Managing Process Development Risk: Aluminum Ultrasonic Wire Bonding for Chip-on-Board Applications

by

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B.S. Electrical Engineering, Rose-Hulman Institute of Technology (1987)

submitted to the Department of Electrical Engineering and Computer Science and the
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and
MASTER OF SCIENCE IN MANAGEMENT

in conjunction with the Leaders for Manufacturing Program at the
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ABSTRACT

The demand for cellular telephones has grown rapidly over the past decade. With this growth, consumers have challenged the designers of cellular phones by requiring product design improvements in features and in portability. Such demands have resulted in smaller and lighter phones and have driven a need for advanced electronics packaging technology. As a result, process technology has become an increasingly important strategy for manufacturers of cellular telephones.

One particular method that fulfills this packaging need is chip-on-board (COB) technology. With COB, the chip is directly attached to the surface of the printed circuit board. Wires are then bonded from the die to the circuit board as a means of transferring electronic signals. Finally, a polymeric encapsulant is dispensed and cured in order to protect the entire assembly. With such an approach, both the area and the thickness of the circuit assembly can be reduced, allowing the design of smaller cellular phones.

This thesis examines two critical issues faced by the Motorola team chartered with developing the COB process. First, project risk assessment was of high importance due to the aggressive development schedule and the limited engineering resources for the project. Using existing fault tree approaches as a guideline, two methods were developed to analyze process development risk on a relative basis by separately considering the risk components of probability and consequence. Each method was then applied to the wire bonding process in specific. This structured approach resulted in a more detailed understanding of wire bonding process risks.

Along with the risk management issues, each member of the COB team was involved with developing a specific aspect of the technology. My research focused on development of aluminum ultrasonic wire bonding for COB. Three subsets of the wire bonding process parameters were evaluated: pre-bond plasma cleaning, substrate and wire metallurgy, and wire bonder (machine) settings. Because of the large number of process parameters, designed experiments were the most logical approach to the problem. This approach was complemented with materials analyses from laboratory resources within Motorola. From the study, critical process parameters were identified and parameter levels established.

Thesis Advisors:

Steven D. Eppinger, Associate Professor of Management
Lionel C. Kimerling, Professor of Materials Science and Engineering

Acknowledgments

Over a year of research, engineering, and writing resulted in this document. To say I did this on my own would be ludicrous; Without the assistance of several others, this thesis would not have been possible.

I gratefully acknowledge the support and resources made available to me through the Leaders for Manufacturing Program, a partnership between MIT and major U.S. manufacturing companies.

I also would like to recognize Motorola Inc. for the use of laboratories and libraries, as well as accepting me as part of the team.

Both Tom Babin at Motorola and Roy Welsch at MIT were of appreciable assistance with designed experiment techniques.

Thanks also to Al Drake at MIT. His 6.938 (Engineering Risk-Benefit Analysis) course is a great one and inspired much of the work in this thesis.

Thanks to Rod Copes and Bonnie Kao, both '93 LFM's who interned at Motorola, for their suggestions throughout the internship process.

Dave Richards at Motorola was a savior. While I was running experiments and doing risk analyses, Dave performed every materials analysis and characterization within this thesis. Thanks for your patience in teaching me the meaning behind all the acronyms.

Three members of the Motorola project team were also influential. Lloyd LaPlante was able to turn on a dime to get things done. Through several late dinners and numerous conversations, Phil Schwarz taught me things about wire bonding, engineering, and life in general. Jeff Norton, never failing to keep things in perspective, forced me to keep sane with our weekly margarita ventures. Phil and Jeff also dedicated numerous hours in creation of the risk methodologies detailed in Chapter 5.

Thanks to my thesis advisors, Steve Eppinger and Lionel Kimerling, for their support from MIT as well as Bob Pfahl for his support from Motorola AMT. The technical savvy and managerial understanding that these three men possess made it nearly impossible to fail on this project. Their dedication made it a sure success.

Special thanks go to my parents, Mel and Elaine Smith, for their concern over the years. My attendance at MIT probably meant more to them than it did to me. Any interest I ever had in math and science originated from my father. Thanks, E, for always being cool.

Most importantly, I want to thank my wife, Janet, for her love and support during the past two years. The program was harder on her than it was on me, as my time was continuously occupied. Thanks for listening when you really didn't want to, putting up with my abnormal study habits, coping with the separation during the internship, etc.
I look forward to once again watching the Bears with you every Sunday and screaming at the TV set as if it were alive.

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Chapter 1
Introduction

1.1 Project Background

The demand for cellular telephones has grown rapidly over the past decade. With this growth, consumers have challenged the designers of cellular phones by requiring product design improvements in features and in portability. Such demands have resulted in smaller and lighter phones and have driven an increased need for advanced electronics packaging technology. As a result, process technology has become an increasingly important strategy for manufacturers of cellular telephones.

One particular method that fulfills this packaging need is chip-on-board (COB) technology. With COB, the chip is directly attached to the surface of the printed circuit board. Wires are then bonded from the die to the circuit board as a means of transferring electronic signals. Finally, a polymeric encapsulant is dispensed and cured in order to protect the entire assembly. With such an approach, both the area and the thickness of the circuit assembly can be reduced, allowing the design of smaller cellular phones.

Motorola was involved with COB in several sectors of the corporation. Within the General Systems Sector in specific, a group known as Advanced Manufacturing Technology (AMT) was chartered with developing COB for cellular applications. As AMT had a strong process development focus, the group was required to work hand-in-hand with both product design and operations during COB development. It was within this AMT group that Bonnie Kao and I, as fellows from the Leaders for Manufacturing (LFM) Program, participated during our internship.

The Leaders for Manufacturing Program is a partnership between the Sloan School of Management, the School of Engineering, and several industrial sponsors. To facilitate the vision of the program, each fellow spends six months interning at one of the sponsoring companies. The purpose of such an internship has several goals:

- provide a unique education that broadens students' experience by exposing them to real manufacturing concerns that can be addressed only through teamwork and the integration of various corporate functions and disciplines
- generate an exciting and relevant engineering and management thesis and project results
- identify principles that should be taught and practiced by manufacturing leaders
- identify manufacturing research issues that are critical to participating companies and of interest to MIT faculty
- foster collaborative research between MIT and individual manufacturing plants
- establish a mechanism for changing behaviors, attitudes, and values in a way that leads to manufacturing excellence [LFM Program, 1993]

The COB development project provided the opportunity to fulfill this vision. As the interns participated directly on the development team, we were able not only to address the manufacturing-related research issues, but also to live in the shoes of a process engineer for the six-month period. This was an invaluable part of the learning experience, as we were fully exposed to a technology transfer that encompassed product design, process design, and international operations.

1.2 Motivation

Development of the process for COB was a technological challenge. Equally as important, the short product life cycles for cellular telephones requires aggressive time schedules to be met with limited resources. In such a scenario, not every issue can be dealt with, and even the important issues cannot be resolved to perfection. This presents an interesting dilemma - the team must not only develop the process at hand, but must also minimize downside risk along the way.

Risk management principles have existed for years and have generally been used to avoid catastrophic events such as nuclear power plant failures. For such low probability, high consequence issues, formal methodologies have been created.

Process development, on the other hand, has relatively higher probabilities and lower consequences of undesired outcomes. How does this impact the use of the traditional methodologies for process development situations? Are there structured methods that one can use to manage risk in process development? If so, what are they, and how are they applied in situations of limited time and resources? If not, can a simple structured method be developed for process engineering teams to readily use?

Along with the risk management issues, each member of the COB team was involved with developing a specific aspect of the technology. As wire bonding is a high-risk process in terms of impact on product yields, it provided a technical directive for focusing the team's ideas in risk management. The development of wire bonding for COB brought about many interesting issues. What level should the parameters of the bonder be set at in order to obtain high quality bonds? What impact does the plating of the substrate have on bond strength for COB? How does plasma cleaning affect the bonding process? Does changing the type of wire improve the bond strength? How are the machine parameters affected by such wire changes?

1.3 Approaches/Results

1.3.1 Risk Management

The purpose of this thesis was to research and resolve issues such as those presented in the previous section. Though literature searches, the existing risk management methods were first compiled. These methodologies were found to be insufficient for managing process development risk. Existing quantitative methods are overly complex for these situations, and the qualitative methods lacked the breadth necessary to capture the expected process failure modes. A structured method for assessing risk in process development was necessary both to challenge engineering intuition and to support project management efforts.

The definition of risk includes both probability and consequence as contributing components. Using the existing fault tree methodologies as a guideline, the COB team developed two methods to analyze process development risk on a relative basis by separately considering the risk components of probability and consequence. These relative methods are referred to throughout the thesis as the "terminal branch method" and the "rated hierarchy method." Both approaches provided an adequate comparison of risks and avoided getting lost in the numbers required for probabilistic assessments.

The methods were each applied to wire bonding in specific, and two particular categories of process parameters were identified as high risk. Various components of the first category, substrate metallurgy, appeared consistently in both analysis methods. The team had felt that defects due to substrate metallurgy were not of high probability, but such defects would cause line shutdown situations that may take days to resolve. Due to these large consequences, substrate metallurgy was seen as having high risk.

The second category identified as high risk was for the wire bond machine parameters. These appeared as high risk, however, for reasons of probability and not for consequence. The probability of improper setting was felt to be high because the wire bonding equipment was new to the group. Most of the wire bond engineering up to this time had been spent learning equipment setup and use. The improvement of bond pull strength had been given limited consideration. On the other hand, the team believed that the parameters could easily be adjusted by manufacturing personnel. Consequences, therefore, were rated low.

In the end, the rated hierarchy method was recommended because of its ability to achieve realistic results in a timely manner. If aggressively applied, such a process could be implemented in two or three business days, a worthwhile investment when one considers the cost of not understanding the process risks. Furthermore, the structure of the method provides a forum for the process development team to share ideas and an understanding of the underlying technology.

1.3.2 Wire Bonding

Development of wire bonding for COB also began with literature searches. These provided process awareness from the aspects of plasma cleaning, metallurgy, and machine parameters. From the literature search, a large number of parameters were identified which could potentially impact bonding integrity. Because of the large number, designed experiments (DOX) were determined to be the best approach to structure the engineering effort.

Resources from a Motorola materials laboratory were utilized to complement the DOX activity. Materials analyses provided feedback which was critical in understanding the bonding process. Such analyses also assisted in simplifying the designed experiments. As an example of this, the results from one such analysis resulted in a decoupling of the plasma cleaning parameters from the metallurgy and machine parameters. Such decoupling allowed two smaller experiments to be performed in lieu of one large matrix.

Through DOX and materials analysis, we found plasma cleaning to have no benefit for either increasing the bond strength or decreasing the variance in bond strength. Using scanning electron microscopy (SEM), we also found excessive abrasions in the surface of the substrate which had been caused by a supplier process instituted to remove plating debris. Finally, through the wire bonding DOX the most critical process parameters were found to be ultrasonic power and the type of wire alloy used. This DOX also resulted in process parameter specifications for aluminum ultrasonic wire bonding.

1.4 Thesis Organization

This section provides a description of the thesis organization by chapter.

Chapter 2 provides background information related to several aspects of the project. First, an overview of the cellular telephone industry is given. The need for smaller and lighter phones leads to a description of various electronics packaging methods. The details for the chip-on-board (COB) method are presented within this section. The chapter ends with a description of the organizational context for the COB process development team.

Chapter 3 describes aluminum ultrasonic wire bonding and the parameters which impact bond quality. In particular, the aspects of plasma cleaning, substrate/wire metallurgy, and machine parameters are examined.

Chapter 4 provides an overview of the risk management process. Existing methods found through literature searches are first explained. A six-step process described by one of the methods is then used as a framework for organizing the literature findings. The six steps are: 1) risk identification, 2) risk analysis, 3) risk prioritization, 4) risk management planning, 5) risk resolution, and 6) risk monitoring.

Chapter 5 focuses on two relative risk assessment methodologies for process development applications. In the first part of the chapter, the methodologies are developed and explained in full detail. A fairly complex example is then given by applying both methods to the wire bonding process.

Chapter 6 presents the experimentation and results for aluminum ultrasonic wire bonding. The chapter begins with some preliminary surface analyses to evaluate the impact of using different plasma cleaning gases. A plasma cleaning designed experiment is then performed in an attempt to locate proper plasma cleaning parameters. Following some additional surface analyses, wire bonding designed experiments are utilized in order to locate key effects and establish process parameters.

Chapter 7 presents the findings from this research and recommends future work.

Chapter 2
Background[1]

George Fisher, chairman and CEO of Motorola Inc., envisioned the future of wireless communication and Motorola's involvement in this effort: "We will enable people and machines access and communicate information seamlessly, anywhere, anytime, and at their convenience ["Wireless Data Communication," 1992, p. 106]." Being the largest land-mobile radio company, Motorola is to achieve this communication network from three fronts: 1) private two-way radio, 2) paging, and 3) public mobile/cellular phone. It is the last segment, cellular products, that represents the most change and volatility.

2.1 Cellular Industry

2.1.1 Background

2.1.1.1 History

Wireless communication has been in use since the 1920's for taxi drivers and emergency personnel. After decades of technological advancements and miniaturization, the total world market for cellular telephone services now surpasses 20 million subscribers. According to the Cellular Telecommunications Industry Association

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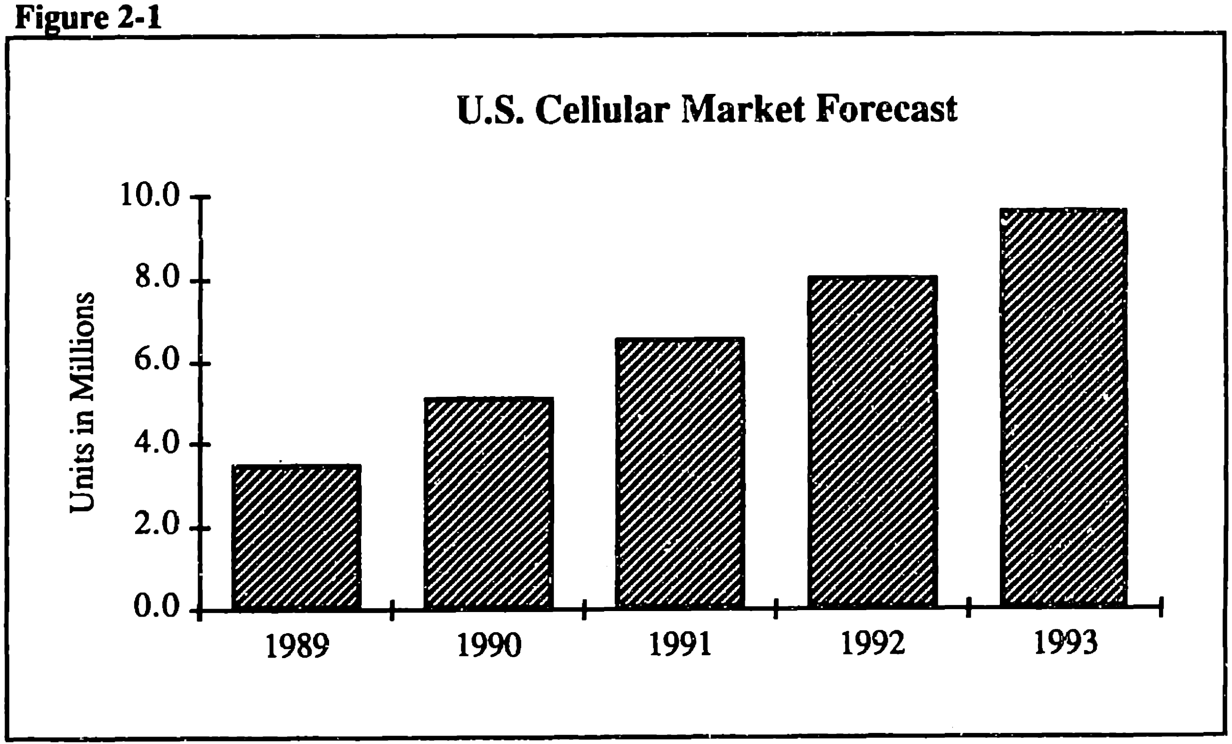
[1] This chapter was written jointly with Bonnie Kao, whom I interned with at Motorola. The chapter also appears in her thesis entitled "Technology Benchmarking and Process Development Tools: A Case Study of Encapsulant Curing for Chip-on-Board Applications," 7 May 1993, for the degrees of S.M. in Management and S.M. in Materials Science and Engineering.

(CTIA), the number of U.S. subscribers reached 7.6 million as of 1992, with a projected annual growth rate of 40%. Other industry analysts predict that 30 to 50 million Americans will be using cellular telephones by the year 2000 [Welbon, 1991]. Annual sales for the U. S. cellular market is shown in Figure 2-1.

Figure 2-1



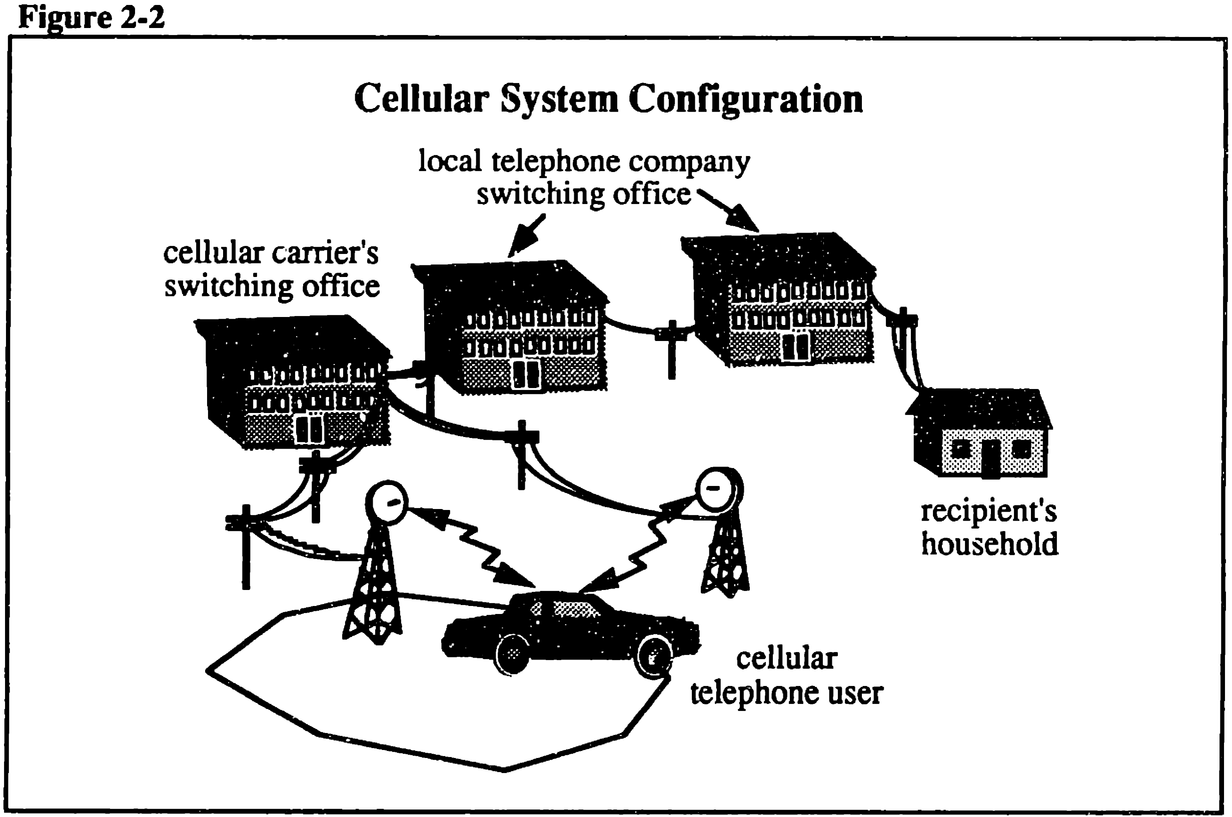
[Source: "Wireless Communication," 1991]

2.1.1.2 Cellular Overview

The market can be divided into service providers, infrastructure equipment providers, and cellular phone makers. The largest domestic cellular service provider is McCaw Cellular Communications. The second sector includes firms such as Motorola, AT&T, Northern Telecom and Ericsson. Presently 75% of the market in the third sector is taken by Motorola, Mitsubishi, Matsushita, Oki, Toshiba and NEC. Some telephone system manufacturers, such as AT&T, Motorola, and Fujitsu, make both cellular switching systems and telephones.

When a user initiates a call using a cellular telephone, the signals are sent to a receiving/transmitting tower (Figure 2-2). The signals travel through the conventional phones lines to the cellular carrier's switching office, to the local telephone switching office, to the long-distance carrier's exchange (if necessary), then to the recipient's household. In the meantime, the cellular carrier's computer is constantly monitoring the caller's position. If the caller is traveling from one area, or cell, to the other, a hand-over would occur to let the nearest tower take over the communication task.

Figure 2-2



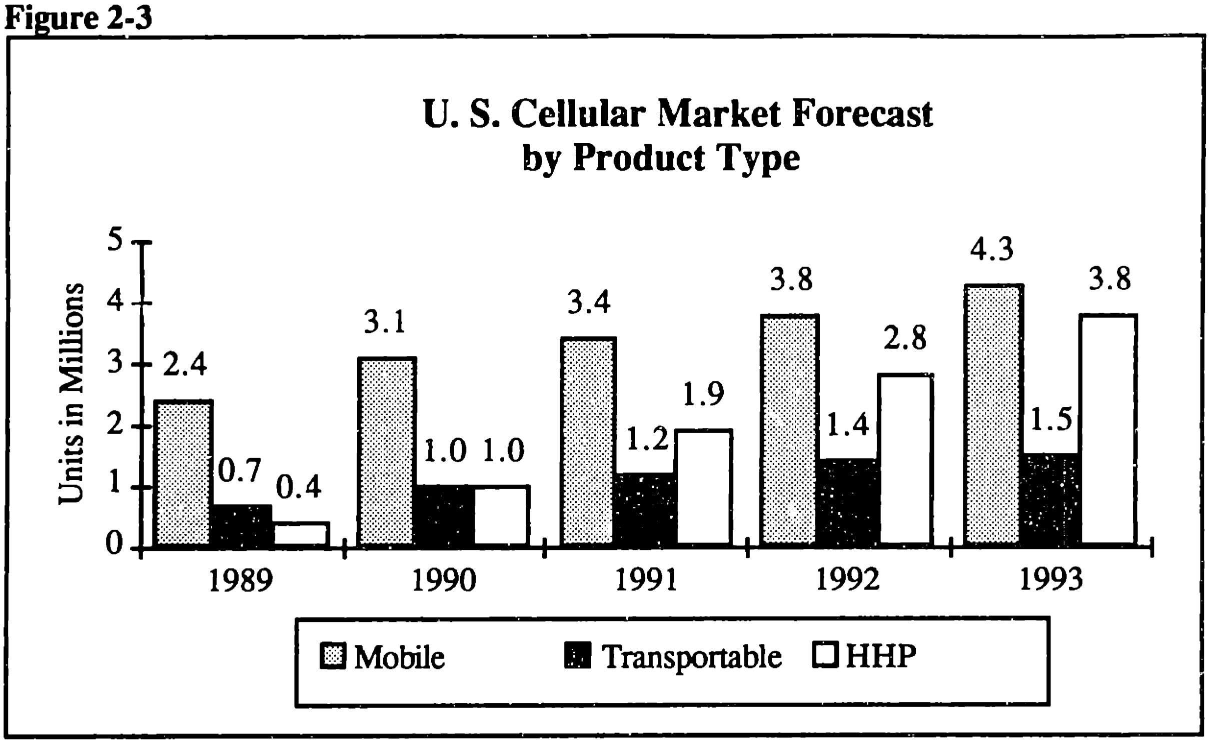
[Source: "Phones to Go," 1993, p. 10]

A cellular telephone can be further categorized into either mobile, transportable, or handheld portable (HHP). The breakdown in annual sales by segment is shown in Figure 2-3. Evident from the figure, the HHP is experiencing the highest growth rate.

2.1.1.3 Profile of a Cellular User

When the cellular phone was initially introduced in 1983, the marketplace was

Figure 2-3



[Source: "Wireless Communication," 1991]

characterized by low level of awareness, purchasing, advertising and distribution accessibility. By 1985, a typical user had increased personal usage and begun to view the cellular telephone more as a personal necessity than as a traditional business tool [CELLTRAC 20]. The average cost of local cellular service declined 8% in 1991 to an average of about $75 per month, and the average cellular call lasted nearly 2.4 minutes [U.S. Industrial Outlook, 1992]. In addition to the drop in calling rates, the unit price of cellular handsets had also been decreasing.

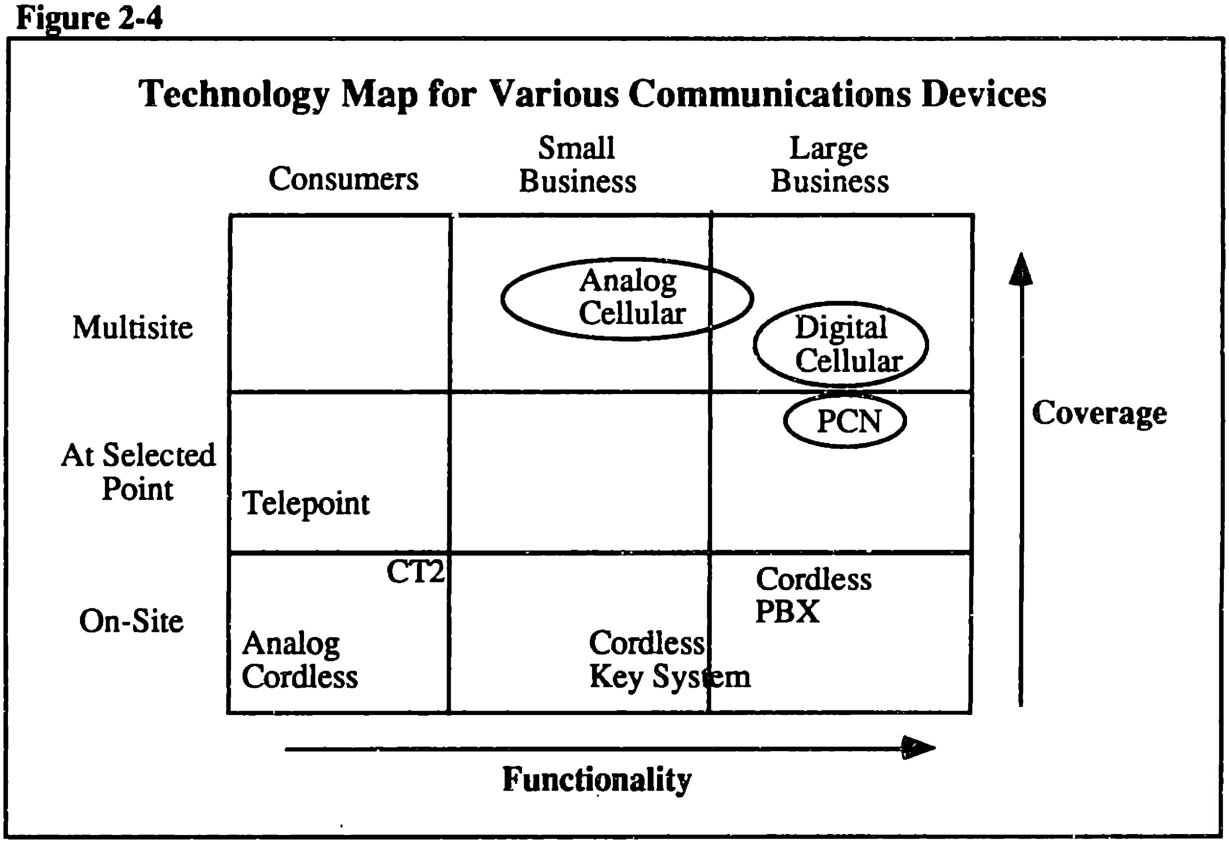
2.1.1.4 Forces Driving the Industry

Several forces drive this industry: substitution, customers, regulations, standards, and technology.

substitutes

The telecommunications industry consists of providers for local exchange, long distance (toll), international, telex and telegraph, cellular and mobile-radio, satellite, data communications, and Value-Added Network Services (VANS). Consumers see different value in each service, and each service is not a perfect substitute for the other. However, when the price of a certain service becomes prohibitively high, consumers will switch to other types of services. Figure 2-4 highlights the different options.

Figure 2-4



[Source: Revised from "Issues & Agendas," 1992, p. 50]

customers & regulations

Customers are demanding better performance and lower price as this product reaches a more mature stage. In terms of regulation, according to Federal Communications Commission (FCC), two licensed carriers are allowed to operate within each cell. Each franchise gets 25 MHz of spectrum, or enough for about 832 channels of 30,000 Hz apiece. Presently all 305 metropolitan areas are served by two licensed providers, and more than half of the Rural Service Areas (RSAs) now have service [U.S. Industrial Outlook, 1992].

standards

As long as cellular phone usage increases and the dedicated frequency spectrum stays fixed, problems such as congestion and potential service degradation will take place. To solve this problem, the industry's shareholders, through the Telecommunications Industry Association (TIA), are aggressively developing a series of standards upon which first generation digital cellular phones will be based [Madrid, 1991]. The digital cellular phones have the potential of increasing the capacity three- to twenty-fold. One advantage of digital over analog standard is privacy, because analog calls can be monitored by a scanner ["Telecommunications: Dialing Up a World of Profits," 1992, p. 70].

technology

Lastly, the cellular industry is definitely driven by technological innovations. Advances in technology for power sources, displays and electronic configurations make the cellular products even more appealing to the masses.

2.1.2 Product

The cellular telephone consists of the following parts: casing/plastic components, radio-frequency (RF) devices, logic devices, display and battery.

2.1.2.1 Casing/Plastic Components

On average, there are 10-15 plastic components constituting approximately one-quarter of the weight of a phone. Three to five of these major components make up the telephone's housing and battery casing, and other essential parts include the acrylic information window and the dial buttons. The trend in this plastics industry is two-fold: to deliver molds quickly with the aid of a CAD design capabilities, and to handle complex processes enabling the integration of 3-D circuit boards and electronic components [Moore, 1992, p. 99].

2.1.2.2 Devices (RF and Logic)

During the transition period of analog to digital standard, designers of cellular telephones have to work with mixed signals: analog RF components operating in the GHz range and digital RF components operating in the MHz range. This presents several challenges. First, the designers must be familiar with the different technologies. Second, they must be concerned with the power consumption issues when dealing with a limited power source - battery. Third, they must also keep pace with the development in standards. Lastly, the cost of these devices has to be competitive, since the cellular telephone is becoming a consumer product ["Cellular Phone Designs Call for Mixed-Signal Solutions," 1991, p. 57]. The industry trend is to produce a highly-integrated, cost-effective solution based on a few chip sets: a DSP (digital signal processing), an RF/IF chip, and a power amplifier.

2.1.2.3 Display

With cellular telephones, the search for a low-cost, high quality display technology is a major concern. Light-emitting diodes (LEDs) used to be the dominant display technology, but their problems with power consumption and size have led to the emergence of liquid crystal displays (LCDs). Presently the top makers of LCD display panels are all Japanese, including Sharp, Hitachi, Seiko Epson, Toshiba, Sanyo, Seiko Instruments, Citizen, and Matsushita (Panasonic). Out of a concern for the need for displays, Motorola recently teamed up with In Focus Systems Inc. to develop an actively addressed passive-matrix LCD. This type of display is said to place signaling algorithms on devices off-screen, thus reducing the power consumption and cost ["In Focus, Motorola Team Up for Display Venture," 1992, p. 140].

2.1.2.4 Battery

A cellular telephone is not possible without a portable power source. In general, batteries need to be easy to fabricate, rugged, safe, and long-lasting. Due to environmental and cost concern, rechargeable batteries, especially the nickel-cadmium (Ni/Cd) system, are preferred over disposable batteries. However, due to the toxicity of cadmium, the industry trend is to move away from Ni/Cd system and into a new, higher performance nickel metal hydride alternative ["Rechargeables Take on Primary Battery Market," 1992, p. S3]. The latter system was adopted by Motorola's new cellular telephone, MicroTAC Ultra Lite.

2.1.3 Critical Dimensions

A comparative analysis of cellular telephones would usually include several key features:

- price
- size
- weight
- sound quality (listening and speaking)
- battery time (talking and standby time)
- additional features (automatic number selection, built-in help) ["Phones to Go," 1993, pp. 14-15].

A more efficient and space-saving electronics packaging process can simultaneously enhance size, weight and price. It is with these multiple benefits in mind that Motorola's AMT organization decided to undertake the development effort of a more compact electronics packaging technology: Chip-on-Board.

2.2 Electronics Packaging

Consumer demand and heavy competition have driven down the price, size and weight of cellular phones. Yet, the new phones have better sound quality and longer talk time than ever before. From a product design standpoint, this translates into significant technological challenges for each of the major subsystems of the phone (electronics, battery, and casing). An especially critical aspect of size, weight, and cost reduction is the advancement of technology in electronics packaging.

This section focuses specifically on how advanced packaging of electronic components has brought product miniaturization to reality. The section begins by giving a brief overview of electronics packaging, which is followed by an introduction to the most prominent packaging methodologies. Finally, the processes and issues for Chip-on-Board technology are addressed.

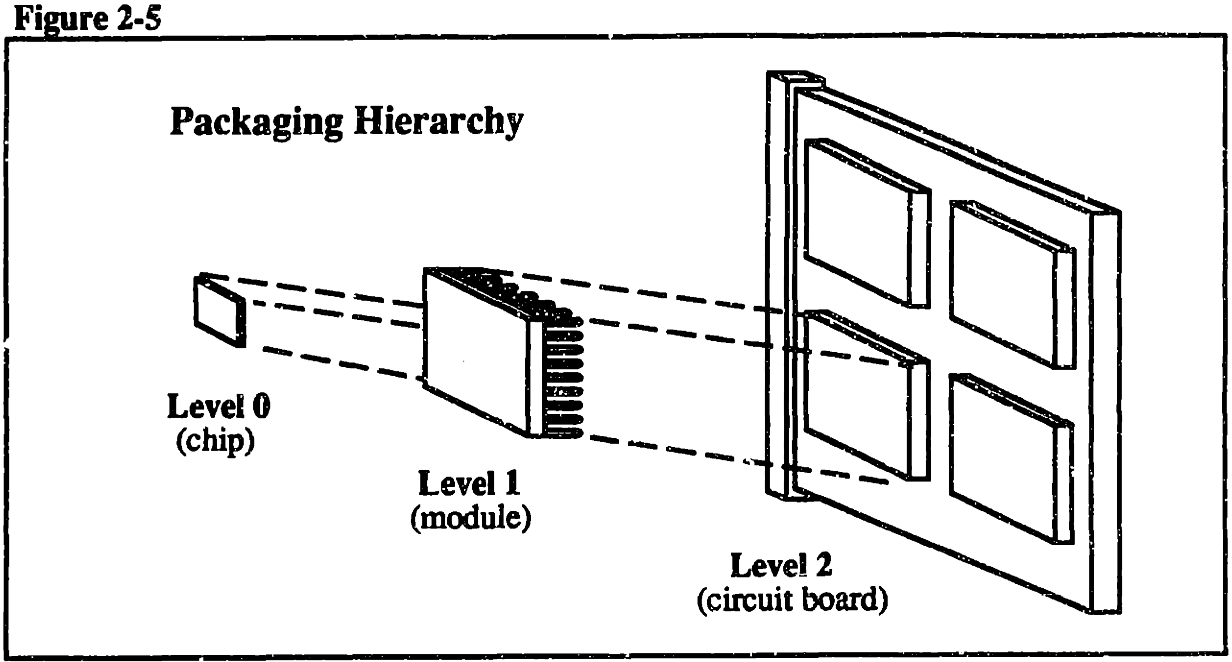
2.2.1 Electronics Packaging Overview

In the early days of electronics, packaging was accomplished by two media: solder and wire. Although sufficient in carrying power and signals between components, this approach was both bulky and labor intensive. As the number of discrete components per circuit increased, the use of solder and wire techniques became impractical and new methods were sought. Printed circuit boards were developed to eliminate most of the external wiring, and the invention of the transistor led to numerous packaging alternatives.

As time passed, this evolution has led to the present hierarchical structure of electronics packaging (Figure 2-5). In this structure, the integrated circuit chip is at the base level, which is annotated as Level 0. The chip is mounted into a module (Level 1), electrical connections are made, and the package is sealed. Several modules are then mounted to a substrate, most commonly referred to as a printed circuit board. This substrate represents a Level 2 packaging technology. A complete electronic assembly often requires multiple printed circuit boards. The assembly would then be referred to as Level 3, and so on [Tummala and Rymaszewski, 1989, p. 7].

Through the combination of levels, electronics packaging serves four functions: power distribution, signal distribution, heat dissipation, and circuit protection [Tummala and Rymaszewski, 1989, p. 3]. Each of these aspects must be considered when

Figure 2-5



[Source: Tummala and Rymaszewski, 1989, p. 7]

specifying design criteria for a given circuit. The selection usually comes down to a tradeoff between product requirements and cost. Other design considerations include physical size, reliability, and testability.

A brief introduction to Level 0 and Level 1 packaging technologies will be given prior to introducing the chip-on-board methodology.

2.2.2 Electronics Packaging Technology

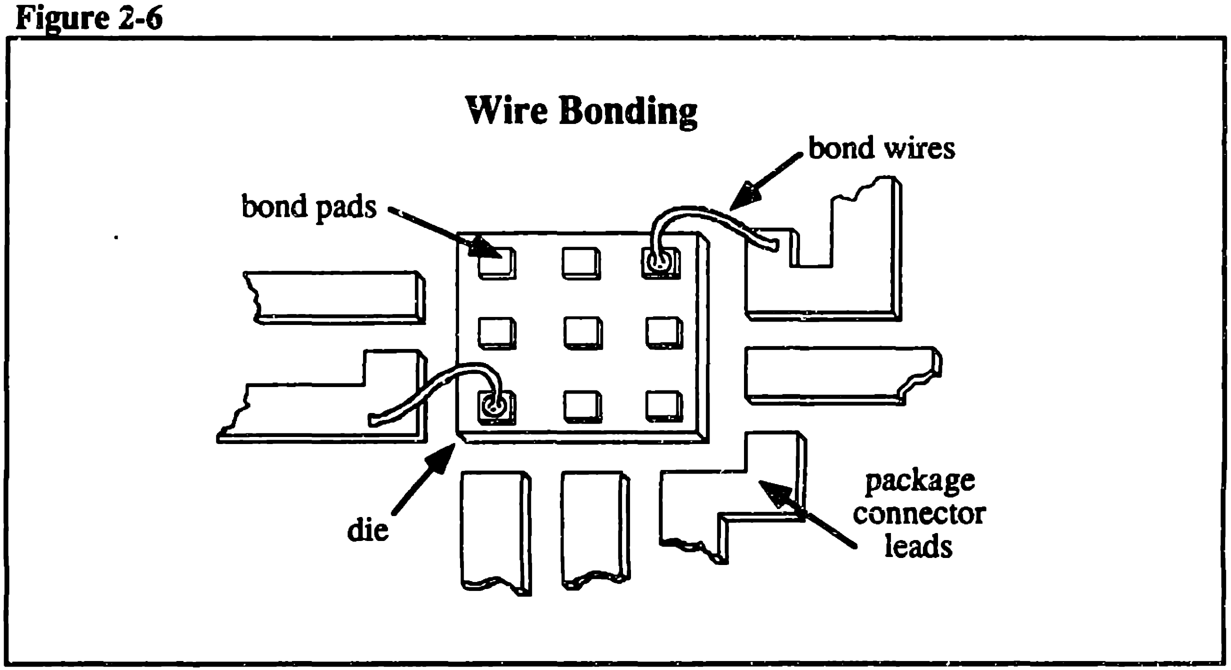
2.2.2.1 Level 0 Technologies

Level 0 technologies deal specifically with chip-to-module interconnections. Three methods are commonly used: Wire Bonding, Tape-Automated Bonding (TAB), and Controlled Collapse Chip Connection (C4).

wire bonding

Wire bonding is the most popular method of Level 0 interconnection [Tummala and Rymaszewski, 1989, p. 391]. Wire bonding begins by mounting the backside of a chip to a package with a conductive epoxy. Gold or aluminum wires of approximately 0.001" diameter are then bonded sequentially using a combination of heat, pressure, and/or ultrasonic energy (Figure 2-6). Three types of wire bonding (ultrasonic, thermocompression, and thermosonic) represent different combinations of these parameters.

Figure 2-6



[Source: Tummala and Rymaszewski, 1989, p. 392]

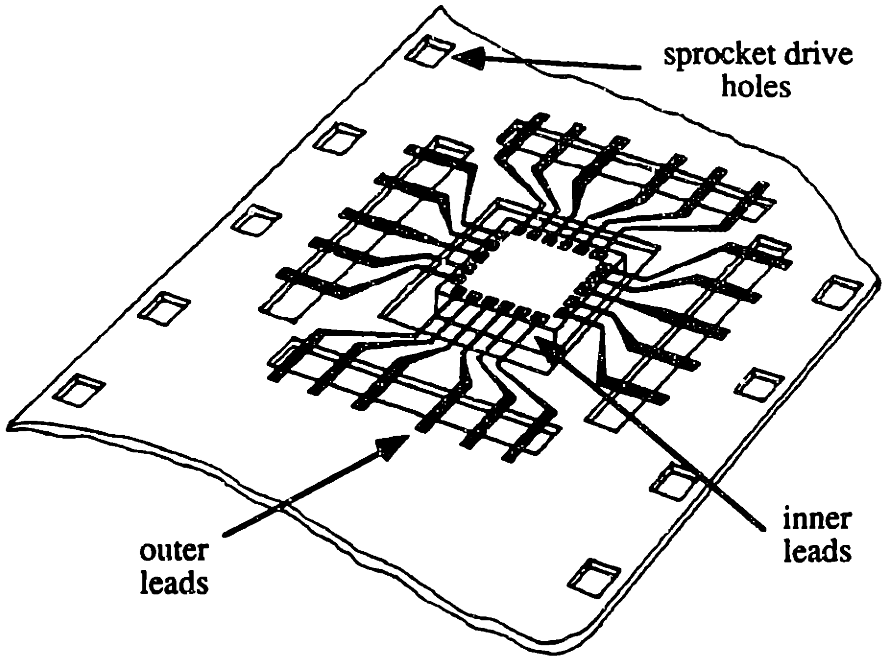
tape-automated bonding (TAB)

Tape-Automated Bonding (TAB) processes use thermocompression bonding to attach silicon chip pads to patterned metal on polymer tape (Figure 2-7). This process is also known as inner lead bonding (ILB). Following ILB, the chip may then be encapsulated or tested as required. The individual die will be subsequently removed from the tape and packaged using outer lead bonding (OLB) techniques.

TAB offers several advantages over traditional wire bonding. Although TAB was originally developed for high volume, low I/O devices, TAB techniques have been used for devices exceeding 300 I/O [Tummala and Rymaszewski, 1989, p. 409]. Furthermore,

Figure 2-7

Tape-Automated Bonding (TAB)



[Source: Charles, 1989, p. 233]

since all leads are bonded simultaneously a substantial increase in throughput is attainable over conventional wire bonding. Finally, quality problems can be detected at an earlier stage because the taped die can be individually tested.

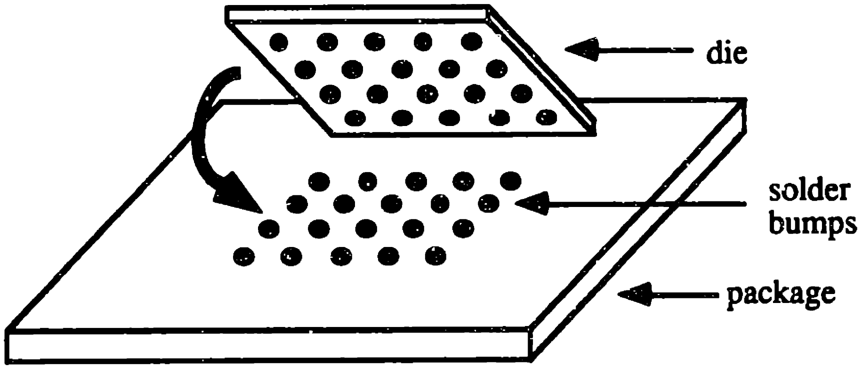
On the other hand, TAB presents new challenges not encountered with wire bonding. The ILB process requires solder bumps on either the ILB tabs or the silicon pads. These solder bumps greatly increase the chance of damage to chip passivation. The other major issues with TAB are tooling costs and availability. Because of the custom layout of many chips, a major investment in inflexible equipment is required.

controlled collapse chip connection (C4)

Controlled Collapse Chip Connection (C4) technology, also known as flip-chip, was developed in the early 1960's to eliminate the expense, unreliability, and low productivity of manual wire bonding. To make the chip-to-package interconnection, C4 utilizes solder bumps deposited to wettable metal terminals on the chip and a matching footprint of solder wettable terminals on the substrate (Figure 2-8). Since interconnection is established via the solder bumps, the need for wires or tabs is completely eliminated. Additionally, production using C4 processing is economical because every solder joint is made simultaneously during the solder reflow process.

Figure 2-8

Controlled Collapse Chip Connection (C4)



[Source: Tummala and Rymaszewski, 1989, p. 366]

However, the general lack of die available with solder bumps has not allowed this technology to flourish. Furthermore, C4 presents many new technological challenges such as prevention of solder bridging and solder joint fatigue due to thermal expansion coefficient mismatches between the silicon and the substrate.

2.2.2.2 Level 1 Technologies

Level 1 technologies deal specifically with module-to-substrate interconnections. Three methods are commonly used: Plated Through Holes (PTH), Surface Mount Technology (SMT), and Solder Ball Carriers. Each type of Level 1 interconnection is independent of the Level 0 (chip-to-module) interconnect. As a result, any of the three Level 0 technologies may be used with any of the Level 1 technologies.

plated through hole (PTH) technology

Plated Through Hole (PTH) technology has been common since the 1960's for packaging of electronic devices. The technology derives its name from the structure of the substrate which has several holes for the insertion of components. When inserted, the component leads protrude through the surface of the substrate but are without mechanical connection. Mechanical attachment is achieved by passing the entire module/substrate assembly over a molten wave of solder (known as "flow soldering"). Chip-to-module interconnection is most often accomplished using wire bonding techniques.

surface mount technology (SMT)

Unlike PTH technology, surface mount technology (SMT) requires no holes in the substrate. Several benefits can be attained by using SMT instead of PTH technology. By eliminating pin and via holes, additional channels for wiring become available, increasing the effective substrate wiring capacity. Secondly, the smaller size of SMT components allows area reduction of about 40% for single-sided substrates. Because SMT components can be mounted on both sides of the substrate, the size reduction factor improves to 70% [Tummala and Rymaszewski, 1989, p. 1043]. Both material and labor cost reductions are achieved since several PTH substrates can be combined into smaller SMT designs. Like PTH, chip-to-module interconnection for SMT is most often accomplished by using wire bonding techniques.

solder ball carriers

Solder ball carriers use the same principles as the C4 (Level 0) technology explained previously. The carriers are used to enhance both heat dissipation and device protection. Additionally, much higher I/O is attainable within a given area because the carrier leads are not limited to its perimeter (as in PTH and SMT).

Solder ball carriers may also use any of the Level 0 interconnection methods. A recent technology developed by Motorola which uses wire bonded chip-to-module connections is OMPAC, or overmolded pad array carrier. This technology uses a 40- to 60-mil pitch array of solder bumps. The 40-mil pitch provides a density of 600 I/O's per square inch. In addition to this high I/O density, placement accuracy is less critical than for conventional SMT devices because the array of solder bumps gives the module a "self-aligning" feature when reflow soldered [Markstein, 1992].

2.2.3 Chip-on-Board (COB) Technology

To reiterate from earlier, electronics packaging serves four functions: power distribution, signal distribution, heat dissipation, and circuit protection. Designers of cellular telephones must meet these requirements while satisfying the consumer's demand for lower cost, weight, and size. By reducing the number of hierarchical levels, engineers can design products which are more responsive to the needs of the market. One method for such level reduction is chip-on-board technology.

2.2.3.1 Description of Technology

"COB has two major subsets:

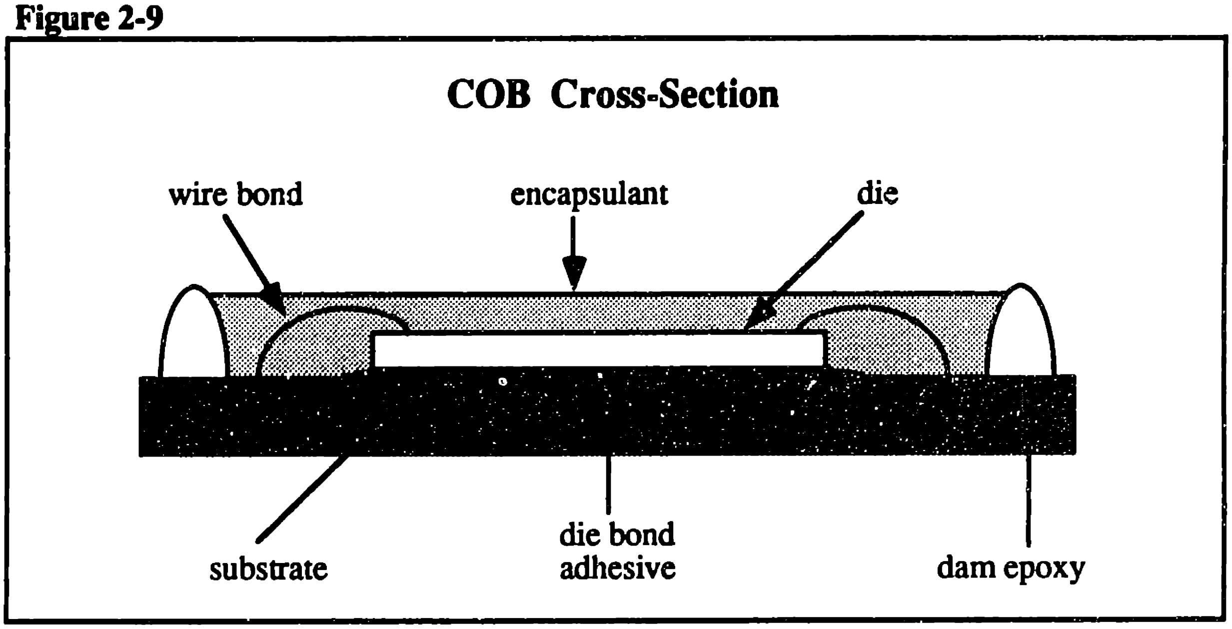
- Chip-and-Wire technology, where the integrated circuit die is first adhesively bonded to a printed wiring board and is then interconnected by wire bonding with either gold or aluminum wire; and
- Flip Chip technology, where the integrated circuit is plated with solder bumps at the interconnect points and soldered in an inverted fashion to the board, thus effecting both attachment and interconnection in one step ["Guidelines for Chip-on-Board Technology Implementation," 1990, p. 1]."

Because Flip Chip technology is often referred to as "C4," "Flip Chip," or "Direct Chip Attach," the term "Chip-on-Board (COB)" is commonly used in place of "Chip-and-Wire." Throughout the balance of this thesis, COB will mean "Chip-and-Wire."

With COB, the Level 1 packaging (i.e., module) is completely eliminated, providing a smaller and lower cost method of chip packaging. The process by which wire-bonded COB is produced can be best understood by the cross-section shown in Figure 2-9.

The first step is to attach the die to the substrate using a conductive adhesive. The adhesive is then cured in an oven. The epoxy dispense and die placement procedures are often automated to increase speed and consistency. For this purpose, bare die may be packaged in waffle packs, in wafer form, or on tape. The particular substrate which is used depends a great deal on the requirements of future process steps. The substrate types are classified by glass transition temperature, with higher temperature boards typically costing more. The desired wire bonding process and curing methodology will, therefore, play major roles in the selection of this material.

Figure 2-9



Once the die epoxy has cured, wires will be bonded using one of the three methods mentioned in the previous section. This process is considered to be very critical from the standpoint of yield, as will be discussed in the next section.

The final step is epoxy encapsulation which protects the wire bonds and device from physical handling and environmental concerns. An epoxy of appropriate viscosity must be used to eliminate voids in the encapsulant. As a consequence, a dam is first dispensed and cured to contain the lower viscosity encapsulant. When the encapsulant has been cured, the COB assembly is complete.

2.2.3.2 Key Issues

By eliminating a level of packaging hierarchy, several benefits can be realized. The advantages include:

- lower cost (in high volume)
- lighter weight
- smaller packages
- lower "z" dimension profile (thinner packages)
- shorter circuit paths (faster switching speeds)
- improved impedance control
- reduced number of interconnection levels in the overall system (fewer solder joints), and
- shorter turnaround time for prototypes and production

However, COB also creates several challenges:

- specialized capital equipment required
- unprotected integrated circuit chip handling techniques required
- user/vendor relationship required for acquisition of fully tested, uncased integrated circuit chips
- the total number of chips per assembly might be limited by the expected burn-in yield per chip, and
- CAD tools may need to be modified to accommodate chip-on-board ["Guidelines for Chip-on-Board Technology Implementation," 1990, pp. 5-6]

Some of the process challenges implied by these disadvantages will now be reviewed.

process flow

Present day circuit board assembly might require SMT and COB on both sides. Thus, a total of four assembly stages must be ordered in a manner which gives an overall process optimum.

By performing COB operations first, two specific risks exist: 1) the COB assembly must withstand two solder reflow cycles for SMT processing, and 2) reflow of transparent encapsulants (for LED's) may cause loss of device transmissivity.

On the other hand, performing SMT operations first poses a major cleaning challenge. Because devices will be wire bonded during COB, residual debris from the SMT processes must be completely removed from the substrate pads. Otherwise, wire bonding yields may be adversely affected.

wire bond yield

Yield from wire bonding is critical in electronics packaging. Since COB devices are mounted directly to a printed circuit board, the consequences of scrap due to wire bond yields are much higher for COB than for traditional packaged modules.

Figure 2-10 shows the effects of wire yield on device yield for a 224-wire device. From this, one sees that high wire bond yields are required to achieve even marginal device yields. As multiple devices are often used on a single substrate, this multiplicative effect is amplified even further.

Figure 2-10

Wire Yield vs. Device Yield

yield per wire	yield per device
0.9	5×10^{-11}
0.99	0.105
0.999	0.799
0.9995	0.894
0.9999	0.978

[Source: Tummala and Rymaszewski, 1989, p. 404]

handling of open wire bonds

Handling of open devices is not an issue for SMT or PTH manufacturers. For COB, one must give strong consideration for transferring product from wire bonding to encapsulation. Because of a limited presence of COB automated equipment, the handling of in-process inventories becomes an important part of the COB process.

adhesion

The structural integrity of the COB assembly depends entirely on encapsulants and adhesives. Five specific areas where adherence is critical are:

1) adherence of die to substrate
2) adherence of dam to substrate
3) adherence of COB encapsulant to die
4) adherence of COB encapsulant to substrate
5) adherence of COB encapsulant to dam

The COB may still be structurally sound without extreme strength in all of the individual areas. The challenge for the development engineer is to identify and address the most critical areas.

cure cycles

Cure cycles are important to the total process time for a COB assembly. For two-sided COB, six cures are required: die attach, dam encapsulant, and COB encapsulant on each side of the substrate. Since such processing requires several hours of cycle time, an understanding of encapsulant curing properties is necessary.

testing

The testing strategy for COB devices is crucial but without a simple solution. Most die are tested by the respective manufacturer to assure functionality on a limited basis. As a result, a problem commonly encountered in any direct chip attach process is one of having "known good die" with which to begin the process. Because many dice are only available from overseas, coordination of supplier relationships to assure proper testing and feedback becomes difficult.

Given known good die, another problem is the ability to detect COB processinduced defects as early as possible in the production cycle. Although the long-term solution is to eliminate testing altogether, in-process testing is necessary to facilitate root-cause problem identification during production ramp-up. Testing of unencapsulated, wire bonded devices presents handling and probing issues. The handling issue can be eliminated by testing only encapsulated die, but at the expense of additional process time and materials. Probe testing of die requires engineering expertise which is often available only from device fabrication houses.

2.3 Organization

The purpose of this section is three-fold: to provide the readers with an understanding of the organizational structure of Motorola, the project structure within the Advanced Manufacturing Technology (AMT) group, and the process development challenges associated with the COB project.

2.3.1 Organizational Structure

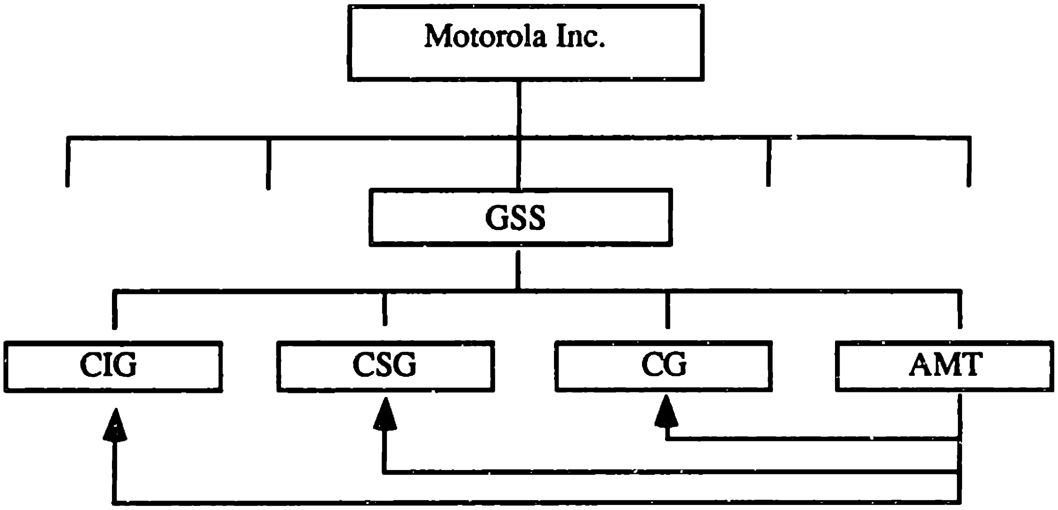
Motorola is built around its radio-frequency competency. An organizational chart is depicted in Figure 2-11. The charter for the General Systems Sector is to design and manufacture computer-based cellular radiotelephones and computer systems [Motorola, 1991, pp. 6-7]. In addition to the functional groups within each sector, there are also several support organizations. The goal of one such support group, Advanced Manufacturing Technology (AMT), is to develop medium-term process technologies for the functional groups.

2.3.2 Project Structure within AMT

The AMT group is structured into four sub-groups: software/factory control systems, advanced electronics packaging, materials analysis, and manufacturing processes. Project tasks could range from cost analysis for a manufacturing line and

Figure 2-11

Organizational Chart for Motorola Inc. (Abridged)



GSS - General Systems Sector
CIG - Cellular Infrastructure Group
CSG - Cellular Subscriber Group
CG - Computer Group
AMT - Advanced Manufacturing Technology

selection of technology and materials to the development of a new process for the sector. The project members usually serve as the interface between design and manufacturing.

The recent surge in demand for cellular services has greatly strained the resources available at AMT. In order to stay ahead in the business and to stay lean in the organization, the time schedule for project development is typically compressed to a matter of months, and each person often ends up with multiple projects. These time and personnel constraints are somewhat compensated for by a flexible budget that allows for capital and material procurement.

2.3.3 Process Development Challenges

The AMT team was given the charter to pioneer the COB technology on a new product for the international cellular market. In addition to developing the specific process steps, the project members interacted with the management team, the product designers, and the manufacturing engineers to exchange and communicate findings.

Although the product design had been defined prior to commencement of the internship, a high degree of interfacing with product design was a necessary part of AMT's role. In advanced electronics packaging, process limitations will dictate the design requirements of product. AMT was a major catalyst for initiating product design changes throughout the duration of the project.

AMT was also responsible for complete equipment selection for the COB process. This selection was based on input from the needs of other functions, especially manufacturing personnel from a European production site. A critical part of AMT's task was working with management within Motorola to assure the capital investment in equipment met the business strategy and justifying how COB fit into that strategy. This required the process development team to occasionally take on tasks in cost accounting to assure this project was a worthwhile investment.

Once the production site was selected and key personnel identified, AMT was challenged with transfer of technical information to the manufacturing engineering group at the production site. The equipment selection and process engineering activity performed by AMT would directly influence production line establishment. Extensive communication with manufacturing engineering was necessary to assure AMT's decisions met the needs for facilities layout, production ramp-up, and line balancing.

From a transitional role between product design and manufacturing, the AMT team was best positioned to assume project management duties. The duties required task organization, prioritization, and scheduling. Through cross-functional meetings led by the AMT development group, project status, schedule updates, and resource needs were communicated.

In parallel with all of these "other" activities, AMT's primary responsibility was to engineer the process technologies for COB. Specifically, five major steps of the process were to be developed: die attach, wire bonding, encapsulation, SMT, and final assembly. These development activities were split among the team members to assure best utilization of resources. As a result, my thesis research focused specifically on the development of the aluminum ultrasonic wire bonding process for COB. Because of the importance of wire bonding yield, the management and reduction of process development risk for wire bonding was a special focus of my research.[2] The next chapter will give an introduction to aluminum ultrasonic wire bonding.

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[2] For information on encapsulant cure studies and benchmarking, please refer to Bonnie Kao's thesis entitled "Technology Benchmarking and Process Development Tools: A Case Study of Encapsulant Curing for Chip-on-Board Applications," 7 May 1993, for the degrees of S.M. in Management and S.M. in Materials Science and Engineering.

Chapter 3
Wire Bonding

The wire bonding process relies on several factors to determine the overall strength of the bond. These elements are 1) pre-bond plasma cleaning, 2) substrate and wire metallurgy, and 3) wire bond machine parameters. This chapter will provide background information on each of these elements. The concepts covered within the chapter will be used for both the relative risk analysis of Chapter 5 and the wire bonding experimentation of Chapter 6.

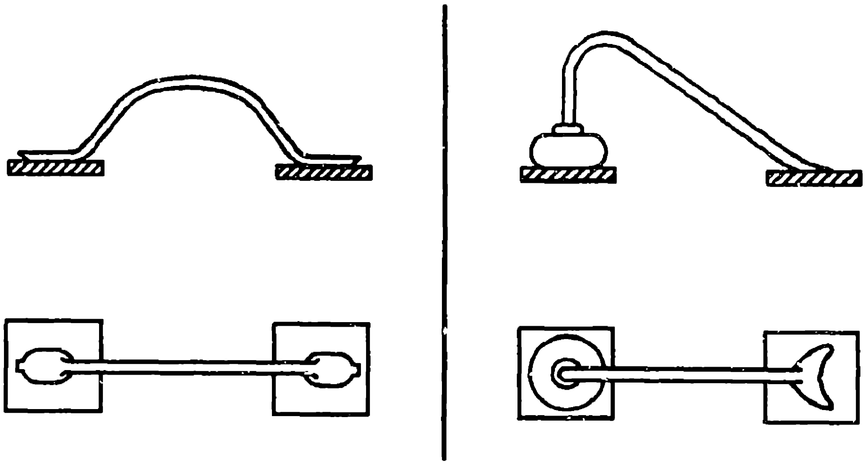
3.1 Wire Bonding - Overview

As discussed in the previous chapter, three types of wire bonding are commonly used: ultrasonic, thermocompression, and thermosonic. Prior to discussing the elements which effect wire bonding strength, each method of wire bonding will be briefly discussed.

In ultrasonic wire bonding, wire is first clamped between a bonding wedge and a substrate surface. An ultrasonic generator then gives a burst of energy, forming a metallurgical cold weld through a combination of this energy and the force of the bonding wedge. The resulting bond is of wedge-wedge configuration, as shown in Figure 3-1. The width of bond foot deformation is often recommended to be 1.5 times the wire diameter.

Figure 3-1

Wire Bonding Configurations



Wedge-Wedge Bond
(Ultrasonic)

Ball-Wedge Bond
(Thermocompression,
Thermosonic)

[Source: Charles, 1989, p. 225]

Thermocompression bonding is accomplished by using a controlled time, temperature, and pressure cycle. Temperatures are typically 300 to 400°C. The required heat is provided by a combination of a heated capillary (through which the wire feeds) and a heated stage. The resulting bond is of ball-wedge configuration (Figure 3-1).

Thermosonic bonding combines the features of ultrasonic and thermocompression bonding. Because of the ultrasonic energy, temperatures can be reduced to between 100 and 150°C. This bond is also of ball-wedge configuration [Charles, 1989, pp. 224-6].

3.2 Plasma Cleaning

3.2.1 Description

Plasma cleaning is a dry process involving gases rather than liquids to clean circuit boards. The intention is to clean organic contamination from surfaces in order to enhance bondability of wires. A radio frequency (RF) energy is used to create gas plasma at low pressures. The resulting electric field imparts energy to free electrons which become excited and collide with gas and substrate molecules. As a result of this "sub-molecular sandblasting," energy is transferred, and free radicals are created. The free radicals then undergo further reactions, resulting in surface modification on even the most stable materials [Advanced Plasma Systems, 1992].

Plasma cleaning requires an RF power generator of several hundred watts, a vacuum pump, and pure gases (usually argon or oxygen). Devices are placed in a chamber, the chamber is evacuated, gases are introduced at about 0.2 Torr, and RF power is switched on for up to 30 minutes to clean the substrate. Because of the chamber evacuation procedure, plasma cleaning is by nature a batch process, although systems are being developed to transfer vacuum via multistage vacuum chambers.

The environmental benefits of plasma cleaning over traditional methods are numerous. No chemical analysis or maintenance is necessary, as chlorinated fluorocarbons, solvents, and acid cleaning chemicals are eliminated. Additionally, process material deposition is not required [Advanced Plasma Systems, 1992].

One must keep in mind, however, that all cleaning processes are subject to mythology. One never really knows if they are effective or not, as a proper measurement of "increased cleanliness" is often difficult to obtain.

3.2.2 Effects on Wire Bonding

The most common gases used in plasma cleaning are oxygen and argon. Oxygen plasma cleaning is expected to eliminate contamination in two ways. First, the RF energy breaks up O_2 into atomic oxygen (O + O). These react with surface hydrocarbons to form H_2O and CO_2. Second, the energetic bombardment by the excited oxygen atoms assists in breaking up the hydrocarbon molecules as well as sputtering off the contaminants.

Excessive use of oxygen plasma cleaning will blacken (oxidize) the silver metallization common in conductive epoxies and may reduce bondability. By changing the oxygen to argon near the end of the cleaning process, the silver may be restored to its original color and bondability loss may be regained.

Ionized argon is not known to form stable compounds. Brief metastable compounds with carbon or other contaminants may be removed, decomposed, and then released out of the gaseous plasma. Because argon has twice the atomic weight of oxygen, it is used to mechanically dislodge the organic contamination. Although this occurs at less than half the rate as for oxygen plasma, argon has the advantage of running at lower temperatures and will not oxidize silver-filled epoxy or exposed metal components [Harman, 1992, p. 125][Buckles, 1987, pp. 476-9].

Once plasma cleaning has been completed using either gas, the recontamination of aluminum surfaces occurs rapidly. For practical purposes, storage after cleaning should not exceed two hours. For longer periods of storage, the device should be recleaned. Although storage in nitrogen filled cabinets may help, this has not been demonstrated to prolong the clean surface period. The reason for this is that waffle packs and other plastics inside the enclosure may outgas organics onto the substrate [Harman, 1992, pp. 129-30].

Plasma cleaning studies have, for the most part, been evaluated using thermocompression wire bonds. Most personnel associated with wire bonding would agree that ultrasonic aluminum bonding is less sensitive to surface contamination than is thermocompression bonding. Because experiments are difficult to design, however, direct comparisons between the methods are rare [Harman, 1992, p. 131].

One recorded experiment was performed by Bushmire and Holloway. By using photoresist diluted with acetone, contamination layers with thicknesses ranging from 50 to 180 Å were created. These numbers represent equivalent carbon thicknesses of 20 to 60 Å. A series of control substrates was created by using a UV-ozone cleaning process, and wire bonding parameters were optimized using the controls. The contaminated substrates were then tested for bondability by using destructive pull tests for each of the different bonding methods.

Ultrasonic aluminum wire bonding tests showed no results of bond foot lifting for up to the maximum of 180 Å of contamination. Thermosonic gold bonding, on the other hand, exhibited bond lifts for greater than 120 Å of contamination and had a 20% decrease in shear strength for 100 Å. Similarly, thermocompression bonding exhibited lifts for greater than 80 Å of contamination and had a 20% decrease in shear strength for 40 Å [Bushmire and Holloway, 1975, pp. 1-23]. From these results, the ability of ultrasonic aluminum wire bonds to "scrub through" existing contamination is evident.

3.3 Substrate and Wire Metallurgy

3.3.1 Intermetallic Compounds

Aluminum ultrasonic wire bonding requires a combination of metallic interfaces to achieve the bond. Pads on the die are of aluminum metallization. The substrate, however, is often gold/nickel/copper to allow for reflow soldering of surface mounted parts. The thicknesses of the metallization is typically 5-15 μin for Au and 50-200 μin for Ni ["Guidelines for Chip-on-Board Technology Implementation," 1990, p. 11]. Thus, the bonding interface at the die is Al-Al, but the interface at the substrate is Al-Au.

When the aluminum wire is ultrasonically bonded to the gold substrate pads, intermetallic compounds are formed at the bond interface. The five intermetallic phases reported in the gold-aluminum system are $AuAl_2$, AuAl, Au_2Al, Au_5Al_2, and Au_4Al. These intermetallic compounds are not the normal cause of failure. Although brittle, they are mechanically strong and electrically conductive. Instead, failures result from the formation of Kirkendall voids and from degradation due to impurities at the interface.

Classical Kirkendall voids may occur on either the gold-rich side or on the aluminum-rich side of the interface. Such voids are caused by an imbalance of mass transport across bond interfaces. Thus, either the Al or the Au diffuses out of one region faster than it can diffuse in from the other side of that region. The Au_5Al_2 intermetallic, for example, will form on the gold-rich side when bake times are greater than an hour at temperatures exceeding 300°C. Similarly, $AuAl_2$ will form on the aluminum-rich side for one hour bake times at greater than 400°C. Much longer times are required for such compounds to form at lower temperatures, although growth of such intermetallics is enhanced by temperature cycling [Harman, 1992, pp. 53-6].

Aluminum wire bonded to thick film gold metallization has always been more subject to Kirkendall voiding than aluminum wire bonded to thin films. The reason is that thick films contain a higher fraction of grain boundaries, vacancies, and impurities which accelerate mass transport across bond interfaces. Hattori and Kashiwabara reported that thinner metallization will restrict the availability of one of the intermetallic compounds, thus limiting Kirkendall voiding [Hattori and Kashiwabara, 1969, pp. 1001-13]. They found that no intermetallic failures would occur under two conditions: 1) the ratio of the width of the aluminum wedge bond to the thickness of the gold film is greater than four, and 2) storage temperatures are less than 350°C.

To further reduce the potential for intermetallic failure, palladium was added to thick film gold in the 1970's for experimentation with aluminum ultrasonic wire bonding. This both slowed the Au and Al diffusions and lengthened the life of the aluminum wire bonds. Although further research is necessary, the results were attained either by formation of a relatively stable Au-Al-Pd ternary of unknown phase or a concentration of Pd at the interface. Since these experiments, palladium has been added as a dopant for many thick film gold applications. For similar reasons, palladium doping of aluminum wire has been attempted, but to date this has resulted in high wire bonding variability.

3.3.2 Wire Metallurgy

Typically, aluminum bonding wire is offered in three configurations: 99.99% pure, silicon doped, and magnesium doped. Pure aluminum wire is rarely used in ultrasonic bonding because it is too soft, with tensile strength in the 8-14 gram range (for 1.25 mil diameter). Aluminum alloy wire was developed in the late 1950's for greater strength and also as a means to avoid the formation of voids in the intermetallic interface. With silicon, the tensile strength is increased to between 19 and 27 grams (1% Si). The disadvantage of using AlSi (1%) wire, however, is that the equilibrium solid state solubility of Si in Al at 20°C is 0.02% by weight. As a result, Si has the tendency to precipitate, forming a silicon second phase. To relieve this problem and give further rigidity, magnesium may be used as an alloy. An AlMg (1%) wire may have tensile strengths exceeding 40 grams, and the equilibrium solid solubility of Mg in Al is about 2% by weight [Tummala and Rymaszewski, 1989, p. 397].

Although many variations in wire are offered, it is important to note that the literature does not address the effects of the Si and Mg dopants on intermetallic defects such as Kirkendall voiding. Ternaries of unknown phase are expected, but the lack of literature suggests that these have minor consequences on the Al-Au interface.

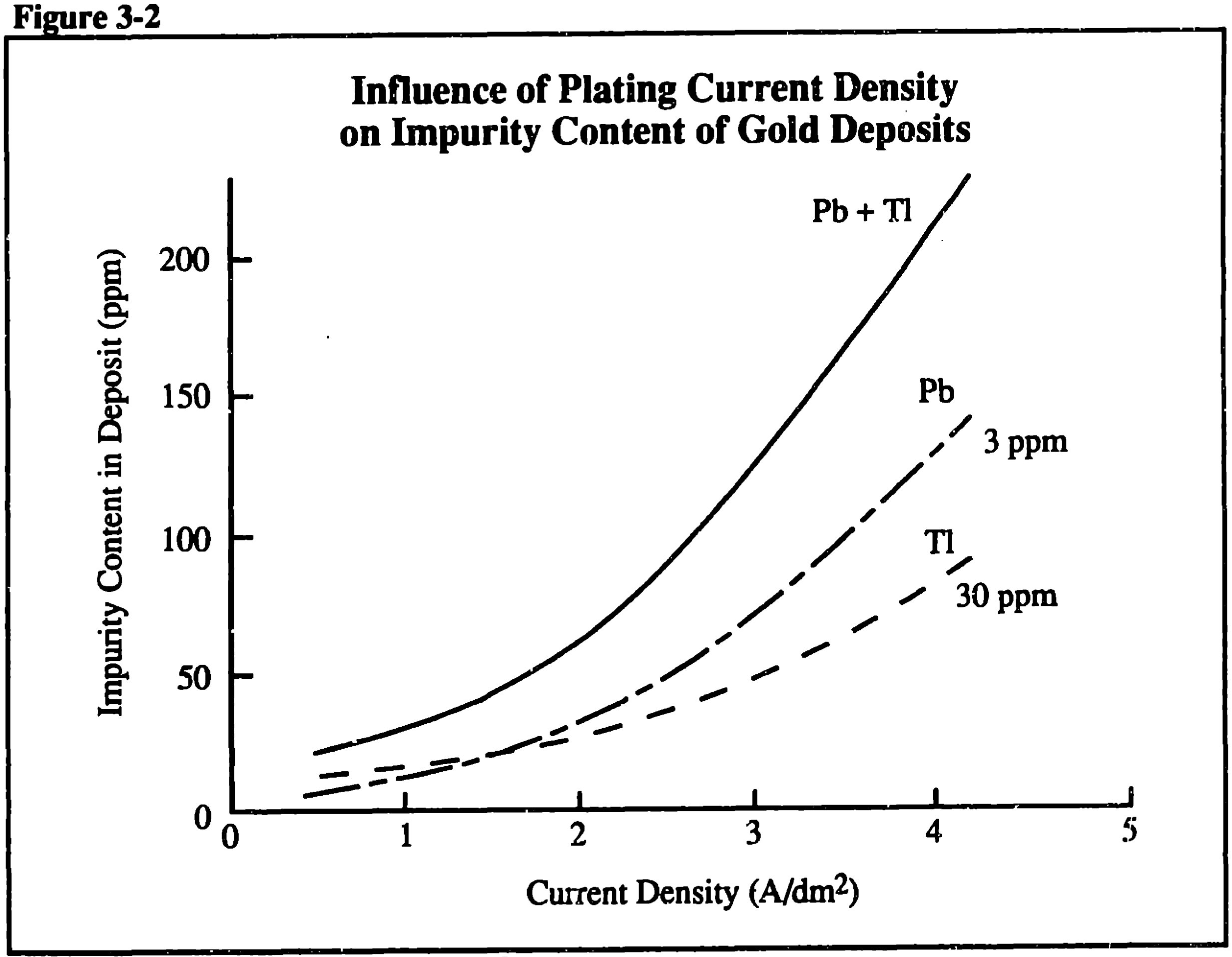
3.3.3 Plating Impurities

Plating impurities in gold films have been one of the earliest classes of documented bonding problems. Plating deficiencies have resulted in both bondability difficulties (quality defects) and premature thermal cycling failures (reliability defects). Because of the large number of plating variables, little agreement exists in the literature as to the influence of a particular variable on wire bonding.

Gold plating baths normally consist of potassium-gold-cyanide, buffers, citrates, lactates, phosphates, and carbonates. To increase plating speed and reduce grain size, thallium, lead, or arsenic are often added. Organic "brighteners" are also commonly added to enhance the appearance of the final product. Each of these items can have adverse effects on the bonding process, with thallium and nickel being the most frequently cited impurities for causing bonding failures [Harman, 1991, pp. 95-109].

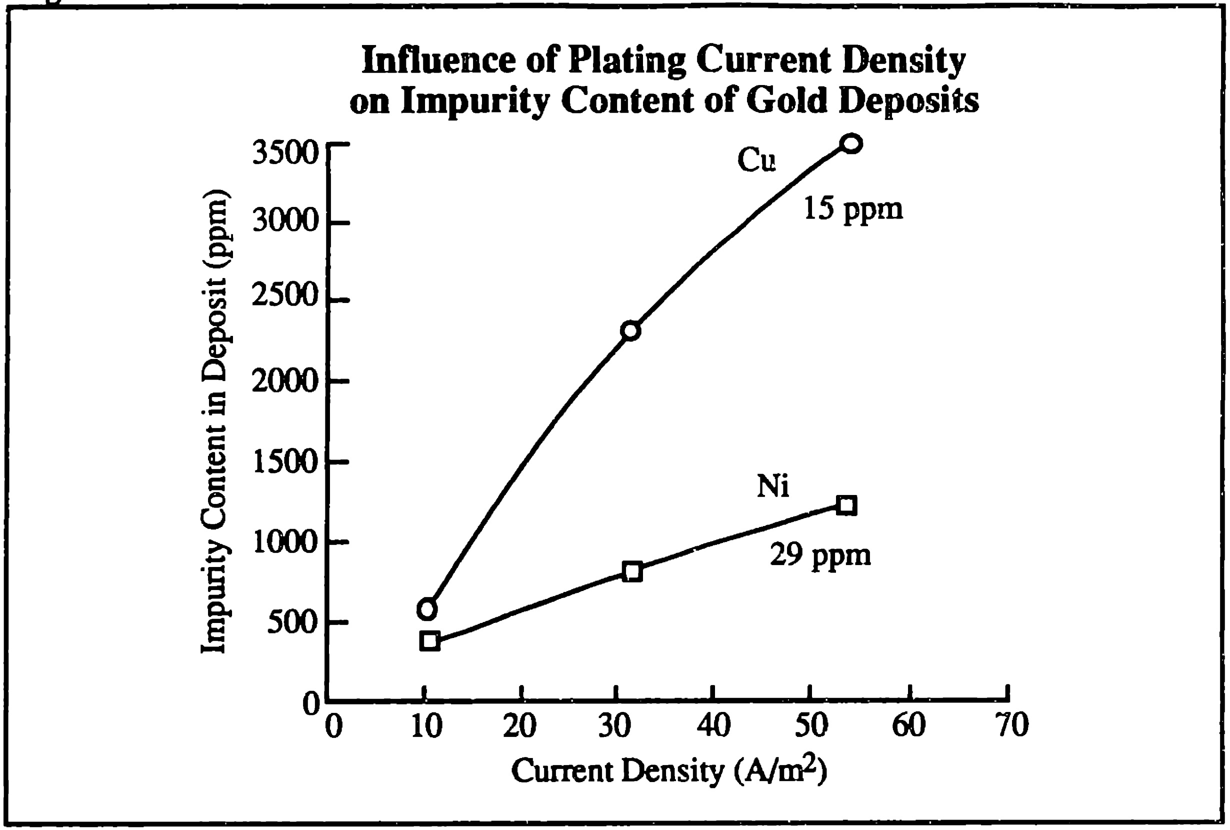
To maintain bond reliability, Wakabayashi et al recommended that the total impurity count be less than 50 ppm [Wakabayashi et al, 1982, pp. 63-8]. Figures 3-2 and 3-3 show, however, that bath concentrations alone will not ensure low impurity content in gold platings. Figure 3-2 shows thallium and lead content as a function of current density. Figure 3-3 shows similar data for nickel and copper impurities. From these graphs, one sees that an increase in plating current densities causes significant increases in impurity content of the substrate. Figure 3-4 reflects the results on bond pull strength for 1.25 mil diameter AlSi 1% wire bonds made to 1.25 µm thick gold films. The initial concentrations of grain refiners (Tl = 20 ppm, Pb = 1.0 ppm, As = 1.0 ppm) are based on recommendations for optimum grain size. Except for a slight increase in bond strength for As at around 7 A/dm^2, strength decreases as plating current density is increased [Harman, 1991, pp. 98-111].

Figure 3-2



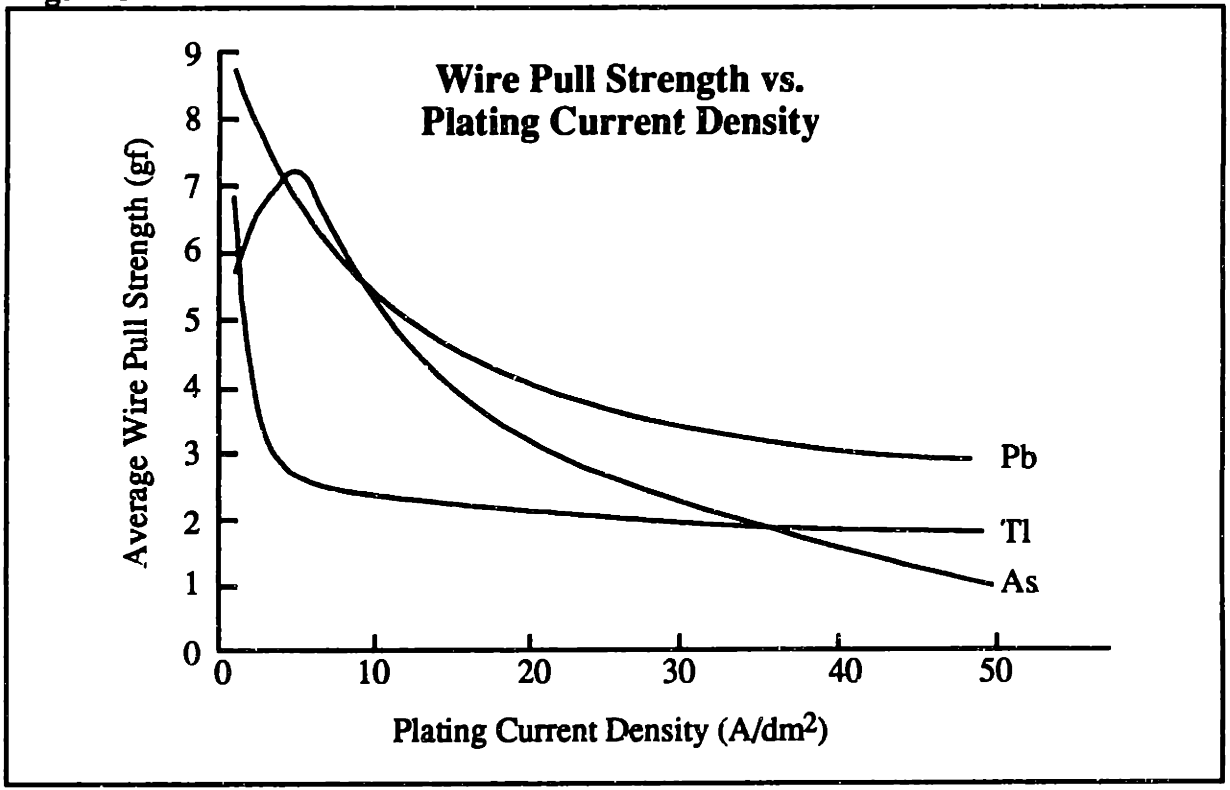
[Source: Wakabayashi et al, 1982, pp. 63-8]

Figure 3-3



[Source: Dini and Johnson, 1979, pp. 89-95]

Figure 3-4



[Source: Endicott, 1981, pp. 58-61]

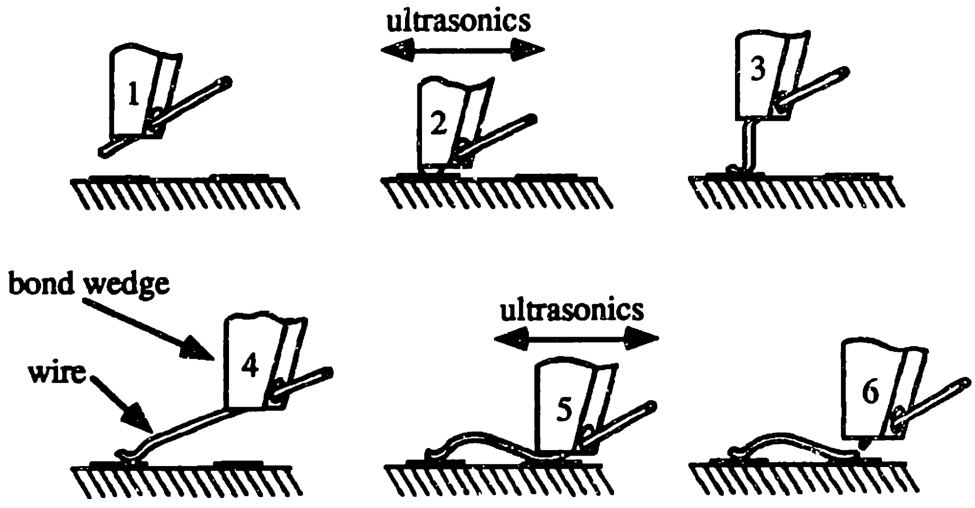
3.4 Ultrasonic Wire Bonding - Machine Parameters

3.4.1 Bonding Cycle

The six steps comprising the ultrasonic aluminum wire bonding cycle are shown in Figure 3-5. The bond head is first lowered to the substrate (z-axis motion). As the bond wedge meets the substrate surface, ultrasonic energy is applied for a set duration. The static force of the bond head may be adjusted to control the amount of downward force applied to the wire during the ultrasonic burst. Following completion of the first bond, the head moves upward and the table is repositioned in the x-y plane so that the wedge hovers above the second bond position. The bond head is again lowered, and ultrasonic energy is applied. A clamping mechanism then allows the wire to tear near the second bond, preparing the wire for a new first bond. This entire sequence takes less than one second as programs are used to set the bond sites in advance. The resulting bond appears similar to the wedge bond shown in Figure 3-1.

Figure 3-5

Ultrasonic Bonding Sequence



[Source: Tummala, 1989, p. 393]

The bonds in Figure 3-5 are formed through high frequency abrasion which results in a local temperature rise, forming a cold weld at the bonding interface. The primary reason for the COB project interest in ultrasonic wire bonding was this low-temperature feature. Such low temperatures allow the use of substrates with lower glass transition temperatures, which are also typically lower cost substrates. This lower cost is a very important issue for manufacture of any competitive consumer product.

3.4.2 Parameters Affecting Bond Quality

Several parameters can be adjusted on the wire bonding equipment to affect the overall quality of the bond. The ultrasonic energy may be controlled in three different ways: bond time, ultrasonic power, and static force. For most all wire bonders, bond time and power can be managed separately (through key punches or dial adjustments) for the first and second bonds. This allows bond profile compensation for differences in wire presentation due to wire tear after the second bond. Static force, however, cannot be readily adjusted on all bonders. For some machines, force can be controlled separately through a keypad. Most machines, however, require force to be set through a mechanical adjustment which is maintained for both first and second bond. The combination of time, power, and force will determine the bond deformation, directly influencing bond strength.

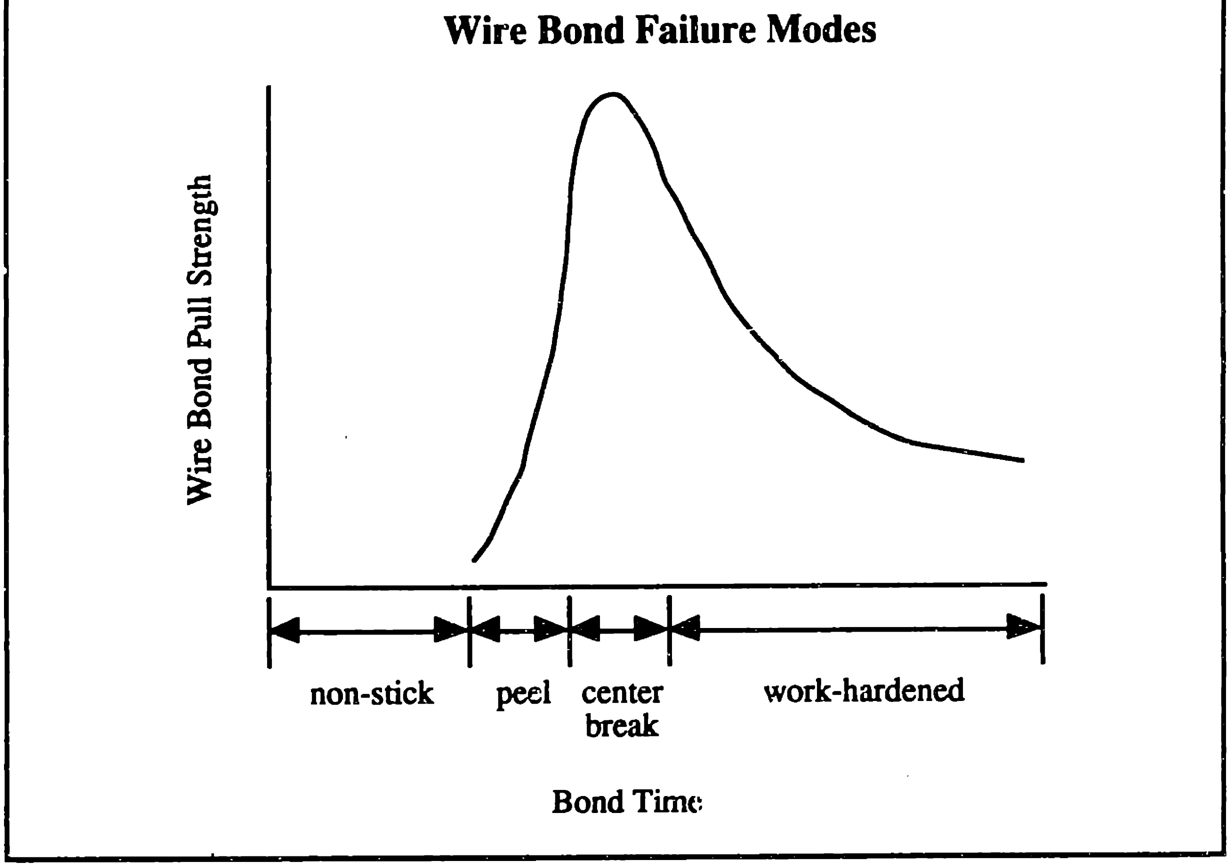
Four other common parameters for wire bonding are loop height, tool inflection point, contact velocity, and overtravel. Loop height is self-explanatory, represented by the distance from the substrate surface to the wire peak. The tool inflection point (TIP) is the z-axis position to which the bond head changes velocity for bonding. Above the TIP, the bond head moves at a rapid rate. Following TIP, the bond head velocity is represented by the contact velocity parameter. Both TIP and contact velocity can be set for each bond. Overtravel represents the amount of z-axis motion that the bond head travels once initial contact with the substrate surface has been made. This parameter cannot be set separately for each bond.

Finally, the shape of the bond foot may be altered by utilizing different bond wedges. Although a select few are recommended by the manufacturer of the bonding equipment, several low-cost replacement wedges are available on the market. These wedges differ in the width and length of the foot as well as in z-dimension alterations to accommodate the holding of the wire during bonding.

3.4.3 Predictive Effects

The ultrasonic energy parameters (time, power, and force) have been the key focus for most ultrasonic bonding experimentation. When destructive pull strength is considered as the response and variables such as plating and wire are held constant, each of the ultrasonic energy parameters is expected to result in a curve similar to that shown in Figure 3-6. The failure mode for the wire will be different along various points of the input parameter.

Figure 3-6



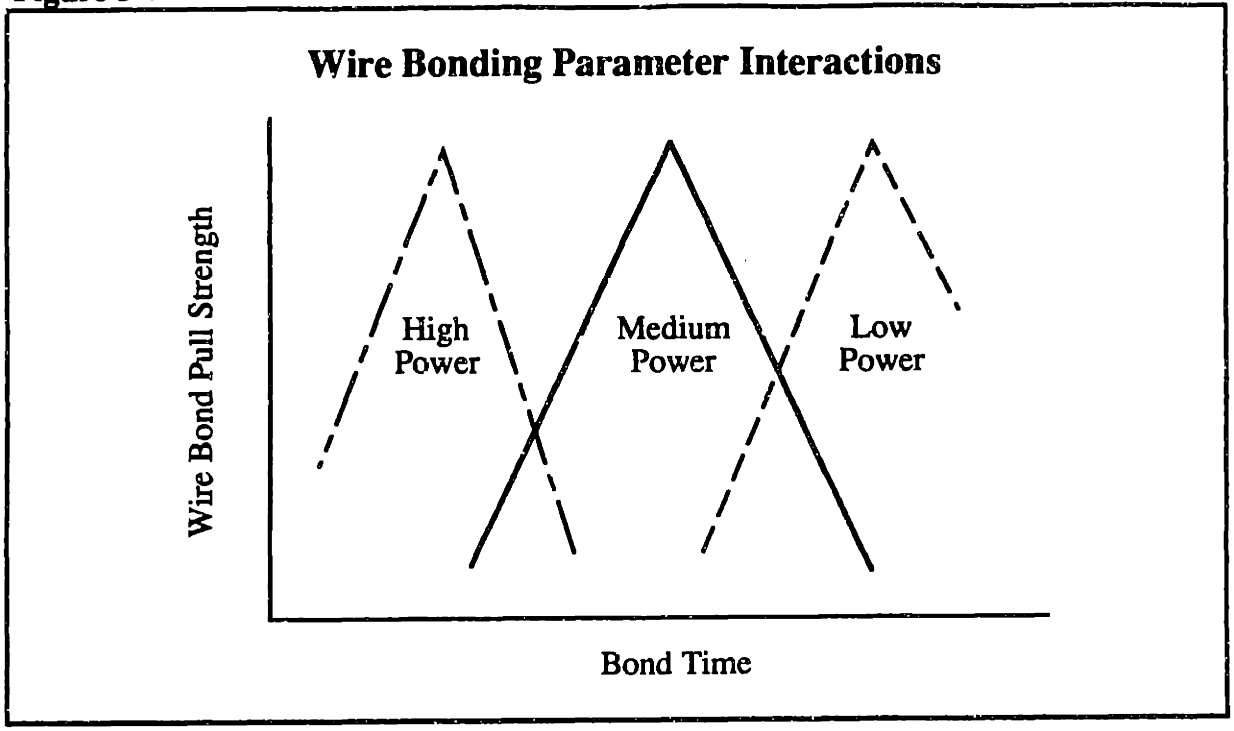
Bond time was used as the input parameter in the example. For significantly low values of bond time, pull strength will be zero as the wire will not adhere to the substrate surface. When bond time is increased, the failure mode changes to one in which the wire adheres during bonding but peels from the surface during pull test. At the peak of the curve, bond strength is at its optimal point, and the failure mode will be a break in the center of the wire being pulled. Finally, the wire becomes excessively deformed or work-hardened as the bond time is further increased.

The curve in Figure 3-6 suggests that a single point exists in which bond pull strength can be maximized. This value of pull strength can be extremely difficult to attain, because its value depends not on a single parameter but rather on a combination of input variables.

To reflect this, consider Figure 3-7. A second parameter, power, has been introduced. For medium power levels, it is expected that pull strength versus time will follow the plot in the center (This plot represents a simplified version of pull strength versus time curve shown in Figure 3-6.). As power is decreased, however, a greater amount of time is necessary to achieve strong wire bonds. The pull strength versus time curve is expected to shift to the right, and the profile of the curve may also change to reflect shifts in variability due to the new parameter combination. Similarly, when power is increased, time must be decreased to realize equivalent wire bond strengths .

By engineering principles, a strong degree of interaction will naturally exist between the individual energy variables. Variables of this type would usually be transformed within the experimental matrix such that only "energy" was used instead of power, time, and force separately. In order to explore the potential interactions of each energy component with other wire bonding parameters, however, the individual components of energy were utilized within the experimental matrices.

Figure 3-7



3.5 Summary

This chapter has shown a broad range of aspects that may influence bond quality and reliability. These include plasma cleaning, intermetallic compounds, wire metallurgy, plating impurities, and bonder machine parameters. Each of these aspects will be considered when finding the project risk due to wire bonding (Chapter 5). Furthermore, experimentation to reduce these inherent risks can be found in Chapter 6.

Prior to evaluating the risk due to wire bonding, an overview of risk management concepts will be presented in the following chapter.

Chapter 4
Risk Management

4.1 History

Risk management principles have been practiced for centuries. In any decision, the rewards of success and the penalties for failure must be weighed with the probabilities of each to adequately determine what specific action should be taken. For most people, this decision process is entirely intuitive. In recent years, however, formalization of risk methodologies has taken shape.

One of the first formal applications of modern risk management principles was performed by the United States Nuclear Regulatory Commission. The Reactor Safety Study "WASH-1400" estimated the public risk that could be involved with potential accidents in commercial nuclear power plants. WASH-1400 first used event trees to identify failure modes. Next, fault trees were used to identify the likelihood of failure for the various systems identified in the event tree accident paths. The study commenced in the summer of 1972 and took nearly three years to complete. Over 70 man-years and about four million dollars went into this effort ["Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," 1975, pp. 1-5].

Since WASH-1400, risk management principles have flourished within business. To gain an understanding of the underlying principles in addressing such risk, this chapter provides an overview of risk management. The concept of risk will first be defined, followed by a description of the risk management process. The components of risk management will then be examined in further detail.

4.2 Definition of Risk

"Risk is the potential for realization of unwanted, negative consequences of an event [Rowe, 1988, p. 24]." Risk involves two major components: 1) the existence of a possible unwanted consequence or loss, and 2) an uncertainty in the occurrence of that consequence which can be expressed in the form of a probability of occurrence [Rowe, 1988, p. 24]. Based on these two components, the concept of risk exposure (RE) can be defined as:

$$RE = Prob(UO) * Loss(UO)$$

where Prob(UO) is the probability of an unsatisfactory outcome and Loss(UO) is the loss to the parties affected if the outcome is unsatisfactory [Boehm, 1989, p. 4].

4.3 Types of Risk

In assessing risk for software project management, F. Warren McFarlan stated that risk results from "exposure to such consequences as:

- Failure to obtain all, or even any, of the anticipated benefits.
- Costs of implementation that vastly exceed planned levels.
- Time for implementation that is much greater than expected.
- Technical performance of resulting systems that turns out to be significantly below estimate.
- Incompatibility of the selected system with the selected hardware and software [McFarlan, 1974]."

These types of risk also bear resemblance to those as defined by other sources.

For example, the Department of Defense (DOD) defines four components of risk: 1) cost, 2) schedule, 3) performance, and 4) support. Support risk is analogous to McFarlan's risk of incompatibility. Each of these components of risk are then rated using the categories of catastrophic, critical, marginal, and negligible in order to assess the overall project risk ["The Software Risk Abatement Process," 1988].

Since incompatibility is interrelated with technological performance, these two can be combined into a single component. Risk is, therefore, defined by three separate dimensions: financial, schedule, and technological performance. Each of these dimensions must be considered when assessing and controlling the risk inherent to any project. The following section will provide an overview of the risk management process.

4.4 The Risk Management Process

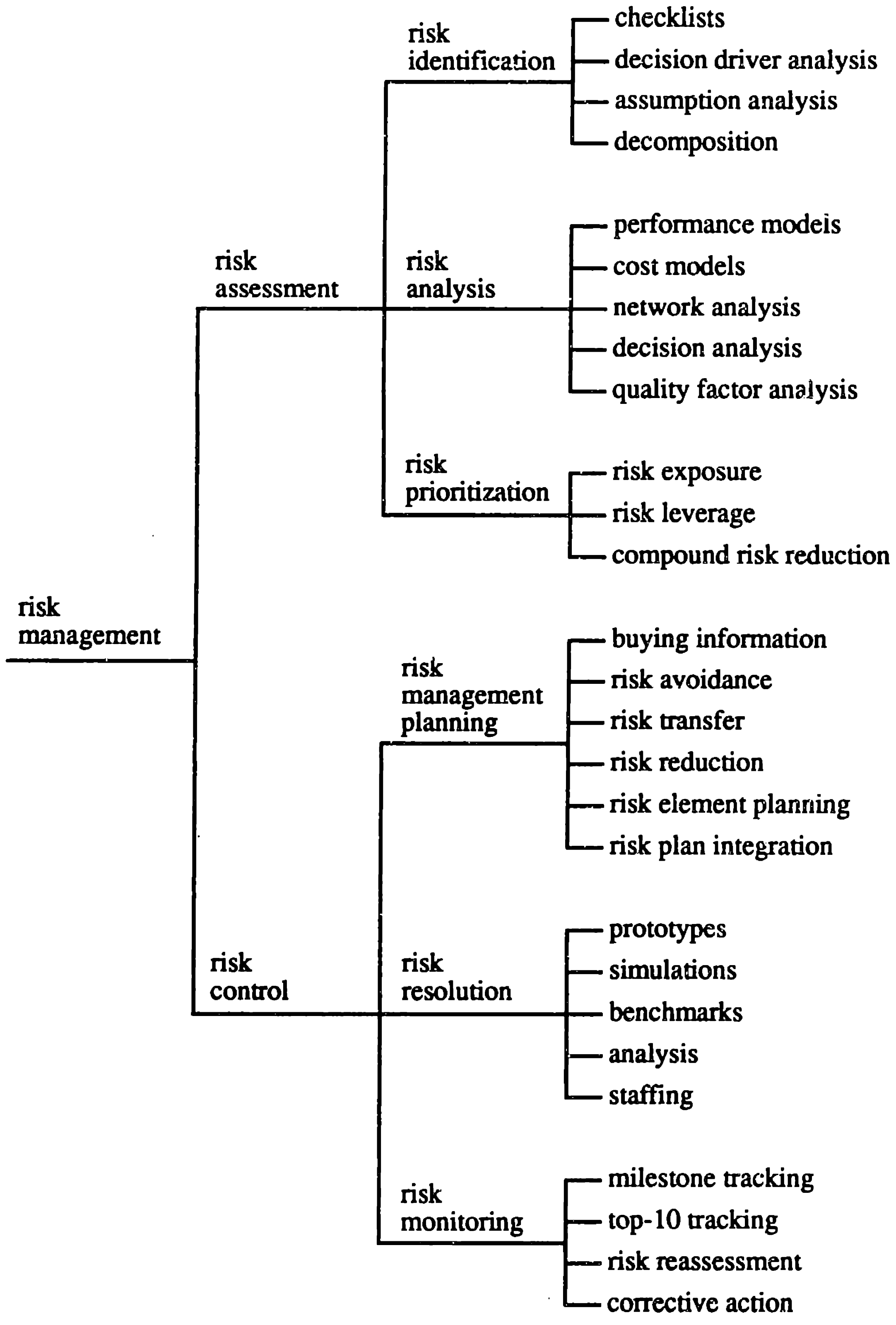
The most comprehensive description of risk management is the six-step procedure introduced by Boehm (Figure 4-1). In this process, risk is first characterized through identification, analysis, and prioritization. Combined, these three steps are referred to as risk assessment. Following this assessment, risk is controlled through the processes of risk management planning, risk resolution, and risk monitoring. The combination of the assessment and control comprise the risk management process [Boehm, 1989, p. 2].

Other risk management models have been utilized which are similar in content and structure to Boehm's model. Rowe uses the model shown in Figure 4-2. In this model, risk estimation is analogous to the risk analysis process proposed by Boehm. The steps which Rowe includes under risk management are also similar to those proposed by Boehm under risk control. Although not readily apparent, the activities of resolving and monitoring risk are included within the risk management steps [Rowe, 1988, p. 45]. Charette uses a six-step model which is somewhat of a hybrid between that of Rowe and Boehm (Figure 4-3) [Charette, 1989, p. 58].

The process of risk management is very dynamic. Elimination of some project risk may cause additional risk to be generated. As a result, a periodic revaluation is essential to assure control of any anomalies. With this in mind, another way to view Boehm's model is shown in Figure 4-4. In this depiction, the monitoring of risk serves as feedback to the initial process of risk identification. The feedback loop will be active

Figure 4-1

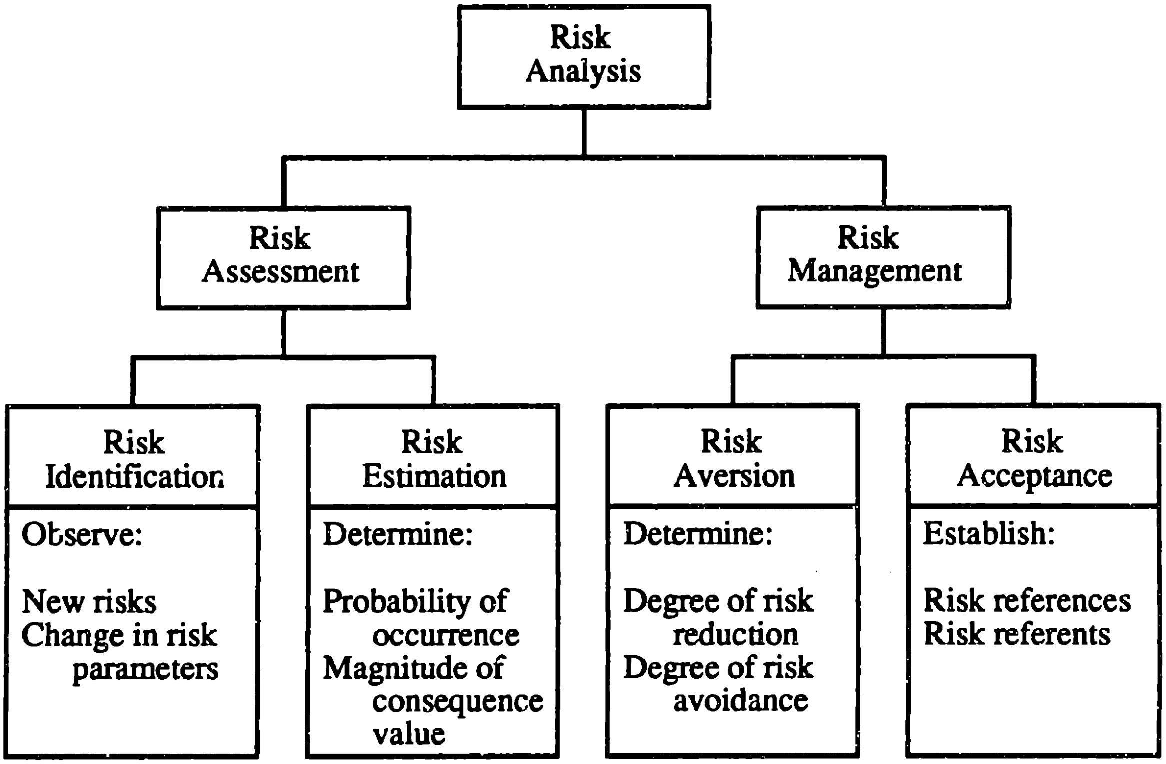
Boehm's Risk Management Steps



[Source: Boehm, 1989, p. 2]

Figure 4-2

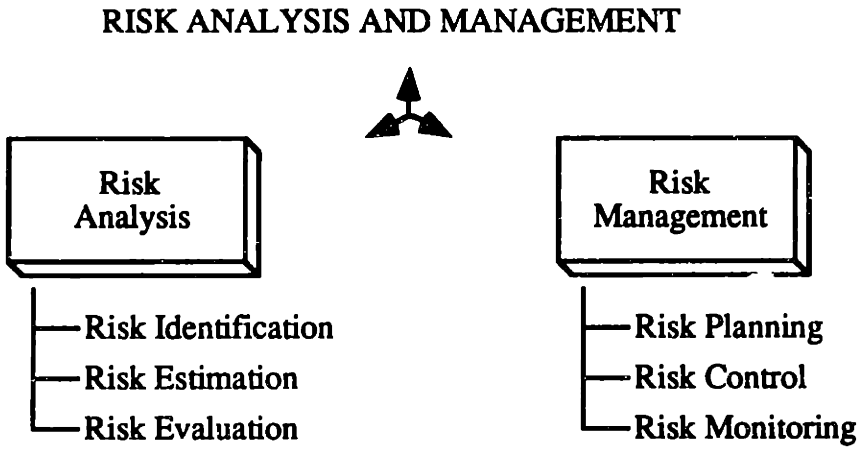
Rowe's Risk Analysis Hierarchy



[Source: Rowe, 1988, p. 45]

Figure 4-3

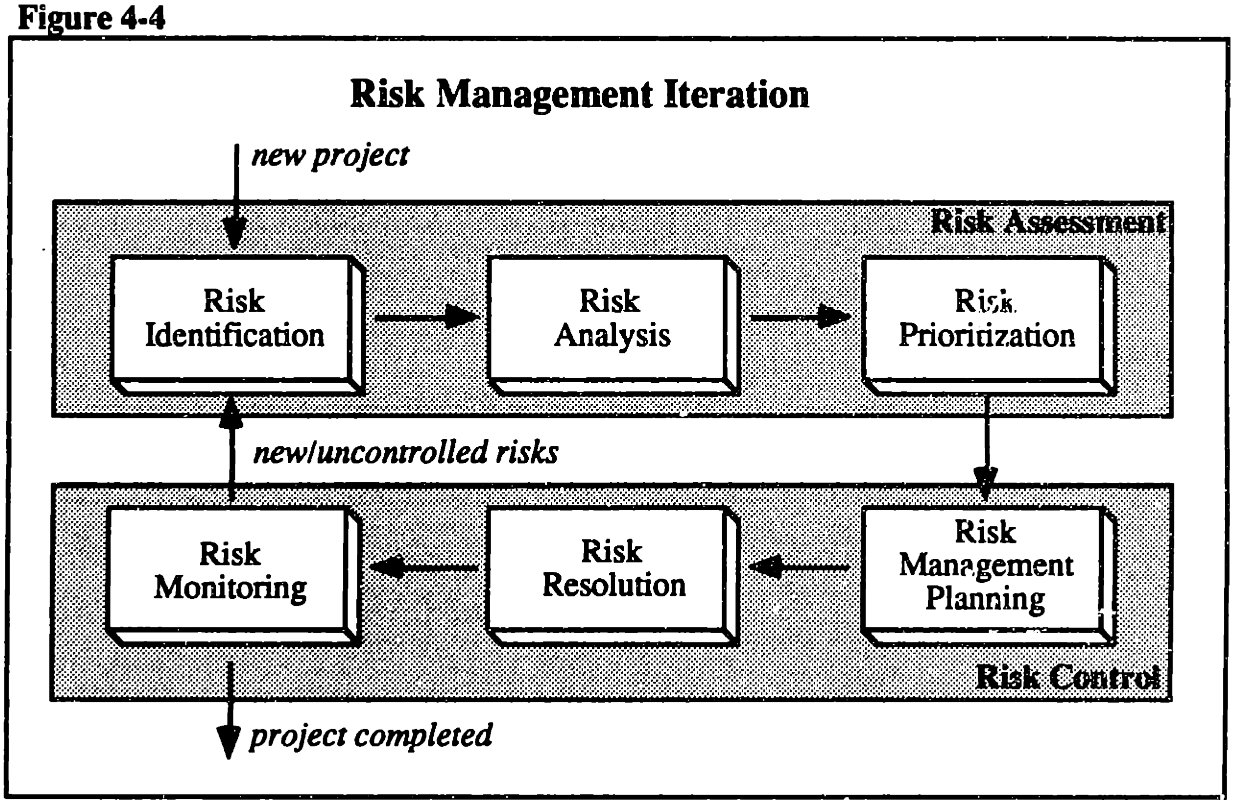
Charette's Model for Risk Analysis and Management



[Source: Charette, 1989, p. 58]

until the level of project risk has been reduced to a satisfactory level. The specific level will be determined by corporate, team, or personal risk standards. When these standards are not explicit, the decisions are often made on a qualitative basis.

Figure 4-4



Any of the methodologies proposed by Boehm, Rowe, or Charette can be used to effectively manage project risk. Because Boehm uses risk management as an overarching principle, the constituents of his model can be explained more readily. Each of the six process steps will be explored in further detail in the following sections.

4.4.1 Risk Identification

Risk identification involves the discovery and/or recognition of threats to a plan, new relationships among known threats, or a change in the consequences of the threats [Rowe, 1988, p. 46]. The process of risk identification is comprised of information gathering and risk categorization.

Sources of information may include any of the following:

- traditional or folk knowledge
- analogies to well known cases
- common-sense arguments
- results of experiments or tests
- reviews of inadvertent exposure
- epidemiological surveys[1] [Charette, 1989, p. 103]

This information is often obtained using either a list of questions or a checklist tailored to the financial, schedule, and technological risks discussed in Section 4.3. The importance of each of these types of risk will vary depending on the context of the problem. For example, schedule risk may address resource constraints, need dates, or technological availability which will not be as critical for all projects.

The use of checklists and questionnaires does assist in formalization of the risk identification process. However, a team must also consider the implications that a rigid methodology might have on creativity during risk identification. As no checklist will be complete, a team which uses checklists must also provide opportunities to find risks which are located outside the list's boundaries. Brainstorming sessions to identify such risks are helpful.

Boehm also recommends decision driver analysis and assumption analysis as additional methods to identify hidden project risks. If a decision has been driven by factors other than technical and managerial achievability, then it will frequently be the source of a critical risk item. Examples include decisions driven by politics, marketing, or short-term focus [Boehm, 1989, p. 122]. Similarly, optimistic assumptions which all team members share must be examined for their potential risk.

4.4.2 Risk Analysis

Once project risks have been identified, they are analyzed using one of several available techniques. The essence of risk analysis is to fully capture the probabilities and

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[1] In other words, statistical surveys over large populations. These are referred to as "epidemiological" because one must be careful not to confuse a symptom (effect) with the disease (cause).

consequences of the possible project outcomes. The risk analysis methodologies vary on the level of qualitative versus quantitative analysis to evaluate such outcomes.

4.4.2.1 Preliminary Hazard Analysis (PHA)

PHA is a qualitative tool used to identify and prevent broad-based hazards. The method is very popular in facilities dedicated to production of chemicals but also has been used by other industries such as aerospace. PHA is performed through a combination of inductive, forward logic (e.g., What happens if the pipe breaks?) with deductive, backward logic (e.g., How could the plant be shut down?).

To perform a PHA, five classifications of each risk are identified in tabular format: hazard, cause, major effects, hazard category, and corrective/preventive measures. The hazard category is assigned by the project team based on the significance of the causes and effects of the accident:

- Category I - Negligible
- Category II - Marginal
- Category III - Critical
- Category IV - Catastrophic

Once categorization has been performed, task responsibility will be assigned to reduce the risks. Some organizations use additional columns to record the assigned follow-up responsibility and implementation schedule [Guidelines for Hazard Evaluation Procedures, 1992, p. 114].

4.4.2.2 Failure Modes and Effects Analysis (FMEA)

FMEA is an inductive analysis that systematically details all possible failure modes and identifies the resulting effects on the system. Possible single modes of failure for each system component are analyzed to determine the effects on surrounding components and the system.

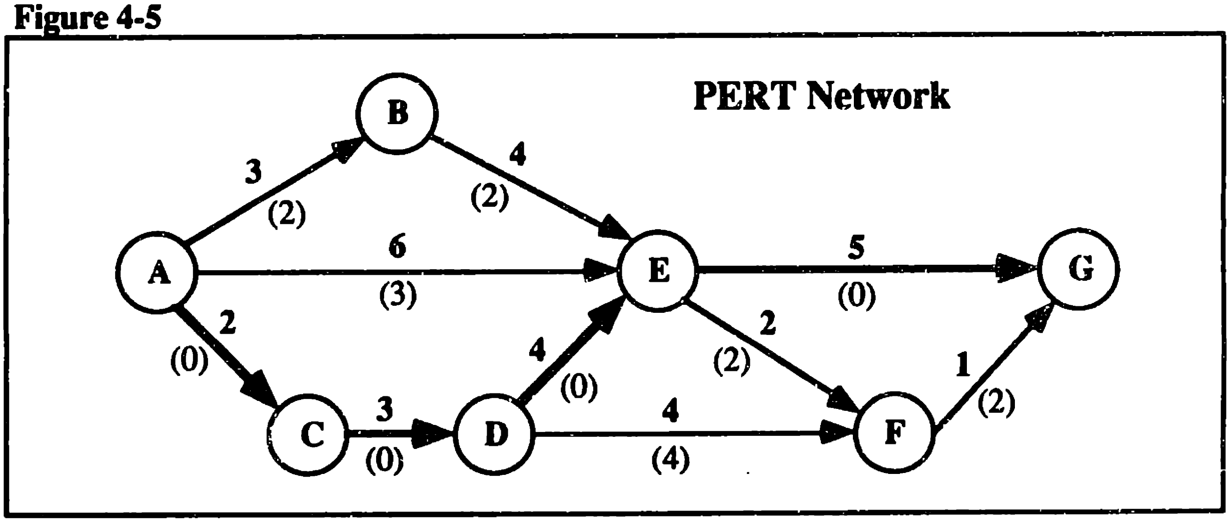
Through FMEA, a qualitative list of failure modes and effects are listed in tabular format. Although no strict rules exist, typical column headings may include: item, failure mode, cause of failure, local effects, method of detection, and system effects. Probability of occurrence is added whenever the data is readily available or can be easily estimated. Furthermore, the table can be supplemented with failure mode criticality and possible risk reductions. Such an analysis is often referred to as a Failure Modes and Effects and Criticality Analysis (FMECA) [Henley and Kumamoto, 1981, pp. 31-4].

4.4.2.3 Project Evaluation and Review Technique (PERT)

PERT is a form of risk analysis that focuses specifically on schedule risk. It is best utilized in situations when several project steps exist. For each of these steps, the PERT diagram shows task relationships and times for completion.

An example of a PERT network is shown in Figure 4-5. In this diagram, items A through F represent projects tasks and the arrows show sequence dependency. Bold arrows identify the critical path, the shortest possible time the project will take if everything goes according to schedule. The first number for each path reflects the time to complete the next node once the previous node has been completed. Numbers in parentheses show the slack time associated with each path. Once this network has been developed, planning resource allocation can take place [Charette, 1989, pp. 201-2].

Figure 4-5



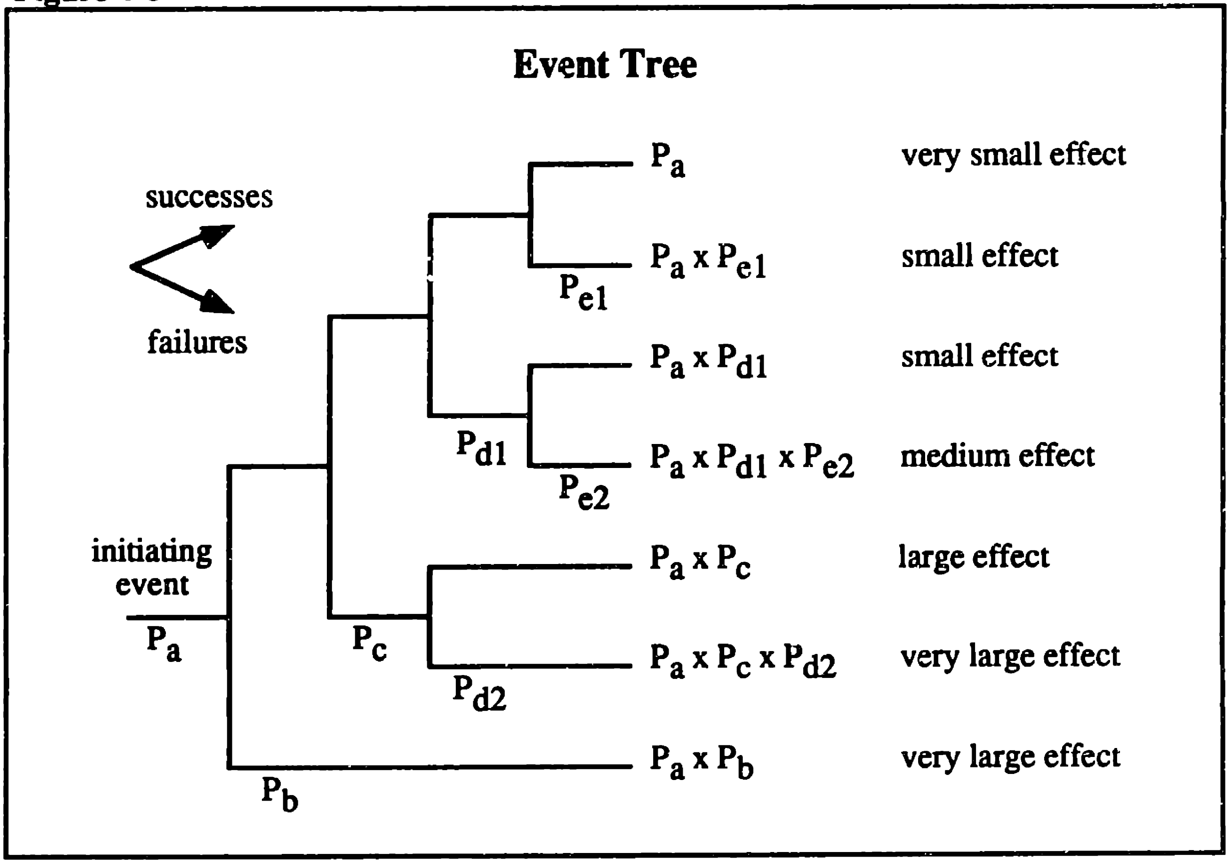
[Source: Charette, 1989, p. 202]

It is important to realize, however, that PERT is more than just a deterministic tool. As each of the individual path events has an associated probability distribution, the overall project duration is probabilistic in nature. The project probability distribution can be readily calculated for critical assignments by using PERT software programs.

4.4.2.4 Event Tree Analysis

Like FMEA, event tree analysis is a inductive risk tool. A single initiating event, such as "the pipe breaks" or "the circuit chip fails," would constitute the first level. The resulting events are then depicted in a tree structure such as the one shown in Figure 4-6. The events which follow the initiating event will have a compounding effect, resulting in more detrimental consequences. If the probabilities can be adequately evaluated, the event tree can be used as a qualitative tool.

Figure 4-6



[Source: Henley and Kumamoto, 1981, p. 25]

4.4.2.5 Decision Tree Analysis

With this technique, a tree is used to portray alternate courses of action, the relationship of alternatives, and the consequences of a specific decision. To construct a decision tree, the initial decision is modeled as a root node from which a number of options exist. Each node has several potential outcomes to which probabilities are assigned. The sum of the branch probabilities going into a node must equal one. The consequence for each potential outcome is then defined, usually in terms of dollars. A decision is made by comparing the expected values of the alternatives.

Decision trees are special cases of the inductive event tree. In event trees, the sum of all probabilities do not add to one because working states are not considered. Since decision trees consider every possible outcome, the probabilities will sum to one [Henley and Kumamoto, 1981, p. 27].

For an example of decision tree evaluation, consider Figure 4-7. The expected value of Alternative 1 is:

$$\begin{aligned} E(A1) &= 0.7(\$200K) + 0.3(-\$150K) \\ &= \$90K \end{aligned}$$

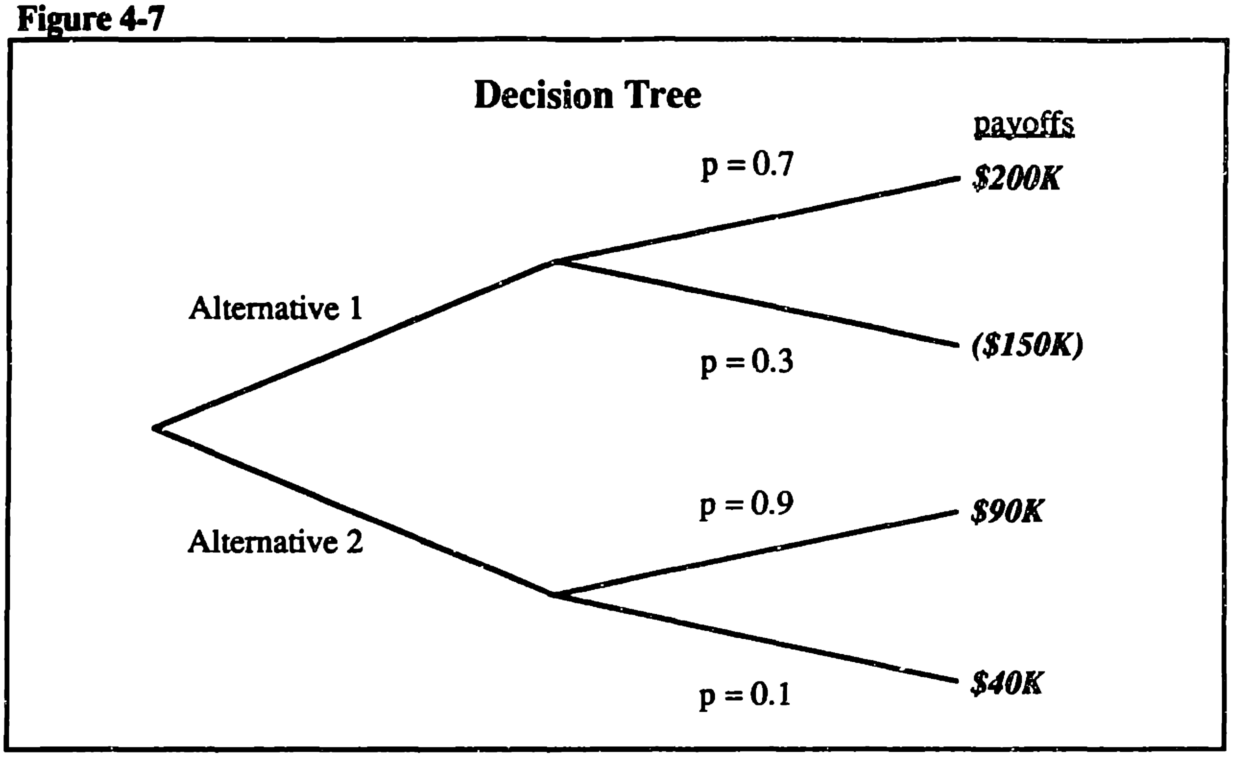
Similarly for Alternative 2:

$$\begin{aligned} E(A2) &= 0.9(\$90K) + 0.1(\$40K) \\ &= \$85K \end{aligned}$$

Based on decision theory, Alternative 1 would be selected.

To compensate for extremely large gains or losses, the utility of the consequence may be used in place of the consequence itself. In previous example, a risk averse person or a person with little money to lose may prefer Alternative 2. By using utility instead of dollar values, $U(A2) > U(A1)$. Quantification of utility, however, poses additional challenges that are beyond the scope of this thesis.

Figure 4-7

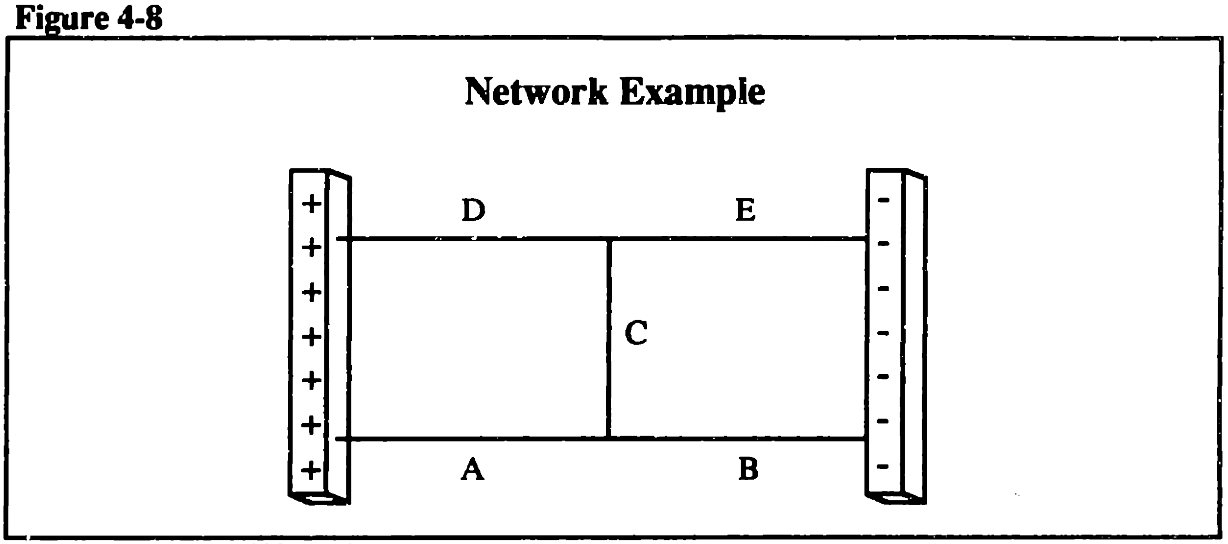


4.4.2.6 Fault Tree Analysis (FTA)

FTA is a deductive methodology for determining the potential causes of system failures and for estimating the failure probabilities. FTA is centered about determining the causes of a catastrophic event, often referred to as the top event. The system is then dissected in increasing detail to determine the root causes or combination of causes of the top event. These root causes are combined using Boolean algebra symbols such as AND and OR gates. The system may then be analyzed both quantitatively and qualitatively [Lewis, 1987, p. 340].

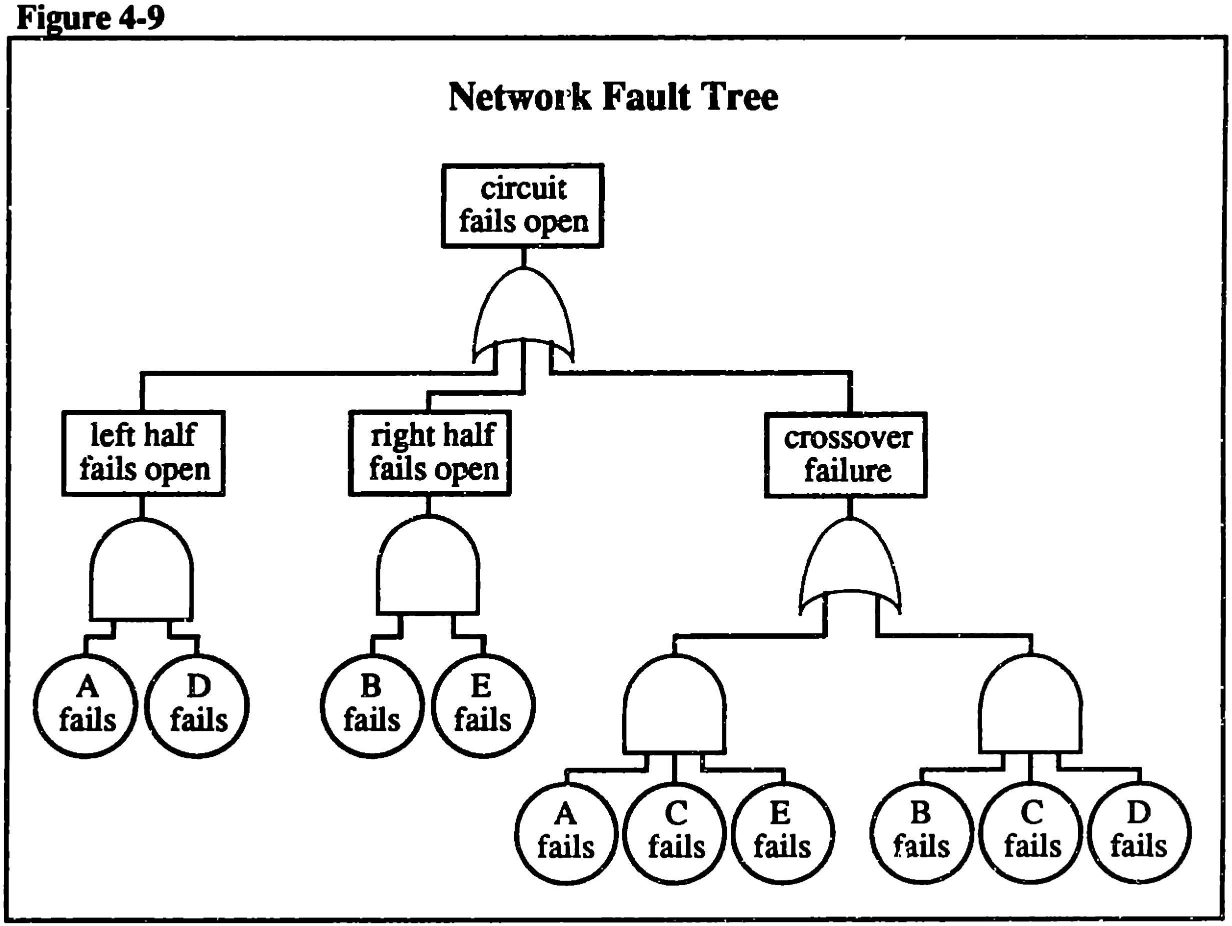
To illustrate FTA, consider the network shown in Figure 4-8. The primary concern is that an open-circuit failure does not occur. Such a failure is defined as the top event. Three different open-circuit possibilities exist: a left-half failure, a right-half failure, or a crossover failure. Each of these failure modes is created by a combination of individual wire failures. For example, a left-half failure occurs when both A and D fail. Continuing in this manner, the fault tree in Figure 4-9 is created.

Figure 4-8



[Source: Denison, 1992, p. 59]

Figure 4-9



[Source: Denison, 1992, p. 62]

Quantitative analysis is performed by first writing the Boolean equation for the top event:

$$\text{Failure (F)} = AD + EB + BCD + ACE$$

System failure probability is then defined as:

$$P(F) = P(AD + EB + BCD + ACE)$$

Through assumption of event independence and application of rare event approximations, the failure probability can be written as:

$$P(F) = P(A)P(D) + P(E)P(B) + P(B)P(C)P(D) + P(A)P(C)P(E)$$

Steps may then be taken to reduce the overall risk by focusing on the path which contributes the greatest probability.

4.4.2.7 Cause-Consequence Analysis (CCA)

CCA combines the inductive reasoning features of Event Tree Analysis with the deductive reasoning features of Fault Tree Analysis. This results in a technique that relates specific risk consequences to their many possible causes. The advantage of this method is that it is able to proceed both forward (toward the consequences) and backward (toward the basic causes) for any event [Guidelines for Hazard Evaluation Procedures, 1992, p. 184]. This results in a diagram which can be described as a multiattribute fault tree. Like event trees and fault trees, cause-consequence diagrams are best analyzed quantitatively.

The disadvantage of CCA is the complexity involved with combining event and fault trees. As a result, CCA can only be used to display and analyze simple models.

4.4.2.8 Summary of Risk Analysis Techniques

Figure 4-10 summarizes the analysis techniques discussed in the preceding pages. Although this list in not all-inclusive, these are the major techniques used in industry to perform risk analyses.

Figure 4-10

Risk Analysis Techniques Summary

name	*method*	*nature of results*
Preliminary Hazard Analysis (PHA)	both	qualitative
Failure Modes and Effects Analysis (FEMA)	inductive	qualitative
Project Evaluation and Review Technique (PERT)	both	quantitative
Event Tree Analysis	inductive	either
Decision Tree Analysis	inductive	quantitative
Fault Tree Analysis (FTA)	deductive	quantitative
Cause-Consequence Analysis (CCA)	both	quantitative

4.4.3 Risk Prioritization

The primary function of risk prioritization is to produce an ordered list of risk items to be addressed during the risk control functions. Since the previous steps of identification and analysis will usually result in an unmanageable number of risks, prioritization is necessary to maintain focus on risk resolution activity.

The main tools of risk prioritization are risk exposure (RE), previously discussed in Section 4.2, and Risk Reduction Leverage (RRL). Since RE may be calculated during the risk analysis steps, risk prioritization will often be done concurrently with risk identification and analysis. RRL is a measure of the relative cost-benefit of performing potential reduction activities. Quantitatively, RRL is defined as:

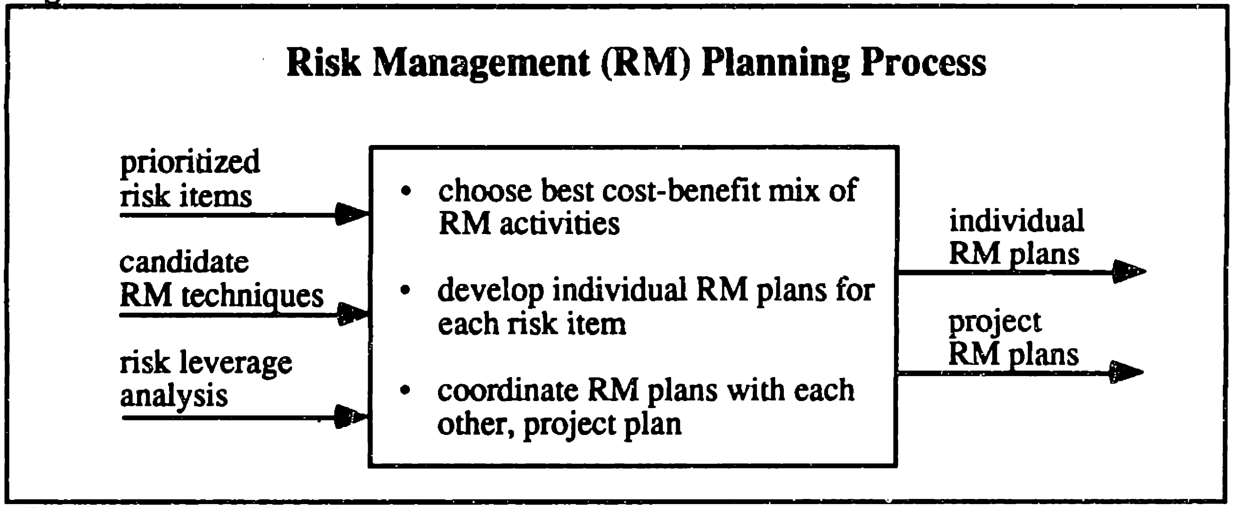
$$\mathrm{RRL} = \frac{\mathrm{RE}_{\mathrm{before}} - \mathrm{RE}_{\mathrm{after}}}{\text{Risk Reduction Cost}}$$

where RE_{before} is the risk exposure before initiating the reduction activity and RE_{after} represents the new level of risk exposure. From RRL, the team can determine how to gain the most leverage from its resources [Boehm, 1989, p. 8].

4.4.4 Risk Management Planning

Upon completion of the risk assessment, risk control is initiated with risk management planning. Three specific activities are performed: 1) choose the best cost-benefit mix of risk activities, 2) develop individual risk management (RM) plans for each risk item, and 3) develop a project plan by coordinating individual RM plans. The RM Planning process is shown in Figure 4-11.

Figure 4-11



[Source: Boehm, 1989, p. 134]

For each individual risk, the project team has several options:

1) reduction (also abatement or mitigation) - Use direct approaches to lower the likelihoods or the impacts of the consequences.

2) protection - Protection also emphasizes reduction of probabilities and consequences, but at a system level. This often requires changes in the structure of the project to provide additional alternatives.

3) transfer - With transfer, risk probabilities are accepted but the effects are reduced by sharing the consequences with others. Another common name for risk transfer is insurance.

4) contingency planning - Like transfer, the probabilities are accepted. Additionally, the consequences are accepted and offset by a contingency fund of project resources. This fund may be comprised of money, people, raw materials, etc.

5) purchase of additional information - Buying of information may occur when a high degree of uncertainty exists in either risk probabilities or consequences.

6) acceptance - If any risk is below business, team, and/or individual thresholds, the risk should be accepted and the consequences dealt with as they occur [Charette, 1989, p. 233].

The outcome of risk management planning will be an assignment of each risk to a specific action plan.

4.4.5 Risk Resolution

Risk resolution is performed by carrying out of the plan determined by the risk management team. Each of the team members will typically be responsible for several risk management activities which center around the items mentioned at the end of the Section 4.4.4.

Risk resolution can be achieved through actions such as prototyping, performing simulations, benchmarking, staffing, life testing, iterating on the design, conducting further analyses, forming partnerships with suppliers, buying insurance, replicating product lines or facilities, or gathering additional data.

4.4.6 Risk Monitoring

By monitoring risk, a project team assures that: 1) risk resolution activities proceed as planned, and 2) additional risks, caused either by external forces or the resolution activity itself, are handled as they arise. A common tool for risk monitoring is to use a list to track the top project risks, the team member responsible for risk resolution, the current and previous prioritization of the top risks, and the scheduled date for completion of each risk. This activity will require the team to occasionally reassess the project risk to guarantee that the focus of the team agrees with the dynamics of the project.

4.5 Summary

The six-step process is an effective way to assess and control the risks that any situation presents. For projects which have aggressive cost, schedule, and/or technology goals, these tools should be used to help eliminate the potential for project disaster. As a minimum, a risk assessment should be performed so that project members understand what they are up against. Once the risks are recognized, risk control can become a central, active part of a project manager's duties. The dynamics of most projects will often necessitate such continuous risk monitoring and reduction.

In the following chapter, the risk assessment tools will be applied to the wire bonding process by identifying, analyzing, and prioritizing the process risks.

Chapter 5

Relative Assessment of Process Development Risk

5.1 Traditional Applications of Risk Management

Since WASH-1400, formal risk analyses have become commonplace in many businesses worldwide. A number of professionals have pursued careers in this "new" field. Furthermore, many consulting firms today have departments which specialize in risk management.

The proliferation of risk management has, however, been somewhat limited to certain types of business. To get a feel for this, one only has to skim the topics of a IEEE Spectrum special report on risk management: aging aircraft, the telephone network, nuclear weapons reactors, the space shuttle, and the Bhopal pesticide plant ["Special Report: Designing and Operating a Minimum-Risk System," 1989]. Although these represent unique industries, a common thread exists. In each of the five cases, the probability of disaster is relatively low, and the result of such occurrence is relatively high in terms lives lost and/or dollars. Situations of this type have dominated the risk literature.

In this chapter, a methodology will be developed for assessing risks in process development. These situations differ significantly from those mentioned above, as process development risks are of much higher probability and lower consequence. Furthermore, process development in state-of-the-art electronics is usually constrained from both a schedule and cost standpoint. The three years taken to develop WASH-1400 is infeasible for a product which has life cycles of less than one year.

To facilitate the need for fast and accurate risk evaluation with limited resources, the risk assessment may be performed on a relative basis. The concept of relative risk assessment will first be described and an example will be given. Following these, the methodology will be applied to the wire bonding process.

5.2 Relative Risk Assessment

The most difficult challenge with probabilistic risk assessments is accurate estimation of the probability and losses associated with an unsatisfactory outcome. Boehm first suggested using relative risk as an alternative to such rigorous probabilistic methods. By assessing the probabilities and losses on a scale of zero to ten, risk exposure (RE) quantities can be estimated and prioritized on a relative basis [Boehm, 1989, p. 8].

As an example, consider the risk exposure factors in Figure 5-1. The probabilities have each been ranked on a relative basis using a scale of zero to ten. The losses are ranked in a similar fashion. RE is then calculated as the product of probability and loss. The risk exposures and RE contours can then be plotted as shown in Figure 5-2.

From this graph, two key points arise. First, the highest risk items are not necessarily those with the highest probability or consequence, but rather a sufficient combination of both. Although Item G was given the highest probability ranking, it had one of the lowest impacts on risk. This is an important point as many people identify risk with probability and fail to consider consequence. Second, uncertainty can cause risk to span several levels of exposure. Item C, for example, has a high degree of uncertainty associated with it. This uncertainty is an additional source of risk.

Figure 5-1

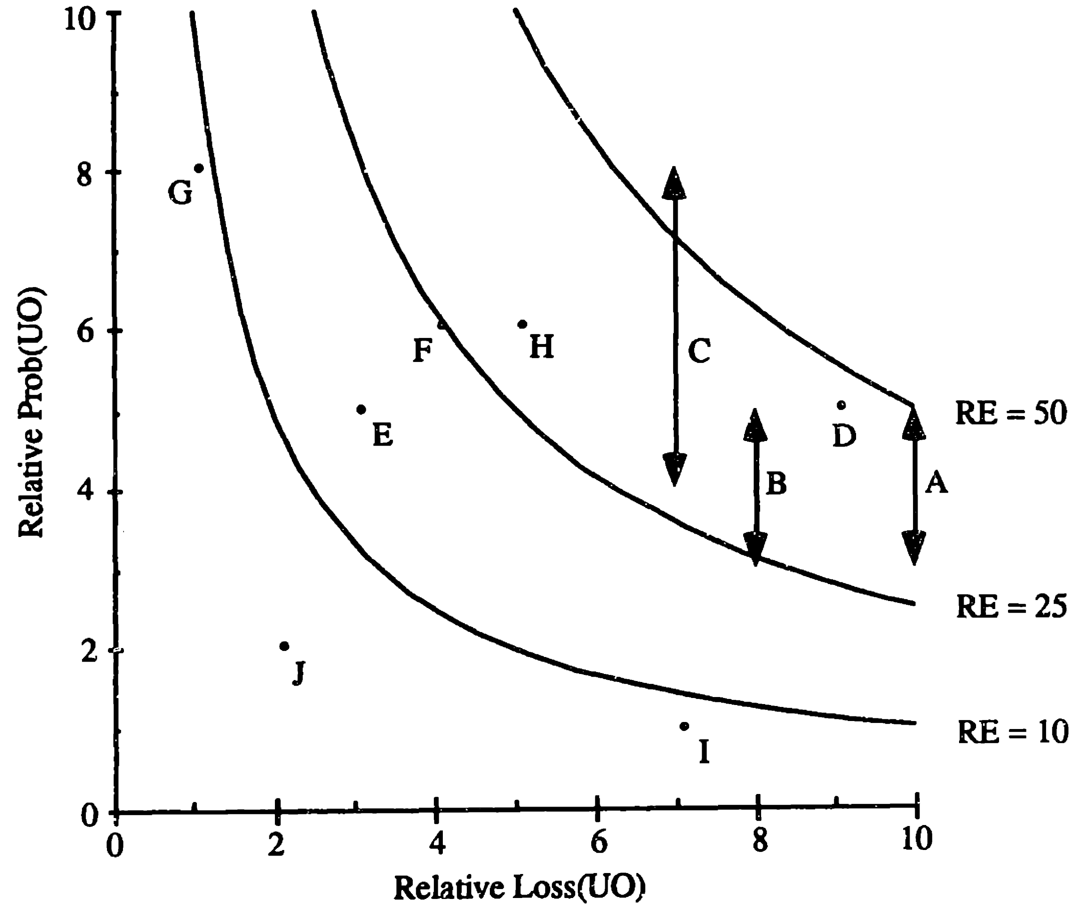
Risk Exposure Factors

	Unsatisfactory Outcome (UO)	prob(UO)	loss(UO)	RE
A	OS error causes meltdown	3-5	10	30-50
B	OS error causes shutdown	3-5	8	24-40
C	OS safety features cause unacceptable performance	4-8	7	28-56
D	display software reports unsafe condition as safe	5	9	45
E	display software reports safe condition as unsafe	5	3	15
F	application error causes inefficient operation	6	4	24
G	accounting system error causes extra work	8	1	8
H	hardware delay causes schedule overrun	6	5	30
I	processor memory insufficient	1	7	7
J	DBMS software loses history data	2	2	4

[Source: Boehm, 1989, p. 9]

Figure 5-2

Risk Exposure Factors and Contours



[Source: Boehm, 1989, p. 9]

5.3 Risk at Various Organizational Levels

Approaches to risk are greatly influenced by one's place within the organizational hierarchy. The context of the particular situation at hand as well as the demands of an occupational role will lead to use of different risk management tools. With such distinct differences based on hierarchy, a methodology is needed so people can evaluate risk using similar tools across organizational boundaries and levels.

Three particular levels of risk may be considered in any corporation. The first is risk at the corporate level. This risk is often minimized using qualitative methods such as strategic planning or corporate technology benchmarking and roadmapping. A second level of risk is found at the project management level. In the example from the previous section, several decisions must be made regarding the direction of the project team. Risk is an inherent part of this decision-making process, but the individual unsatisfactory outcomes may have limited relationship as we have seen. The third level of risk is at the task level. As risk assessments are performed at this level, the details become more relational, and the specific causes and effects can be more readily stated.

The methodology used in the previous section does not acknowledge the complexity involved in task-level risk assessments due to cause-effect relationships. On the other extreme, a methodology such as cause-consequence analysis provides a structure for quantitative analysis with multiple consequences. This method, however, becomes increasingly limited as problems become more involved. Also, cause-consequence has the additional disadvantages associated with probabilistic assessment.

To resolve this dilemma, a relative methodology using a tree structure would be preferred. With such a methodology, cause-effect relationship is maintained while minimizing unnecessary complexity. The next section will detail two potential methods for performing such an assessment. The methodologies will then be applied to the wire bonding process, the area of highest perceived risk for COB.

5.4 Relative Risk Assessment - Example

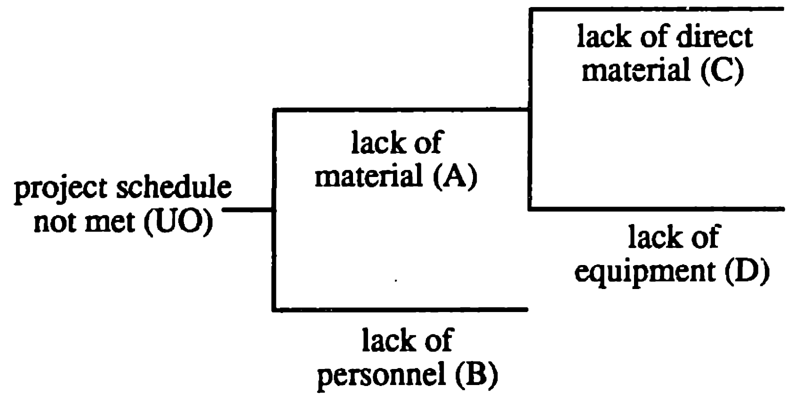
5.4.1 Risk Identification

Consider a situation for which the Unsatisfactory Outcome (UO) is "project schedule not met." When this outcome is probed for potential causes, two are identified: a lack of material and a lack of personnel. Furthermore, the lack of material may be caused by either a lack of direct material or a lack of equipment (capital assets).

This simple situation can be represented by the tree shown in Figure 5-3. The tree is very similar to the fault tree discussed in Chapter 2. A deductive methodology was used for its creation, and the tree portrays cause-effect relationships through its branches.

Figure 5-3

Relative Risk Tree Example



A distinct difference, however, is that the consequences of failure in fault trees has a single dimension. For example, in WASH-1400 the number of deaths was used as the UO. This is a unilateral consequence, as either a person will live or die as a result of a failure. On the other hand, for Figure 5-3 the amount of time by which the schedule is missed will vary depending on the initiating event. A lack of direct material will have an impact of entirely different magnitude than a lack of personnel would have. The relative risk assessment must, therefore, account for these differences.

Another distinction from fault trees is that only OR gates were used in the creation of Figure 5-3. These gates are implicit with the junction of any branches within the tree. For example, either a lack of material OR a lack of personnel will cause the project schedule to slip. The strict use of OR gates reduces complexity in tree establishment and evaluation.

5.4.2 Risk Analysis

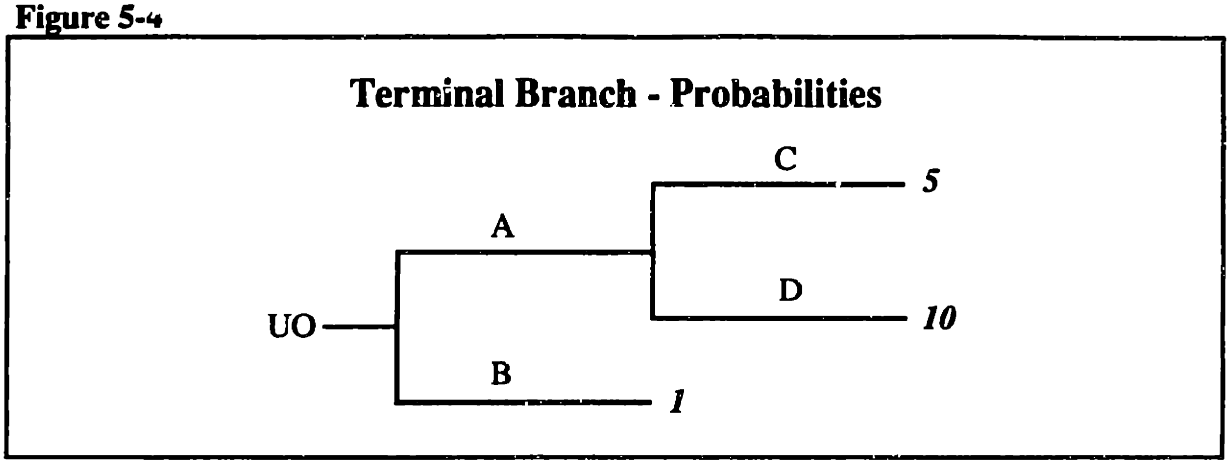
Once the risk tree has been established, relative analysis may be performed. The Motorola project team identified two potential evaluation methods: terminal branch analysis and rated hierarchy analysis. With each method, probabilities and consequences are evaluated separately, and the overall risk exposure (RE) is then found as the product of each probability and consequence. The details of the two methodologies are described below.

5.4.2.1 Terminal Branch Method

With terminal branch analysis, relative comparisons are made at each of the terminal tree branches. For example, consider again the risk tree in Figure 5-3. To make a terminal branch comparison for probabilities, the chain of events leading to branches B, C, and D would be compared on a relative basis. It is very important that the chain of events is considered rather than the terminal event itself. In complex trees, the events may repeat themselves in different sections of the tree. Furthermore, consistency with probability theory is maintained by evaluating the entire chain.

Figure 5-4 depicts the relative ranking of probabilities using the terminal branch method. The relative scale need not be limited, such as the zero to ten suggestion of Boehm. Instead, the rankings should represent the true ratio of the representative probabilities. The numbers represent the relative likeliness of the chain of events leading

Figure 5-4



from each terminal branch to the UO. For example, chain D-A-UO is twice as likely to happen as chain C-A-UO and ten times more likely than B-UO. Because the tree contains all information regarding the potential UO, each ranking can be expressed as a probability of occurrence given that the UO occurs. For example, P(D-A-UO given UO) = 10/16.

The consequences can be evaluated in a relative manner similar to the probability evaluation. This consequence ranking is shown in Figure 5-5. When estimating consequences, it is important to keep a consistent theme throughout the process. In the project scheduling example, the obvious consequence is the number of days or weeks late. The project loss could also be stated in terms of lost revenue or increased costs due to the delays. Although any of these consequences is acceptable, consistency should be maintained during the evaluation process.

The numbers from the consequence evaluation have different meaning from those of the probability evaluation . With consequence, the rating represents the relative impact that each initiating event will have on the UO. As in probabilities, each chain of events must be considered when performing the rating. Thus, chain B-UO has twice the impact as chain C-A-UO and has 6/11 of the cumulative consequence weight for the tree.

Once the probability and consequence trees have been completed, a composite RE tree can be created by multiplying the probability and consequence terminal branch

Figure 5-5

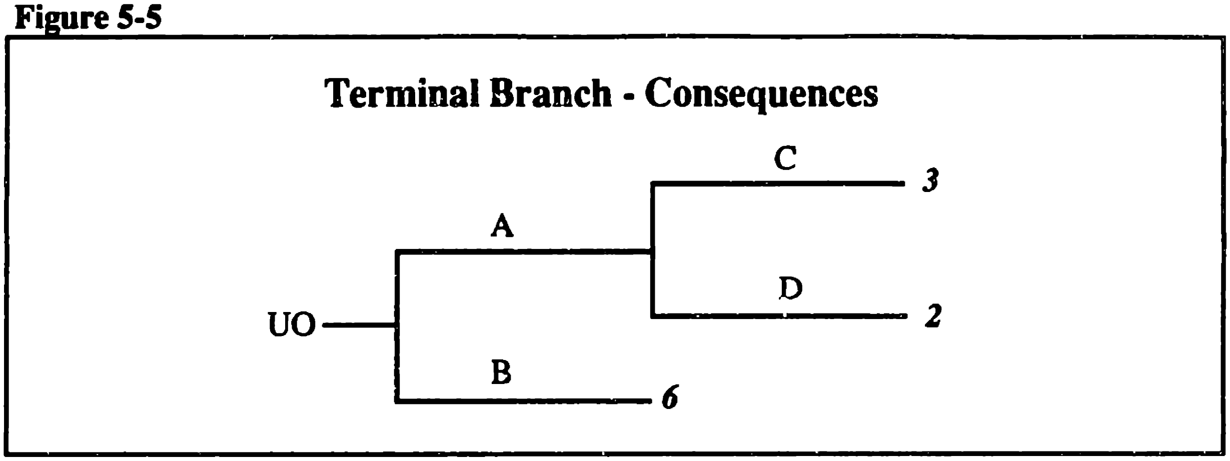
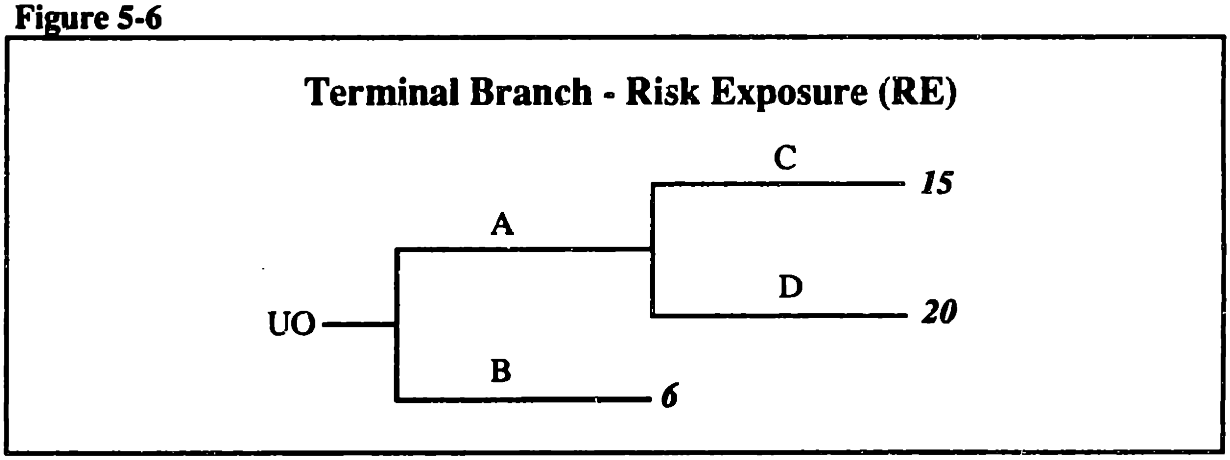


Figure 5-6



values (Figure 5-6). From the RE tree, one sees that the lack of equipment (D) presents the highest degree of project schedule risk.

5.4.2.2 Rated Hierarchy Method

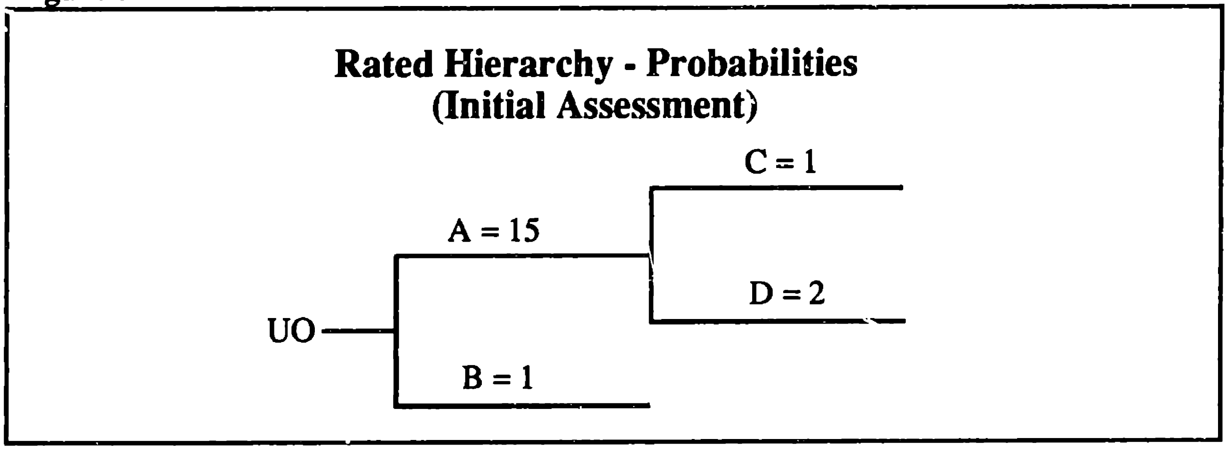
Although the terminal branch analysis method has the benefit of simultaneously considering all terminal nodes, there are two main disadvantages. First, as the number of terminal branches increases, the relative comparison becomes exponentially complex. In the previous example, only three terminal branches required evaluation. In the wire bonding application which follows in Section 5.5, however, 66 terminal nodes were identified. Comparison using such a large data set is a very complicated task.

A second disadvantage is the need to evaluate the complete chain of events for each terminal branch. For trees with many levels of hierarchy, it is difficult to compare more than two chains at a time. Each additional chain must be compared to existing evaluated chains, requiring a great deal of re-learning throughout the assessment.

To eliminate the disadvantages of the terminal branch approach, we created a rated hierarchy structure. With this method, events on similar levels which feed a common node are compared on a relative basis. The ratings for each level are then normalized such that the sum equals one. Terminal branch values are found by multiplying the normalized numbers at each node in the chain of events.

Figure 5-7 reflects the initial evaluation of probabilities using the rated hierarchy method. In this hierarchy, A is fifteen times more likely to lead to UO than is B. Similarly, D is twice as likely to cause A than is C. Thus, to make the comparison between events on a given level, consideration must be given between the events themselves (causes) and their terminal node (effects).

Figure 5-7



Rated Hierarchy - Probabilities (Initial Assessment)

Once the initial ranking has been completed, the normalization is performed at each level as shown in Figure 5-8. The normalized values are then multiplied throughout the chain to give the terminal probabilities shown in italics. Like the terminal branch results, these numbers represent the probability of chain occurrence given that UO occurs. Figure 5-9 shows the rated hierarchy results for the consequences. The resulting RE tree is shown in Figure 5-10. From the RE tree, one again sees that the lack of equipment (D) presents the highest degree of project schedule risk.

Figure 5-8

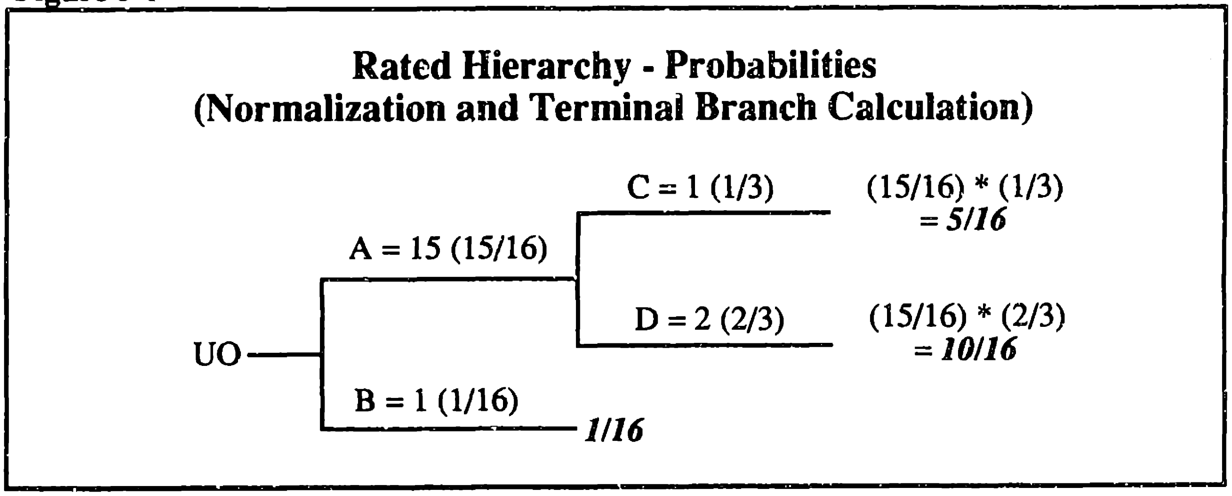


Figure 5-9

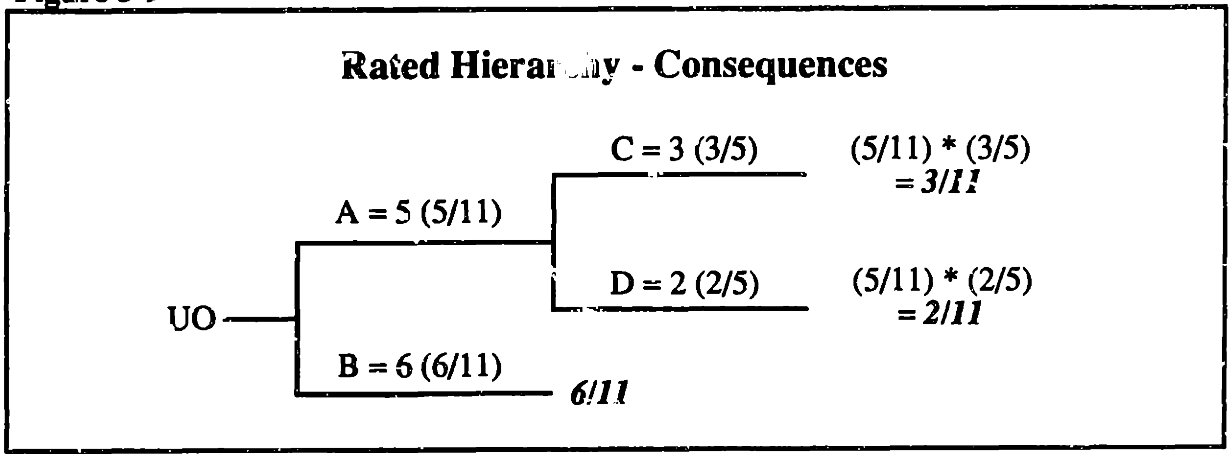
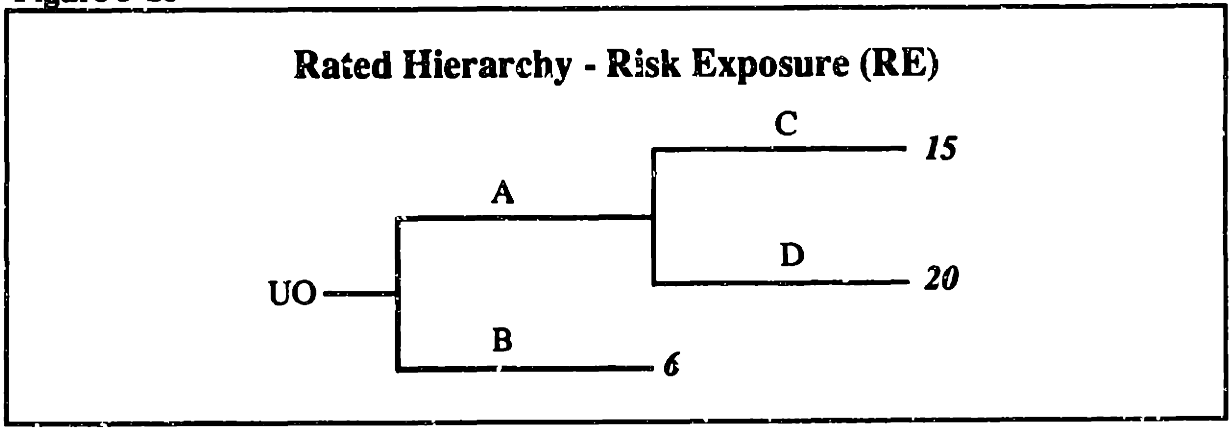


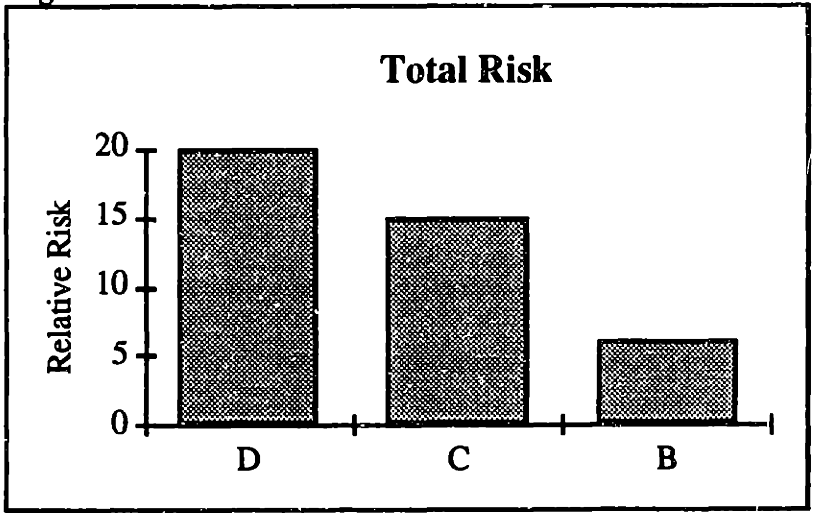
Figure 5-10



5.4.3 Risk Prioritization

The final step in risk assessment is to prioritize the risks for the future steps of risk control. With either risk analysis method described above, the risk prioritization is a straightforward task. Using the risk exposure tree, the RE values for any identical terminal branch events are first added to represent an equivalent value for that initiating event. The equivalent values are than ordered and graphed in a Pareto chart. For example, the risk tree from Figure 5-10 would be plotted as shown in Figure 5-11. From such a Pareto, trends are observed, and decisions are made as to which risks should be minimized.

Figure 5-11



An important part of the risk decision is establishment of an acceptable level of risk. As noted in the previous chapter, the specific level will be determined by corporate, team, or personal risk standards. Because the acceptance level is quantitative (usually in terms of dollars or time) and the relative risks are without unit, the Pareto of relative risks is not adequate for comparison purposes. One way to alleviate this problem is to actually quantify a few of the important relative risks as depicted by the Pareto. From this quantification, the risk management team can determine which individual risks should be reduced without spending the time to quantify every risk.

5.5 Relative Risk Assessment - Wire Bonding

5.5.1 Risk Identification

The wire bond risk tree is tabulated in Appendix A. Each level of indentation from left to right represents a level of hierarchy within the tree. The "risk event #" column represents the various terminal branches within the tree. The "risk group" column was created by assigning a letter to all similar initiating events. Once the RE's have been found, the total risk will be calculated using these groupings.

This tree was created by initially using the deductive reasoning process discussed in the previous section. As the wire bonding process was being developed, the Unsatisfactory Outcome (UO) was defined as a "suboptimal wire bonding process" being transferred into production. The three main components of this suboptimal process were: 1) bond does not adhere, 2) excessive wire breakage, and 3) suboptimal machine performance. Further cause-effect relationships were used to develop the levels throughout the tree.

The terms "suboptimal" was used to allow flexibility in assignment of values for the consequences. As stated earlier, a difference of this relative risk methodology from the traditional fault tree approach is that the consequences are allowed to have a range of outcome. Thus, a bond which does not adhere will lead to a failure of entirely different consequence value (in terms of line shut down, for example) than a wire breakage will lead to. "Suboptimal" was used to capture this flexibility while still holding the context of the consequence. Other terms such as "inadequate" or "insufficient" could have equally been used.

Although theory states that deductive reasoning should be used for trees of this type, in practice inductive reasoning can be used as an additional asset. As terminal branches were reached by deduction, the terminal events were questioned for their ability to create subsequent effects. New paths were often identified in this manner and refined by iterating with the deductive methodology. In the end, the goal was to have a tree which showed the complete cause-and-effect relationship for the process failure modes.

The risk tree went through several iterations to arrive at the final format in Appendix A, which was the fourth version. I created the initial version based on technical literature searches, project team discussions, and hands-on experimentation with the wire bonding equipment. The tree was created by using a combination of the forward and reverse logic methods discussed in Chapter 2. Two questions were repetitively asked to capture the full cause-effect relationships: 1) "If (some particular bonding parameter) is changed, what is the resulting effect?", and 2) "In what ways would wire bonding cause the transfer of technology to fail if the process were transferred today?" With this approach, the initial version was created.

The initial version had a total of 73 terminal branches when it was presented to the project team which consisted of three other individuals. The team felt that one of the original sections, wire bond reliability, was out of place with the theme of the tree: real-time quality. The reliability sections were removed, leaving the second version with 60 terminal branches (The reliability aspects will be discussed further in Section 5.7).

Each of the team members was asked to review the second version for its completeness and to suggest additional changes. Most of the structural revision had already taken place, but some time had elapsed to accommodate a product prototype. The increased knowledge from the prototype prompted the team to request more specific information for the third version, and the number of terminal branches grew to 96. This increase was driven by the subsequent detail to accommodate plasma clean, wire bond, and wire parameters in various sections of the tree. Furthermore, through prototyping the team had encountered problems with tilted die and decided that another section should be added.

The fourth and final version was created during the terminal node analysis described in the following section. In the time between the third and fourth versions, the team had decided to wire bond LED's manually. As a result, several sections concerning pattern recognition system (PRS) failures for LED's were no longer relevant and were, therefore, eliminated. Some other minor changes were also made during the initial analysis. The final version of the risk tree had 66 terminal branches.

The most important point here is that the dynamic nature of a critical-path project will cause focus to change abruptly. This change will, in turn, require the need for tree iteration and revaluation, even if analysis has already been performed. The bottom line is that the project's risk structure is often altered and, as a result, must be continuously monitored.

Project management must also contend with "outside forces" during the risk assessment process. During creation of the risk tree, the risk management team will try to eliminate as much complexity as possible. Other functions, such as marketing and finance, add complexity to the tree which may be transparent. This presents a challenge for the risk management team to minimize the complexity of the tree while assuring that it is truly representative of the situation at hand.

Once the wire bonding tree structure was satisfactory to the risk team, the terminal branch and rated hierarchy analysis techniques were applied.

5.5.2 Risk Analysis & Prioritization

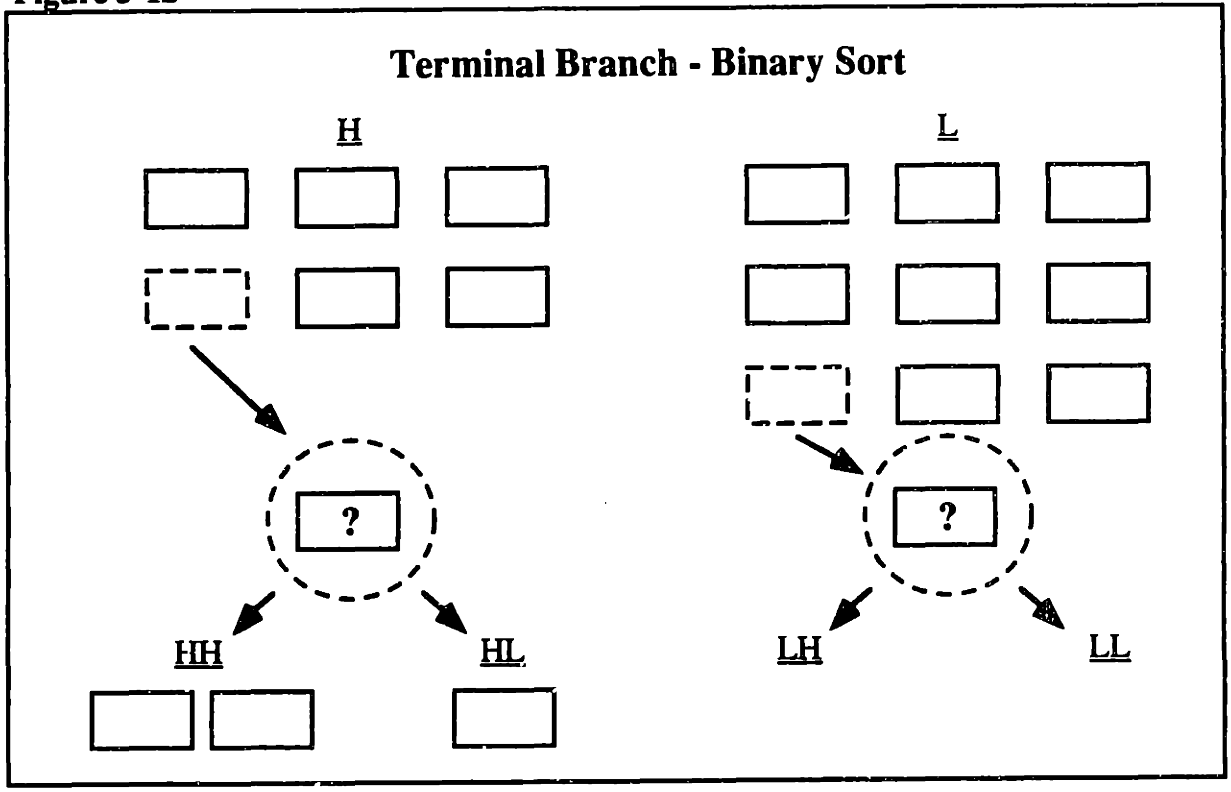
5.5.2.1 Terminal Branch Method

The first analysis that the team performed was for probability using the terminal branch method. The chain of events for each of the 66 terminal branches were compared and rated relative to each other. The team decided that given the large number of comparisons, the best approach would be to first rank-order the 66 items and then to make the relative comparisons.

The rank-order was performed using a binary sorting method. A summary of the chain of events for each terminal branch was written on a note pad and placed on a white board. The team then segregated the 66 event chains into two groups: one of a "high"

(H) probability and another of "low" (L) probability. This process was best accomplished with a facilitator who restated the chain from the note and asked the team whether the item belonged in the high group or the low group. Each team member gave input, and a consensus was sought for every item. Because of the large quantity of items, the facilitator was often required to take a majority opinion from the group members to keep the session moving. The high and low groups were further subdivided into groups of HH, HL, LH, and LL using a similar process (Figure 5-12). After additional grouping, the result was a total of eight categories of approximately eight notes each.

Figure 5-12



An observation from this process was that the groupings were dynamic, with notes often changing from high to low categories as they were subdivided. This occurred because initial items which were thought to have high probability had no reference or nominal to be judged against. As each event chain was assessed three separate times through this evaluation, the notes were eventually placed in the proper categories.

Following the binary sort, the notes within each of the eight categories were rank-ordered. The lowest item for each category was compared to the highest item from the next lowest category to confirm the order.

Once rank-ordering was completed, a relative comparison of probabilities could be made. Like the rank-ordering, the determination of probabilities was performed on a consensus basis. This worked well as each team member brought knowledge on different aspects of the process to the table. Before each relative rating, some deliberation occurred in which the most knowledgeable team member would state his belief. Other team members would then test their knowledge and intuition, and a rating was made.

During this process, consistency in definition of probability was of high importance. Our team occasionally wavered on the definition, resulting in the need for massive category reorganization and probability revaluation. Ultimately, the definition was pinned down as the "probability of a line shut down at the future operating site if we were to transfer the process as it stands today." It was very important to carry a specific time frame with the definition, as the probabilities are expected to decrease with further learning. With such a definition, we were able to keep the analysis both customer-focused and real-time.

To assist in the probability assessment, the top notes across the categories were first compared, and the ratings within the categories followed. The "top note" approach served two purposes. First, each category was bounded by its top note and the top note from the next lowest category. This simplified the completion of the relative assessment for each category. Second, because the initial evaluations were distributed more evenly among the 66 notes, a lower potential for error existed. If we had started with the lowest note, for example, and progressed one-by-one to the highest, we would have been building on past errors. As such, a grossly uneven error distribution would have resulted.

The results of the final categorization and relative assessment are shown in

Appendix B. The column "prob" represents the raw outcome from the above process. The probabilities were then scaled with the lowest probability equal to one. These scaled probabilities are represented by column "scaled prob."

Once the probabilities were completed, the consequences were ordered and evaluated in a similar manner. By this time, we had learned the importance of having a firm definition up front. The definition of consequence was stated as the "consequence of a line shut down at the future operating site if we were to transfer the process as it stands today." In specific, we used time as the critical dimension to a line shut down. Line down-time was seen as being especially important for the high volume product that was to be produced.

Because of the time aspect, the relative consequence ranking was much more tangible than the probability ranking. Whereas the relative ranking was necessary for the probabilities, consequences were ranked by addressing how much downtime would result in terms of minutes lost. As such, the consequence ranking used much more of an absolute approach than initially anticipated.

Appendix B reflects the final consequence categorization and ranking. This data was also scaled with the lowest consequence equal to one (column "scaled cons"). Appendix C shows the resulting RE which was calculated by multiplying the scaled terminal branch probabilities and consequences. RE was then scaled such that the lowest RE was equal to one.

Risk was found by adding scaled RE which had similar groupings, represented by the letters A through QQ in Appendix C. For any initiating events which were identical, the same letter was used in the "risk group" category. The RE's for items with similar risk groups were added to find risk because the top consequence might be realized through several paths in the tree. For example, risk group "A" consists of risk event numbers 1, 51, and 57. Thus, if an initiating event was replicated in several branches of the tree, the risk valuation would capture the additional data due to the repetition.

Figure 5-13

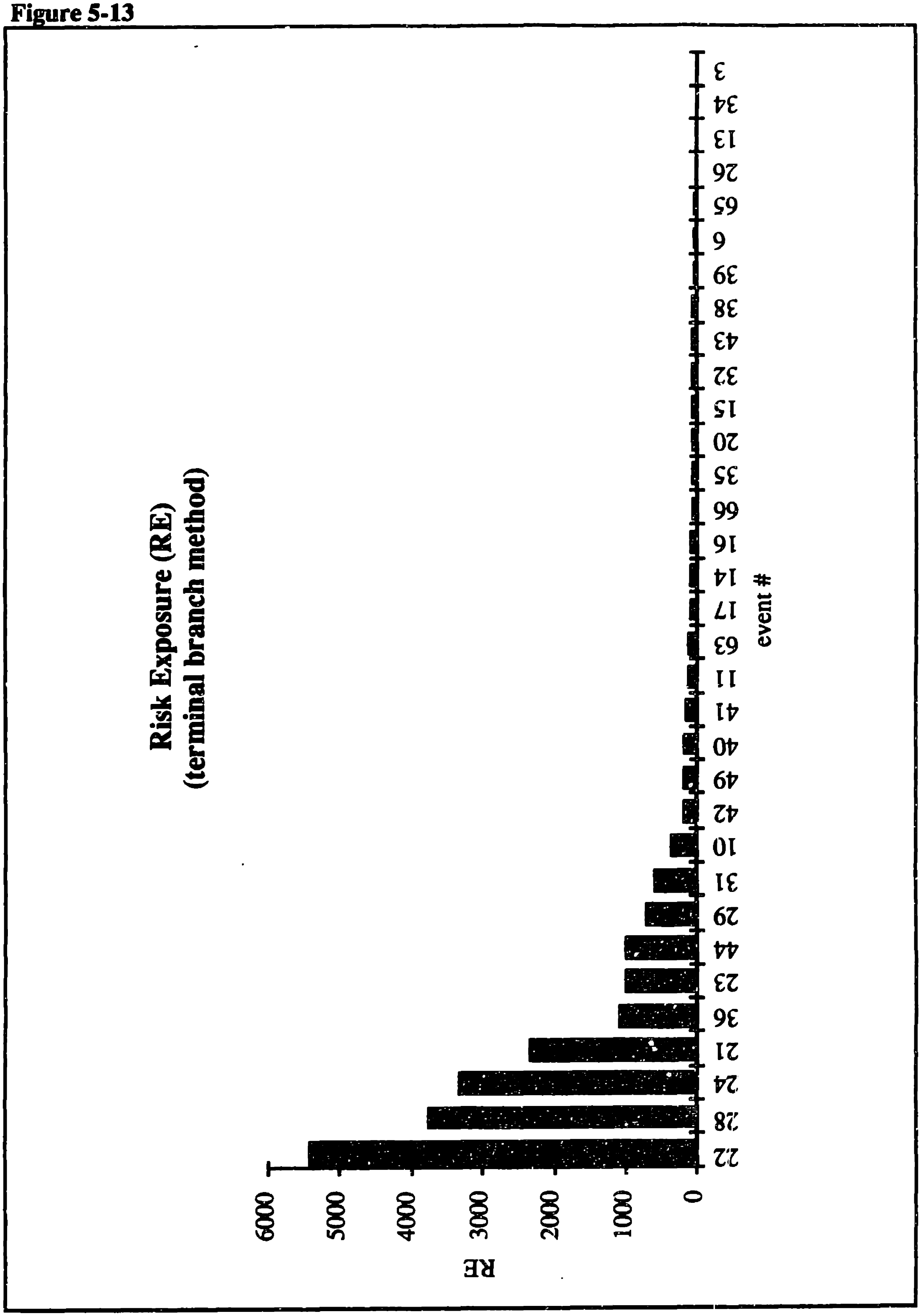

Risk Exposure (RE)
(terminal branch method)
RE
0
1000
2000
3000
4000
5000
6000
event #
22
28
24
21
36
23
44
29
31
10
42
49
40
41
11
63
17
14
16
66
35
20
15
32
43
38
39
6
65
26
13
34
3

Figure 5-14

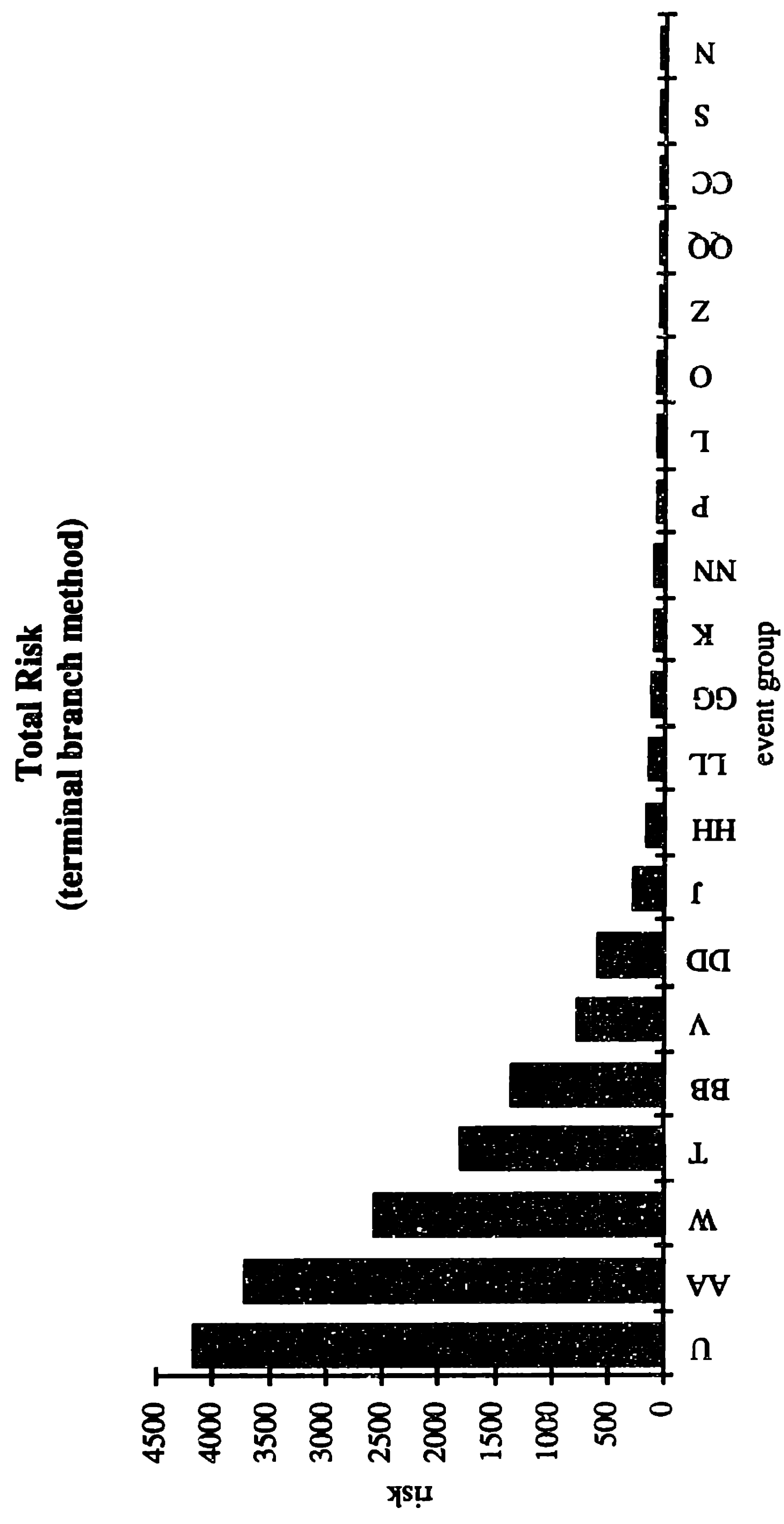

Total Risk
(terminal branch method)
risk
4500
4000
3500
3000
2500
2000
1500
1000
500
0
event group
U
AA
W
T
BB
V
DD
J
HH
LL
GG
K
NN
P
L
O
Z
QQ
CC
S
N

Figure 5-15

Terminal Branch Method- Top Risks

event group	*risk*	*relative rating*
U	suboptimal gold thickness	4167
AA	suboptimal bond head static force	3726
W	suboptimal surface roughness	2564
T	excessive substrate impurities	1795
BB	suboptimal bond time	1354
V	suboptimal nickel thickness	769
DD	suboptimal ultrasonic power	596
J	suboptimal die bond machine parameters (LED)	269

Pareto diagrams of the scaled RE and scaled risk are shown in Figure 5-13 and Figure 5-14. The appearance of an exponential decay reflects the multiplication of two independent series which were approximately linear: one for probability and the other for consequence. The top eight risks are summarized in Figure 5-15. Eight risks were chosen because this is where the knee of the curve breaks upward. In general, these risks fall into two categories: substrate metallurgy and wire bond machine parameters.

5.5.2.2 Rated Hierarchy Method

The rating of hierarchies was performed as described in the example from Section 5.4. Items on a similar level of hierarchy which also had a common node were assessed relative to each other. These ratings were first made at the lowest levels of hierarchy and then at progressively higher levels until the entire tree was completed. Although such an approach was not necessary, we felt we would have a better framework for the higher levels if we progressed upward through the tree structure.

Relative assessment of probabilities was first performed using the definitions established for the terminal branch method. As discussed in Section 5.4, items were not required to be terminal branches in order to receive relative ranking. For example, terminal branch 14 was compared to non-terminal node "suboptimal cleaning procedure (pre-WB)."

Like the terminal branch method, a team consensus was used for each of the decisions. The team first ordered the items and then assigned relative numbers based on consensus. Because the hierarchical groupings had at most six events and a less extensive rank-ordering was required, the team completed the hierarchical method in much less time than that required for the terminal branch approach. Once the tree had been completed, the probability ranking for hierarchy required about one hour versus the six hours required for the terminal branch model.

The complete probability rankings for the rated hierarchy method are shown in Appendix D. Once the evaluation was completed, the numbers were normalized for each group such that the sum of the ratings for the group equaled one. For example, for terminal branch 1:

$$\text{norm} = \frac{20}{20+15+10+10+5+1} = 0.328$$

After all other normalizations had been performed in this manner, the terminal probabilities were calculated by multiplying the normalizations through the tree structure. Again using terminal branch 1 as an example:

$$\text{prob} = 0.389 * 0.007 * 0.001 * 0.328 = 8.97\text{E-07}$$

This number represents P(chain of events which lead to terminal event 1 given that the process fails). Once the chain probabilities were found, they were scaled with a value of one representing the lowest probability.

The consequences were evaluated in a manner identical to that described for the

Figure 5-16

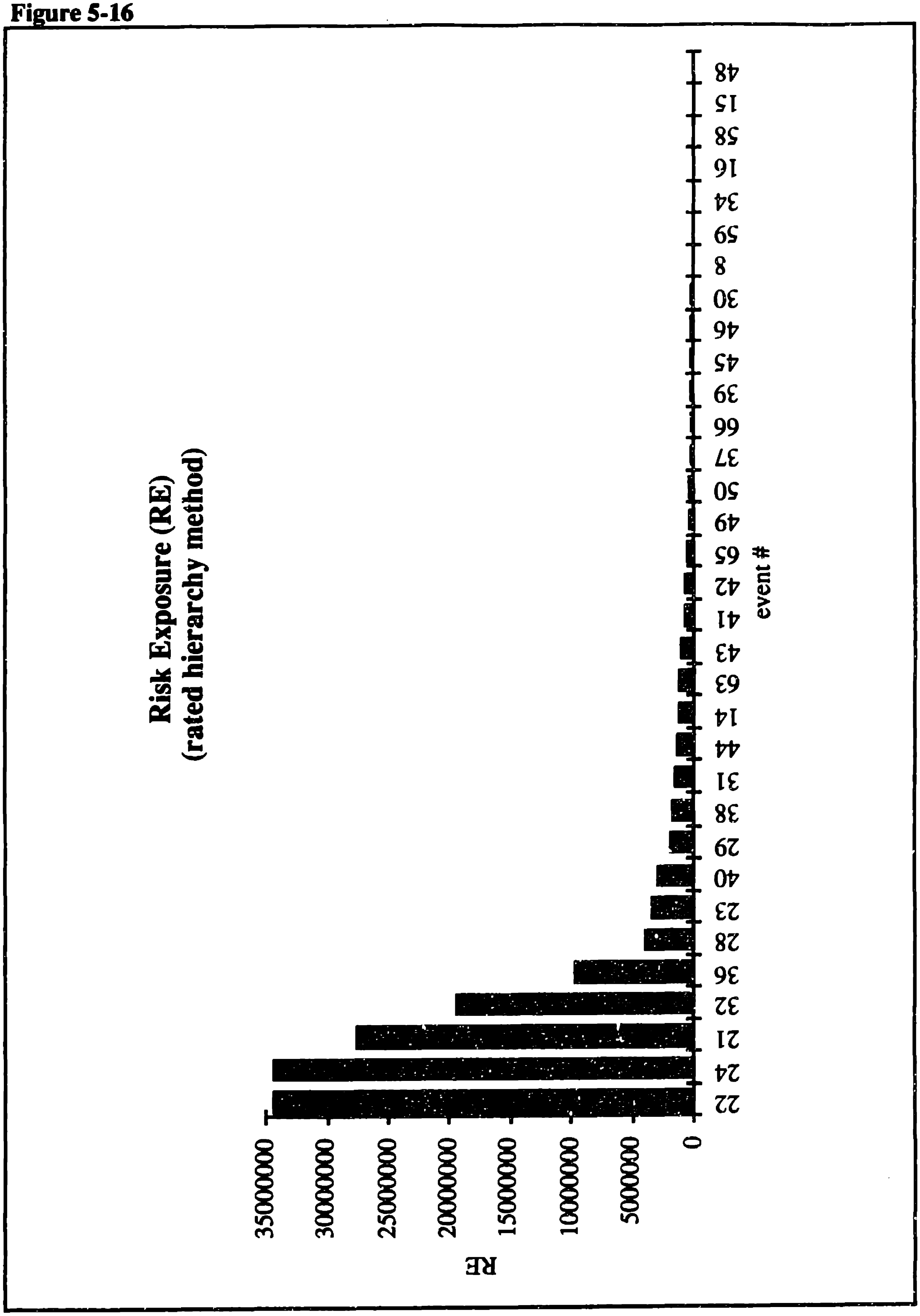

Risk Exposure (RE)
(rated hierarchy method)
RE
35000000
30000000
25000000
20000000
15000000
10000000
5000000
0
event #
22
24
21
32
36
28
23
40
29
38
31
44
14
63
43
41
42
65
49
50
37
66
39
45
46
30
8
59
34
16
58
15
48

Figure 5-17

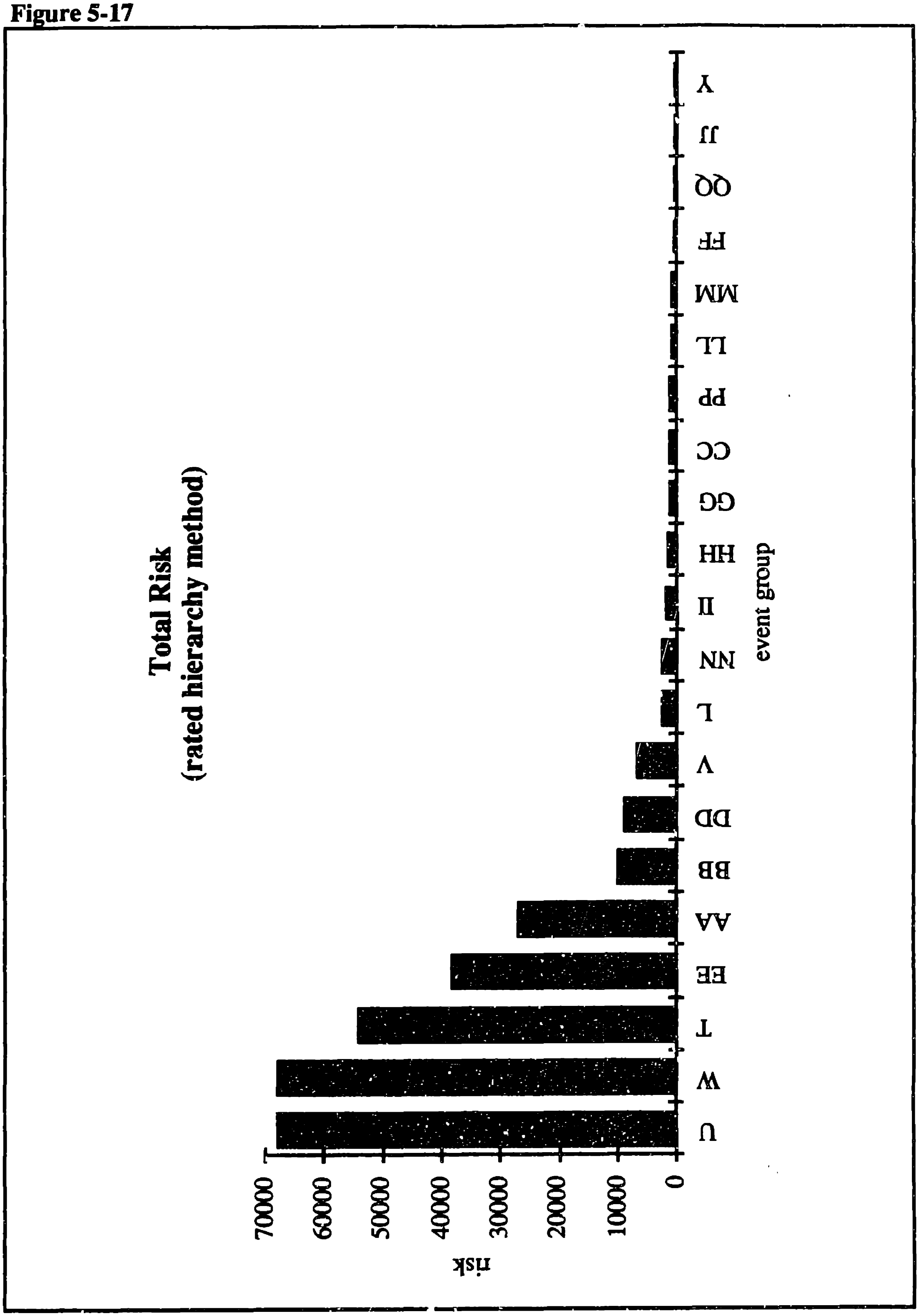

Total Risk
(rated hierarchy method)
risk
70000
60000
50000
40000
30000
20000
10000
0
U
W
T
EE
AA
BB
DD
V
L
NN
II
HH
GG
CC
PP
LL
MM
FF
QQ
JJ
Y
event group

Figure 5-18

Rated Hierarchy Method- Top Risks

event group	risk	relative rating
U	suboptimal gold thickness	67795
W	suboptimal surface roughness	67795
T	excessive substrate impurities	54236
EE	parts mishandled (post wire bond)	38149
AA	suboptimal bond head static force	26917
BB	suboptimal bond time	10167
DD	suboptimal ultrasonic power	9098
V	suboptimal nickel thickness	6780

probabilities. The consequences were normalized, terminal values were found, and the terminal branches were scaled. The results are shown in Appendix E.

Risk exposure (RE) was then found by taking the product of probability and consequence and again scaling. The RE results for the rated hierarchy method are shown in Appendix F. This appendix also shows the total risk which was found by adding RE's from similar groupings.

Pareto diagrams of the scaled RE and scaled risk are shown in Figure 5-16 and Figure 5-17. The top eight risks are summarized in Figure 5-18. Again, these risks generally fall into the categories of substrate metallurgy and wire bond machine parameters. The appearance of these categories as "high risk" issues for both methodologies will be discussed in the following section.

5.6 Discussion of Results

5.6.1 Similarities

In comparing the top-eight risks from Figures 5-14 and 5-17, several similarities are evident. For the terminal branch method, the eight (of 43) risks represent 91% of the total wire bonding risk. Similarly, for the rated hierarchy method the eight risks represent 93% of the total. Thus, the total risk profile is consistent with the two methods.

Additionally, seven of the top eight risks are consistent between methods. These risks fall into two categories:

substrate metallurgy
excessive substrate impurities
suboptimal gold thickness
suboptimal nickel thickness
suboptimal surface roughness

wire bond machine parameters
suboptimal bond static force
suboptimal bond time
suboptimal ultrasonic power

Note that each of these two categories have high risk for different reasons. The risks in reference to substrate metallurgy were among highest in terms of consequence for both risk analysis methods. The rationale used by the team was that a defective substrate would shut the plant down for a couple of days until more substrates could be received or the defective substrates could be reworked.

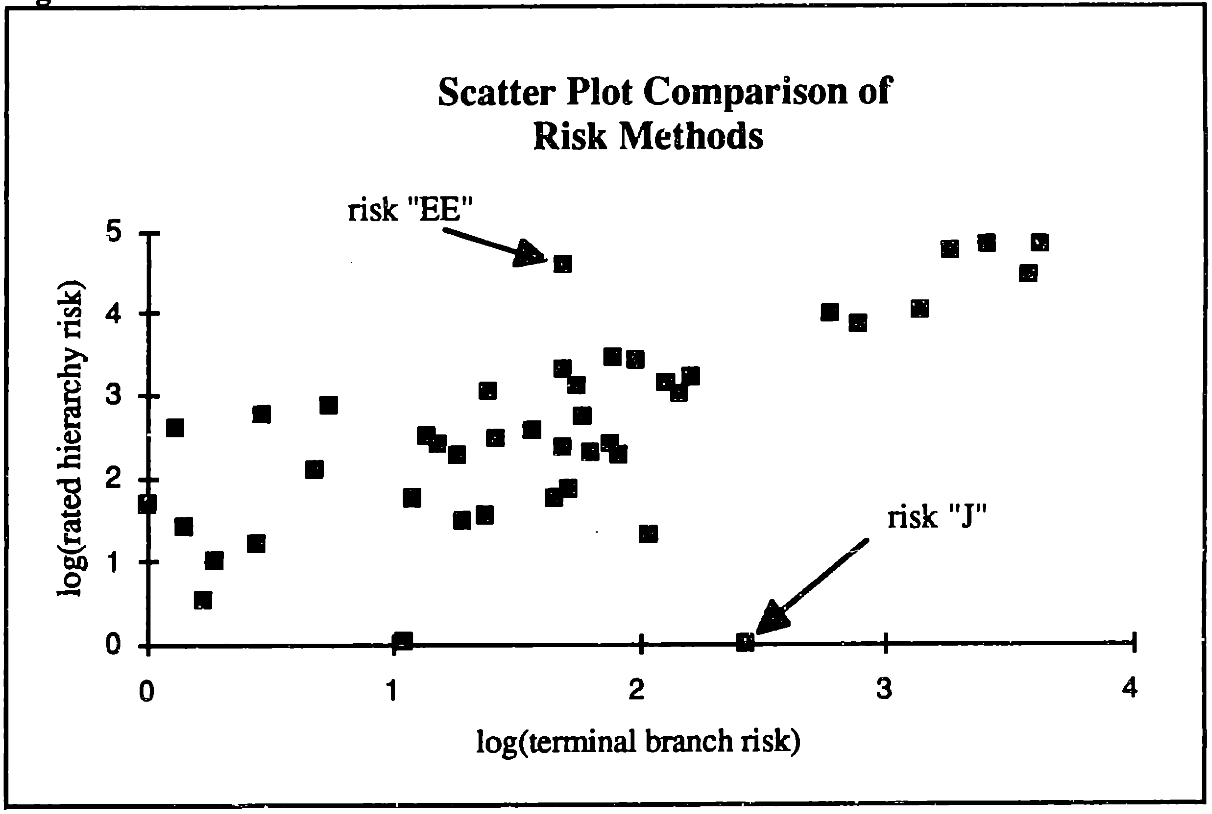
On the other hand, the team felt that the present status of the wire bond machine parameters had a very high probability of being suboptimal. Because the wire bonding equipment was new to the group, most of the engineering time had been spent learning machine setup and use. The improvement of bond pull strength had been given limited consideration. The consequences of suboptimal wire bond machine parameters, however, were much lower. The team felt that the wire bonding expertise at the operating site would allow quick resolution of product failure due to problems with wire bonding. As a result, the perception line downtime was not expected to be significant.

5.6.2 Discrepancies

As shown in the scatter plot of Figure 5-19, a correlation between the results of the two methods is evident. At the leftmost portion of the scatter plot, a higher degree of variability exists, whereas the right half is much more streamlined. This difference could be due to both the uncertainty and difficulty in estimating the lower probabilities and consequences. Because these items were expected to happen so infrequently or to show very little consequence, the team had a much more difficult time with their ranking then we did with the ranking of the higher items.

Although much consistency in results is seen from the two methods, there was a discrepancy in one of the top eight risks that deserves further consideration. Risk "J" appeared in the top eight for the terminal branch method but not for the rated hierarchy method. Instead, risk "EE" appeared in the top eight of the rated hierarchy method. Each of these items will be analyzed separately to determine root causes.

Figure 5-19



5.6.2.1 Differences Due to Hierarchy

To determine the problem with risk EE (parts mishandled - post wire bonding), the components of each methodology were analyzed to determine whether the problem arose from probability or consequence. A summary of the risk, RE, probability, and consequence rankings for each method is shown in Figure 5-20. From these, one sees

Figure 5-20

Discrepancy Analysis - Risk Group EE (Item #32)

Terminal Branch Method	*Rated Hierarchy Method*
EE 22nd highest in total risk	EE 4th highest in total risk
#32 25th highest in RE	#32 4th highest in RE
#32 8th highest in prob (25% of max)	#32 19th highest in prob (25% of max)
#32 62nd highest in cons (< 1% of max)	#32 4th highest in cons (86% of max)

that the risk discrepancy has been caused by a difference in the consequence rankings.

An audio tape from the evaluation session for the terminal branch method was reviewed. This revealed that the team had, indeed, rated item #32 (parts mishandled) as having a relatively low consequence for the terminal branch method. The team believed that while some parts may be destroyed on the line, feedback could occur rapidly to correct the problem and avoid a complete line shutdown. With this in mind, the team eventually assessed item #32 as the 62nd highest consequence (out of 66 total).

With the rated hierarchy method, the team also felt that the mishandling of parts would be of little consequence. The hierarchy rating gave item #32 one point, suboptimal wire metallurgy one point, and suboptimal wire bond machine parameters two points (see Appendix E). The team obviously felt that each of these items were of low consequence relative to one another, hence the low relative ratings. The other component of item #32's consequence is the next higher level of hierarchy. The node above item #32 received a seven with the other two nodes of that higher level receiving a nine and a one. The consequence of item #32 was then calculated as:

$$\text{cons}(32) = \frac{1}{1+1+2} * \frac{7}{7+9+1} = 0.103$$

Considering our definition of consequence as being the total time of line shutdown, such a large consequence for parts mishandling should not have occurred.

By exploring further, a unique feature of item #32 was found. It was the only terminal branch at the third level of hierarchy in the tree. As a result, item #32 was much more sensitive to the normalized consequences which it is composed of. Although we took a bottom-to-top approach when assessing each group hierarchy, we failed to fully consider the lower levels of hierarchy which fed the node being evaluated. As discussed in Section 5.4.2.2, "to make the comparison between events on a given level, consideration must be given between the events themselves (causes) and their terminal node (effects)." From the results, however, the importance of considering the lower levels in the ranking cannot be understated. If we had considered these lower levels, the evaluation would not have been nearly as biased toward item #32.

To realize this, observe the scaled consequences of the terminal branch method in Appendix C. In particular, consider all terminal branch events within the first level of hierarchy for "excessive wire breakage." From this, one can see that item #36 (37.5) is 25 times higher than item #32 (1.5). Since both of these items are within the same first level of hierarchy, the 9:7:1 ratio for the common higher level is irrelevant. What is relevant is the ratio for events "parts mishandled" : "suboptimal wire metallurgy" : "suboptimal wire bond machine parameters." In order to achieve the 25 times difference and maintain all other equality, the ratio must be 1:10:60, a much larger ratio than 1:1:2. A disregard for the lower level items caused significant error in the team's estimation of the second level of hierarchy.

5.6.2.2 Differences Due to Inconsistency

For item J (suboptimal die bond machine parameters (LED)), the summary of the risk, RE, probability, and consequence ratings for each method is shown in Figure 5-21. From these, one sees that the risk discrepancy has been caused by a difference in the

Figure 5-21

Discrepancy Analysis - Risk Group J (Item #10)

Terminal Branch Method	*Rated Hierarchy Method*
J 8th highest in total risk	J 43rd highest in total risk
#10 10th highest in RE	#10 60th highest in RE
#10 13th highest in prob (7% of max)	#10 60th highest in prob (< 0.1% of max)
#10 19th highest in cons (3% of max)	#10 20th highest in cons (5% of max)

probability ratings. The discrepancy resulted from the team's inconsistency in evaluation.

Because items #7 through #11 all enter a common node, their ratios should be consistent for each method. Risk J is represented by item #10. For the terminal branch method, the ratio is 2.6 : 3.5 : 2.4 : 70.0 : 7.0, where the 70.0 represents item #10 (Appendix C). The ratio between items #7 through #11 for the rated hierarchy process is 100 : 200 : 10 : 1 : 10, as found from Appendix D. In the first method, the team rated item #10 as almost 30 times higher than any other event within the group. In the second method, however, the same item was 200 times lower than the highest event. This inconsistency in probability evaluation caused the discrepancy in the risk results.

5.6.2.3 Magnitude of Risk

Another significant difference between the two methods is the magnitude of the resulting risk. For example, items #22 and #24 have scaled RE's of 3.4×10^7 using the hierarchical method, but the highest RE with the terminal branch method is 5417. This same phenomena can be observed with the probabilities and consequences.

The difference can be explained by the number of product terms used to calculate risk, compounded with human tendency to think linearly. For the terminal branch method, two evaluations were made, and the numbers were multiplied together to find RE. Each of the two assessments had a maximum ratio of 1000 to 1, a range which pushes the limits that we easily comprehend. As such, RE was found by multiplying two linear ranges together.

With the rated hierarchy approach, however, up to five levels were multiplied together to achieve the resulting probabilities and consequences. Additional product terms resulted in greater orders of magnitude in probabilities and consequences. This effect was furthered with calculation of RE. Thus, the multiple decisions that were made had a compounding effect on the overall risk. Even with the difference in magnitude, it is important to note that the top order of magnitude for each method was composed of similar risks.

5.7 Critique of Methods

After completing the two methods, the team gathered to qualitatively reflect on each methodology. These comments were collected from that meeting.

For either method the team members agreed that the most important aspect was understanding the scenario of the top event in the tree. Because this top item must capture multiple levels of failure, by definition it must be broad for a complex problem. For our specific problem, we had to constantly keep the problem in the context of "What would happen if we transferred our existing process into production?" This context was important, as we reverted back to it more than a dozen times throughout the process.

5.7.1 Terminal Branch

There were a few general items that the team felt important. First, information to represent the events must be portable enough to allow the binary sorting process. Index cards or tape-backed note pads provide the necessary flexibility. The written information on these cards must represent the chain of events leading to the undesired outcome in a clear, concise format.

Second, a trained leader in the technique is necessary for this method to be successful. This requires knowledge of the subject and tree as well as clear definitions of probabilities and consequences. This methodology would not work in roundtable format or with large groups.

The advantage of the terminal branch method is that a global view is used. This results in a more accurate comparison of events. The method can also be advantageous if quantities can be stated on more absolute terms, eliminating the need for the binary sort. One further benefit is that fault tree construction is less important than that of the rated hierarchy method because all items in the chain of events are considered simultaneously.

The main disadvantage is the completion time required for complex applications As stated earlier, this method required about six hours compared to the one hour for the other method. The extensive time was required for the many illogical comparisons necessitated by totally different event chains. Even if software was written to represent this process, the multiple comparisons could not have been avoided. The team felt that the binary sort helped, but the degree of information overload cause by the constant re-learning of event chains was very high.

5.7.2 Rated Hierarchy

The advantages of the second method were the reductions in time and effort required by the team. As fewer comparisons were required, the method was intellectually less taxing. Furthermore, the relative ranking process was accomplished in roundtable fashion, with less of a requirement for a leader. Consequently, this method may be better for larger groups of people.

The disadvantage of the method centers on the loss of a global sense when performing the evaluation. The team knew that higher levels in the hierarchy would be more important, but the events at the higher levels were also the most abstract, making evaluation difficult. The team felt that more time should have been spent on the higher-level items in order to fully understanding the contents of each item. Finally, this method required a higher degree of quantitative evaluation. Such evaluation, however, could be easily automated with software.

5.8 Relative Risk Assessment - Caveats and Considerations

5.8.1 General

- The relative risk methodologies are not intended to be "computer programs" for decision making. Rather, the methodologies are meant to provide a better understanding of the risk a project presents through a combination of qualitative reasoning and quantitative decision support. Through use of a standard, structured method, communication of risk is fostered within the project team as well as to the external community.
- A specific time frame of the unsatisfactory outcome should be considered when assessing consequences. For example, quality and reliability issues should not be combined into a single tree. Rather, all possible failure modes should be identified and analyzed on the most important dimension.
- The stage of process design is an important consideration when applying risk analysis methodologies. The team considered four specific stages of process design: definition, development, refinement, and maturity. The wire bonding process was in the development stage. If we had applied the methods during definition, the team felt that the tree would have consisted of fewer levels and uncertainty in estimates would have been higher. Even with these disadvantages, the tree would have still served as a useful framework for thinking through issues.
- As processes are transferred into production, the trees can be used as diagnostic tools to troubleshoot failures. This is possible since much engineering wisdom is included in the tree. Furthermore, actual process defect data will allow a migration from

relative to absolute numbers. As a resulting effect, the trees should also become simplified as process learning improves.

- As the risk tree will serve as an important tool to transfer technology and continuous improvement, manufacturing involvement is recommended.
- The costs versus benefits of risk management must be considered prior to investing in any formal risk program. For a problem with less than 100 terminal nodes, the rated hierarchy method should take two or three business days to complete, with most of the time devoted to the development of the tree. This is a significant improvement over the traditional quantitative methods. The benefits of the assessment are not only a prioritized listing of the risks, but also a better understanding of the underlying process. Unless the project is trivial or risks are negligible, a method such as this is highly recommended.
- The role of functions "external" to technology development must be strongly considered when assessing technological risk. Impact of these functional issues - such as marketing forecasts or levels of financial support for capital asset procurement - must be kept in perspective during this entire risk assessment process. Such higher level issues can render the lower level technology risks irrelevant or cause dramatic swings in how technology might be used in fulfillment of the business needs.

5.8.2 Risk Identification

- Identifying risk through risk trees is an art, especially when the trees must be in a format for relative analysis. The team members would agree that the development of the tree took far too long, with two major revisions and several meetings in-between. The completeness and consistency in levels throughout the tree can only be improved, however, with practice. The combined use of literature, hands-on experience, and others' expertise will provide a solid framework for the risk identification.

- The use of OR gates throughout the tree structure may be a limitation for less complex problems. For the wire bonding situation, we had so many possible failure channels that the issue never even arose.

5.8.3 Risk Analysis and Prioritization

- The definition of probability and consequence should be stated in terms of identifiable units. For the wire bonding study, we used "the probability of line shutdown" and "the amount of time lost during shutdown." Many options exist here, and the choice itself must both be representative of your problem and be identifiable by the team. As mentioned earlier, the team will come back to the definition throughout the analysis process.
- The uncertainty of probabilities and consequences is an important issue that the preceding methodologies did not address. As shown in Section 5.2, the uncertainty can be the greatest source of risk. Although uncertainty could be included in analyses consisting of a small number of risks (such as in Boehm's example), for large trees the analysis becomes overly complicated. One recommendation would be to side on the high end of uncertainty when performing the evaluation. If something ends up in the high risk category for this reason, risk reduction methods can be taken to remove the uncertainty in the next stage of risk management.

5.8.4 Risk Control

- The establishment of an acceptable level of project risk is critical. This importance is often based on the need for individuals to juggle multiple projects. The intention of risk management is not to reduce every risk on the project, but rather to deploy resources efficiently. Once the Pareto charts have been completed, the team can pick a few risks at various levels of the chart for quantitative analysis. This will allow the team to fully understand its role in risk management planning, reduction, and control.

5.9 Summary

Typically, results from the risk assessment should be used to assist in planning for process development. Based on the commonality in top risks found using two different methods, the substrate metallurgy and wire bond machine parameters would be the key wire bonding concerns of the process development team. Because of the time required to develop the methodologies, however, the team was forced to begin process development without instituting the risk control steps.

The team decided it would be best to focus on four areas of the process: plasma cleaning, substrate metallurgy, wire metallurgy, and wire bond parameters. The experimentation that was performed follows in Chapter 6. Had the risk assessment methodologies been completed earlier in the internship, a formal risk control process would have been instituted with increased emphasis on the substrate and wire bonder.

Even though these steps could not be implemented, the risk assessment methodology that was developed and applied in this chapter was a very useful tool. The team was able to identify the top wire bonding risks, but we also gained a broadened understanding of the many possible aspects of aluminum ultrasonic wire bonding. Areas of high uncertainty, in turn, initiated discussions with equipment manufacturers, materials suppliers, and other technical experts within Motorola. Therefore, the risk assessment indirectly assisted in the learning process for new technology development.

Through the relative risk assessment, the many engineering ideas that each of the team members had were structured to provide a common means of communicating ideas and concerns. Such structured methodologies are essential for grasping complex processes such as wire bonding. Consequently, the time required for development and assessment of the risk tree using the rated hierarchy method was a sound investment.

Chapter 6
Wire Bonding Experimentation

Development of the wire bonding process required several types of experimentation. These experiments consisted of: 1) preliminary analyses of the bonding surfaces, 2) plasma cleaning fractional factorial experimentation, 3) additional bonding analyses, and 4) wire bonding fractional factorial experimentation. The approach, analysis, and discussion of results for each set of experiments are detailed within this chapter.

6.1 Development of Experimental Plan

The wire bonding process can be defined by three sets of process parameters: pre-bond plasma cleaning, substrate and wire metallurgy, and wire bonder (machine) settings. Because of the large number of process parameters, designed experiments (DOX) were the most logical approach to the problem. Such methods allowed rapid convergence on the most important bond parameters as well as efficient elimination of the most negligible ones. To understand how the DOX approach was applied to the wire bonding process, the response variables and control parameters must first be understood.

6.1.1 Response Variables

Four variations of the experiment (i.e., four separate designed experiments for both plasma cleaning and wire bonding) were initially considered. These variations were as follows:

	metallization	response variable
(1)	Au substrate pad	destructive pull test (immediate)
(2)	Au substrate pad	destructive pull test (following hi-temp bake)
(3)	Al die pad	destructive pull test (immediate)
(4)	Al die pad	destructive pull test (following hi-temp bake)

The destructive pull test is accomplished with a specialized piece of equipment designed specifically for pulling wire bonds. A hook assembly is inserted through the arch of the bonded wire, and the bond is pulled to destruction at a preset velocity. A digital readout then displays the pull strength to an accuracy of +/- 0.125 gf. For all experimentation within this chapter, a 3 mil diameter hook was used at a pull velocity of 0.5 mm/sec.

In each of experiments (1) and (2) above, Al wire would be bonded from Au substrate to Au substrate. Similarly, in (3) and (4) Al wire would be bonded from Al die pad to Al die pad. Since the failures can be isolated to each particular bonding surface, separation of the experiments by metallization will enhance understanding of the bonding mechanism. Following analysis of experimental results, the parameters could then be set at levels to increase the overall strength of a wire bonded from Al die pad to Au substrate. Such a combination can be performed because many of the parameters for the first bond can be varied independently from those of the second bond.

For parameters which cannot be isolated to a specific bond, some conflict in resulting parameter levels may exist. In other words, the results of the experiments for bond one may suggest a different setting for a particular parameter than suggested by bond two. Such conflicts may be resolved by performing a sensitivity analysis on the parameters to determine the level at which the settings will have the highest payoff.

I proposed performing the pull tests both before and after a one-hour bake at 390°C in a protective nitrogen atmosphere. The primary purpose of the bake is to accentuate defects which do not appear immediately following bonding. My expectation was that a post-bake pull test would highlight impurities present within the metallization as well as contamination not removed during pre-bond cleaning [Harman, 1991, p. 38].

As these response variables were evaluated by the project team, however, we discovered that it would not be possible to perform the high-temperature bake due to the low glass transition temperature of the substrate being used. Thus, items (2) and (4) were eliminated from the experimental plan, and items (1) and (3) were used as the response variables for all designed experiments.

6.1.2 Control Parameters

6.1.2.1 Plasma Cleaning

The parameters for plasma cleaning were identified through literature searches, familiarization with the equipment, and discussions with plasma cleaning experts. These experts included both internal Motorola personnel as well as designers of the equipment. The most important parameters are:

gas type/ratio
cleaning time
gas cycle time
RF power
temperature
position in chamber
elapsed time (cleaning to wire bonding)
pressure (if mass flow)
gas flow rate (if fixed flow)

From this list, the gas flow rate and temperature can be eliminated. The chamber pressure (mass flow) will be used in combination with the gas ratio parameter, making the gas flow rate deterministic. The flow will be automatically adjusted by the machine's controller.

Temperature is a dependent parameter as a function of RF power. Since the operator will have direct control over the RF power level and the power is expected to have a major impact on cleaning rate, RF power is preferred to temperature as a control parameter.

In addition to the parameters specified above, the plasma unit allowed up to five different "segments" per run. For each segment, many of the above parameters could be altered. Multiple segments substantially increased the number of combinations for the plasma parameters.

6.1.2.2 Substrate and Wire Metallurgy

Metallurgical control parameters were identified through literature searches and discussions with various experts. These experts included personnel from Motorola and MIT, as well as metallurgists from suppliers of the wire, wire bonder, and substrate. Thickness, impurity content, and hardness were found to be the important parameters for nickel and gold plating.

Studies from Harman documented in Chapter 3 of this thesis suggest that a relationship exists between the plating current density and the impurity level. Furthermore, the plating current density may also affect the microhardness of the Au or Ni. Thus, the substrate parameters can be represented by:

Ni thickness	Ni plating current density
Au thickness	Au plating current density

The wire supplier offers wire of different size, alloy, and tensile strength. Since wire size is determined by the size of the bond site for a specific application, the only parameters which will be considered for the wire are:

wire alloys	wire tensile strength (t.s.)

6.1.2.3 Wire Bonder

Adjustments can be made to the machine parameters which will directly affect the quality of the wire bond. Parameters which may be varied by keypad or ultrasonic generator controls include:

loop height	tool inflection point
bond time	reset height

contact velocity
ultrasonic power
overtravel

Another important parameter which requires mechanical adjustment of the bond head is:

static force

All parameters except reset height, static force, and overtravel can differ between the first and second bond.

6.1.2.4 Parameter Summary

plasma cleaning = 27

gas type/ratio (x5)
cleaning time (x5)
gas cycle time (x5)
RF power (x5)
position in chamber
elapsed time (cleaning to wire bonding)
pressure (x5)

substrate and wire metallurgy = 6

Ni thickness (d_{Ni})
Au thickness (d_{Au})
wire dopants
Ni plating current density (J_{Ni})
Au plating current density (J_{Au})
wire tensile strength (t.s.)

wire bonder = 12

loop height
bond time (x2)
contact velocity (x2)
static force
tool inflection point (x2)
reset height
ultrasonic power (x2)
overtravel

6.1.3 Experimental Design - Key Issues

There are three ways in which the complexity of experimental design matrices can be simplified. First, the number of parameters being explored can be reduced. This is done through side experiments that determine whether the parameters should be included in the design matrix. The second way to reduce complexity is by using a minimal number of levels per parameter. For most experiments, two levels per parameter are recommended. The third way to reduce complexity is to conduct experiments which are concerned only with the main effects of the parameters and not with interactions between parameters. The interactions are a function of the physical process being studied, however, so elimination using the third method is somewhat limited.

For wire bonding, the number of parameters may be eliminated via side experiments. The number of levels per parameter and the degree of interaction cannot be restricted so easily. The plot of pull strength is expected to be concave downward (refer to Figure 3-6) due to the many possible bonding failure modes. Anticipation of such a quadratic response suggests the need for more than two experimentation levels per parameter. Additionally, more than two levels are desired for some non-continuous parameters (e.g., gas type, wire alloys) in order to explore the wide variation in design options.

At the same time, the expectation for parameter interactions (refer to Figure 3-7) requires that a larger number of experiments be performed to attain sufficient statistical resolution. Although experimentation for more than two levels per parameter can be conducted using Taguchi's orthogonal arrays, most of these arrays will fail to capture the interactions anticipated for wire bonding. Fractional factorial designs of Resolution V, on the other hand, will give unconfounded main effects and unconfounded two-factor interactions but require a greater number of experiments. These designs become excessively complex when a large number of parameters and greater than two levels per parameter are considered.

6.1.4 Experimental Design - Coupling vs. Decoupling

Because each of the three sets of wire bonding parameters can affect the ultimate bond quality, combining all three groups into a single matrix is desirable. Otherwise, one runs the risk of pursuing local optima for each set of parameters and failing to optimize the combined set. On the other hand, a large matrix requires much more time to design, perform, and analyze the experiments. Thus, larger experimental designs contradict the need for faster process development cycles and faster design iterations. Furthermore, the bonding mechanism may be better understood through a series of small experiments rather than through a single, large experiment.

6.1.5 Experimental Plan

Ideally, the wire bonding experimental design requires a large number of parameters, three or more levels per parameter, a high degree of resolution, and a decoupled design to enhance speed and learning. This approach is the best of all worlds, but the large number of experiments necessary to carry out such a plan is prohibitive in terms of both cost and time.

The team decided that decoupled experiments and exploration of interactions would be the best approach for the wire bonding process. By decoupling, plasma cleaning and wire bonding would be explored separately. Because of the potentially large number of experiments required, only two levels per parameter could be explored.

As explained above, a concern with experimental separation is that local maxima are pursued at the expense of a system maximum. The team felt that this concern could be rendered irrelevant if plasma cleaning was shown to have no physical effect on the surface roughness of the substrate. If only contaminants are removed with the plasma, than it can assumed that "cleaner is better." With such an assumption, the plasma process parameters which give the best pull strength could first be found. This output could be held constant during the wire bonding fractional factorial experiments. To determine whether this decoupling could, indeed, take place, preliminary surface analyses were conducted.

6.2 Preliminary Surface Analysis

Preliminary experimentation served several purposes. First, the surface textures would be examined to determine if the plasma DOX could be separated from the wire bond DOX. Second, some preliminary experimentation would assist in selection of gas mixtures for the plasma process. Finally, initial feedback as to the benefit of plasma cleaning for wire bonding could be captured.

6.2.1 Approach

6.2.1.1 Values for Parameters

The parameters from Section 6.1.2.4 were first reviewed. The only parameter that was varied throughout these preliminary experiments was the gas mixture. To reduce complexity, only a single segment of the plasma cleaning cycle was utilized.

The process parameters for the preliminary plasma experiments are shown in Figure 6-1. Plasma cleaning parameters were set with the assistance of the equipment manufacturer. The elapsed time (between plasma cleaning and wire bonding) was not originally considered, so it is listed as TBD.

Figure 6-1

Parameters for Preliminary Experiments

plasma parameters		metallurgical parameters		wire bonder parameters		
clean time	15 min	d_{Ni}	> 200 µin	loop height (units)	200	200
RF power	750 W	d_{Au}	15 µin nom	bond time (msec)	50	100
gas type	***variable***	J_{Ni}	20-25 A/ft^2	contact vel (units)	5	5
pressure	230 mTorr	J_{Au}	10-15 A/ft^2	static force (gf)	28	28
gas cycle	2 min	wire diam.	1.25 mil	tool inflection	-	-
position	center	wire dopant	AlSi 1%	reset height	-	-
elapsed time	TBD	wire t.s.	21-24 gf	power (units)	2.5	1.9
				overtravel (units)	22	22

The substrates for this experimentation had been purchased for other uses, so the documentation of the processes used to produce the substrates was incomplete. New substrates were not acquired due to the lead time necessary for their receipt. The existing substrates were considered sufficient for the experimentation which would take place.

Wire bonder parameter levels were based on the values used for a previous prototype build. The first column represents the levels for bond one, and the second column represents bond two. Through some experimentation, the tool inflection point and reset height were found to have no impact on bond strength.

During all wire bonding experiments within this chapter, wire bond length was held at a length representative of the bond for the final product being developed. This length, in combination with the loop height parameter, dictates the angle of inclination at which the wire leaves the surfaces of the die and the substrate. This angle is an important consideration for pull strength.

6.2.1.2 Preparation

The plasma chamber was cleaned and calibrated using an interactive program supplied with the equipment software. A new bond tool was inserted into the bond head and the table x-y motion was calibrated for the wire bonder. Calibration of the wire bond pull tester was also performed.

The sample substrates were first cleaned to remove inorganic contamination with a 75%/25% alcohol/deionized (DI) water mixture. These samples were then sectioned, and any residual particles were removed with a high-pressure, pure nitrogen stream. A silver-filled die bond epoxy was dispensed onto the gold surface of the substrate, and die were attached with the die bonder. The die/substrate combination was cured for about one hour at 130°C.

6.2.1.3 Experimental Data

Three different gas mixtures and a control were run for the die and substrate separately. These gas mixtures were: 1) 10%/90% Ar/O_2, 2) 90%/10% Ar/O_2, and 3) NF_3 (for which the gas cylinder stated that the mixture was 95% O_2 and 5% NF_3). The control had been cleaned with the alcohol/DI rinse but had not been plasma cleaned.

Because of some initial problems with calibration of the wire bonder, the elapsed time from plasma cleaning to wire bonding was three days. During this time, the samples were stored in a nitrogen-filled cabinet. Once the wire bonder was repaired and calibrated, bonding commenced.

For each of the four die samples, six wires were bonded from die pad to die pad. Six was the maximum number allowed because of the configuration of die pads and the requirement to maintain consistent bond length. Ten data points per sample were collected for each of the substrate samples. For these, wire was bonded from gold substrate to gold substrate. As discussed earlier, this separation was done to isolate failures to a particular metallurgy.

The results of this experimentation, in terms of the sample means (xbar) , sample standard deviations (s), and 95% confidence intervals for the sample means, are shown in Figure 6-2.

Figure 6-2

Plasma Cleaning Preliminary Experiments (3-day lag)
Wire Bonding Pull Strength (gf)

		die	substrate			die	substrate
control	xbar	17.47	12.68	*NF*$_3$	xbar	13.79	10.00
	s	0.77	1.13		s	0.84	1.40
	95% ci	16.66 - 18.28	11.87 - 13.49		95% ci	12.91 - 14.67	9.00 - 11.00
10/90 AR/O$_2$	xbar	15.69	11.74	*90/10 AR/O*$_2$	xbar	15.80	12.68
	s	1.32	1.82		s	1.77	1.32
	95% ci	14.30 - 17.08	10.44 - 13.04		95% ci	13.94 - 17.66	11.74 - 13.62

For both the die and the substrate, the sample mean of the control was significantly higher than that of the sample plasma cleaned using NF_3. In all other samples, the controls showed higher but insignificant results. To assure that excessive experimental noise had not been caused by the 3-day lag, the experiment was repeated with a controlled, 15-minute elapsed time from plasma cleaning to wire bonding in which the samples cooled in a 70°F, 50% relative humidity laboratory environment. The results are shown in Figure 6-3.

Figure 6-3

Plasma Cleaning Preliminary Experiments (15-minute lag)
Wire Bonding Pull Strength (gf)

		die	substrate			die	substrate
control	xbar	16.18	13.18	*NF_3*	xbar	15.44	10.75
	s	1.66	0.65		s	1.45	1.64
	95% ci	14.44 - 17.92	12.72 - 13.64		95% ci	13.92 - 16.96	9.58 - 11.92
10/90	xbar	15.64	11.59	*90/10*	xbar	10.57	9.61
AR/O_2	s	1.80	1.70	*AR/O_2*	s	2.80	1.02
	95% ci	13.76 - 17.52	10.37 - 12.81		95% ci	7.63 - 13.51	8.88 - 10.34

Each of the samples from this last experimental set was also analyzed for surface effects of plasma cleaning.

6.2.2 Analysis/Discussion of Results

For the samples with the 15-minute time lag, the control again had a higher average pull strength for both die and substrate than any of the plasma cleaned samples had. Not all of the lower averages of the plasma cleaned means were significant, however. For the die, the control had pull strengths which were significantly higher than those for the 90/10 Ar/O_2 sample. For the substrate, the control mean was significantly higher than the means of both the 90/10 Ar/O_2 and the NF_3 samples.

These differences may have been caused by variation in the substrates which were being bonded. As said earlier, these substrates were not procured particularly for the tests which were run, but instead were used to avoid long substrate lead times. Some of the samples were analyzed using energy dispersive x-ray fluorescence (EDXF). This analysis showed the presence of Au, Ni, and Cu on the samples. As the Au/Ni ratio varied from sample to sample, an inconsistent thickness of plating was indicated.

The only sample mean which varied significantly from 3-day lag to 15-minute lag was the 90/10 Ar/O_2 samples. The smaller mean and higher standard deviation of the 15-minute lag sample can only be attributed to the differences in the substrates used. Other than the substrate, the only experimental variable which was different was the elapsed time. One would expect that the shorter elapsed time would have given a higher average pull strength and lower standard deviation. Since this was not so, the differences in substrates are the suspected cause.

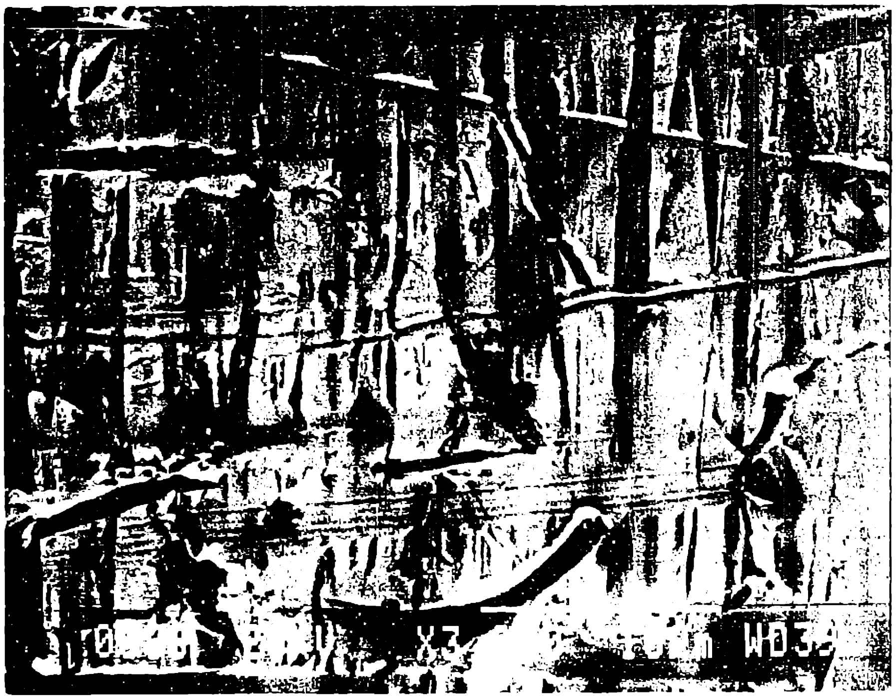
To probe these issues further and to assist in decoupling of the plasma cleaning DOX from the wire bonding DOX, additional materials characterizations were performed. Figure 6-4 is a SEM photograph at 3000x for the 90/10 Ar/O_2 sample with 15 minutes elapsed time between plasma cleaning and wire bonding. In this photo, micron size abrasions are seen. These abrasions were not expected, so the substrate supplier was contacted and questioned about the marks.

Apparently, the scratches were caused by a post-plating "burnishing," a manual operation performed both prior to nickel plating and following gold plating to remove residual debris. Such burnishing appears to cause excessive variation in the substrate surface, variation which is in addition to the differences in metallization thicknesses mentioned earlier.

Another concern was the depth of the scratches, many of which seemed to be greater than 1 µm deep per the SEM photos. Because the metallization is gold/nickel/copper, the concern was that the nickel might oxidize. Oxidized surfaces may

Figure 6-4

90/10 Ar/O_2 Sample at 3000x



cause problems for wire bonding as well as for surface mount reflow soldering.

An x-ray dot map from the SEM (Appendix G) revealed that Ni was, indeed, exposed. The light areas in the Au portion of the map shows deficiencies in gold plating. Similarly, the dark regions of the Ni map reflect portions which are Ni rich. Although this map was not performed on the particular SEM sample from Figure 6-4, the map was performed on a similar sample at 3000x. The Au-weak and Ni-rich areas have micron size features like the marks in Figure 6-4. Fourier-transform infrared spectroscopy (FTIR) was used in attempt of detecting organic contamination, but none was found.

A comparison of SEM photographs for samples made with various gases and lag times showed no distinguishable differences. This suggests that plasma cleaning has no effect on the roughness of the surface, at least relevant to the micron-sized abrasions. As a result, the plasma cleaning DOX may be effectively decoupled from the wire bonding DOX. Each of these experimental sets will be performed using the substrates with abrasions. These substrates had been manufactured prior to discovery of the abrasions, and the effects of burnishing were yet to be proven detrimental. Samples of substrates which did not go through the burnishing were ordered for follow-up experimentation (see Section 6.4).

Based on the results of the experiments, one may question whether plasma cleaning could be eliminated as only decreases in pull strength were found. Plasma cleaning was not eliminated at this stage for two reasons: 1) the variation in substrate metallization may have helped cause the decreases in pull strength, and 2) a different set of plasma parameters may have given different results (i.e., additional areas of the response surface should be explored). The next section describes the details of the plasma cleaning DOX.

6.3 Plasma Cleaning DOX

6.3.1 Approach

Of the seven plasma cleaning parameters listed in Figure 6-1, only four were used in the designed experiment: clean time, RF power, gas type, and pressure. The other three parameters were expected to have less of an impact on the pull strength, so they were held constant during the DOX. Preliminary experimentation confirmed the negligible effects of these parameters.

For the plasma DOX, the gas cycle was set at two minutes, the best allowed by the machine. Substrate samples were positioned in the center of the chamber, and the elapsed time from plasma cleaning to wire bonding was 15 minutes.

The parameters for the wire metallurgy were identical to those used in the experimentation of the previous section. Machine settings for the wire bonder also remained the same. For the plasma cleaning DOX, however, new substrates were used. These had Au thickness of 13 μin, and were plated with current densities of 18 A/ft^2 and

33 A/ft^2 for Au and Ni respectively. These substrates had all been burnished, however. A summary of the parameters used for the plasma cleaning DOX is shown in Figure 6-5.

Figure 6-5

Plasma Cleaning DOX - Parameters

plasma parameters		metallurgical parameters		wire bonder parameters		
clean time	***variable***	d_{Ni}	> 200 µin	loop height (units)	200	200
RF power	***variable***	d_{Au}	13 µin nom	bond time (msec)	50	100
gas type	***variable***	J_{Ni}	33 A/ft^2	contact vel (units)	5	5
pressure	***variable***	J_{Au}	18 A/ft^2	static force (gf)	28	28
gas cycle	2 min	wire diam.	1.25 mil	tool inflection	-	-
position	center	wire dopant	AlSi 1%	reset height	-	-
elapsed time	15 min	wire t.s.	21-24 gf	power (units)	2.5	1.9
				overtravel (units)	22	22

The levels for each of the four plasma parameters are shown in Figure 6-6. The values for time, power, and pressure were chosen based on input from the equipment supplier. For the gas ratio parameter, we decided that only Ar and O_2 would be utilized in production due to environmental issues surrounding the use of NF_3. The 80/20 and 20/80 Ar/O_2 ratios were chosen to give enough variation from the 50/50 nominal so that some effect could be observed.

The resulting experimental configuration is shown in the left half of Appendix H. The first eight rows of the matrix are the fractional factorial experimental levels. These

Figure 6-6

Plasma Cleaning DOX - Parameter Levels

parameter	low (-)	nom (o)	high (+)
clean time (min)	5	15	25
RF power (W)	500	750	1000
gas type (ratio Ar/O_2)	80/20	50/50	20/80
pressure (mTorr)	160	230	300

eight experiments are configured in a 2^{4-1} Resolution IV fractional factorial. Such a design allows calculation of the main effects of the experiment without confounding the main effects with two-factor interactions. Two-factor interactions are confounded, however, with other two factor interactions.

In addition to the eight experiments of the fractional factorial, three experiments at nominal levels and three control experiments were performed. The nominal experiments were run at the levels indicated in Figure 6-6. The controls received no plasma cleaning. All fractional factorial and control experiments were randomly ordered, and the nominal experiments were performed at the beginning, middle, and end of the experimental matrix. The plasma chamber was warmed up for 45 minutes using the nominal parameters prior to the first experiment being run.

For each of the fourteen experiments, the response variable was measured by destructive wire bond pull tests for the die and substrate separately. Nine wires were bonded from die pad to die pad using the automatic mode of the bonder and a program which held the bond length constant. Nine wires were also used for each of the substrate samples. After bonding the eighteen wires for each experimental pair, the wires were pulled and data was recorded. The sample means and sample standard deviations are shown in Appendix H.

6.3.2 Analysis/Discussion of Results

From the data in Appendix H, plasma cleaning appears to have not improved wire bond pull strength. This statement can be made through comparison with the three sets of control experiments, each of which had higher average pull strengths (for both die and substrate) than any single outcome of the plasma DOX. To assure the differences were significant, the confidence intervals were considered at 95% (see Appendix I).

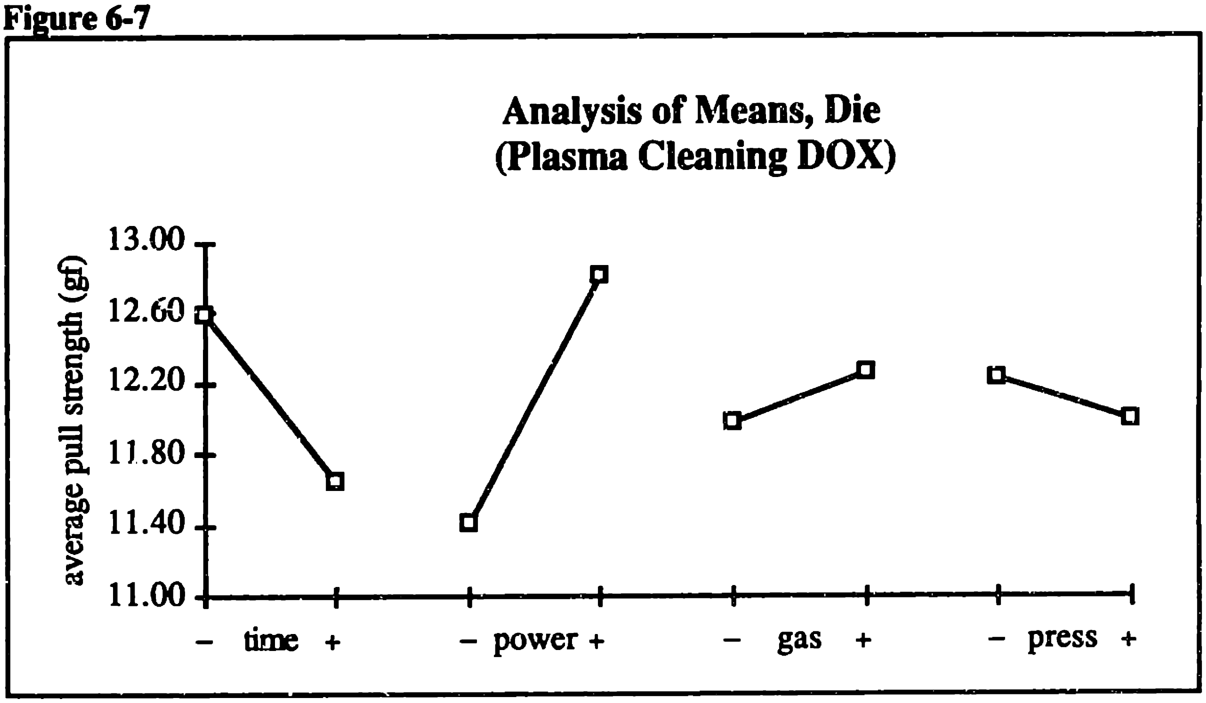
From this data, one sees that the control experimental means are significantly higher than the those for the plasma cleaning DOX experiments. This difference cannot be attributed to response surface nonlinearity, as the plasma DOX and the nominal means did not vary by a significant amount according to Appendix I. Thus, plasma cleaning was, indeed, ineffective.

To explore this further, two approaches were taken. First, an analysis of means (AOM) was conducted to understand which plasma parameters had impacted the bond pull strength. Second, Auger analyses were performed.

6.3.2.1 Analysis of Means

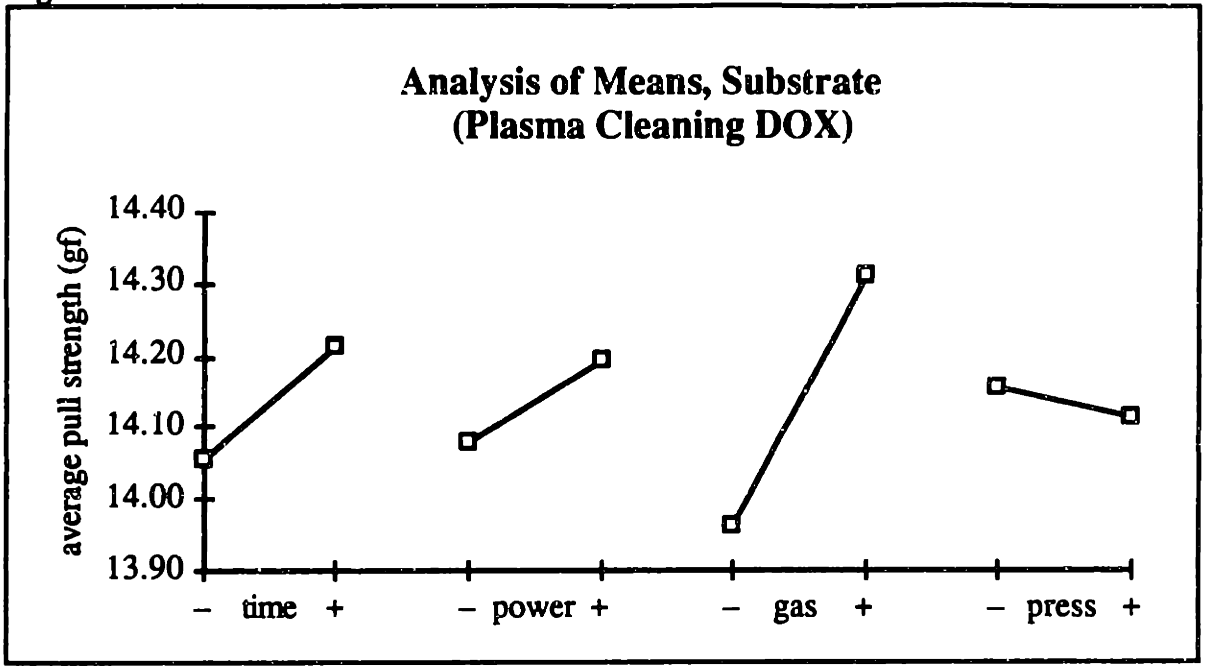
The AOM data can be found in Appendix J. This data is graphically represented in Figures 6-7 and 6-8. RF power appears to have had the greatest impact for the die, and gas mixture had the greatest impact for the substrate.

Figure 6-7



Based on the data in Appendix I, the 95% confidence interval for an effect is +/- 0.64 for the die, and +/- 0.17 for the substrate. By viewing the Δ/2 column from Appendix J, one sees that almost all of the effects capture the zero point when the uncertainties are considered. (For example, for the parameter "time" on the die, -0.47 +/-

Figure 6-8



0.64 captures zero. Therefore, this effect is rendered insignificant.) The only parameter which is significant is the RF power for the die. Figure 6-7 suggests that a higher RF power helped curb the detrimental effects of plasma cleaning for the die.

6.3.2.2 Auger Analysis

Two additional samples (one die and one substrate) were plasma-cleaned using the parameters for DOX02. These samples and two controls which had not been plasma cleaned were analyzed using Auger electron spectroscopy (AES). Auger typically has a probing depth of 1-5 nm, so detection of additional layers of carbon or oxygen is possible. Auger gives both graphical and quantitative data for analysis.

The intent of the using Auger analysis was to determine if oxygen and carbon had actually been removed from the surface as theory suggests. For each of the four samples two readings were taken. To permit crosswise comparisons, the oxygen and carbon measurements were taken as a percentage of the underlying metal (Figure 6-9).

From this data, it is apparent that oxygen and carbon were removed according to

Figure 6-9

Auger Analysis Data (%)

	O/Au	C/Au	O/Al	C/Al
Au pad, control	3.12	18.44		
	2.85	14.88		
Au pad, plasma-cleaned	1.32	1.01		
	1.81	1.08		
Al pad, control			2.71	1.64
			2.75	1.70
Al pad, plasma-cleaned			2.13	0.17
			2.31	0.21

theory. The carbon removal is roughly a ten times reduction, whereas the oxygen removal was much more subtle. The Auger energy spectra for the aluminum pad reflected this reduction in the carbon peak at around 270 eV.

Based on the Auger data, we cannot conclude that plasma cleaning decreased the wire bonding pull strength as a result of increases in either surface oxidation or in the presence of surface hydrocarbons. Another possibility, which was not evaluated, was that residual contaminants from the inside of the plasma chamber had redeposited on the bonding surfaces. This would take considerable analysis, as samples would first have to be taken from the plasma chamber to be analyzed. Once a materials analysis had been performed, the wire bonding pads would be required to undergo further analysis. In order to assure that the other parameter levels are addressed for wire bonding, this issue is left for future research.

The goal of the preceding experimentation was to set the parameter levels for the plasma chamber. As it stands, plasma cleaning was shown to be unnecessary for aluminum ultrasonic wire bonding in this particular case. The wire bonding experiments of Section 6.5, therefore, will be performed without plasma cleaning.

6.4 Additional Bonding Analyses

6.4.1 Approach

Prior to the wire bonding DOX, additional substrate experiments were run for several purposes. First, substrates which had not been burnished had been received and required some experimentation. Although the wire bonding DOX would be performed using burnished boards, this additional experimentation would serve as a basis for further prototype direction. Second, gold substrate samples from two other suppliers would be analyzed to determine their bondability. Third, samples of the substrates were received with various levels of gold thickness, gold plating current density, and nickel plating current density. The bondability of these substrates was also to be tested as a precursor to the wire bonding DOX.

For each experiment, nine wires were first bonded using the wire metallurgy and wire bonder parameters from Figure 6-10. Nickel and gold current densities were varied for all samples received from supplier #1. Nickel current densities were 16, 33, and 49 A/ft^2 for the low, medium, and high values respectfully. Similarly, gold current densities were 9, 18, and 27 A/ft^2. The control sample from source #1 had medium levels for both current densities. Samples from sources #2 and #3 had no current density data supplied with the parts.

Figure 6-10

Additional Bonding Experiments - Parameters

plasma parameters		metallurgical parameters		wire bonder parameters		
clean time	15 min	d_{Ni}	***variable***	loop height (units)	200	200
RF power	750W	d_{Au}	***variable***	bond time (msec)	50	100
gas type	50/50 Ar/O$_2$	J_{Ni}	***variable***	contact vel (units)	5	5
pressure	230 mTorr	J_{Au}	***variable***	static force (gf)	28	28
gas cycle	2 min	wire diam.	1.25 mil	tool inflection	-	-
position	center	wire dopant	AlSi 1%	reset height	-	-
elapsed time	15 min	wire t.s.	21-24 gf	power (units)	2.5	1.9
				overtravel (units)	22	22

Thickness data also varied from sample to sample. For source #1, the differences in current densities for the parts required that the time of the plating baths be monitored closely to achieve the desired thicknesses. Because there was much trial and error with the plating bath setups, the thicknesses were inconsistent across samples. Again, samples #2 and #3 had no thickness information supplied with them.

Two samples were bonded for each experiment: one had been plasma cleaned at the nominal parameter levels and the other had not been subjected to plasma cleaning. Nine bonds were pulled to destruction for each sample, and pull strengths were recorded.

6.4.2 Analysis/Discussion of Results

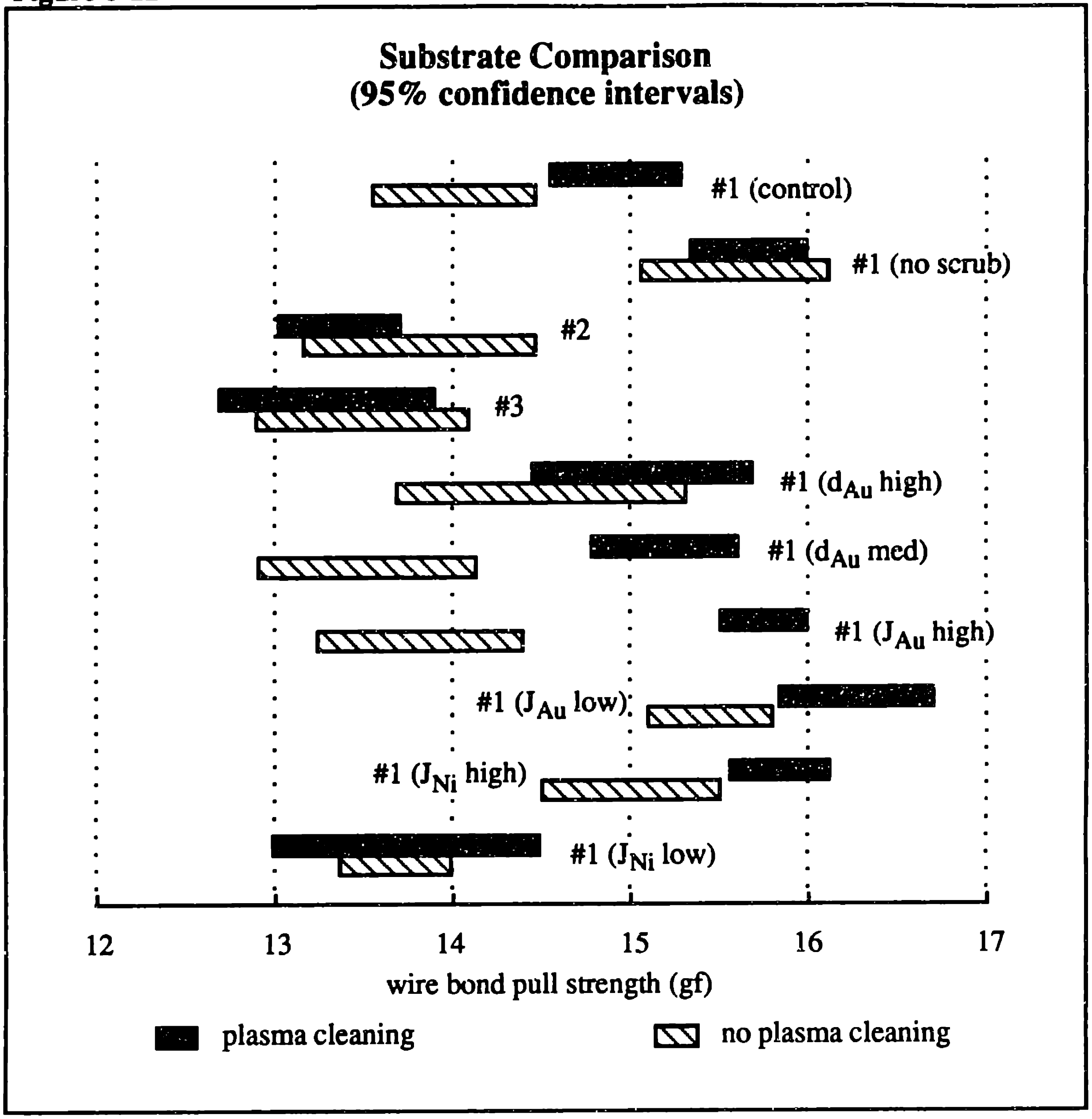
The sample means and sample standard deviations for the experiments are shown in Appendix K. Measurements of the Ni and Au plating thickness were also made by using x-ray fluorescence (XRF). The thickness data in Appendix K is the average of three readings per sample. Variation in these readings was insignificant. Based on the pull strength data, 95% confidence intervals were calculated. A box plot of these confidence intervals is shown in Figure 6-11.

From the plot, several interesting observations can be made. First, the control from source #1 had significantly higher pull strengths associated with it than either the sample from source #2 or #3. In addition, the sample which had not been burnished (" #1 no scrub") had greater strength than the control from source #1. These two observations suggest that future prototypes should be made using substrates from source #1, and the burnishing operation requires further investigation.

Another key observation is that no case exists in which plasma cleaning resulted in significantly higher pull strengths for corresponding samples. Thus, the plasma cleaning results from the previous section are confirmed.

Finally, a high nickel current density appears to result in greater pull strength. When this is probed further, however, one finds from Appendix K that the sample with

Figure 6-11



J_{Ni} high had a significantly lower gold plating thickness (5.8 μin) than the sample with J_{Ni} low (65.2 μin). As such, it should be questioned whether nickel current density itself caused the increased pull strength.

This points out a caveat with the comparison of Figure 6-11. Because of the inability to control plating thicknesses to the desired degree, the results cannot be isolated specifically to a single parameter. The control sample from source #1, for example, had considerably more gold plating than the source #1 "no scrub" sample. Such differences should be considered when making pull strength comparisons.

Another caveat concerns the plating techniques used by the three different sources. Appendix L contains SEM photographs showing the surface texture of the samples from each source. Sources #1 and #3 have a very similar appearance, with grain widths of approximately 5 µm and circular in shape. The dark areas of the samples, however, represent distinct differences. The dark area in the sample from source #1 is an abrasion caused by the burnishing process. The dark area in the sample from source #3 is underlying nickel which appears to have become exposed due to a faulty gold plating process. The sample from source #2 has a considerably different structure. The plating is much more uniform and grain sizes are smaller (approximately 1 µm).

Because of the differences in plating appearance, one consideration is that parameters for the wire bonder may have affected pull strength. As these parameters were originally set with respect to samples received from source #1, the parameters may not have been ideal for samples from sources #2 or #3. To resolve this issue, samples could have been attained from each of the sources and used within the wire bonding DOX. This was not considered as an option, however, because at the time we were not aware of any problems with source #1. Bringing additional suppliers into the wire bonding DOX at this point would have made the experimentation sequence overly complex as well as difficult to coordinate.

Even with these caveats, the additional bonding experiments helped us to identify some potential areas for improvement. The need to explore unburnished samples from source #1 is evident. Additional wire bonding windows for substrate sources #2 and #3 should also be pursued, and such experimentation would be simplified if a few key bonding parameters were targeted. The next section, which explains the wire bonding designed experiments, will locate the significant parameters affecting wire bond pull strength.

6.5 Wire Bonding DOX

6.5.1 Approach

The approach for the wire bonding DOX was very similar to that used for the plasma DOX: identify parameters, choose the design matrices, and perform the experiments. Because these experiments included a greater number of parameters, however, the experimentation was slightly more complex.

6.5.1.1 Parameters/Levels

Figure 6-12 reflects the parameters considered for the wire bonding DOX. Due to results found from the preceding experimentation, samples were not plasma cleaned prior to wire bonding. Thus, the only parameters utilized were those for the substrate and wire metallurgy as well as those for the wire bonder.

Figure 6-12

Wire Bonding DOX - Parameters

plasma parameters		metallurgical parameters		wire bonder parameters		
clean time	none	d_{Ni}	> 200 µin	loop height (units)	200	200
RF power	none	d_{Au}	***variable***	***bond time (msec)***	***variable***	
gas type	none	J_{Ni}	***variable***	***contact vel (units)***	***variable***	
pressure	none	J_{Au}	***variable***	***static force (gf)***	***variable***	
gas cycle	none	wire diam.	1.25 mil	tool inflection	-	-
position	none	***wire dopant***	***variable***	reset height	-	-
elapsed time	none	wire t.s.	21-28 gf	***power (units)***	***variable***	
				overtravel (units)	***variable***	

For the metallurgy, four parameters were considered: gold thickness (d_{Au}), gold plating current density (J_{Au}), nickel plating current density (J_{Ni}), and wire dopant. All four parameters were used in the substrate experiments, whereas only the wire was varied for the die. Die metallurgy was not considered as a variable for two reasons: 1) The die was a more standard part than the substrate. Since the substrate was custom, the substrate supplier was very willing to make the process alterations for experimentation. Variation in die metallization would have been much more difficult acquire. 2) The die was expected to be less critical, since the interface was Al wire to an Al die pad.

Additionally, the only wire parameter considered was wire dopants. Although variations in tensile strength for each dopant were possible, tensile strength was seen as a parameter which might be varied slightly in a final tuning of parameters performed within the actual production environment.

The five parameters selected from the wire bonder were bond time, contact velocity, static force, power, and overtravel. These parameters were explained in Chapter 3 of this thesis. Loop height was not varied because this would naturally cause pull strengths to differ. As changing the loop height will alter the inclination angles of the wire from the substrate, a change in the resolution of forces will occur. This would cause pull strengths to differ even for bonds which have identical integrity at the bond interface.

The levels for the wire bonding parameters are shown in Figure 6-13. The substrate and metallurgy levels were established through discussions with and recommendations from the material suppliers. Wire bonder levels were found through

Figure 6-13

Wire Bonding DOX - Parameter Levels

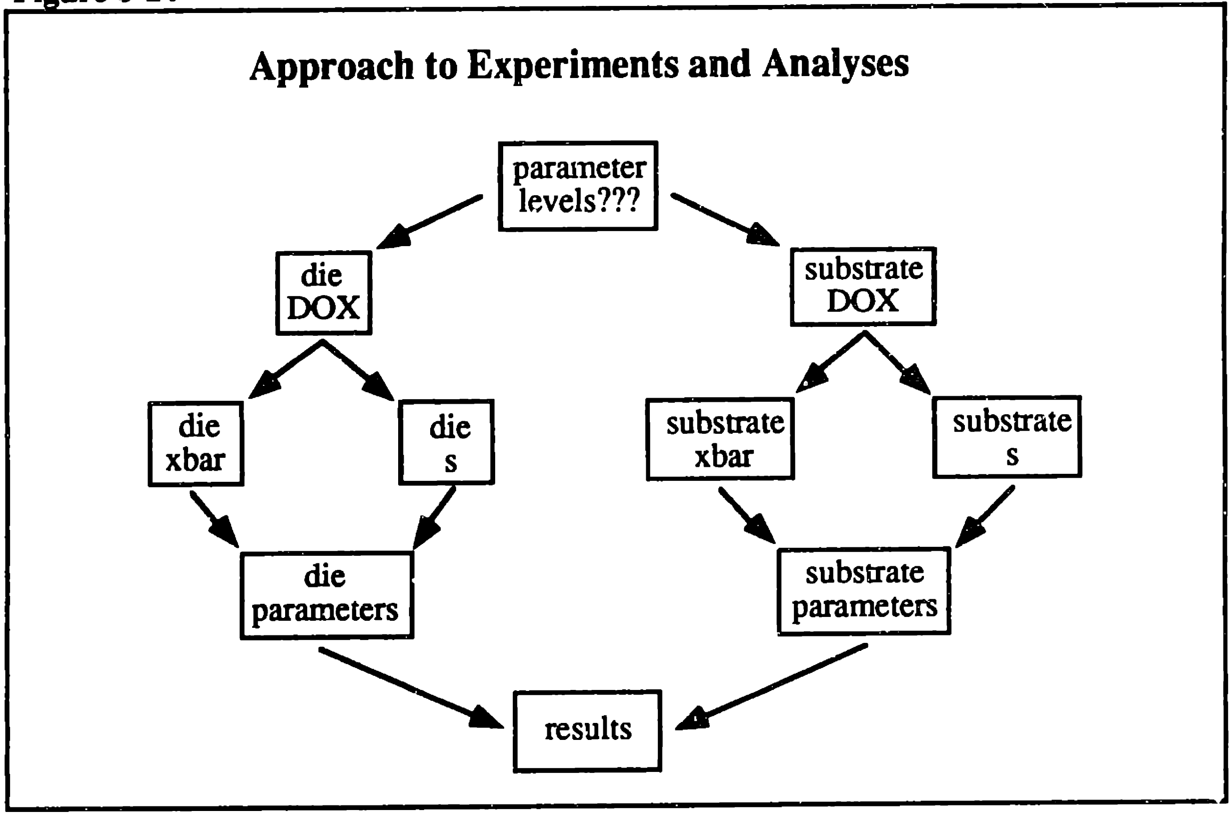
	die			**substrate**		
parameter	low (-)	nom (o)	high (+)	low (-)	nom (o)	high (+)
d_{Au} (μin)	x	x	x	14	x	35
J_{Au} (A/ft^2)	x	x	x	9	18	27
J_{Ni} (A/ft^2)	x	x	x	16	33	49
wire metallurgy	AlSi (1%)	x	AlMg (0.5%)	AlSi (1%)	x	AlMg (0.5%)
time (msec)	80	100	120	40	50	60
contact velocity (units)	3	5	7	3	5	7
force (gf)	23	28	33	23	28	33
power (units)	1.6	1.9	2.2	2.0	2.5	3.0
overtravel (units)	14	22	30	14	22	30

preliminary experimentation. It is important to note that for the ultrasonic energy variables (time, force, and power), the levels were all offset approximately 20% from the nominal parameters established during previous product builds. In this way, a fair comparison could be made in determining which of these variables would have the largest impact.

6.5.1.2 Experimental Structure

To understand the wire bonding DOX structure for experiments and analyses, consider Figure 6-14. In actuality, two designed experiments were run: one for the die and another for the substrate. Each of these two experiments were then analyzed with both the average pull strength and the standard deviation of the pull strength as response variables, so that four analyses in total were performed.

Figure 6-14



Analysis of means (AOM) and analysis of variance (ANOVA) were used to determine the important effects and their levels of significance. AOM and ANOVA were performed separately on the sample means and sample standard deviations. Each of the four analyses resulted in recommended levels for the process parameters. Once all analyses had been completed, the results were compiled and any conflicts were resolved. Because of the separation of the die and substrate DOX, the experimentation and analyses for each will be considered sequentially beginning with the die.

6.5.2 Die Experiments

6.5.2.1 Approach

The configuration of the die experiments is shown in the left half of Appendix M. The 32 experiments are configured in a 2^{6-1} Resolution VI fractional factorial design. For such a configuration, every main effect and two-factor interaction is not confounded with any other main effect or two-factor interaction. Two-factor interactions are confounded with three-factor interactions. However, three-factor interactions are not expected to be significant for this experiment so that unconfounded two-factor interactions will give the necessary degree of resolution.

A silver-filled epoxy was dispensed onto the gold surface of the substrate, and the die were attached with the die bonder. Although the die could have been fixtured, we felt that the attachment of die to the substrate would better represent the samples as they would appear in production. The die bond epoxy was cured, and the experiments were performed.

Nine wires were bonded from die pad to die pad for each of the 32 experiments. The automatic mode of the bonder was used. Like all other experimentation within this chapter, bond length was held constant with a bonding program. After each sample was bonded, the nine wires were pulled to destruction and the experimental values recorded. For wire bonds which did not stick to the die pad, a value of zero gf was used. The sample means and sample standard deviations for this data are shown in the right half of Appendix M.

6.5.2.2 Analysis

From the data in Appendix M for xbar, an analysis of average pull strength for the die was conducted. The analytical tools which were used is found in Appendix N. These consist of: 1) an analysis of means (AOM), 2) a plot of the main effects, 3) an analysis of variance (ANOVA), and 4) plots of two-factor interactions. Each of these will be addressed separately.

The analysis of means shows the impact of varying the parameters from low to high levels. The "avg–" column represents the average of all responses for the low level of the particular parameter being considered. For example, the 11.14 for "cvel" is the average of all responses (16 DOX runs in total) where a low value of contact velocity was used. The "effect Δ" column represents the difference between the "avg–" and the "avg+" columns. "Δ/2" is the amount that the pull strength is expected to increase (decrease) from the experimental grand mean as the parameter in question is varied from nominal to its high (low) value. Obviously, an effect with a higher |Δ/2| has had a more significant impact.

For a two-factor interaction, "avg–" represents the case where one of the two parameters was at a high level and the other at a low. Likewise, "avg+" represents two parameters which are either both at high levels or both at low levels.

Based on the analysis of means, the main effects (single factors) were plotted. These show that increasing the ultrasonic power had a major impact on increasing the average pull strength. From the plot, the AlMg 0.5% wire also appears to have had a positive effect, whereas an increase in static force appears to have resulted in decreases for the average pull strength. To test which of these effects are significant, an ANOVA table (Appendix N) was used at a 95% significance level. Significant items are in boxes.

The two-factor interaction of time and power was then plotted (Appendix N). This chart shows that the highest average pull strength occurs when the power is at a high level and the time is at a low level. When this happens, the average result is 15.80 gf, or 3.83 gf over the grand mean of 11.97 gf.

Based on the analysis from Appendix N, the effects are summarized by decreasing order of importance in Figure 6-15. Recommendations for levels are based on the expected increase to pull strength according to the "Δ/2" variable. For the two-factor interaction, the negative sign in the "Δ/2" figure indicates that a "+ –" or a "– +" combination of time and power should be used to increase pull strength. The -1.49 variable, in fact, is the exact average increase that the 15.80 and 11.11 interaction values have on the grand mean:

$$11.97 - (15.80 + 11.11)/2 = -1.49$$

To decide which levels are recommended for the two-factor interaction, the plot should be used as a guide. In this particular case, the "– +" option will result in the higher expected pull strength increase.

The significant effects for the standard deviation of bond pull strength were found in a similar manner. The analytical tools which were used appear in Appendix O. A

Figure 6-15

Significant Effects, Die (xbar)

effect	Δ/2	recommended
power	2.75	+
wire	1.52	+
time*power	-1.49	+ – (11.11) – + ***(15.80)*** – – (7.32) + + (13.62)
force	-1.23	–
cvel	0.83	+

summary of the significant effects is shown in Figure 6-16. Since a smaller standard deviation is better, levels are recommended which will provide decreases to the average standard deviation.

Figure 6-16

Significant Effects, Die (std dev)

effect	Δ/2	recommended	
power	-1.29	+	
wire	-0.81	+	
wire*power	0.61	+– (2.81)	–+ (1.85)
		–– (5.64)	++ *(1.46)*
time*power	0.58	+– (3.41)	–+ *(1.31)*
		–– (5.04)	++ (2.00)

6.5.3 Substrate Experiments

6.5.3.1 Approach

The experimental configuration for the substrate DOX is shown in the left half of Appendix P. The 64 experiments are configured in a 2^{9-3} Resolution IV fractional factorial design. Similar to the die experiments, this arrangement provides unconfounded main effects. Unlike the die experiments, however, some two-factor interactions will be confounded with other two-factor interactions. To achieve the same resolution as in the die experiments, 128 samples would have to be bonded. This increase would be necessary to accommodate the additional three substrate parameters. Because 128 experiments was infeasible, a lower level of resolution was accepted.

Nine wires were bonded from substrate to die pad for each experiment. The automatic mode of the bonder was again used. After each sample was bonded, the nine wires were pulled to destruction and the experimental values recorded. A value of zero gf was again used for wire bonds which did not stick to the substrate. The sample means and sample standard deviations for this data are shown in the right half of Appendix P.

6.5.3.2 Analysis

AOM, plots of main effects, ANOVA, and two-factor interaction plots were also utilized for substrate analysis. These analyses are found in Appendix Q for the xbar values and in Appendix R for the standard deviations. Summaries of the significant effects and recommended levels are shown in Figures 6-17 and 6-18.

Figure 6-17

Significant Effects, Substrate (xbar)

effect	Δ/2	recommended	
wire*power	2.70	+− (7.16)	−+ (13.70)
		−− (14.31)	++ ***(17.35)***
power	2.40	+	
J_{Au}	-1.58	−	
d_{Au}	-1.37	−	
d_{Au}*J_{Au}	-1.30	+− (14.63)	−+ (14.22)
		−− ***(14.78)***	++ (8.87)
power*J_{Au}	1.13	+− ***(15.97)***	−+ (8.02)
		−− (13.44)	++ (15.08)
time*power	-1.09	+− (12.17)	−+ ***(16.27)***
		−− (9.29)	++ (14.78)
wire	-0.87	−	
power*d_{Au}	0.76	+− ***(16.14)***	−+ (8.61)
		−− (12.86)	++ (14.91)

Figure 6-18

Significant Effects, Substrate (std dev)

effect	Δ/2	recommended	
power	-1.01	+	
wire	0.57	−	
d_{Au}	0.51	−	
ovt*force	0.50	+− ***(1.36)***	−+ (1.44)
		−− (2.41)	++ (2.41)
power*d_{Au}	-0.40	+− ***(0.78)***	−+ (3.82)
		−− (2.01)	++ (1.00)

6.5.4 Summary of Results

A summary of significant effects from all experiments is shown in Figure 6-19.

Figure 6-19

Significant Effects, Summary

effect	die (xbar)	die (std dev)	substrate (xbar)	substrate (std dev)
cvel	+			
wire	+	+	–	–
force	–			
power	+	+	+	+
J_{Au}			–	
d_{Au}			–	–
ovt*force				+ –
time*power	– +	– +	– +	
wire*power		+ +	+ +	
power*d_{Au}			+ –	+ –
power*J_{Au}			+ –	
d_{Au}*J_{Au}			– –	

6.5.5 Discussion of Results

From this compiled list, several key observations can be made. Power has the most significant all-around impact on wire bonding. This is based on the multiple inclusions of power as a main effect as well as the appearance of power in a majority of the two-factor interactions. In the twelve occurrences where power was significant, all suggested that it be set at a high level.

To appreciate the effects of increasing the power, consider the SEM photos in Appendix S. These photos were from a sample bonded to a die pad with cvel and time at high levels, and both wire and force at low levels. For the top photo, power was set at a low level and for the bottom photo it was set high. From these photos, it appears that power has a significant impact on the bond foot deformation. Also, the two-factor interactions from the first and second columns in Figure 6-19 recommend time to be at a low level when power is high. The high value of time used for the photographed samples may have caused the apparent cracks at the heels of each bond foot.

The other two energy variables, bond time and static force, did not have as significant of an impact as power. Static force was significant in the main effects of only one of the response variables and also in one two-factor interaction. Time only appeared in the two-factor interactions. Although the effects of these parameters were limited, each of these parameters was recommended to be set at a low level. This agrees with the theory of interaction of the energy variables discussed at the end of Chapter 3.

For the substrate metallurgy, all significant factors which included d_{Au} and J_{Au} suggested low levels for each. This is in agreement with the literature described in Chapter 3. For the thickness, the recommendation to use 14 μin of Au is within the IPC specification for COB (5-15 μin). Further fine-tuning studies could be conducted on thicknesses centered around 14 μin. The gold plating current density recommendation is for 9 A/ft^2, or approximately 1 A/dm^2. This level should allow high pull strength to be achieved through fewer impurities in the substrate, as reflected in Figures 3-2 and 3-4.

The only conflicting recommendation was for the wire metallurgy. For the die, the main effects of each response variable suggested a high level (AlMg 0.5%), whereas the substrate preferred a low level (AlSi 1%). The two-factor interactions, one each from the die and substrate, also would benefit from the AlMg 0.5%. To evaluate what level would give the highest level of impact, the prediction equation for the DOX output was evaluated.

The general form of the prediction equation can be written as:

$$\hat{y} = \bar{y} + \left(\frac{\Delta_A}{2}\right)A + \left(\frac{\Delta_B}{2}\right)B + \left(\frac{\Delta_{AB}}{2}\right)AB + \ldots$$

[Schmidt and Launsby, 1992, p.19]

The four prediction equations for wire bonding can then be written as:

$$\text{die } \hat{\bar{x}} = 11.97 + (0.83)\text{cvel} + (1.52)\text{wire} - (1.23)\text{force} + (2.75)\text{power} - (1.49)(\text{time})(\text{power})$$

$$\text{die } \hat{s} = 2.94 - (0.81)\text{wire} - (1.29)\text{power} + (0.58)(\text{time})(\text{power}) + (0.61)(\text{wire})(\text{power})$$

$$\begin{aligned}\text{substrate } \hat{\bar{x}} = 13.13 &- (0.87)\text{wire} + (2.40)\text{power} - (1.37)d_{Au} - (1.58)J_{Au} \\ &- (1.09)(\text{time})(\text{power}) + (2.70)(\text{wire})(\text{power}) + (0.76)(\text{power})(d_{Au}) \\ &+ (1.13)(\text{power})(J_{Au}) - (1.30)(d_{Au})(J_{Au})\end{aligned}$$

$$\begin{aligned}\text{substrate } \hat{s} = 1.90 &+ (0.57)\text{wire} - (1.01)\text{power} + (0.51)d_{Au} + (0.50)(\text{ovt})(\text{force}) \\ &- (0.40)(\text{power})(d_{Au})\end{aligned}$$

From these equations, the impact that wire has on each of the response variables can be found. For example, with wire at a high level, the predicted average pull strength for the die is:

$$\begin{aligned}\text{die } \hat{\bar{x}} &= 11.97 + (0.83)(+1) + (1.52)(+1) - (1.23)(-1) + (2.75)(+1) - (1.49)(-1)(+1) \\ &= 19.79 \text{ gf}\end{aligned}$$

Similarly, the values can be predicted for the other response variables. A summary of the predicted values is shown in Figure 6-20.

The prediction of a negative standard deviation for the substrate reflects the fact that an error term is an inherent part of the prediction equation. From the values in Figure 6-20, a high value for wire appears to give the best overall result, so AlMg 0.5% wire is recommended. A summary of the recommended levels for the parameters is listed in Figure 6-21.

Although J_{Ni} was not a significant variable, the substrate AOM's indicated that a

Figure 6-20

Predicted Responses for Variations in the "Wire" Parameter

variable	wire –, gf	wire +, gf
die $\hat{\bar{x}}$	16.75	19.79
die $\hat{s}$	1.27	0.87
substrate $\hat{\bar{x}}$	16.38	18.21
substrate $\hat{s}$	-0.29	0.85

Figure 6-21

Wire Bonding DOX Results - Parameter Levels

	die		substrate	
parameter	low (-)	high (+)	low (-)	high (+)
d_{Au} (μin)			14	
J_{Au} (A/ft^2)			9	
J_{Ni} (A/ft^2)			16	
wire metallurgy		AlMg (0.5%)		AlMg (0.5%)
time (msec)	80		40	
contact velocity (units)		7		7
force (gf)	23		23	
power (units)		2.2		3.0
overtravel (units)		30		30

low value would move both the average pull strength and the standard deviation in the proper direction. In a similar manner, cvel was recommended at a high level for the substrate.

The center points of the response surface were checked using nominal levels from Figure 6-13. Because a nominal wire and a nominal gold thickness were not available, the center points had to be checked at two points for the die (wire – and wire +)

and four points for the substrate (combinations of wire and J_{Au}). The center points were compared to the experimental means for each, and a slight nonlinear experimental response was suggested for the average pull strengths. This nonlinearily had been anticipated in Chapter 3.

Because of this nonlinearity, a fine tuning experiment should be run by varying some of the significant parameters from Figure 6-19 at three levels each. Such an experiment was not run because of time constraints. For further work, however, it is strongly recommended that both the parameters of power and time (high interactions) be varied at some levels which will explore the region between their recommended values (Figure 6-21) and the nominal values (Figure 6-13).

6.5.6 Confirmation Experiments

Confirmation of the above parameters was performed on three separate substrates and die using a total of 27 bonds per medium. The confirming results, along with the process improvements are reflected in Figure 6-22.

Figure 6-22

Confirmation of Wire Bonding
Process Parameters

variable	predicted	confirmed	control	% improved
die $\hat{\bar{x}}$	19.79	20.31	14.93	36%
die $\hat{s}$	0.87	0.56	1.09	49%
substrate $\hat{\bar{x}}$	18.21	19.33	14.97	29%
substrate $\hat{s}$	0.85	1.04	0.62	(68%)

From Figure 6-22, one can see significant improvement in all process outcomes except for wire standard deviation of pull strength for the substrate. For this particular measurement, we had consciously made the choice (a few pages back) to use AlMg 0.5%

wire, a choice which most likely increased the substrate standard deviation per the prediction equations. If the reduction in the substrate standard deviation ever became a critical issue, this choice could be reevaluated. One further approach would be to try using a softer AlMg alloy and to include this wire in the fine tuning experiment recommended in the previous section.

6.6 Summary

Through using a combination of designed experiments and materials analyses, the process specifications for wire bonding were established. Several important observations were made throughout this process:

- The use of plasma cleaning showed no visible surface effects at 3000x magnification. This allowed the plasma cleaning and wire bonding experiments to be decoupled.
- Analysis of the substrates for the impact of plasma cleaning led to an unexpected finding. The substrate surface had been burnished, a manual operation intended to remove debris which scratches the gold-plated surface down to the underlying nickel. From the comparison with the unburnished substrate, it is recommended that further work be pursued with the substrate supplier.
- In all experiments performed within this chapter, plasma cleaning was found to be ineffective for increasing the pull strength of aluminum ultrasonic wire bonds. Auger analysis showed, however, that plasma cleaning was effective in removing surface carbon and oxygen.
- Through the wire bonding DOX, the most critical parameters for ultrasonic aluminum wire bonding were found. The power setting of the bonder as well as the type of wire used gave the most dramatic shifts in average pull strength and variation.

The DOX approaches used in this chapter allowed an efficient use of time in order to focus on the critical issues which surrounded wire bonding. Furthermore, designed experiments provided a framework for the overall experimental method, as even those experiments which did not use DOX principles fit into a higher purpose. As such, designed experiments provided the necessary structure for grasping the complexity of a process like aluminum ultrasonic wire bonding.

In retrospect, the approaches used in this chapter would be repeated if this same situation were again presented. These approaches were very high-level in nature, evaluating the effectiveness of processes such as plasma cleaning by the impact on the ultimate response of pull strength. Thus, even though plasma was found to remove carbon and oxygen it was rendered ineffective for reasons not entirely known. Given a limited timeframe, knowledge of such "lower-level" issues could not always be afforded.

However, we learned that such a high-level, structured approach requires some deeper probing of basic experimental assumptions. For example, we did not blindly accept what the material suppliers had given. Findings such as abrasions and plating thickness inconsistency were necessary to help draw higher-level conclusions. Pursuit of such lower-level activity is based on confidence in existing material suppliers. A little common sense here goes a long way.

One must also be careful not to use statistical techniques without an understanding of the underlying process. A great deal of literature search and side experimentation went into the preceding process development. Additionally, the plasma and wire bonding DOX's were complemented with a significant number of materials analyses to assist in process specification. Such an approach was effective in this particular case and is recommended for any other which plans the use of designed experiments as a method for process parameter specification.

Chapter 7
Findings and Recommendations

This thesis examined issues regarding the use of structured methodologies for wire bonding development. These methodologies included relative assessment of process development risk and designed experiments for parameter specification. From the research detailed in the previous pages, several general conclusions can be drawn and recommendations for future work can be made.

7.1 Risk Management

7.1.1 Findings

The methodology for assessing process development risk on a relative basis provided benefits of first and second order. The primary benefit was creation and use of the methodology itself. With the rated hierarchy approach, the team had developed a framework for addressing risk which met the team's original criteria for ease of use with limited resources. Application of this method also allowed us to determine the major process risks for wire bonding. This was done in a manner which provided a true understanding of the components of risk, represented as probabilities and consequences.

A secondary effect was also realized through participation on the risk management team. The sharing of ideas and technological knowledge was enhanced by regular meetings of the team. The meetings gave project members an opportunity to share their understanding of the variables which affect wire bonding.

7.1.2 Recommendations for Future Work

Much future work is necessary to fully develop the principles generated by this research. The most evident area for improvement is in the application of the relative risk methods to other levels of project hierarchy. Because the concept of relative risk was foreign to the entire team at the commencement of the project, we decided to first develop the methods by using a specific process such as wire bonding. By using such a tangible process for evaluation, we could easily measure our progress.

As the relative risk approaches are applied at higher levels of project management, however, one must question how the overall methodology would operate. One option is to develop several trees to represent the total process, but this would require a tremendous amount of effort from the project team. With the COB project, for example, trees would have been required for die attach, wire bond, encapsulation, curing, surface mount, and final assembly. Even if these were all created, there would be additional risks which would not fit into any specific process tree. Examples include strategic management of the supply chain, procurement and delivery of equipment, marketing forecasts, etc. Also, the question remains as to how non-value added operations such as testing and inspection would be handled.

Rather than using several risk trees, an alternative would be to evaluate the project with much less detail for the specific process components. For example, the COB project risk tree may have included risks in market forecasting, technology development, supplier dependency, financial support, etc. If each of these could be evaluated relatively, the need for process details would only be required to evaluate those processes identified as critical.

7.2 Wire Bonding

7.2.1 Findings

From the experimentation of Chapter 6, several findings for wire bonding were made. First, abrasions on the surface of the substrate were not expected but were inadvertently detected with SEM. When contacted, the substrate supplier identified these abrasions with a burnishing process intended to remove plating debris. Further experimentation, although limited in scope, showed the unburnished sample to result in higher average pull strength for wire bonding.

Plasma cleaning was found to be ineffective for improving the strength of aluminum ultrasonic wire bonds. This was demonstrated with side experimentation as well as with the plasma cleaning DOX. Because of these results, procurement of a plasma cleaning unit specifically for COB was not necessary, resulting in a cost avoidance of approximately $250,000.

The wire bonding DOX resulted in identification of ultrasonic power and wire alloy as the two most influential parameters for bond pull strength. Additionally, the other process parameter levels could be recommended as a result of the wire bonding DOX.

A very important result of the experimentation was the complementary nature of the designed experiments with the materials analyses. By performing either of these in isolation, the results in this thesis would not have been achieved. The designed experiments provided a statistical method for reducing the number of experiments run, and also provided the overall strategy for experimental direction. The key decision points throughout this process, however, were determined not by the designed experiments but instead by the results of materials characterizations.

7.2.2 Recommendations for Future Work

Continuation of this project would require several different levels of experimentation and analysis. First, the recommended iteration on the wire bonding DOX experiments should be performed. These would include variation in the power and time parameters to experiment in the region between the recommended levels and nominal. Variations in the tensile strength of the AlMg 0.5% wire could also be included to see if this may help curb the increased pull strength variance shown on the substrate.

Although these experiments are recommended to be performed initially in a three-level design matrix, the results should be fully examined with the SEM. This would allow a link between the parameter levels and the physical result, a useful tool both for engineering and for production.

Since the type of substrate being used also affected bondability, the impact of the burnished versus unburnished samples should be evaluated with the assistance of the substrate supplier. Additional studies should also be performed using the substrates from source #2, as the surface of the received sample appeared to be very consistent. Both the unburnished source #1 and source #2 samples could be evaluated within DOX. Such matrices could use the parameters found to have highest impact during the wire bonding DOX, thus reducing the amount of effort to achieve adequate evaluation.

7.3 Summary

In summary, the use of structured methods to develop complex processes such as that of aluminum ultrasonic wire bonding are essential. This thesis examined two such methods: relative risk assessment and designed experiments. Without these approaches, risk remains an intuitive, abstract concept and evaluation of process parameters interactions becomes impractical. Such structure also provides a secondary effect, in that the project engineers have a common framework for communication of ideas and results.

Wire Bonding Risk Tree

suboptimal wire bonding process						risk event #	risk group
	bond does not adhere (non-stick)						
		excessive die tilt					
			excessive driver die tilt				
				foreign object in die bond material (drivers)		1	A
				improper die bond tooling alignment (drivers)		2	B
				inconsistent die bond material dispense (drivers)		3	C
				suboptimal die bond dispense pattern (drivers)		4	D
				suboptimal die bond machine parameters (drivers)		5	E
				variation due to curing (drivers)		6	F
			excessive LED die tilt				
				foreign object in die bond material (LED)		7	G
				improper die bond tooling alignment (LED)		8	H
				inconsistent epoxy transfer methods (LED)		9	I
				suboptimal die bond machine parameters (LED)		10	J
				variation due to curing (LED)		11	K
		wire bonding surfaces not clean					
			inorganic contamination				
				inadequate parts handling (post clean/pre-WB)		12	L
				suboptimal cleaning procedure (pre-WB)		13	M
			organic contamination				
				inadequate parts handling (post clean/pre-WB)		14	L
				suboptimal cleaning procedure (pre-WB)			
					suboptimal cleaning time	15	N
					suboptimal RF power	16	O
					suboptimal gas mixture	17	P
					suboptimal positioning in chamber	18	Q
					suboptimal gas cycle time	19	R
					suboptimal chamber pressure	20	S
		suboptimal substrate metallurgy					
			excessive substrate impurities			21	T
			suboptimal gold thickness			22	U
			suboptimal nickel thickness			23	V
			suboptimal surface roughness			24	W
		suboptimal wire metallurgy					
			suboptimal wire hardness			25	X

Appendix A
(continued)

		wrong wire dopants			26	Y
		suboptimal wire bond machine parameters				
			suboptimal bond head overtravel		27	Z
			suboptimal bond head static force		28	AA
			suboptimal bond time		29	BB
			suboptimal contact velocity		30	CC
			suboptimal ultrasonic power		31	DD
	excessive wire breakage					
		parts mishandled (post-WB)			32	EE
		suboptimal wire metallurgy				
			suboptimal wire hardness		33	X
			wrong wire dopants		34	Y
		suboptimal wire bond machine parameters				
			suboptimal bond head overtravel		35	Z
			suboptimal bond head static force		36	AA
			suboptimal bond loop height		37	FF
			suboptimal bond time		38	BB
			suboptimal contact velocity		39	CC
			suboptimal ultrasonic power		40	DD
	suboptimal machine performance					
		excessive cycle time				
			suboptimal program written for bond sites (drivers)		41	GG
			insufficient tooling		42	HH
			rotational error in die placement (drivers)		43	II
			suboptimal wire bond machine parameters (drivers)			
				suboptimal bond energy (drivers)	44	BB
				suboptimal contact velocity (drivers)	45	CC
				suboptimal bond head reset height (drivers)	46	JJ
				suboptimal tool inflection point (drivers)	47	KK
		inaccurate wire bonds				
			insufficient tooling		48	HH
			inaccurate program written for bond sites (drivers)		49	LL
			poor eyepoint calibration		50	MM
		pattern recognition system (PRS) fails to detect				
			excessive driver die tilt			
				foreign object in die bond material (drivers)	51	A

				improper die bond tooling alignment (drivers)	52	B
				inconsistent die bond material dispense (drivers)	53	C
				suboptimal die bond dispense pattern (drivers)	54	D
				suboptimal die bond machine parameters (drivers)	55	E
				variation due to curing (drivers)	56	F
			excessive variation in x/y/theta die position (drivers)			
				foreign object in die bond material (drivers)	57	A
				improper die bond tooling alignment (drivers)	58	B
				inconsistent die bond material dispense (drivers)	59	C
				suboptimal die bond machine parameters (drivers)	60	D
				suboptimal die bond dispense pattern (drivers)	61	E
				variation due to curing (drivers)	62	F
			improper lighting		63	NN
			wrong magnification		64	OO
		unreliable missing wire detector (MWD)				
			MWD fails to detect		65	PP
			MWD falsely detects		66	QQ

Appendix B

Terminal Branch Method - Probabilities and Consequences

suboptimal wire bonding process				scaled		scaled
bond does not adhere (non-stick)	#	grp	prob	prob	cons	cons
excessive die tilt						
excessive driver die tilt						
foreign object in die bond material (drivers)	1	A	2.3	2.3	6	3.0
improper die bond tooling alignment (drivers)	2	B	1.7	1.7	60	30.0
inconsistent die bond material dispense (drivers)	3	C	5	5	45	22.5
suboptimal die bond dispense pattern (drivers)	4	D	3.6	3.6	40	20.0
suboptimal die bond machine parameters (drivers)	5	E	1.6	1.6	60	30.0
variation due to curing (drivers)	6	F	2.2	2.2	240	120.0
excessive LED die tilt						
foreign object in die bond material (LED)	7	G	2.6	2.6	6	3.0
improper die bond tooling alignment (LED)	8	H	3.5	3.5	60	30.0
inconsistent epoxy transfer methods (LED)	9	I	2.4	2.4	12	6.0
suboptimal die bond machine parameters (LED)	10	J	70	70	60	30.0
variation due to curing (LED)	11	K	7	7	240	120.0
wire bonding surfaces not clean						
inorganic contamination						
inadequate parts handling (post clean/pre-WB)	12	L	4	4	3	1.5
suboptimal cleaning procedure (pre-WB)	13	M	3.9	3.9	75	37.5
organic contamination						
inadequate parts handling (post clean/pre-WB)	14	L	400	400	3	1.5
suboptimal cleaning procedure (pre-WB)						
suboptimal cleaning time	15	N	8.5	8.5	90	45.0
suboptimal RF power	16	O	13	13	90	45.0
suboptimal gas mixture	17	P	12	12	105	52.5
suboptimal positioning in chamber	18	Q	2	2	13	6.5
suboptimal gas cycle time	19	R	1.9	1.9	90	45.0
suboptimal chamber pressure	20	S	7.5	7.5	105	52.5
suboptimal substrate metallurgy						

			excessive substrate impurities	21	T	14	14	2000	1000.0
			suboptimal gold thickness	22	U	65	65	1000	500.0
			suboptimal nickel thickness	23	V	6	6	2000	1000.0
			suboptimal surface roughness	24	W	20	20	2000	1000.0
		suboptimal wire metallurgy							
			suboptimal wire hardness	25	X	9.5	9.5	15	7.5
			wrong wire dopants	26	Y	20	20	15	7.5
		suboptimal wire bond machine parameters							
			suboptimal bond head overtravel	27	Z	2.7	2.7	35	17.5
			suboptimal bond head static force	28	AA	600	600	75	37.5
			suboptimal bond time	29	BB	700	700	12	6.0
			suboptimal contact velocity	30	CC	3.2	3.2	35	17.5
			suboptimal ultrasonic power	31	DD	600	600	12	6.0
	excessive wire breakage								
		parts mishandled (post-WB)		32	EE	250	250	3	1.5
		suboptimal wire metallurgy							
			suboptimal wire hardness	33	X	9	9	15	7.5
			wrong wire dopants	34	Y	18	18	15	7.5
		suboptimal wire bond machine parameters							
			suboptimal bond head overtravel	35	Z	25	25	35	17.5
			suboptimal bond head static force	36	AA	175	175	75	37.5
			suboptimal bond loop height	37	FF	3.8	3.8	12	6.0
			suboptimal bond time	38	BB	60	60	12	6.0
			suboptimal contact velocity	39	CC	17	17	35	17.5
			suboptimal ultrasonic power	40	DD	175	175	12	6.0
	suboptimal machine performance								
		excessive cycle time							
			suboptimal program written for bond sites (drivers)	41	GG	1000	1000	2	1.0
			insufficient tooling	42	HH	240	240	10	5.0
			rotational error in die placement (drivers)	43	II	50	50	15	7.5

Appendix B

(continued)

suboptimal wire bond machine parameters (drivers)						
suboptimal bond energy (drivers)	44	BB	800	800	15	7.5
suboptimal contact velocity (drivers)	45	CC	10.5	10.5	15	7.5
suboptimal bond head reset height (drivers)	46	JJ	10	10	2	1.0
suboptimal tool inflection point (drivers)	47	KK	11	11	2	1.0
inaccurate wire bonds						
insufficient tooling	48	HH	8	8	10	5.0
inaccurate program written for bond sites (drivers)	49	LL	150	150	15	7.5
poor eyepoint calibration	50	MM	17	17	5	2.5
pattern recognition system (PRS) fails to detect						
excessive driver die tilt						
foreign object in die bond material (drivers)	51	A	2.1	2.1	6	3.0
improper die bond tooling alignment (drivers)	52	B	1.4	1.4	30	15.0
inconsistent die bond material dispense (drivers)	53	C	5.5	5.5	20	10.0
suboptimal die bond dispense pattern (drivers)	54	D	1.3	1.3	20	10.0
suboptimal die bond machine parameters (drivers)	55	E	1	1	30	15.0
variation due to curing (drivers)	56	F	1.1	1.1	30	15.0
excessive variation in x/y/theta die position (drivers)						
foreign object in die bond material (drivers)	57	A	2.8	2.8	6	3.0
improper die bond tooling alignment (drivers)	58	B	2.9	2.9	30	15.0
inconsistent die bond material dispense (drivers)	59	C	3.4	3.4	20	10.0
suboptimal die bond machine parameters (drivers)	60	D	6.5	6.5	30	15.0
suboptimal die bond dispense pattern (drivers)	61	E	3	3	20	10.0
variation due to curing (drivers)	62	F	4.5	4.5	30	15.0
improper lighting	63	NN	50	50	30	15.0
wrong magnification	64	OO	15	15	5	2.5
unreliable missing wire detector (MWD)						
MWD fails to detect	65	PP	3.1	3.1	120	60.0
MWD falsely detects	66	QQ	450	450	2	1.0

Terminal Branch Method - RE and Risk

suboptimal wire bonding process			scaled	scaled		scaled		scaled
bond does not adhere (non-stick)	#	grp	prob	cons	RE	RE	risk	risk
excessive die tilt								
excessive driver die tilt								
foreign object in die bond material (drivers)	1	A	2.3	3.0	7	1	4	3
improper die bond tooling alignment (drivers)	2	B	1.7	30.0	51	9	19	15
inconsistent die bond material dispense (drivers)	3	C	5.0	22.5	113	19	34	26
suboptimal die bond dispense pattern (drivers)	4	D	3.6	20.0	72	12	30	23
suboptimal die bond machine parameters (drivers)	5	E	1.6	30.0	48	8	16	12
variation due to curing (drivers)	6	F	2.2	120.0	264	44	58	45
excessive LED die tilt								
foreign object in die bond material (LED)	7	G	2.6	3.0	8	1	1	1
improper die bond tooling alignment (LED)	8	H	3.5	30.0	105	18	18	13
inconsistent epoxy transfer methods (LED)	9	I	2.4	6.0	14	2	2	2
suboptimal die bond machine parameters (LED)	10	J	70.0	30.0	2100	350	350	269
variation due to curing (LED)	11	K	7.0	120.0	840	140	140	108
wire bonding surfaces not clean								
inorganic contamination								
inadequate parts handling (post clean/pre-WB)	12	L	4.0	1.5	6	1	101	78
suboptimal cleaning procedure (pre-WB)	13	M	3.9	37.5	146	24	24	19
organic contamination								
inadequate parts handling (post clean/pre-WB)	14	L	400.0	1.5	600	100	see 12	
suboptimal cleaning procedure (pre-WB)								
suboptimal cleaning time	15	N	8.5	45.0	383	64	64	49
suboptimal RF power	16	O	13.0	45.0	585	98	98	75
suboptimal gas mixture	17	P	12.0	52.5	630	105	105	81
suboptimal positioning in chamber	18	Q	2.0	6.5	13	2	2	2
suboptimal gas cycle time	19	R	1.9	45.0	86	14	14	11
suboptimal chamber pressure	20	S	7.5	52.5	394	66	66	50
suboptimal substrate metallurgy								

			excessive substrate impurities	21	T	14.0	1000.0	14000	2333	2333	1795
			suboptimal gold thickness	22	U	65.0	500.0	32500	5417	5417	4167
			suboptimal nickel thickness	23	V	6.0	1000.0	6000	1000	1000	769
			suboptimal surface roughness	24	W	20.0	1000.0	20000	3333	3333	2564
		suboptimal wire metallurgy									
			suboptimal wire hardness	25	X	9.5	7.5	71	12	23	18
			wrong wire dopants	26	Y	20.0	7.5	150	25	48	37
		suboptimal wire bond machine parameters									
			suboptimal bond head overtravel	27	Z	2.7	17.5	47	8	81	62
			suboptimal bond head static force	28	AA	600.0	37.5	22500	3750	4844	3726
			suboptimal bond time	29	BB	700.0	6.0	4200	700	1760	1354
			suboptimal contact velocity	30	CC	3.2	17.5	56	9	72	55
			suboptimal ultrasonic power	31	DD	600.0	6.0	3600	600	775	596
	excessive wire breakage										
		parts mishandled (post-WB)		32	EE	250.0	1.5	375	63	63	48
		suboptimal wire metallurgy									
			suboptimal wire hardness	33	X	9.0	7.5	68	11	see 25	
			wrong wire dopants	34	Y	18.0	7.5	135	23	see 26	
		suboptimal wire bond machine parameters									
			suboptimal bond head overtravel	35	Z	25.0	17.5	438	73	see 27	
			suboptimal bond head static force	36	AA	175.0	37.5	6563	1094	see 28	
			suboptimal bond loop height	37	FF	3.8	6.0	23	4	4	3
			suboptimal bond time	38	BB	60.0	6.0	360	60	see 29	
			suboptimal contact velocity	39	CC	17.0	17.5	298	50	see 30	
			suboptimal ultrasonic power	40	DD	175.0	6.0	1050	175	see 31	
	suboptimal machine performance										
		excessive cycle time									
			suboptimal program written for bond sites (drivers)	41	GG	1000.0	1.0	1000	167	167	128
			insufficient tooling	42	HH	240.0	5.0	1200	200	207	159
			rotational error in die placement (drivers)	43	II	50.0	7.5	375	63	63	48

suboptimal wire bond machine parameters (drivers)								
suboptimal bond energy (drivers)	44	BB	800.0	7.5	6000	1000	see 29	
suboptimal contact velocity (drivers)	45	CC	10.5	7.5	79	13	see 30	
suboptimal bond head reset height (drivers)	46	JJ	10.0	1.0	10	2	2	1
suboptimal tool inflection point (drivers)	47	KK	11.0	1.0	11	2	2	1
inaccurate wire bonds								
insufficient tooling	48	HH	8.0	5.0	40	7	see 42	
inaccurate program written for bond sites (drivers)	49	LL	150.0	7.5	1125	188	188	144
poor eyepoint calibration	50	MM	17.0	2.5	43	7	7	5
pattern recognition system (PRS) fails to detect								
excessive driver die tilt								
foreign object in die bond material (drivers)	51	A	2.1	3.0	6	1	see 1	
improper die bond tooling alignment (drivers)	52	B	1.4	15.0	21	4	see 2	
inconsistent die bond material dispense (drivers)	53	C	5.5	10.0	55	9	see 3	
suboptimal die bond dispense pattern (drivers)	54	D	1.3	10.0	13	2	see 4	
suboptimal die bond machine parameters (drivers)	55	E	1.0	15.0	15	3	see 5	
variation due to curing (drivers)	56	F	1.1	15.0	17	3	see 6	
excessive variation in x/y/theta die position (drivers)								
foreign object in die bond material (drivers)	57	A	2.8	3.0	8	1	see 1	
improper die bond tooling alignment (drivers)	58	B	2.9	15.0	44	7	see 2	
inconsistent die bond material dispense (drivers)	59	C	3.4	10.0	34	6	see 3	
suboptimal die bond machine parameters (drivers)	60	D	6.5	15.0	98	16	see 4	
suboptimal die bond dispense pattern (drivers)	61	E	3.0	10.0	30	5	see 5	
variation due to curing (drivers)	62	F	4.5	15.0	68	11	see 6	
improper lighting	63	NN	50.0	15.0	750	125	125	96
wrong magnification	64	OO	15.0	2.5	38	6	6	5
unreliable missing wire detector (MWD)								
MWD fails to detect	65	PP	3.1	60.0	186	31	31	24
MWD falsely detects	66	QQ	450.0	1.0	450	75	75	58

Appendix D

Rated Hierarchy Method - Probabilities

suboptimal wire bonding process	#	grp	rank	norm	prob	scaled prob
bond does not adhere (non-stick)			7	0.389		
excessive die tilt			1	0.007		
excessive driver die tilt			1	0.001		
foreign object in die bond material (drivers)	1	A	20	0.328	8.97E-07	20
improper die bond tooling alignment (drivers)	2	B	15	0.246	6.73E-07	15
inconsistent die bond material dispense (drivers)	3	C	10	0.164	4.49E-07	10
suboptimal die bond dispense pattern (drivers)	4	D	5	0.082	2.24E-07	5
suboptimal die bond machine parameters (drivers)	5	E	1	0.016	4.49E-08	1
variation due to curing (drivers)	6	F	10	0.164	4.49E-07	10
excessive LED die tilt			1000	0.999		
foreign object in die bond material (LED)	7	G	100	0.312	8.52E-04	19003
improper die bond tooling alignment (LED)	8	H	200	0.623	1.70E-03	38006
inconsistent epoxy transfer methods (LED)	9	I	10	0.031	8.52E-05	1900
suboptimal die bond machine parameters (LED)	10	J	1	0.003	8.52E-06	190
variation due to curing (LED)	11	K	10	0.031	8.52E-05	1900
wire bonding surfaces not clean			20	0.141		
inorganic contamination			1	0.048		
inadequate parts handling (post clean/pre-WB)	12	L	10	0.909	2.37E-03	52867
suboptimal cleaning procedure (pre-WB)	13	M	1	0.091	2.37E-04	5287
organic contamination			20	0.952		
inadequate parts handling (post clean/pre-WB)	14	L	5	0.833	4.35E-02	969222
suboptimal cleaning procedure (pre-WB)			1	0.167		
suboptimal cleaning time	15	N	90	0.332	2.89E-03	64376
suboptimal RF power	16	O	100	0.369	3.21E-03	71529
suboptimal gas mixture	17	P	50	0.185	1.60E-03	35765
suboptimal positioning in chamber	18	Q	10	0.037	3.21E-04	7153
suboptimal gas cycle time	19	R	1	0.004	3.21E-05	715
suboptimal chamber pressure	20	S	20	0.074	6.42E-04	14306
suboptimal substrate metallurgy			40	0.282		

			excessive substrate impurities	21	T	8	0.205	2.25E-02	501013
			suboptimal gold thickness	22	U	20	0.513	5.62E-02	1252533
			suboptimal nickel thickness	23	V	1	0.026	2.81E-03	62627
			suboptimal surface roughness	24	W	10	0.256	2.81E-02	626267
		suboptimal wire metallurgy				1	0.007		
			suboptimal wire hardness	25	X	1	0.333	9.13E-04	20354
			wrong wire dopants	26	Y	2	0.667	1.83E-03	40707
		suboptimal wire bond machine parameters				80	0.563		
			suboptimal bond head overtravel	27	Z	1	0.004	9.28E-04	20699
			suboptimal bond head static force	28	AA	50	0.212	4.64E-02	1034932
			suboptimal bond time	29	BB	100	0.424	9.28E-02	2069864
			suboptimal contact velocity	30	CC	5	0.021	4.64E-03	103493
			suboptimal ultrasonic power	31	DD	80	0.339	7.43E-02	1655892
	excessive wire breakage					1	0.056		
		parts mishandled (post-WB)		32	EE	50	0.331	1.84E-02	410154
		suboptimal wire metallurgy				1	0.007		
			suboptimal wire hardness	33	X	1	0.333	1.23E-04	2734
			wrong wire dopants	34	Y	2	0.667	2.45E-04	5469
		suboptimal wire bond machine parameters				100	0.662		
			suboptimal bond head overtravel	35	Z	1	0.008	2.87E-04	6409
			suboptimal bond head static force	36	AA	40	0.313	1.15E-02	256346
			suboptimal bond loop height	37	FF	5	0.039	1.44E-03	32043
			suboptimal bond time	38	BB	30	0.234	8.62E-03	192260
			suboptimal contact velocity	39	CC	2	0.016	5.75E-04	12817
			suboptimal ultrasonic power	40	DD	50	0.391	1.44E-02	320433
	suboptimal machine performance					10	0.556		
		excessive cycle time				2	0.333		
			suboptimal program written for bond sites (drivers)	41	GG	1	0.111	2.06E-02	458765
			insufficient tooling	42	HH	1	0.111	2.06E-02	458765
			rotational error in die placement (drivers)	43	II	3	0.333	6.17E-02	1376296

			suboptimal wire bond machine parameters (drivers)				4	0.444		
				suboptimal bond energy (drivers)	44	BB	5	0.357	2.94E-02	655379
				suboptimal contact velocity (drivers)	45	CC	3	0.214	1.76E-02	393227
				suboptimal bond head reset height (drivers)	46	JJ	5	0.357	2.94E-02	655379
				suboptimal tool inflection point (drivers)	47	KK	1	0.071	5.88E-03	131076
		inaccurate wire bonds					1	0.167		
			insufficient tooling		48	HH	1	0.048	4.41E-03	98307
			inaccurate program written for bond sites (drivers)		49	LL	5	0.238	2.20E-02	491534
			poor eyepoint calibration		50	MM	15	0.714	6.61E-02	1474602
		pattern recognition system (PRS) fails to detect					2	0.333		
			excessive driver die tilt				1	0.017		
				foreign object in die bond material (drivers)	51	A	20	0.328	1.03E-03	22945
				improper die bond tooling alignment (drivers)	52	B	15	0.246	7.72E-04	17208
				inconsistent die bond material dispense (drivers)	53	C	10	0.164	5.15E-04	11472
				suboptimal die bond dispense pattern (drivers)	54	D	5	0.082	2.57E-04	5736
				suboptimal die bond machine parameters (drivers)	55	E	1	0.016	5.15E-05	1147
				variation due to curing (drivers)	56	F	10	0.164	5.15E-04	11472
			excessive variation in x/y/theta die position (drivers)				25	0.424		
				foreign object in die bond material (drivers)	57	A	1	0.012	9.45E-04	21079
				improper die bond tooling alignment (drivers)	58	B	40	0.482	3.78E-02	843146
				inconsistent die bond material dispense (drivers)	59	C	25	0.301	2.36E-02	526966
				suboptimal die bond machine parameters (drivers)	60	D	3	0.036	2.84E-03	63236
				suboptimal die bond dispense pattern (drivers)	61	E	10	0.120	9.45E-03	210787
				variation due to curing (drivers)	62	F	4	0.048	3.78E-03	84315
			improper lighting		63	NN	30	0.508	9.42E-02	2099434
			wrong magnification		64	OO	3	0.051	9.42E-03	209943
		unreliable missing wire detector (MWD)					1	0.167		
			MWD fails to detect		65	PP	1	0.020	1.82E-03	40479
			MWD falsely detects		66	QQ	50	0.980	9.08E-02	2023964

Rated Hierarchy Method - Consequences

suboptimal wire bonding process	#	grp	rank	norm	cons	scaled cons
bond does not adhere (non-stick)			9	0.529		
excessive die tilt			10	0.099		
excessive driver die tilt			1	0.333		
foreign object in die bond material (drivers)	1	A	1	0.063	1.09E-03	5
improper die bond tooling alignment (drivers)	2	B	3	0.188	3.28E-03	15
inconsistent die bond material dispense (drivers)	3	C	3	0.188	3.28E-03	15
suboptimal die bond dispense pattern (drivers)	4	D	3	0.188	3.28E-03	15
suboptimal die bond machine parameters (drivers)	5	E	2	0.125	2.18E-03	10
variation due to curing (drivers)	6	F	4	0.250	4.37E-03	19
excessive LED die tilt			2	0.667		
foreign object in die bond material (LED)	7	G	1	0.083	2.91E-03	13
improper die bond tooling alignment (LED)	8	H	3	0.250	8.74E-03	39
inconsistent epoxy transfer methods (LED)	9	I	2	0.167	5.82E-03	26
suboptimal die bond machine parameters (LED)	10	J	2	0.167	5.82E-03	26
variation due to curing (LED)	11	K	4	0.333	1.16E-02	52
wire bonding surfaces not clean			6	0.059		
inorganic contamination			1	0.250		
inadequate parts handling (post clean/pre-WB)	12	L	1	0.167	1.31E-03	6
suboptimal cleaning procedure (pre-WB)	13	M	5	0.833	6.55E-03	29
organic contamination			3	0.750		
inadequate parts handling (post clean/pre-WB)	14	L	1	0.125	2.95E-03	13
suboptimal cleaning procedure (pre-WB)			7	0.875		
suboptimal cleaning time	15	N	7	0.184	3.80E-03	17
suboptimal RF power	16	O	7	0.184	3.80E-03	17
suboptimal gas mixture	17	P	10	0.263	5.43E-03	24
suboptimal positioning in chamber	18	Q	1	0.026	5.43E-04	2
suboptimal gas cycle time	19	R	3	0.079	1.63E-03	7
suboptimal chamber pressure	20	S	10	0.263	5.43E-03	24
suboptimal substrate metallurgy			80	0.792		

			excessive substrate impurities	21	T	2	0.286	1.20E-01	532
			suboptimal gold thickness	22	U	1	0.143	5.99E-02	266
			suboptimal nickel thickness	23	V	2	0.286	1.20E-01	532
			suboptimal surface roughness	24	W	2	0.286	1.20E-01	532
		suboptimal wire metallurgy				1	0.010		
			suboptimal wire hardness	25	X	1	0.500	2.62E-03	12
			wrong wire dopants	26	Y	1	0.500	2.62E-03	12
		suboptimal wire bond machine parameters				4	0.040		
			suboptimal bond head overtravel	27	Z	2	0.200	4.19E-03	19
			suboptimal bond head static force	28	AA	4	0.400	8.39E-03	37
			suboptimal bond time	29	BB	1	0.100	2.10E-03	9
			suboptimal contact velocity	30	CC	2	0.200	4.19E-03	19
			suboptimal ultrasonic power	31	DD	1	0.100	2.10E-03	9
	excessive wire breakage					7	0.412		
		parts mishandled (post-WB)		32	EE	1	0.250	1.03E-01	457
		suboptimal wire metallurgy				1	0.250		
			suboptimal wire hardness	33	X	1	0.500	5.15E-02	228
			wrong wire dopants	34	Y	1	0.500	5.15E-02	228
		suboptimal wire bond machine parameters				2	0.500		
			suboptimal bond head overtravel	35	Z	1	0.100	2.06E-02	91
			suboptimal bond head static force	36	AA	4	0.400	8.24E-02	365
			suboptimal bond loop height	37	FF	1	0.100	2.06E-02	91
			suboptimal bond time	38	BB	1	0.100	2.06E-02	91
			suboptimal contact velocity	39	CC	2	0.200	4.12E-02	183
			suboptimal ultrasonic power	40	DD	1	0.100	2.06E-02	91
	suboptimal machine performance					1	0.059		
		excessive cycle time				3	0.250		
			suboptimal program written for bond sites (drivers)	41	GG	2	0.222	3.27E-03	15
			insufficient tooling	42	HH	2	0.222	3.27E-03	15
			rotational error in die placement (drivers)	43	II	1	0.111	1.63E-03	7

			suboptimal wire bond machine parameters (drivers)				4	0.444		
				suboptimal bond energy (drivers)	44	BB	20	0.690	4.51E-03	20
				suboptimal contact velocity (drivers)	45	CC	5	0.172	1.13E-03	5
				suboptimal bond head reset height (drivers)	46	JJ	3	0.103	6.76E-04	3
				suboptimal tool inflection point (drivers)	47	KK	1	0.034	2.25E-04	1
		inaccurate wire bonds					1	0.083		
			insufficient tooling		48	HH	4	0.444	2.18E-03	10
			inaccurate program written for bond sites (drivers)		49	LL	4	0.444	2.18E-03	10
			poor eyepoint calibration		50	MM	1	0.111	5.45E-04	2
		pattern recognition system (PRS) fails to detect					2	0.167		
			excessive driver die tilt				8	0.533		
				foreign object in die bond material (drivers)	51	A	1	0.100	5.23E-04	2
				improper die bond tooling alignment (drivers)	52	B	2	0.200	1.05E-03	5
				inconsistent die bond material dispense (drivers)	53	C	2	0.200	1.05E-03	5
				suboptimal die bond dispense pattern (drivers)	54	D	1	0.100	5.23E-04	2
				suboptimal die bond machine parameters (drivers)	55	E	2	0.200	1.05E-03	5
				variation due to curing (drivers)	56	F	2	0.200	1.05E-03	5
			excessive variation in x/y/theta die position (drivers)				4	0.267		
				foreign object in die bond material (drivers)	57	A	1	0.111	2.90E-04	1
				improper die bond tooling alignment (drivers)	58	B	1	0.111	2.90E-04	1
				inconsistent die bond material dispense (drivers)	59	C	2	0.222	5.81E-04	3
				suboptimal die bond machine parameters (drivers)	60	D	2	0.222	5.81E-04	3
				suboptimal die bond dispense pattern (drivers)	61	E	1	0.111	2.90E-04	1
				variation due to curing (drivers)	62	F	2	0.222	5.81E-04	3
			improper lighting		63	NN	2	0.133	1.31E-03	6
			wrong magnification		64	OO	1	0.067	6.54E-04	3
		unreliable missing wire detector (MWD)					6	0.500		
			MWD fails to detect		65	PP	100	0.990	2.91E-02	129
			MWD falsely detects		66	QQ	1	0.010	2.91E-04	1

Appendix F

Rated Hierarchy Method - RE and Risk

	#	grp	scaled prob	scaled cons	RE	scaled RE	scaled risk
suboptimal wire bonding process							
bond does not adhere (non-stick)							
excessive die tilt							
excessive driver die tilt							
foreign object in die bond material (drivers)	1	A	20	5	9.69E+01	1.00E+01	16
improper die bond tooling alignment (drivers)	2	B	15	15	2.18E+02	2.25E+01	238
inconsistent die bond material dispense (drivers)	3	C	10	15	1.45E+02	1.50E+01	287
suboptimal die bond dispense pattern (drivers)	4	D	5	15	7.27E+01	7.50E+00	36
suboptimal die bond machine parameters (drivers)	5	E	1	10	9.69E+00	1.00E+00	56
variation due to curing (drivers)	6	F	10	19	1.94E+02	2.00E+01	55
excessive LED die tilt							
foreign object in die bond material (LED)	7	G	19003	13	2.46E+05	2.53E+04	50
improper die bond tooling alignment (LED)	8	H	38006	39	1.47E+06	1.52E+05	300
inconsistent epoxy transfer methods (LED)	9	I	1900	26	4.91E+04	5.07E+03	10
suboptimal die bond machine parameters (LED)	10	J	190	26	4.91E+03	5.07E+02	1
variation due to curing (LED)	11	K	1900	52	9.82E+04	1.01E+04	20
wire bonding surfaces not clean							
inorganic contamination							
inadequate parts handling (post clean/pre-WB)	12	L	52867	6	3.07E+05	3.17E+04	2645
suboptimal cleaning procedure (pre-WB)	13	M	5287	29	1.54E+05	1.59E+04	31
organic contamination							
inadequate parts handling (post clean/pre-WB)	14	L	969222	13	1.27E+07	1.31E+06	see 12
suboptimal cleaning procedure (pre-WB)							
suboptimal cleaning time	15	N	64376	17	1.09E+06	1.12E+05	221
suboptimal RF power	16	O	71529	17	1.21E+06	1.25E+05	246
suboptimal gas mixture	17	P	35765	24	8.62E+05	8.89E+04	176
suboptimal positioning in chamber	18	Q	7153	2	1.72E+04	1.78E+03	4
suboptimal gas cycle time	19	R	715	7	5.17E+03	5.34E+02	1
suboptimal chamber pressure	20	S	14306	24	3.45E+05	3.56E+04	70
suboptimal substrate metallurgy							

			excessive substrate impurities	21	T	501013	532	2.66E+08	2.75E+07	54236
			suboptimal gold thickness	22	U	1252533	266	3.33E+08	3.44E+07	67795
			suboptimal nickel thickness	23	V	62627	532	3.33E+07	3.44E+06	6780
			suboptimal surface roughness	24	W	626267	532	3.33E+08	3.44E+07	67795
		suboptimal wire metallurgy								
			suboptimal wire hardness	25	X	20354	12	2.37E+05	2.44E+04	175
			wrong wire dopants	26	Y	40707	12	4.73E+05	4.88E+04	351
		suboptimal wire bond machine parameters								
			suboptimal bond head overtravel	27	Z	20699	19	3.85E+05	3.97E+04	198
			suboptimal bond head static force	28	AA	1034932	37	3.85E+07	3.97E+06	26917
			suboptimal bond time	29	BB	2069864	9	1.93E+07	1.99E+06	10167
			suboptimal contact velocity	30	CC	103493	19	1.93E+06	1.99E+05	1269
			suboptimal ultrasonic power	31	DD	1655892	9	1.54E+07	1.59E+06	9098
	excessive wire breakage									
		parts mishandled (post-WB)		32	EE	410154	457	1.87E+08	1.93E+07	38149
		suboptimal wire metallurgy								
			suboptimal wire hardness	33	X	2734	228	6.24E+05	6.44E+04	see 25
			wrong wire dopants	34	Y	5469	228	1.25E+06	1.29E+05	see 26
		suboptimal wire bond machine parameters								
			suboptimal bond head overtravel	35	Z	6409	91	5.85E+05	6.04E+04	see 27
			suboptimal bond head static force	36	AA	256346	365	9.37E+07	9.67E+06	see 28
			suboptimal bond loop height	37	FF	32043	91	2.93E+06	3.02E+05	596
			suboptimal bond time	38	BB	192260	91	1.76E+07	1.81E+06	see 29
			suboptimal contact velocity	39	CC	12817	183	2.34E+06	2.42E+05	see 30
			suboptimal ultrasonic power	40	DD	320433	91	2.93E+07	3.02E+06	see 31
	suboptimal machine performance									
		excessive cycle time								
			suboptimal program written for bond sites (drivers)	41	GG	458765	15	6.65E+06	6.86E+05	1355
			insufficient tooling	42	HH	458765	15	6.65E+06	6.86E+05	1548
			rotational error in die placement (drivers)	43	II	1376296	7	9.98E+06	1.03E+06	2032

Appendix F

(continued)

suboptimal wire bond machine parameters (drivers)						
suboptimal bond energy (drivers)	44	BB	655379	20	1.31E+07	1.35E+06	see 29
suboptimal contact velocity (drivers)	45	CC	393227	5	1.97E+06	2.03E+05	see 30
suboptimal bond head reset height (drivers)	46	JJ	655379	3	1.97E+06	2.03E+05	400
suboptimal tool inflection point (drivers)	47	KK	131076	1	1.31E+05	1.35E+04	27
inaccurate wire bonds							
insufficient tooling	48	HH	98307	10	9.50E+05	9.81E+04	see 42
inaccurate program written for bond sites (drivers)	49	LL	491534	10	4.75E+06	4.90E+05	968
poor eyepoint calibration	50	MM	1474602	2	3.56E+06	3.68E+05	726
pattern recognition system (PRS) fails to detect							
excessive driver die tilt							
foreign object in die bond material (drivers)	51	A	22945	2	5.32E+04	5.49E+03	see 1
improper die bond tooling alignment (drivers)	52	B	17208	5	7.98E+04	8.24E+03	see 2
inconsistent die bond material dispense (drivers)	53	C	11472	5	5.32E+04	5.49E+03	see 3
suboptimal die bond dispense pattern (drivers)	54	D	5736	2	1.33E+04	1.37E+03	see 4
suboptimal die bond machine parameters (drivers)	55	E	1147	5	5.32E+03	5.49E+02	see 5
variation due to curing (drivers)	56	F	11472	5	5.32E+04	5.49E+03	see 6
excessive variation in x/y/theta die position (drivers)							
foreign object in die bond material (drivers)	57	A	21079	1	2.72E+04	2.80E+03	see 1
improper die bond tooling alignment (drivers)	58	B	843146	1	1.09E+06	1.12E+05	see 2
inconsistent die bond material dispense (drivers)	59	C	526966	3	1.36E+06	1.40E+05	see 3
suboptimal die bond machine parameters (drivers)	60	D	63236	3	1.63E+05	1.68E+04	see 4
suboptimal die bond dispense pattern (drivers)	61	E	210787	1	2.72E+05	2.80E+04	see 5
variation due to curing (drivers)	62	F	84315	3	2.17E+05	2.24E+04	see 6
improper lighting	63	NN	2099434	6	1.22E+07	1.26E+06	2480
wrong magnification	64	OO	209943	3	6.09E+05	6.28E+04	124
unreliable missing wire detector (MWD)							
MWD fails to detect	65	PP	40479	129	5.23E+06	5.40E+05	1065
MWD falsely detects	66	QQ	2023964	1	2.62E+06	2.70E+05	533

X-ray Dot Map of Sample Plasma Cleaned with 90%/10% Ar/O_2

Au (light areas represent Au deficiencies)

Ni (dark areas are Ni rich)

Appendix H

Plasma Cleaning DOX - Configuration and Data

					die pull strength (gf)		substrate pull strength (gf)	
exp. #	time	power	gas	press	*xbar*	*s*	*xbar*	*s*
DOX01	–	–	–	–	11.37	2.99	13.36	0.73
DOX02	+	–	–	+	10.96	3.19	14.06	0.67
DOX03	–	+	–	+	13.64	1.75	14.08	1.01
DOX04	+	+	–	–	11.93	2.87	14.35	0.84
DOX05	–	–	+	+	11.52	2.87	14.38	0.50
DOX06	+	–	+	–	11.82	3.30	14.51	0.67
DOX07	–	+	+	–	13.81	1.93	14.41	0.59
DOX08	+	+	+	+	11.87	2.21	13.94	0.75
				grand mean	12.12	2.70	14.14	0.73
NOM01	o	o	o	o	10.91	2.17	13.57	0.58
NOM02	o	o	o	o	12.07	1.89	14.07	0.69
NOM03	o	o	o	o	12.54	2.31	14.28	0.48
				grand mean	11.84	2.13	13.97	0.59
CTRL01	x	x	x	x	14.72	1.15	15.17	0.35
CTRL02	x	x	x	x	15.31	0.66	15.05	0.33
CTRL03	x	x	x	x	14.75	1.35	14.70	0.96
				grand mean	14.93	1.09	14.97	0.62

Plasma Cleaning Significance Tests

From Hogg and Ledolter [Hogg and Ledolter, 1992, pp. 322-8]

$$\boxed{95\%\ \text{c.i.} = \bar{x} \pm (t_{\upsilon,\,\alpha/2} \times s_{error})}$$

For the plasma DOX experiments on the die:

$$\boxed{\begin{array}{l}
t_{\upsilon,\alpha/2} = t_{72-8,\,0.05/2} \cong t_{60,\,0.05/2} = 2.00 \\
s_{error} = {}^{s_p}\!\big/\!_{\sqrt{N}} = 2.70 / \sqrt{72} = 0.318 \\
95\%\ \text{c.i.} = 12.12 \pm (2.00 \times 0.318) = 12.12 \pm 0.64 \\
95\%\ \text{c.i.} = (11.48, 12.76)
\end{array}}$$

For the plasma DOX experiments on the substrate:

$$\boxed{\begin{array}{l}
t_{\upsilon,\alpha/2} = t_{72-8,\,0.05/2} \cong t_{60,\,0.05/2} = 2.00 \\
s_{error} = {}^{s_p}\!\big/\!_{\sqrt{N}} = 0.73 / \sqrt{72} = 0.0860 \\
95\%\ \text{c.i.} = 14.14 \pm (2.00 \times 0.0860) = 14.14 \pm 0.17 \\
95\%\ \text{c.i.} = (13.97, 14.31)
\end{array}}$$

For the nominal experiments on the die:

$$\boxed{\begin{array}{l}
t_{\upsilon,\alpha/2} = t_{27-3,\,0.05/2} = 2.064 \\
s_{error} = {}^{s_p}\!\big/\!_{\sqrt{N}} = 2.13 / \sqrt{27} = 0.410 \\
95\%\ \text{c.i.} = 11.84 \pm (2.064 \times 0.410) = 11.84 \pm 0.85 \\
95\%\ \text{c.i.} = (10.99, 12.69)
\end{array}}$$

For the nominal experiments on the substrate:

$$t_{v,\alpha/2} = t_{27-3,\,0.05/2} = 2.064$$
$$s_{error} = {}^{s_p}\!\big/_{\sqrt{N}} = 0.59 / \sqrt{27} = 0.114$$
$$95\%\ \text{c.i.} = 13.97 \pm (2.064 \times 0.114) = 13.97 \pm 0.23$$
$$95\%\ \text{c.i.} = (13.74, 14.20)$$

For the control experiments on the die:

$$t_{v,\alpha/2} = t_{27-3,\,0.05/2} = 2.064$$
$$s_{error} = {}^{s_p}\!\big/_{\sqrt{N}} = 1.09 / \sqrt{27} = 0.210$$
$$95\%\ \text{c.i.} = 14.93 \pm (2.064 \times 210) = 14.93 \pm 0.43$$
$$95\%\ \text{c.i.} = (14.50, 15.36)$$

For the control experiments on the substrate:

$$t_{v,\alpha/2} = t_{27-3,\,0.05/2} = 2.064$$
$$s_{error} = {}^{s_p}\!\big/_{\sqrt{N}} = 0.62 / \sqrt{27} = 0.119$$
$$95\%\ \text{c.i.} = 14.97 \pm (2.064 \times 0.114) = 14.97 \pm 0.25$$
$$95\%\ \text{c.i.} = (14.72, 15.22)$$

Plasma Cleaning DOX - Analysis of Means

Analysis of Means, Die (xbar)

average pull strength (gf)

effect	avg –	avg +	Δ	Δ/2
time	12.59	11.65	-0.94	-0.47
power	11.42	12.81	1.40	0.70
gas	11.98	12.26	0.28	0.14
pressure	12.23	12.00	-0.23	-0.12

Analysis of Means, Substrate (xbar)

average pull strength (gf)

effect	avg –	avg +	Δ	Δ/2
time	14.06	14.22	0.16	0.08
power	14.08	14.20	0.12	0.06
gas	13.96	14.31	0.35	0.17
pressure	14.16	14.12	-0.04	-0.02

Appendix K

Additional Bonding Experiments - Experimental Data

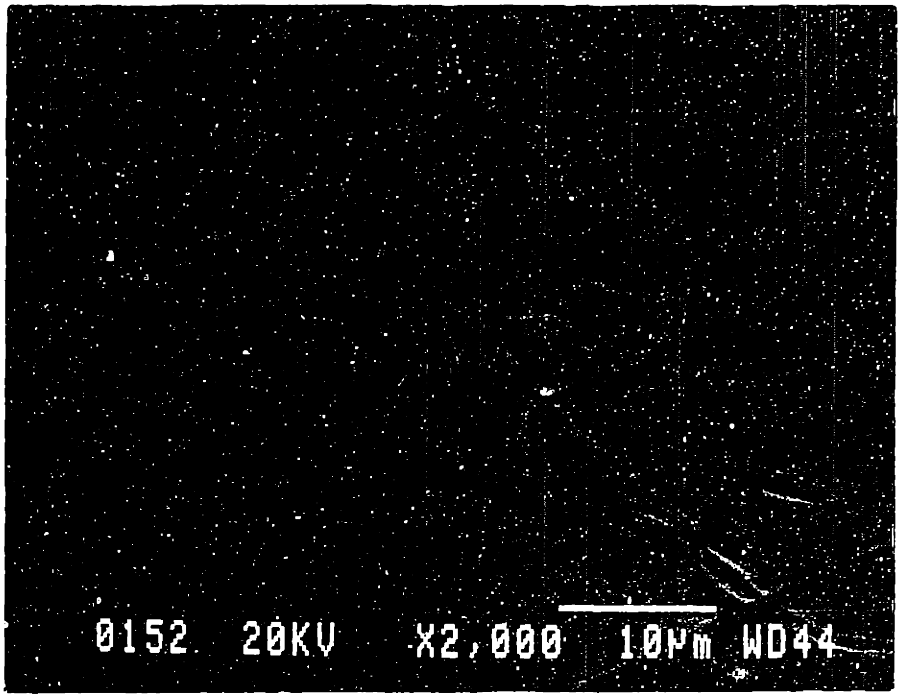
not plasma cleaned

sample	xbar (gf)	s	95% ci	d_{Au} (μin)	d_{Ni} (μin)
source #1 (control)	14.91	0.49	(14.54, 15.28)	13.9	297.1
source #1 (no scrub)	15.66	0.43	(15.33, 15.99)	7.6	144.8
source #2	13.36	0.45	(13.02, 13.70)	24.5	300.8
source #3	13.27	0.76	(12.69, 13.85)	13.2	328.7
source #1 (d_{Au} high)	15.07	0.81	(14.45, 15.69)	43.8	317.1
source #1 (d_{Au} med)	15.19	0.53	(14.78, 15.60)	19.4	201.5
source #1 (J_{Au} high)	15.74	0.31	(15.50, 15.98)	5.8	185.9
source #1 (J_{Au} low)	16.27	0.55	(15.84, 16.70)	8.5	364.5
source #1 (J_{Ni} high)	15.84	0.36	(15.56, 16.12)	5.8	314.0
source #1 (J_{Ni} low)	13.74	0.97	(12.99, 14.49)	65.2	184.4

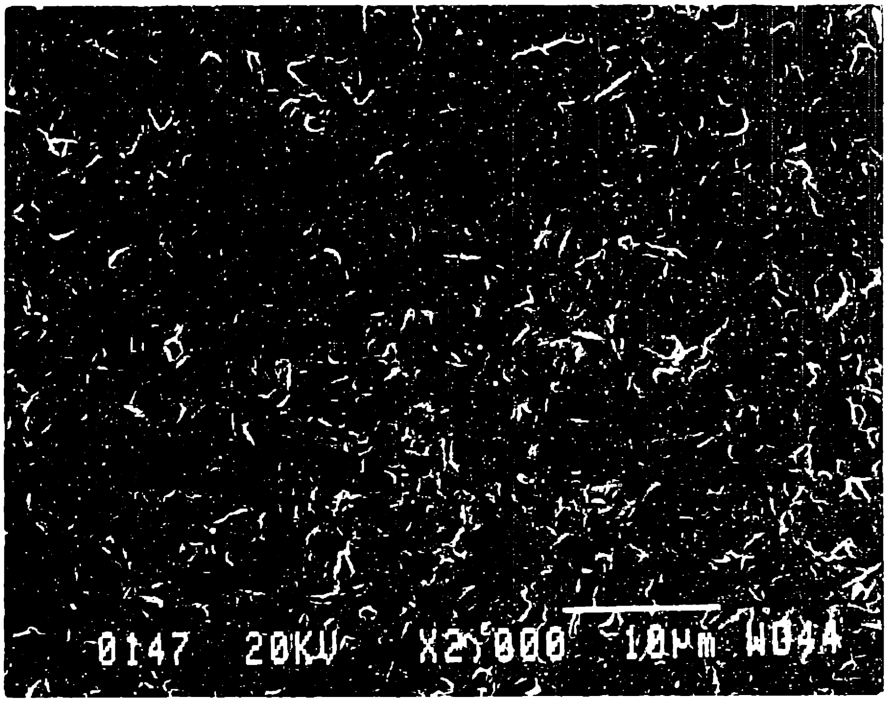
plasma cleaned

sample	xbar (gf)	s	95% ci	d_{Au} (μin)	d_{Ni} (μin)
source #1 (control)	14.00	0.60	(13.54, 14.46)	13.9	297.1
source #1 (no scrub)	15.59	0.69	(15.06, 16.12)	7.6	144.8
source #2	13.81	0.85	(13.16, 14.46)	24.5	300.8
source #3	13.49	0.79	(12.89, 14.09)	13.2	328.7
source #1 (d_{Au} high)	14.50	1.07	(13.68, 15.32)	43.8	317.1
source #1 (d_{Au} med)	13.52	0.79	(12.91, 14.13)	19.4	201.5
source #1 (J_{Au} high)	13.82	0.76	(13.24, 14.40)	5.8	185.9
source #1 (J_{Au} low)	15.45	0.45	(15.10, 15.80)	8.5	364.5
source #1 (J_{Ni} high)	14.83	0.42	(14.51, 15.15)	5.8	314.0
source #1 (J_{Ni} low)	13.67	0.40	(13.36, 13.98)	65.2	184.4

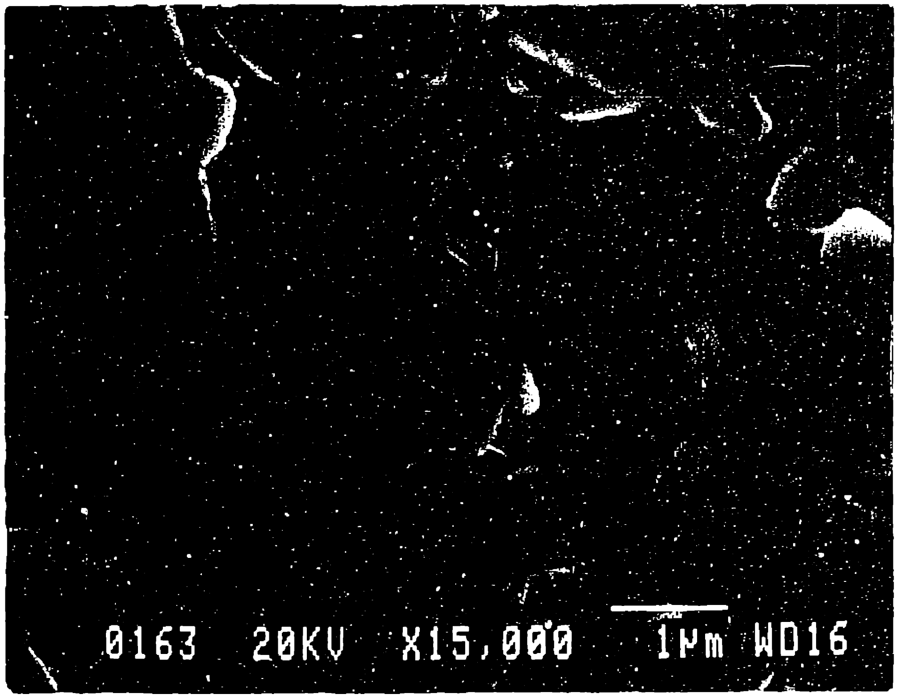
Source #1 Substrate at 2000x



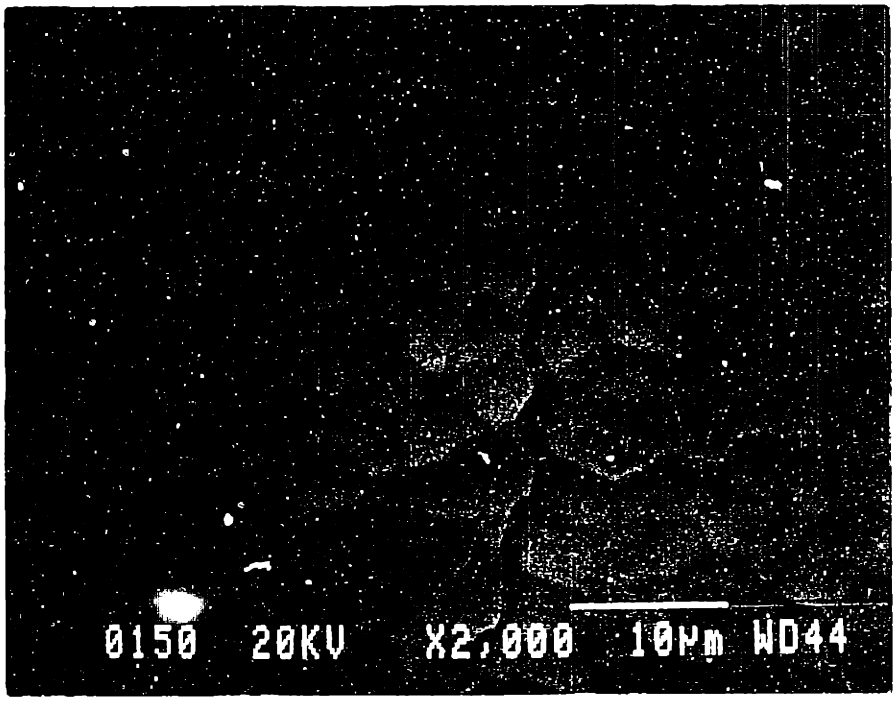
Source #2 Substrate at 2000x



Source #2 Substrate at 15000x



Source #3 Substrate at 2000x



Source #3 Substrate at 15000x

Appendix M

Wire Bonding DOX - Die, Configuration and Data

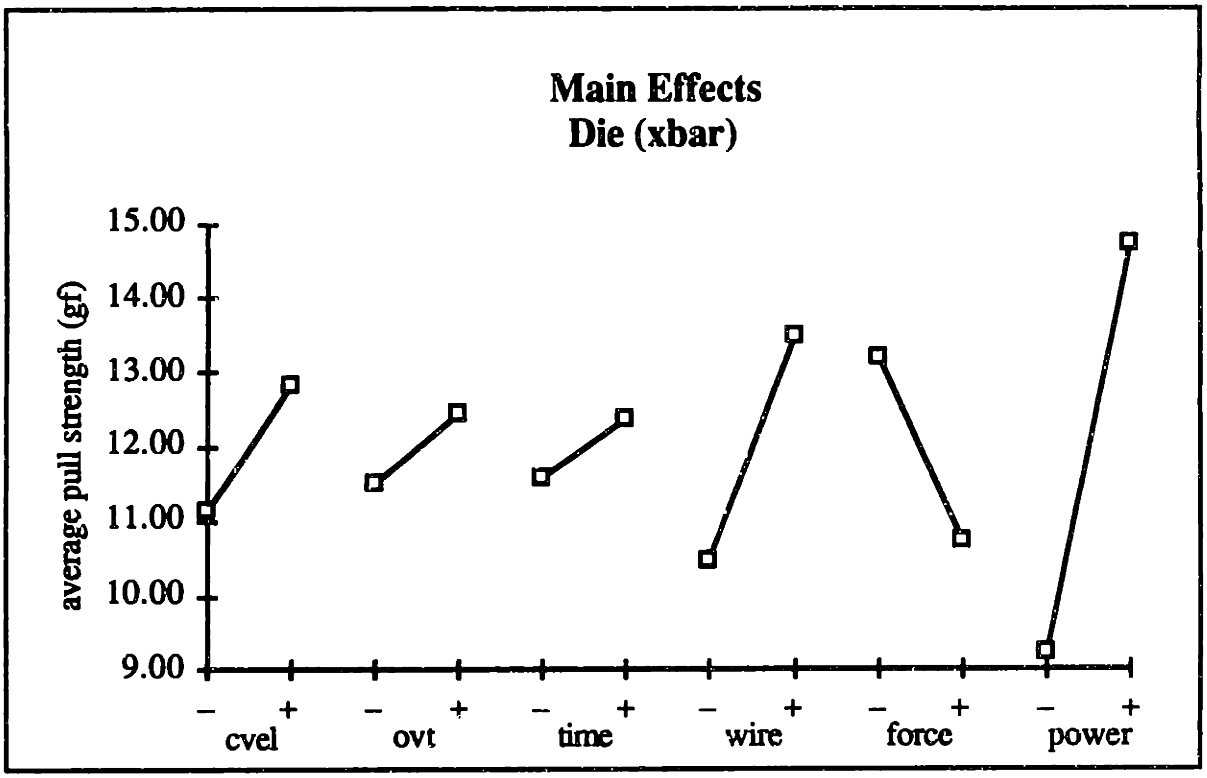
							die pull strength (gf)	
exp. #	cvel	ovt	time	wire	force	power	*xbar*	*s*
DOX01	−	−	−	−	−	−	7.04	8.36
DOX02	+	−	−	−	−	+	14.38	1.35
DOX03	−	+	−	−	−	+	15.00	0.65
DOX04	+	+	−	−	−	−	7.48	6.77
DOX05	−	−	+	−	−	+	12.83	1.85
DOX06	+	−	+	−	−	−	13.38	3.06
DOX07	−	+	+	−	−	−	10.95	4.91
DOX08	+	+	+	−	−	+	13.36	0.80
DOX09	−	−	−	+	−	+	17.12	0.70
DOX10	+	−	−	+	−	−	11.51	2.48
DOX11	−	+	−	+	−	−	9.88	4.69
DOX12	+	+	−	+	−	+	18.51	1.39
DOX13	−	−	+	+	−	−	12.60	1.78
DOX14	+	−	+	+	−	+	15.33	1.27
DOX15	−	+	+	+	−	+	15.96	1.90
DOX16	+	+	+	+	−	−	15.76	1.44
DOX17	−	−	−	−	+	+	12.68	1.75
DOX18	+	−	−	−	+	−	9.49	4.52
DOX19	−	+	−	−	+	−	3.31	5.77
DOX20	+	+	−	−	+	+	14.23	1.49
DOX21	−	−	+	−	+	−	1.58	4.73
DOX22	+	−	+	−	+	+	12.73	1.16
DOX23	−	+	+	−	+	+	9.74	5.76
DOX24	+	+	+	−	+	−	9.03	6.98
DOX25	−	−	−	+	+	−	2.90	3.71
DOX26	+	−	−	+	+	+	15.92	1.19
DOX27	−	+	−	+	+	+	18.58	1.99
DOX28	+	+	−	+	+	−	6.98	4.05
DOX29	−	−	+	+	+	+	13.44	1.48
DOX30	+	−	+	+	+	−	11.05	2.10
DOX31	−	+	+	+	+	−	14.55	2.24
DOX32	+	+	+	+	+	+	15.60	1.77

Die (xbar) Analysis

Analysis of Means, Die (xbar)

average pull strength (gf)

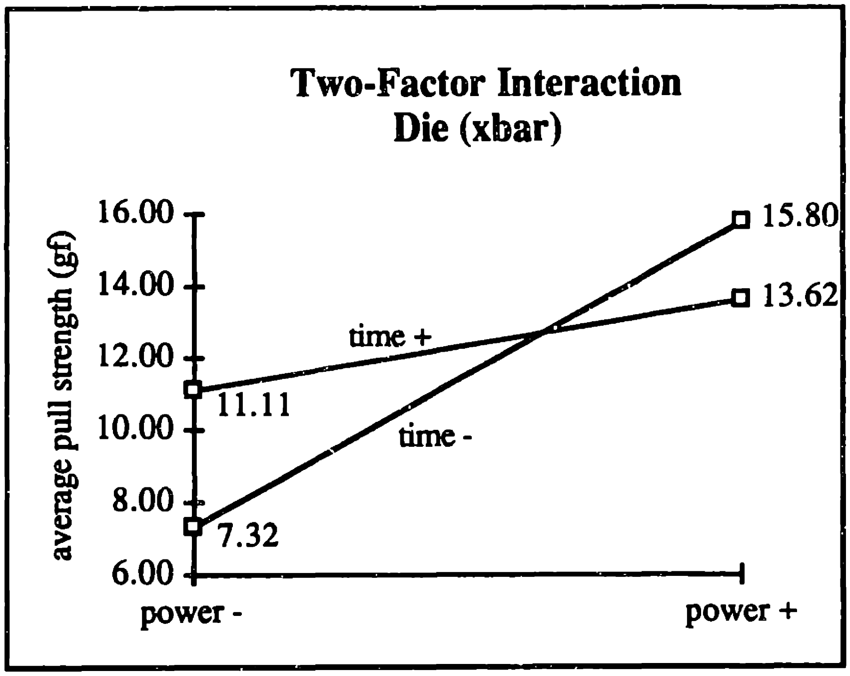
effect	avg –	avg +	Δ	Δ/2
cvel	11.14	12.80	1.66	0.83
ovt	11.51	12.44	0.93	0.47
time	11.57	12.37	0.80	0.40
wire	10.46	13.49	3.03	1.52
force	13.20	10.74	-2.46	-1.23
power	9.22	14.72	5.50	2.75
cvel*ovt	12.58	11.36	-1.23	-0.61
cvel*time	11.89	12.05	0.16	0.08
cvel*wire	12.45	11.49	-0.96	-0.48
cvel*force	11.66	12.28	0.62	0.31
cvel*power	12.51	11.43	-1.07	-0.54
ovt*time	11.69	12.25	0.57	0.28
ovt*wire	11.44	12.50	1.06	0.53
ovt*force	11.67	12.27	0.60	0.30
ovt*power	12.03	11.91	-0.12	-0.06
time*wire	11.57	12.37	0.81	0.40
time*force	12.15	11.79	-0.35	-0.18
time*power	13.46	10.48	-2.98	-1.49
wire*force	11.85	12.09	0.25	0.12
wire*power	11.89	12.05	0.16	0.08
force*power	11.34	12.60	1.26	0.63
grand mean	11.97			


Main Effects
Die (xbar)
average pull strength (gf)
15.00
14.00
13.00
12.00
11.00
10.00
9.00
–
+
cvel
ovt
time
wire
force
power

Analysis of Variance, Die (xbar)

Source	df	Sum of Squares	Mean Square	F-ratio	Prob
cvel	1	22.0780	22.0780	5.0934	0.0476
ovt	1	6.97511	6.97511	1.6092	0.2333
time	1	5.18420	5.18420	1.1960	0.2998
wire	1	73.4472	73.4472	16.944	0.0021
force	1	48.2162	48.2162	11.123	0.0076
power	1	241.560	241.560	55.728	0.0000
cvel*ovt	1	13.2870	13.2870	3.0653	0.1105
cvel*time	1	0.211250	0.211250	0.04874	0.8297
cvel*wire	1	7.33445	7.33445	1.6921	0.2225
cvel*force	1	3.07520	3.07520	0.70945	0.4193
cvel*power	1	9.20205	9.20205	2.1229	0.1758
ovt*time	1	2.57645	2.57645	0.59439	0.4586
ovt*wire	1	8.98880	8.98880	2.0737	0.1804
ovt*force	1	2.83220	2.83220	0.65339	0.4377
ovt*power	1	0.105800	0.105800	0.02441	0.8790
time*wire	1	5.20031	5.20031	1.1997	0.2991
time*force	1	0.987013	0.987013	0.22770	0.6435
time*power	1	71.2221	71.2221	16.431	0.0023
wire*force	1	0.495012	0.495012	0.11420	0.7424
wire*power	1	0.201612	0.201612	0.04651	0.8336
force*power	1	12.6756	12.6756	2.9243	0.1180
Error	10	43.3464	4.33464		
Total	31	579.202			

parameters in boxes are significant at 95%

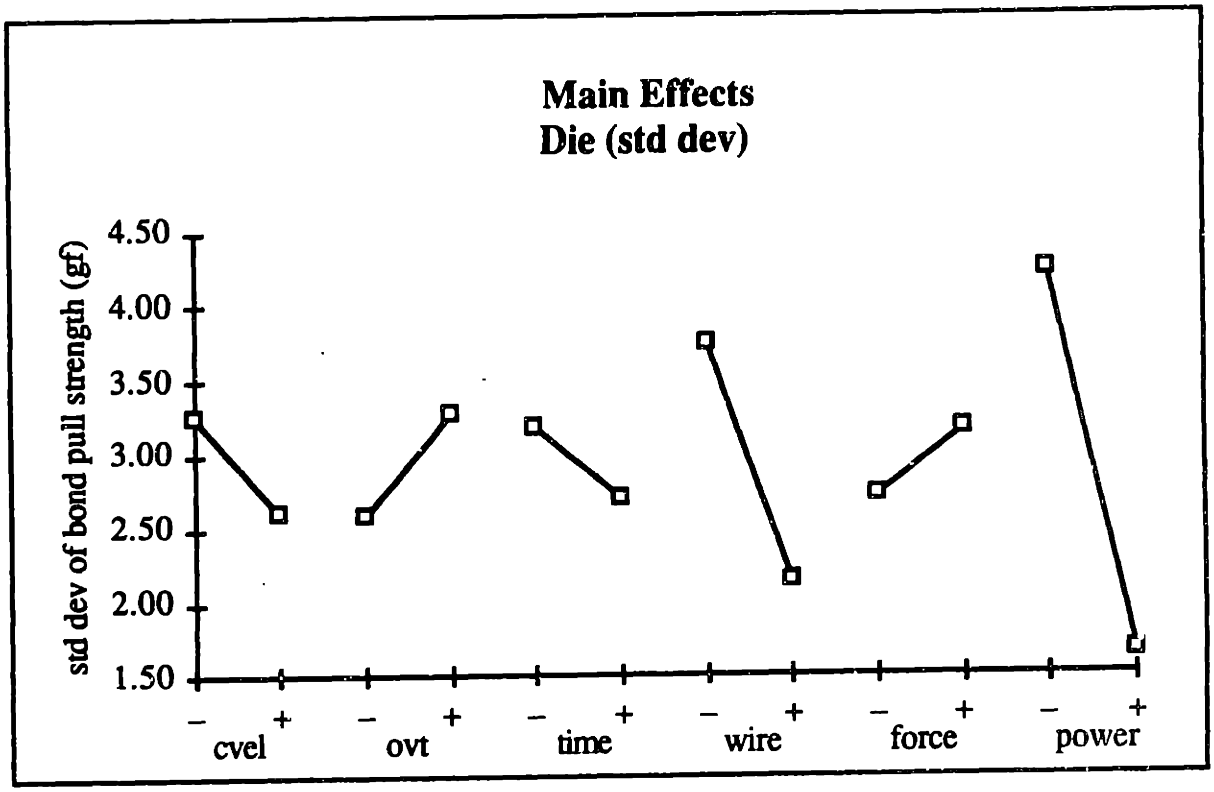

Two-Factor Interaction
Die (xbar)
average pull strength (gf)
16.00
14.00
12.00
10.00
8.00
6.00
power -
power +
time +
time -
11.11
7.32
15.80
13.62

Die (std dev) Analysis

Analysis of Means, Die (std dev)

average pull strength (gf)

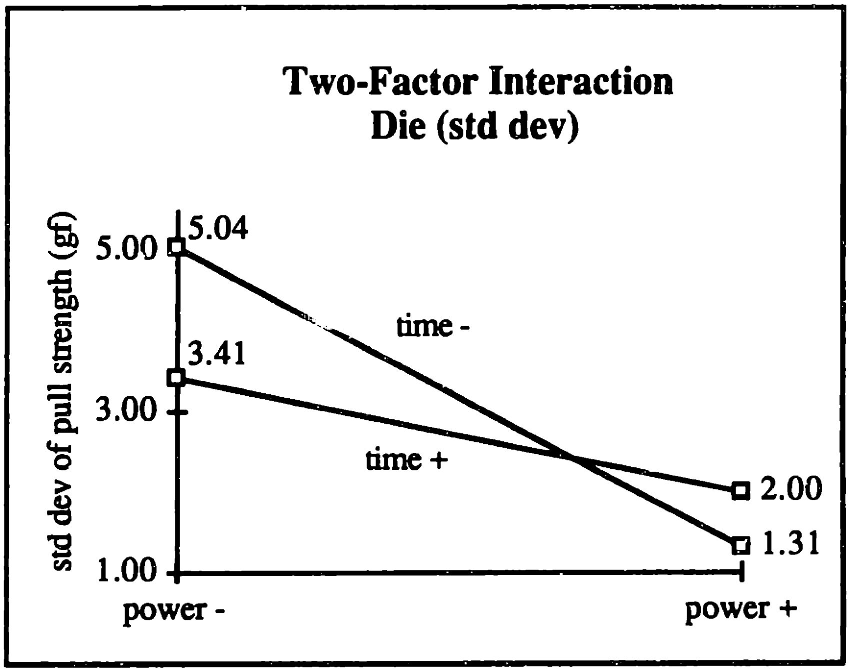
effect	avg –	avg +	Δ	Δ/2
cvel	3.27	2.62	-0.65	-0.33
ovt	2.60	3.29	0.69	0.35
time	3.18	2.70	-0.48	-0.24
wire	3.75	2.14	-1.61	-0.81
force	2.71	3.17	0.46	0.23
power	4.23	1.66	-2.57	-1.29
cvel*ovt	2.81	3.07	0.25	0.13
cvel*time	2.99	2.89	-0.11	-0.05
cvel*wire	2.79	3.09	0.30	0.15
cvel*force	2.87	3.01	0.13	0.07
cvel*power	2.97	2.91	-0.05	-0.03
ovt*time	2.76	3.12	0.35	0.18
ovt*wire	2.99	2.89	-0.10	-0.05
ovt*force	2.70	3.18	0.48	0.24
ovt*power	2.97	2.91	-0.07	-0.03
time*wire	2.79	3.09	0.30	0.15
time*force	2.59	3.29	0.70	0.35
time*power	2.36	3.52	1.16	0.58
wire*force	2.99	2.89	-0.10	-0.05
wire*power	2.33	3.55	1.22	0.61
force*power	2.75	3.13	0.38	0.19
grand mean	2.94			

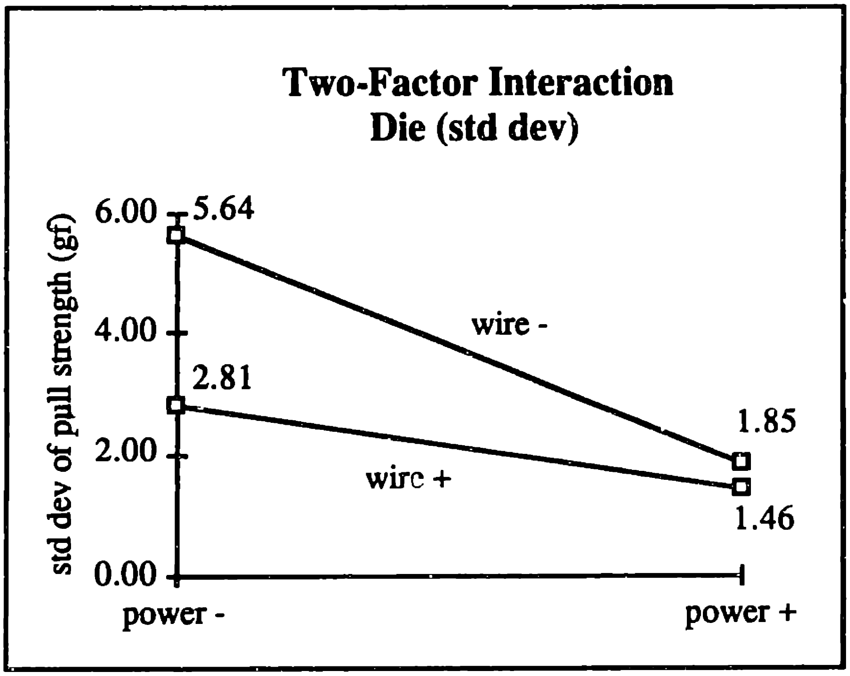

Main Effects
Die (std dev)
std dev of bond pull strength (gf)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
–
+
cvel
–
+
ovt
–
+
time
–
+
wire
–
+
force
–
+
power

Analysis of Variance, Die (std dev)

Source	df	Sum of Squares	Mean Square	F-ratio	Prob
cvel	1	3.41258	3.41258	1.9332	0.1946
ovt	1	3.85725	3.85725	2.1851	0.1701
time	1	1.81928	1.81928	1.0306	0.3339
wire	1	20.6885	20.6885	11.720	0.0065
force	1	1.66075	1.66075	0.94080	0.3549
power	1	52.7621	52.7621	29.889	0.0003
cvel*ovt	1	0.502503	0.502503	0.28466	0.6053
cvel*time	1	0.089253	0.089253	0.05056	0.8266
cvel*wire	1	0.735078	0.735078	0.41642	0.5333
cvel*force	1	0.139128	0.139128	0.07881	0.7846
cvel*power	1	0.023653	0.023653	0.01340	0.9101
ovt*time	1	0.990528	0.990528	0.56113	0.4711
ovt*wire	1	0.079003	0.079003	0.04475	0.8367
ovt*force	1	1.85763	1.85763	1.0523	0.3291
ovt*power	1	0.038503	0.038503	0.02181	0.8855
time*wire	1	0.723003	0.723003	0.40957	0.5366
time*force	1	3.87115	3.87115	2.1930	0.1694
time*power	1	10.7996	10.7996	6.1179	0.0329
wire*power	1	11.8706	11.8706	6.7246	0.0268
wire*force	1	0.073153	0.073153	0.04144	0.8428
force*power	1	1.15140	1.15140	0.65226	0.4381
Error	10	17.6525	1.76525		
Total	31	134.797			

parameters in boxes are significant at 95%


Two-Factor Interaction
Die (std dev)
std dev of pull strength (gf)
5.00
3.00
1.00
5.04
3.41
time -
time +
2.00
1.31
power -
power +


Two-Factor Interaction
Die (std dev)
std dev of pull strength (gf)
6.00
4.00
2.00
0.00
5.64
2.81
wire -
wire +
1.85
1.46
power -
power +

Wire Bonding DOX – Substrate, Configuration and Data

exp. #	cvel	ovt	time	wire	force	pwr	d_{Au}	J_{Au}	J_{Ni}	substrate pull strength (gf) *xbar*	*s*
DOX01	–	–	–	–	–	–	+	+	+	3.21	6.52
DOX02	+	–	–	–	–	–	–	–	+	17.58	0.22
DOX03	–	+	–	–	–	–	–	+	+	16.19	1.65
DOX04	+	+	–	–	–	–	+	–	+	16.23	1.64
DOX05	–	–	+	–	–	–	–	–	–	17.48	0.47
DOX06	+	–	+	–	–	–	+	+	–	6.13	7.34
DOX07	–	+	+	–	–	–	+	–	–	17.85	0.42
DOX08	+	+	+	–	–	–	–	+	–	17.73	0.33
DOX09	–	–	–	+	–	–	–	+	–	2.31	3.50
DOX10	+	–	–	+	–	–	+	–	–	8.23	5.19
DOX11	–	+	–	+	–	–	+	+	–	0.58	1.74
DOX12	+	+	–	+	–	–	–	–	–	11.76	1.47
DOX13	–	–	+	+	–	–	+	–	+	10.50	6.44
DOX14	+	–	+	+	–	–	–	+	+	11.93	1.58
DOX15	–	+	+	+	–	–	–	–	+	10.47	4.15
DOX16	+	+	+	+	–	–	+	+	+	5.02	5.04
DOX17	–	–	–	–	+	–	+	–	–	17.43	0.30
DOX18	+	–	–	–	+	–	–	+	–	17.15	0.87
DOX19	–	+	–	–	+	–	–	–	–	17.21	0.92
DOX20	+	+	–	–	+	–	+	+	–	5.46	5.22
DOX21	–	–	+	–	+	–	–	+	+	17.15	0.27
DOX22	+	–	+	–	+	–	+	–	+	17.55	0.19
DOX23	–	+	+	–	+	–	+	+	+	6.78	5.18
DOX24	+	+	+	–	+	–	–	–	+	17.64	0.78
DOX25	–	–	–	+	+	–	–	–	+	3.91	4.78
DOX26	+	–	–	+	+	–	+	+	+	2.79	4.26
DOX27	–	+	–	+	+	–	+	–	+	3.68	5.67
DOX28	+	+	–	+	+	–	–	+	+	4.93	5.90
DOX29	–	–	+	+	+	–	+	+	–	1.70	3.39
DOX30	+	–	+	+	+	–	–	–	–	13.16	1.50
DOX31	–	+	+	+	+	–	–	+	–	9.22	3.79
DOX32	+	+	+	+	+	–	+	–	–	14.41	2.56
DOX33	–	–	–	–	–	+	+	–	–	15.28	0.51
DOX34	+	–	–	–	–	+	–	+	–	14.10	0.49
DOX35	–	+	–	–	–	+	–	–	–	15.68	0.81
DOX36	+	+	–	–	–	+	+	+	–	13.86	0.81
DOX37	–	–	+	–	–	+	–	+	+	14.48	0.54
DOX38	+	–	+	–	–	+	+	–	+	13.75	0.53

exp. #	cvel	ovt	time	wire	force	pwr	d_{Au}	J_{Au}	J_{Ni}	substrate pull strength (gf)	
										xbar	*s*
DOX39	−	+	+	−	−	+	+	+	+	13.50	0.51
DOX40	+	+	+	−	−	+	−	−	+	13.60	0.74
DOX41	−	−	−	+	−	+	−	−	+	19.09	0.91
DOX42	+	−	−	+	−	+	+	+	+	14.34	1.91
DOX43	−	+	−	+	−	+	+	−	+	19.68	0.66
DOX44	+	+	−	+	−	+	−	+	+	19.06	0.37
DOX45	−	−	+	+	−	+	+	+	−	16.89	1.10
DOX46	+	−	+	+	−	+	−	−	−	17.71	1.08
DOX47	−	+	+	+	−	+	−	+	−	19.04	0.92
DOX48	+	+	+	+	−	+	+	−	−	19.00	0.56
DOX49	−	−	−	−	+	+	+	+	+	11.91	0.66
DOX50	+	−	−	−	+	+	−	−	+	14.23	0.51
DOX51	−	+	−	−	+	+	−	+	+	14.59	0.53
DOX52	+	+	−	−	+	+	+	−	+	14.75	0.74
DOX53	−	−	+	−	+	+	−	−	−	13.24	0.89
DOX54	+	−	+	−	+	+	+	+	−	9.13	0.39
DOX55	−	+	+	−	+	+	+	−	−	13.16	0.95
DOX56	+	+	+	−	+	+	−	+	−	13.97	0.58
DOX57	−	−	−	+	+	+	−	+	−	19.26	0.80
DOX58	+	−	−	+	+	+	+	−	−	19.65	1.24
DOX59	−	+	−	+	+	+	+	+	−	16.15	0.97
DOX60	+	+	−	+	+	+	−	−	−	18.74	0.67
DOX61	−	−	+	+	+	+	+	−	+	12.97	2.23
DOX62	+	−	+	+	+	+	−	+	+	16.45	0.83
DOX63	−	+	+	+	+	+	−	−	+	15.01	1.82
DOX64	+	+	+	+	+	+	+	+	+	14.53	2.27

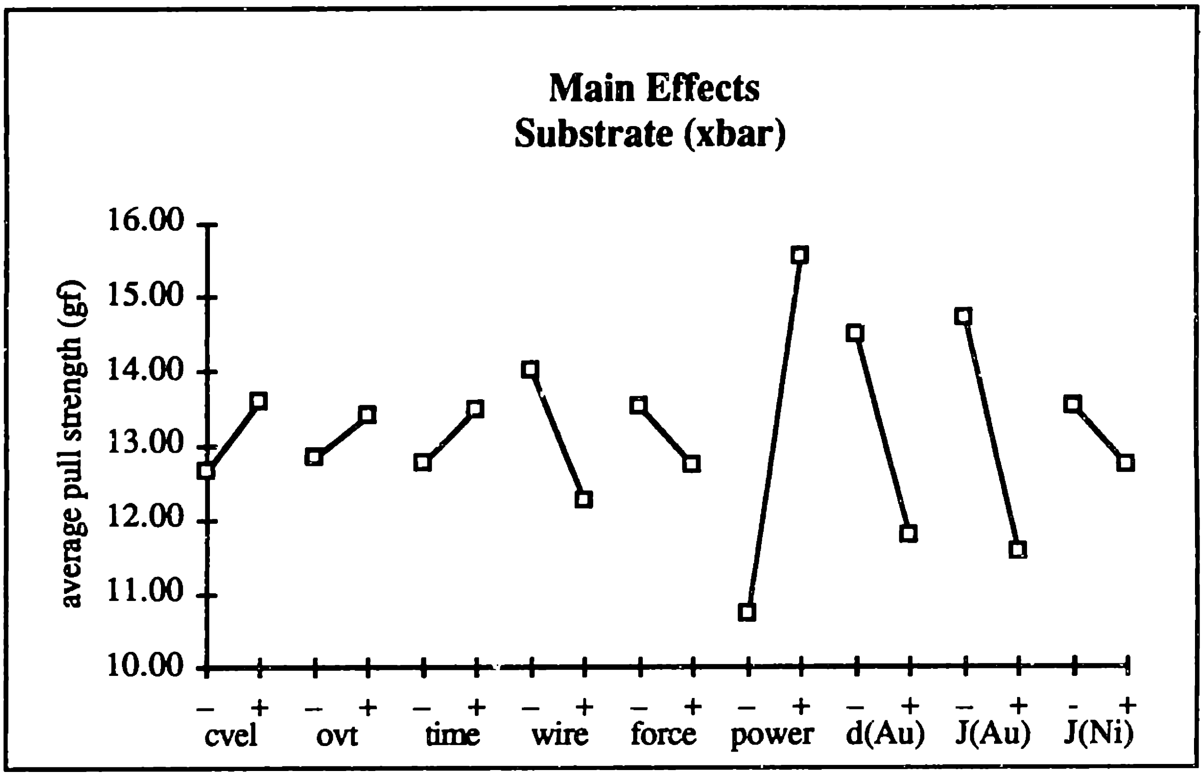
Substrate (xbar) Analysis

Analysis of Means, Substrate (xbar)

average pull strength (gf)

effect	avg –	avg +	Δ	Δ/2
cvel	12.67	13.58	0.91	0.45
ovt	12.83	13.42	0.59	0.29
time	12.78	13.47	0.69	0.35
wire	14.00	12.26	-1.74	-0.87
force	13.51	12.75	-0.76	-0.38
power	10.73	15.52	4.79	2.40
d_{Au}	14.50	11.75	-2.75	-1.37
J_{Au}	14.71	11.55	-3.16	-1.58
J_{Ni}	13.52	12.73	-0.79	-0.39
cvel*ovt	13.21	13.05	-0.16	-0.08
cvel*time	13.20	13.06	-0.14	-0.07
cvel*wire	x	x	x	x
cvel*force	12.92	13.34	0.42	0.21
cvel*power	13.68	12.58	-1.10	-0.55
cvel*d_{Au}	13.16	13.10	-0.06	-0.03
cvel*J_{Au}	x	x	x	x
cvel*J_{Ni}	x	x	x	x
ovt*time	13.09	13.17	0.08	0.04
ovt*wire	13.10	13.16	0.06	0.03
ovt*force	13.65	12.60	-1.05	-0.53
ovt*power	13.05	13.20	0.15	0.08
ovt*d_{Au}	13.01	13.25	0.24	0.12
ovt*J_{Au}	13.06	13.20	0.14	0.07
ovt*J_{Ni}	13.30	12.95	-0.35	-0.17
time*wire	12.73	13.53	0.80	0.40
time*force	13.34	12.91	-0.43	-0.21

effect	avg –	avg +	Δ	Δ/2
time*power	14.22	12.03	-2.19	-1.09
time*d_{Au}	13.17	13.08	-0.09	-0.04
time*J_{Au}	12.92	13.34	0.42	0.21
time*J_{Ni}	13.00	13.26	0.26	0.13
wire*force	13.34	12.91	-0.43	-0.21
wire*power	10.43	15.82	5.39	2.70
wire*d_{Au}	12.75	13.50	0.75	0.38
wire*J_{Au}	x	x	x	x
wire*J_{Ni}	x	x	x	x
force*power	13.41	12.84	-0.57	-0.29
force*d_{Au}	13.12	13.13	0.01	0.01
force*J_{Au}	12.97	13.28	0.31	0.16
force*J_{Ni}	13.68	12.58	-1.10	-0.55
power*d_{Au}	12.37	13.89	1.52	0.76
power*J_{Au}	11.99	14.26	2.27	1.13
power*J_{Ni}	13.14	13.12	-0.02	-0.01
d_{Au}*J_{Au}	14.43	11.83	-2.60	-1.30
d_{Au}*J_{Ni}	13.16	13.09	-0.07	-0.04
J_{Au}*J_{Ni}	x	x	x	x
grand mean	13.13			

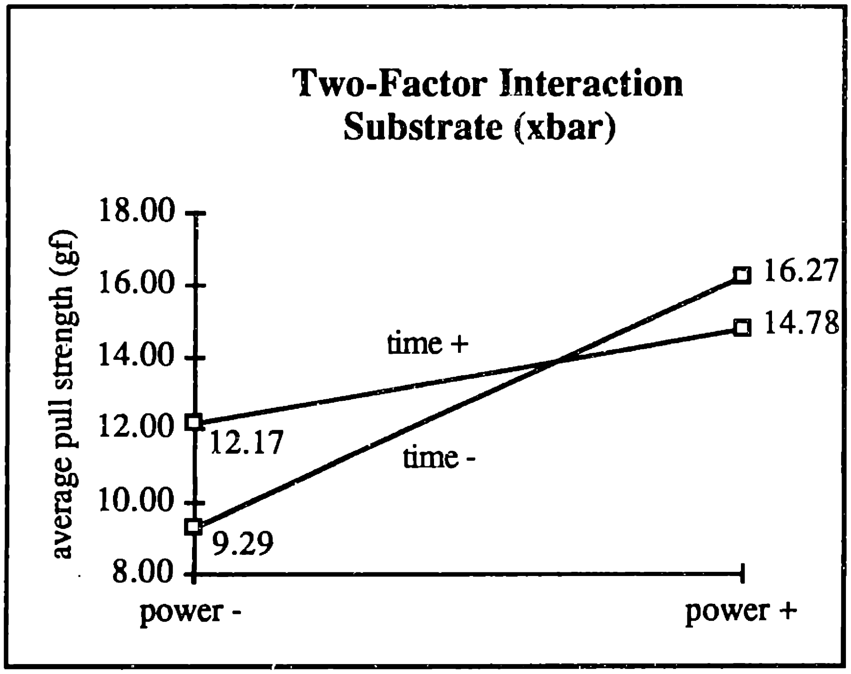

Main Effects
Substrate (xbar)
average pull strength (gf)
16.00
15.00
14.00
13.00
12.00
11.00
10.00
– +
cvel
– +
ovt
– +
time
– +
wire
– +
force
– +
power
– +
d(Au)
– +
J(Au)
- +
J(Ni)

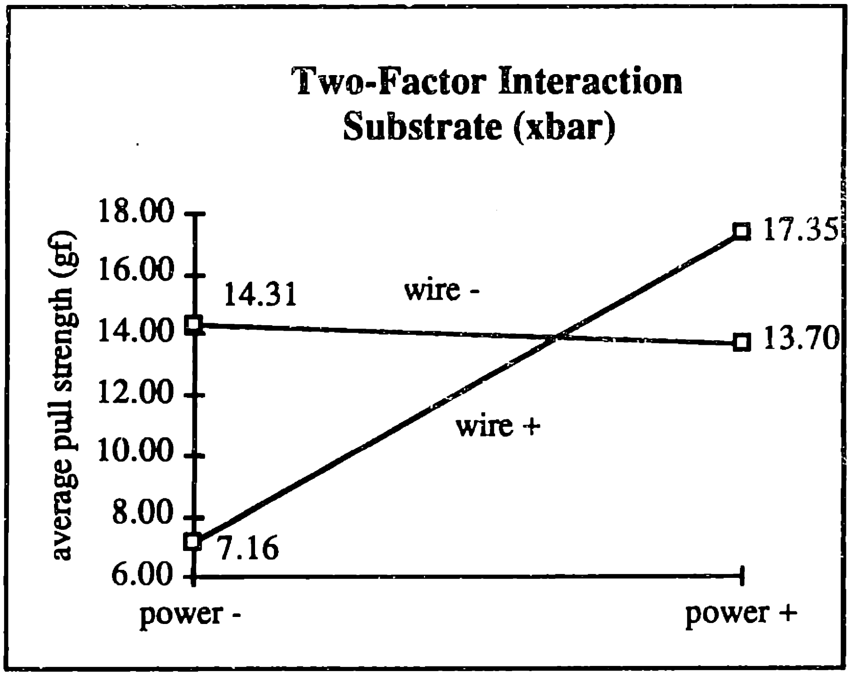
Analysis of Variance, Substrate (xbar)

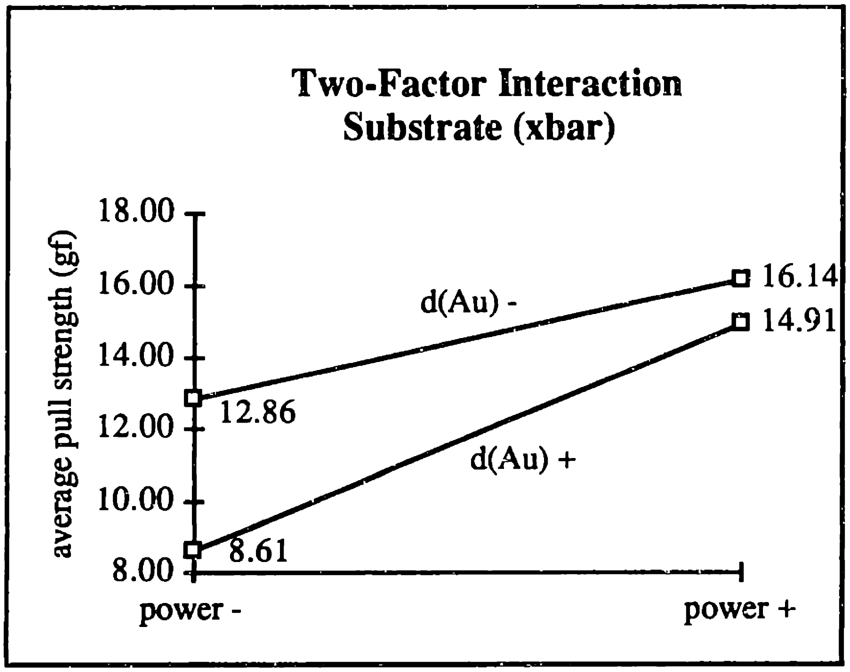
Source	df	Sum of Squares	Mean Square	F-ratio	Prob
cvel	1	13.1135	13.1135	2.6197	0.1229
ovt	1	5.51663	5.51663	1.1021	0.3077
time	1	7.65214	7.65214	1.5287	0.2322
wire	1	48.7030	48.7030	9.7295	0.0059
force	1	9.26441	9.26441	1.8508	0.1905
power	1	367.824	367.824	73.481	0.0000
d_{Au}	1	120.918	120.918	24.156	0.0001
J_{Au}	1	159.675	159.675	31.898	0.0000
J_{Ni}	1	9.89889	9.89889	1.9775	0.1767
cvel*ovt	1	0.417639	0.417639	0.08343	0.7760
cvel*time	1	0.306639	0.306639	0.06126	0.8073
cvel*wire	0	0	•	•	0
cvel*force	1	2.79308	2.79308	0.55798	0.4647
cvel*power	1	19.2392	19.2392	3.8434	0.0656
cvel*d_{Au}	1	0.053477	0.053477	0.01068	0.9188
cvel*J_{Au}	1	3.68901	3.68901	0.73696	0.4019
cvel*J_{Ni}	1	1.43439	1.43439	0.28655	0.5990
ovt*time	1	0.108077	0.108077	0.02159	0.8848
ovt*wire	1	0.061877	0.061877	0.01236	0.9127
ovt*force	1	17.7346	17.7346	3.5429	0.0761
ovt*power	1	0.373627	0.373627	0.07464	0.7878
ovt*d_{Au}	1	0.895389	0.895389	0.17887	0.6774
ovt*J_{Au}	1	0.326327	0.326327	0.06519	0.8014
ovt*J_{Ni}	1	1.94254	1.94254	0.38806	0.5411
time*wire	1	10.2160	10.2160	2.0409	0.1702
time*force	1	2.91983	2.91983	0.58330	0.4549
time*power	1	76.5844	76.5844	15.299	0.0010
time*d_{Au}	1	0.126914	0.126914	0.02535	0.8753
time*J_{Au}	1	2.80144	2.80144	0.55965	0.4641

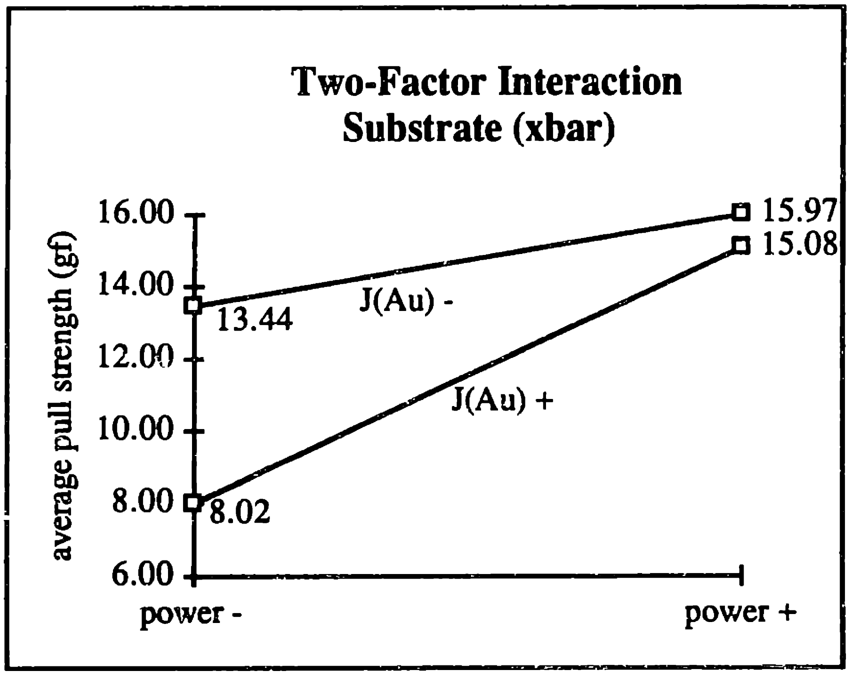
Source	df	Sum of Squares	Mean Square	F-ratio	Prob
time*J_{Ni}	1	1.04806	1.04806	0.20937	0.6527
wire*force	1	2.95410	2.95410	0.59014	0.4523
wire*power	1	464.995	464.995	92.893	0.0000
wire*d_{Au}	1	9.08269	9.08269	1.8145	0.1947
wire*J_{Au}	0	0	•	•	0
wire*J_{Ni}	0	0	•	•	0
force*power	1	5.22694	5.22694	1.0442	0.3204
force*d_{Au}	1	0.001914	0.001914	0.00038	0.9846
force*J_{Au}	1	1.54691	1.54691	0.30903	0.5851
force*J_{Ni}	1	19.3270	19.3270	3.8610	0.0650
power*d_{Au}	1	36.8601	36.8601	7.3636	0.0142
power*J_{Au}	1	82.1969	82.1969	16.421	0.0007
power*J_{Ni}	1	0.007014	0.007014	0.00140	0.9706
d_{Au}*J_{Au}	1	108.134	108.134	21.602	0.0002
d_{Au}*J_{Ni}	1	0.080514	0.080514	0.01608	0.9005
J_{Au}*J_{Ni}	1	8.78329	8.78329	1.7546	0.2019
Error	18	90.1030	5.00572		
Total	63	1728.84			

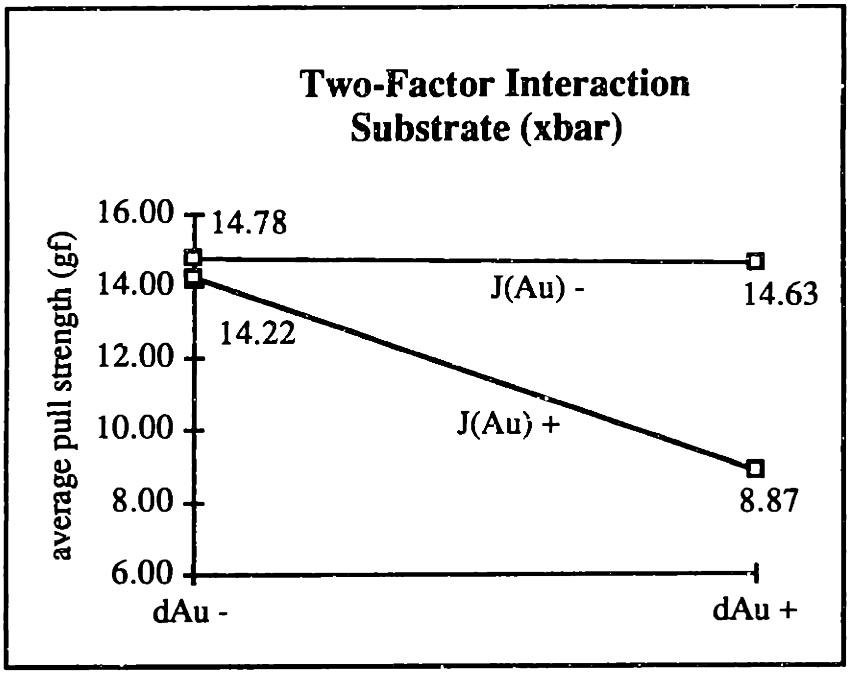
parameters in boxes are significant at 95%


Two-Factor Interaction
Substrate (xbar)
average pull strength (gf)
18.00
16.00
14.00
12.00
10.00
8.00
power -
power +
time +
time -
12.17
9.29
16.27
14.78


Two-Factor Interaction
Substrate (xbar)
average pull strength (gf)
18.00
16.00
14.00
12.00
10.00
8.00
6.00
power -
power +
wire -
wire +
14.31
7.16
17.35
13.70


Two-Factor Interaction
Substrate (xbar)
average pull strength (gf)
18.00
16.00
14.00
12.00
10.00
8.00
power -
power +
d(Au) -
d(Au) +
12.86
16.14
8.61
14.91


Two-Factor Interaction
Substrate (xbar)
average pull strength (gf)
16.00
14.00
12.00
10.00
8.00
6.00
power -
power +
J(Au) -
J(Au) +
13.44
15.97
8.02
15.08


Two-Factor Interaction
Substrate (xbar)
average pull strength (gf)
16.00
14.00
12.00
10.00
8.00
6.00
14.78
14.22
J(Au) -
14.63
J(Au) +
8.87
dAu -
dAu +

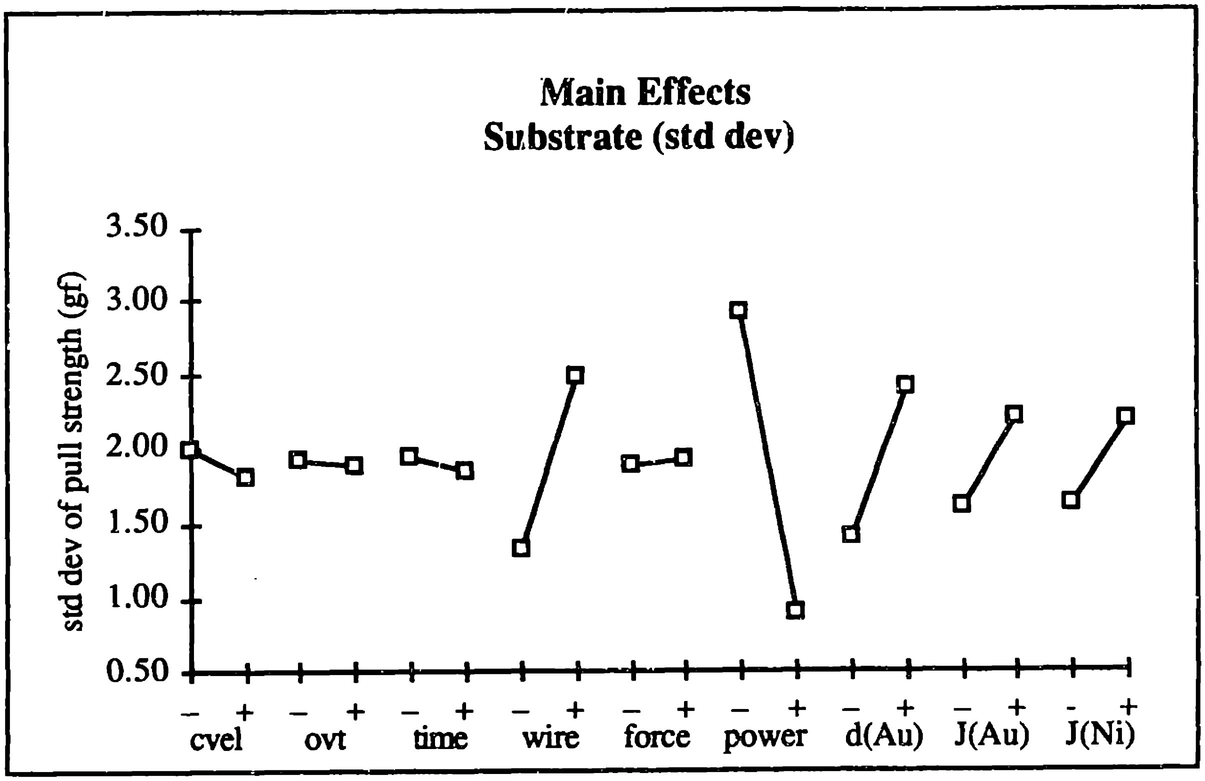
Substrate (std dev) Analysis

Analysis of Means, Substrate (std dev)

average pull strength (gf)

effect	avg –	avg +	Δ	Δ/2
cvel	2.00	1.81	-0.19	-0.10
ovt	1.92	1.89	-0.03	-0.02
time	1.95	1.86	-0.10	-0.05
wire	1.33	2.48	1.15	0.57
force	1.88	1.93	0.05	0.02
power	2.92	0.89	-2.02	-1.01
d_{Au}	1.40	2.41	1.01	0.51
J_{Au}	1.61	2.20	0.58	0.29
J_{Ni}	1.62	2.19	0.57	0.29
cvel*ovt	1.84	1.97	0.13	0.07
cvel*time	2.02	1.79	-0.23	-0.11
cvel*wire	x	x	x	x
cvel*force	1.95	1.86	-0.10	-0.05
cvel*power	1.84	1.97	0.13	0.06
cvel*d_{Au}	1.72	2.08	0.36	0.18
cvel*J_{Au}	x	x	x	x
cvel*J_{Ni}	x	x	x	x
ovt*time	1.83	1.98	0.15	0.07
ovt*wire	1.95	1.85	-0.10	-0.05
ovt*force	1.40	2.40	1.00	0.50
ovt*power	1.91	1.90	-0.01	-0.01
ovt*d_{Au}	2.11	1.69	-0.42	-0.21
ovt*J_{Au}	1.84	1.96	0.12	0.06
ovt*J_{Ni}	1.72	2.08	0.36	0.18
time*wire	1.88	1.93	0.05	0.02
time*force	2.06	1.75	-0.31	-0.15

effect	avg –	avg +	Δ	Δ/2
time*power	1.75	2.06	0.31	0.15
time*d_{Au}	1.82	1.98	0.16	0.08
time*J_{Au}	1.92	1.88	-0.04	-0.02
time*J_{Ni}	1.98	1.83	-0.14	-0.07
wire*force	1.74	2.07	0.33	0.17
wire*power	2.22	1.58	-0.64	-0.32
wire*d_{Au}	2.06	1.74	-0.32	-0.16
wire*J_{Au}	x	x	x	x
wire*J_{Ni}	x	x	x	x
force*power	1.81	1.99	0.18	0.09
force*d_{Au}	2.07	1.73	-0.34	-0.17
force*J_{Au}	1.88	1.93	0.05	0.03
force*J_{Ni}	1.83	1.98	0.15	0.08
power*d_{Au}	2.30	1.51	-0.79	-0.40
power*J_{Au}	1.57	2.23	0.66	0.33
power*J_{Ni}	2.10	1.71	-0.38	-0.19
d_{Au}*J_{Au}	1.65	2.16	0.51	0.25
d_{Au}*J_{Ni}	1.82	1.99	0.16	0.08
J_{Au}*J_{Ni}	x	x	x	x
grand mean	1.90			

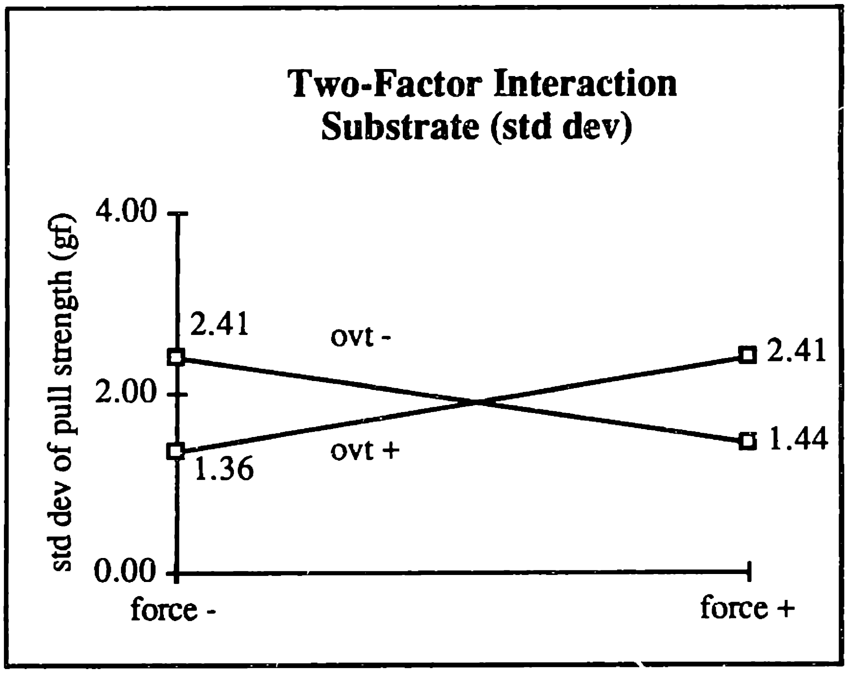

Main Effects
Substrate (std dev)
std dev of pull strength (gf)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
– +
cvel
– +
ovt
– +
time
– +
wire
– +
force
– +
power
– +
d(Au)
– +
J(Au)
- +
J(Ni)

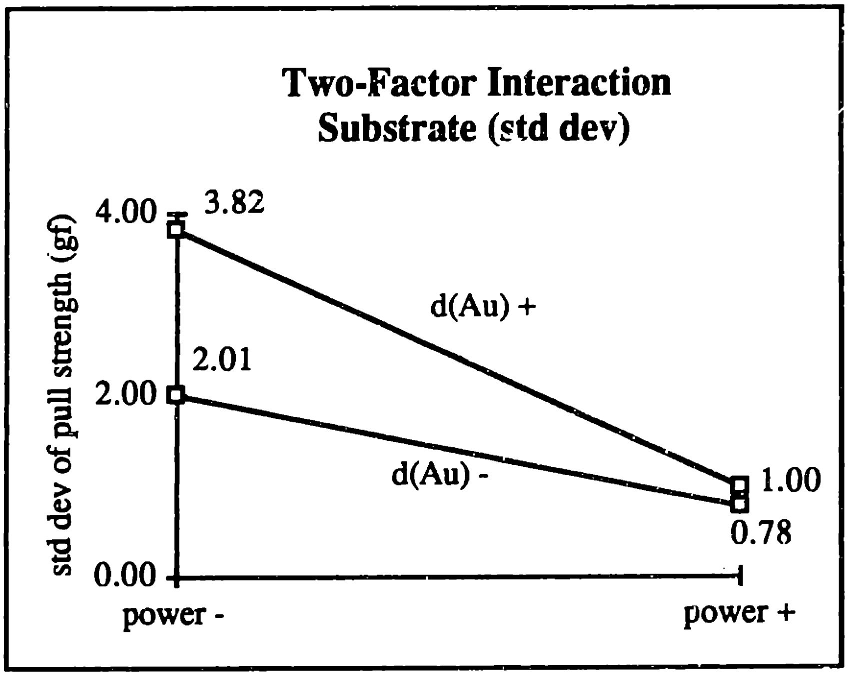
Analysis of Variance, Substrate (std dev)

Source	df	Sum of Squares	Mean Square	F-ratio	Prob
cvel	1	0.579502	0.579502	0.27182	0.6085
ovt	1	0.021389	0.021389	0.01003	0.9213
time	1	0.157014	0.157014	0.07365	0.7892
wire	1	21.2636	21.2636	9.9740	0.0054
force	1	0.040502	0.040502	0.01900	0.8919
power	1	65.7113	65.7113	30.823	0.0000
d_{Au}	1	16.5751	16.5751	7.7748	0.0121
J_{Au}	1	5.52838	5.52838	2.5932	0.1247
J_{Ni}	1	5.26129	5.26129	2.4679	0.1336
cvel*ovt	1	0.258827	0.258827	0.12141	0.7316
cvel*time	1	0.867227	0.867227	0.40679	0.5316
cvel*wire	1	0.339282	0.339282	0.15915	0.6946
cvel*force	1	0.139689	0.139689	0.06552	0.8009
cvel*power	1	0.238877	0.238877	0.11205	0.7417
cvel*d_{Au}	1	2.09164	2.09164	0.98111	0.3351
cvel*J_{Au}	1	2.68251	2.68251	1.2583	0.2767
cvel*J_{Ni}	0	0	•	•	0
ovt*time	1	0.364514	0.364514	0.17098	0.6841
ovt*wire	1	0.179564	0.179564	0.08423	0.7750
ovt*force	1	15.8504	15.8504	7.4348	0.0138
ovt*power	1	0.000977	0.000977	0.00046	0.9832
ovt*d_{Au}	1	2.86879	2.86879	1.3456	0.2612
ovt*J_{Au}	1	0.212752	0.212752	0.09979	0.7557
ovt*J_{Ni}	1	2.07000	2.07000	0.97096	0.3375
time*wire	1	0.031064	0.031064	0.01457	0.9053
time*force	1	1.52214	1.52214	0.71398	0.4092
time*power	1	1.52214	1.52214	0.71398	0.4092
time*d_{Au}	1	0.404814	0.404814	0.18988	0.6682
time*J_{Au}	1	0.026814	0.026814	0.01258	0.9119

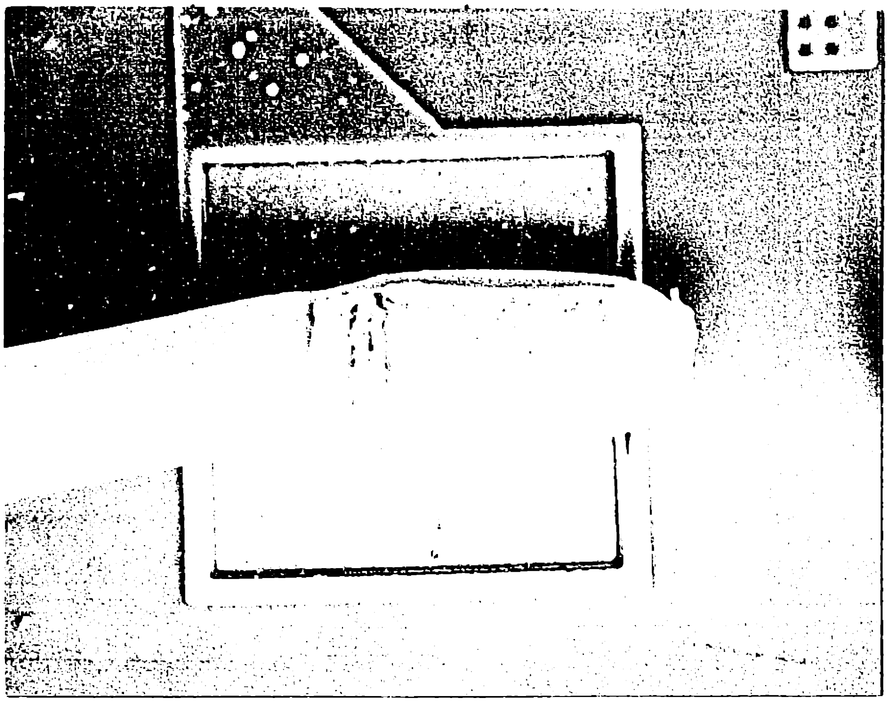
Source	df	Sum of Squares	Mean Square	F-ratio	Prob
time*J_{Ni}	1	0.343689	0.343689	0.16121	0.6928
wire*force	1	1.79225	1.79225	0.84068	0.3713
wire*power	1	6.62419	6.62419	3.1072	0.0949
wire*d_{Au}	1	1.57816	1.57816	0.74026	0.4009
wire*J_{Au}	1	4.39932	4.39932	2.0636	0.1680
wire*J_{Ni}	0	0	•	•	0
force*power	1	0.498789	0.498789	0.23396	0.6344
force*d_{Au}	1	1.82588	1.82588	0.85645	0.3670
force*J_{Au}	1	0.045689	0.045689	0.02143	0.8852
force*J_{Ni}	1	0.392189	0.392189	0.18396	0.6731
power*d_{Au}	1	10.1363	10.1363	4.7546	0.0427
power*J_{Au}	1	6.98941	6.98941	3.2785	0.0869
power*J_{Ni}	1	2.39089	2.39089	1.1215	0.3036
d_{Au}*J_{Au}	1	4.17691	4.17691	1.9592	0.1786
d_{Au}*J_{Ni}	1	0.450577	0.450577	0.21135	0.6512
J_{Au}*J_{Ni}	0	0	•	•	0
Error	18	38.3742	2.13190		
Total	63	234.250			

parameters in boxes are significant at 95%

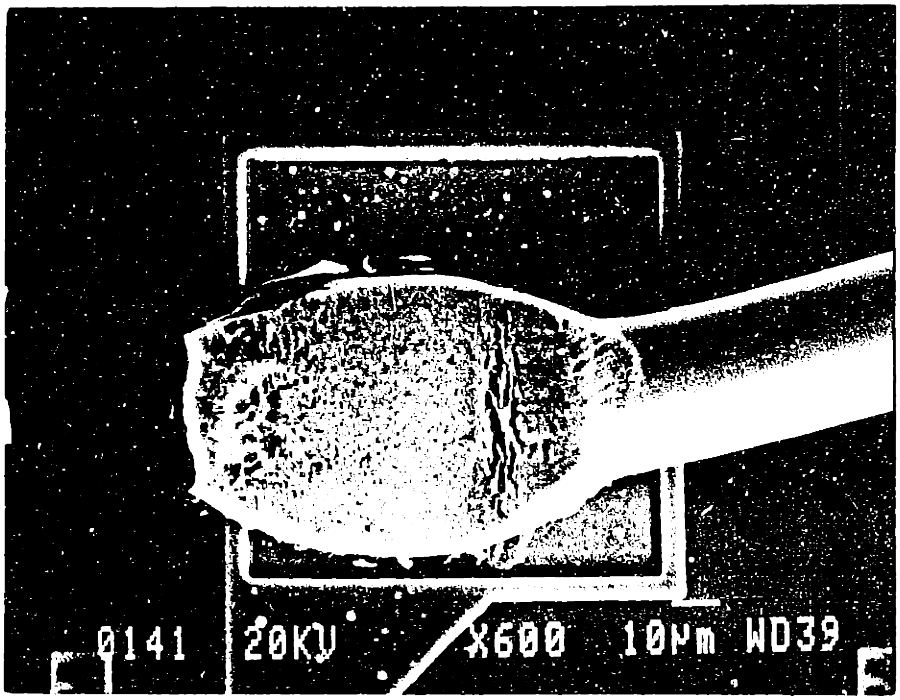

Two-Factor Interaction
Substrate (std dev)
std dev of pull strength (gf)
4.00
2.00
0.00
2.41
ovt -
2.41
1.44
1.36
ovt +
force -
force +


Two-Factor Interaction
Substrate (std dev)
std dev of pull strength (gf)
4.00
3.82
d(Au) +
2.01
2.00
d(Au) -
1.00
0.78
0.00
power -
power +

Die DOX Sample at 600x (time +, power –)



Die DOX Sample at 600x (time +, power +)



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