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Ultrasonic Cleaning for Military PWB's

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FOREWORD

This Brief is part of a series of Technology Briefs published by the Electronics Manufacturing Productivity Facility (EMPF). Describing research projects designed to further the understanding of manufacturing processes, this series provides a vehicle for technology transfer between government and the electronics manufacturing industry.

Established by the Navy as a research center for electronics manufacturing, our objective is to improve what has been called the "world's most complicated process" - the process of taking a weapons system from design through production. We work in close cooperation with industry to develop and demonstrate the high quality materials, processes, and process controls necessary to strengthen the Nation's electronics manufacturing base.

This Brief describes the initial phases of research on ultrasonic cleaning of printed wiring assemblies. These phases involved designing the functional test board and screening aqueous and solvent ultrasonic cleaners to support successive test phases. Results of this research will benefit industry and government in increased board quality and lower production costs.

HAROLD G. PEACOCK
Director, Electronics Manufacturing Productivity Facility (EMPF)
Naval Industrial Resources Support Activity

ABSTRACT

The Materials and Processes Research Laboratory of the EMPF undertook research on an alternative to the conventional printed wiring board cleaning process. Ultrasonic cleaning is gaining significant notice as a possible option since military specifications require higher levels of cleanliness than can be achieved in optimum time through traditional cleaning methods. The initial phases of the four-phase research project are completed, and results are presented in this technology brief.

ACKNOWLEDGEMENTS

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INTRODUCTION

The growth in surface mount technology (SMT) has increasingly brought new post-solder problems into focus. Among these post-solder problems is the issue of printed wiring board (PWB) cleanliness. This issue has gained considerable attention because of limitations imposed on the cleaning process to meet military specifications. Conventional cleaning methods are no longer adequate to achieve these high cleanliness levels in optimum cleaning time. The tight standoffs accompanying SMT necessitate better cleaning methods.

The Electronics Manufacturing Productivity Facility (EMPF), has taken the initiative to conduct a comprehensive study to determine the effects of ultrasonic energy on PWAs. This effort has resulted in a research project to investigate the potential use of ultrasonic energy to clean PWBs.

Phases I and II of the project involved designing a functional test board and screening different ultrasonic cleaners (aqueous and solvent) to determine which equipment would best meet the needs of the Phase III and IV tests.

The purpose of Phase III is to demonstrate that boards cleaned with ultrasonic energy have an equal or higher level of cleanliness as those boards cleaned by conventional methods. An in-line solvent cleaner will be used on the boards for conventional cleaning. The boards will also be tested before and after ultrasonic and conventional cleaning. Residual contamination will be measured, and the boards will be tested for functionality. Failure analysis of a faulty component will determine if ultrasonics is actually the cause of failure. Those boards that pass the functional test will be passed on to Phase IV.

The final test phase will establish that the reliability of boards cleaned with ultrasonic energy is the same or better than those cleaned by conventional methods. Reliability tests that may be included are thermal shock, vibration, and power cycling.

BACKGROUND

Ultrasonic cleaning is recognized as a successful means of achieving the required level of cleanliness on PWAs demanded by industry and the military. This method of cleaning has also become controversial because of possible damage caused by ultrasonic energy on the wire interconnect between the die and terminal. In Metallurgical Failure Modes of Wire Bonds, the Institute of Applied Technology, National Bureau of Standards recommended that ultrasonic cleaning be avoided unless in-depth studies indicated no bond damage occurred.

In a 1984 report on ultrasonic cleaning, Systems Development Corporation concluded that "there is no detrimental adverse effect to the integrated chip (IC) interconnect system as a result of ultrasonic cleaning of PWAs at a frequency of 43KHz for 8 minutes."

A failure analysis report by TRW Systems concluded that cleaning PWAs with standard 54L microcircuits in a flatpack casing (type FX, Appendix C of MIL-M-38510) can transmit sufficient energy through the package of a sealed device to cause metal failure degradation of the wire bond after 10 seconds and catastrophic failure after 60 seconds in an ultrasonic cleaner.

These controversial conclusions led to the current research at EMPF on use of ultrasonic energy to clean PWBs.

PHASE I - FUNCTIONAL BOARD DEVELOPMENT

INTRODUCTION

A literature survey revealed that although ultrasonic cleaning is not a new process, extensive work has not been conducted to test its use for cleaning military PWBs. The process of ultrasonic cleaning has been theoretically explained by varied complex equations, but none of these equations could be experimentally realized.

Investigating the wire bond configuration of a faulty component was necessary to test for long-term reliability of a PWB cleaned with ultrasonic energy. This step required a functional board which had components that would be susceptible to ultrasonic degradation. The selection of these components was based on the theory that a wire bond interconnect which had a resonant frequency close to that of the ultrasonic cleaner being used would most likely degrade.

THEORETICAL BACKGROUND

When a system is subjected to forced harmonic excitation, the induced vibrations are at the excitation frequency. Most systems undergo damped harmonic motion rather than pure undamped motion. Harmonic excitation can be in the form of an acting force or displacement. Applying the theory of vibration to the wire bond interconnect, it can be stated that the interconnect in an IC chip may be subjected to harmonic excitation when the IC is exposed to ultrasonic cleaning. The response of the interconnect vibrating at the excitation frequency depends on the relation between the forced and the natural frequency of the interconnect system. The solution of the equation of motion of such a system is given in Equation (1).

$$x = \frac{F}{G} \sin (w''t - \phi)$$

where x = the displacement (dependent on the amplitude of excitation)
F = acting force
w'' = frequency of excitation
t = time
$\phi = \cos^{-1}\left[\frac{bw''}{G}\right]$ where b is the damping constant
$G = \sqrt{m^2 (w''^2 - w^2)^2 + b^2 w''^2}$
where m is the mass and w is the natural frequency of the system

For no damping ($b = 0$), the G factor is large when w" is different from the natural frequency (w). As the excitation frequency approaches the natural frequency, w" tends to w, G tends to 0, and the amplitude (F/G) tends to ∞. For actual damped oscillations ($b \neq 0$), there is a characteristic value of w" at which the amplitude of oscillation is a maximum. This condition is called resonance, and the value of w" at which resonance occurs is termed the resonant frequency. It is this condition that could cause wire bond degradation in integrated circuits subjected to ultrasonic cleaning.

CALCULATION OF RESONANT FREQUENCIES

Figure 1 shows the structure of the wire bond interconnect in an IC. The resonant frequencies of the largest and smallest possible interconnect wires were calculated. If the operating frequency of any cleaner fell in the range of resonant frequencies obtained for a component, then that component was said to be theoretically susceptible to ultrasonic damage.

Figure 2 shows a view of typical interconnect wires in an IC. To determine the resonant frequency of an interconnect wire, the total length of the wire was calculated using the loop height, separation between bonds, difference in heights of bonds, and the dimensions of the inner cavity.

An approximate linear model was used to calculate the total length to avoid complex finite element modeling of the interconnect structure. The approximate model (Figure 3) was converted to a linear approximation (Figure 4). The interconnect

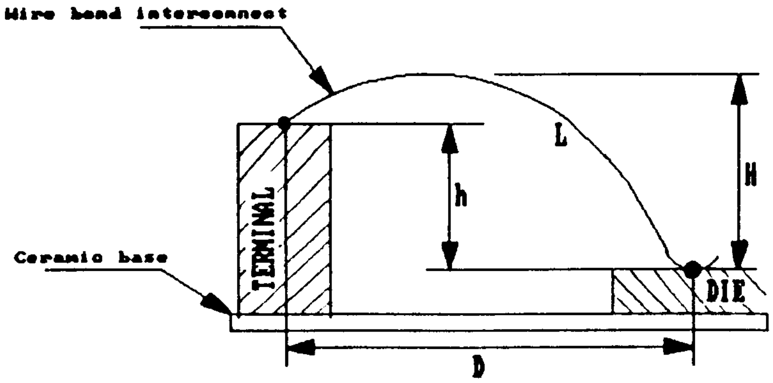


FIGURE 1. WIRE BOND CONFIGURATION.

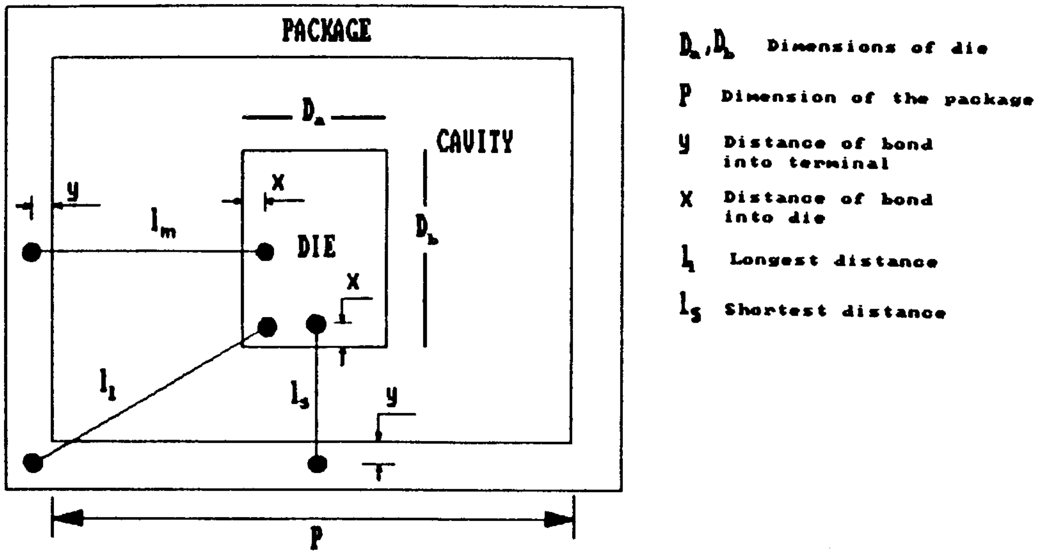
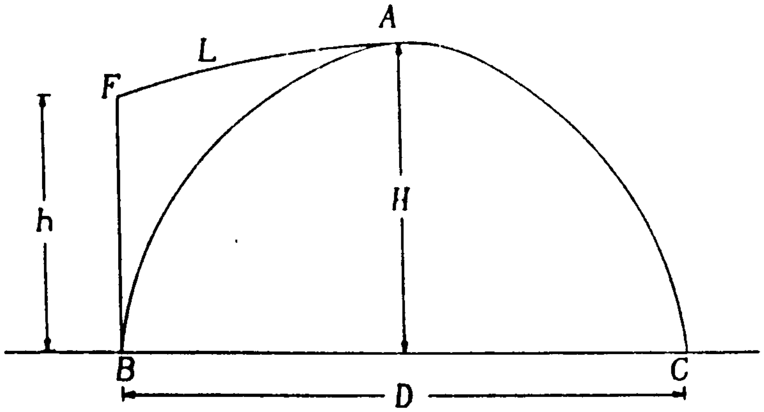


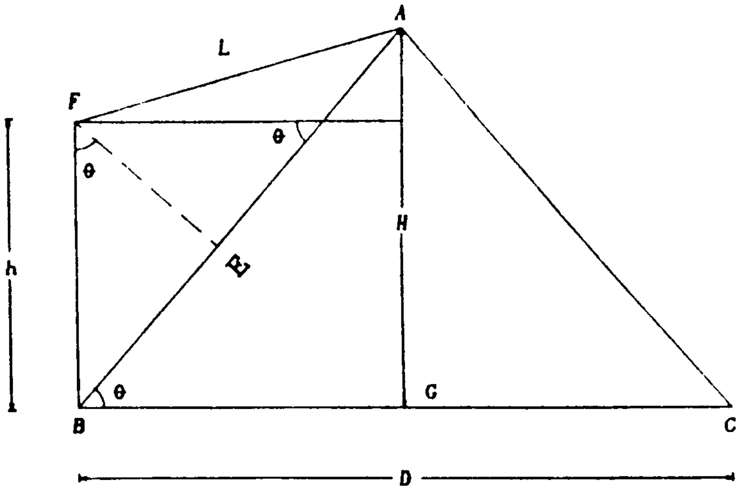
FIGURE 2. WIRE BOND INTERCONNECT CONFIGURATION.



Base assumed to be plane of die

BAC is parabola used to calculate length of FAC, the actual wire bond length

FIGURE 3. REDUCED MODEL OF A WIRE BOND INTERCONNECT.



The ratio $x = L/BA$ can be calculated as follows:

$$\tan\theta = AG/BG = 2H/D$$

$$\theta = \tan^{-1}(2H/D)$$

$$AB = \sqrt{(D/2)^2 + H^2}$$

$$BE = h\sin\theta$$

$$FE = h\cos\theta$$

$$EA = AB - BE$$

$$= \sqrt{(D/2)^2 + H^2} - h\sin\theta$$

$$AF^2 = L^2 = EA^2 + FE^2$$

$$= \left[\sqrt{(D/2)^2 + H^2} - h\sin\theta\right]^2 + (h\cos\theta)^2$$

$$x = L/AB = \frac{\sqrt{\left(\sqrt{(D/2)^2 + H^2} - h\sin\theta\right)^2 + (h\cos\theta)^2}}{\sqrt{(D/2)^2 + H^2}}$$

where D = separation between bonds
H = loop height
h = difference in heights of package and die

FIGURE 4. LINARIZED MODEL OF A WIRE BOND INTERCONNECT.

structure was approximated to a "clamped-hinged" support by making adjustments to the frequency coefficient of the vibration mode under consideration.

The theory was incorporated into a computer program that generated resonant frequencies for the first three modes of vibration based on user choices of loop height, diameter, and type of wire and package configuration.

A list of components was compiled based on the generated data. All components selected for the functional board had aluminum interconnect wires. Table 1 presents the components used for the functional board.

TABLE 1. LIST OF COMPONENTS FOR FUNCTIONAL BOARD.

Device	Catalog # JM38510/	Description
54LS04	30003B2A	Hex Invertor
54LS08	31004B2A	Quad 2-Input AND Gate
54LS11	31001B2A	Triple 3-Input AND Gate
54LS20	30007B2A	Dual 4-Input AND Gate
54LS32	30501B2A	Quad 2-Input OR Gate
54LS74A	30102B2A	Dual d Flip-Flop
54LS86	30502B2A	Quad Exclusive OR Gate
54LS139	30702B2A	Dual 1-of-4 Decoder/Mux
54LS161A	31504B2A	4-Bit Binary Counter
54LS175	30107B2A	Quad D Flip-Flop with Clear
54LS253	30908B2A	Dual 4-Input Mux, 3-State

An uncomplicated functional design was needed to avoid any functional faults not caused by ultrasonic energy. Therefore, a basic 4-bit data latch was repeated several times to achieve a fairly populated board. The analog circuit consisted of an independent pulse generator capable of being interconnected with the digital circuit. The design resulted in a four layer board which needed to have a constraining core to avoid any mismatch in the thermal coefficient of expansion between the board and the components. All surface mounted components utilized different package configurations. Leadless ceramic chip carrier (LCCC) components were used to simulate a worst case of cleanliness. Besides the functional 20-pin LCCCs, each board had some 28-pin and 68-pin LCCCs to generate a greater standoff area. Ceramic flat packages were included in the design to investigate the effects of standoff on cleanliness. It was proposed to vary the standoff height in a factorial design of testing. To correlate the results from the cleanliness test, a comb pattern was placed under the 68-pin package in the center of the board for surface insulation resistance measurements. Figure 5 shows the layout of the components on the board.

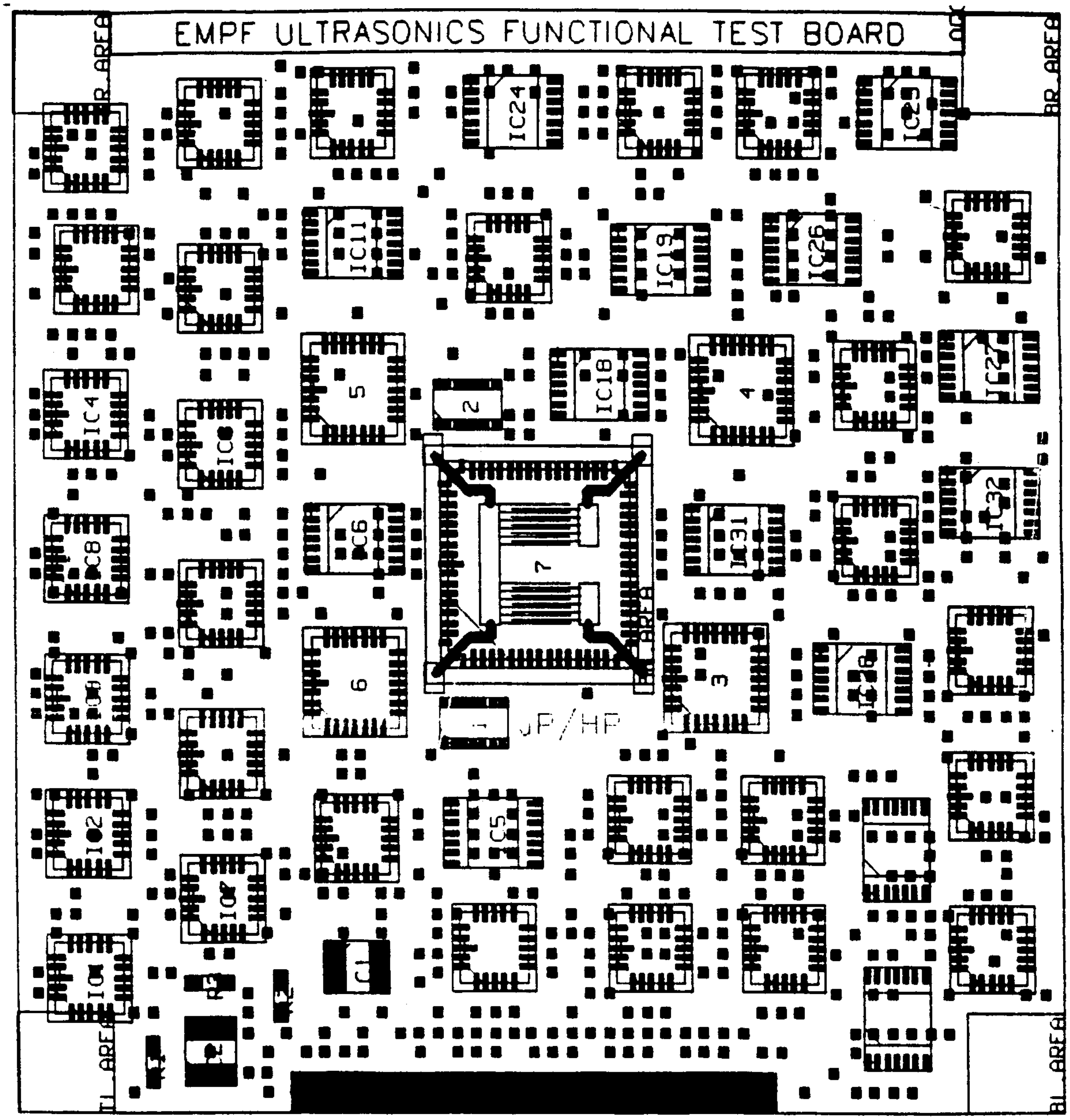


FIGURE 5. FUNCTIONAL BOARD LAYOUT.

PHASE II - SCREENING AQUEOUS AND SOLVENT ULTRASONIC CLEANERS

INTRODUCTION

The second phase of the ultrasonics research project screened off-the-shelf ultrasonic equipment to determine which units to use in the study of the effects of ultrasonic energy on cleanliness and wire bond interconnects. The requirements for the units' selection included the capability to perform an optimum cleaning process in minimum time and to provide reasonable process control. These requirements had to be met to study the effects of different parameters on cleanliness and cleanliness stability. In addition to determining which systems to use, responses such as system efficiency were also observed.

EQUIPMENT DESCRIPTION

All solvent and aqueous units tested were off the shelf. The range of operating frequencies of the aqueous units was 40 KHz to 88 KHz. All solvent units operated around 40 KHz.

Instrumentation equipment included an Ionograph, Dynamic Signal Analyzer, and a piezo-electric probe. The Ionograph 200 was calibrated according to the manufacturer's procedure and measured ionic contamination levels remaining on test coupons. (This test was used as a screening technique only.) The piezo-electric probe was connected to a Dynamic Signal Analyzer to measure the amplitude of the pressure wave. The analyzer produced a Fourier Transform of the ultrasonic wave.

TESTS

Testing was conducted on both the aqueous cleaning units and the solvent cleaning units to determine which unit of each style provided an optimum cleaning process. Three test variables and two tests were selected for each cleaning unit style.

Test Variables

There are several variables affecting cleanliness such as cleaning medium, rate of filtration, type of transducer, operating temperature, and cavitation.

Cavitation, the most important factor, depends on four parameters – frequency of the pressure wave, radius of bubble nucleus, hydrostatic pressure, and alternating pressure amplitude. Cavitation can only be measured as a function of the amplitude of the pressure wave. A piezo-electric probe is not capable of measuring cavitation because the alternating pressures in the tank induce an alternating voltage in the piezo-electric crystal, and the resulting value cannot be considered absolute. Therefore, the measured amplitude is a measure of the cavitation used only for comparison. By taking several readings of the pressure wave amplitude, the stability of the pressure wave is also obtained.

During testing, cleanliness was measured on a test sample that was also used to show the effects of tight standoffs (device-to-board distance) of SMT. Temperature, time of cleaning, and standoff were selected as the three variables used for testing consistency (Table 2).

TABLE 2. TEST VARIABLES AND RESPONSES.

Variables

Temperature
Time of cleaning
Standoff

Responses

Cleanliness
Cleanliness ratio
Amplitude of pressure wave
Stability of pressure wave
System efficiency

Procedures

One segment of tests was used to determine the best aqueous cleaning unit for further research. Although plain tap water is normally not utilized in industry for cleaning rosin-based fluxes, it was included in this test to help determine the unit that gave an optimum cleaning process. That unit underwent further testing using an aqueous detergent solution to study the effects of the variables on the responses.

The second test segment involved the use of two solvents with the solvent cleaning units.

A cleanliness test and amplitude test were designed as part of the testing procedures on both aqueous and solvent cleaning units. To obtain the variable effects in Table 1, the investigation was divided into four processes for the aqueous units and four processes for each solvent used in the solvent units.

Cleanliness Test. A test sample simulating SMT was designed for this test (Figure 6). The test coupon was a 3-inch by 2-inch FR-4 laminate. The brass slide was made with a 1/8-inch thick sheet and was 1-1/2 inches square in size. The slide had two channels uniformly milled perpendicular to each other on one side. The slide was mounted on the coupon using four screws. A controlled flux application resulted in a thin layer of flux in the shaded area.

The cleanliness test followed the sequence presented in Figure 7. Sample calculations used to obtain the total contamination and cleanliness ratio appear in Table 3.

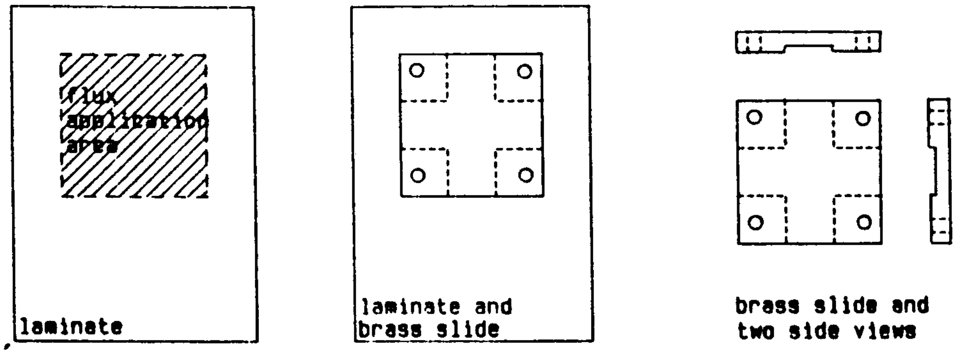
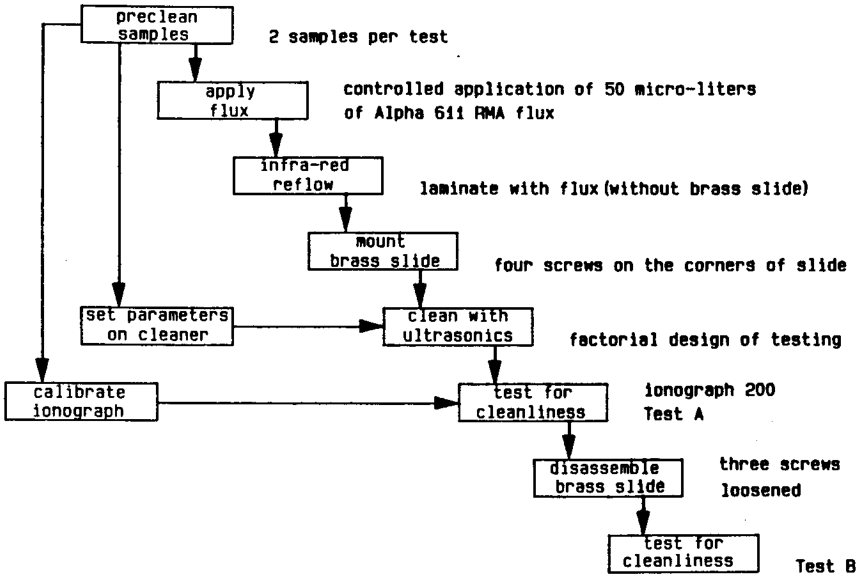


FIGURE 6. TEST SAMPLE FOR CLEANLINESS TEST.



2 samples per test

controlled application of 50 micro-liters of Alpha 611 RMA flux

laminate with flux (without brass slide)

four screws on the corners of slide

factorial design of testing

ionograph 200
Test A

three screws loosened

Test B

FIGURE 7. TEST SEQUENCE FOR CLEANLINESS TEST.

TABLE 3. CALCULATIONS TO OBTAIN CONTAMINATION AND CLEANLINESS RATIO

	ug./sq. in.	
Sample	Test A (Assembled)	Test B (Disassembled)
#1	14.2	33.05
#2	16.17	4.81
Mean	15.2	3.93

Total Contamination
(A + B) 15.2 + 3.93 = 19.13

Cleanliness Ratio
(B/(A + B)) 3.93 / 19.13 = 0.205

NOTE: ug./sq.in. = microgram per square inch of ionic contamination

Results. Since a low cleanliness ratio was the desired results, the contamination results in Test B should have read at zero. The total contamination was also important in relation to the cleanliness ratio. As seen in the table above, although the indicated cleanliness ratio had a low value (.205), the total contamination (19.13) still exceeded the allowable military specification of 10 micrograms per square inch of ionic contamination.

Amplitude Test. The amplitude test design incorporated a vertical plane since the boards were usually loaded vertically or diagonally to achieve good cleanliness levels (Figure 8). The vertical plane was divided into a number of data points. At each data point, 100 readings were obtained in sets of 20 each. This method resulted in a total of five acquisitions at each data point. Table 4 shows a sample acquisition for the amplitude test. Only the fundamental frequency was considered to avoid complicated theoretical analysis.

Results. The Dynamic Signal Analyzer successfully obtained the amplitude at the fundamental frequency.

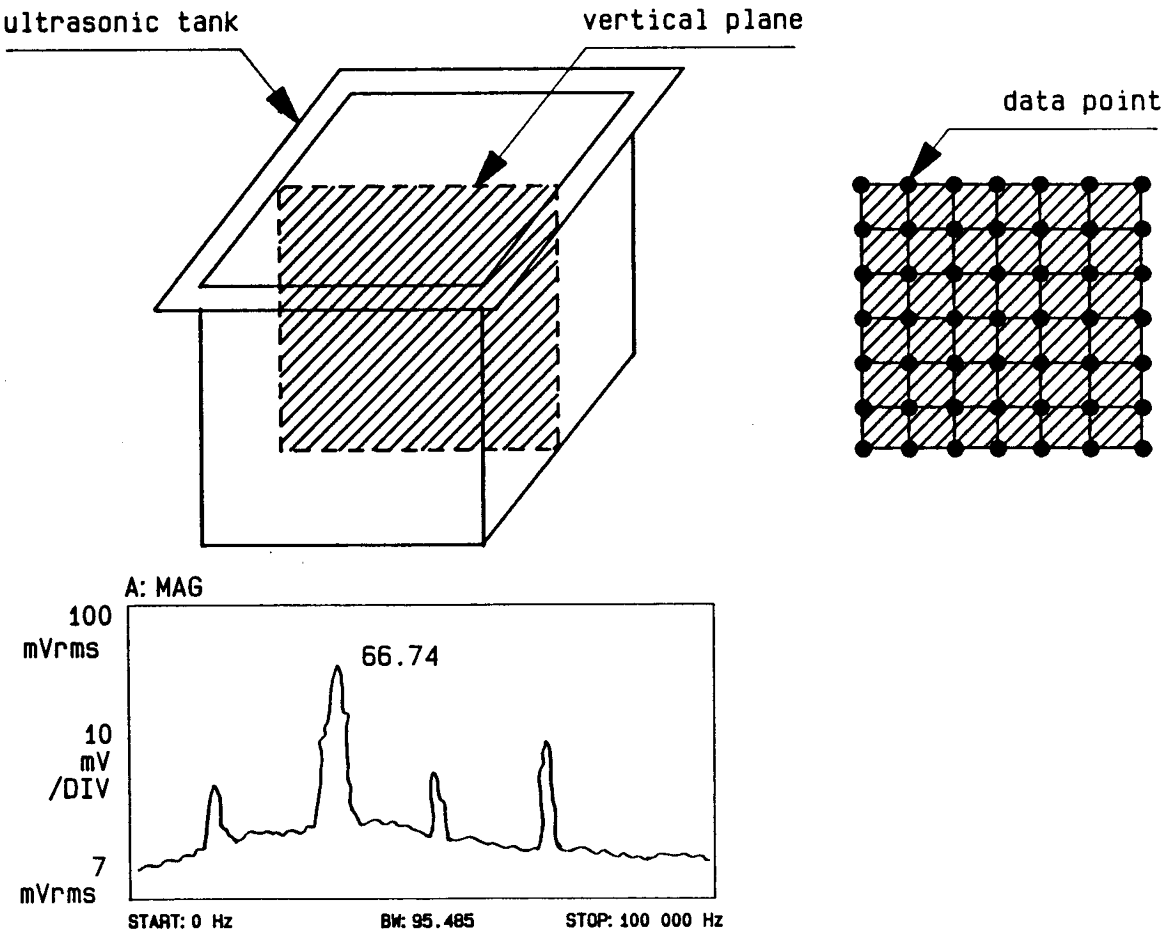


FIGURE 8. AMPLITUDE TEST DESIGN.

TABLE 4. SAMPLE ACQUISITION FOR AMPLITUDE TEST.

Data Point	Acquisition #1	#2	#3	#4	#5	Mean	s.d.
#1	X11	X12	X13	X14	X15	X1	S1
#2	X21	X22	X23	X24	X25	X2	S2
....							
....							
#n	Xn1	Xn2	Xn3	Xn4	Xn5	Xn	Sn

NOTE: s.d. = standard deviation

Calculations:

Amplitude = Mean of X_i = X mVrms
Stability Ratio = 1/Standard deviation of S_i = S
Define impedance constant = K
Power in the tank = (X^2/K) Watts
Power supplied to tank = Output of generator
= Y Watts
Power per unit volume = Y/volume = Z
System efficiency ratio = $X^2/(KZ)$

Aqueous Units. The testing was divided into four processes. The processes and the high and low values of the variables are contained in Table 5.

TABLE 5. TEST PROCESSES AND VARIABLE VALUES (AQUEOUS UNITS).

Process	Temperature	Time of Cleaning	Standoff
pr-1	30°C	3 minutes	3 mils
pr-2	70°C	30 seconds	3 mils
pr-3	30°C	30 seconds	8 mils
pr-4	70°C	3 minutes	8 mils

Testing on the aqueous units was divided into two groups because of research timing constraints. The first set was tested prior to the solvent units. As a result of use in the solvent testing, the piezo-electric probe was degraded and did not facilitate comparison between the two sets of aqueous units. Units from their respective groups were ranked according to their performance, and one unit was selected from each group.

Results. Results of ranking the cleaners according to performance is presented in Table 6. A ranking of 1 denoted worst case and 4 indicated best case.

TABLE 6. RANKING OF AQUEOUS CLEANERS.

GROUP 1

Cleanliness	Unit 1	Unit 2	Unit 3	Unit 4
pr 1	3	4	1	2
pr 2	2	3	4	1
pr 3	1	2	4	3
pr 4	3	1	2	4
Cleanliness ratio				
pr 1	3	2	4	1
pr 2	1	4	3	2
pr 3	1	2	4	3
pr 4	2	3	1	4
Stability ratio				
pr 1	3	1	4	2
pr 2	3	1	2	4
pr 3	3	1	4	2
pr 4	3	1	2	4
Efficiency ratio				
pr 1	1	3	4	2
pr 2	1	4	2	3
pr 3	1	3	4	2
pr 4	1	4	2	3

TABLE 6. (Contd).

Controllable variables	Unit 1	Unit 2	Unit 3	Unit 4
	2	2	2	2
Total	34	41	49	44

GROUP 2

Cleanliness	Unit 5	Unit 6	Unit 7
pr 1	3	1	2
pr 2	1	3	2
pr 3	1	3	2
pr 4	1	3	2
Cleanliness ratio			
pr 1	3	1	2
pr 2	2	1	3
pr 3	2	3	1
pr 4	1	2	3
Stability ratio			
pr 1	1	2	3
pr 2	3	1	2
pr 3	1	3	2
pr 4	3	1	2
Efficiency ratio			
pr 1	1	3	2
pr 2	1	3	2
pr 3	1	3	2
pr 4	1	3	2
Controllable variables			
	1	1	4
Total	27	37	38

The ranking of the cleaners shown in Table 6 can be seen in Figure 9. The stability ratio and the efficiency ratio depended on amplitude. Amplitude was based on temperature which for process 1 and 3 was the same, and likewise the same for 3 and 4. As a result of the testing, two units were selected to be used in further testing. Both units had piezo-electric transducers and heated tanks for which the temperature can be preset. The generators unique to each unit operated at 40Khz and 66Khz. The 40Khz unit generated 700 watts and had the capability for both amplitude and frequency control, while the 66Khz unit generated 440 watts with the capability for amplitude control.

Solvent Units. The solvent unit experiments were divided into four processes for each solvent used. One solvent was chloroflurocarbon (CFC-113) based and the other solvent was 1,1,1 trichloroethane based. Table 7 shows the different processes and the values of the variables of each process. All solvent units were operated at the manufacturer's suggested temperatures for the boiling and ultrasonic sumps.

TABLE 7. TEST PROCESSES AND VARIABLE VALUES
(SOLVENT UNITS).

Solvent S1 Process	Standoff	Time of Cleaning Boiling Sump	Ultrasonic Sump
pr-1	3 mils	45 seconds	1 minute
pr-2	8 mils	45 seconds	5 minutes
pr-3	8 mils	20 seconds	1 minute
pr-4	3 mils	20 seconds	5 minutes

Solvent S2 Process	Standoff	Time of Cleaning Boiling Sump	Ultrasonic Sump
pr-5	3 mils	45 seconds	5 minutes
pr-6	8 mils	20 seconds	5 minutes
pr-7	3 mils	20 seconds	1 minute
pr-8	8 mils	45 seconds	1 minute

Units were ranked in the order of performance. The results indicated which solvent and unit working together produced an optimum cleaning process.

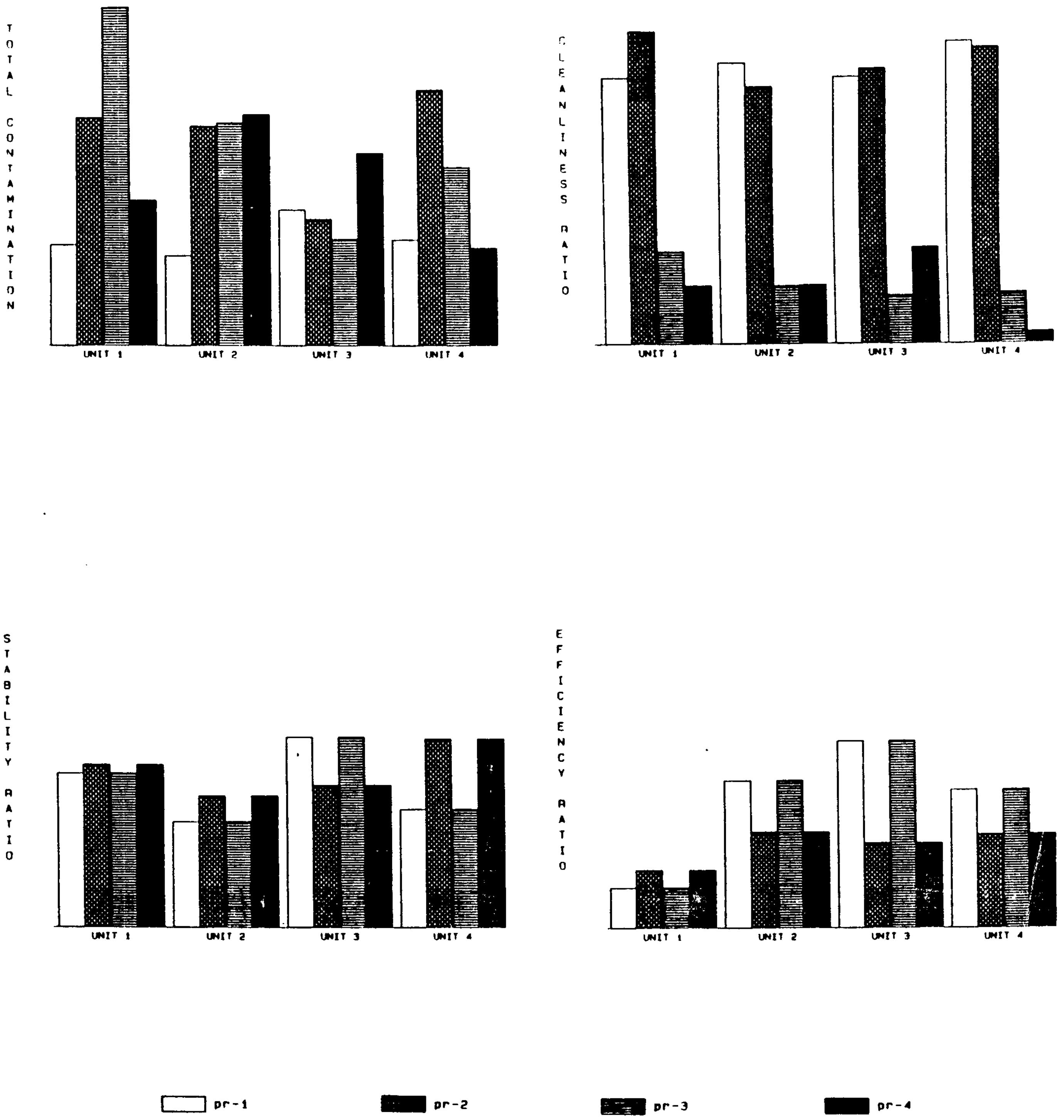


FIGURE 9. RANKING OF AQUEOUS UNITS.

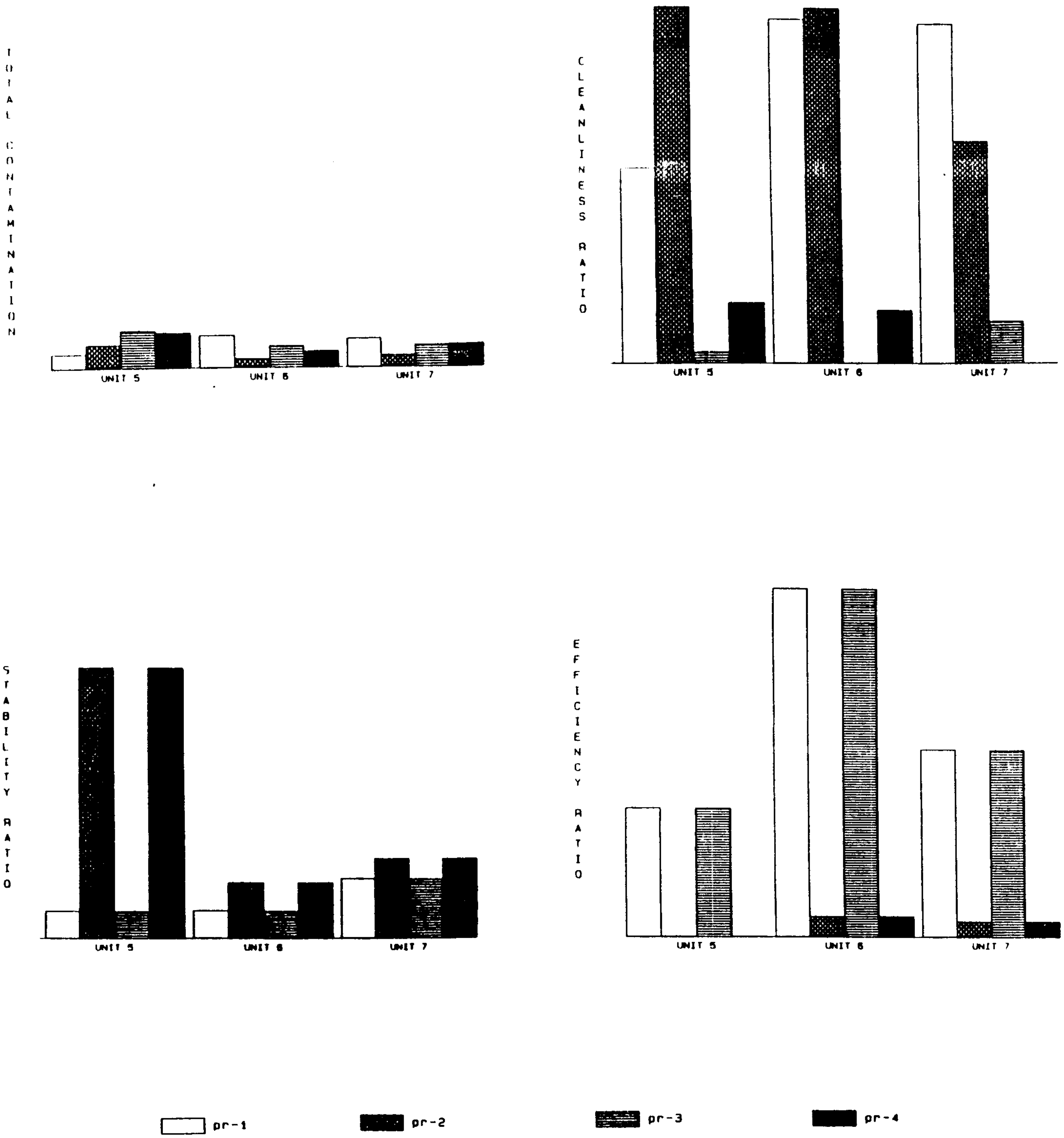


FIGURE 9. RANKING OF AQUEOUS UNITS. (Contd)

Results. Table 8 shows the ranking of the solvent units based on their performance.

TABLE 8. RANKING OF SOLVENT CLEANERS.

SOLVENT S1

Cleanliness	Unit 1	Unit 2	Unit 3
pr 1	1	2	3
pr 2	1	3	2
pr 3	1	2	3
pr 4	3	2	1
Cleanliness ratio			
pr 1	3	2	1
pr 2	3	1	2
pr 3	1	3	2
pr 4	1	2	3
Stability ratio			
	3	2	1
Efficiency ratio			
	1	3	2
Controllable variables			
	1	0	0
Total	19	22	20

SOLVENT S2

Cleanliness			
pr 5	3	1	2
pr 6	3	1	2
pr 7	3	2	1
pr 8	3	2	1

TABLE 8. RANKING OF SOLVENT CLEANERS. (Contd)

SOLVENT S2

Cleanliness ratio	Unit 1	Unit 2	Unit 3
pr 5	1	3	2
pr 6	2	3	3
pr 7	1	3	2
pr 8	2	3	1
Stability ratio			
	2	3	1
Efficiency ratio			
	3	1	2
Controllable variables			
	1	0	0
Total	24	20	17

Ranking was obtained from the graphs in Figure 10. Figure 10 shows that based on cleanliness, unit 1 was the best performing unit with solvent S2 in the cleaning process. The selected unit was a vapor degreaser with 400 watts supplied by the generator. The unit also had the capability to control the input power to the ultrasonic tank.

Conclusions. The following equipment will be used in projected testing to investigate the effects of ultrasonic energy on cleanliness and wire bond degradation of PWBs.

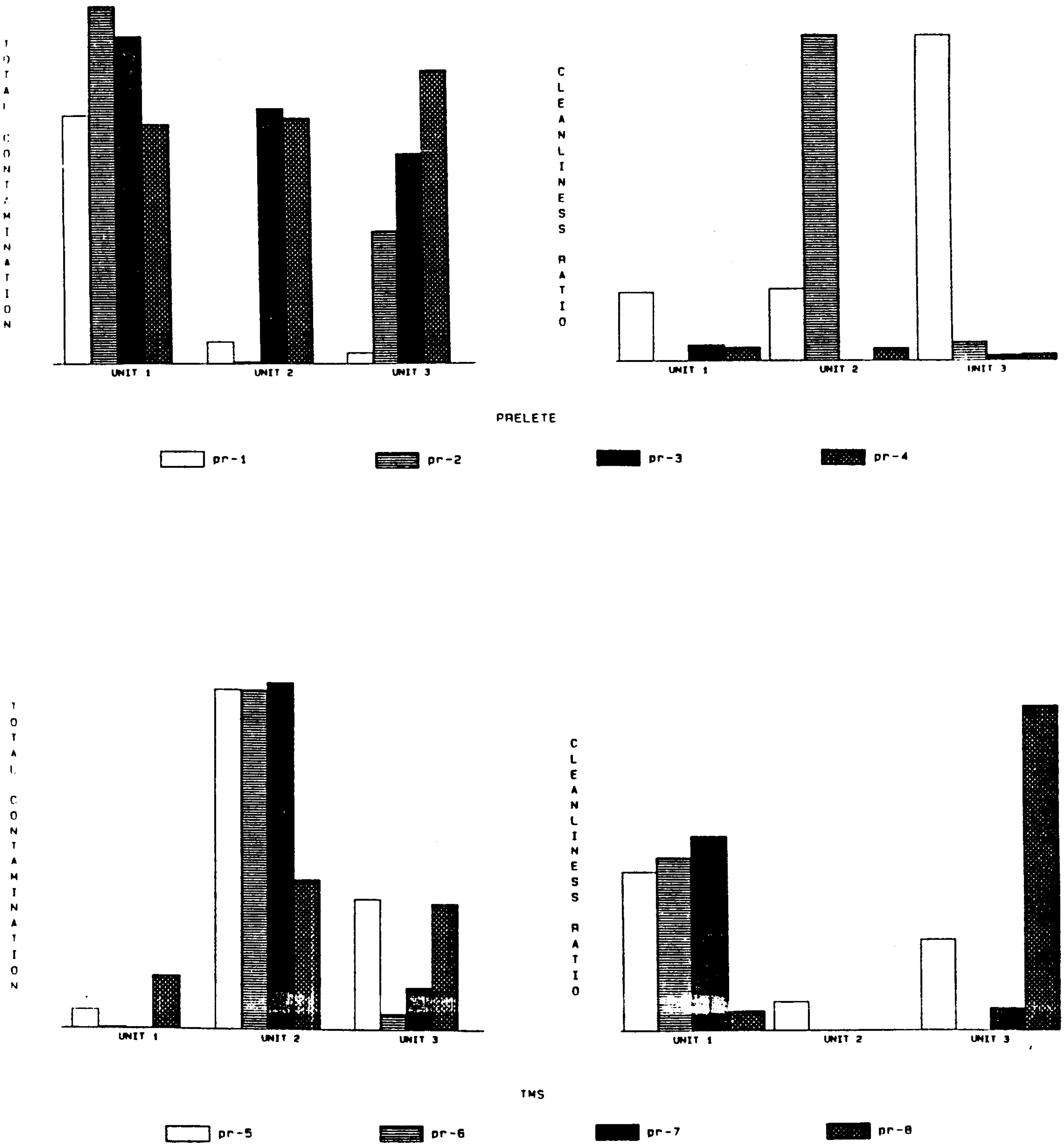


FIGURE 10. RANKING OF SOLVENT UNITS.

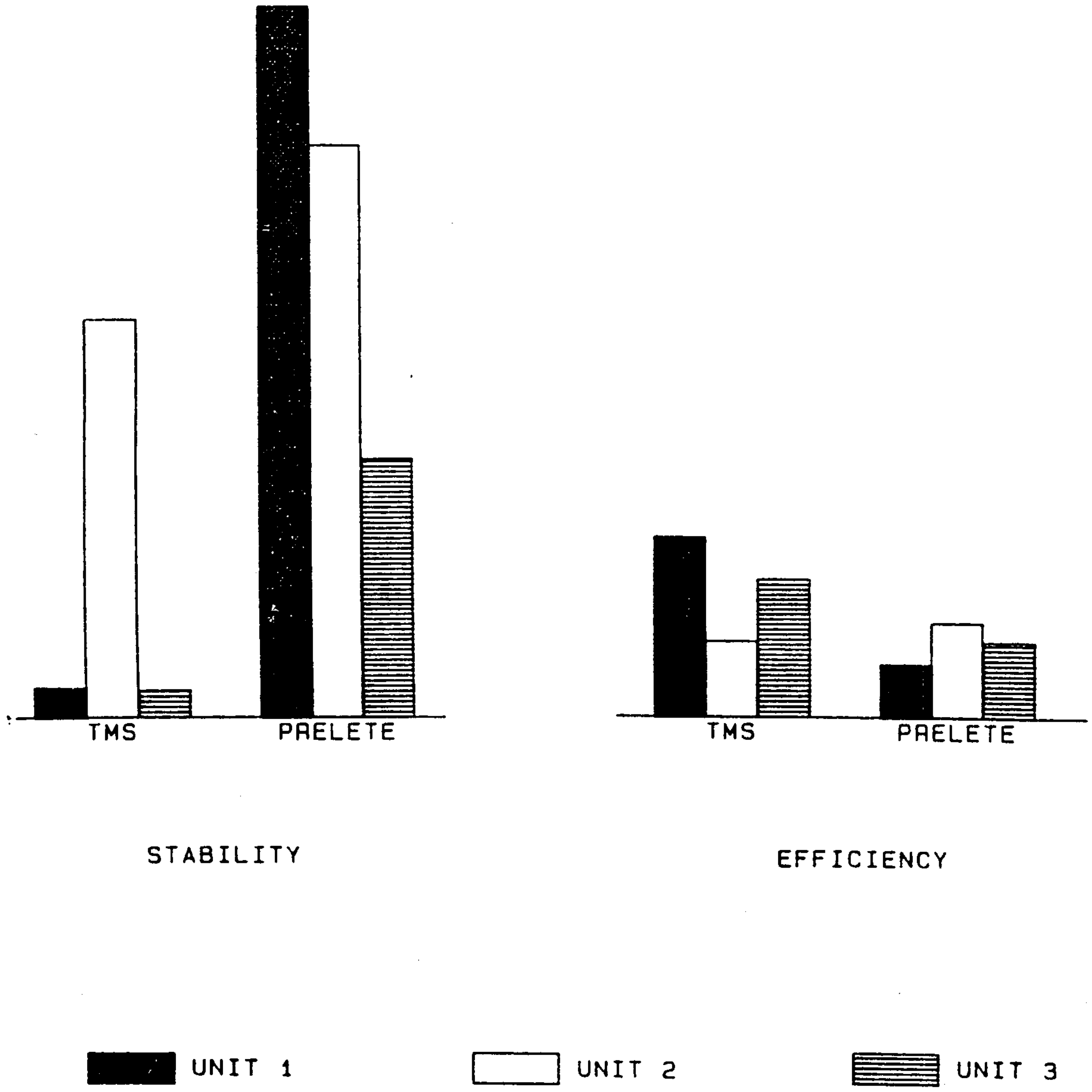


FIGURE 10. RANKING OF SOLVENT UNITS. (Contd)

AQUEOUS

Unit 3	Generator	- 66Khz actual operating frequency - 440 watts variable output
	Tank	- Temperature controlled
	Transducers	- Piezo-electric
Unit 7	Generator	- 40Khz variable between 39 - 41Khz with sweep control - 700 watts variable output
	Tank	- Temperature controlled
	Transducers	- Piezo-electric

(Note: Unit 4 was evaluated at frequency levels outside the manufacturer's specification. Reevaluation indicated that further analysis of this unit may be required.)

<u>SOLVENT</u>

Unit 1	Vapor degreaser	
	Generator	- 43.75 actual operating frequency - 400 watts variable output
	Tank	- Boiling and ultrasonic sumps - Temperature fixed based on solvent being used
	Transducers	- Piezo-electric

<u>Ultrasonic Cleaning Process</u>. In addition to screening the different cleaner units, experiments were conducted to study the cleaning process and the variables that affect the process when changed. One aqueous unit and one solvent unit were used in a factorial design incorporating all variables that could be controlled on a unit.

Aqueous Cleaning. Using one of the selected units, a factorial experiment was executed to investigate the effects of temperature, power, and the time of cleaning. In addition, a 1% Kester 5776 detergent was added to plain tap water and used as the cleaning medium. With a 20% experimental error, the allowable contamination level was 8 micrograms per square inch. (10 micrograms per square inch of ionic contamination is the allowable limit for military PWBs.) Figure 11 illustrates the temperature effect graphs, which are linear approximations, at varying power levels and at different cleaning times.

The graphs in Figure 11 were extrapolated to show that the required cleanliness level was obtained near boiling temperatures in minimum cleaning time. By combining the graphs shown in Figure 11, an approximate linear relationship between power and temperature was calculated to demonstrate that a unit did not have to be operated at maximum rated power to realize the required cleanliness level. This information can be particularly useful to minimize damage to wire bonds. Reducing the operating temperature requires increasing the power level in order to achieve the same level of cleanliness as that of the boiling temperature. Therefore, energy savings and required cleanliness can both be achieved if the unit is operated near boiling temperatures.

Figure 12 shows the approximate linear relationship obtained from Figure 11 for two different cleaning times. These figures illustrate that at temperatures below boiling, increased power is required to achieve the same cleanliness level as that at boiling. There is also a cutoff temperature below which the same level of cleanliness cannot be obtained without increased cleaning time.

Solvent Cleaning. Based on the factorial testing used in the screening design, the boiling sump time was found to have had a greater effect on cleanliness than the ultrasonic cleaning time.

The effects of boiling and ultrasonic sump times are illustrated by observing their relationship. Figure 13 shows that the boiling sump time had a greater effect on cleanliness than the ultrasonic sump time at the selected cleanliness level of 8 micrograms per square inch. As with the aqueous units, minimal cleaning time is preferred to avoid bond damage from ultrasonic energy exposure. To reach the required cleanliness level, 100% of the rated power need not be utilized, thereby resulting in energy savings.

Aqueous versus Solvent Units. Table 9 presents the contamination level values for both Test A (assembled) and Test B (disassembled) for some processes to illustrate the variations of different cleaning processes. This data demonstrates that either aqueous detergent or solvent with ultrasonics achieves higher cleanliness levels than conventional cleaning. The same cleanliness level of the third process (aqueous detergent) can be

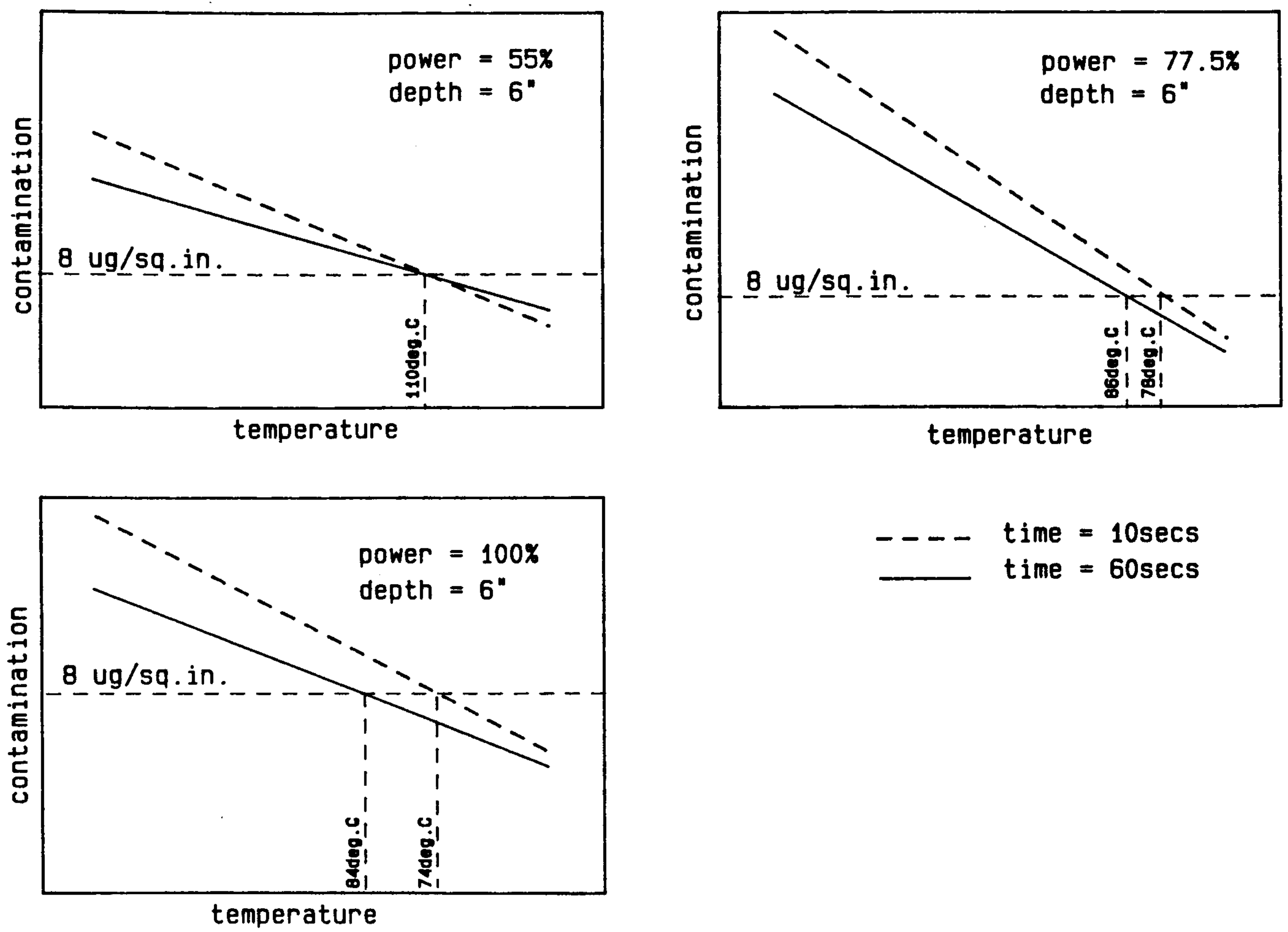
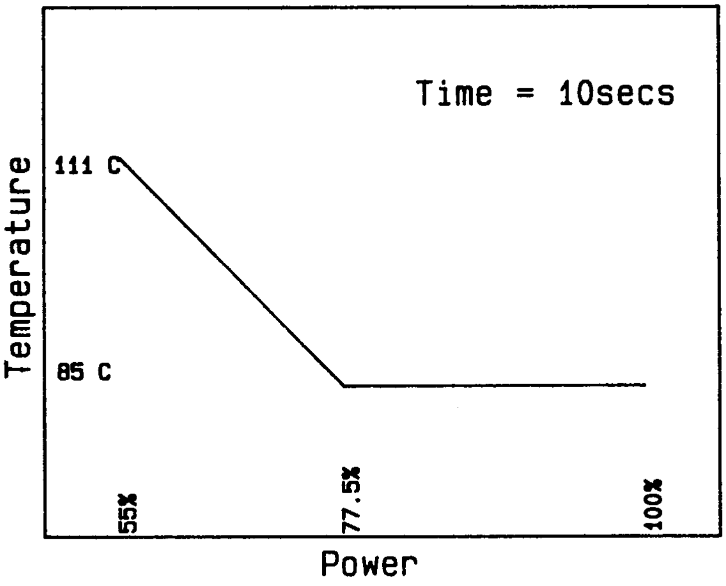


FIGURE 11. EFFECTS OF TEMPERATURE.



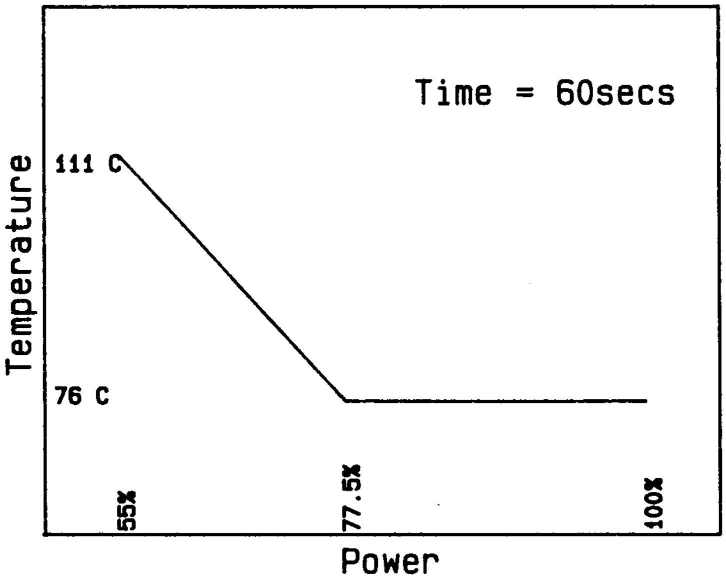


FIGURE 12. TEMPERATURE VERSUS POWER.

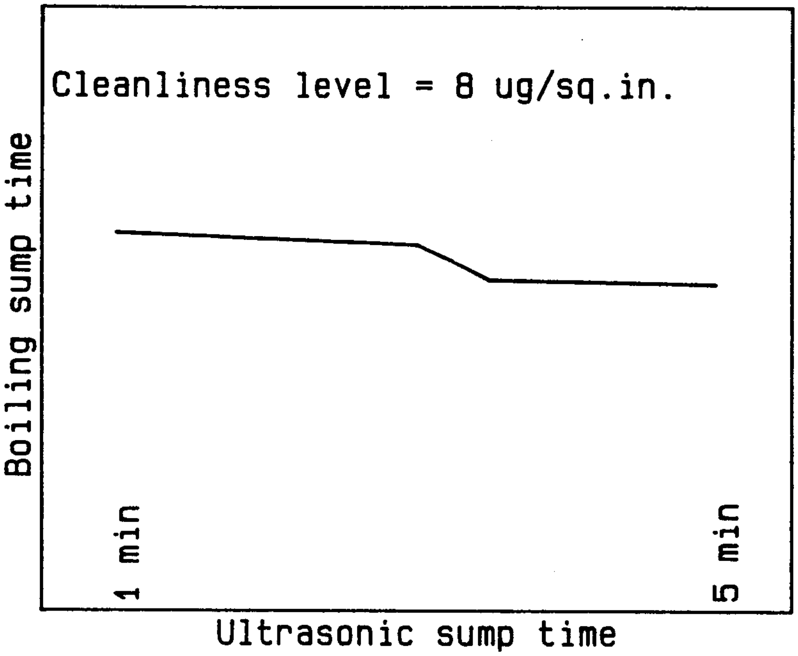


FIGURE 13. BOILING SUMP TIME VERSUS ULTRASONIC SUMP TIME.

achieved by operating the unit near boiling temperatures and 10-second exposure to ultrasonics. This cleaning method could be an alternative to the use of CFC-based solvents.

TABLE 9. COMPARISON OF DIFFERENT PROCESSES

micro grams per square inch

	Process	Closed	Open	Total
No Ultrasonics	In-line solvent cleaning system with solvent S1	4.9	20.65	25.55
With Ultrasonics	Aqueous 30 degC, 3 min	3.51	13.08	16.59
	Aqueous Detergent 30 degC, 60 sec	0.0	1.32	1.32
	Solvent S1 45 sec, 1min	0.505	0.471	0.976

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APPENDIX A

ACRONYMS

LIST OF ACRONYMS

CFC	Chloroflurocarbon
EMPF	Electronics Manufacturing Productivity Facility
IC	Integrated chip
LCCC	Leadless ceramic chip carrier
PWA	Printed wiring assembly
PWB	Printed wiring board
SMT	Surface mount technology