REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-01

AD-A282 022

2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	THESIS/~~DISSERTATION~~

4. TITLE AND SUBTITLE STRATEGIC MODERNIZATION OF A SMALL MANUFACTORING FACILITY USING A SYSTEM APPROACH

5. FUNDING NUMBERS

6. AUTHOR(S)

SCOTT MICHEAL PEARL

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

AFIT Student Attending:

UNIVERSITY OF MARYLAND

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/CI/CIA-94-082

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

DEPARTMENT OF THE AIR FORCE
AFIT/CI
2950 P STREET
WRIGHT-PATTERSON AFB OH 45433-7765

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release IAW 190-1
Distribution Unlimited
MICHAEL M. BRICKER, SMSgt, USAF
Chief Administration

SOPY 94-22752

13. ABSTRACT (Maximum 200 words)

94 7 20 016

14. SUBJECT TERMS

15. NUMBER OF PAGES 43

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

94-082

M.S. Program in Systems Engineering
Scholarly Paper Submission/Approval Form

This is to verify that SCOTT M. PEARL,
(Printed Name of Student)

has submitted the Systems Engineering Scholarly Paper for completion of degree requirements for the Non-Thesis Option for the M.S. Degree in Systems Engineering. Our signatures below indicate that we have read and approve the scholarly paper as submitted.

Dr. Mark A. Shayman — Printed Name/Scholarly Paper Reader

Mark A. Shayman — Signature/Scholarly Paper Reader

DR IOANNIS MINIS — Printed Name/MSSE Advisor

Ioannis Minis — Signature of MSSE Advisor

4/22/94

NOTE: A COPY OF THE APPROVED SCHOLARLY PAPER MUST BE ATTACHED TO THIS FORM PRIOR TO SUBMISSION TO THE MSSE OFFICE

4/94

UNIVERSITY OF MARYLAND AT COLLEGE PARK

INSTITUTE FOR SYSTEMS RESEARCH

April 4, 1994

Dear Spring 1994 Anticipated Graduate:

I am aware that you have applied for graduation for the Spring 1994 semester in the Non-Thesis Degree Option for the M.S. Program in Systems Engineering. The Non-Thesis Option requires that you submit and obtain approval of a Scholarly Paper from your advisor and a second reader. Attached is the Scholarly Paper Submission/Approval Form that must be signed by your advisor and the reader, and submitted to our office before final graduation clearance can be granted. Please return the signed form and a copy of the approved scholarly paper no later than April 22, 1994. If you do not return the required form and a copy of your scholarly paper by this date, we will assume that you did not meet the scholarly paper requirements for graduation this semester.

If you have any additional questions, please contact Ms. Mattie Riley at (301) 405-6608. We look forward to hearing from you by April 22nd.

Sincerely,

Alan R. Hevner
Director, MSSE Program

Enclosure: Scholarly Paper Submission/Approval Form

cc: Student File

A. V. WILLIAMS BUILDING (115) • COLLEGE PARK, MARYLAND 20742 • (301) 405-6632 • E-MAIL: src@ra.src.umd.edu • FAX (301) 405-6707

Strategic Modernization of a Small Manufacturing Facility Using a Systems Approach

by

Scott Michael Pearl

Scholarly Paper submitted to the Faculty of the Graduate School
of the University of Maryland in partial fulfillment
of the requirements for the degree of
Master of Science
1994

Advisor: Professor Ioannis Minis
Department of Mechanical Engineering
and the
Institute for Systems Research

ABSTRACT

Title of Scholarly Paper: STRATEGIC MODERNIZATION OF A SMALL MANUFACTURING FACILITY USING A SYSTEMS APPROACH

Name of degree candidate: Scott Michael Pearl

Degree and Year: Master of Science, 1994

Scholarly Paper directed by: Professor Ioannis Minis
Department of Mechanical Engineering
Institute for Systems Research

This paper presents the results of an effort to reengineer several manufacturing processes at a small microwave printed circuit board production facility. Emphasis was placed on improving the cleaning, developing, etching, and stripping manufacturing processes. This work was performed at Modular Components National (MCN), located in Bel Air, Maryland.

The author studied the industry in which MCN participates in order to ensure that any changes made would improve the company's competitive posture within the industry. Company operations as a whole were then evaluated to uncover system-wide problems. Once the most promising improvement area was found, each process within that area was analyzed in detail to determine the critical process parameters. A literature search was conducted and equipment requirements were defined. Emphasis was placed on environmentally-conscious manufacturing and on minimizing the amount of manual material handling. Once set in place, the machines had to be modified and fine-tuned to the company products and processes. The author worked extensively to test out the new equipment and to determine the optimal speeds and feeds for different input materials. Cost data were gathered and a cost-benefit analysis was performed on a part critical to the company's long-term relationship with Westinghouse, a major purchaser.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

This paper shall trace the development and implementation of an automated clean line, developer, etcher, and stripper, all with environmentally conscious practices, for Modular Components National (MCN), a small microwave printed circuit board manufacturer located in Bel Air, Maryland (a description of the company may be found in Appendix A). The effort was sponsored by the Air Force's Program to Revitalize Industrial Defense Efficiency (PRIDE) in America, a program designed to help critical small defense contractors that have been adversely impacted by foreign competition.

The objective of this project is to enhance the competitive posture of MCN by improving quality and reducing costs in the chemical cleaning, developing, etching, and stripping areas. The author's role in this implementation was to act as the system facilitator, integrating all the functional efforts and supporting the analysis, fact-finding, trade-off studies, optimization, decision-making, and fine-tuning of the workcell. Also included in this work were evaluating the earlier study's results, compiling and analyzing of data for the cost-benefit analysis, and researching the state-of-the art practices for etching and waste minimization.

The main cost and quality drivers were identified in an earlier study conducted by BDM International and were found to be scrap and rework rates. A major source of scrap and rework is the improper handling of boards during the cleaning and drying processes. Teflon circuit boards in particular are very delicate and improper handling can easily result in irreparable damage. Scratches, dents, and to a lesser extent, fingerprints, can cause problems during the manufacturing process and can result in scrap or rework. Quite often, these surface imperfections are not caught until numerous other value-added functions have been performed, thus wasting valuable resources on nonproductive work. Automation of cleaning and developing boards in the photolithography area will eliminate single developing cycles of dry film and improve work load capacity, as well as prevent potentially damaging material handling. Automation of the etcher will eliminate the need to manually manipulate the boards between etching cycles and improve production workload. We also determined the implementation of this workcell will help achieve greater productivity and higher quality products, enabling MCN to meet the present and future needs of its customers. In addition, the company can enhance its position as a leader in quick turnaround prototyping of difficult board designs by reducing cycle time, increasing board processing envelopes, and reducing the probability of defects. The project strengthens MCN's innovation and first mover status, while adding a position as a cost leader.

A literature search was conducted and equipment requirements were defined. Emphasis was placed on environmentally-conscious manufacturing and on minimizing the amount of manual material handling. Once the machines were set in place, the had to be modified and fine-tuned to the company products and processes. The author worked extensively to test out the new equipment and to determine the optimal speeds and feeds for different input materials. Cost data were gathered and a cost-benefit analysis was performed on a part critical to the company's long-term relationship with Westinghouse, a major purchaser.

This Scholarly Paper is structured as follows. Section Two covers the Background, briefly explaining the PRIDE program and describing the approach used to undertake this endeavor. In Section Three, the author provides a detailed assessment of the current environment found at MCN, looking first at the industry, then the company operations as a whole, and finally focusing in on cleaning, developing, etching, and stripping. Section Four covers the proposed environment, providing the description of a new manufacturing cell that was setup to included these operations, modifications and any fine-tuning performed on the cell's equipment, and the resultant benefits. Results of a cost-benefit analysis conducted using a typical product may be found in Section Five. Section Six contains the conclusions of this work.

2. BACKGROUND

PRIDE is a two-phased effort conceived by the author while working at Air Force Systems Command in 1989. Phase I involves conducting a top-down factory analysis in which a baseline of the current processes is achieved. Costs are gathered for each activity and thus high cost areas, bottlenecks, and areas of opportunity can be found. Phase II involves the design, development, and implementation of the top improvement recommendations of the Phase I effort (i.e. projects that reduce costs, open bottlenecks, or provide other significant savings to the company). A support contractor is normally hired to facilitate the Phase I analysis.

In this case, an outside contractor, BDM International, supported MCN's work during Phase I. A key part of BDM's effort involved capturing data on the company's cost of doing business (both in operations and administration). These data were used to develop IDEF diagrams in order to find the resulting breakdown of costs by activity. Since this resulting cost breakdown was used as the baseline for the author's work, it has been included in Appendix B for the interested reader. Specifically, this project impacts the costs assigned to node A244, "Fabricate Microwave Circuits", of the IDEF activity diagram of Appendix B, as well as all lower-level nodes.

A three stage approach was used for the development and implementation of the workcell. Each stage is briefly described below:

<u>Stage I: System Specification</u>.

The current cleaning, developing, and etching operations were analyzed to identify future system specifications and requirements. Technical solutions were generated and the optimal one based on cost effectiveness was chosen. Problems with the current system are covered in the Current Environment section. The proposed system definition included looking at new etchants and chemical oxidizers, etching time rates, process windows, and cosmetic characteristics.

Stage II: Develop and Evaluate Prototype System.

This stage included design and delivery of ordered equipment from the equipment manufacturer (Summit), on site installation, training, and test and evaluation of the system. A significant amount of trial and error was required to optimize the system.

Stage III: Demonstration.

The final stage involves a demonstration of the fully automated Chemical Cleaning, Developing, and Etching workcell and a preliminary cost-benefit analysis. The demonstration illustrated the labor savings of the workcell compared with the current process.

3. ASSESSMENT OF CURRENT ENVIRONMENT

This assessment of the company state began by analyzing the industry in which MCN competes: the microwave printed circuit board industry. We then examined problems with company-wide operations and practices. Finally, we focused on understanding the processes and parameters involved in the cleaning, developing, etching, and stripping operations. (Note that the current environment is frequently referred to as the "As-Is" environment.)

This industry analysis is a critical part of the PRIDE effort. If a company is competing in an industry where the structure will not let them succeed, there is no investment that can improve the company's performance. Company-wide operations must also be evaluated prior to focusing on the cell because improvements made in one area may not be synergistic with activities in the other areas. This is similar to implementing an "island of automation."

3.1 Industry Structure

In his book, Competitive Advantage, Porter describes this "five forces model" as the key to capturing the forces governing competition in an industry [6]. These forces are as follows: threat of new entrants, threat of substitute products, bargaining power of suppliers, bargaining power of customers, and competition within the industry itself. Figure 1 shows a diagram of the model. Note how each of the other four forces can affect the industry.

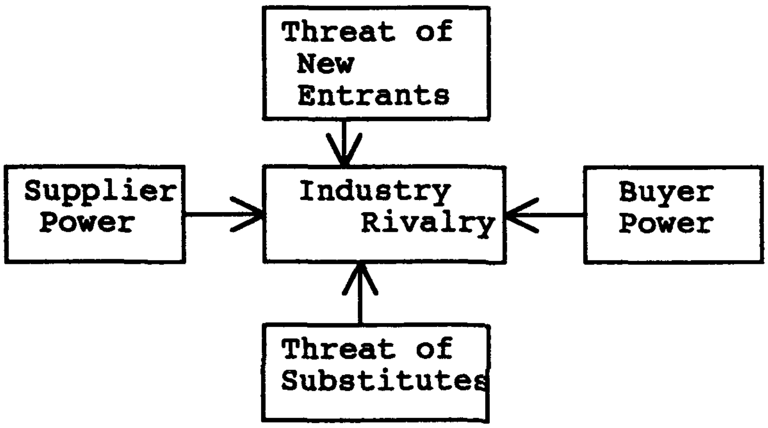

Figure 1: Porter's Five Forces Model

The goal of any improvement project will be to impact as many of these areas as possible. An analysis of the microwave printed circuit board industry shows the threat of new entrants to be fairly high. The basic production processes are mature and well-established and the capital required to perform these basic processes is reasonable. In addition, the test and inspection methods required may be difficult to conduct internally, and may be contracted out.

The threat of substitute products is very low, almost non-existent due to the highly specialized nature of microwave printed circuit boards.

The supplier power is fairly high since there are very few suppliers of raw stock. These suppliers are well-established in the business. The author surveyed these firms and found significant price differences when long-term purchasing agreements were in place and substantial price breaks for larger orders. Raw materials and purchasing account for almost 17% of the total facility costs; thus this is a cost driver worthy of close management.

Customer power is marginal. The product specifications and other technical requirements are set by the customer. However, the customers lose some power since there are so few suppliers in this industry. Thus, a company that can deliver high quality product and differentiate itself based on this product or lower cost can gain significant advantage in the customer's eyes and increase buyer dependence on them. This is the global goal set at MCN.

Industry competitor rivalry is fairly low within the United States. Globally, however, it is very high. If MCN is to compete in the global marketplace, it must raise the buyer cost of purchasing from another company. Its competitive advantage at present is its ability to quickly prototype new board designs that others cannot make due to complexity. The improvements envisioned in the cell will enhance this advantage and create further first mover advantages that should be sustainable over the long-term.

3.2 Company Operations

The Cost Baseline Analysis developed during the factory analysis identified several high cost areas in the facility. These costs may be the result of market forces dictating raw material prices or they could be the result of waste. The author conducted a quantitative waste area analysis by searching out cost driving practices and issues. These included overproduction, queuing time, in-plant flow, excessive processing, labor motion, unnecessary observations, product defects, and inventory problems/issues.

The waste areas were identified through a series of interviews with MCN managers, direct observation of the production process, and examination of internal

Quality Control/Material Discrepancy Reports. Six distinct areas of waste were found:

1) Rework and Scrap. Many parts must be reworked to correct improperly performed manufacturing operations. Some parts must be scrapped due to the severity of the damage or errors made on the part during manufacturing. Since the initial analysis was completed in October 1992, some immediate improvements were realized through better handling, improved training, and increased cleanliness.

2) Value-Added After Defective Work. Parts are passed through one or more additional work stations before defective work from a previous process is caught. This results in wasted labor, materials, and machine time.

3) Repeated Scheduling of Jobs. Jobs are often scheduled two or three times before they are actually worked. Hot jobs in the shop always take precedence, and as a result, non-hot jobs are frequently bumped and rescheduled. This introduces the potential for defects from additional handling and raises setup costs.

4) Uneven Flow of Work. Workers throughout MCN's facility are frequently idle due to an uneven flow of work from one part of the factory to another. This results not only in wasted labor but also in wasted potential machine time.

5) Poor Interpretation of Prints. All work in the factory is performed directly from blueprints and route sheets that travel with each job. Reading these prints incorrectly can result in machining errors, incorrectly sized holes, deburring errors such as removal of circuits mistaken for plating bars, and imaging and plating errors such as out of tolerance line widths.

6) Improper Handling of Boards. Microwave circuit boards are very delicate and incorrect handling can result in irreparable damage. Scratches, dents, and even fingerprints can cause problems during the manufacturing process, resulting in scrap or rework.

The figure below shows how these waste areas interact with each other and can cause significant problems in the facility.

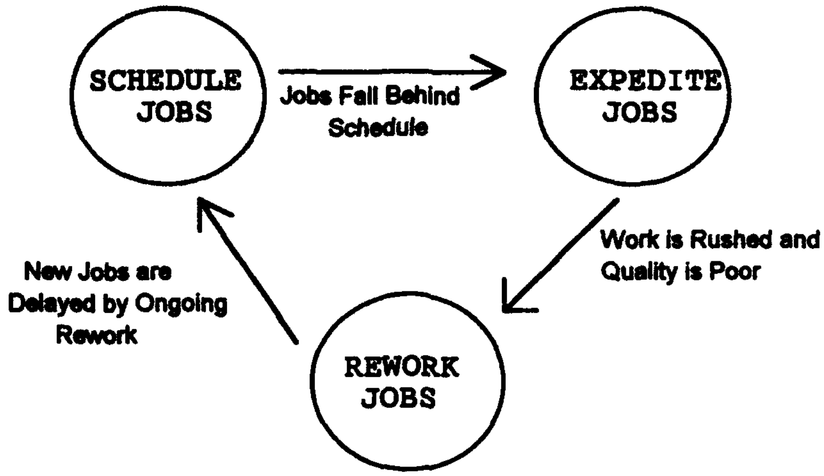

Figure 2: The Job Scheduling Dilemma

Several of these findings dictated the need to improve the production processes of the circuit boards to ensure a better product and more efficient use of the facility. Preliminary research done by the engineers within MCN, particularly the engineering director, David Chapman, led to the development of this project to streamline the process flow and to semi-automate the cleaning, developing, etching, and stripping of the boards. These processes are the main generators of the scrap and rework which were identified as causes of MCN's reduced competitiveness. This improvement will increase the company's stature in the microwave printed circuit board industry through reduced errors, improved quality, reduced waste generated. In addition, the increased capabilities and processing envelopes should pen new markets for MCN.

3.3 Clean Line

The chemical clean line that exists in the plating lab area is used both in the plating preparation function and the photolithographic function. The clean line is comprised of a number of baths, water, acid, and antioxidant, which remove contamination by microetching a very thin layer of metal off the boards. The boards are moved through the baths by hand, and the technicians leave each board in the bath for an exact period of time to etch off a precisely defined layer (50 microinches for 30 seconds). The water baths are used to wash off the acids to stop the etching process, and the antioxidant is used to prevent the copper from oxidizing while it waits to be plated. A clean, unoxidized board is the end product of the chemical clean line. This leaves a fresh surface for the critical plating process. The clean line is also used to etch the boards coming out of photolithography. The photomask is etched off, exposing the printed copper tracks on the board.

Unsupported boards are prepped for imaging in the clean line. Aluminum backed boards are shipped in matched pairs and if one board in the pair is scrapped during the production, both are ruined. The raw material arrives with a chromate coating on it that prevents oxidation. These aluminum-copper and copper-copper boards are up to 1/8" thick. This raw material is first sent through the baths, then manually scrubbed by hand with a pumice, and then air dried with unfiltered air. This process takes approximately five minutes per board and is extremely labor intensive.

A major contributor to the cost of processing the boards is the manual maintenance of the chemicals as well as the manual drying with the air hose. Scrap is a frequent occurrence, often from fingerprints. Invariably, the worker will cough or sneeze on the board, requiring it to be recleaned and redried. The processing is one at a time and since the acid cleaner attacks aluminum, the processing time is critical. The pumice cleaning of copper boards can cause problems because cleaning stretches the copper. This stretching can often cause delaminations in the boards. Figure 3 shows the cost per square foot of board for the period December 1992 through April 1993. These costs are high for such a basic operation.

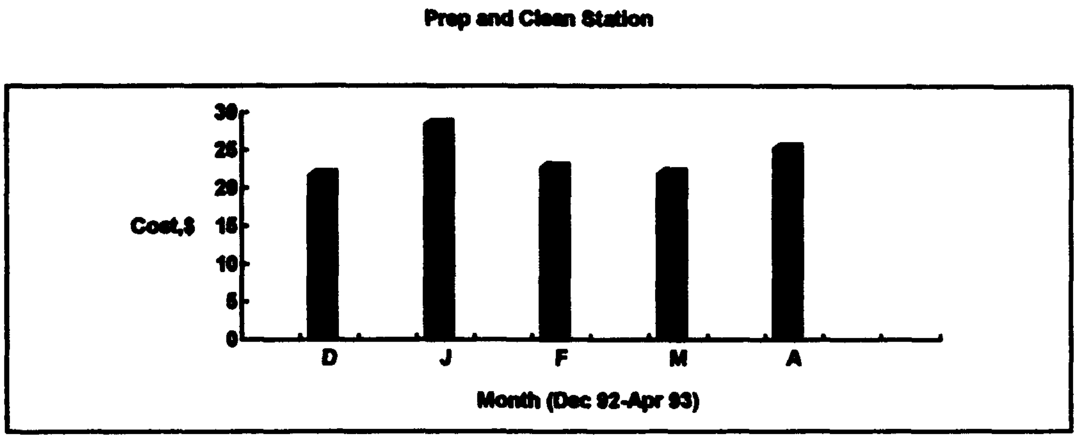

Figure 3: Cleaning and Preparation Cost per Square Foot

3.4 Developing

The developer in use at MCN is very similar to the etcher. The boards are placed in a chamber, developed, removed, placed in a rinse tank, and manually dried by an air hose. Each board is manually laminated with the film developer, imaged, and developed. 95% of MCN's work is done with dry film. The other 5% is done via photoresist. Semi-aqueous developer is used (one kilowatt bulbs) since the cost of light sources for aqueous development cannot be justified for MCN's needs.

During the lamination process, the temperature, speed, and pressure are monitored and held invariant for ten minutes. The image is then shot on the film. A vacuum is drawn for one minute and the delivered light energy is measured with timers (not by delivered millijoules). A Stouffer Step is used to verify the exposure time (approximately eighteen seconds). Capacity is approximately a board per minute or 60 boards per hour in imaging and 100 boards per day in developing.

Problems that occur during imaging include loss of vacuum, underexposure, overexposure, and dirty boards. As Figure 4 shows, during the period 12/21/92 through 2/12/93, the mean time to develop boards was 71.067 minutes, with a standard deviation of 44.94 minutes. This is a significant amount of time and the standard deviation is very high, showing the high variance and nonconformity in the existing process. Also, Figure 5 showing cost per square foot displays the high cost involved.

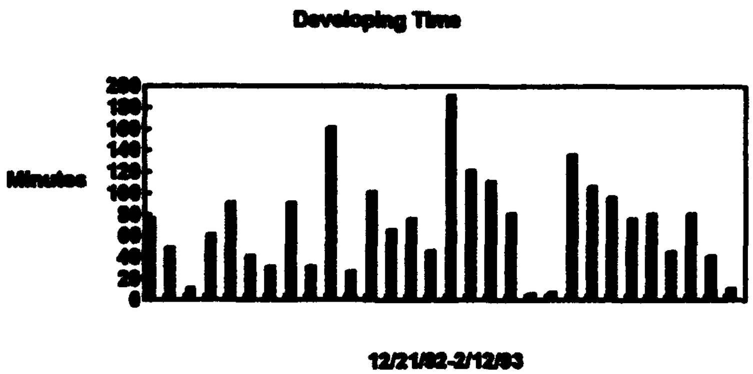

Figure 4: Developing Time using Existing Process

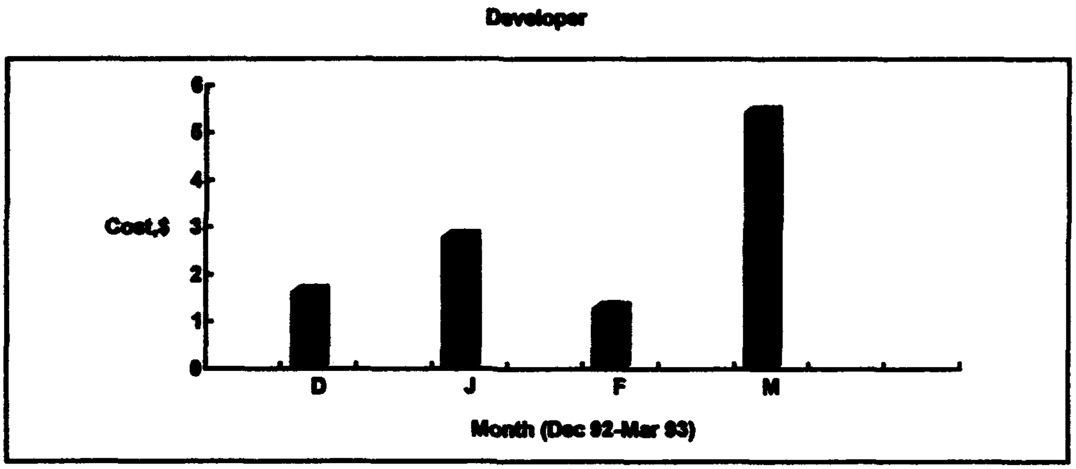

Figure 5: Developer Cost per Square Foot

3.5 Etcher

Etching is currently performed using a manual vertical etcher which allows for a 20 inch by 20 inch process window. The boards are placed on a wheel and vertically etched. Chemistry is critical during the process. Most boards are etched several times before being strip plated. The boards are etched, inspected under a microscope, touched up where required, etched again, dried, stripped, and plated.

Etching is done in an environment where pH is set and specific gravity is monitored. Free chlorides are used to reduce oxidation. The carrier is ammonia-based. The pH must be kept up since a low pH can cause the metals to drop out. Dry film is used as the etch resistant.

As Figure 6 shows, from December 21st 1992 through February 12th 1993, the mean board etching time was 129.81 minutes, with a standard deviation of 112.86 minutes. Again, this is very high and shows how labor intensive and uncontrolled the existing process is. Cost per square foot is also high, as shown in Figure 7.

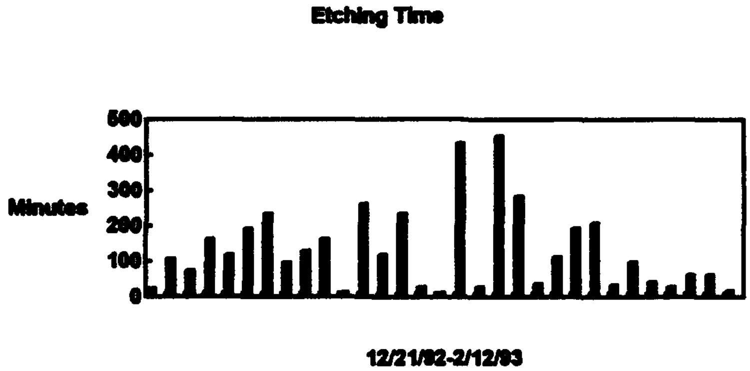

Figure 6: Etching Time for the Existing Process

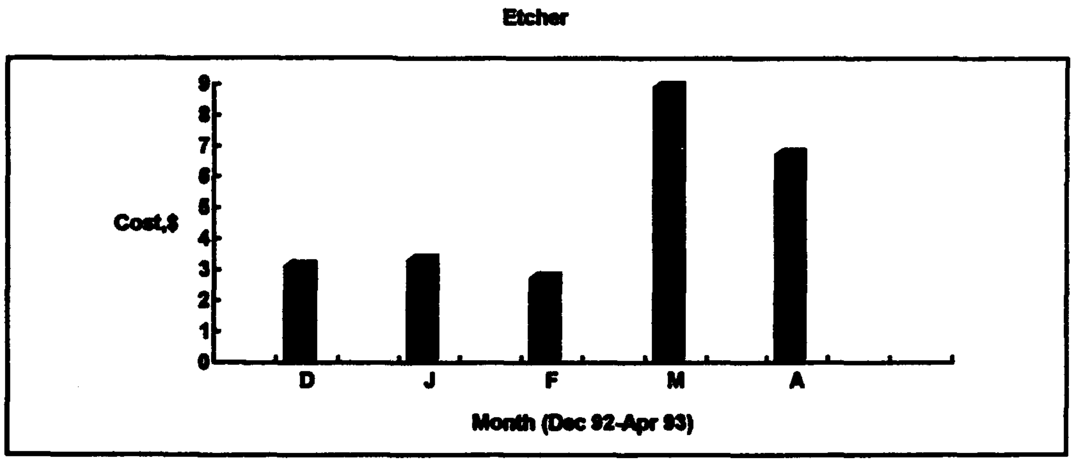

Figure 7: Etcher Cost per Square Foot

The etcher has a small process envelope and the machine is simple. Chemistries cannot be easily changed; they are only monitored and etching is done when the mixture is correct.

3.6 Stripper

MCN's current stripper is very basic: it includes a five gallon tank with a heating element. Boards are placed in the tank for several minutes until dry film is no longer visible. Boards are then removed and manually rinsed and dried. The remaining solution must be disposed of. This process costs almost $3.00 per square foot of board (see Figure 9) and averages 109.46 minutes, with a standard deviation of 107.65 minutes, as shown in Figure 8. While this is a significant amount of time, the board is simply soaking in solution and very little labor is actually spent on it. Regardless, the time varies greatly.

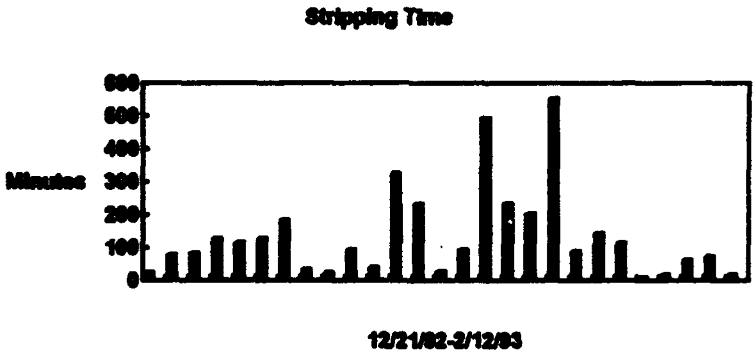

Figure 8: Stripping Time for Existing Process

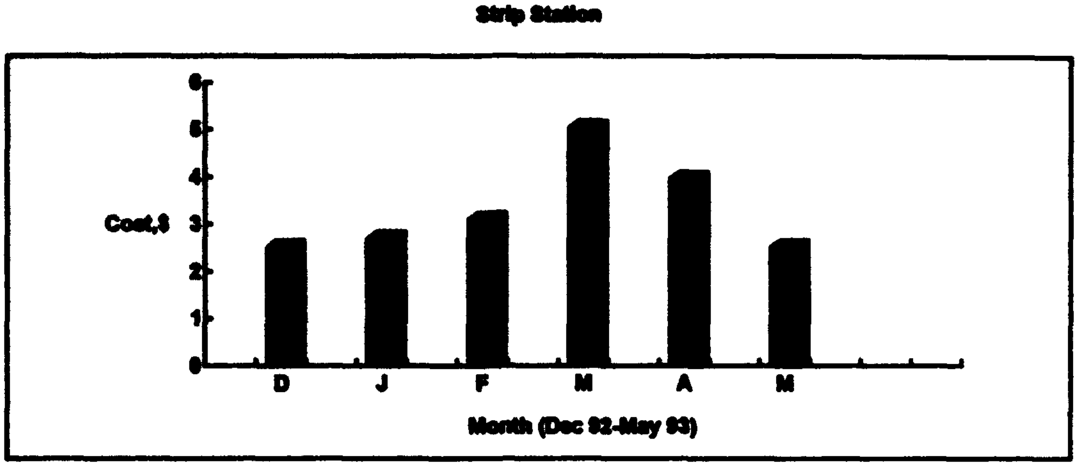

Figure 9: Strip Station Cost per Square Foot

3.7 Touch Up Station

The existing processes placed a great strain on the touch up station since there is a need to fix and touch up boards during the process to preclude them from becoming scrap. With the existing processes, the average touch up station time during the above data collection period was 144.58 minutes (see Figure 10). The standard deviation during this time was 126.28 minutes. Thus, new controlled and repeatable methods are expected to make a substantial improvement in this area. Touch up cost per square foot was $6.95 (as shown in Figure 11).

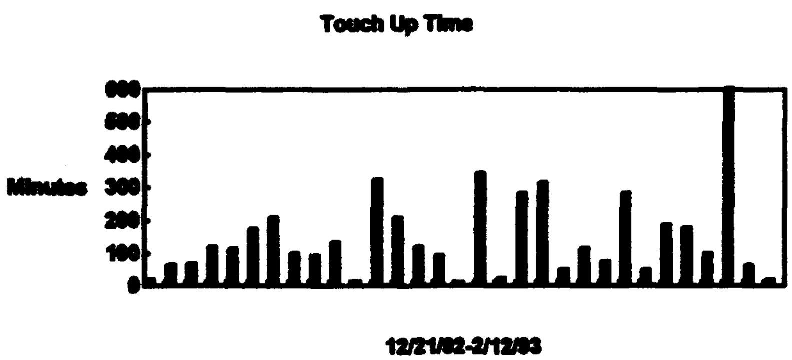

Figure 10: Touch Up Time for Existing Process

Touch Up Station

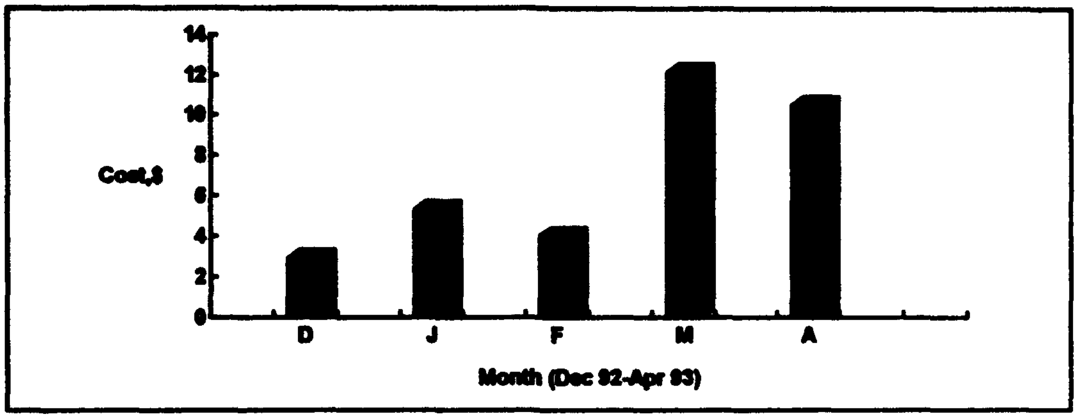

Figure 11: Touch Up Station Cost per Square Foot

4. PROPOSED ENVIRONMENT

In response to the study of the shortfalls of the existing environment, we were able to purchase custom-built machines for the cell. Each one is described in this section, followed by a narrative of the modifications required to prepare the equipment for production. Any extensive tuning, as was done on the etcher, is also described. Finally, a description of the benefits of each improvement is presented.

To assist the reader in following the material flow, Figure 12 provides a detailed layout of the cell. Parts enter the clean line at point A, exit at B, enter the developer at point D, and continue in process until exiting the stripper at point H. The dotted line from point G to point F is followed by parts that are etched more than one time. .

4.1 Clean Line

Description: A Chemcut Chemical Clean Line was purchased. It is a seven chamber unit, each chamber being equipped with a sprayer system to deliver its contents. Chambers can be turned on and off independently depending on the type of board in process.

1) The first chamber contains phosphoric acid which strips off the chromate coating the vendor places on the board to prevent oxidation during shipment.

2) The spray in the second chamber rinses off the acid.

3) The third chamber contains a mild sulfuric acid (concentration between two and five percent). This acid is used to microetch the boards and to clean them further.

4) The spray of chamber four rinses off the acid.

5) In chamber five, a CUKOS treatment is applied to the boards to prevent copper oxidation.

6) The boards are rinsed again in chamber six.

7) In chamber seven, air is blown on the boards to dry them.

This machine is placed in a polypropylene trough in order to contain possible leakages. Feed rate is controlled by an electronic control that allows the rollers to feed as fast as 132 inches per minute, far faster than MCN currently needs. A setting of approximately thirty-five inches per minute has provided the best results to-date in terms of cleanliness and microetch quality.

Modifications: We replaced the chamber covers with lift-open lexan hoods so the parts could be monitored as they proceed through the cleaning process. A circuit breaker was installed in the hoods to shut off the spray when a hood is raised over a chamber and thus prevents injuries. We also installed smaller rollers on the conveyor to increase the clearance between rollers and the hoods. The machine can now accept boards up to .438 inches in thickness. This change was made in anticipation of future MCN needs.

During installation, each chamber was equipped with an overflow tank with a sump pump. This arrangement prevents the acid microetchant and cleaning agents from escaping should a leak occur. The sump, when engaged, pushes the liquid to the waste stream where it is processed.

Benefits: This alkaline cleaning system replaces the hand cleaning operation and provides filtered air to the drying operation. The throughput using the hand cleaning method is approximately twelve boards per hour, while the automated clean line

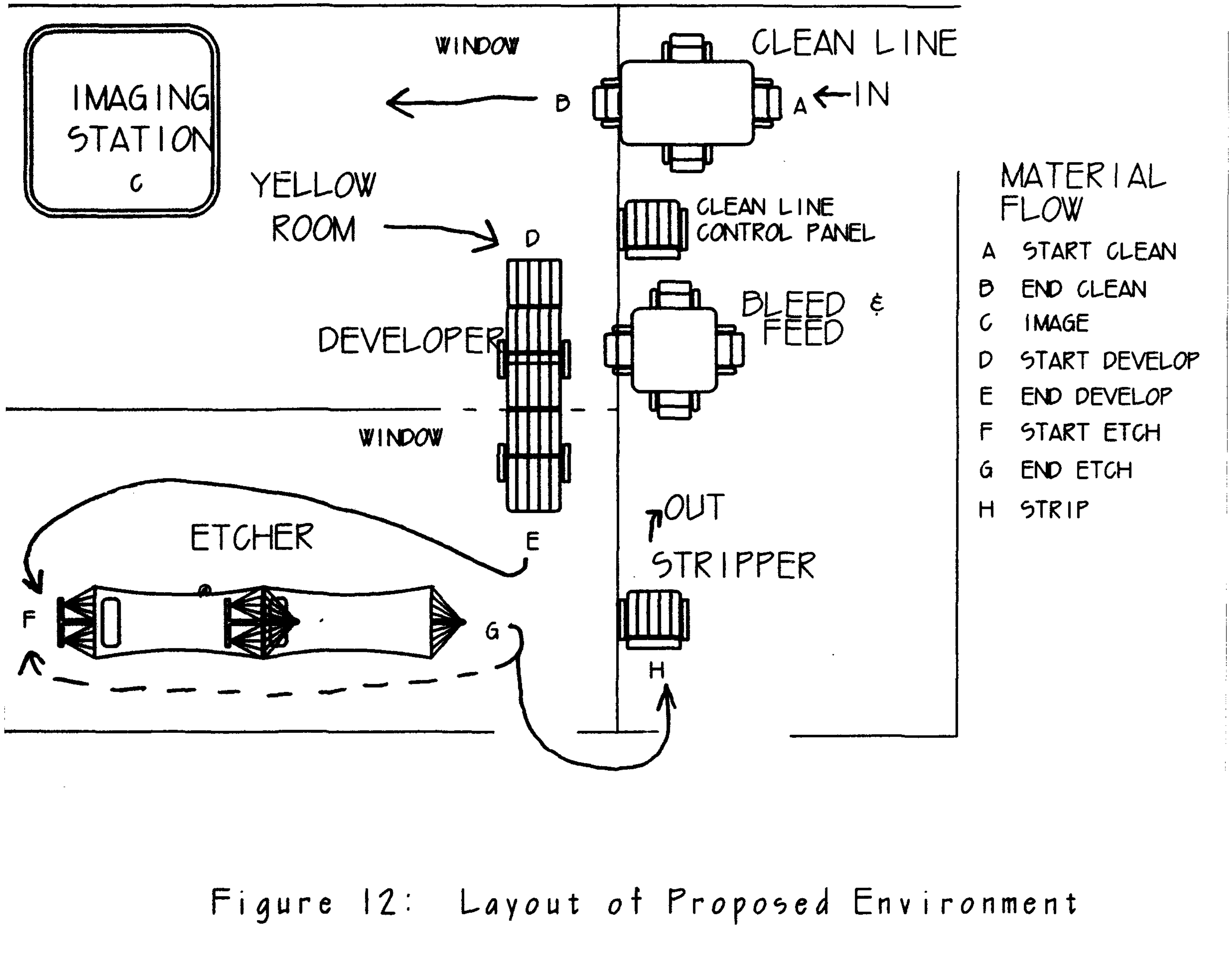

Figure 12: Layout of Proposed Environment

throughput is limited only by the rate at which a worker can insert and remove the boards. The first board in this new system takes almost twelve minutes to process, but boards can be fed continuously thereafter. As Figure 13 shows, the "as-is" cleaning process cost MCN over $22 per square foot of board while the preliminary data compiled on the new system shows costs below $9 per square foot.

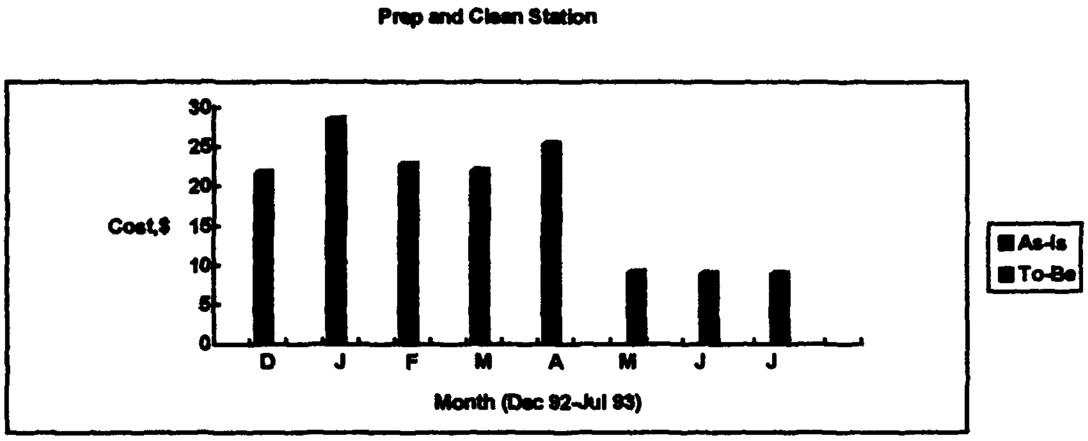

Figure 13: Prep and Clean Station Cost Per Square Foot

4.2 Developer

Description: A Summit Developer has been installed in close proximity to the chemical clean line and the imaging lab, in a clean room environment. This vertical developer is equipped with a three chamber system and an attached bleed and feed system to maintain the developer chemistry within pre-specified limits. The first chamber is the process developing chamber. Halfway through this chamber is the break point at which the copper is fully stripped. If this break point is not correctly defined, an over or an under development condition may occur. This, in turn, may cause serious problems with the quality of the board.

The bleed and feed system monitors and optimizes the pH and the film resist chemistry. The developer liquid is mixed and charged in the bleed and feed tank until the proper pH is reached and then sent to the developer.

Much like the chemical clean line, the developer is placed in its own trough and is equipped with sumps and overflow lines to preclude any environmental problems. The developer is in a separate clean room with the imaging laboratory. Parts are set in the machine vertically and exit at the other end in a different room. Spray nozzles are square-shaped to deliver as much developer as possible.

Modifications: The bleed and feed system that accompanies the developer is normally used for aqueous developing and had to be "tricked" into accepting semi-aqueous developer. This was accomplished through the use of an additional liquid tank. A change was also required in the anti-foam chamber. The first anti-foam agent tested dissolved the rubber seals in the chamber. Thus, a different agent was procured.

Part feed rate is a critical parameter that was determined through experimentation. The feed rate target is such that development occurs at the midpoint of the chamber to prevent the over or under development described above. Numerous trials were performed to find this optimal rate.

A safety feature was also added to the system. Downstream sprays will remain on if the first chamber's circuit is opened. These sprays must stay on since the downstream boards will overdevelop otherwise.

Benefits: The new developer enhances the developing throughput from 100 boards per day to 100 boards per hour. The developing cost per square foot has been lowered from $2.76 to $1.18, as shown in Figure 14.

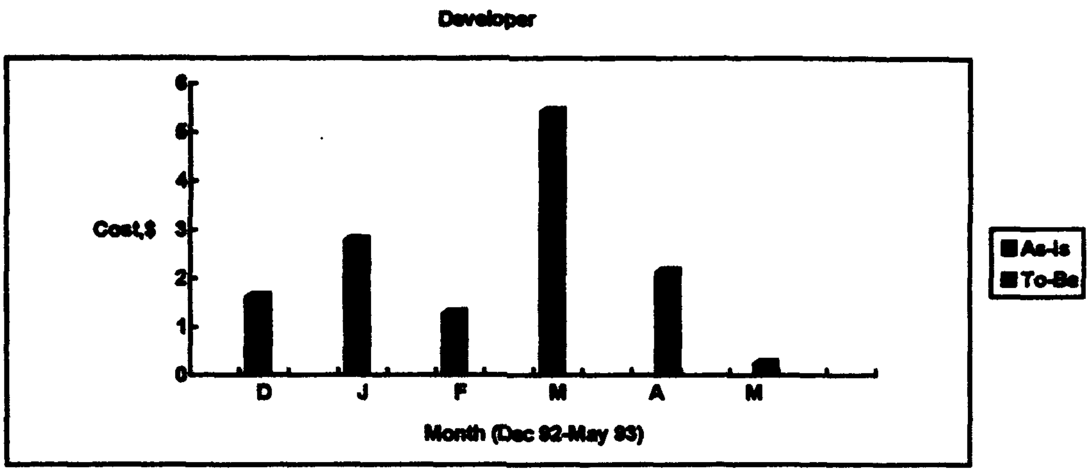

Figure 14: Developer Cost Per Square Foot

4.3 Etcher

Description: The etcher design is very similar to the developer's. While the existing etcher facilitated a 20 inch by 20 inch processing window, the new one enhances the window to 24 inch by 84 inch. This new capability has been installed in anticipation of MCN's future market- large antennae up to eight feet long.

The new etcher is a continuous feed system and contains four chambers. The first chamber contains the alkaline etchant, the second has a flood replenisher, and the third and fourth chambers rinse and dry the boards. Dry film is used as the etch resistant.

The etcher is placed in a trough and is equipped with sump pumps. Each chamber has a cascading rinse system that ensures environmentally conscious manufacture is performed.

The etching system uses the linear action of a flat spray array on a printed circuit panel. The force of this spray pattern causes the circuit panel to contact a roller. The roller reactively supports the force of the sprays and maintains the forward tracking of the panel. Thus, a uniform gross spray pattern is formed on the circuit panel and the motion is controlled by a simple mechanical scheme.

Modifications: Since the author spent significant time researching how best to design the etchant delivery system, some of the supporting findings are included in this section. The disinterested reader may disregard this material without any loss of continuity.

To ensure the etching is maximized on the surface, MCN designed the spray nozzles for maximum theoretical impact (MTI), rather than droplet size. This MTI ensures proper pressure on the boards (impingement) and, as stated by Marshall Gurian in his October 1992 article in **PC Fabrication**, titled "Fine-Line Processing: The Real World," there is no evidence that a droplet ever encounters an active etching surface [4]."

Many theories have been published on the design and operating philosophy upon which conveyorized spray process equipment is based. Most are biased due to the need to justify the particular mechanical scheme selected. There is a need for gross uniformity in the distribution of etchant flow to the surface of a circuit panel conveyed by some motion-controlling scheme. Many designs the author surveyed incorporate moving nozzles to attain gross uniformity, which compensates for the generally inadequate spray uniformity of a nozzle array design. Gurian notes, "As panel thickness has decreased, with inner layer core material as thin as three mils, the flexibility of circuit panels requires more mechanical control devices. These devices have led to the proliferation of increasingly complicated spray and conveyor mechanics, including periodic shutdown of sprays and programmed spray restrictions. This complexity is fundamentally unnecessary for both uniformity and for conveying thin panels [4]."

As Dave Chapman, MCN's engineering director, states, "It isn't the gross distribution of solution that is critical to line formation, it is the fine-line flow pattern causing liquid exchange in the very close local environment of the etched feature. The initial stage of etching has a different requirement than the last stages since during the final stage, nearly all the copper has been removed from the channel, and etchant is acting almost entirely on the sidewalls. This discrepancy cannot be resolved completely by mechanics due to different design patterns and panel sizes [1]."

Benefits: The faster automated etcher reduces processing time 50% for parts that pass through one time and considerably more for parts that are required to pass through more than once. The improved etching process also results in considerable time savings in the subsequent inspection and touch up steps, since the critical process parameters are controlled. Cost per square foot has lowered from $4.93 to $.82 in the first month, a good indication of the significant savings potential (see Figure 15).

The strategy chosen requires no auxiliary mechanical support schemes and allows the free path of etchant to all panel surfaces without restriction by intervening rollers or guides. In addition, no motion of the spray heads is required for uniform application. This design results in a durable, low-maintenance, high-productivity machine with a simple spray scheme. The progressive staggering of the square-tipped spray nozzles provides uniformity of application, avoiding any inherent pattern in the nozzle delivery itself. This type of system has reliably etched patterns below two mils, well within MCN's current needs.

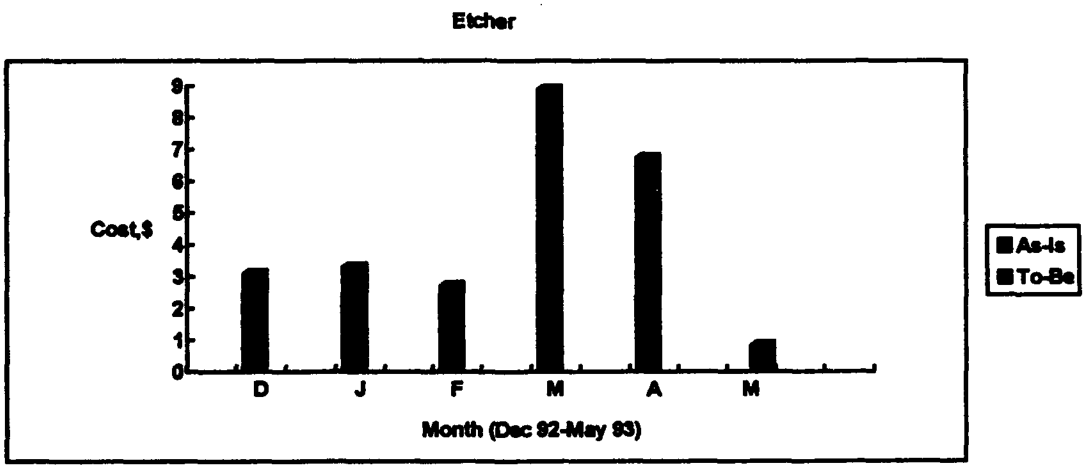

Figure 15: Etcher Cost Per Square Foot

4.4 Stripper

Description: Three conventional methods are used to strip off the resist after etching: sheet removal, particle removal, and resist dissolving. The sheet and particle removal methods neutralize and dry the waste before discarding. Dissolving involves placing the boards in solution until the resist has been removed and enters into the solution.

MCN engineered and constructed a new three-chamber stripper. It is noted that the cost of an automated stripper is approximately $40,000. However, this expenditure was not justified and the decision was made to build a larger batch stripper in-house.

The first chamber is a thirty-gallon chamber containing Dynachem stripping solution. The purpose of the first chamber is to dissolve the dry film on the boards. The second chamber is also a thirty-gallon chamber, but contains a stripping solution designed to catch any residual dry film left on the board from the first chamber, ensuring the integrity of the stripping process. The third thirty-gallon chamber contains a water rinse designed to totally rinse the board free of any remaining stripping solution and to ensure the cleanliness of the boards for further processing. The first and second chambers are equipped with 5 kw heaters and controllers.

Modifications: The system is designed as an enlarged basket system to be used with specially-engineered baskets that hold from five to ten boards each. This enhancement enables the stripping of as many as twenty boards at a time as compared to one or two using the conventional method.

Benefits: The new stripper increases MCN's throughput by a factor of eight. Cost per square foot of the new, larger stripper is $1.53, as compared to $3.29 for the previous system. These costs are shown in Figure 16.

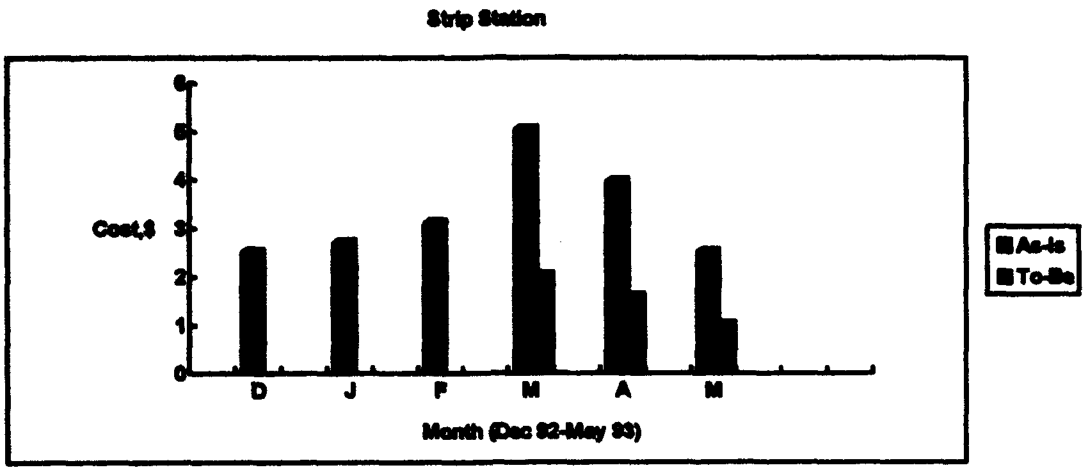

Figure 16: Strip Station Cost Per Square Foot

4.5 Touch Up Station

While a description of the touch up station is not included, it is important to highlight the significant benefits the touch up process received from this proposed environment. The improvements made in the upstream activities greatly increase quality and reduce the need to rework the boards. These benefits are obvious in the following chart. Costs have gone from an average of $6.95 per square foot to $1.48.

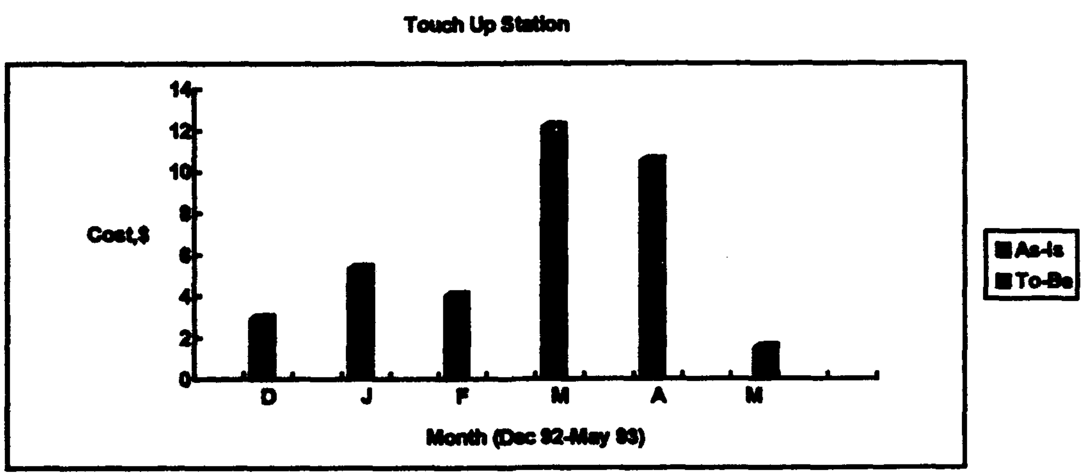

Figure 17: Touch Up Station Cost Per Square Foot

4.6 Environmental Considerations

The workcell was implemented at MCN with full consideration to environmentally conscious manufacturing. Circuit board manufacturing is notorious for generating waste that must be processed. By keeping the waste streams separated and by reusing certain fluids, waste can be minimized. In addition to benefitting the environment, this practice contributes to the company's cash flow since waste disposal is extremely costly.

The SVP-424 Vertical Processor Alkaline Etcher was leased and placed in operation in March of 1993. The four months of operation of the unit and the effect on pollution reduction, processing efficiency, and quality of product are described in this section.

Background: As Tat Choo, an electrical engineer for Morton International, writes, "To image with dry film (as MCN does), PCB manufacturers must safely and legally handle spent developer containing dissolved and chelated metals, chelating agents, high and low molecular weight polymers, and other organics. The increasing popularity of dry-film photoresists focuses greater attention on the disposal options available for treating the heterogeneous mixture of wastes produced by these processes [2]."

We looked at three options:

1) Off-Site Treatment. Shipping waste for treatment or disposal in landfill sites can be inordinately expensive. Even after paying steep shipping and treatment fees, the waste generator remains liable should the treatment agency fail in any way to perform.

2) On-Site Treatment Using Conventional Technology. Although on-site treatment is more economical, the heterogeneous nature of dry-film wastes makes conventional treatments difficult to impossible: Dissolved dry-film polymers physically attach themselves to membranes and ion exchange resins, resulting in costly shutdowns and replacements. Upsets such as floating sludge, poor floc formation, and clogged pipes are commonplace. Acidification processes remove only a portion of dissolved polymers, leaving large amounts of low-molecular weight organics in supernatants and

leading to system upset. During electrowinning, the dissolved film in the developer can make the plated metal spongy and difficult to reclaim.

3. Bleed Organic-Laden Solutions in at the End of the Treatment System, Using the Total Flow to Stay in Compliance. This is a risky process since many organic solutions contain regulated metals in quantities exceeding federal discharge limits.

MCN chose option two, noting the importance of using common-sense goals. According to John MacNeill, a Morton engineer, these goals are as follows:

"1) Practice waste minimization by using fewer products and installing good process control, housekeeping, and recycling programs.

2) Ensure that waste is classified as nonhazardous, which reduces disposal costs. If uncertainty exists about a substance, do not classify it as nonhazardous.

3) Choose the best available technology for treating high-volume organic waste [6]."

Several of these methods are described by Roland Horvath in PC Fab magazine. In particular, MCN looked at electrodialysis, ultrafiltration, and electrowinning.

"1) Electrodialysis. Electrodialysis is a concentration technique. Direct current is applied across a series of alternating anion and cation exchange membranes to remove dissolved metal salts from plating rinse waters. Careful operation and periodic maintenance are required to avoid damaging the expensive membranes.

2) Ultrafiltration. Ultrafiltration technology is similar to reverse osmosis. Dissolved or suspended materials are separated under pressure using a semipermeable membrane. The treated stream can be reused as rinse water, and the recovered concentrate can be waste treated.

3) Electrowinning. This technique recovers metals from a variety of electroplating process solutions. Metal ions in solution are electrolytically reduced and deposited as a metal onto the cell cathode, eliminating or significantly reducing solid waste. Every pound of recovered metal reduces the amount of sludge by several pounds.

Electrowinning ranks high among waste minimization techniques. In contrast with other methods, it can be applied at various points in the electroplating process. These include treatment of spent plating baths, static rinse, and flowing rinse waters. When used with ion exchange, electrowinning forms a closed-loop system by recovering metals from the concentrated metal-bearing solution obtained by regeneration of the ion exchange resin [5]."

Waste-metal ions are the primary source of toxic heavy-metal sludge. Electrowinning efficiently recovers these metals and significantly reduces or eliminates sludge. The process offers MCN a simple waste reduction and recovery method that can be used alone or in combination with other waste treatment processes.

High-Surface-Area cathode electrowinning systems can recover metals from concentrated or dilute solutions. This metal recovery includes copper, nickel, tin, lead, cadmium, zinc, silver, and gold. Solutions typically treated are spent etch baths or metal-bearing solutions from ion exchange systems. Depending on the application, treatment may be single pass or by recirculation. Recirculation is preferred when metal concentration must be reduced to compliance levels.

A 100-gallon plating bath with 20 grams per liter of copper contains nearly seventeen pounds of metal. If not recovered, the waste metal will translate to about 100 pounds of sludge requiring disposal.

Description: The installation of the SVP-424 Vertical Etcher has allowed MCN to remove the ferric chloride etching process from the etching line. This has resulted in a decrease in sludge production associated with the chemical precipitation pretreatment process. Ferric chloride typically results in a large quantity of sludge production.

The removal of the ferric chloride etch will also allow the installation of an ion exchange system for removal of copper associated with the etching process and in conjunction with an electrowinning system, produce recyclable copper. The iron in the ferric chloride etch would have prohibited the use of an ion exchange system.

Additionally, the installation of the SVP-424 Etcher has allowed the removal of our previous alkaline etch system from the etch line. It is currently used for backup. The rinse waters from the new alkaline etch line contain approximately 25 mg/L of copper. The same volume of rinse waters are produced by the two systems, therefore, installation of the vertical etcher has resulted in a decrease of 1600% in waste copper. This estimate does not include the additional removal of the copper which has resulted from the elimination of the ferric chloride etch line.

With the installation of the ion exchange-electrowinning system in September 1993, the copper produced as a result of MCN's etching operations will be recovered for recycling. The etcher is an efficient system that will prolong the life of the resin columns in the ion exchange system, lengthen regeneration time, and result in less chemical usage in the waste treatment process. Additionally, less sludge will be produced by chemical precipitation.

The automatic sensing and feed system of the etcher allows for efficient use of the alkaline etch and should result in less product usage, thereby reducing the production of pollutants associated with the manufacture of alkaline etch. The alkaline etchant can now be shipped back to the manufacturer for re-processing instead of shipping to a waste disposal facility as had been MCN's practice previous to the installation of the etcher.

Benefits: The installation of the etcher has resulted in a ten-fold decrease in process handling time for large boards and a five-fold decrease in process handling time for small boards. Note that the "as-is" process flow involves disjointed moves totalling over one-half mile and introducing potential material mishandling. The "to-be" process cuts this distance to less than 100 yards total. This results from the automatic feed on the system versus hand-feeding and one-at-a-time processing with the old system. In the old process, large boards had to be taped into a special holding rack for processing. The rack had to be cleaned and dried between each board, thereby increasing handling time. Currently, the SVP-424 is not being utilized to its full capacity. As full capacity is approached, it is anticipated that handling efficiency will further increase. The etcher is designed for continuous operation. A discontinuous operation, as described in the Current Environment section, results in additional setup time.

After the installation of the etcher, the quality of the product was comparable to the quality of the old process. This can be attributed to the learning curve in the use of a new piece of equipment. The quality of the product has shown a trend toward improvement (in terms of the amount of scrap) but at this time it is too early to determine the ultimate effect this installation will have on quality.

5. COST-BENEFIT ANALYSIS

No implementation is complete until a cost-benefit analysis is performed, verifying that the improvements do make the company more efficient and the entire operation more economical. A cost-benefit analysis of a selected part has been performed and is included in this section.

The company is actively pursuing a long-term contract to produce a circuit board for the Westinghouse on-board wind shear detection program. This Westinghouse program is critical to MCN's long-term survival since it provides the potential for a steady profit stream.

We chose this part to validate and consolidate the savings discussed in Section Four (Proposed Environment). It is an ideal selection for two reasons: i) it is critical that MCN's cost data be accurate and succinct, and ii) this part is representative of a typical MCN board in terms of features, size, and processing steps.

The part was made using both methods. Figure 18 provides a summary of the results and the savings. Using the conventional (as-is) method, the job processing time was twenty-four hours. Processing time using the proposed (to-be) method was decreased to eight hours. This clearly demonstrates not only the benefit of the system, but also the direct impact on quality of the end product since the systematic processing of the boards enhanced overall quality by eliminating unnecessary touch-ups and manual handling of the boards.

The conventional etcher generated 350-450 parts per million (ppm) of copper at the waste stream lines. Only 16-20 ppm of copper were found at the waste stream after processing with the new etcher. These are summarized in Figure 18. The overall reduction in copper content reduces the amount of sludge produced by the waste treatment system which ultimately is hauled away by a costly licensed waste hauler. The net yearly savings of this reduction is estimated to be $20,000 per year based on this reduction.

MCN has set its hurdle rate at 15%. The hurdle rate, or minimally attractive rate of return (MARR), is the minimum acceptable return of its investment a company will accept. If this rate cannot be met within a set time frame, a company will normally not invest. MCN takes a strategic focus in its investments and strives to break-even within four years. In this project, the company breaks even after approximately 2.7 years, based solely on the Westinghouse part. Many other parts will be processed in this cell and will shorten the break-even period. The following calculations show the break-even period for the Westinghouse part. The total equipment design, purchase, and implementation costs for the cell were $160, 674 (approximately $110,000 for the equipment, $25,000 for site preparation, and the remaining for labor). Cost savings on the Westinghouse part are based on producing 2000 parts per year and reducing processing costs nearly $30 per part.

Cost = $160,674

Savings = $20,000 for waste treatment + $57,020 for Westinghouse part (($160-$131.49)*2000 parts/year)

Total Yearly Savings = $77,020

Break-Even:

Cost = Savings (P/A,i,n)

$160,674 = $77,020 (P/A,15%,n)

n = 2.7 years to break-even

Comparison of As-Is and To-Be Environments for Sample Westinghouse Part

	As-Is	To-Be	Savings
Processing Time	24 hours	8 hours	66%
Waste Stream Copper	350-450 ppm	16-20 ppm	95%

Figure 18: Benefits Achieved on a Sample Part

6. CONCLUSIONS

This project proved to be very successful. The established objective, improving the company's competitive posture in the microwave printed circuit board industry, was exceeded through the implementation of new manufacturing processes. In particular, substantial improvements in product quality and material throughput resulted. Scrap and rework were reduced and material handling was kept to a minimum.

The author began by conducted a thorough assessment of the existing environment. This work included an external analysis of the microwave industry forces and then focused in on company operations as a whole. The specific cleaning, developing, etching, and stripping processes were then evaluated in greater detail. A proposed environment was designed and optimized. Equipment was purchased and installed in the facility and modifications were made to fine-tune the equipment to company specifications. Finally, a cost-benefit analysis was performed to validate the improvements.

Problems were encountered during this effort, but were successfully solved. These problems generated several lessons learned that will be considered in future PRIDE endeavors. An example is the need to actively manage supplier delivery dates. In this case, many delivery problems were encountered. In a Government contract where schedule is closely monitored, this could have been very damaging. In addition, no matter how well an effort is planned, the new system must be optimized through experimentation. The notion that a machine can be hooked up and ready to use upon delivery is incorrect. Time must be allocated for fine-tuning.

We found small companies such as MCN do not have the resources readily available to dedicate an individual full-time to work on projects of this type. An outside facilitator or technical support consultant can assist in maintaining momentum and progress toward implementation. This effort demonstrated the strong potential of the PRIDE program, a program which can assist companies with this facilitation.

This project improved MCN's position in the microwave circuit board industry. The reduced costs and quick turnaround times the company can now offer customers gives MCN a sustainable competitive advantage as both an innovator and a cost leader. Finally, the Air Force will benefit from MCN's increased competitive stature, continued domestic sourcing of microwave circuit boards, and hopefully from the author's gained insight.

REFERENCES

1. Chapman, David. Discussion with Capt Scott Pearl on site at Modular Components National, February 4, 1993.

2. Choo, Tat. "Dry-Film Waste Treatment," *PC Fabrication*, July 1992, p. 25.

3. Gurian, Marshall. "Fine-Line Processing: The Real World," *PC Fabrication*, October 1992, pp. 20-23.

4. Horvath, Roland. "High-Technology and Waste Minimization," *PC Fabrication*, June 1992, pp. 39-40.

5. MacNeill, John. "Dry-Film Waste Treatment," *PC Fabrication*, July 1992, p. 26.

6. Porter, Michael. Competitive Advantage. New York, The Free Press: 1985.

APPENDIX A

AS-IS MODEL OF MCN's
FUNCTIONAL DECOMPOSITION

Compiled by BDM International

As-Is Model: First Level

A0: Conduct MCN Business (100%)

- A1: Administer Company (27.3%)
  - A11: Sell Products (9%)
  - A12: Accomplish Admin Functions (13.6%)
  - A13: Control Financial Activities (3.5%)
- A2: Operate Company (71.6%)
  - A21: Develop New Product Capabilities (5%)
  - A22: Coordinate Operations (1.3%
  - A23: Purchase Goods (16.8%)
  - A24: Manufacture Products (53.6%)
  - A25: Ship Products (2.4%)
  - A26: Manage Facility (2.8%)

As-Is Model: Second Level

- A21: Develop New Product Capability (5%)
  - A211: Identify Needs
  - A212: Identify Available Technologies
  - A213: Identify Constraints
  - A214: Design New Production
  - A215: Build New Production
  - A216: Implement New Capability
- A22: Coord Operations (1.3%)
  - A221: Develop Job Schedules (1.3%)
  - A222: Manage Daily/Shop
- A23: Purchase Goods (16.8%)
- A24: Manufacture Products (53.6%)
  - A241: Engineer Production
  - A242: Coordinate Production (.3%)
  - A243: Manage Quality (5.7%)
  - A244: Fabricate Microwave Circuits (47.6%)

As-Is Model: Second Level (Cont'd)

- A25: Ship Products (2.4%)
  - A251: Receive Finished Component
  - A252: Receive MCN C ertificate of Competency
  - A253: Prepare Components for Ship (.2%)
  - A254: Ship Components (2.2%)
- A26: Manage Facility (2.8%)
  - A261: Manage Security (.6%)
  - A262: Maintain Facility & Equipment (2.2%)
  - A263: Control Pollutants

As-Is Model: Third Level for A244

- A244: Fabricate Microwave Circuits (47.6%)
  - A2441: Machine Components (30.5%)
  - A2442: Photolithograph Components (2.7%)
  - A2443: Etch Components (.9%)
  - A2444: Plate Components (8.9%)
  - A2445: Clean Components (4.5%)
  - A2446: Bond Components (.1%)
  - A2447: Transfer Components

APPENDIX B

MCN COMPANY DESCRIPTION

COMPANY BACKGROUND

Modular Components National (MCN) is a high technology service company which manufactures microwave circuit boards, wave guides, housings, and components for use in defense applications and in commercial telecommunications. The company, located in Forest Hill Maryland, is qualified as both a small and a female-owned business.

Founded in 1981 in Massachusetts by a small group of technically involved entrepreneurs, MCN has grown to be a leader in microwave services in many ways. Its founding concept was to specialize in serving the microwave industry and to incorporate the diverse phases of microwave circuit board fabrication under one roof. The printing and etching of copper circuitry on dielectric materials, the gold, nickel, copper, tin, or tin-lead plating of circuits and housings, the bonding of stripline boards and the drilling, routing, and CNC precision machining of metal-clad circuit boards and housings are all done in-house. Much of MCN's success is due to its ability to closely monitor these operations within its own facility, thus assuring the quality of the total end product. The company also owes its success to its single-minded specialization in microwave services alone and its ability to offer the expertise and technical assistance, as well as state of the art specialized equipment which enables it to lead in manufacturing as the needs of the microwave industry change and grow.

MCN is one of only several companies in the entire United States that is both technically qualified and able to successfully and repeatedly manufacture microwave printed circuit boards on teflon fiberglass dielectric laminates (duroid material) either metal backed or unsupported.

The manufacturing processes used at MCN have been developed as proprietary processes by its qualified and talented technical staff.

MCN has developed a reputation in the industry of being able to meet specific customer needs and requirements that its competitors were unable to fill.

Due to the creative ingenuity of their technical staff, MCN leads the industry in the plated through hole technology on metal backed teflon laminates.

Because of its need to expand in an environment which could better supply a trainable labor force, MCN moved its facility from Massachusetts to Forest Hill, Maryland. Here, expansion has continued at a comfortable rate. The company currently occupies 18,000 square feet. MCN, in a few short years, has become known for its expertise in trouble shooting and solving problems of redesign. Its technical staff, with continuing emphasis on research and development, has implemented many innovative state of the art manufacturing techniques which have provided the company with the drive and ability to move ahead with the fast pace of the microwave industry.

MCN's current capabilities include the following:

- Bonded assemblies/multilayer boards
- Fine line etching of microstrip and strip line boards to +/- .0005 inches
- Full in-house plating capabilities for plating gold, nickel, tin, tin-lead, copper, zincate
- Plated through-hole and plated through-hole on metal clad teflon substrates
- Edge plating and plated slots
- CNC laser profiling
- CNC precision machining
- Complete in-house design and production capabilities for military and commercial quality circuit boards
- Engineering capabilities using CAD/CAM system
- Technical assistance through a newly expanded technical team

MCN has made a strong commitment to serving and delivering quality products to prime military contractors involved in building systems for missile guidance, ECM/EW, radar landing, and communications applications (such as ground-based data or voice transmission, cellular phones, radar, or high speed logic systems for computers and commercial microwave landing systems. The company's dedication was evidenced by the fact that the co-owners and the lead engineer were active participants in implementing the workcell.

Many of MCN's products are used in defense systems, particularly Air Force and Army systems. Currently, 90% of sales are to military contractors or subcontractors.