	150	290	325	GOLD	10MIL	19	23	22	18	21	20.60
77	13231	150	290	325	GREEN	7MIL	21	26	28	18	23	23.20
78	13232	150	290	325	GREEN	10MIL	24	23	29	24	24	24.80
79	13241	150	290	325	RED	7MIL	16	26	13	16	18	17.80
80	13242	150	290	325	RED	1OMIL	21	19	23	16	26	21.00
81	13311	150	290	330	BLACK	7MIL	18	13	18	19	18	17.20
82	13312	150	290	330	BLACK	1 omiL	21	21	21	19	20	20.40
83	13321	150	290	330	GOLD	7MIL	18	13	21	23	19	18.80

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
84	13322	150	290	330	GOLD	iomIL	16	24	23	22	23	21.60
85	13331	150	290	330	GREEN	7MIL	19	21	18	21	24	20.60
86	13332	150	290	330	GREEN	10MIL	21	21	28	16	28	22.80
87	13341	150	290	330	RED	7MIL	21	16	19	14	19	17.80
88	13342	150	290	330	RED	iomIL	21	21	24	21	23	22.00
89	13411	150	290	335	BLACK	7MIL	13	14	28	16	24	19.00
90	13412	150	290	335	BLACK	10MIL	18	19	19	21	24	20.20
91	13421	150	290	335	GOLD	7MIL	16	18	21	18	11	16.80
92	13422	150	290	335	GOLD	10MIL	18	28	24	19	18	21.40
93	13431	150	290	335	GREEN	7MIL	18	13	18	26	18	18.60
94	13432	150	290	335	GREEN	10MIL	21	19	16	19	23	19.60
95	13441	150	290	335	RED	7MIL	16	19	19	19	19	18.40
96	13442	150	290	335	RED	10MIL	13	23	18	24	13	18.20
97	14111	150	300	320	BLACK	7MIL	18	19	23	23	19	20.40
98	14112	150	300	320	BLACK	10MIL	21	19	21	19	19	19.80
99	14121	150	300	320	GOLD	7MIL	11	19	14	11	19	14.80
100	14122	150	300	320	GOLD	10MIL	28	24	28	19	24	24.60
101	14131	150	300	320	GREEN	7MIL	31	23	26	16	16	22.40
102	14132	150	300	320	GREEN	10MIL	19	23	21	26	18	21.40
103	14141	150	300	320	RED	7MIL	18	14	19	13	24	17.60
104	14142	150	300	320	RED	iomIL	16	13	18	11	18	15.20
105	14211	150	300	325	BLACK	7MIL	18	13	14	18	16	15.80
106	14212	150	300	325	BLACK	10MIL	21	21	19	22	22	21.00
107	14221	150	300	325	GOLD	7MIL	19	16	18	16	21	18.00
108	14222	150	300	325	GOLD	10MIL	24	24	22	20	18	21.60
109	14231	150	300	325	GREEN	7MIL	19	14	19	24	24	20.00
110	14232	150	300	325	GREEN	10MIL	19	23	23	24	21	22.00
111	14241	150	300	325	RED	7MIL	19	21	16	18	14	17.60
112	14242	150	300	325	RED	10MIL	21	16	11	14	23	17.00
113	14311	150	300	330	BLACK	7MIL	14	16	19	18	23	18.00
114	14312	150	300	330	BLACK	10MIL	19	19	24	23	17	20.40
115	14321	150	300	330	GOLD	7MIL	18	28	11	16	11	16.80
116	14322	150	300	330	GOLD	iomiL	16	21	23	23	21	20.80
117	14331	150	300	330	GREEN	7MIL	13	21	18	23	23	19.60
118	14332	150	300	330	GREEN	10MIL	19	18	23	24	21	21.00
119	14341	150	300	330	RED	7MIL	13	13	21	16	18	16.20
120	14342	150	300	330	RED	IOMIL	19	21	13	24	26	20.60
121	14411	150	300	335	BLACK	7MIL	16	18	16	21	18	17.80
122	14412	150	300	335	BLACK	10MIL	18	19	21	24	14	19.20
123	14421	150	300	335	GOLD	7MIL	13	19	19	13	14	15.60
124	14422	150	300	335	GOLD	iomiL	18	14	24	19	19	18.80
125	14431	150	300	335	GREEN	7MIL	19	16	16	13	18	16.40
126	14432	150	300	335	GREEN	10MIL	18	24	16	14	21	18.60
127	14441	150	300	335	RED	7MIL	11	18	23	24	16	18.40

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Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
128	14442	150	300	335	RED	10MIL	21	16	14	23	23	19.40
129	21111	160	270	320	BLACK	7MIL	18	11	13	16	19	15.40
130	21112	160	270	320	BLACK	10MIL	19	19	19	19	21	19.40
131	21121	160	270	320	GOLD	7MIL	29	9	14	13	23	17.60
132	21122	160	270	320	GOLD	10MIL	13	18	21	18	23	18.60
133	21131	160	270	320	GREEN	7MIL	11	18	26	24	16	19.00
134	21132	160	270	320	GREEN	10MIL	19	19	19	23	24	20.80
135	21141	160	270	320	RED	7MIL	11	23	18	16	16	16.80
136	21142	160	270	320	RED	10MIL	23	23	23	11	26	21.20
137	21211	160	270	325	BLACK	7MIL	13	16	18	14	13	14.80
138	21212	160	270	325	BLACK	10MIL	16	24	24	23	24	22.20
139	21221	160	270	325	GOLD	7MIL	19	9	18	19	14	15.80
140	21222	160	270	325	GOLD	IOMIL	26	16	19	23	23	21.40
141	21231	160	270	325	GREEN	7MIL	18	21	28	24	33	24.80
142	21232	160	270	325	GREEN	IOMIL	19	23	19	19	21	20.20
143	21241	160	270	325	RED	7MIL	23	13	18	19	13	17.20
144	21242	160	270	325	RED	10MIL	26	26	28	23	23	25.20
145	21311	160	270	330	BLACK	7MIL	14	11	18	16	19	15.60
146	21312	160	270	330	BLACK	10MIL	24	26	19	23	18	22.00
147	21321	160	270	330	GOLD	7MIL	19	18	18	23	16	18.80
148	21322	160	270	330	GOLD	10MIL	24	24	23	28	16	23.00
149	21331	160	270	330	GREEN	7MIL	23	24	23	24	21	23.00
150	21332	160	270	330	GREEN	10MIL	16	21	28	21	14	20.00
151	21341	160	270	330	RED	7MIL	23	19	21	18	14	19.00
152	21342	160	270	330	RED	10MIL	33	24	26	18	23	24.80
153	21411	160	270	335	BLACK	7MIL	13	16	18	13	13	14.60
154	21412	160	270	335	BLACK	10MIL	16	24	24	26	24	22.80
155	21421	160	270	335	GOLD	7MIL	11	14	16	23	16	16.00
156	21422	160	270	335	GOLD	10MIL	21	24	19	23	23	22.00
157	21431	160	270	335	GREEN	7MIL	19	21	26	26	33	25.00
158	21432	160	270	335	GREEN	10MIL	43	21	16	19	23	24.40
159	21441	160	270	335	RED	7MIL	19	13	14	14	16	15.20
160	21442	160	270	335	RED	10MIL	11	23	21	23	26	20.80
161	22111	160	280	320	BLACK	7MIL	19	14	16	14	11	14.80
162	22112	160	280	320	BLACK	10MIL	21	23	33	19	24	24.00
163	22121	160	280	320	GOLD	7MIL	11	11	11	8	13	10.80
164	22122	160	280	320	GOLD	10MIL	19	21	23	19	19	20.20
165	22131	160	280	320	GREEN	7MIL	19	19	21	23	23	21.00
166	22132	160	280	320	GREEN	IOMIL	21	21	26	28	18	22.80
167	22141	160	280	320	RED	7MIL	9	13	13	11	21	13.40
168	22142	160	280	320	RED	10MIL	24	21	21	18	21	21.00
169	22211	160	280	325	BLACK	7MIL	13	19	13	11	9	13.00
170	22212	160	280	325	BLACK	10MIL	24	24	23	23	24	23.60
171	22221	160	280	325	GOLD	7MIL	14	16	21	19	11	16.20

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
172	22222	160	280	325	GOLD	1 omiL	18	23	21	23	26	22.20
173	22231	160	280	325	GREEN	7MIL	19	6	13	8	21	13.40
174	22232	160	280	325	GREEN	10MIL	28	29	26	28	28	27.80
175	22241	160	280	325	RED	7MIL	11	19	16	11	13	14.00
176	22242	160	280	325	RED	10MIL	21	23	21	18	23	21.20
177	22311	160	280	330	BLACK	7MIL	18	14	16	14	16	15.60
178	22312	160	280	330	BLACK	1 omiL	18	24	24	24	21	22.20
179	22321	160	280	330	GOLD	7MIL	14	18	21	16	13	16.40
180	22322	160	280	330	GOLD	I °mil,	18	24	24	21	23	22.00
181	22331	160	280	330	GREEN	7MIL	19	21	14	13	14	16.20
182	22332	160	280	330	GREEN	10MIL	16	18	21	21	24	20.00
183	22341	160	280	330	RED	7MIL	13	14	11	18	13	13.80
184	22342	160	280	330	RED	1OMIL	24	23	26	18	23	22.80
185	22411	160	280	335	BLACK	7MIL	9	14	11	16	11	12.20
186	22412	160	280	335	BLACK	10MIL	21	23	14	26	18	20.40
187	22421	160	280	335	GOLD	7MIL	16	16	8	18	14	14.40
188	22422	160	280	335	GOLD	10MIL	23	23	16	19	26	21.40
189	22431	160	280	335	GREEN	7MIL	19	21	18	18	14	18.00
190	22432	160	280	335	GREEN	loMIL	19	23	26	21	26	23.00
191	22441	160	280	335	RED	7MIL	13	14	13	16	8	12.80
192	22442	160	280	335	RED	10MIL	26	13	19	19	28	21.00
193	23111	160	290	320	BLACK	7MIL	8	6	14	14	29	14.20
194	23112	160	290	320	BLACK	i omiL	13	23	28	23	19	21.20
195	23121	160	290	320	GOLD	7MIL	21	18	16	21	14	18.00
196	23122	160	290	320	GOLD	10MIL	24	19	26	26	21	23.20
197	23131	160	290	320	GREEN	7MIL	21	16	18	16	23	18.80
198	23132	160	290	320	GREEN	10MIL	26	16	19	23	21	21.00
199	23141	160	290	320	RED	7MIL	16	14	16	16	21	16.60
200	23142	160	290	320	RED	10MIL	23	19	23	26	21	22.40
201	23211	160	290	325	BLACK	7MIL	13	9	13	14	21	14.00
202	23212	160	290	325	BLACK	10MIL	13	14	13	21	21	16.40
203	23221	160	290	325	GOLD	7MIL	18	19	19	21	19	19.20
204	23222	160	290	325	GOLD	lomIL	24	29	24	28	19	24.80
205	23231	160	290	325	GREEN	7MIL	19	21	16	19	11	17.20
206	23232	160	290	325	GREEN	1OMIL	21	28	18	18	16	20.20
207	23241	160	290	325	RED	7MIL	21	14	18	11	16	16.00
208	23242	160	290	325	RED	10MIL	23	19	21	18	21	20.40
209	23311	160	290	330	BLACK	7MIL	8	13	21	8	11	12.20
210	23312	160	290	330	BLACK	10mIL	23	24	16	16	24	20.60
211	23321	160	290	330	GOLD	7MIL	23	19	19	23	14	19.60
212	23322	160	290	330	GOLD	1OMIL	28	23	21	18	23	22.60
213	23331	160	290	330	GREEN	7MIL	18	26	23	11	13	18.20
214	23332	160	290	330	GREEN	1 omIL	23	26	26	19	23	23.40
215	23341	160	290	330	RED	7MIL	14	21	13	8	9	13.00

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
216	23342	160	290	330	RED	10MIL	11	16	16	18	18	15.80
217	23411	160	290	335	BLACK	7MIL	14	8	9	13	16	12.00
218	23412	160	290	335	BLACK	10MIL	21	16	11	24	19	18.20
219	23421	160	290	335	GOLD	7MIL	8	16	13	11	14	12.40
220	23422	160	290	335	GOLD	10MIL	26	28	26	28	26	26.80
221	23431	160	290	335	GREEN	7MIL	11	14	13	11	11	12.00
222	23432	160	290	335	GREEN	10MIL	11	18	24	19	18	18.00
223	23441	160	290	335	RED	7MIL	18	16	24	14	9	16.20
224	23442	160	290	335	RED	10MIL	24	26	28	19	23	24.00
225	24111	160	300	320	BLACK	7MIL	11	9	8	13	14	11.00
226	24112	160	300	320	BLACK	10MIL	19	21	19	19	23	20.20
227	24121	160	300	320	GOLD	7MIL	19	9	16	21	18	16.60
228	24122	160	300	320	GOLD	10MIL	29	26	24	19	13	22.20
229	24131	160	300	320	GREEN	7MIL	21	11	18	19	14	16.60
230	24132	160	300	320	GREEN	10MIL	14	19	21	21	23	19.60
231	24141	160	300	320	RED	7MIL	18	19	16	11	19	16.60
232	24142	160	300	320	RED	10MIL	24	24	19	21	24	22.40
233	24211	160	300	325	BLACK	7MIL	31	8	6	8	6	11.80
234	24212	160	300	325	BLACK	10MIL	24	21	18	24	21	21.60
235	24221	160	300	325	GOLD	7MIL	19	21	14	11	13	15.60
236	24222	160	300	325	GOLD	10MIL	24	19	23	16	21	20.60
237	24231	160	300	325	GREEN	7MIL	19	18	18	21	29	21.00
238	24232	160	300	325	GREEN	10MIL	19	23	19	21	21	20.60
239	24241	160	300	325	RED	7MIL	13	14	13	19	11	14.00
240	24242	160	300	325	RED	10MIL	23	21	26	24	21	23.00
241	24311	160	300	330	BLACK	7MIL	8	14	18	18	16	14.80
242	24312	160	300	330	BLACK	10MIL	28	23	13	24	18	21.20
243	24321	160	300	330	GOLD	7MIL	8	14	23	19	13	15.40
244	24322	160	300	330	GOLD	10MIL	24	24	23	24	19	22.80
245	24331	160	300	330	GREEN	7MIL	14	11	14	14	14	13.40
246	24332	160	300	330	GREEN	10MIL	19	23	19	24	18	20.60
247	24341	160	300	330	RED	7MIL	13	18	16	19	19	17.00
248	24342	160	300	330	RED	10MIL	21	26	23	23	23	23.20
249	24411	160	300	335	BLACK	7MIL	11	11	14	8	8	10.40
250	24412	160	300	335	BLACK	10MIL	16	23	19	19	28	21.00
251	24421	160	300	335	GOLD	7MIL	19	18	21	11	19	17.60
252	24422	160	300	335	GOLD	10MIL	24	23	24	31	24	25.20
253	24431	160	300	335	GREEN	7MIL	11	14	24	23	21	18.60
254	24432	160	300	335	GREEN	10MIL	23	21	16	23	23	21.20
255	24441	160	300	335	RED	7MIL	13	19	16	19	18	17.00
256	24442	160	300	335	RED	10MIL	18	24	18	23	28	22.20
257	31111	170	270	320	BLACK	7MIL	29	28	18	18	19	22.40
258	31112	170	270	320	BLACK	10MIL	28	23	18	23	16	21.60
259	31121	170	270	320	GOLD	7MIL	21	21	18	13	13	17.20

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
260	31122	170	270	320	GOLD	10MIL	21	24	23	29	24	24.20
261	31131	170	270	320	GREEN	7MIL	23	26	21	21	13	20.80
262	31132	170	270	320	GREEN	10MIL	18	23	26	24	24	23.00
263	31141	170	270	320	RED	7MIL	14	26	21	23	14	19.60
264	31142	170	270	320	RED	lomiL	24	24	23	23	23	23.40
265	31211	170	270	325	BLACK	7MIL	16	14	19	28	18	19.00
266	31212	170	270	325	BLACK	10MIL	16	19	21	26	28	22.00
267	31221	170	270	325	GOLD	7MIL	13	14	18	26	24	19.00
268	31222	170	270	325	GOLD	1 omIL	18	24	23	29	23	23.40
269	31231	170	270	325	GREEN	7MIL	23	18	18	18	19	19.20
270	31232	170	270	325	GREEN	IOMIL	24	24	23	21	21	22.60
271	31241	170	270	325	RED	7MIL	18	14	16	18	18	16.80
272	31242	170	270	325	RED	10MIL	18	23	26	24	19	22.00
273	31311	170	270	330	BLACK	7MIL	24	21	21	23	19	21.60
274	31312	170	270	330	BLACK	IOMIL	21	19	23	19	21	20.60
275	31321	170	270	330	GOLD	7MIL	26	24	23	18	28	23.80
276	31322	170	270	330	GOLD	1 omIL	26	28	24	19	19	23.20
277	31331	170	270	330	GREEN	7MIL	18	21	16	14	18	17.40
278	31332	170	270	330	GREEN	10mIL	23	21	19	19	23	21.00
279	31341	170	270	330	RED	7MIL	16	18	21	16	11	16.40
280	31342	170	270	330	RED	1 omIL	18	23	28	21	23	22.60
281	31411	170	270	335	BLACK	7MIL	13	23	19	19	13	17.40
282	31412	170	270	335	BLACK	1 omIL	19	21	21	23	21	21.00
283	31421	170	270	335	GOLD	7MIL	13	18	19	26	19	19.00
284	31422	170	270	335	GOLD	10MIL	23	21	24	21	21	22.00
285	31431	170	270	335	GREEN	7MIL	31	18	26	23	16	22.80
286	31432	170	270	335	GREEN	IOMIL	19	19	24	19	21	20.40
287	31441	170	270	335	RED	7MIL	18	16	16	16	16	16.40
288	31442	170	270	335	RED	1 omiL	21	28	21	26	23	23.80
289	32111	170	280	320	BLACK	7MIL	13	14	21	11	11	14.00
290	32112	170	280	320	BLACK	10MIL	26	18	18	19	29	22.00
291	32121	170	280	320	GOLD	7MIL	19	23	24	23	24	22.60
292	32122	170	280	320	GOLD	1OMIL	19	23	16	18	19	19.00
293	32131	170	280	320	GREEN	7MIL	16	24	16	23	13	18.40
294	32132	170	280	320	GREEN	1 omiL	29	19	26	28	21	24.60
295	32141	170	280	320	RED	7MIL	21	23	29	18	21	22.40
296	32142	170	280	320	RED	1 omiL	21	29	29	16	24	23.80
297	32211	170	280	325	BLACK	7MIL	18	14	21	14	19	17.20
298	32212	170	280	325	BLACK	10mIL	19	19	19	23	19	19.80
299	32221	170	280	325	GOLD	7MIL	24	14	28	26	21	22.60
300	32222	170	280	325	GOLD	1 omiL	19	24	14	28	21	21.20
301	32231	170	280	325	GREEN	7MIL	16	24	23	16	21	20.00
302	32232	170	280	325	GREEN	1OMIL	26	23	21	23	26	23.80
303	32241	170	280	325	RED	7MIL	14	23	18	21	18	18.80

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
304	32242	170	280	325	RED	10MIL	24	18	28	19	24	22.60
305	32311	170	280	330	BLACK	7MIL	18	21	19	13	14	17.00
306	32312	170	280	330	BLACK	10MIL	23	16	18	23	23	20.60
307	32321	170	280	330	GOLD	7MIL	18	23	19	18	19	19.40
308	32322	170	280	330	GOLD	10MIL	19	24	21	21	24	21.80
309	32331	170	280	330	GREEN	7MIL	23	19	21	19	19	20.20
310	32332	170	280	330	GREEN	10MIL	21	24	26	28	24	24.60
311	32341	170	280	330	RED	7MIL	13	24	18	14	19	17.60
312	32342	170	280	330	RED	10MIL	29	23	19	21	21	22.60
313	32411	170	280	335	BLACK	7MIL	14	14	19	24	24	19.00
314	32412	170	280	335	BLACK	10MIL	29	28	26	26	24	26.60
315	32421	170	280	335	GOLD	7MIL	14	13	23	24	21	19.00
316	32422	170	280	335	GOLD	10MIL	18	23	21	23	18	20.60
317	32431	170	280	335	GREEN	7MIL	18	14	21	18	16	17.40
318	32432	170	280	335	GREEN	10MIL	23	26	24	23	23	23.80
319	32441	170	280	335	RED	7MIL	24	18	11	21	9	16.60
320	32442	170	280	335	RED	10MIL	16	23	26	23	26	22.80
321	33111	170	290	320	BLACK	7MIL	13	16	13	8	18	13.60
322	33112	170	290	320	BLACK	10MIL	18	24	26	23	19	22.00
323	33121	170	290	320	GOLD	7MIL	19	16	16	23	18	18.40
324	33122	170	290	320	GOLD	10MIL	21	24	13	21	26	21.00
325	33131	170	290	320	GREEN	7MIL	16	21	16	19	18	18.00
326	33132	170	290	320	GREEN	10MIL	23	28	23	26	23	24.60
327	33141	170	,290	320	RED	7MIL	16	19	16	18	16	17.00
328	33142	170	290	320	RED	10MIL	23	26	26	26	23	24.80
329	33211	170	290	325	BLACK	7MIL	13	19	14	31	36	22.60
330	33212	170	290	325	BLACK	10MIL	26	28	24	26	24	25.60
331	33221	170	290	325	GOLD	7MIL	13	14	13	16	11	13.40
332	33222	170	290	325	GOLD	10MIL	19	21	26	28	24	23.60
333	33231	170	290	325	GREEN	7MIL	16	19	21	11	21	17.60
334	33232	170	290	325	GREEN	10MIL	14	24	21	13	26	19.60
335	33241	170	290	325	RED	7MIL	21	18	19	14	13	17.00
336	33242	170	290	325	RED	10MIL	16	26	29	19	21	22.20
337	33311	170	290	330	BLACK	7MIL	11	16	33	16	13	17.80
338	33312	170	290	330	BLACK	10MIL	28	26	19	29	24	25.20
339	33321	170	290	330	GOLD	7MIL	21	16	21	13	13	16.80
340	33322	170	290	330	GOLD	10MIL	26	28	23	21	18	23.20
341	33331	170	290	330	GREEN	7MIL	19	16	21	16	16	17.60
342	33332	170	290	330	GREEN	10MIL	18	24	28	18	26	22.80
343	33341	170	290	330	RED	7MIL	18	28	19	16	19	20.00
344	33342	170	290	330	RED	10MIL	28	14	19	26	24	22.20
345	33411	170	290	335	BLACK	7MIL	14	23	14	11	21	16.60
346	33412	170	290	335	BLACK	10MIL	24	24	19	21	29	23.40
347	33421	170	290	335	GOLD	7MIL	19	18	26	21	16	20.00

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
348	33422	170	290	335	GOLD	1OMIL	19	28	24	23	18	22.40
349	33431	170	290	335	GREEN	7MIL	24	18	21	19	21	20.60
350	33432	170	290	335	GREEN	1OMIL	28	24	24	26	26	25.60
351	33441	170	290	335	RED	7MIL	21	23	16	18	21	19.80
352	33442	170	290	335	RED	10MIL	24	24	28	18	19	22.60
353	34111	170	300	320	BLACK	7MIL	14	23	13	11	21	16.40
354	34112	170	300	320	BLACK	IOMIL	18	24	19	23	19	20.60
355	34121	170	300	320	GOLD	7MIL	18	14	18	18	19	17.40
356	34122	170	300	320	GOLD	1OMIL	21	24	19	24	26	22.80
357	34131	170	300	320	GREEN	7MIL	18	13	16	16	26	17.80
358	34132	170	300	320	GREEN	1OMIL	19	16	21	24	31	22.20
359	34141	170	300	320	RED	7MIL	16	8	13	13	16	13.20
360	34142	170	300	320	RED	1OMIL	24	26	24	19	19	22.40
361	34211	170	300	325	BLACK	7MIL	14	16	11	18	24	16.60
362	34212	170	300	325	BLACK	1OMIL	16	23	16	24	24	20.60
363	34221	170	300	325	GOLD	7MIL	21	19	21	23	19	20.60
364	34222	170	300	325	GOLD	1OMIL	19	23	18	19	16	19.00
365	34231	170	300	325	GREEN	7MIL	18	16	18	33	14	19.80
366	34232	170	300	325	GREEN	1OMIL	28	24	26	24	23	25.00
367	34241	170	300	325	RED	7MIL	23	11	18	16	18	17.20
368	34242	170	300	325	RED	1OMIL	26	24	28	23	16	23.40
369	34311	170	300	330	BLACK	7MIL	19	16	19	16	18	17.60
370	34312	170	300	330	BLACK	1OMIL	21	23	23	19	26	22.40
371	34321	170	300	330	GOLD	7MIL	11	24	21	16	21	18.60
372	34322	170	300	330	GOLD	1OMIL	18	24	19	26	23	22.00
373	34331	170	300	330	GREEN	7MIL	11	14	14	16	14	13.80
374	34332	170	300	330	GREEN	1OMIL	16	23	21	24	18	20.40
375	34341	170	300	330	RED	7MIL	23	28	19	19	16	21.00
376	34342	170	300	330	RED	IOMIL	23	18	26	23	18	21.60
377	34411	170	300	335	BLACK	7MIL	11	18	16	13	14	14.40
378	34412	170	300	335	BLACK	1OMIL	19	24	26	21	19	21.80
379	34421	170	300	335	GOLD	7MIL	24	19	18	19	13	18.60
380	34422	170	300	335	GOLD	1OMIL	23	26	21	23	19	22.40
381	34431	170	300	335	GREEN	7MIL	21	13	13	21	23	18.20
382	34432	170	300	335	GREEN	IOMIL	19	18	23	14	23	19.40
383	34441	170	300	335	RED	7MIL	21	23	23	21	24	22.40
384	34442	170	300	335	RED	IOMIL	14	14	21	18	24	18.20
385	41111	180	270	320	BLACK	7MIL	18	11	13	16	19	15.40
386	41112	180	270	320	BLACK	1OMIL	20	22	19	19	21	20.20
387	41121	180	270	320	GOLD	7MIL	15	12	14	13	23	15.40
388	41122	180	270	320	GOLD	IOMIL	14	18	21	18	23	18.80
389	41131	180	270	320	GREEN	7MIL	11	18	26	24	16	19.00
390	41132	180	270	320	GREEN	10MIL	19	19	19	23	24	20.80
391	41141	180	270	320	RED	7MIL	10	21	18	17	16	16.40

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
392	41142	180	270	320	RED	iomIL	20	23	23	11	26	20.60
393	41211	180	270	325	BLACK	7MIL	14	16	18	14	13	15.00
394	41212	180	270	325	BLACK	10MIL	22	24	24	23	24	23.40
395	41221	180	270	325	GOLD	7MIL	19	11	18	19	14	16.20
396	41222	180	270	325	GOLD	1 oMIL	21	16	19	22	23	20.20
397	41231	180	270	325	GREEN	7MIL	18	21	28	24	33	24.80
398	41232	180	270	325	GREEN	IOMIL	19	23	19	19	21	20.20
399	41241	180	270	325	RED	7MIL	22	13	18	19	13	17.00
400	41242	180	270	325	RED	10MIL	26	26	28	23	23	25.20
401	41311	180	270	330	BLACK	7MIL	14	15	18	16	19	16.40
402	41312	180	270	330	BLACK	10MIL	24	26	19	23	18	22.00
403	41321	180	270	330	GOLD	7MIL	19	18	18	23	16	18.80
404	41322	180	270	330	GOLD	1 omiL	24	24	23	26	16	22.60
405	41331	180	270	330	GREEN	7MIL	23	24	23	24	21	23.00
406	41332	180	270	330	GREEN	1OMIL	18	21	28	21	14	20.40
407	41341	180	270	330	RED	7MIL	20	19	21	18	14	18.40
408	41342	180	270	330	RED	1 omiL	27	24	26	18	23	23.60
409	41411	180	270	335	BLACK	7MIL	14	16	18	15	13	15.20
410	41412	180	270	335	BLACK	1 omiL	16	24	24	26	24	22.80
411	41421	180	270	335	GOLD	7MIL	11	14	16	23	16	16.00
412	41422	180	270	335	GOLD	10MIL	20	24	19	23	23	21.80
413	41431	180	270	335	GREEN	7MIL	19	21	26	26	23	23.00
414	41432	180	270	335	GREEN	1OMIL	23	21	17	20	23	20.80
415	41441	180	270	335	RED	7MIL	19	13	14	14	16	15.20
416	41442	180	270	335	RED	1 omiL	20	23	21	23	26	22.60
417	42111	180	280	320	BLACK	7MIL	19	14	16	14	11	14.80
418	42112	180	280	320	BLACK	10MIL	22	23	25	19	24	22.60
419	42121	180	280	320	GOLD	7MIL	11	11	11	12	13	11.60
420	42122	180	280	320	GOLD	1 omiL	20	21	23	19	19	20.40
421	42131	180	280	320	GREEN	7MIL	19	19	21	23	23	21.00
422	42132	180	280	320	GREEN	10MIL	22	21	26	28	18	23.00
423	42141	180	280	320	RED	7MIL	18	13	13	11	21	15.20
424	42142	180	280	320	RED	1 omiL	22	21	21	18	21	20.60
425	42211	180	280	325	BLACK	7MIL	13	19	13	11	12	13.60
426	42212	180	280	325	BLACK	i omiL	23	24	23	23	24	23.40
427	42221	180	280	325	GOLD	7MIL	14	16	21	19	11	16.20
428	42222	180	280	325	GOLD	iomiL	19	23	21	23	22	21.60
429	42231	180	280	325	GREEN	7MIL	19	15	13	18	21	17.20
430	42232	180	280	325	GREEN	iomiL	29	27	25	27	28	27.20
431	42241	180	280	325	RED	7MIL	11	19	16	11	13	14.00
432	42242	180	280	325	RED	10MIL	22	23	21	18	23	21.40
433	42311	180	280	330	BLACK	7MIL	18	14	16	14	16	15.60
434	42312	180	280	330	BLACK	1 omiL	19	24	24	24	21	22.40
435	42321	180	280	330	GOLD	7MIL	14	18	21	16	13	16.40

Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
436	42322	180	280	330	GOLD	1OMIL	19	22	24	21	23	21.80
437	42331	180	280	330	GREEN	7MIL	19	21	14	13	14	16.20
438	42332	180	280	330	GREEN	IOMIL	18	18	21	21	24	20.40
439	42341	180	280	330	RED	7MIL	13	14	11	18	13	13.80
440	42342	180	280	330	RED	MIL	24	23	25	18	23	22.60
441	42411	180	280	335	BLACK	7MIL	12	14	11	16	11	12.80
442	42412	180	280	335	BLACK	1OMIL	20	23	14	26	18	20.20
443	42421	180	280	335	GOLD	7MIL	16	16	13	18	14	15.40
444	42422	180	280	335	GOLD	1OMIL	22	23	16	19	24	20.80
445	42431	180	280	335	GREEN	7MIL	19	21	18	18	14	18.00
446	42432	180	280	335	GREEN	MIL	20	23	26	21	24	22.80
447	42441	180	280	335	RED	7MIL	13	14	13	16	18	14.80
448	42442	180	280	335	RED	IOMIL	25	13	19	19	28	20.80
449	43111	180	290	320	BLACK	7MIL	10	11	14	14	29	15.60
450	43112	180	290	320	BLACK	1OMIL	17	23	28	23	19	22.00
451	43121	180	290	320	GOLD	7MIL	19	18	16	21	14	17.60
452	43122	180	290	320	GOLD	1OMIL	21	19	26	26	21	22.60
453	43131	180	290	320	GREEN	7MIL	21	16	18	16	23	18.80
454	43132	180	290	320	GREEN	1OMIL	25	16	19	23	21	20.80
455	43141	180	290	320	RED	7MIL	17	15	17	16	21	17.20
456	43142	180	290	320	RED	1OMIL	22	19	23	24	21	21.80
457	43211	180	290	325	BLACK	7MIL	13	9	13	14	21	14.00
458	43212	180	290	325	BLACK	MIL	15	14	13	21	21	16.80
459	43221	180	290	325	GOLD	7MIL	18	19	19	21	19	19.20
460	43222	180	290	325	GOLD	10MIL	27	24	24	28	19	24.40
461	43231	180	290	325	GREEN	7MIL	19	21	16	19	11	17.20
462	43232	180	290	325	GREEN	1OMIL	21	22	18	18	16	19.00
463	43241	180	290	325	RED	7MIL	21	14	18	11	16	16.00
464	43242	180	290	325	RED	10MIL	22	19	21	19	21	20.40
465	43311	180	290	330	BLACK	7MIL	10	13	21	10	11	13.00
466	43312	180	290	330	BLACK	1OMIL	23	24	16	16	24	20.60
467	43321	180	290	330	GOLD	7MIL	21	19	19	23	14	19.20
468	43322	180	290	330	GOLD	IOMIL	24	23	21	18	23	21.80
469	43331	180	290	330	GREEN	7MIL	18	26	23	11	13	18.20
470	43332	180	290	330	GREEN	MIL	21	24	24	19	23	22.20
471	43341	180	290	330	RED	7MIL	14	21	13	8	9	13.00
472	43342	180	290	330	RED	MIL	14	16	16	18	18	16.40
473	43411	180	290	335	BLACK	7MIL	14	11	10	13	16	12.80
474	43412	180	290	335	BLACK	1OMIL	20	16	11	24	19	18.00
475	43421	180	290	335	GOLD	7MIL	11	16	13	11	14	13.00
476	43422	180	290	335	GOLD	MIL	26	28	26	28	26	26.80
477	43431	180	290	335	GREEN	7MIL	11	14	13	11	11	12.00
478	43432	180	290	335	GREEN	MIL	17	18	24	19	18	19.20
479	43441	180	290	335	RED	7MIL	18	16	24	14	9	16.20

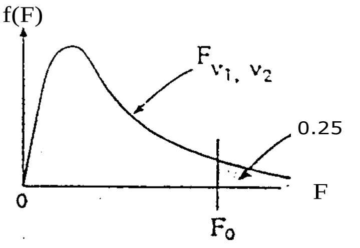
Table A.1. The Experiment Results. (Continued)

No	Pattern	Force	Power	Timer	Wire Color	Tip	P1	P2	P3	P4	P5	Avg.
480	43442	180	290	335	RED	10MIL	24	25	27	19	23	23.60
481	44111	180	300	320	BLACK	7MIL	11	9	8	13	14	11.00
482	44112	180	300	320	BLACK	10MIL	21	21	19	19	23	20.60
483	44121	180	300	320	GOLD	7MIL	19	10	16	21	18	16.80
484	44122	180	300	320	GOLD	10MIL	25	26	24	19	13	21.40
485	44131	180	300	320	GREEN	7MIL	21	11	18	19	14	16.60
486	44132	180	300	320	GREEN	10MIL	18	19	21	21	23	20.40
487	44141	180	300	320	RED	7MIL	18	19	16	11	19	16.60
488	44142	180	300	320	RED	10MIL	23	24	19	21	24	22.20
489	44211	180	300	325	BLACK	7MIL	11	12	10	9	12	10.80
490	44212	180	300	325	BLACK	1OMIL	22	21	18	24	21	21.20
491	44221	180	300	325	GOLD	7MIL	19	20	14	11	13	15.40
492	44222	180	300	325	GOLD	10MIL	21	19	23	16	21	20.00
493	44231	180	300	325	GREEN	7MIL	19	18	18	21	25	20.20
494	44232	180	300	325	GREEN	10MIL	20	23	19	21	21	20.80
495	44241	180	300	325	RED	7MIL	14	15	14	19	11	14.60
496	44242	180	300	325	RED	10MIL	22	21	24	24	21	22.40
497	44311	180	300	330	BLACK	7MIL	12	14	18	18	16	15.60
498	44312	180	300	330	BLACK	1 omIL	22	23	21	24	18	21.60
499	44321	180	300	330	GOLD	7MIL	14	14	13	19	13	14.60
500	44322	180	300	330	GOLD	1 omIL	24	24	23	24	19	22.80
501	44331	180	300	330	GREEN	7MIL	15	12	15	14	14	14.00
502	44332	180	300	330	GREEN	1OMIL	19	23	19	24	18	20.60
503	44341	180	300	330	RED	7MIL	14	18	16	19	19	17.20
504	44342	180	300	330	RED	1 omIL	24	26	23	23	23	23.80
505	44411	180	300	335	BLACK	7MIL	11	11	14	10	10	11.20
506	44412	180	300	335	BLACK	10MIL	18	23	19	19	28	21.40
507	44421	180	300	335	GOLD	7MIL	19	18	21	11	19	17.60
508	44422	180	300	335	GOLD	10MIL	24	23	24	27	24	24.40
509	44431	180	300	335	GREEN	7MIL	11	14	24	23	21	18.60
510	44432	180	300	335	GREEN	10MIL	22	21	16	23	23	21.00
511	44441	180	300	335	RED	7MIL	15	19	16	19	18	17.40
512	44442	180	300	335	RED	10MIL	18	24	18	23	26	21.80

APPENDIX B

F- TABLES

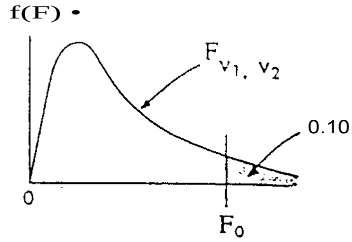
Table B.1. F-Table Probability 0.25, 87.5% Confidence.



v	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	bc.
1	5.83	7.50	8.20	8.58	8.82	8.98	9.10	9.19	9.26	9.32	9.41	9.49	9.58	9.61	9.67	9.71	9.76	9.80	9.85
2	2.57	3.00	3.15	3.23	3.28	3.31	3.34	3.35	3.37	3.38	3.39	3.41	3.43	3.43	3.41	3.45	3.16	3.47	3.43
3	2.02	2.28	2.36	2.39	2.41	2.42	2.43	2.14	2.44	2.44	2.45	2.46	2.46	2.46	2.47	2.47	2.47	2.47	2.47
4	1.81	2.00	2.05	2.06	2.07	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08
5	1.69	1.85	1.88	1.89	1.89	1.89	1.89	1.89	1.89	. 1.89	1.89	1.89	1.88	1.88	1.88	1.88	1.87	1.87	1.87
6	1.62	1.76	1.78	1.79	1.79	1.78	1.78	1.78	1.77	1.77	1.77	1.76	1.76	1.75	1.75	1.75	1.74	1.74	1.74
7	1.57	1.70	1.72	1.72	1.71	1.71	1.70	1.70	1.70	1.69	1.68	1.68	1.67	1.67	1.66	1.66	1.65	1.65	1.65
8	1.54	1.66	1.67	1.66	1.66	1.65	1.6/	1.64	1.63	1.63	1.62	1.62	1.61	1.60	1.60	1.59	1.59	1.58	1.58
9	1.51	1.62	1.63	1.63	1.62	1.61	1.60	1.60	1.59	1.59	1.58	1.57	1,56	1.56	1.55	1.54	1.54	1.53	1.53
10	1.49	1.60	1.60	1.59	1.59	1.58	1.57	1.56	1.56	1.55	1.54	1.53	1.52	1.52	1.51	1.51	1.50	1.49	1.48
11	1.47	1.58	1.58	1.57	1.56	1.55	1.54	1.53	1.53	1.52	1.51	1.50	1.49	1.49	1.18	1.47	1.47	1.46	1.45
12	1.46	1.56	1.56	1.55	1.54	1.53	1.52	1.51	1.51	1.50	1.49	1.48	1.17	146	1.45	1.15	141	1.43	1.42
13	1.45	1.55	1.55	1.53	1.52	1.51	1.50	1.49	1.49	1.48	1.47	1.46	1.45	1.44	1.43	1.42	1.42	1.41	1.40
14	1.44	1.53	1.53	1.52	1.51	1.50	1.49	1.48	1.47	1.46	1.45	1.44	1.13	1.42	1.41	1.41	1.40	1.39	1.38
15	1.43	1.52	1.52	1.51	1.49	7.48	1.47	1.46	1.46	1.45	*1.44*	1.43	1.41	1.41	1.40	1.39	1.38	1.37	1.36
16	1.42	1.51	1.51	1.50	1.48	1.47	1.16	1.45	1.44	1.44	1.43	1.41	1.40	1.39	1.38	1.37	1.36	1.35	1.31
17	1.42	1.51	1.50	1.19	1.47	1.46	1.45	1.44	1.43	1.43	1.41	1.40	1.39	1.38	1.37	1.36	1.35	1.34	1.33
18	1.11	1.50	1.49	1.48	1.46	1.45	1.44	1.43	1.42	1.42	1.40	1.39	1.38	1.37	1.36	1.35	1.34	1.33	1.32
19	1.41	1.49	1.49	1.47	1.46	*1.44*	1.43	1.12	1.41	1.41	*1.40*	T.38	1.37	1.36	1.35	1.34	1.33	1.32	1.30
20	1.40	1.49	1.48	1.47	145	1.44	1.43	1.42	1.41	1.40	1.39	1.37	1.36	1.35	1.34	1.33	1.32	1.31	1.29
21	1.40	1.48	1.48	1.46	1.44	1.43	1.42	1.41	1.40	1.39	1.38	1.37	1.35	1.34	1.33	1.32	1.31	1.30	1.28
22	1.40	1.48	1.47	1.45	*1.44*	1.42	1.41	1.40	1.39	1.39	1.37	1.36	1.34	1.33	1.32	1.31	1.30	1.29	1.28
23	1.39	1.47	1.47	1.45	1.13	1.42	1.41	1.10	1.39	1.38	1.37	1.35	1.31	1.33	1.32	1.31	1.30	1.28	1.27
24	1.39	1.17	1.46	1.14	1.43	1.41	1.40	1.39	1.38	7.38	1.36	1.35	1.33	1.32	1.31	1.30	1.29	1.28	1.26
25	1.39	1.47	1.46	1.44	1.42	1.41	1.40	1.39	1.38	1.37	1.36	1.34	1.33	1.32	1.31	1.29	1.28	1.27	1.25
26	1.38	1.46	1.45	*1.44*	1.42	1.41	1.39	1.38	1.37	1.37	1.35	1.34	1.32	1.31	1.30	1.29	1.28	1.26	1.25
27	1.38	1.46	1.45	1.43	1.42	1.40	1.39	1.38	1.37	1.3o	1.35	1.33	1.32	1.31	1.30	1.28	1.27	1.26	1.24
28	1.38	1.46	1.45	1.43	1.41	1.40	1.39	1.38	1.37	1.36	1.34	1.33	1.31	1.30	1.29	1.28	1.27	1.25	1.24
29	1.38	1.45	1.45	1.43	1.41	1.40	1.38	1.37	1.36	1.35	1.34	1.32	1.31	1.30	1.29	1.27	1.26	1.25	1.23
30	1.38	1.45	1.44	1.42	1.41	1.39	1.38	1.37	1.36	1.35	1.34	1.32	1.30	1.29	1.28	1.27	1.26	1.24	1.23
40	1.36	1.44	1.42	1.40	1.39	1.37	1.36	1.35	1.34	1.33	1.31	1.30	1.28	1.26	1.25	1.24	1.22	1.21	1.19
60	1.35	1.42	1.41	1.38	1.37	1.35	1.33	1.32	1.31	1.30	1.29	1.27	1.25	1.24	1.22	1.21	1.19	1.17	1.15
120	1.34	1.10	1.39	1.37	1.35	1.33	1.31	1.30	1.29	1.28	1.26	1.24	1.22	1.21	1.19	1.18	1.16	1.13	1.10
0.	1.32	1.39	1.37	1.35	1.33	1.31	1.29	1.28	1.27	1.25	1.24	1.22	1.19	1.18	1.16	1.14	1.12	1.08	1.00

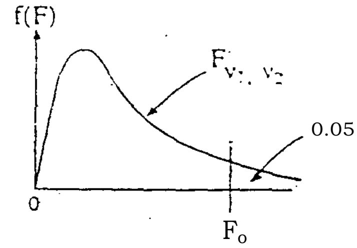
St. Gabriel's Library

Table B.2. F-Table Probability 0.10, 90% Confidence.



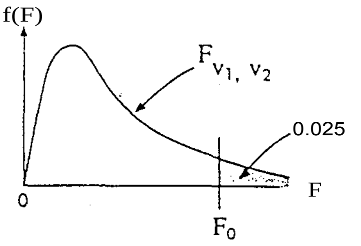
V_2	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	c...
1	39.86	49.50	53.59	55.83	57.2d	58.20	58.91	59.dd	59.86	60.19	60.71	61.22	61.7d	62.00.	62.26	62.53	62.79	63.06	63.33
2	8.53	9.00	9.16	9.24	9.29	9.33	9.35	9.37	9.38	9.39	9.41	9.42	9.dd	9.45	9.46	9.47	9.47	9.48	9.49
3	5.54	5.16	5.39	5.34	.5.31	5.28	5.27	5.25	5.24	5.23	5.22	5.20	5.18	5.18	5.17	5.16	5.15	5.14	5.13
el	4.54	4.32	4.19	4.11	4.05	4.01	3.98	3.95	3.94	3.92	3.90	3.87	3.84	3.83	3.82	3.80	3.79	3.78	3.76
5	4.06	3.78	3.62	3.52	3.45	3.40	3.37	3.31	3.32	3.30	3.27	3.2d	3.21	3.19	3.17	3.16	3.14	3.12	3.10
6	3.78	3.16	3.29	3.18	3.11	3.05	3.01	2.98	2.96	2.94	2.90	2.87	2.84	2.82	2.80	2.78	2.76	2.74	2.72
7	3.59	3.26	3.07	2.96	2.88	2.83	2.78	2.75	2.72	2.70	2.67	2.63	2.59	2.58	2.56	2.54	2.51	2.49	2.17
8	3.46	3.11	2.92	2.81	2.73	2.67	2.62	2.59	2.56	2.54	2.50	2.16	2.42	2.40	2.38	2.36	2.34	2.32	2.29
9	3.36	3.01	2.81	2.69	2.61	2.55	2.51	2.47	2.41	2.42	2.38	2.34	2.30	2.28	2.25	2.23	2.21	2.18	2.16
10	3.29	2.92	2.71	2.61	2.52	2.46	2,11	2.38	2.35	2.32	2.28	2.24	2.20	2.18	2.16	2.13	2.11	2.08	2.06
11	3.23	2.86	2.66	2.54	2.45	2.39	2.3d	2.30	2.27	2.25	2.21	2.17	2.12	2.10	2.08	2.05	2.03	2.00	1.97
12	3.18	2.81	2.61	2.48	2.39	2.33	2.28	2.24	2.21	2.19	2.15	2.10	2.06	2.01	2.01	1.99	1.96	1.93	1.90
13	3.14	2.76	2.56	2.43	2.35	2.28	2.23	2.20	2.16	2.14	2.10	2.05	2.01	1.98	1.96	1.93	1.90	1.88	1.85
14	3.10	2.73	2.52	2.19	2.31	2.24	2.19	2.15	2.12	2.10	2.05	2.01	1.96	1.94	1.91	1.89	1.86	1.83	1.80
15	3.07	2.70	2.49	2.36	2.27	2.21	2.16	2.12	2.09	2.06	2.02	1.97	1.92	1.90	1.87	1.85	1.82	1.79	1.76
16	3.05	2.67	2.46	2.33	2.24	2.18	2.13	2.09	2.06	2.03	1.99	1.94	1.89	1.87	1.84	1.81	1.78	1.75	1.72'
17	3.03	2.64	2.44	2.31	2.22	2.15	2.10	2.06	2.03	2.00	1.96	1.91	1.86	1.84	1.81	1.78	1.75	1.72	1.69
18	3.01	2.62	2.42	2.29	2.20	2.13	2.08	2.04	2.00	1.98	1.93	1.89	1.84	1.81	1.78	1.75	1.72	1.69	1.66
19	2.99	2.61	2.40	2.27	2.18	2.11	2.06	2.02	1.98	1.96	1.91	1.86	1.81	1.79	1.76	1.73	1.70	1.67	1.63
20	2.97	2.59	2.38	2.25	2.16	2.09	2.0d	2.00	1.96	1.94	1.89	1.84	1.79	1.77	1.74	1.71	1.68	1.64	1.61
21	2.96	2.57	2.36	2.23	2.1d	2.08	2.02	1.98	1.95	1.92	1.87	1.83	1.78	1.75	1.72	1.69	1.66	1.62	1.59
22	2.95	2.56	2.35	2.22	2.13	2.06	2.01	1.97	1.93	1.90	1.86	1.81	1.76	1.73	1.70	1.67	1.6d	1.60	0.57
23	2.94	2.55	2.34	2.21	2.11	2.05	1.99	1.95	1.92	1.89	1.84	1.80	1.74	1.72	1.69	1.66	1.62	1.59	1.55
24	2.93	2.54	2.33	2.19	2.10	2.04	1.98	1.94	1.91	1.88	1.83	1.78	1.73	1.70	1.67	1.64	1.61	1.57	1.53
25	2.92	2.53	2.32	2.18	2.09	2.02	1.97	1.93	1.89	1.87	1.82	1.77	1.72	1.69	1.66	1.63	1.59	1.56	1.52
26	2.91	2.52	2.31	2.17	2.08	2.01	1.96	1.92	1.88	1.86.	1.81	1.76	1.71	1.68	1.65	1.61	1.58	1.54	1.50
27	2.90	2.51	2.30	2.17	2.07	2.00	1.95	1.91	1.87	1.85	1.80	1.75	1.70	1.67	1.64	1.60	1.57	1.53	1.49
28	2.89	2.50	2.29	2.16	2.06	2.00	1.94	1.90	1.87	1.81	1.79	1.74	1.69	1.66	1.63	1.59	1.56	1.52	1.48
29	2.89	2.50	2.28	2.15	2.06	1.99	1.93	1.89	1.86	1.83	1.78	1.73	1.68	1.65	1.62	1.58	1.55	1.51	1.47
30	2.88	2.49	2.28	2.14	2.03	1.98	1.93	1.88	1.85	1.82	1.77	1.72	1.67	1.64	1.61	1.57	1.54	1.50	1.46
AO	2.84	2.44	2.23	2.09	2.00	1.93	1.87	1.83	1.79	1.76	1.71	1.66	1.61	1.57	1.54	1.51	1.47	1.42	1.38
60	2.79	2.39	2.18	2.04	1.95	1.87	1.82	1.77	1.74	1.71	1.66	1.60	1.54	1.51	1.18	1.44	1.40	1.35	1.29
120	2.75	2.35	2.13	1.99	1.90	1.82	1.77	1.72	1.68	1.65	1.60	1.55	1.48	1.45	1.41	1.37	1.32	1.26	1.19
«	2.71	2.30	2.08	1.94	1.85	1.77	1.72	1.67	1.63	1.60	1.55	1.49	1.42	1.38	1.34	1.30	1.24	1.17	1.00

Table B.3. F-Table Probability 0.05, 95% Confidence.



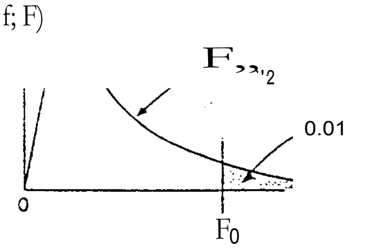
). ; \	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	cx*
1	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5	241.9	243.9	245.9	248.0	249.1	250.1	251.1	252.2	253.3	254.3
2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.41	19.43	19.45	19.45	19.46	19.47	19.48	19.49	19.50
3	10.13	9.55	9.28	9.12	9.01	8.94	8.69	8.85	8.81	8.79	8.74	8.70	8.66	8.64	8.62	8.59	8.57	8.55	8.53
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.91	5.86	5.80	5.77	5.75	5.72	5.69	5.66	5.63
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4.68	4.62	4.56	4.53	4.50	4.46	4.13	4.40	1.16
6	- 5:99	5.14	4_76	4.51	4.39	4.28	4.21	4.15	4.10	4.06	4.00	3.94	3.87	3.84	3.81	3.77	3.74	3.70	3.67
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64	3.57	3.51	3.44	3.41	3.38	3.34	3.30	3.27	3.23
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.14	3.39	3.35	3.28	3.22	3.15	3.12	3.08	3.04	3.01	2.97	2.93
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.07	3.01	2.94	2.90	2.86	2.83	2.79	2.75	2.71
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98	2.91	2.85	2.77	2.74	2.70	2.66	2.62	2.58	2.54
11	4.84	3.96	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.85	2.79	2.72	2.65	2.61	2.57	2.53	2.49	2.45	2.40
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75	2.69	2.62	2.54	2.51	2.47	2.43	2.38	2.34	2.30
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71	2.67	2.60	2.53	2.46	2.42	2.38	2.34	2.30	2.25	2.21
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65	2.60	2.53	2.46	2.39	2.35	2.31	2.27	2.22	2.18	2.13
15	4.54	3.68	3.29	3.06	2.90	2-79	2.71	2.64	2.59	2.54	2.48	2.40	2.33	2.29	2.25	2.20	2.16	2.11	2.07
16	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54	2.49	2.42	2.35	2.28	2.24	2.19	2.15	2.11	2.06	2.01
17	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49	2.45	2.38	2.31	2.23	2.19	2.15	2.10	2.06	2.01	1.96
18	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46	2.41	2.34	2.27	2.19	2.15	2.11	2.06	2.0'2	1.97	1.92
19	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42	2.38	2.31	2.23	2.16	2.11	2.07	2.03	1.98	1.93	1.88
20	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39	2.35	2.28	2.20	2.12	2.08	2.04	1.99	1.95	1.90	1.84
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37	2.32	2.25	2.18	2.10	2.05	2.01	1.96	1.92	1.87	1.81
22	4.30	3.44	3.05	2.82	2.66	2.55	246	2.40	2.34	2.30	2.23	2.15	2.07	2.03	1.98	1.94	1.89	1.84	1.78
23	4.28	3.42	3.03	2.80	2.64	2.53	2.44	2.37	2.32	2.27	2.20	2.13	2.05	2.01	1.96	1.91	1.86	1.81	1.76
24	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30	2.25	2.18	2.11	2.03	1.98	1.94	1.89	1.8d	1.79	1.73
25	4.28	1.39	2.99	2.76	2.60	2.49	2.40	2.34	2.28	2.24	2.16	2.09	2.01	1.96	1.92	1.87	1.82	1.77	1.71
26	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27	2.22	2.15	2.07	1.99	1.95	1.90	1.85	1.80	1.75	1.69
27	4.21	3.35	2.96	2.73	2.57	2.86	2.37	2.31	2.25	2.20	2.13	2.06	1.97	1.93	1.88	1.84	1.79	1.73	1.67
28	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24	2.19	2.12	2.04	1.96	1.91	1.87	1.82	1.77	1.71	1.65
29	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22	2.18	2.10	2.03	1.94	1.90	1.85	1.81	1.75	1.70	1.64
30	4.17	3.12	2.92	2.69	2.53	2.42	2.33	2.27	2.21	2.16	2.09	2.01	1.93	1.89	1.84	1.79	1.74	1.68	1.62
40	4.06	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12	2.08	2.00	1.92	1.84	1.79	1.74	1.69	1.64	1.58	1.51
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04	1.99	1.92	1.84	1.75	1.70	1.65	1.59	1.53	1.47	1.39
120	3.92	3.07	2.68	2.45	2.29	2.17	2.09	2.02	1.96	1.91	1.83	1.75	1.66	1.61	1.55	1.55	1.43	1.35	1.25
..,	3.84	3.00	2.60	2.37	2.21	2.10	2.01	1.94	1.88	1.83	1.75	1.67	1.57	1.52	1.46	1.39	1.32	1.22	1.00

Table B.4. F-Table Probability 0.025, 97.5% Confidence.



V \ V1	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	c‹,
1	647.8	799.5	864.2	899.6	921.8	937.1	948.2	956.7	963.3	968.6	976.7	984.9	993.1	997.2	1001	1006	1010	1014	1018
2	38.51	39.00	39.17	39.25	39.30	39.33	39.36	39.37	39.39	39.40	39.41	39.43	39.45	39.46	39.46	39.47	39.48	39.49	39.50
3	17.44	16.04	15.44	15.10	14.88	14.73	14.62	14.54	14.47	14.42	14.34	14.25	14.17	14.12	14.08	14.0d	13.99	13.95	13.90
A	12.22	10.65	9.98	9.60	9.36	9.20	9.07	8.98	8.90	8.8d	8.75	8.66	8.56	8.51	8.46	8.41	8.36	8.31	8.26
5	10.01	8.43	7.76	7.39	7.15	6.98	6.85	6.76	6.68	6.62	6.52	6.43	6.33	6.28	6.23	6.18	6.12	6.07	6.02
6	8.81	7.26	6.60	6.23	5.99	5.82	5.70	5.60	5.52	5.46	5.37	5.27	5.17	5.12	5.07	5.01	4.96	4.90	4.85
7	8.07	6.54	5.89	5.52	5.29	5.12	4.99	4.90	4.82	4.76	4.67	4.57	4.47	4.42	4.36	4.31	4.25	4.20	4.14
8	7.57	6.06	5.42	5.05	4.82	4.65	4.53	4.43	4.36	4.30	4.20	4.10	4.00	3.95	3.89	3.84	3.78	3.73	3.67
9	7.21	5.71	5.08	4.72	4.48	4.32	4.20	4.10	4.03	3.96	3.87	3.77	3.67	3.61	3.56	3.51	3.45	3.39	3.33
10	6.94	5.46	4.83	4.47	4.24	4.07	3.95	3.85	3.78	3.72	3.62	3.52	3.42	3.37	3.31	3.26	3.20	3.14	3.08
11	6.72	5.26	4.63	4.28	4.04	3.88	3.76	3.66	3.59	3.53	3.43	3.33	3.23	3.17	3.12	3.06	3.00	2.9d	2.88
12	6.55	5.10	4.47	4.12	3.89	3.73	3.61	3.51	3.44	3.37	3.28	3.18	3.07	3.02	2.96	2.91	2.85	2.79	2.72
13	6.41	4.97	4.35	4.00	3.77	3.60	3.48	3.39	3.31	3.25	3.15	3.05	2.95	2.89	2.8d	2.78	2.72	2.66	2.60
14	6.30	4.86	4.24	3.89	3.66	3.50	3.38	3.29	3.21	3.15	3.05	2.95	2.84	2.79	2.73	2.67	2.61	2.55	2.49
15	6.20	4.77	4.15	3.80	3.58	3.41	3.29	3.20	3.12	3.06	2.96	2.86	2.76	2.70	2.64	2.59	2.52	2.46	2.40
16	6.12	4.69	4.08	3.73	3.50	3.3d	3.22	3.12	3.05	2.99	2.89	2.79	2.68	2.63	2.57	2.51	2.45	2.38	2.32
17	6.04	4.62	4.01	3.66	3.4d	3.28	3.16	3.06	2.98	2.92	2.82	2.72	2.62	2.56	2.50	2.44	2.38	2.32	2.25
18	5.98	4.56	3.95	3.61	3.38	3.22	3.10	3.01	2.93	2.87	2.77	2.67	2.56	2.50	2.44	2.38	2.32	2.26	2.19
19	5.92	4.51	3.90	3.56	3.33	3.17	3.05	2.96	2.88	2.82	2.72	2.62	2.51	2.45	2.39	2.33	2.27	2.20	2.13
20	5.87	4.46	3.86	3.51	3.29	3.13	3.01	2.91	2.84	2.77	2.68	2.57	2.46	2.41	2.35	2.29	2.22	2.16	2.09
21	5.83	4.42	3.82	3.48	3.25	3.09	2.97	2.87	2.80	2.73	2.64	2.53	2.42	2.37	2.31	2.25	2.18	2.11	2.0d
22	5.79	4.38	3.78	3.44	3.22	3.05	2.93	2.8d	2.76	2.70	2.60	2.50	2.39	2.33	2.27	2.21	2.1d	2.08	2.00
23	5.75	4.35	3.75	3.41	3.18	3.02	2.90	2.81	2.73	2.67	2.57	2.47	2.36	2.30	2.24	2.18	2.11	2.04	1.97
24	5.72	4.32	3.72	3.38	3.15	2.99	2.87	2.78	2.70	2.6d	2.5d	2.44	2.33	2.27	2.21	2.15	2.08	2.01	1.9d
25	5.69	4.29	3.69	3.35	3.13	2.97	2.85	2.75	2.68	2.61	2.51	2.41	2.30	2.2d	2.18	2.12	2.05	1.98	1.91
26	5.66	4.27	3.67	3.33	3.10	2.94	2.82	2.73	2.65	2.59	2.49	2.39	2.28	2.22	2.16	2.09	2.03	1.95	1.88
27	5.63	4.24	3.65	3.31	3.08	2.92	2.80	2.71	2.63	2.57	2.47	2.36	2.25	2.19	2.13	2.07	2.00	1.93	1.85
28	5.61	4.22	3.63	3.29	3.06	2.90	2.78	2.69	2.61	2.55	2.45	2.34	2.23	2.17	2.11	2.05	1.98	1.91	1.83
29	5.59	4.20	1.61	3.27	3.0d	2.88	2.76	2.67	2.59	2.53	2.43	2.32	2.21	2.15	2.09	2.03	1.96	1.89	1.81
30	5.57	4.18	3.59	3.25	3.03	2.87	2.75	2.65	2.57	2.51	2.41	2.31	2.20	2.14	2.07	2.01	1.94	1.87	1.79
AO	5.42	4.05	3.46	3.13	2.90	2.74	2.62	2.53	2.45	2.39	2.29	2.18	2.07	2.01	1.94	1.88	1.80	1.72	1.6d
60	5.29	3.93	3.34	3.01	2.79	2.63	2.51	2.41	2.33	2.27	2.17	2.06	1.94	1.88	1.82	1.7d	1.67	1.58	1.48
120	5.15	3.80	3.23	2.89	2.67	2.52	2.39	2.30	2.22	2.16	2.05	1.94	1.82	1.76	1.69	1.61	1.53	1.43	1.31
…	5.02	3.69	3.12	2.79	2.57	2.41	2.29	2.19	2.11	2.05	1.94	1.83	1.71	1.6d	1.57	1.48	1.39	1.27	1.00

Table B.5. F-Table Probability 0.01, 99% Confidence.



Vz	1	2	3	4	5	6	7	8	9	10	12	15	20	26	30	AO	60	120	00
1	4052	4999.5	5403	5625	5764	5859	5928	5982	6022	6056	6106	6157	6209	6235	6261	6287	6313	6339	6366
2	98.50	99.00	99.17	99.25	99.30	99.13	99.36	99.37	99.39	99.40	99.42	99.43	99.45	99.46	99.47	99.47	99.48	99.49	99.50
3	34.12	30.82	29.46	28.71	28.2d	27.91	27.67	27.49	27.35	27.23	27.05	26.87	26.69	26.00	26.50	26.41	26.32	26.22	26.13
4	21.20	18.00	16.69	15.98	15.52	15.21	14.98	14.80	14.66	14.55	14.37	14.20	14.02	13.93	13.84	13.75	13.65	13.56	13.46
5	16.26	13.27	12.06	11.39	10.97	10.67	10.46	10.29	10.16	10.05	9.89	9.72	9.55	9.47	9.38	9.29	9.20	9.11	9.02
6	13.75	10.92	9.78	9.15	8.75	8.47	8.26	8.10	7.98	7.87	7.72	7.56	7.40	7.31	7.23	7.14	7.06	6.97	6.88
7	12.25	9.55	8.45	7.85	7.46	7.19	6.99	6.84	6.72	6.62	6.47	6.31	6.16	6.07	5.99	5.91	5.82	5.74	5.65
8	11.26	8.65	7.59	7.01	6.63	6.37	6.18	6.03	5.91	5.81	5.67	5.52	5.36	5.28	5.20	5.12	5.03	L95	4.86
9	10.56	8.02	6.99	6.42-	6.06	5.80	5.61	5.47	5.35	5.26	5.11	4.96	4.81	4.73	4.65	4.57	4.48	4.40	4.31
10	10.04	7.56	6.55	5.99	5.64	5.39	5.20	5.06	4.9d	4.85	4.71	4.56	4.41	4.33	4.25	4.17	4.08	4.00	3.91
11	9.65	7.21	6.22	5.67	5.32	5.07	4.89	4.74	4.63	4.54	4.40	4.25	4.10	4.02	3.94	3.86	3.78	3.69	3.60
12	9.33	6.98	5.95	5.41	5.06	4.82	4.64	4.50	4.39	4.30	4.16	4.01	3.86	3.78	3.70	3.62	3.54	3.45	3.36
13	9.07	6.70	5.7d	5.21	4.86	4.62	4.44	4.30	4.19	4.10	1.96	3.82	3.66	3.59	3.51	3.43	3.34	3.25	3.17
14	8.86	6.51	5.56	5.04	4.69	4.46	4.25	4.14	4.03	3.94	3.80	3.66	3.51	3.43	3.35	3.27	3.18	3.09	3.00
15	8.68	6.36	5.42	4.89	4.36	4.32	4.14	4.00	3.89	3.80	3.67	3.52	3.37	3.29	3.21	3.13	3.05	2.96	2.87
16	8.53	6.23	5.29	4.77	4.44	4.20	4.03	3.89	3.78	3.69	3.55	3.41	.3.26	3.18	3.10	3.02	2.93	2.84	2.75
17	8.40	6.11	5.18	4.67	4.34	L10	3.93	3.79	3.68	3.59	3.46	3.31	3.16	3.08	3.00	2.92	2.83	2.75	2.65
18	8.29	6.01	5.09	4.58	4.25	4.01	3.84	3.71	3.60	3.51	3.37	3.23	3.08	3.00	2.92	2.84	2.75	2.66	2.57
19	8.18	5.93	5.01	4.50	4.17	3.9d	3.77	3.63	3.52	3.43	3.30	3.15	3.00	2.92	2.84	2.76	2.67	2.58	2.49
20	8.10	5.85	4.94	4.43	4.10	3.87	3.70	3.56	3.46	3.37	3.23	3.09	2.94	2.86	2.78	2.69	2.61	2.52	2.42
21	8.02	5.78	4.87	4.37	4.04	3.81	3.64	3.51	3.40	3.31	3.17	3.03	2.88	2.80	2.72	2.64	2.55	2.46	2.36
22	7.95	5.72	£82	4.31	3.99	3.76	3.59	3.45	3.35	3.26	3.12	2.98	2.83	2.75	2.67	2.58	2.50	2.40	2.31
21	7.88	5.66	4.76	4.26	3.94	3.71	3.54	3.41	3.30	3.21	3.07	2.93	2.78	2.70	2.62	2.54	2.45	2.35	2.26
24	7.82	5.61	4.72	4.22	3.90	3.67	3.50	3.36	3.26	3.17	1..03	2.89	2.74	2.66	2.58	2.49	2.40	2.31	2.21
25	7.77	5.57	4.68	4.18	3.85	3.63	3.46	3.32	3.22	3.13	2.99	2.85	2.70	2.62	2.54	2.45	2.36	2.27	2.17
26	7.72	5.53	4.64	4.14	3.82	3.59	3.42	3.29	3.18	3.09	2.96	2.81	2.66	2.58	2.50	2.42	2.33	2.23	2.13
27	7.68	5.49	4.60	4.11	3.78	3.56	3.39	3.26	3.15	3.06	2.93	2.78	2.63	2.55	2.47	2.38	2.29	2.20	2.10
28	7.6d	5.45	4.57	4.07	3.75	3.53	3.36	3.23	3.12	3.03	2.90	2.75	2.60	2.52	2.dd	2.35	2.26	2.17	2.06
29	7.60	5.42	4.54	4.04	3.73	3.50	3.31	3.20	3.09	3.00	2.87	2.73	2.57	2.49	2.41	2.33	2.23	2.14	2.03
30	7.56	5.39	4.51	4.02	3.70	3.47	3.10	3.17	3.07	2.96	2.84	2.70	2.55	2.47	2.39	2.30	2.21	2.11	2.01
AO	7.31	5.18	4.31	3.83	3.51	3.29	3.12	2.99	2.89	2.80	2.66	2_52	2.37	2.29	2.20	2.11	2.02	1.92	1.80
60	7.08	4.98	4.13	3.65	3.34	3.12	2.95	2.82	2.72	2.63	2.50	2.35	2.20	2.12	2.03	1.94	1.8d	1.73	1.60
120	6.85	4.79	3.95	3.48	3.17	2.96	2.79	2.66	2.56	2.47	2.34	2.19	2.03	1.95	1.86	1.76	1.66	1.53	1.38
.0	6.63	4.61	3.78	3.32	3.02	2.80	2.64	2.51	2.41	2.32	2.18	2.04	1.88	1.79	1.70	1.59	1.47	1.32	1.00

APPENDIX C

HSA MANUFACTURING ENVIRONMENT

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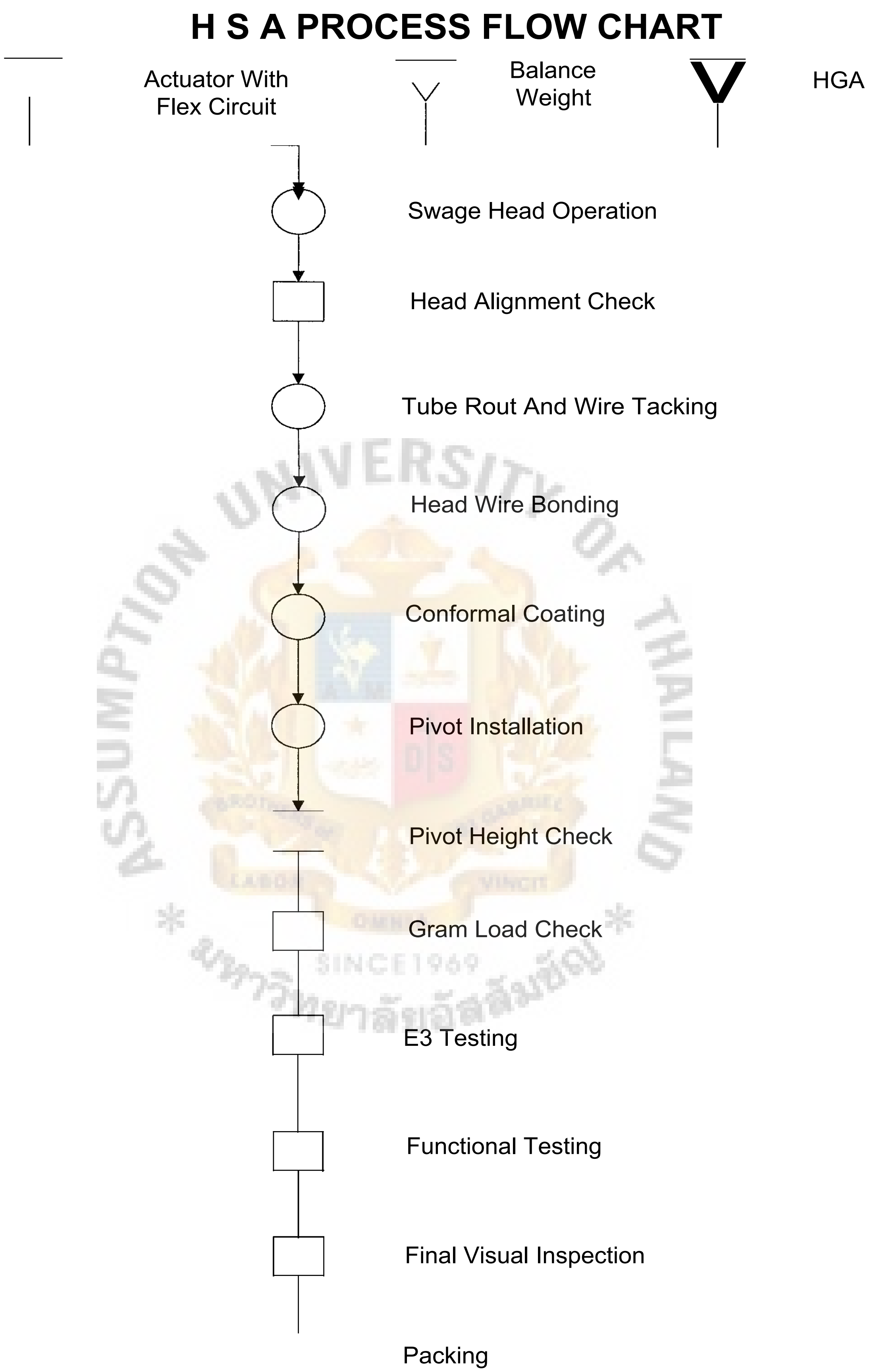

Figure C.1. HSA Process Flow Chart.

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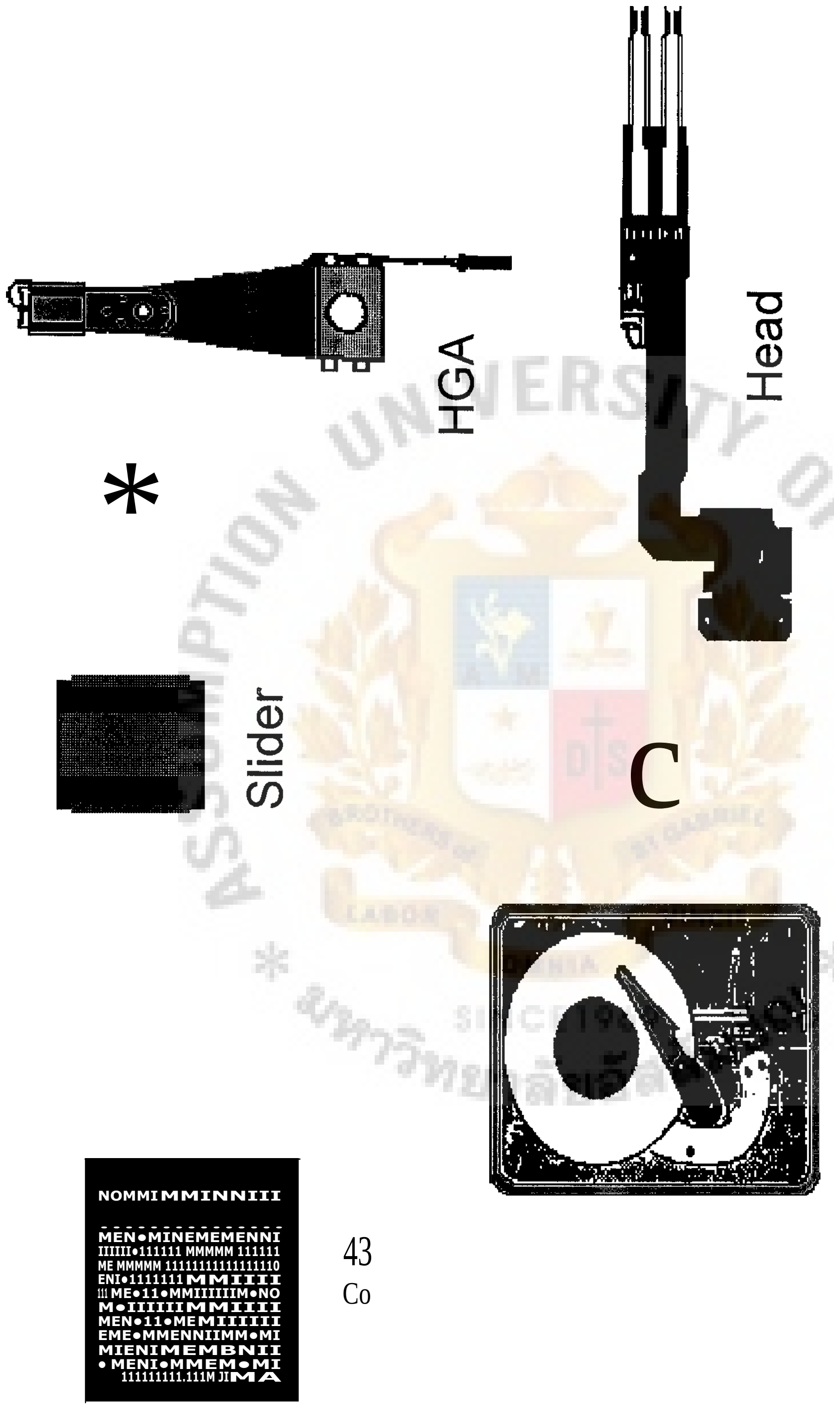


Process Assembly from Wafer Fabrication to Disk Drive.

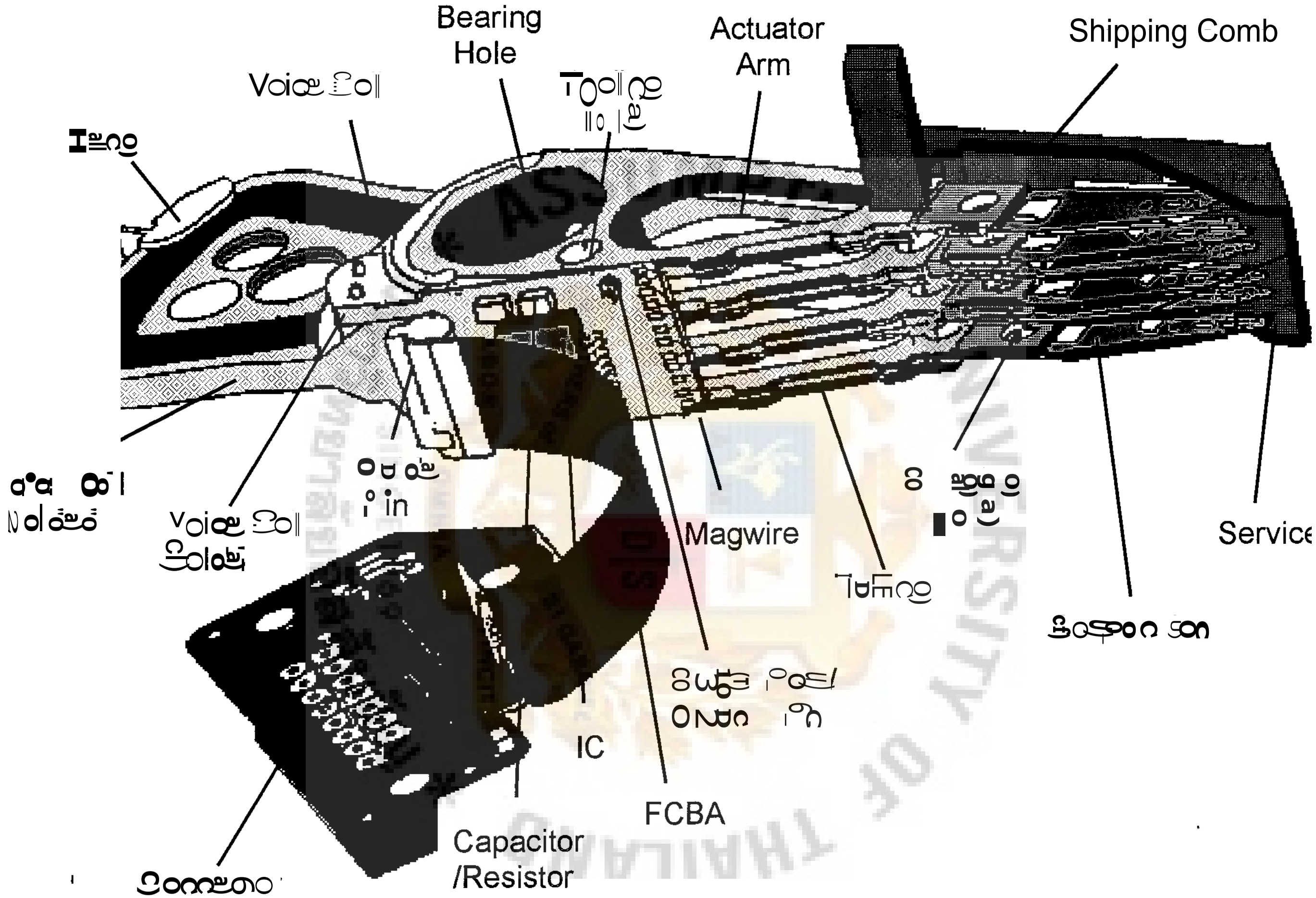
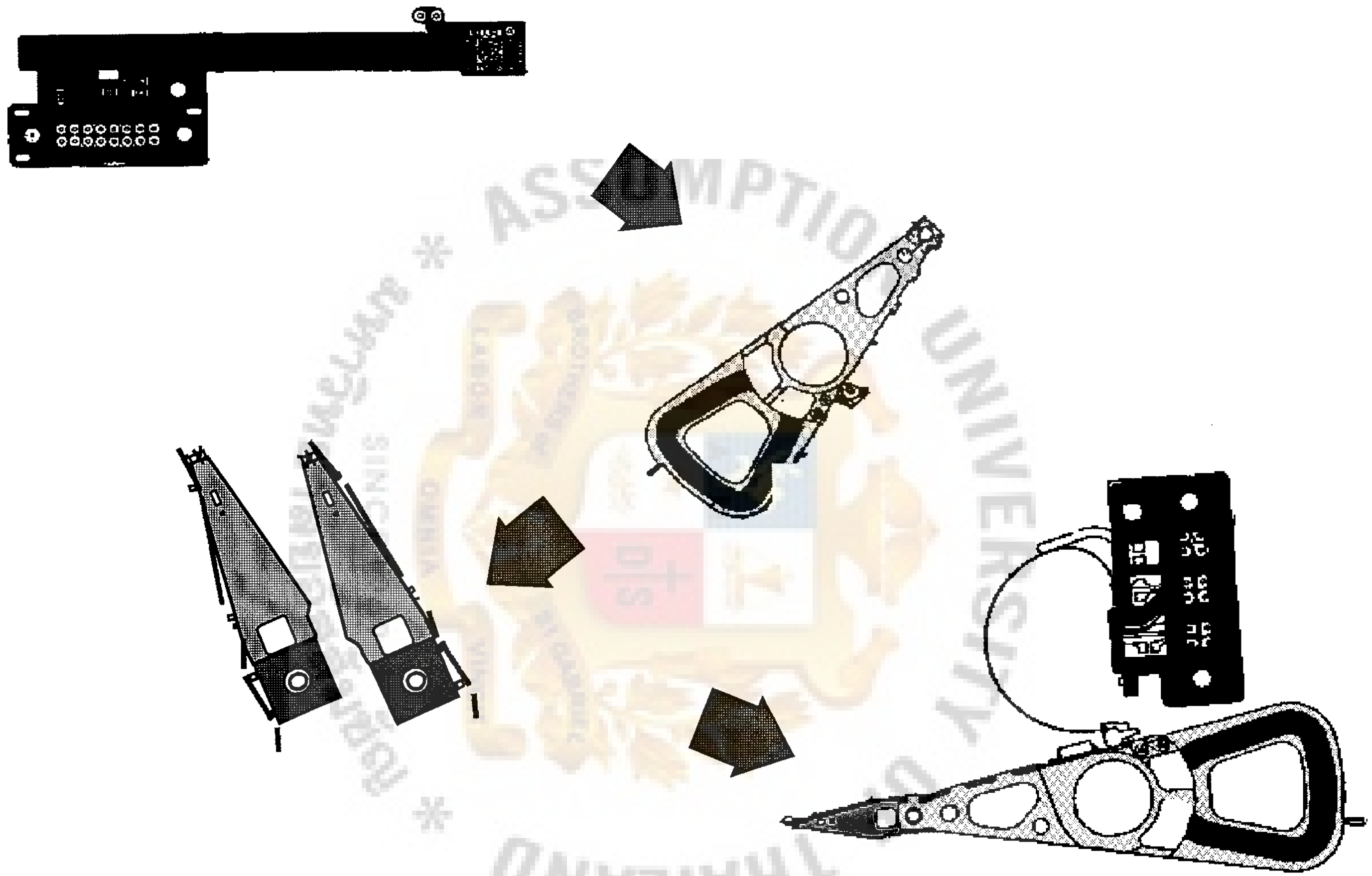
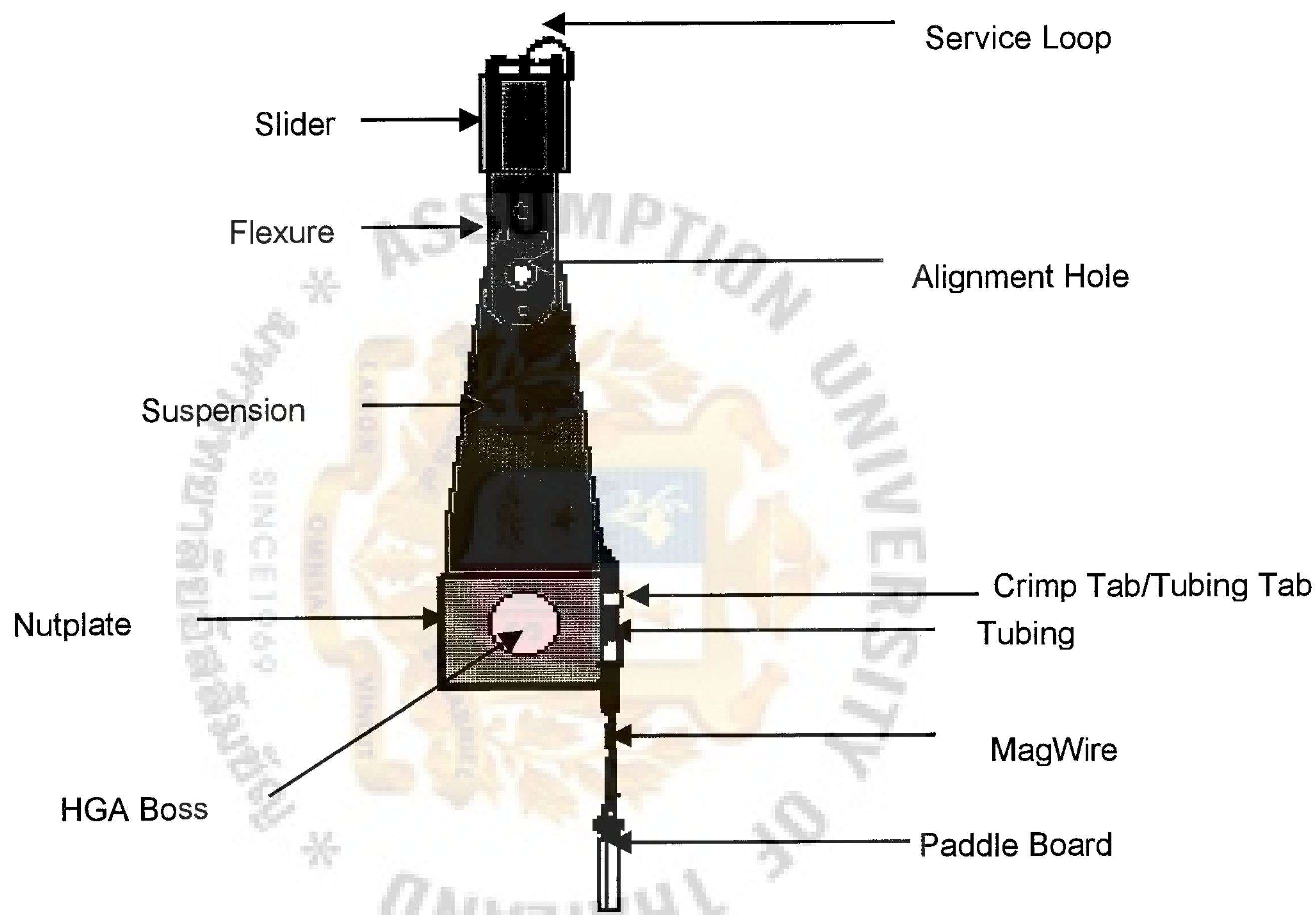
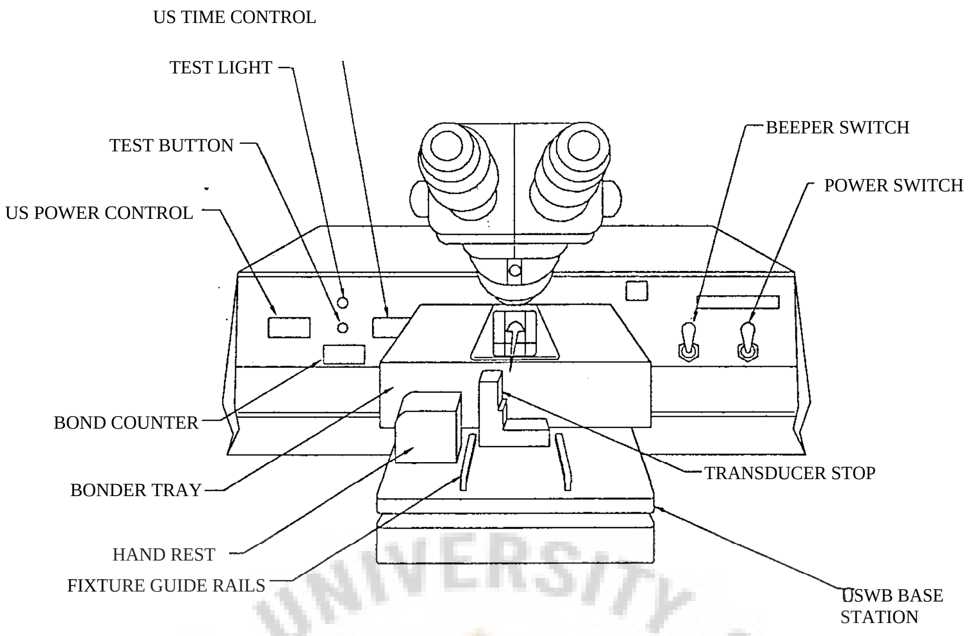


Figure C.3. HSA Component Name.



HSA Assembly Flow.


Service Loop
Slider
Flexure
Alignment Hole
Suspension
Crimp Tab/Tubing Tab
Tubing
Nutplate
MagWire
HGA Boss
Paddle Board



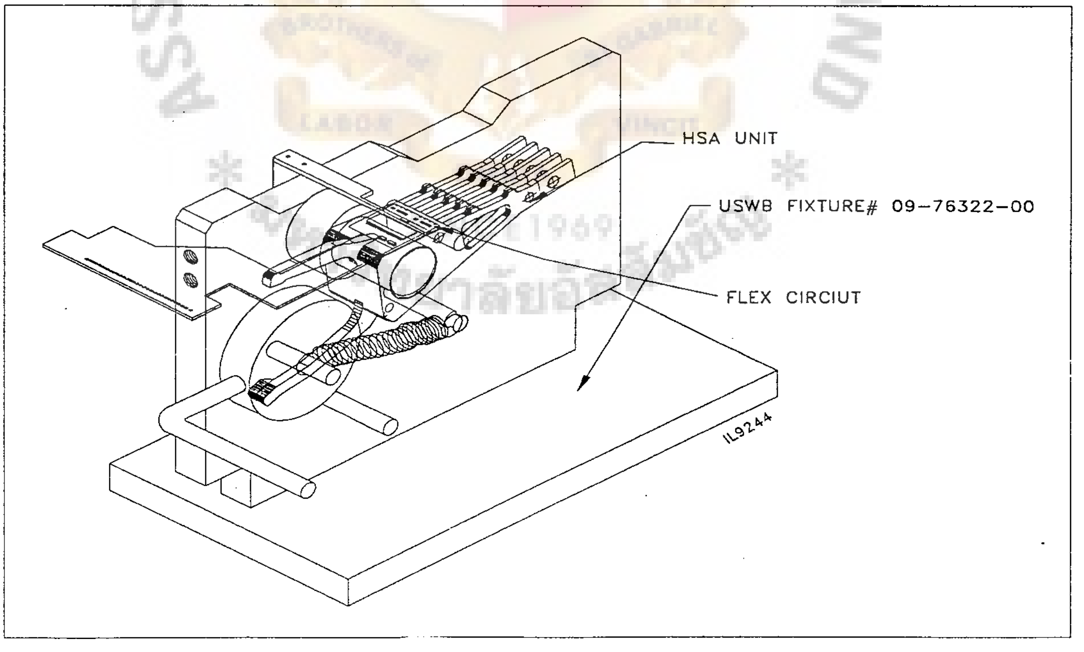


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Figure C.6. Wire Bonder Machine and USWB Fixture.

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