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# Modifications to Reduce Drag Out at a Printed Circuit Board Manufacturer

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# MODIFICATIONS TO REDUCE DRAG OUT AT A PRINTED CIRCUIT BOARD MANUFACTURER

by

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# FOREWORD

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The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report, "Modifications to Reduce Drag Out at a Printed Circuit Board Manufacturer," discusses evaluation of two low cost, low technology modifications to rinsing operations at a printed circuit board manufacturer. Both modifications reduce waste by reducing drag out of process chemicals from the line. The information contained in this report should be helpful to operators and designers of circuit board lines, and other closely related metal finishing processes, in identifying and implementing waste reduction technologies within their operations.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

# ABSTRACT

The MnTAP/EPA WRITE project at Micom, Inc. demonstrated the waste reducing capability of two simple rinsing modifications on two processes that are typically found within electronic circuit board manufacturing operations. The simple, low (or no) cost, low technology changes that were made were 1) slowing the withdrawal rate of the racks containing the printed circuit boards as they are pulled from concentrated process tanks and 2) combining an intermediate withdrawal rate with a longer drain time over the process tanks before transfer to the rinse tanks. As compared to baseline sampling, both modifications significantly reduced drag out of concentrated copper containing bath solutions into the rinse water systems that followed the bath tanks.

The two processes tested were: an etchant bath and the countercurrent rinsing system following it and an electroless copper plating bath and the countercurrent rinsing system following it. The reduction in drag out for the micro-etch bath was 45% as a result of the first modification and 41% as a result of the second modification. For the electroless bath, drag out was reduced by 50% after the first modification and 52% after the second modification.

By reducing drag out in these amounts, 203 and 189 grams of copper per day were prevented from being discharged as waste in the rinse water waste stream, for modifications 1 and 2 respectively. Because copper concentration in rinse water was reduced, the potential for conserving rinse water flows was also shown, although this was not directly tested. Rinse water flows could be turned down proportionate to the reduction in drag out and still maintain the same rinsing efficiencies.

The economic savings due to these reductions were calculated by considering avoided cost of treatment of the rinse water and avoided charges for water and sewer service. If implemented, the first modification would save the company \$3350  \$2640 savings in treatment costs and \$710 in avoided water and sewer costs. The same figures for implementing the second modification would be \$3120 - \$2460 in treatment costs and \$660 in avoided water and sewer charges. Since no capital costs were incurred in making the changes, payback would be immediate.



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CONTENTS

# INTRODUCTION

The Waste Reduction Innovative Technology Evaluation (WRITE) Program is a national research demonstration program designed to evaluate the use of innovative engineering and scientific technologies to reduce the volume and/or toxicity of wastes produced from the manufacture, processing, and use of toxic materials. The U.S. EPA Office of Research and Development, Risk Reduction Engineering Laboratory, and the Minnesota Technical Assistance Program (MnTAP) entered into a cooperative agreement as part of the "WRITE Pilot Program with State and Local Governments" in July, 1989. Funding of the WRITE program is provided jointly by the EPA and the state and local governments. The joint approach was chosen because state and local government officials are familiar with local industry practices and regional manufacturing interests, and these factors can affect the potential success and widespread applicability of proposed pollution prevention technologies.

## PROGRAM OBJECTIVES

The Minnesota/EPA WRITE program is one of seven such programs nationwide. The program in Minnesota targets the metal finishing industry, specifically rinsing processes within metal finishing operations, as the focus of waste reduction evaluations. The two most effective methods for reducing wastes from these rinsing processes are 1) reducing drag out, the carryover of concentrated solutions from plating baths, and 2) practicing water conservation.

The present report discusses the results of the first project performed under the Minnesota/EPA WRITE program. The project evaluated modifications which reduce drag out at a single plating line within a printed circuit board manufacturing facility. It is hoped that by demonstrating the success of the modification in a fully operational setting, the technology will be transferred to other plating/rinsing systems within the company as well as to other facilities within the metal finishing industry.

## RINSING OPERATIONS AT PLATING FACILITIES

The basic plating operation involves submerging parts in a process solution, then rinsing off the excess film of plating chemicals known as drag out. This rinsing process can waste several pounds per day of expensive plating chemicals which must be removed from the rinse water before rinse waters can be discharged to the sewer to comply with effluent limit requirements. More efficient rinsing operations could reduce the loss of plating chemicals, saving on the material cost and reducing the amount of waste to be managed (Cushnie, 1985).

Rinsing is essentially an operation of dilution; its objective is to dilute the dissolved chemicals on the surface of the work to the point where they are insignificant, not only in their effect on the quality of the work being processed, but also with respect to plating solution contamination in the operation of a plating line over a long period of time. Efficient rinsing is obtained when this objective is accomplished with the minimum use of water (Durney, 1984). Reducing drag out should reduce treatment needs and allow for reductions in the flow of water required for rinsing.

## WRITE COMPANY SELECTION

Solicitation of metal plating companies for participation in the WRITE Program began in early 1989 through newsletter articles, metal finishing association presentations, and direct mailings. Twenty-five companies responded with interest in evaluating source reduction opportunities via rinsing modifications. Work began in mid-August 1989 when site visits were conducted to assess each company's interest and applicability to the project. Companies were evaluated for inclusion in the WRITE Program on the basis of a number of criteria which included potential for pollution prevention, willingness to make modifications, willingness to share information, production variability, and measurable quantity and concentration of contaminant to be reduced.

## WRITE COMPANY DESCRIPTION

Micom Inc. was selected largely because of its willingness to make changes and because of its relatively stable production. Micom is a medium-sized job shop in New Brighton, Minnesota, employing approximately 240 people. The company manufactures printed circuit boards under a number of military and commercial contracts. Annual revenues for 1989 were $17 million. An average production day consists of two eight-hour shifts with a work load of 1,000-1,200 square feet ($ft^2$) of panels.

Micom manufactures double-sided and multilayered printed circuit boards. The average circuit board size is 18 inches by 21 inches with 8000 holes per panel. Printed circuit boards are produced by depositing and etching metal from a fiberglass sheet (board). The steps in this process include: cutting the boards to size, coating the boards with a photosensitive material (resist), developing the resist, drilling holes, deburring, cleaning, etching, plating the inside of the holes (using an electroless plating process), and plating the boards; inspections are performed at many points along the way. Water rinses follow many of these steps. All printed circuit boards at Micom pass through the sensitize line (Figure 1). This line is used to deposit copper onto the inside of the circuit board holes and consists of micro-etch, activator, accelerator, electroless copper and rinse tanks.

The WRITE project tested changes to the operation of the micro-etch bath and the two countercurrent rinses which follow it, and the electroless copper bath and the two countercurrent rinses which follow it. Micom was interested in evaluating modifications to the micro-etch and electroless

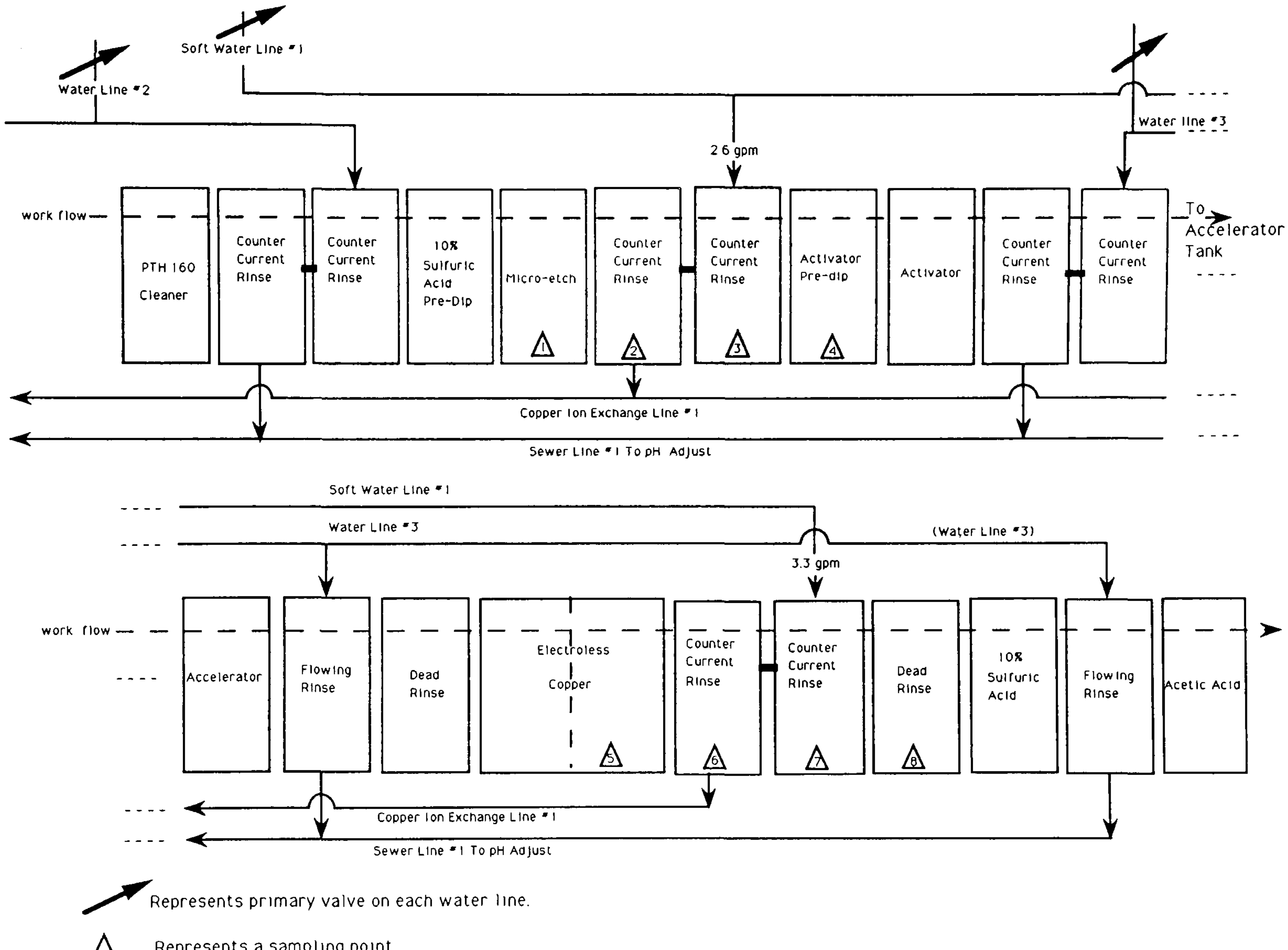


Figure 1. Micom Sensitize Line

copper plating and rinsing processes because these processes are significant contributors of copper to the ion exchange system used to treat metal bearing wastewaters. Softened water at a restricted flow of about 3 gallons per minute makes up the influent to the countercurrent rinses following the micro-etch bath and the electroless copper bath. The copper bearing waste stream from the rinse tanks is piped to an ion exchange system for copper removal and then sewered. The ion exchange canisters are regenerated off site.

The printed circuit boards enter the sensitive line in racks which hold 24 boards each. The boards vary in size with the largest being 18 inches by 24 inches. The racks are 34 inches by 19.5 inches wide by 13 inches deep and are transported by a hoist from tank to tank. The operator controls the hoist and allows the rack to drain 3-5 seconds before proceeding to the next tank. The approximate residence time is 75 seconds in the micro-etch bath, 30 minutes in the electroless copper bath, and 2 to 3 minutes in each rinse bath.

The electroless copper plating process is the rate determining step for production throughput. The plating tank holds two racks of printed circuit boards which remain in the bath for 30 minutes each. In order to maximize production, each pair of racks are started in the line at approximately 30 minute intervals. This allows the electroless copper bath to remain in use and minimizes the delay between plating each rack.

## TECHNOLOGY DESCRIPTION: DRAG OUT REDUCTION

### BENEFITS OF REDUCING DRAG OUT

The micro-etch process prepares the printed circuit board for plating by removing oxidized copper from its surface. Reducing the drag out from the micro-etch process solution will also reduce the amount of water required for rinsing and reduce the operating costs of the ion exchange wastewater treatment system. However, the micro-etch process solution may require more frequent replacement due to the additional buildup of copper which was previously removed by drag out.

Reducing the copper drag out from the electroless copper plating solution results in three possible benefits. If copper in the rinse water is reduced by capturing the process solution before rinsing, raw material costs may be reduced, since the need for chemical additions could be reduced by returning process solution to the bath. Treatment costs may also be reduced, especially where relatively expensive treatment is used to remove copper from the rinse waters. In addition, reducing copper discharge by capturing process solution can reduce the amount of water needed for rinsing, since less process solution requiring dilution (rinsing) will be present.

Disposal of spent micro-etch and electroless baths included copper recovery in both cases and regeneration of etchant in the case of the micro-etch solution. When the micro-etch bath had to be removed from the line and replaced with fresh bath it was company practice to reclaim copper from the bath as copper sulfate and reuse it in another copper plating solution on site. The etchant was regenerated and also used on site for less critical operations such as stripping copper from carrier racks. The company also recovered copper from the spent electroless copper bath, although the copper was sent off site for reuse. Thus, copper-containing bath solution retained in the process baths due to implementing drag out reduction changes would ultimately be subjected to the company's recovery operations.

### MODIFICATIONS FOR MICOM

At Micom, the criteria for selecting implementable rinsing process modifications included: availability of equipment, impact of a modification on process solutions, maintaining product quality, and effect on production throughput. Production objectives (quality and throughput) were paramount, as might be expected.

Before the WRITE Program's involvement with Micom, the company had already made modifications which reduced rinse water requirements including the installation of countercurrent rinses, water flow restrictors, softened water, air agitation and mechanical agitation. Countercurrent rinses had been installed following the micro-etch and electroless copper process baths, and water flow restrictors on rinse tank inlets maintained an approximate flow of 3 gallons per minute (gpm). Softened water was used in the copper bearing rinses to improve rinsing and the efficiency of the ion exchange system. The filled racks were mechanically agitated in each tank to force solution through the circuit board holes, and some rinses were air agitated to increase the dilution of the drag out by mixing the rinse.

The first modification that was evaluated at Micom was slowing the rate of withdrawal of the racks from the process solution tanks. This was accomplished by lowering the speed of the motor on the mechanical hoist used for raising, lowering and transporting racks of circuit boards. The slower rate of withdrawal allows the process solution viscosity to aid solution removal by pulling the solution from boards like a squeegee. The total drain time is also increased as the boards are being withdrawn more slowly, thereby allowing the part to drain longer.

The effects of reducing the drag out on process solutions is an important consideration. The micro-etch bath removes copper from the printed circuit boards and continually builds up copper in the solution until it no longer is able to remove copper. At this point, the bath is replaced with new solution. For an etchant bath, retaining solution which was formerly lost to drag out could mean the etchant bath must be replaced more often due to the increased build-up of copper. However, managing the concentrated waste stream which results from bath replacement is preferable to managing diluted rinse waters because opportunities for metals recovery are improved if the wastestream is concentrated. As previously discussed, at Micom, spent concentrated micro-etch and electroless bath solutions were subjected to on-site copper recovery processes, and for the micro-etch bath, an etchant recovery process. Another advantage of reducing drag out to rinse water is that rinse water can be reduced proportionate to drag out reduction, thereby requiring less treatment chemicals and reducing sludge generation at on-site wastewater treatment systems.

Retaining electroless plating solution which was formerly lost to drag out could increase the life of the plating bath. Since fewer plating chemicals are lost to drag out of solution, fewer chemical additions will be required to maintain the chemical composition of the bath. However, a filtration step may have to be added to remove impurities which were previously removed by drag out. Drag out reduction from preceding tanks could also lower the amount of impurities carried into the plating bath.

The second modification evaluated was increasing the drain time over the process bath before transferring the racks into the rinse tanks. This was accomplished by having the line operator wait longer (10 seconds for this evaluation) before moving the draining rack to the rinse. The baseline withdrawal rate was not reproduced for the second modification due to the installation of a new air hoist, which could not be adjusted to exactly the same withdrawal rate as the original hoist. This resulted in a withdrawal rate that was slower than the baseline and faster than the first modification This rate will be referred to as the "intermediate" withdrawal rate. The combination of increased drain times and the intermediate withdrawal rate allow solutions to drip back into the process tank, thus reducing the drag out.

## SAMPLING AND ANALYSIS

To evaluate the modifications of the rinsing process, MnTAP established a baseline for process solution drag out, rinse water use, rate of rack withdrawal, and drain time for the Micom sensitize line. To measure the drag out of solution from the process tank, the incoming softened water flow to the rinse tanks was temporarily shut off. To account for copper already present in the rinse tanks (Figure 1), samples were taken before and after a known quantity of printed circuit boards were rinsed (one or two racks of 24 boards). The total copper concentration in the samples was analytically determined by atomic absorption. The change in copper concentration was calculated by subtracting the initial (before rinsing) concentration of copper in each rinse from the final (after rinsing) concentration. The process tank was sampled immediately after a rack of boards was removed. The surface area of the printed circuit boards rinsed during the sample period was calculated to enable a comparison based on square footage of production. The additional mass of copper in the rinses is equal to the change in copper concentration in the rinses multiplied by the volume of each rinse. The drag out was calculated, as shown below, by dividing the total amount of copper in the rinses by the concentration of the process solution and then normalizing the result by dividing by the surface area of the boards processed. (Quality Assurance Project Plan, Section III, page 7, 1990)

$$\text{Drag out } (\text{ml/ft}^2) = \frac{\text{(change in copper concentration in rinses) mg/L} \times \text{(volume of rinses) ml}}{\text{(copper concentration in process solution) mg/L} \times \text{(surface area of boards) ft}^2}$$

The tank following the countercurrent rinses was sampled to check the amount of copper build-up. This was monitored during the baseline period to indicate the effectiveness of these rinses. This measurement provides a standard to use while comparing rinse water reduction modifications.

The water flow rate was calculated by measuring the time it took to fill a five gallon container from the rinse tank discharge. The rinse water flow rate is expressed in gallons per minute. The withdrawal time was determined by measuring the time it took to lift a rack of boards from the process bath to the height needed to clear the wall of the tank (A to B in Figure 2). The withdrawal height was 34 inches. The average withdrawal rate was determined by dividing the height by the average withdrawal time.

$$\text{Withdrawal Rate (ft/min)} = \frac{\text{withdrawal height}}{\text{average withdrawal time}}$$

The drain time was determined by measuring the time after the rack was withdrawn until the rack was halfway over the next tank (B to C in Figure 3). The total time is the sum of the withdrawal time and the drain time (A to C in Figures 2 & 3).

## BASELINE SAMPLING

The baseline samples were collected from March 12-23, 1990. The micro-etch bath and rinses were sampled before and after a single rack of printed circuit boards were rinsed. The electroless copper plating bath and rinses were sampled before and after each pair of racks were rinsed. One hundred thirty-six samples were analyzed to determine the volume of drag out from the micro-etch and the electroless copper baths for twelve pairs of racks over a two week period. The withdrawal time and total drain time were measured for each rack transfer. The withdrawal rate was calculated from the average withdrawal time. The flow rates of the rinses following the micro-etch and electroless copper baths were monitored twelve times over two days. The surface area of the boards in each rack was calculated from measurements of the boards.

## FIRST MODIFICATION SAMPLING

The first modification, slowing the rate of withdrawal, was tested on November 15, 1990. One hundred thirty-six (136) samples were analyzed in order to determine the volume of drag out from the micro-etch and the electroless copper baths for twelve pairs of racks over a one day period. The withdrawal time and total drain time were measured for each rack transfer. The flow rates of the rinses were not sampled due to the water being turned off to determine the drag out. The surface area of the boards in each rack was calculated from measurements of the boards.

## SECOND MODIFICATION SAMPLING

The second modification, increasing the drain time with an intermediate withdrawal rate, was tested on December 10 and 11, 1990. One hundred and nine samples (109) were analyzed in order to calculate the volume of drag out from the micro-etch and the electroless copper baths for nine pairs of racks over a two day period. The withdrawal time and total drain time were measured for each rack transfer. During chemical sampling of the rinse tanks, rinse water was turned off; flow rates were measured after the rinse waters had been turned back on. The surface area of the boards in each rack was calculated from measurements of the boards.

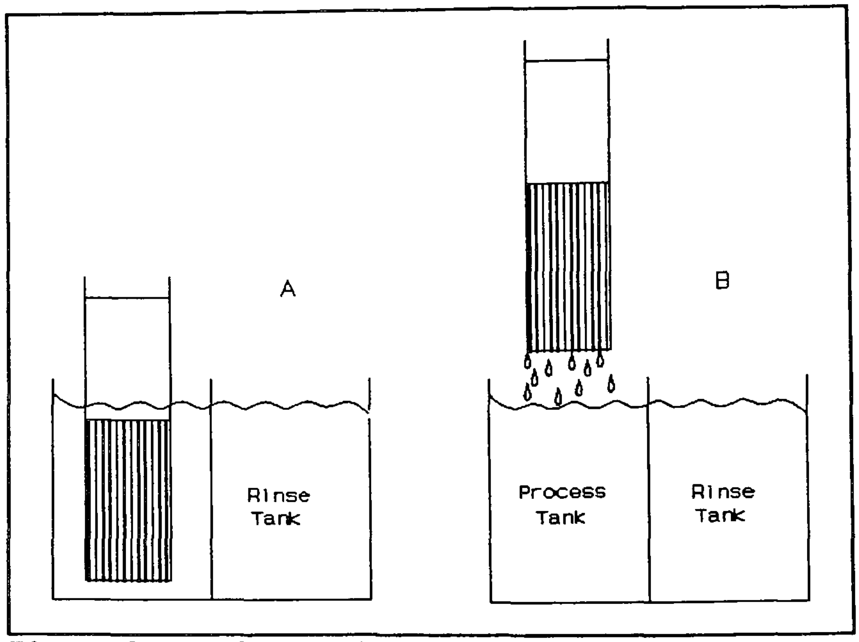


**Figure 2.** Rack Positions Used in Determining Withdrawal Rate

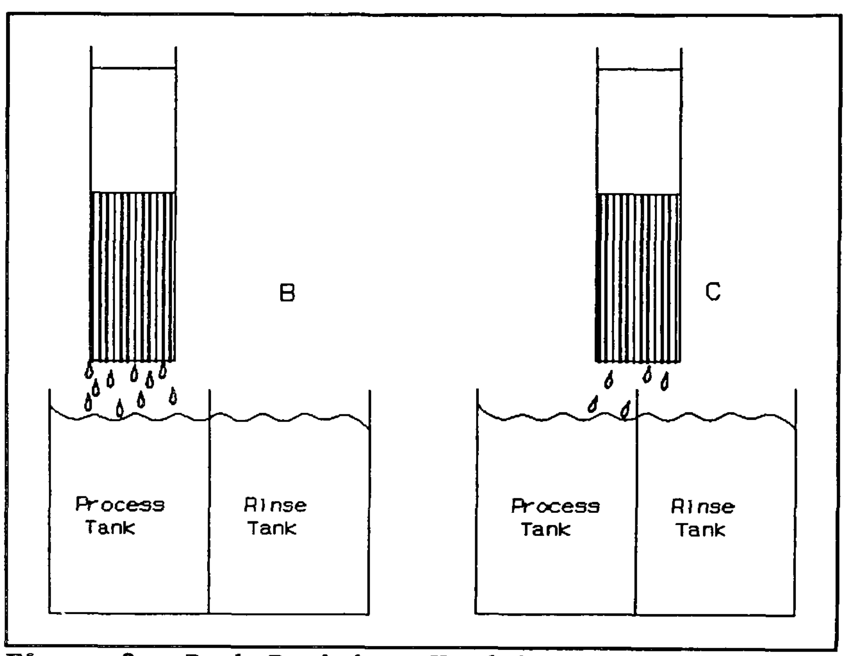


**Figure 3.** Rack Positions Used in Determining Drain Time

## RESULTS

The calculated amount of drag out during the baseline evaluation was 12.1 $ml/ft^2$ from the micro-etch bath and 6.0 $ml/ft^2$ from the electroless copper bath. Racks of printed circuit boards were withdrawn from the tanks very quickly, usually taking less than two seconds. The average drain time for racks being removed from the electroless copper bath was longer than those removed from the micro-etch bath because of an additional distance some racks travel while still draining over the wider electroless copper tank. The results of the baseline evaluation are summarized in Tables 1 & 2.

TABLE 1. RESULTS OF BASELINE MICRO-ETCH EVALUATION

| | Average | Range | | n | Std. Dev. |
|---|---|---|---|---|---|
| | | Low | High | | |
| Drag out ($ml/ft^2$) | 12.1 | 9.3 | 14.5 | 12 | 1.5 |
| Withdrawal Time (seconds) | 1.7 | 1.0 | 3.2 | 12 | 0.8 |
| Withdrawal Rate (ft/min) | 100 | - | | - | - |
| Drain Time (seconds) | 3.4 | 1.2 | 7.6 | 12 | 2.1 |
| Total Time (seconds) | 5.1 | 2.3 | 8.9 | 12 | 2.3 |
| Surface Area/Rack ($ft^2$) | 88 | 48 | 126 | 12 | 24 |
| Water Flow Rate (GPM) | 2.6 | 2.5 | 2.7 | 6 | 0.04 |

TABLE 2. RESULTS OF BASELINE ELECTROLESS COPPER EVALUATION

| | Average | Range | | n | Std. Dev. |
|---|---|---|---|---|---|
| | | Low | High | | |
| Drag out (ml/ft$^2$) | 6.0 | 4.7 | 7.6 | 12 | 1.1 |
| Withdrawal Time (seconds) | 1.8 | 1.0 | 3.2 | 23 | 1.6 |
| Withdrawal Rate (ft/min) | 94 | - | | - | - |
| Drain Time (seconds) | 5.2 | 0.8 | 10.2 | 23 | 2.6 |
| Total Time (seconds) | 7.0 | 1.3 | 11.4 | 23 | 3.1 |
| Surface Area/Rack (ft$^2$) | 169 | 124 | 234 | 12 | 33 |
| Water Flow Rate (GPM) | 3.3 | 3.2 | 3.3 | 6 | 0.05 |

The calculated amount of drag out during the evaluation of the first modification was 6.7 ml/ft$^2$ from the micro-etch bath and 3.0 ml/ft$^2$ from the electroless copper bath. Racks of printed circuit boards were withdrawn from the tanks slowly, taking from thirteen to sixteen seconds. The results of the first modification evaluation are summarized in Tables 3 & 4.

TABLE 3. RESULTS OF MODIFICATION 1 MICRO-ETCH EVALUATION - SLOWED RATE OF WITHDRAWAL

| | Average | Range | | n | Std. Dev. |
|---|---|---|---|---|---|
| | | Low | High | | |
| Drag out (ml/ft$^2$) | 6.7 | 5.2 | 9.7 | 12 | 1.3 |
| Withdrawal Time (seconds) | 14.9 | 13.6 | 16.0 | 11 | 0.7 |
| Withdrawal Rate (ft/min) | 11 | | | - | - |
| Drain Time (seconds) | 2.5 | 1.4 | 4.6 | 11 | 0.9 |
| Total Time (seconds) | 17.4 | 15.5 | 19.4 | 11 | 1.1 |
| Surface Area/Rack (ft$^2$) | 83 | 56 | 114 | 12 | 14 |

TABLE 4. RESULTS OF MODIFICATION 1 ELECTROLESS COPPER EVALUATION SLOWED RATE OF WITHDRAWAL

| | Average | Range | | n | Std. Dev. |
|---|---|---|---|---|---|
| | | Low | High | | |
| Drag out ($ml/ft^2$) | 3.0 | 2.1 | 3.4 | 12 | 0.4 |
| Withdrawal Time (seconds) | 13.9 | 13.1 | 15.4 | 23 | 0.7 |
| Withdrawal Rate (ft/min) | 12 | - | - | - | |
| Drain Time (seconds) | 3.2 | 1.1 | 8.7 | 23 | 2.1 |
| Total Time (seconds) | 17.1 | 14.4 | 23.0 | 23 | 2.3 |
| Surface Area/Rack ($ft^2$) | 162 | 104 | 220 | 12 | 32 |

The calculated amount of drag out during the evaluation of the second modification was 7.1 $ml/ft^2$ from the micro etch bath and 2.9 $ml/ft^2$ from the electroless copper bath. Racks of printed circuit boards were withdrawn from the tanks slightly faster than the baseline but much slower than the first modification, taking from two to five seconds. The results of the second modification evaluation are summarized in Tables 5 & 6.

TABLE 5. RESULTS OF MODIFICATION 2 MICRO-ETCH EVALUATION LONGER DRAIN TIME WITH INTERMEDIATE WITHDRAWAL RATE

| | Average | Range | | n | Std. Dev. |
|---|---|---|---|---|---|
| | | Low | High | | |
| Drag out ($ml/ft^2$) | 7.1 | 5.5 | 8.2 | 12 | 0.9 |
| Withdrawal Time (seconds) | 4.3 | 2.1 | 5.6 | 10 | 0.9 |
| Withdrawal Rate (ft/min) | 40 | - | - | - | |
| Drain Time (seconds) | 12.1 | 11.2 | 13.7 | 10 | 0.9 |
| Total Time (seconds) | 16.4 | 13.7 | 18.0 | 10 | 1.3 |
| Surface Area/Rack ($ft^2$) | 92 | 60 | 119 | 10 | 17 |

TABLE 6. RESULTS OF MODIFICATION 2 ELECTROLESS COPPER EVALUATION LONGER DRAIN TIME WITH INTERMEDIATE WITHDRAWAL RATE

| | Average | Range | | n | Std. Dev. |
|---|---|---|---|---|---|
| | | Low | High | | |
| Drag out ($ml/ft^2$) | 2.9 | 1.9 | 3.7 | 12 | 0.5 |
| Withdrawal Time (seconds) | 4.3 | 3.5 | 4.9 | 19 | 0.4 |
| Withdrawal Rate (ft/min) | 40 | - | - | - | - |
| Drain Time (seconds) | 11.9 | 11.1 | 16.4 | 19 | 1.2 |
| Total Time (seconds) | 16.3 | 15.0 | 20.5 | 19 | 1.2 |
| Surface Area/Rack ($ft^2$) | 175 | 60 | 228 | 10 | 49 |

## DIFFERENCES IN DRAG OUT DUE TO RINSING MODIFICATIONS

Slowing the rate of withdrawal (modification 1) lowered the drag out from the micro-etch solution from the baseline drag out of 12.1 $ml/ft^2$ to 6.7 $ml/ft^2$, while extending the drain time combined with an intermediate withdrawal rate (modification 2) yielded a similar drag out of 7.1 $ml/ft^2$. The drag out from the electroless copper plating bath was reduced from 6.0 $ml/ft^2$ to 3.0 $ml/ft^2$ when the withdrawal rate was slowed and reduced to 2.9 $ml/ft^2$ after the drain time was lengthened using an intermediate withdrawal rate.

These lower drag out volumes represent a 45 percent reduction for modification 1 and 41 percent reduction for modification 2 from the micro-etch; for the elecroless copper, modification 1 resulted in a 50 percent reduction, while modification 2 resulted in a 52 percent reduction in drag out. The differences in drag out are summarized in Table 7 and Table 8.

Comparisons of the baseline to each modification using statistical analysis confirm significant reduction at an $\alpha$ error level less than 0.005. This yields a confidence level greater than 99.5% when each modification is compared to the baseline. The evaluation indicates a significant reduction in drag out when the withdrawal rate is slowed or the drain time is increased with an intermediate withdrawal rate. A statistical analysis to determine the significance of the difference between modifications 1 and 2 was not performed.

The reduction in drag out from the first modification was equivalent to preventing 194 grams of copper from the micro-etch bath and 9 grams of copper from the electroless bath per day from entering the rinse water waste stream, for a total of 203 grams/day. The figures for the second modification

TABLE 7. SUMMARY OF MICRO-ETCH RESULTS

| | Withdrawal Rate (ft/min) | Time Withdrawal (seconds) | Drain Time (seconds) | Total Time (seconds) | Dragout ($ml/ft^2$) |
|---|---|---|---|---|---|
| BASELINE | 100 | 1.7 | 3.4 | 5.1 | 12.1 |
| MODIFICATION 1 slower rate of withdrawal | 11 | 14.9 | 2.5 | 17.4 | 6.7 |
| MODIFICATION 2 longer drain time with intermediate withdrawal rate | 40 | 4.3 | 12.1 | 16.4 | 7.1 |

TABLE 8. SUMMARY OF ELECTROLESS COPPER RESULTS

| | Withdrawal Rate (ft/min) | Time Withdrawal (seconds) | Drain Time (seconds) | Total Time (seconds) | Dragout ($ml/ft^2$) |
|---|---|---|---|---|---|
| BASELINE | 94 | 1.8 | 5.2 | 7.0 | 6.0 |
| MODIFICATION 1 slower rate of withdrawal | 12 | 13.9 | 3.2 | 17.1 | 3.0 |
| MODIFICATION 2 longer drain time with intermediate withdrawal rate | 40 | 4.3 | 11.9 | 16.3 | 2.9 |

are 180 grams prevented from leaving the micro-etch bath and 9 grams, for a total of 189 grams/day, prevented from leaving the electroless bath. These figures assumed a copper concentration of 30 grams/liter in the micro-etch bath and 2.4 grams/liter in the electroless bath and a production level of 1200 $ft^2$ of printed circuit board per day.

Because copper concentration in rinse water was reduced, the potential for conserving rinse water flows was also shown, although this was not directly tested. Rinse water flows could be turned down proportionate to the reduction in drag out and still maintain the same rinsing efficiencies.

## QUALITY ASSURANCE PROJECT PLAN RESULTS

Sampling procedures were followed according to the Quality Assurance Project Plan (QAPjP). The baseline sampling was performed over a two week period, the first modification was tested and sampled over a two shift period, and the second modification was sampled over a two day period. A wide variety of printed circuit boards were being manufactured during each of the sampling periods. Although the boards were not identical in each case, they were representative of the work at Micom.

To assure compliance with the QAPjP, field audits were conducted by Barb Loida, MnTAP engineer. The auditor reviewed the field activities at Micom such as sample collection, chain of custody, and sample information.

Analytical methods were followed according to the approved QAPjP by PACE Laboratories, Inc., with the exception of the electroless copper plating bath samples. These samples, when preserved with nitric acid according to instructions from the laboratory, precipitated out the copper as the solution cooled. The analytical procedure was modified to include preservation with a hydrochloric/nitric acid mixture, digestion of the sample, and analysis for total copper.

The analytical results for the electroless copper bath samples for the baseline evaluation averaged 1600 mg/l and one sample was lost due to a laboratory accident during the digestion process. Despite additional validation of the procedure, the results from the samples taken during the first modification period averaged only 1800 mg/l with one sample as low as 900 mg/l. The samples during the second modification averaged 2200 mg/l after the laboratory recalculated the results to account for the 30 ml of acid that had been added to each sample per the modified analytical procedure.

These results do not compare well with the electroless copper bath operating concentrations according to Micom's laboratory analysis and line operating procedures. It should also be pointed out that an electroless copper plating solution will not plate at such low copper concentrations. This led to the decision to accept an average bath copper concentration of 2400 mg/L as determined by Micom process control charts and results from the Micom laboratory. The control charts show an operating range of ± 100 mg/L of copper; additions are automatically pumped into the plating bath as required.

This average of 2400 mg/L was used in place of analytical results for the electroless copper solution only, and was used for baseline, modification 1, and modification 2 evaluation calculations.

Although the reason for the poor analytical results for the electroless copper samples is not clear, several possibilities include: improper acidification, plate out of sample on container walls, sample not maintained at bath temperature of 103 F, or the results may not have been adjusted to account for the addition of acid.

Quality control samples were analyzed for copper. Field blank, precision - relative percent difference (RPD), and percent recovery - matrix spike/matrix spike duplicates (MS/MSDs) were analyzed. Copper was not detectable at the method detection limit in the field blanks. All of the RPDs between duplicates were less than the 20 percent QC target range. All of the percent recoveries were within the 75 to 125 percent recovery target range.

## DISCUSSION

### TECHNICAL EVALUATION

Although possible, the ability to slow the mechanical hoist's rate of withdrawal is complicated by a few items. The mechanical hoist at Micom is capable of a slower vertical rate, but this not only slows the rate of withdrawal but also slows the rate of insertion. The slower overall rate therefore demands more of the hoist's operating time, making it difficult to move the hoist to the opposite end of the line in time to transfer another rack, thus slowing production. The maximum horizontal speed of 40 feet per minute is not fast enough to allow travel from one end to the other and still maintain current production levels. The mechanical hoist was also prone to breakdown, requiring repair.

The extended drain time was tested by manually signaling the rack transfer after a ten second drain time over the copper bearing process solutions. The line operator could implement this by counting to ten slowly before transferring the rack.

### ECONOMIC ANALYSIS

An economic evaluation showed that the company could save $2640 per year in rinse water treatment and disposal costs by implementing modification 1 or $2460 per year by implementing modification 2. Rinse water was treated using on-site ion exchange cannisters which had a capacity of 46 pounds of copper before requiring off-site regeneration at a cost of $1096 per cannister. Savings were calculated using the following formula:

$$\text{Savings} = \frac{(\text{amount of copper prevented})\ (\text{cost of canister})}{\text{capacity of ion exchange canister}}$$

The savings do not take into account the time required to change the peed of the hoist or train the operators to extend the drain time. The additional time required to withdraw or drain the racks could be offset by shortening some rinsing and/or holding times or by reducing the spacing between production runs. One production run consists of a pair of racks which enter the electroless copper bath at approximately the same time. Filled racks are often held in rinse tanks or placed at the loading area before entering the sensitize line. The electroless copper plating process is the rate determining step and a production run remains in this bath for 30 minutes before being rinsed.

## IMPLEMENTATION

For a number of site specific reasons the company decided to implement a longer drain time to reduce drag out instead of altering the withdrawal rate. As discussed above, the programmable mechanical hoist used for modification 1 at Micom was unreliable and often broke down. Another problem with the mechanical hoist at Micom was its inflexibility in programming. To slow the withdrawal rate for modification 1 the vertical speed had to be adjusted, thus slowing not only the withdrawal rates but also the insertion rates; these rates were slowed for insertion and withdrawal into all tanks on the sensitize line, not just the micro-etch and the electroless tanks. In order to maintain production rates at previous levels, operators supplemented the mechanical hoist with an air-assisted hoist.

As a result of recurrent break downs of the mechanical hoist and the inability to specifically target and program slower withdrawal rates for the two bath tanks, the company took the mechanical hoist out of service. Air-assisted hoists were used as replacements. With this type operation it made more sense for the company to implement a longer drain time to achieve drag out reduction. The company believed that it would be easier to train operators to increase the drain time over the two tanks rather than have them slow withdrawal rates.

For modification 2 the additional time added to the sensitize line to allow the intermediate withdrawal rate and longer drain time as compared to baseline was 21 seconds. This amount was negligible when compared to the 60 minute total production time through the sensitize line. Minor modifications to the operation of the line could offset the added time so that the baseline production rate could be maintained. At Micom, filled racks were often held beyond the necessary times in rinse tanks while processing in the sensitize line or placed at the loading area before entering the line. Changes such as shortening the timing between rack starts and/or reducing holding times in rinse tanks that were known to be more than adequate could makeup for the added 21 seconds.

## FUTURE MODIFICATIONS

Once drag out reduction has been optimized, less water would be required to maintain the cleanliness of the rinses. Using less water will decrease water and sewer charges, which is especially important at Micom where incoming water must be softened before use on the sensitize line. Decreased rinse water volumes may reduce treatment costs by making the ion exchange system at Micom more effective at removing copper from rinse water and by reducing the amount of water which must pass through the resin beds.

Water use can be reduced proportionately with contaminant reduction. An additional savings of $710 per year for modification 1, or $660 for modification 2, could be realized in avoided water and sewer charges if the company reduced rinse water flow rates proportional to the reduced copper contamination of the rinse water that would result from implementing the drag out reducing modifications tested. Less water would also need to be softened, but lower costs would not be evident as water softening is billed as a monthly fee independent of water use. This fee may also be reduced through negotiations with the water softening company.

MnTAP intended to maintain or improve the current rinsing effectiveness. This was monitored during the baseline by checking the amount of copper build-up in the non-flowing tank which follows the countercurrent rinses. Copper buildup in tank 4, Figure 1, ranged between zero and 12 mg/l over eight hours while copper buildup in tank 8 ranged between 0.01 and 0.08 mg/l. This monitoring was not continued during the modifications as the rinse water was turned off for a considerable amount of time during the drag out evaluations. These rinses should be monitored when the rinse water flow rates are reduced. The buildup of copper in these tanks can be a good monitor of the quality of the rinsing when it is compared to a baseline.

## TRANSFERRING PROJECT RESULTS

For the Micom project, not only is the work centered on one process line, but also further narrowed to concentrate on two process steps within that line, the micro-etch and the electroless copper plating solution. The reason for the narrow focus was first a matter of available budget for performing the evaluation, since a limited amount of time and money is available to perform the necessary sampling, analysis and data reduction for such an evaluation. Another reason is that these two processes are the most concentrated copper sources on the process line. The focus is also part of a larger philosophy, one which MnTAP calls "planting seeds." The hope is that if rinsing process modifications are demonstrated to be successful in one location in a plating operation, plant management will be more likely to attempt similar modifications on other process lines. Rather than attempting plant-wide modifications, or changes applied to large, aggregated waste streams, a staged approach is not only more manageable, but may improve accuracy of cost and product quality assessments.

## RECOMMENDATIONS

Besides the two objectives of reducing copper discharge and water use, in the future MnTAP plans to develop and test a procedure for evaluating and modifying rinsing processes which will be transferable to and useful to other operations. This procedure would address such imperatives as protecting product quality while modifying the production process, evaluating the impact of modifications on production throughput, and providing a "rule-of-thumb" for such decisions as number of samples required for evaluation. This procedure will be an important product of the project. By evaluating various rinsing modifications at additional companies and additional process lines, MnTAP intends to collect the information necessary for companies to attempt a modification to their rinsing practices.

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The Minnesota Technical Assistance Program (MnTAP) was created in 1984 with support from the Minnesota Office of Waste Management (OWM). MnTAP is located at the University of Minnesota and is a non-regulatory program designed to help Minnesota business and industry prevent pollution at its source and properly manage industrial wastes. These services include: telephone assistance, on-site visits, student interns, and an information clearinghouse.

# APPENDIX

## Raw Data and Calculated Drag Out Values

Laboratory Data and Calculations for Baseline - March 12 - 23, 1990

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | | 33800 | | | | | |
| 03/12/90 | 14:00 | 9 | 24 | 56.0 | 2 | 160 | 250 | 90 | 21483 | 895 | 384 | 11.3 |
| | | 10 | 21 | 71.2 | 3 | 4.8 | 7 | 2.2 | | | | |
| | | 9 & 10 | 45 | 127.2 | 4 | 38 | 44 | 6 | | | | |
| | | | | | 5 | | 240 | | | | | |
| | | | | | 6 | 3 | 9.1 | 6.1 | 1450 | 32 | 11 | 4.7 |
| | | | | | 7 | 0.07 | 0.14 | 0.07 | | | | |
| | | | | | 8 | 0.05 | 0.11 | 0.06 | | | | |
| | | | | | 1 | | 33700 | | | | | |
| 03/13/90 | 13:00 | 1 | 24 | 48.0 | 2 | 0.63 | 68 | 67.37 | 15821 | 659 | 330 | 9.8 |
| | | 2 | 24 | 76.0 | 3 | 0.03 | 0.56 | 0.53 | | | | |
| | | 1 & 2 | 48 | 124 | 4 | | | | | | | |
| | | | | | 5 | | 250 | | | | | |
| | | | | | 6 | 2.2 | 8.4 | 6.2 | 1476 | 31 | 12 | 5.0 |
| | | | | | 7 | 0.02 | 0.1 | 0.08 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 31400 | | | | | |
| 03/13/90 | 16:30 | 8 | 24 | 108.5 | 2 | 9 | 205 | 196 | 46048 | 1919 | 424 | 13.5 |
| | | 9 | 20 | 32.4 | 3 | 0.07 | 1.7 | 1.63 | | | | |
| | | 8 & 9 | 44 | 140.9 | 4 | 54 | 62 | 8 | | | | |
| | | | | | 5 | | 380 | | | | | |
| | | | | | 6 | 0.17 | 11 | 10.83 | 2566 | 58 | 18 | 7.6 |
| | | | | | 7 | 0.07 | 0.16 | 0.09 | | | | |
| | | | | | 8 | 0.1 | 0.12 | 0.02 | | | | |
| | | | | | 1 | | 30600 | | | | | |
| 03/14/90 | 16:00 | 11 | 24 | 84.0 | 2 | 240 | 370 | 130 | 30768 | 1282 | 366 | 12.0 |
| | | 10 | 24 | 89.0 | 3 | 2.5 | 4.55 | 2.05 | | | | |
| | | 10 & 11 | 48 | 173 | 4 | | | | | | | |
| | | | | | 5 | | 2200 | | | | | |
| | | | | | 6 | 8 | 18 | 10 | 2373 | 49 | 14 | 5.7 |
| | | | | | 7 | 0.26 | 0.36 | 0.1 | | | | |
| | | | | | 8 | | | | | | | |

Baseline

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | | 29000 | | | | | |
| 03/14/90 | 16:30 | 12 | 24 | 88.5 | 2 | 220 | 355 | 135 | 31944 | 1331 | 361 | 12.4 |
| | | 13 | 24 | 84.0 | 3 | 2.7 | 4.8 | 2.1 | | | | |
| | | 12 & 13 | 48 | 172.5 | 4 | 70 | 79 | 9 | | | | |
| | | | | | 5 | | 2400 | | | | | |
| | | | | | 6 | 8.3 | 17 | 8.7 | 2086 | 43 | 12 | 5.0 |
| | | | | | 7 | 0.19 | 0.37 | 0.18 | | | | |
| | | | | | 8 | 0.08 | 0.15 | 0.07 | | | | |
| | | | | | 1 | | 38500 | | | | | |
| 03/15/90 | 13:00 | 6 | 24 | 86.0 | 2 | 440 | 570 | 130 | 30756 | 1282 | 358 | 9.3 |
| | | 5 | 24 | 96.0 | 3 | 7.4 | 9.4 | 2 | | | | |
| | | 5 & 6 | 48 | 182 | 4 | 86 | 88 | 2 | | | | |
| | | | | | 5 | | 2100 | | | | | |
| | | | | | 6 | 7.8 | 17 | 9.2 | 2197 | 46 | 12 | 5.0 |
| | | | | | 7 | 0.06 | 0.21 | 0.15 | | | | |
| | | | | | 8 | 0.07 | 0.14 | 0.07 | | | | |
| | | | | | 1 | | 31400 | | | | | |
| 03/16/90 | 16:00 | 12 | 24 | 126.0 | 2 | 1 | 200 | 199 | 46712 | 1946 | 371 | 11.8 |
| | | 13 | 25 | 107.5 | 3 | 0.02 | 1.5 | 1.48 | | | | |
| | | 12 & 13 | 49 | 233.5 | 4 | 100 | 110 | 10 | | | | |
| | | | | | 5 | | 1800 | | | | | |
| | | | | | 6 | 0.17 | 18 | 17.83 | 4239 | 87 | 18 | 7.6 |
| | | | | | 7 | 0.05 | 0.26 | 0.21 | | | | |
| | | | | | 8 | 0.15 | 0.22 | 0.07 | | | | |
| | | | | | 1 | | 31600 | | | | | |
| 03/19/90 | 16:15 | 7 | 24 | 84.0 | 2 | 140 | 290 | 150 | 35393 | 1475 | 421 | 13.3 |
| | | 6 | 24 | 84.0 | 3 | 1.3 | 3.2 | 1.9 | | | | |
| | | 6 & 7 | 48 | 168 | 4 | 88 | 100 | 12 | | | | |
| | | | | | 5 | | 1300 | | | | | |
| | | | | | 6 | 1 | 11 | 10 | 2378 | 50 | 14 | 5.9 |
| | | | | | 7 | 0.07 | 0.19 | 0.12 | | | | |
| | | | | | 8 | 0.16 | 0.17 | 0.01 | | | | |

Baseline

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | | 31900 | | | | | |
| 03/20/90 | 12:45 | 1 | 24 | 64.0 | 2 | 0.03 | 110 | 109.97 | 25910 | 1080 | 405 | 12.7 |
| | | 2 | 24 | 64.0 | 3 | 0.37 | 1.6 | 1.23 | | | | |
| | | 1 & 2 | 48 | 128 | 4 | | | | | | | |
| | | | | | 5 | | NA | | | | | |
| | | | | | 6 | 1.1 | 9 | 7.9 | 1880 | 39 | 15 | 6.1 |
| | | | | | 7 | 0 | 0.1 | 0.1 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 25400 | | | | | |
| 03/20/90 | 14:30 | 8 | 24 | 84.0 | 2 | 340 | 470 | 130 | 30896 | 1287 | 368 | 14.5 |
| | | 7 | 24 | 107.8 | 3 | 4.4 | 7 | 2.6 | | | | |
| | | 7 & 8 | 48 | 191.8 | 4 | 120 | 120 | 0 | | | | |
| | | | | | 5 | | 2400 | | | | | |
| | | | | | 6 | 3.7 | 18 | 14.3 | 3412 | 71 | 18 | 7.4 |
| | | | | | 7 | 0.06 | 0.28 | 0.22 | | | | |
| | | | | | 8 | 0.09 | 0.12 | 0.03 | | | | |
| | | | | | 1 | | 34000 | | | | | |
| 03/22/90 | 14:15 | 3 | 24 | 105.0 | 2 | 91 | 290 | 199 | 46880 | 1953 | 446 | 13.1 |
| | | 4 | 23 | 74.5 | 3 | 2.5 | 4.7 | 2.2 | | | | |
| | | 3 & 4 | 47 | 179.5 | 4 | 140 | 160 | 20 | | | | |
| | | | | | 5 | | 2200 | | | | | |
| | | | | | 6 | 2.4 | 11 | 8.6 | 2053 | 44 | 11 | 4.8 |
| | | | | | 7 | 0.02 | 0.16 | 0.14 | | | | |
| | | | | | 8 | 0.06 | 0.09 | 0.03 | | | | |
| | | | | | 1 | | 38200 | | | | | |
| 03/23/90 | 14:00 | 7 | 24 | 115.5 | 2 | 300 | 510 | 210 | 50351 | 2098 | 436 | 11.4 |
| | | 8 | 24 | 85.8 | 3 | 7.9 | 14 | 6.1 | | | | |
| | | 7 & 8 | 48 | 201.25 | 4 | 160 | 160 | 0 | | | | |
| | | | | | 5 | | 2300 | | | | | |
| | | | | | 6 | 4.1 | 18 | 13.9 | 3313 | 69 | 16 | 6.9 |
| | | | | | 7 | 0.05 | 0.25 | 0.2 | | | | |
| | | | | | 8 | | 0.1 | 0.1 | | | | |

Laboratory Data and Calculations for Modification 1 - November 15, 1990

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | | 22000 | | | | | |
| 11/15/90 | 08:30 | 2 | 24 | 80.0 | 2 | 91 | 150 | 59 | 14148 | 589 | 177 | 8.0 |
| | | 1 | 20 | 140.0 | 3 | 0.78 | 2.5 | 1.72 | | | | |
| | | 1 & 2 | 44 | 220 | 4 | 190 | 210 | 20 | | | | |
| | | | | | 5 | | 2100 | | | | | |
| | | | | | 6 | 0 | 4.7 | 4.7 | 1125 | 26 | 5 | 2.1 |
| | | | | | 7 | 0 | 0.09 | 0.09 | | | | |
| | | | | | 8 | 0.15 | 0.215 | 0.065 | | | | |
| | | | | | 1 | | 32400 | | | | | |
| 11/15/90 | 10:15 | 3 | 19 | 66.5 | 2 | 40 | 100 | 60 | 14423 | 759 | 217 | 6.7 |
| | | 4 | 24 | 84.0 | 3 | 0.55 | 2.45 | 1.9 | | | | |
| | | 3 & 4 | 43 | 150.5 | 4 | | | | | | | |
| | | | | | 5 | | 2100 | | | | | |
| | | | | | 6 | 0.45 | 4.8 | 4.35 | 1043 | 24 | 7 | 2.9 |
| | | | | | 7 | 0 | 0.09 | 0.09 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 35700 | | | | | |
| 11/15/90 | 11:00 | 5 | 24 | 84.0 | 2 | 55 | 140 | 85 | 19984 | 833 | 238 | 6.7 |
| | | 6 | 24 | 84.0 | 3 | 0.93 | 1.7 | 0.77 | | | | |
| | | 5 & 6 | 48 | 168 | 4 | | | | | | | |
| | | | | | 5 | | 1900 | | | | | |
| | | | | | 6 | 2 | 6.8 | 4.8 | 1105 | 23 | 7 | 2.7 |
| | | | | | 7 | 0.24 | 0.14 | -0.1 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 29700 | | | | | |
| 11/15/90 | 11:45 | 7 | 24 | 84.0 | 2 | 110 | 180 | 70 | 16636 | 693 | 198 | 6.7 |
| | | 8 | 24 | 104.0 | 3 | 1.1 | 2.5 | 1.4 | | | | |
| | | 8 | 24 | 104 | 4 | | | | | | | |
| | | | | | 5 | | 900 | | | | | |
| | | | | | 6 | 4 | 7.4 | 3.4 | 808 | 34 | 8 | 3.2 |
| | | | | | 7 | 0.09 | 0.13 | 0.04 | | | | |
| | | | | | 8 | | | | | | | |

Modification 1

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | | 32400 | | | | | |
| 11/15/90 | 13:15 | 10 | 24 | 84.0 | 2 | 170 | 280 | 110 | 26352 | 1098 | 314 | 9.7 |
| | | 9 | 24 | 94.0 | 3 | 2 | 5.1 | 3.1 | | | | |
| | | 9 & 10 | 48 | 178 | 4 | | | | | | | |
| | | | | | 5 | | 1600 | | | | | |
| | | | | | 6 | 2.8 | 8.8 | 6 | 1452 | 30 | 8 | 3.4 |
| | | | | | 7 | 0 | 0.18 | 0.18 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 37600 | | | | | |
| 11/15/90 | 14:00 | 12 | 24 | 84.0 | 2 | 200 | 270 | 70 | 16869 | 703 | 201 | 5.3 |
| | | 11 | 13 | 45.5 | 3 | 2.8 | 5.2 | 2.4 | | | | |
| | | 11 & 12 | 37 | 129.5 | 4 | | | | | | | |
| | | | | | 5 | | 2100 | | | | | |
| | | | | | 6 | 4.55 | 8.1 | 3.55 | 855 | 23 | 7 | 2.8 |
| | | | | | 7 | 0.09 | 0.18 | 0.09 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 39900 | | | | | |
| 11/15/90 | 14:45 | 13 | 24 | 84.0 | 2 | 190 | 275 | 85 | 20178 | 841 | 240 | 6.0 |
| | | 14 | 24 | 84.0 | 3 | 3.9 | 5.5 | 1.6 | | | | |
| | | 13 & 14 | 48 | 168 | 4 | | | | | | | |
| | | | | | 5 | | 1500 | | | | | |
| | | | | | 6 | 5.7 | 11 | 5.3 | 1273 | 27 | 8 | 3.2 |
| | | | | | 7 | 0.2 | 0.32 | 0.12 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 36100 | | | | | |
| 11/15/90 | 15:15 | 15 | 24 | 84.0 | 2 | 320 | 400 | 80 | 18757 | 782 | 223 | 6.2 |
| | | 16 | 24 | 100.0 | 3 | 9.2 | 9.7 | 0.5 | | | | |
| | | 15 & 16 | 48 | 184 | 4 | | | | | | | |
| | | | | | 5 | | 2000 | | | | | |
| | | | | | 6 | 7.2 | 12 | 4.8 | 1147 | 24 | 6 | 2.6 |
| | | | | | 7 | 0.33 | 0.41 | 0.08 | | | | |
| | | | | | 8 | | | | | | | |

Modification 1

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | | 27800 | | | | | |
| 11/15/90 | 16:00 | 17 | 24 | 84.0 | 2 | 290 | 350 | 60 | 14155 | 590 | 169 | 6.1 |
| | | 18 | 24 | 84.0 | 3 | 5.8 | 6.55 | 0.75 | | | | |
| | | 17 & 18 | 48 | 168 | 4 | | | | | | | |
| | | | | | 5 | | 1400 | | | | | |
| | | | | | 6 | 4.9 | 9.2 | 4.3 | 1133 | 24 | 7 | 2.8 |
| | | | | | 7 | 0.14 | 0.67 | 0.53 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 41400 | | | | | |
| 11/15/90 | 16:45 | 20 | 25 | 55.5 | 2 | 290 | 340 | 50 | 11860 | 474 | 214 | 5.2 |
| | | 19 | 24 | 84.0 | 3 | 4.1 | 5 | 0.9 | | | | |
| | | 19 & 20 | 49 | 139.5 | 4 | | | | | | | |
| | | | | | 5 | | 2300 | | | | | |
| | | | | | 6 | 4.5 | 8.7 | 4.2 | 1003 | 20 | 7 | 3.0 |
| | | | | | 7 | 0.15 | 0.22 | 0.07 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 39500 | | | | | |
| 11/15/90 | 17:30 | 21 | 26 | 114.0 | 2 | 170 | 300 | 130 | 30593 | 1177 | 268 | 6.8 |
| | | 22 | 24 | 84.0 | 3 | 2.5 | 3.8 | 1.3 | | | | |
| | | 21 & 22 | 50 | 198 | 4 | | | | | | | |
| | | | | | 5 | | 2800 | | | | | |
| | | | | | 6 | 4.1 | 8.7 | 4.6 | 1107 | 22 | 6 | 2.3 |
| | | | | | 7 | 0.11 | 0.22 | 0.11 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 40600 | | | | | |
| 11/15/90 | 18:00 | 23 | 24 | 84.0 | 2 | x | 430 | 430 | 101355 | 4223 | 1207 | x |
| | | 24 | 17 | 51.6 | 3 | x | 5 | 5 | | | | |
| | | 23 & 24 | 41 | 135.6 | 4 | | | | | | | |
| | | | | | 5 | | 1500 | | | | | |
| | | | | | 6 | 5.7 | 9 | 3.3 | 794 | 19 | 6 | 2.4 |
| | | | | | 7 | 0.14 | 0.22 | 0.08 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 32400 | | | | | |
| 11/15/90 | 13:10 | 9 | 24 | 94.0 | 2 | 72 | 170 | 98 | 23300 | 971 | 248 | 7.7 |
| | | | | | 3 | 0 | 2 | 2 | | | | |

Laboratory Data and Calculations for Modification 2 - December 10 & 11, 1990

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 5 | | 2300 | | | | | |
| 12/10/90 | 11:00 | 5 | 24 | 108.0 | 6 | 3.8 | 9.3 | 5.5 | 1332 | 28 | 6 | 2.6 |
| | | 6 | 24 | 108.0 | 7 | 0 | 0.17 | 0.17 | | | | |
| | | 5 & 6 | 48 | 216 | | | | | | | | |
| | | | | | 5 | | 2100 | | | | | |
| | 11:30 | 7 | 24 | 108.0 | 6 | 7 | 14 | 7 | 1673 | 35 | 8 | 3.2 |
| | | 8 | 24 | 108.0 | 7 | 0.2 | 0.32 | 0.12 | | | | |
| | | 7 & 8 | 48 | 216 | | | | | | | | |
| | | | | | 1 | | 36200 | | | | | |
| 12/10/90 | 12:00 | 9 | 21 | 94.5 | 2 | 250 | 340 | 90 | 21669 | 1032 | 229 | 6.3 |
| | | 10 | 24 | 108.8 | 3 | 8 | 11 | 3 | | | | |
| | | 9 & 10 | 45 | 203.25 | 4 | | | | | | | |
| | | | | | 5 | | 2000 | | | | | |
| | | | | | 6 | 4.5 | 10.4 | 5.9 | 1419 | 32 | 7 | 2.9 |
| | | | | | 7 | 0.08 | 0.22 | 0.14 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 33200 | | | | | |
| 12/10/90 | 13:15 | 11 | 24 | 87.5 | 2 | 140 | 240 | 100 | 23743 | 989 | 271 | 8.2 |
| | | 12 | 24 | 93.5 | 3 | 3.3 | 5.2 | 1.9 | | | | |
| | | 11 & 12 | 48 | 181 | 4 | | | | | | | |
| | | | | | 5 | | 2300 | | | | | |
| | | | | | 6 | 1.8 | 6.4 | 4.6 | 1095 | 23 | 6 | 2.5 |
| | | | | | 7 | 0 | 0.06 | 0.06 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 33200 | | | | | |
| 12/10/90 | 13:20 | 12 | 24 | 93.5 | 2 | 240 | 330 | 90 | 21646 | 902 | 232 | 7.0 |
| | | | | | 3 | 5.2 | 8.1 | 2.9 | | | | |
| | | 11 & 12 | 48 | 181 | | | | | | | | |
| | | | | | 1 | | 33200 | | | | | |
| | | | | | 2 | 140 | 330 | 190 | 45764 | 953 | 253 | 7.6 |
| | | | | | 3 | 3.3 | 8.1 | 4.8 | | | | |

Modification 2

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | | 31100 | | | | | |
| 12/10/90 | 14:45 | 13 | 24 | 108.5 | 2 | 54 | 170 | 116 | 27517 | 1147 | 254 | 8.2 |
| | | 14 | 24 | 119.0 | 3 | 1.4 | 3.5 | 2.1 | | | | |
| | | 13 & 14 | 48 | 227.5 | 4 | | | | | | | |
| | | | | | 5 | | 2000 | | | | | |
| | | | | | 6 | 0.95 | 7.95 | 7 | 1664 | 35 | 7 | 3.0 |
| | | | | | 7 | 0 | 0.08 | 0.08 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 31100 | | | | | |
| 12/10/90 | 14:50 | 14 | 24 | 119.0 | 2 | 170 | 290 | 120 | 28869 | 1203 | 243 | 7.8 |
| | | | | | 3 | 3.5 | 7.4 | 3.9 | | | | |
| | | 13 & 14 | 48 | 227.5 | | | | | | | | |
| | | | | | 1 | | 31100 | | | | | |
| | | | | | 2 | 54 | 290 | 236 | 56852 | 1184 | 250 | 8.0 |
| | | | | | 3 | 1.4 | 7.4 | 6 | | | | |
| | | | | | 1 | | 32950 | | | | | |
| 12/11/90 | 09:30 | 4 | 21 | 59.5 | 2 | 160 | 220 | 60 | 13980 | 666 | 235 | 7.1 |
| | | | | | 3 | 4.7 | 4.7 | 0 | | | | |
| | | 4 | 21 | 59.5 | 4 | | | | | | | |
| | | | | | 5 | | 2200 | | | | | |
| | | | | | 6 | 7.9 | 10 | 2.1 | 524 | 25 | 9 | 3.7 |
| | | | | | 7 | 0 | 0.13 | 0.13 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 32900 | | | | | |
| 12/11/90 | 10:15 | 5 | 24 | 108.0 | 2 | 120 | 200 | 80 | 19642 | 818 | 182 | 5.5 |
| | | 6 | 11 | 49.5 | 3 | 2.9 | 7.2 | 4.3 | | | | |
| | | 5 & 6 | 35 | 157.5 | 4 | | | | | | | |
| | | | | | 5 | | 2300 | | | | | |
| | | | | | 6 | 6.5 | 9.5 | 3 | 728 | 21 | 5 | 1.9 |
| | | | | | 7 | 0.04 | 0.14 | 0.1 | | | | |
| | | | | | 8 | | | | | | | |

Modification 2

| date | time | rack # | number of boards in rack | board area in rack sqft | tank # | Cu conc. before rinse mg/l | Cu conc after rinse mg/l | change in Cu conc mg/l | dragout/ rack mg/sqft | dragout/ board mg/sqft | dragout/ area mg/sqft | dragout volume ml/sqft |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | | 36000 | | | | | |
| 12/11/90 | 11:00 | 7 | 24 | 84.0 | 2 | 135 | 230 | 95 | 22508 | 938 | 268 | 7.4 |
| | | 8 | 24 | 84.0 | 3 | 5.4 | 7 | 1.6 | | | | |
| | | 7 & 8 | 48 | 168 | 4 | | | | | | | |
| | | | | | 5 | | 2300 | | | | | |
| | | | | | 6 | 4.2 | 8 | 3.8 | 914 | 19 | 5 | 2.3 |
| | | | | | 7 | 0 | 0.09 | 0.09 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 33300 | | | | | |
| 12/11/90 | 11:45 | 9 | 24 | 80.0 | 2 | 190 | 255 | 65 | 15681 | 653 | 196 | 5.9 |
| | | 10 | 24 | 64.0 | 3 | 6.4 | 8.7 | 2.3 | | | | |
| | | 9 & 10 | 48 | 144 | 4 | | | | | | | |
| | | | | | 5 | | 2200 | | | | | |
| | | | | | 6 | 9.5 | 13 | 3.5 | 867 | 18 | 6 | 2.5 |
| | | | | | 7 | 0.12 | 0.31 | 0.19 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 1 | | 35700 | | | | | |
| 12/11/90 | 12:15 | 11 | 25 | 87.5 | 2 | 240 | 320 | 80 | 19036 | 761 | 218 | 6.1 |
| | | 12 | 26 | 91.0 | 3 | 9.3 | 11 | 1.7 | | | | |
| | | 11 & 12 | 51 | 178.5 | 4 | | | | | | | |
| | | | | | 5 | | 2500 | | | | | |
| | | | | | 6 | 4.1 | 9.9 | 5.8 | 1409 | 28 | 8 | 3.3 |
| | | | | | 7 | 0.12 | 0.32 | 0.2 | | | | |
| | | | | | 8 | | | | | | | |
| | | | | | 5 | | 2500 | | | | | |
| 12/11/90 | 12:15 | 11 | 25 | 87.5 | 6 | 4.1 | 6.7 | 2.6 | 622 | 25 | 7 | 3.0 |
| | | | | | 7 | 0.12 | 0.19 | 0.07 | | | | |
| | | 12 | 26 | 91.0 | | | | | | | | |
| | | | | | 5 | | 2500 | | | | | |
| | | | | | 6 | 6.7 | 9.9 | 3.2 | 782 | 30 | 9 | 3.6 |
| | | | | | 7 | 0.19 | 0.32 | 0.13 | | | | |

notes:

| | | |
|---|---|---|
| 03/20/90 | 12:45 | The sample from tank #5 was destroyed in a laboratory accident. |
| 11/15/90 | 18:00 | Tank #2 & tank #3 were not sampled before the racks were rinsed - Sampling error. Dragout volumes could not be calculated. |

Dragout and Withdrawal/Drain Time
Micro Etch Baseline
04/23/91

| DATE | TIME | RACK # | dragout volume ml/sqft | withdrawal time (s) | drain time (s) | total time (s) |
|---|---|---|---|---|---|---|
| 03/12/90 | 14:00 | 9 | 11.3 | 1 | 3.4 | 4.4 |
| 03/13/90 | 13:00 | 1 | 9.8 | 1.5 | 5.5 | 7 |
| 03/13/90 | 16:30 | 8 | 13.5 | 2.9 | 2.7 | 5.6 |
| 03/14/90 | 16:00 | 11 | 12.0 | 1.3 | 7.6 | 8.9 |
| 03/14/90 | 16:30 | 12 | 12.4 | 1.5 | 6.2 | 7.7 |
| 03/15/90 | 13:00 | 6 | 9.3 | 3.2 | 3.2 | 6.4 |
| 03/16/90 | 16:00 | 12 | 11.8 | 2.7 | 4.3 | 7 |
| 03/19/90 | 16:15 | 7 | 13.3 | 1.8 | 1.2 | 3 |
| 03/20/90 | 12:45 | 1 | 12.7 | 1.2 | 1.5 | 2.7 |
| 03/20/90 | 14:30 | 8 | 14.5 | 1 | 1.3 | 2.3 |
| 03/22/90 | 14:15 | 3 | 13.1 | 1.7 | 1.5 | 3.2 |
| 03/23/90 | 14:00 | 7 | 11.4 | 1 | 2.3 | 3.3 |
| | | total | 145.2 | 20.8 | 40.7 | 61.5 |
| | | average | 12.1 | 1.7 | 3.4 | 5.1 |
| standard deviation(n-1) | | | 1.5 | 0.8 | 2.1 | 2.3 |
| | range | 9.3 | 14.5 | | | |

Dragout and Withdrawal/Drain Time
Electroless Copper Baseline
04/23/91

| DATE | TIME | RACK # | dragout volume ml/sqft | Withdrawal Time (seconds) first | Withdrawal Time (seconds) second | Drain Time (seconds) first | Drain Time (seconds) second | Total Time (seconds) first | Total Time (seconds) second |
|---|---|---|---|---|---|---|---|---|---|
| 03/12/90 | 14:00 | 9 & 10 | 4.7 | | 1 | | 9.7 | | 10.7 |
| 03/13/90 | 13:00 | 1 & 2 | 5.0 | 1.6 | 2.2 | 4.7 | 8.3 | 6.3 | 10.5 |
| 03/13/90 | 16:30 | 8 & 9 | 7.6 | 8.7 | 0.5 | 6.3 | 0.8 | 15 | 1.3 |
| 03/14/90 | 16:00 | 10 & 11 | 5.7 | 1 | 1 | 2.7 | 9.8 | 3.7 | 10.8 |
| 03/14/90 | 16:30 | 12 & 13 | 5.0 | 1.3 | 0.8 | 5.2 | 7.5 | 6.5 | 8.3 |
| 03/15/90 | 13:00 | 5 & 6 | 5.0 | 1.9 | 1.6 | 4.1 | 5.5 | 6 | 7.1 |
| 03/16/90 | 16:00 | 12 & 13 | 7.6 | 3.7 | 1.1 | 1.4 | 2.9 | 5.1 | 4 |
| 03/19/90 | 16:15 | 6 & 7 | 5.9 | 1.6 | 1.2 | 4.4 | 10.2 | 6 | 11.4 |
| 03/20/90 | 12:45 | 1 & 2 | 6.1 | 0.7 | 1.3 | 7.6 | 4 | 8.3 | 5.3 |
| 03/20/90 | 14:30 | 7 & 8 | 7.4 | 1.7 | 1.4 | 3.3 | 3.8 | 5 | 5.2 |
| 03/22/90 | 14:15 | 3 & 4 | 4.8 | 2.2 | 1.5 | 4.8 | 6.5 | 7 | 8 |
| 03/23/90 | 14:00 | 7 & 8 | 6.9 | 1.8 | 1.3 | 2.9 | 4 | 4.7 | 5.3 |
| | | Total | 71.7 | 26.2 | 14.9 | 47.4 | 73.0 | 73.6 | 87.9 |
| | | Average | 6.0 | 2.4 | 1.2 | 4.3 | 6.1 | 6.7 | 7.3 |
| Standard deviation (n-1) | | | 1.1 | 2.2 | 0.4 | 1.7 | 3.1 | 3.0 | 3.2 |
| Range | | 4.7 | 7.6 | 0.5 | 8.7 | 0.8 | 10.2 | 1.3 | 11.4 |
| | | | | ave. | 1.8 | | 5.2 | | 7.0 |
| | | | | stds. | 1.6 | | 2.6 | | 3.1 |

Dragout and Withdrawal/Drain Time
Micro Etch - Modification 1
04/24/91

| DATE | TIME | RACK# | dragout volume ml/sqft | withdrawal time (s) | drain time (s) | total time (s) |
|---|---|---|---|---|---|---|
| 11/15/90 | 08:30 | 2 | 8.0 | 13.6 | 1.9 | 15.5 |
| 11/15/90 | 10:15 | 3 | 6.7 | 14.6 | 3.0 | 17.6 |
| 11/15/90 | 11:00 | 5 | 6.7 | 14.8 | 2.2 | 17.0 |
| 11/15/90 | 11:45 | 7 | 6.7 | 14.5 | 1.6 | 16.1 |
| 11/15/90 | 13:10 | 9 | 7.7 | | | |
| 11/15/90 | 13:15 | 10 | 9.7 | 14.8 | 4.6 | 19.4 |
| 11/15/90 | 14:00 | 12 | 5.3 | 14.8 | 3.0 | 17.8 |
| 11/15/90 | 14:45 | 13 | 6.0 | 14.4 | 2.4 | 16.8 |
| 11/15/90 | 15:15 | 15 | 6.2 | 16.0 | 1.8 | 17.8 |
| 11/15/90 | 16:00 | 17 | 6.1 | 15.0 | 3.0 | 18.0 |
| 11/15/90 | 16:45 | 20 | 5.2 | 15.6 | 1.4 | 17.0 |
| 11/15/90 | 17:30 | 21 | 6.8 | 15.6 | 2.4 | 18.0 |
| | | Total | 81.0 | 163.7 | 27.3 | 191.0 |
| Average | | | 6.7 | 14.9 | 2.5 | 17.4 |
| Standard Deviation (n-1) | | | 1.2 | 0.7 | 0.9 | 1.1 |
| Range | | 5.2 | 9.7 | | | |

Dragout and Withdrawal/Drain Time
Electroless Copper - Modification 1
04/23/91

| DATE | TIME | RACK # | dragout volume ml/sqft | Withdrawal Time (seconds) first | Withdrawal Time (seconds) second | Drain Time (seconds) first | Drain Time (seconds) second | Total Time (seconds) first | Total Time (seconds) second |
|---|---|---|---|---|---|---|---|---|---|
| 11/15/90 | 09:30 | 1 & 2 | 2.1 | 14.9 | 14.3 | 3.7 | 8.7 | 18.6 | 23.0 |
| 11/15/90 | 11:15 | 3 & 4 | 2.9 | 13.8 | 13.5 | 2.3 | 2.2 | 16.1 | 15.7 |
| 11/15/90 | 12:00 | 5 & 6 | 2.7 | 13.5 | 14.8 | 1.4 | 4.8 | 14.9 | 19.6 |
| 11/15/90 | 13:00 | 8 | 3.2 | | 13.2 | | 6.7 | | 19.9 |
| 11/15/90 | 14:15 | 9 & 10 | 3.4 | 13.4 | 13.1 | 2.0 | 1.3 | 15.4 | 14.4 |
| 11/15/90 | 15:00 | 11 & 12 | 2.8 | 13.1 | 13.4 | 4.3 | 2.3 | 17.4 | 15.7 |
| 11/15/90 | 15:30 | 13 & 14 | 3.2 | 13.2 | 13.4 | 2.2 | 3.0 | 15.4 | 16.4 |
| 11/15/90 | 16:15 | 15 & 16 | 2.6 | 14.9 | 14.2 | 1.1 | 4.5 | 16.0 | 18.7 |
| 11/15/90 | 17:00 | 17 & 18 | 2.8 | 13.8 | 13.8 | 1.6 | 6.6 | 15.4 | 20.4 |
| 11/15/90 | 17:42 | 19 & 20 | 3.0 | 14.1 | 15.4 | 1.1 | 5.9 | 15.2 | 21.3 |
| 11/15/90 | 18:30 | 21 & 22 | 2.3 | 14.0 | 13.5 | 2.6 | 2.4 | 16.6 | 15.9 |
| 11/15/90 | 19:00 | 23 & 24 | 2.4 | 14.1 | 13.2 | 2.1 | 1.9 | 16.2 | 15.1 |
| | | Total | 33.49 | 152.8 | 165.8 | 24.4 | 50.3 | 177.2 | 216.1 |
| Average | | | 3.04 | 13.9 | 13.8 | 2.2 | 4.2 | 16.1 | 18.0 |
| Standard Deviation(n-1) | | | 0.4 | 0.6 | 0.7 | 1.0 | 2.4 | 1.1 | 2.8 |
| Range | | 2.1 | 3.4 | 13.1 | 15.4 | 1.1 | 8.7 | 14.4 | 23.0 |
| | | | | ave. | 13.9 | | 3.2 | | 17.1 |
| | | | | stds. | 0.7 | | 2.1 | | 2.3 |

Dragout and Withdrawal/Drain Time
Micro Etch - Modification 2
04/24/91

| DATE | TIME | RACK # | dragout volume ml/sqft | withdrawal time (s) | drain time (s) | total time (s) |
|---|---|---|---|---|---|---|
| 12/10/90 | 12:00 | 9 | 6.3 | 4.5 | 13.5 | 18 |
| 12/10/90 | 13:15 | 11 | 8.2 | 4.5 | 11.4 | 15.9 |
| 12/10/90 | 13:15 | 11 & 12 | 7.6 | | | |
| 12/10/90 | 13:20 | 12 | 7.0 | 4.3 | 11.1 | 15.4 |
| 12/10/90 | 14:45 | 13 | 8.2 | 2.1 | 11.6 | 13.7 |
| 12/10/90 | 14:45 | 13 & 14 | 7.8 | | | |
| 12/10/90 | 14:50 | 14 | 8.0 | 5.6 | 11.8 | 17.4 |
| 12/11/90 | 09:30 | 4 | 7.1 | 4.3 | 11.8 | 16.1 |
| 12/11/90 | 10:15 | 5 | 5.5 | 4.4 | 11.8 | 16.2 |
| 12/11/90 | 11:00 | 7 | 7.4 | 4.7 | 12.2 | 16.9 |
| 12/11/90 | 11:45 | 9 | 5.9 | 4.2 | 13.7 | 17.9 |
| 12/11/90 | 12:15 | 11 | 6.1 | 4.1 | 12 | 16.1 |
| | | total | 85.17 | 42.70 | 120.90 | 163.60 |
| Average | | | 7.1 | 4.3 | 12.1 | 16.4 |
| Standard deviation(n-1) | | | 0.9 | 0.9 | 0.9 | 1.3 |
| Range | | 5.5 | 8.2 | | | |

Dragout and Withdrawal/Drain Time
Electroless Copper - Modification 2
04/24/91

| DATE | TIME | RACK # | dragout volume ml/sqft | Withdrawal Time (seconds) first | Withdrawal Time (seconds) second | Drain Time (seconds) first | Drain Time (seconds) second | Total Time (seconds) first | Total Time (seconds) second |
|---|---|---|---|---|---|---|---|---|---|
| 12/10/90 | 11:00 | 5 & 6 | 2.6 | 4.9 | 4.4 | 11.2 | 11.2 | 16.1 | 15.6 |
| 12/10/90 | 11:30 | 7 & 8 | 3.2 | 4.0 | 4.8 | 11.4 | 11.8 | 15.4 | 16.6 |
| 12/10/90 | 12:00 | 9 & 10 | 2.9 | 3.5 | 4.2 | 11.6 | 12.8 | 15.1 | 17.0 |
| 12/10/90 | 13:15 | 11 & 12 | 2.5 | 3.9 | 4.1 | 12.1 | 16.4 | 16.0 | 20.5 |
| 12/10/90 | 14:45 | 13 & 14 | 3.0 | 4.2 | 4.9 | 11.8 | 11.8 | 16.0 | 16.7 |
| 12/11/90 | 09:30 | 4 | 3.7 | | 4.2 | | 11.3 | | 15.5 |
| 12/11/90 | 10:15 | 5 & 6 | 1.9 | 4.3 | 4.0 | 12.4 | 11.9 | 16.7 | 15.9 |
| 12/11/90 | 11:00 | 7 & 8 | 2.3 | 4.4 | 4.9 | 11.9 | 11.4 | 16.3 | 16.3 |
| 12/11/90 | 11:45 | 9 & 10 | 2.5 | 4.9 | 4.4 | 11.1 | 11.1 | 16.0 | 15.5 |
| 12/11/90 | 12:15 | 11 | 3.0 | | | | | | |
| 12/11/90 | 12:20 | 12 | 3.6 | | | | | | |
| 12/11/90 | 12:25 | 11 & 12 | 3.3 | 3.5 | 4.4 | 11.5 | 11.6 | 15.0 | 16.0 |
| | | total | 34.47 | 37.6 | 44.3 | 105.0 | 121.3 | 142.6 | 165.6 |
| Average | | | 2.9 | 4.2 | 4.4 | 11.7 | 12.1 | 15.8 | 16.6 |
| Standard deviation(n-1) | | | 0.5 | 0.5 | 0.3 | 0.4 | 1.6 | 0.6 | 1.5 |
| Range | | 1.9 | 3.7 | 3.5 | 4.9 | 11.1 | 16.4 | 15.0 | 20.5 |
| | | | | ave. | 4.3 | | 11.9 | | 16.2 |
| | | | | stds. | 0.4 | | 1.2 | | 1.2 |



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