DTIC FILE COPY

(1)

SOLDERING TECHNOLOGY

E900 566

Sponsored by:

ELECTRONICS MANUFACTURING SUPPORT OFFICE

PROCEEDINGS

OF

8TH ANNUAL SEMINAR

22 - 23 February 1984

This is an informal report containing preliminary information. It is not an official report of the Naval Weaopns Center and mus not be used as a basis for action unless enclosed in official correspondence in which the purpose of the transmittal is made clear.

CODE 36803

NAVAL WEAPONS CENTER

China Lake, California

DEPARTMENT OF THE NAVY
NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555

IN REPLY REFER TO

Thank you for your continued interest in soldering technology, and your attendance at this seminar.

It is vital that we continue to maintain a concerted effort to resolve production line problems first, by understanding them, then by developing methods and process controls to resolve them. It is critical that our designers learn from past problems and that they design for ease of manufacturing.

We should not try new materials and equipment on production lines until a thorough evaluation has been conducted and test data proves that they can not only be cost effective, but that they also improve product quality.

These proceedings are published for your information and do not necessarily reflect the views of the Navy.

Thanks for your attendance.

Jim D. Raby
Head, Electronics
Manufacturing Support Office
Code 36803
February 22, 1984

INDEX

ARE WAVE SOLDERING AND TOUCHUP PROBLEMS
AFFECTING YOU?

Flo G. Benson and Gayne J. Maloney

Military Avionics Division
St. Louis Park, Minnesota

Are Wave Soldering and Touch-up Problems Affecting You?

Flo G. Benson and Gayne J. Maloney
Military Avionics Division, Honeywell Inc.

INTRODUCTION

In the Printed Wiring Assembly (PWA) area of Honeywell's Military Avionics Division (MAvD), we touchup PWAs after wave soldering with 70% fewer operators than we needed 19 months ago. We accomplished this through a new program called Solder Surveillance, which has also aided us to make substantial improvements in other areas of the wave soldering process. Although we encountered some problems while developing this new program, we were able to solve or minimize them by—

- Enhancing the wave soldering process
- Controlling the touch-up process
- Improving vendor communication and control
- Developing producibility standards for design of PWAs
- Pretinning component leads.

The benefits realized are improved productivity, increased yield and product reliability, reduced process time, reduced touch-up confusion, and a greater sense of pride and accomplishment among the engineers and operators. This is enough incentive to share our success with you.

BACKGROUND

The PWA area is consistently faced with monthly schedules of 5,000 to 7,000 assemblies. These schedules consist of over 320 different types of PWAs in any given month, from over 1000 active part numbers. The average lot size processed through wave solder is fifteen. The PWA sizes and densities are as varied as our schedules. The size ranges from 1½ inches square to 18 by 22 inches, and density per assembly ranges from 10 to 650 components. In the past our normal process time was an expected six to eight weeks.

With this kind of environment, it is important to understand what was happening in our day-to-day operation before discussing how the much improved system works today.

THE OLD PROCESS

The old wave solder process consisted of standard carrier speeds set virtually the same for all assemblies of the same board thickness. Only lower board heaters were used. The solder wave was adjusted as necessary, and the oil flow into the wave was checked at the start of the shift and after lunch.

After the PWAs were wave soldered and cleaned, they were returned to the various build groups for workmanship and solder evaluation. These evaluations were performed by any operator of the proper labor grade assigned to the job. This former process is illustrated in Figure 1. In some instances, as many as 15 to 20 operators were making decisions regarding soldering discrepancies that required touch-up to meet specifications. With this many operators making independent touch-up decisions, uniformity was nearly impossible. A great deal of confusion was caused by some operators who touched up cosmetic defects but missed major defects. Correlation between touch-up operators and inspectors was difficult if not impossible. This was further complicated by people movements because of union agreements. Training was also a tremendous problem. As a result, screening and touch-up became a lengthy, overdone operation that increased processing time, decreased reliability, and caused bottlenecks on the assembly lines.

There was another problem with the old system. Very little or no data was recorded to evaluate the effectiveness of the soldering process, and the effect of any process change was difficult to evaluate.

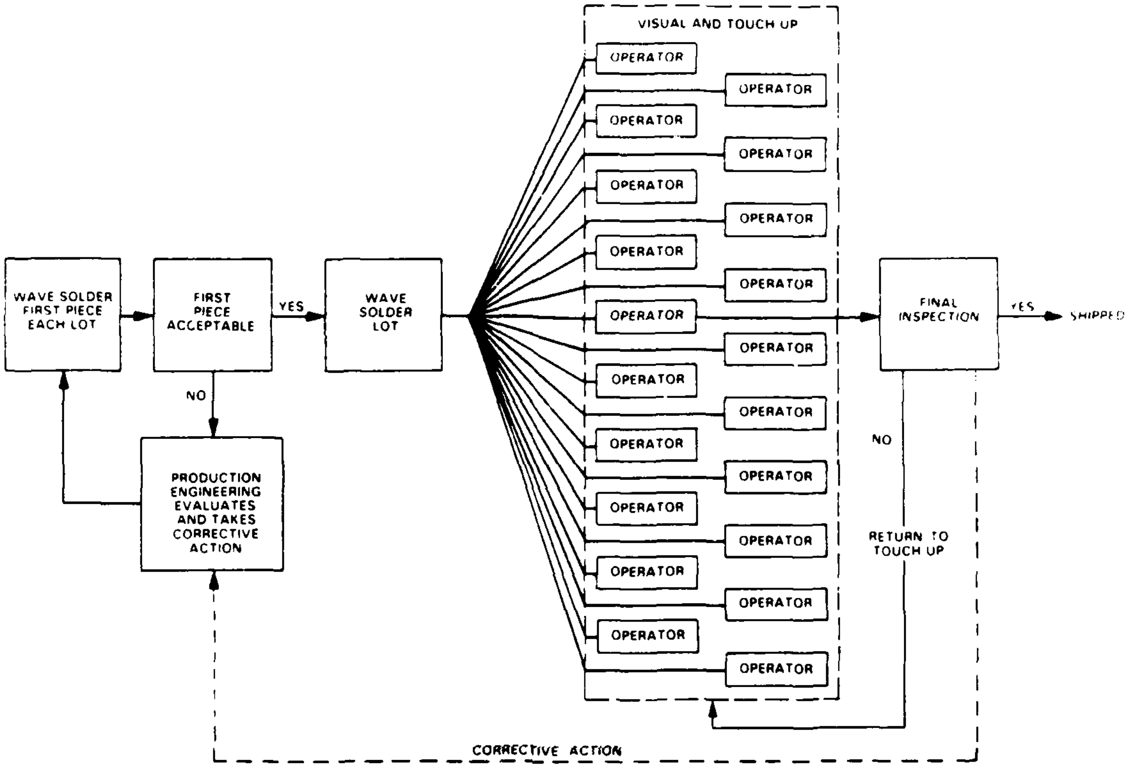


Figure 1. Previous Visual Inspection and Touch-up Process

In otherwords, we had a poorly controlled touch-up process with no feedback to monitor the many elements affecting wave soldering. It was time for a dramatic change in our overall wave solder and touch-up process!

THE NEW PROCESS

To minimize or eliminate many of the problems inherent in our old system, the new Solder Surveillance process incorporates special procedures to control and evaluate the many elements affecting wave soldering. This process, illustrated in Figure 2, provides engineering with the data needed and reduces the number of people making decisions on discrepancies to the two production operators who evaluate and disposition the hardware. Furthermore, Solder Surveillance control is flexible enough to accommodate the large variety of PWA types being processed monthly.

Our process utilizes a sample (4 pieces) from every lot wave soldered. Based on the quality level observed in a sample, the production operator dispositions the lot into one of the following four categories and records the action on the Solder Surveillance form, shown as Figure 3:

- **100% Solder Screen** — A total of five solder defects or more on the 4-board sample requires the production operator to identify and mark all defects on each board in the lot. The touch-up operator then reworks only the marked defects on each board.
- **Defined Solder Screen** — The same defect on each board of the 4-board sample indicates a specific problem. For example, a component with poor lead solderability would be a defined solder screen. The production operator places the 4-board sample on the top layer of the lot so that the touch-up operator can use them as a

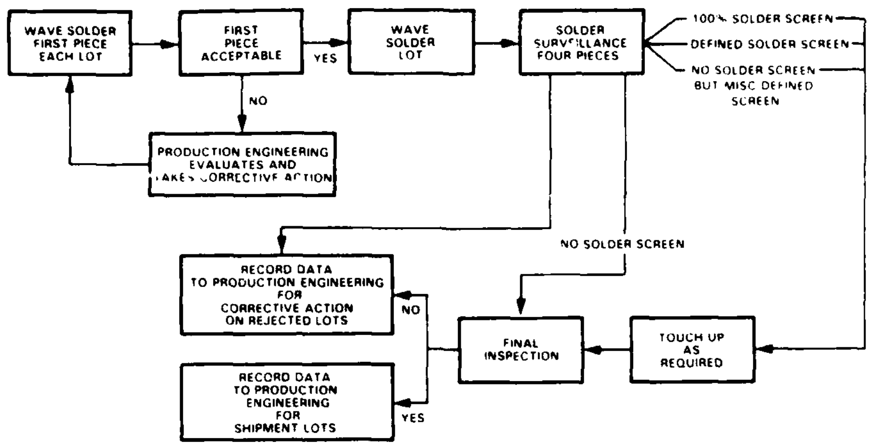
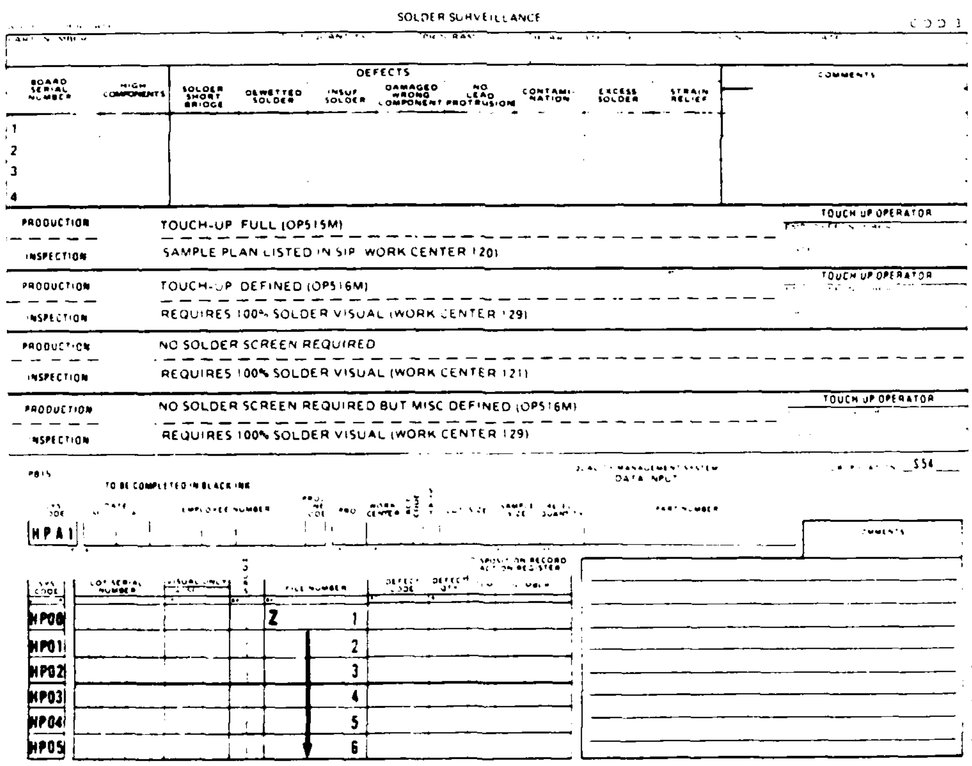


Figure 2. Solder Surveillance Visual Inspection and Touch-up Process


SOLDER SURVEILLANCE

BOARD SERIAL NUMBER	HIGH COMPONENTS	SOLDER SHORT BRIDGE	DEWETTED SOLDER	INSUF SOLDER	DAMAGED WRONG COMPONENT	NO LEAD PROTRUSION	CONTAMINATION	EXCESS SOLDER	STRAIN RELIEF	COMMENTS
1										
2										
3										
4										

PRODUCTION	TOUCH-UP FULL (OP515M)	TOUCH UP OPERATOR
INSPECTION	SAMPLE PLAN LISTED IN SIP WORK CENTER 120)	
PRODUCTION	TOUCH-UP DEFINED (OP516M)	TOUCH UP OPERATOR
INSPECTION	REQUIRES 100% SOLDER VISUAL (WORK CENTER 129)	
PRODUCTION	NO SOLDER SCREEN REQUIRED	
INSPECTION	REQUIRES 100% SOLDER VISUAL (WORK CENTER 121)	
PRODUCTION	NO SOLDER SCREEN REQUIRED BUT MISC DEFINED (OP516M)	TOUCH UP OPERATOR
INSPECTION	REQUIRES 100% SOLDER VISUAL (WORK CENTER 129)	

TO BE COMPLETED IN BLACK INK

DATA INPUT

HPA1

COMMENTS

	FILE NUMBER
HP00	Z 1
HP01	2
HP02	3
HP03	4
HP04	5
HP05	6

Figure 3. Solder Surveillance Form

guide to touch up the rest of the boards in the lot.

- **No Solder Screen** — A total of four solder defects or less on the four-board sample places the lot in the "no solder screen" category. The touch-up operator reworks the defects found on the four boards, and the lot moves to the next operation with no further touch-up.
- **No Solder Screen, but Miscellaneous Defined Defects** — A total of four defects or less in the four-board sample plus other miscellaneous nonsolder defects (e.g., component height over maximum, stamping incorrect, contamination, etc.) comprise this category. The touch-up operator reworks the solder defects on the 4-board sample and the miscellaneous nonsolder defects on the entire lot.

During the production operator's Solder Surveillance evaluation, if a major problem or unfavorable trend is noted, the operator will stop further work on the lot and contact Production Engineering before final disposition is made.

Upon completion of the evaluation, the Solder Surveillance 3-part form is completed, with the top copy going to Engineering and the two remaining copies traveling with the lot as it is processed.

When the lot is completed and submitted to final inspection, the remaining two sheets are completed. One sheet goes to Production Engineering where it is used to compare the production operator's findings with the inspector's conclusions. As required, on-the-spot retraining is conducted to align more closely the Production and Inspection standards.

The last sheet of the Solder Surveillance form goes into our data system to provide inputs for our Daily Acceptance and Yield (DAY) reports. These reports provide daily, weekly, and monthly information to all levels of MAvD. At the production levels these reports are used by all disciplines to formulate immediate remedial actions and, further, to generate refinements and/or enhancements to the overall production process.

ENGINEERING CHANGES AND ENHANCEMENTS

Although the Solder Surveillance Program was primarily designed to disposition lots and control our touch-up process, the data and information obtained has lead to many key engineering changes that have enhanced the process. Four of these changes are described in the following paragraphs.

1. Improved Solderability of Piece Parts

As Solder Surveillance data was gathered and analyzed, it became increasingly apparent that piece part solderability needed to be improved. The data indicated that piece part solderability problems were the largest contributor to solder defects. Both component piece parts and PWBs were affected. It was at this time that several actions were taken to minimize these problems:

- **Improved Solderability Testing and Vendor Communication** — All piece parts were re-evaluated relative to receiving-inspection solderability requirements. Changes were made with particular emphasis on solderability life testing and improved vendor communications as required.

- ***Pretinning of Component Leads*** — Although improved solderability testing was implemented at receiving inspection, it did not solve all solderability problems. A further cause was the unpredictable degree of oxidation of the leads during storage. Many leads are currently being pretinned manually to minimize the problem, but this operation is time consuming and costly.

  To solve this problem, Honeywell is currently designing and fabricating an automatic machine that will pretin taped/reeled axial and radial components. The prototype has been completed and tested, and Honeywell expects to have the first production unit operational early this spring. This new machine is capable of pretinning approximately 120 components—both leads—per minute.

2. Development of a Producibility Manual

Another major cause of solder defects was a result of design related practices. A team of representatives from Procurement, Quality, Design, Drafting, Advanced Manufacturing Technology and Production Engineering were formed to resolve these design related problems affecting production. The team established a usable compulsary standard for the design of printed wiring assemblies that minimizes producibility problems. Some benefits of the new Printed Wiring Board Producibility Standards are:

- Control of new design and E.O. changes affecting PWAs.
- Improved CAD/CAM interface.
- Provision of data for more effective cost trade-off evaluations.
- Improved documentation for vendor of PWBs.
- Improved interdepartmental communication.

3. Minicomputer Control of Wave Solder Machine Parameters

Solder Surveillance data also indicated problems with the wave solder process. For example, preheat settings and conveyor speed could not be determined by board thickness alone. Variables such as density, component size and placement, design, solder mask, physical size and board thickness all needed to be reviewed before a set-up could be determined. With many active part numbers and variables, it became necessary to computerize each individual board assembly number to provide the information necessary for fast, accurate setup. The following information is now available in the minicomputer:

- Preheat temperature
- Conveyor speed
- Top board temperature
- Direction of board assembly through solder wave
- Tooling required
- General comments and requirements.

4. Improved Workmanship Standards

A workmanship standard manual was developed as a training tool to communicate acceptable and nonacceptable criteria to production and inspection personnel. This manual is also used as a ready reference on the production floor.

SUMMARY

The Solder Surveillance Program has been extremely successful in our division, surpassing our initial expectations and producing many benefits. In addition to the tangible improvements, the following intangible benefits have been realized:

- Increased pride in the job and ownership
- Increased flow of communication between disciplines
- Faster response time to solution of problems
- More effective training
- Creation of a common base of information for all disciplines.

The tangible benefits can best be measured by the effect the Solder Surveillance Program has had on the following process trend indicators:

• Final Inspection Soldering Defects per Unit:	Reduced 52%
• Rework:	Reduced 77%
• First Pass Yield:	Increased 42%
• Final Board Test Yield:	Increased 7%
• Productivity:	Increased 22%

We hope, through sharing our experience, that the Solder Surveillance Program will also be beneficial to you.

TROUBLESHOOTING WAVE SOLDERING PROBLEMS WITH STATISTICAL QUALITY CONTROL (SQC)

Mr. P. Prasad P.E.

Boeing Aerospace Company
Seattle, Washington

TROUBLESHOOTING WAVE SOLDERING PROBLEMS WITH STATISTICAL QUALITY CONTROL (SQC)

P. Prasad*, P.E.
D. Fitzsimmons**, C.Q.E.

Boeing Aerospace Company
Seattle, WA

Wave or flow soldering is the most prevalent method of soldering PWA's en masse but does produce some solder defects. These defects occur in the range of 1% to 3% in the aerospace industry. 3% is considered an industry average (Automatic Soldering Technology - The Inspection Prior to Touch-up System, J. W. Williams, General Dynamics, Naval Weapon Center Soldering Technology Seminar, 1981). This is higher than solder defects in commercial industries, but the difference can be accounted for by looser specs for commercial applications and higher volumes which allow standardization.

While 1% to 3% defect rate is consistent with the rates of other kinds of defects and typical Acceptable Quality Levels (AQL's) in aerospace industries, its effect on PWA's having hundreds of solder joints is that comparatively few assemblies come through defect-free. This results in delays to manufacturing, possible deterioration in quality due to the touch-up process, and extra expenses in all affected organizations. Boeing's Electronic Systems Division tackled this problem with the tools of Statistical Quality Control (SQC).

HISTORY

SQC began as a conscious discipline in the 1920's with in-house applications at Bell Labs. During World War II our government adopted it wholeheartedly and private applications proliferated. Thereafter, general disillusionment with government regulations led many companies here to discard the SQC systems as unnecessary paperwork. In Japan however, strict regulations and the associated paperwork were

*Mr. Prasad is a lead engineer in Manufacturing Research and Development at Boeing Electronic Systems Division (BESD), responsible for SMD and soldering technology.

**Mr. Fitzsimmons is a statistical engineer in the Boeing Aerospace Company - Quality Control Assurance organization and an American Society for Quality Control-Certified Quality Engineer.

seen as the solution for a long-standing reputation for poor quality; SQC was not only adopted, but became a source of national pride. The remarkable post war recovery of Japanese industry and its subsequent dominance over world wide markets are largely attributed to SQC.

Among other things, the Japanese followed the advice of an American statistician named W. Edwards Deming. Dr. Deming taught them how to use SQC as a powerful tool that allows the user to measure and then to correct a given process. The major benefit derived from SQC comes from identifying, measuring, and reducing process complexity.

What is SQC?

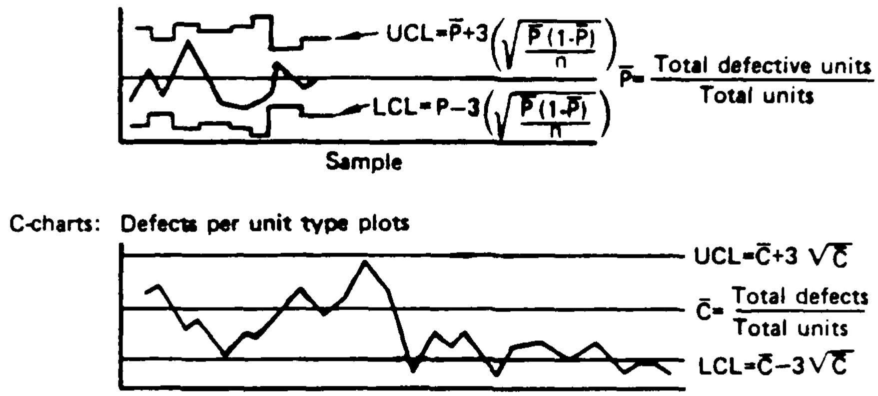
According to Gluckman, a student of Dr. Deming, (Introduction to Statistical Quality Control, Dr. Perry Gluckman, PC FAB, March 1983.) SQC consists of three major elements:

- Process analysis to understand the system
- Inductive reasoning to measure the system
- Leadership to change the system.

To practice all three elements, Gluckman advises to think of manufacturing operations as a series of processes rather than collection of unique events. He believes that reducing process complexity is faster and less costly than increasing process efficiency. One way this is done is by use of a control chart.

The control chart, a graphic record of data, is a tool used to monitor the natural precision of any process by measuring its process average and the amount of fluctuations from that average. The natural precision of a process tells us what to expect as the usual behavior of the fluctuations of a process. The details on how to construct a control chart can be found in the following pamphlets: ANSI Z1.1-1958 (R 1975), Z1.2-1958 (R 1975), and Z1.3-1958 (R 1975) published by the American National Standards Institute, Inc., 1430 Broadway, New York, New York 10018. Examples of common SQC analysis tools, including control charts are shown in Figure 1.

In the following pages we will discuss how we at Boeing Electronics Systems Division (BESD) are using SQC to troubleshoot wave soldering defects.



$$T=\frac{(\bar{X}_2-\bar{X}_1)-0}{\sqrt{S_1{}^2/n_1+S_2{}^2/n_2}}$$

Figure 1. Examples of Common SQC Analysis Tools

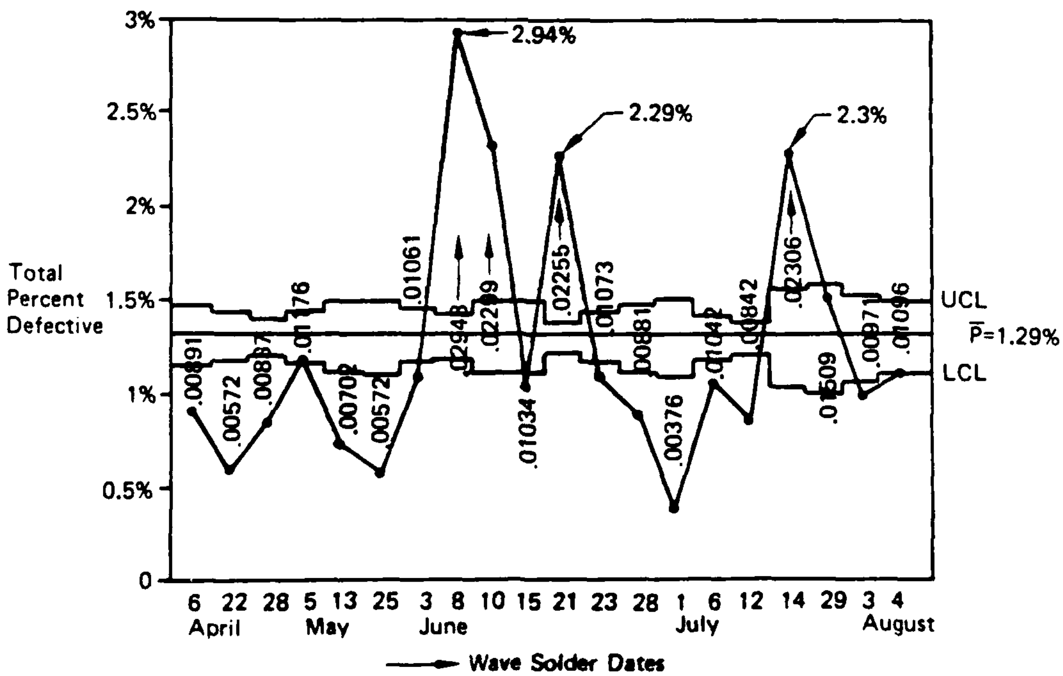


Figure 2. Control Charts for Program A, From April – August, 84

BESD Program Set-Up

We started our wave solder SQC project by attempting to determine statistically what defect rate would indicate a significant change - as opposed to just random variation - from the established average for each of several defect codes. First we regrouped major solder defects into four major categories (Table 1). We also identified the possible machine and non-machine controllable variables (Table 2) that can cause solder defects. Then we determined the relationships, to the extent possible, between the wave solder defects and the wave solder variables. As we can see, there are numerous machine and non-machine controllable variables. It is not an easy task to pin-point the actual cause of a specific defect. This problem is compounded by the fact that more than one variable is generally the cause of a specific defect. We expected the statistical analysis at least to help in narrowing the list of suspect variables.

We collected the data most likely to be related to wave solder defects and sifted it to see which factors were correlated with fluctuations in quality. Most importantly, a statistical software package was developed to facilitate the ongoing use of these techniques as a new standard of business. This software package was made capable of generating graphical reports from many different perspectives to highlight planned process changes and to verify the effectiveness of corrective actions. It also pointed out unplanned changes in quality, both positive and negative.

Large, statistically significant differences between lots existed which would hide any nominal changes we might make in the process average. The quality was not predictable from lot to lot within the bounds of random chance; until we could predict it at least that closely, we would not understand the process well enough to make "conscious and consistent" improvements.

We looked for characteristics which differed between lots that might explain the large variation and found that the list of possible causes was enormous - far more possible causes existed than we could evaluate in the small-lot, short-run environment of aerospace industry. We had to sort these possible causes out some way to identify the few possible causes that had the best chance of explaining the unusual variation.

Table 1. Major Categories of Solder Defects

I Too much solder
- A. Bridging
- B. Excess — component side
- C. Excess — solder side
- D. Icicles

II Too little solder
- A. Dewet lead
- B. Dewet pad
- C. Insufficient flow through
- D. Insufficient — solder side
- E. Holes unsoldered
- F. Pinholes/blow holes/solder voids

III Heat damage
- A. Lifted circuits
- B. Lifted pads

IV Other
- A. Solder wicking
- B. Contamination
- C. Flux residue
- D. Inadequate lead tinning

Table 2. Controlling Variables for Solder Defects

Machine Controllable Variables:

I Flux control
- A. Specific gravity
- B. Inadequate/improper flux application
- C. Contaminated flux

II Preheat temperature
- A. Desired temperature
- B. Uniformity in board temperature

III Conveyor
- A. Speed/angle
- B. Uniformity in two posts
- C. Pallet warpage/improper fixturing

IV Solder wave
- A. Temperature
- B. Roughness
- C. Shape
- D. Depth
- E. Contamination
- F. Composition
- G. Oil intermix

V Mechanical shock before solder solidification

Non-Machine Controllable Variables:

I Printed wiring board (PWB)
- A. Cracked PTH barrel
- B. Organic contamination
- C. Age/oxidation/poor solderability
- D. Insufficient/improper Sn plating
- E. Exposed glass fiber
- F. Exposed intermetallic or a crack at knee of PTH
- G. Moisture in board
- H. Inadequate cure
- I. Large heat sink

II Component Lead
- A. Improper component mounting
- B. Improper lead/hole ratio
- C. Poor lead/hole solderability
- D. Excessive drainage on long leads

III Improper orientation of multileaded devices to direction of soldering

IV Human variables
- A. Inspectors
- B. Operators

RP 84.1

Narrowing of Solder Variables:

A critical event occurred almost immediately after our list of important process factors began to gel. We plotted results from a manufacturing lot of PWA's that were totally homogeneous in their production methods, i.e., same part number, operator, machine settings, wave soldered at the same time, boards with largely the same supplier, date codes, and orientation to the wave. The defect rates, both gross defect rate and defect rates by individual defect codes, were substantially less erratic, but still outside of statistical limits.

Within these lots several factors varied that we could respond to:

- o Board manufacturer
- o Date code of board manufacture
- o Lead length
- o Pallet warpage
- o Rail straightness
- o Oil flow rate
- o Solder schedule

Any study of these factors necessarily had to be done in an environment where the between-lot factors were held constant, i.e., where the subject boards were all wave soldered on the same day, by the same operator, were inspected by the same inspector, and were of the same part number, etc. This limited the information available to evaluate the above factors, so for some we simply initiated corrective actions without proof of those factors actually being a cause of poor quality. For example, a positive pressure oil pump replaced the older, less reliable gravity feed system. We straightened the pallets and replaced the stainless steel rails with straighter, more stable aluminum-titanium rails. We then obtained solderability information on the boards. We also implemented a revised procedure where a production verifier Printed Wiring Assemblies (PWA), a sample PWA from each lot, is soldered and inspected by the operator. If the PWA is satisfactory, the remaining PWA's in that lot are soldered. If not, the corrective action is taken before soldering the remaining PWA's. With these actions we had enough data to give some confidence in the ensueing results discussed below.

Program Unique Differences

One program, designated Program "A" here, was having more solder defects than others. Solder defects for this program were outside of statistical limits (Figure 2) and the defect levels for other programs were within limits (Figure 3). Hence, program A received the spotlight first and three substantial differences appeared: 1) the boards were designed with a metal core not present with other programs, 2) the component leads were not pretrimmed before soldering as was the case on other programs, and 3) the boards were purchased from outside suppliers, whereas on other programs the boards were made in-house.

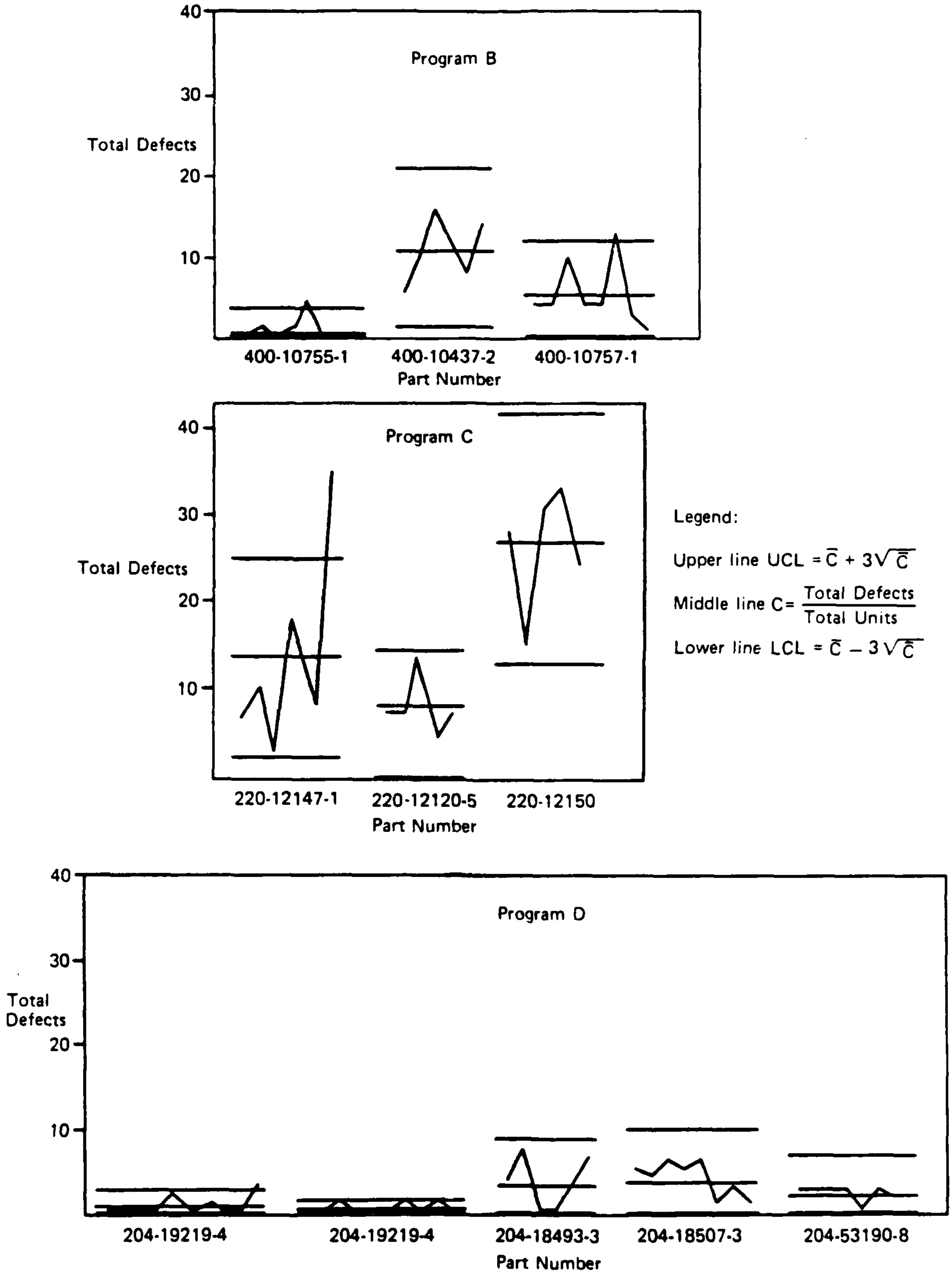
The impact of these three program unique variables on solder defects were investigated. The findings are reported in the next section.

SIGNIFICANT RESULTS

Solder Schedule

Program A defects were analyzed in detail. Control charts on major defects - voids, dewet pad, and dewet leads were prepared. Following the Pareto principle, we decided to tackle the most prevalent solder defects - voids - first.

Voids are generally caused by insufficient drying of flux or poor quality of plated through holes (PTH's). We have found baking to be helpful in reducing voids and measling. So these boards are baked at 200°F for 16 hours before soldering. We checked by float test for the presence of voids caused by poor quality of PTH plating. In this test, a test coupon is dipped in flux and floated on a solder pot to check for voids. PTH quality was found not be the cause of voids. The results were negative. The next item we decided to check was to see if insufficient drying of flux during preheat was the cause for voids. We changed the solder schedule by lengthening the time of preheat. Now board went over four preheaters as opposed to two preheaters before. The preheaters were also adjusted to increase the top side board preheat temperature from 200°F to 230°F. Due to this new preheat schedule, both total defects and voids dropped by 50% (Table 3). This appeared to be significant, but as the control charts show in Figures 4a, b, c, and d, the new schedule improved the process only slightly. Using this SQC tool (control charts, Figure 4), we knew that we made progress, but our job was not done. More variables were studied as discussed below.



RP 84.4

Figure 3. Control Charts for Programs with Process under Control

Table 3. Improvement in Solder Defects Through Solder Schedule for Program A

Defects	Old Schedule	New Schedule
Total defects	1.24%	.84%
Voids	.79%	.53%

Table 4. Improvement in Solder Defects Through Shorter Lead Length — Part Number 1

Defects	Long Leads (0.5")	Short Leads (0.1")
Total defects	3.19%	1.22%
Dewet Leads	1.52%	0.88%
Voids	0.76%	-0-

Table 5. Improvement in Solder Defect Through Shorter Lead Length — Part Number 2

Defects	Medium Leads (0.3")	Short Leads (0.1")
Total defects	1.14%	0.53%
Dewet Leads	0.60%	0.34%
Insufficient Solder	0.29%	-0-

Table 6. Wetting Balance Solderability Test Results (Seconds)

	Program A Boards	
	Vendor 1	Vendor 2
As received	2.69	3.39
After Hot Air Leveling	3.11	3.89

RP 84.2

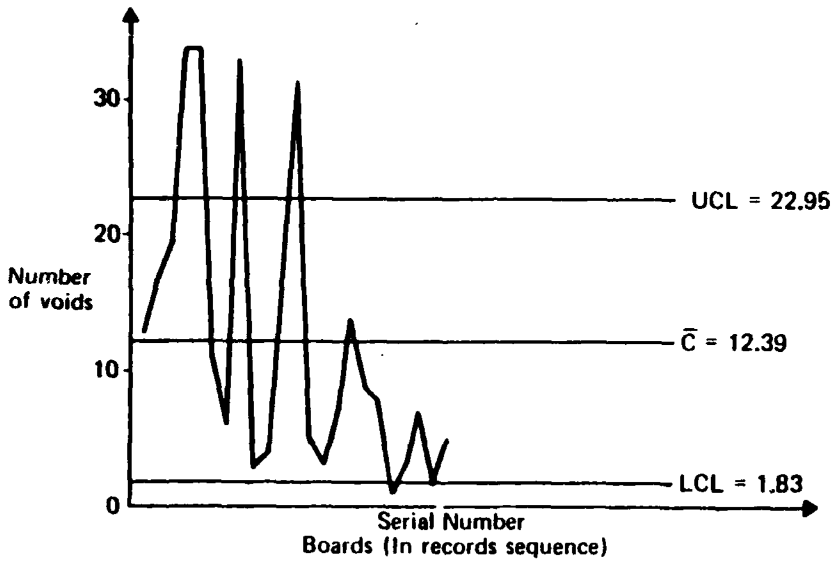


Figure 4A. Void vs Serial Number Old Solder Schedule

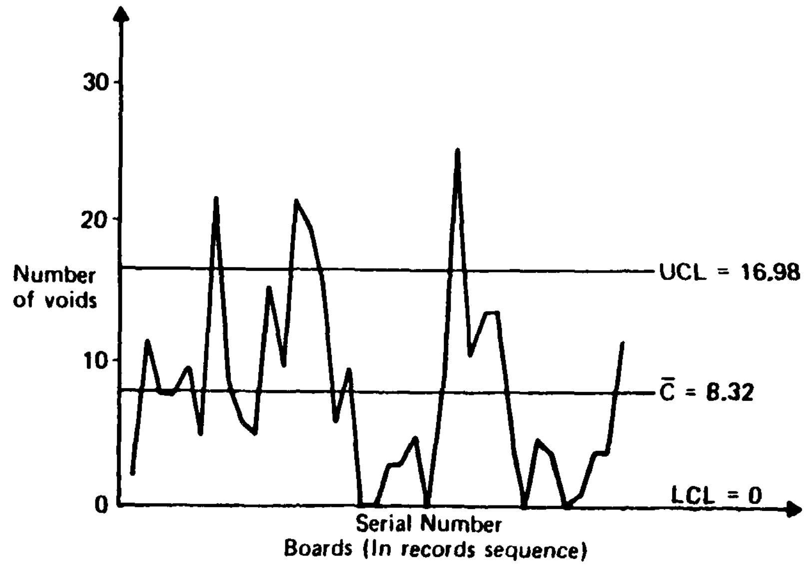


Figure 4C. Void vs Serial Number New Solder Schedule

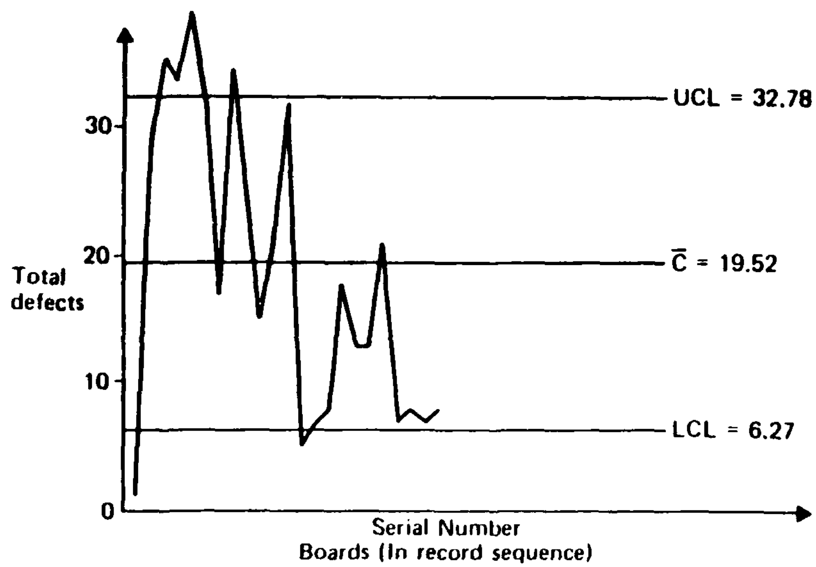


Figure 4B. Total Defect vs Serial Number Old Solder Schedule

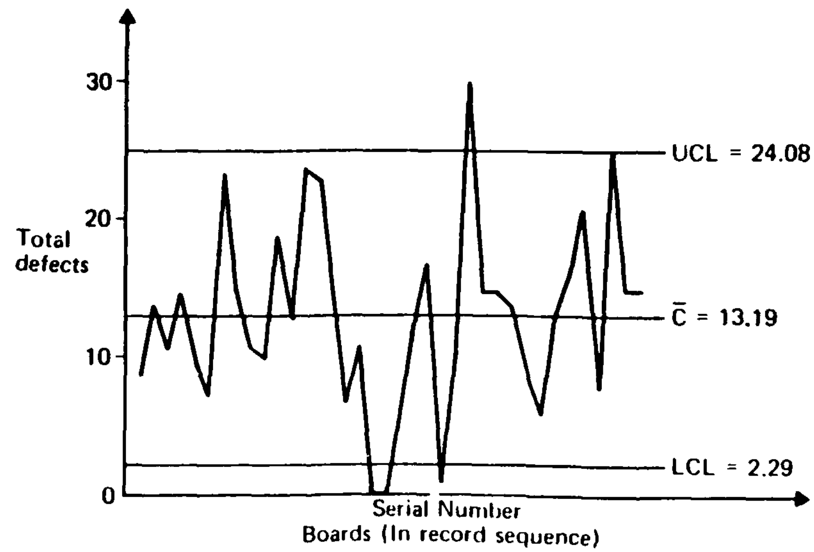


Figure 4D. Total Defect vs Serial Number New Solder Schedule

Long leads:

The most promising possibilities came out of the study of lead length. The component leads on Program "A" were not trimmed before soldering because the flush lead requirement was met more easily if the leads were trimmed after soldering. It was suspected that longer leads might be draining solder causing top side voids or top side dewet leads. Also, there is the everpresent danger of leads hitting the edges of the wave solder pot.

Twenty-one boards were soldered with usual long leads (0.5" lead extension beyond the bottom side of the board to be trimmed flush after soldering) and nine boards with short lead extension of 0.1". The PWA's with shorter leads had less than half as many total defects (Table 4). There was also a dramatic difference in voids - none with short leads and 0.762% with long leads. Performing statistical T test analysis confirmed the differences between short and long leads to be significant.

We were so encouraged by the improvement in solder defects through shorter lead length and its statistical significance that we decided to follow-up on the above lead length study with larger sample size. We selected 60 PWA's: 30 PWA's with medium length leads (0.3 inch) and 30 PWA's with short leads (0.1 inch). The longer leads in this study are only 0.3 inch as opposed to 0.5 inch in the previous study. This was due to practical manufacturing considerations in the shop. Given the evidence of improvement from the first study, the shop could no longer go back to 0.5 inch leads.

The results of this study are shown in Table 5. The defect rate for 0.1 inch leads is half of defect rate for 0.3 inch leads. This turned out to be more due to poor board solderability than lead length although shorter lead length helped some. The difference is not as dramatic as in the first study when lead lengths were 0.5 and .1". This became clear when we plotted defect rate for individual boards for 0.3 inch (Figure 5a) and 0.1 inch (Figure 5b) leads. The defect rate for first half of Figure 6a is about the same as that for Figure 6b. All the short lead board samples and half of long lead board samples were of the same date code. The other half of the long lead boards were of different date code. This sort of thing happens inevitably because these "experiments" are conducted in the shop floor on actual production hardware. In such a situation, selection of sample in a totally scientific manner is not always feasible. But as it turned out, this date code difference led us to another interesting investigation on the effects of board date code, vendors and board solderability on solder defects in more detail. This is the subject of our discussion in the next section.

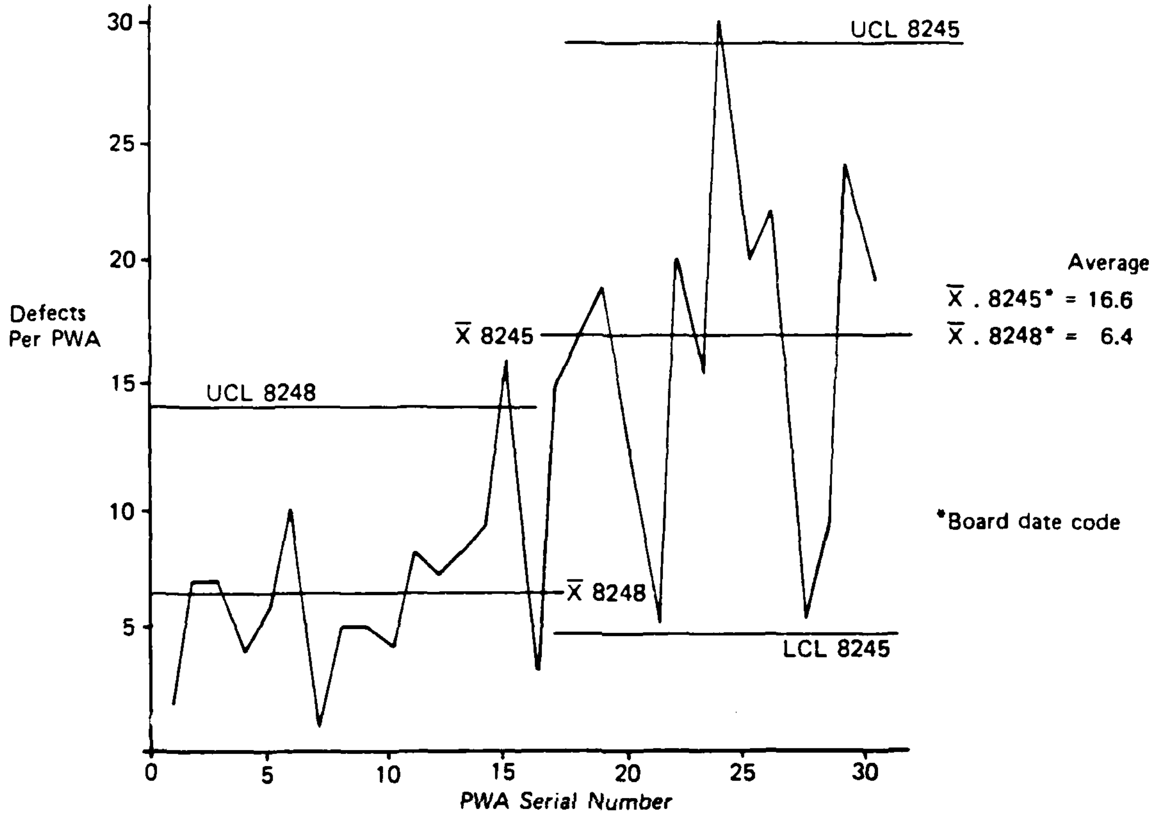


Figure 5A. Defect Versus Board Serial Number for PWA's With 0.3" Lead Extension

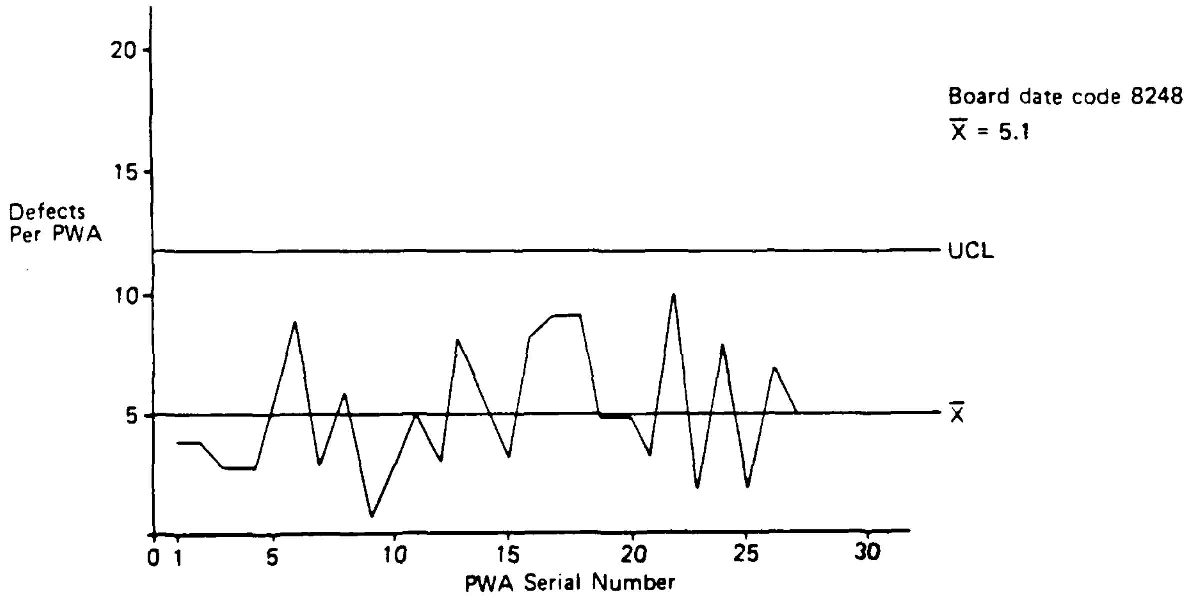


Figure 5B. Defect Versus Board Serial Number for PWA's With 0.1" Lead Extension

RP 84.6

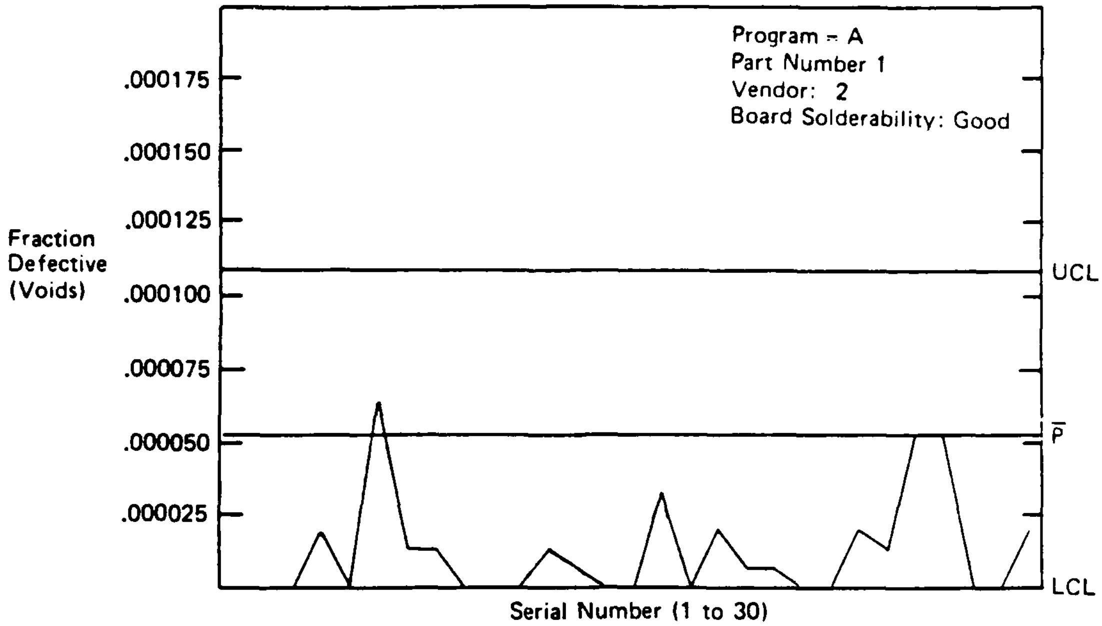


Figure 6A. Control Chart for Defect Versus Serial Number — Date Code 8246

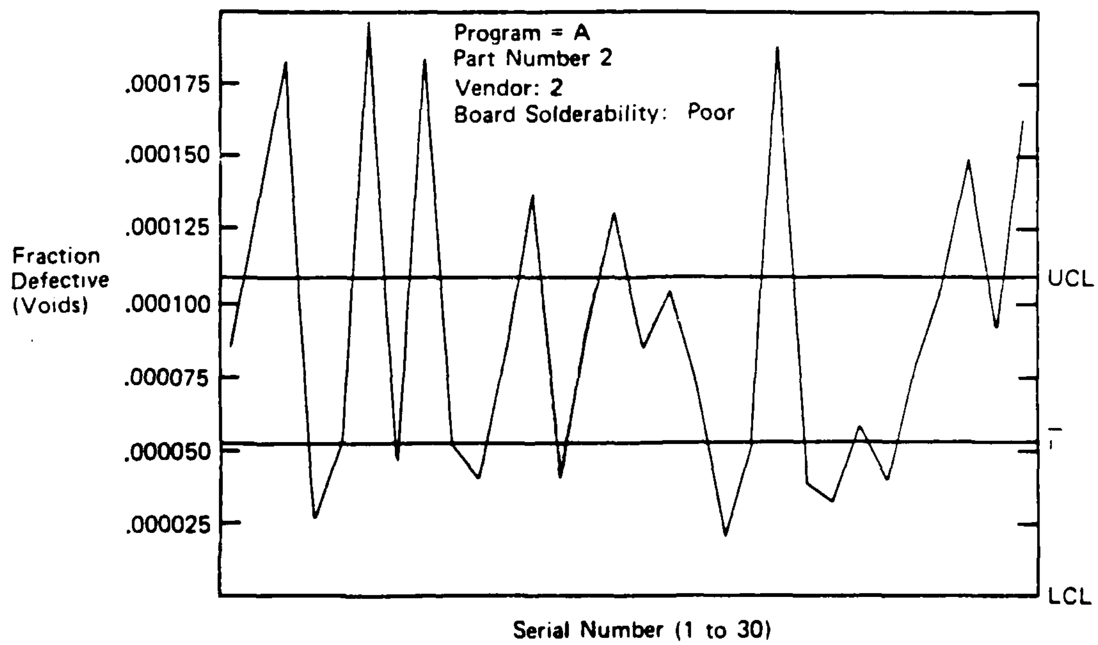


Figure 6B. Control Chart for Defect Versus Serial Number — Date Code 8242

RP 84.7

Board Solderability & Vendors:

Two different lots, 30 PWA's in each lot, were soldered same day by the same operator. Control charts on these two lots indicated one lot to be within control limits (Figure 6a) and the second lot to be out of statistical limits (Figure 6b). When we investigated further, we found that the boards for both lots were supplied by the same vendor, but had different date codes. Using a wetting balance solderability-tester, we determined the plated-through hole (PTH) solderability of the test coupons from each lot. The lot that was out of statistical limits had poor solderability and the lot within control had good solderability.

This led us to further analyze date code versus PTH solderability. Strikingly, older boards were found to be more solderable than the new ones. At first, it appeared to be an anomaly. But this may also have indicated that the supplier was on guard in the beginning and supplied better boards. Later on, however, more schedule than quality pressure may have resulted in poorer quality boards.

We also investigated the difference between the solderability of test coupons between two suppliers. One supplier was consistently better than other (Table 5), even though the difference is not dramatic. This table also shows that hot air leveling was not effective in improving solderability of boards.

Human Variables:

The same operator performed all soldering operations but at least ten inspectors inspected the PWA's. Evidence became available which strongly suggested that these inspectors would report different quality levels even if looking at the same PWA's. We analyzed the defect data for three months (Figure 7). Inspector D reported three times more defects than the average of all inspectors. When this analysis was expanded to defect data for nine months, wide variation in reported defects still existed (Figure 8). This is consistent with the results of many inspector accuracy studies. (The effects of variable inspector errors on rectified single and double sampling plan, J. W. Tucker, et al, Army Materiel Command, Texarkana, Texas, July 1971.)

Further analysis of defect data was conducted by charting defects by each inspector for different part numbers of the same program. The results of only four inspectors

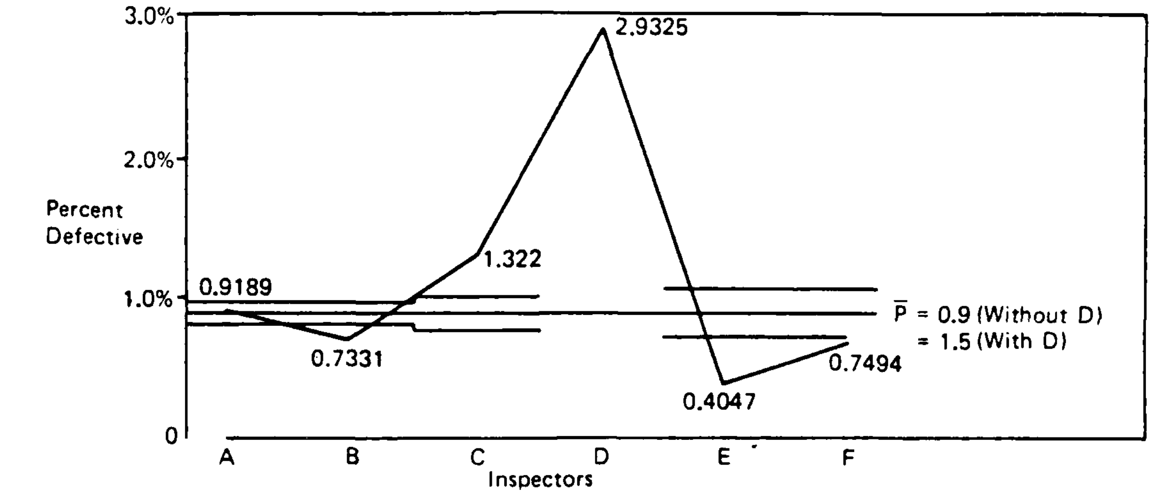


Figure 7. Defect Rate Versus Inspectors for June – August, 1983, Program A

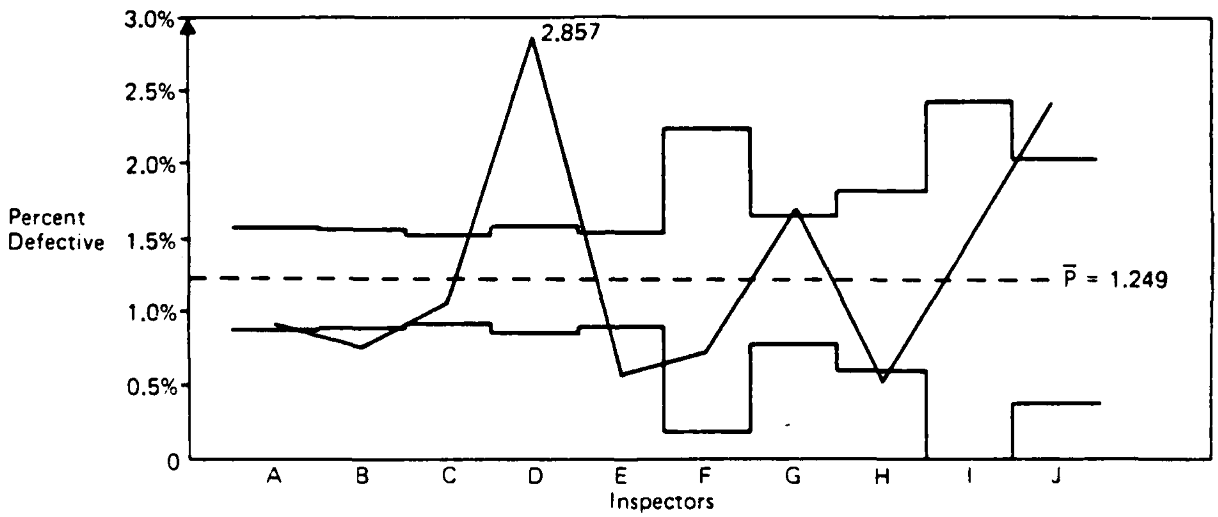


Figure 8. Defect Rate Versus Inspectors for April – October, 1983, Program A

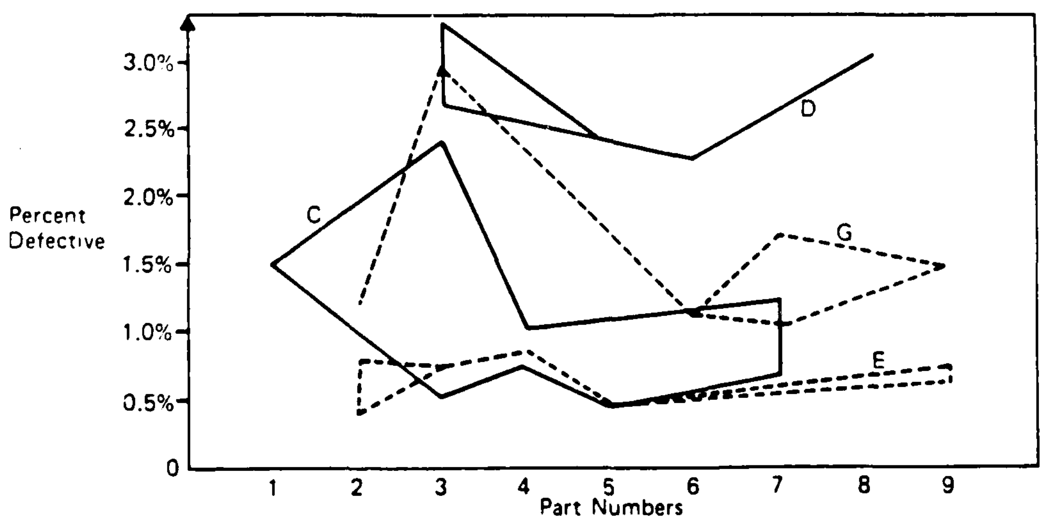


Figure 9. Defect Rate Versus Part Number for Different Inspectors for April – October, 1983, Program A

RP 84.8

are plotted in Figure 9 for clarity. Again, inspector D reported consistently higher defect than others. Inspector E consistently reported lower defect than others and inspectors C and G reported wide fluctuations in defects.

Conclusion

We in RESD have just begun to implement SQC to reduce wave solder defects. The program began in August 1983. The tangible benefits demonstrated by SQC have brought about some changes and more changes are planned for the future. We have also developed SQC software for statistical analysis. We have implemented a few items such as positive pressure oil intermix, improved pallets, new solder schedules, and shorter lead lengths (0.1-0.3 inch). These items have reduced process complexity to some extent and have helped in reducing the defect rate. We have also implemented a revised procedure where a production verifier PWA, a sample PWA from each lot, is soldered and inspected by the operator. If the PWA is satisfactory, the remaining PWA's in that lot are soldered. If not, the corrective action is taken before soldering the remaining PWA's.

The other two important variables that we identified are inspectors and vendors. The most effective way to reduce the human aspects of inspection is to switch to automated inspection of solder joints. Considerable developmental work in this area is being done in the industry. Clarification of vague military requirements and elimination of cosmetic requirements are necessary for auto-inspection to be effective.

At this time, it appears that very little can be done about the vendor related problems especially when the size of the order is fairly small as is the case in small lot production of aerospace industry. However, we are collecting data to be turned over to our Materiel department for necessary action.

The road to total SQC implementation in American companies, ours included, is not an easy one. The cost of data collection and reporting are considered unnecessary. This misconception can be clarified with the tangible benefits of SQC like reducing defect rates and the intangible benefits such as improved quality and better customer relations. We have to realize that it is better to change the process so there is less spilled milk than to spill the milk and then to save it.

THE MEASUREMENT OF FATIGUE SUPPRESSION IN ELECTRONIC SOLDER JOINTS

C.A.Neugebauer, H.F.Webster, H.D.Solomon, and R.O.Carlson
General Electric Corporate Research & Development
Schenectady, NY 12345

ABSTRACT

The large cyclic plastic deformation experienced by the solder joints in electronic equipment while in service generally limits its useful service life due to fatigue failure. In this paper the solder joint fatigue phenomenon is observed with an acoustic microscope, and also by following the increasing thermal resistance of the joint.

The acoustic microscope allows the direct observation of the fatigue crack in the solder joint. Under optimum conditions, considerable defect structure is also visible in the solder joints, such as trapped solder slag, solder voids, and even the grain structure.

The increased thermal resistance of the solder joint is another sensitive measure of the extent to which the fatigue crack has propagated. Using this technique, it was possible to demonstrate the strong detrimental effect of cycling in a non-hermetic package on the one hand, and the strong positive effect on fatigue life by mechanically reinforcing the solder joint. In this latter approach it was shown that even a modest pressure on the solder joint in the direction perpendicular to the shear plane resulted in a manifold reduction in the rate of the thermal resistance increase in thermal cycling. Attempts to compare different solder compositions will be shown and how the fatigue life may be estimated.

The Measurement of Fatigue Suppression in Electronic Solder Joints

C.A. Neugebauer, H.F. Webster, H.S. Solomon and R.O. Carlson

General Electric Corporate Research & Development

Schenectady, NY 12345

Introduction

The large cyclic plastic deformation experinced by solder joints in electronic equipment while in service generally limits its useful life due to fatigue failure. Approaches are being developed to suppress this fatigue, such as the use of Kevlar-epoxy wiring boards, instead of glass-epoxy boards, to better match the thermal expansion coefficients. In this paper we describe our experience in measuring solder fatigue in electronic joints to measure our success in devising methods to suppress it. These include direct observation of the fatigue crack in the acoustic microscope, the increasing thermal resistance of the solder joint, and decreasing load required to traverse a given plastic excursion in stress-strain cycling in shear, in an Instron machine.

Direct Observation of the Fatigue Crack in the Acoustic Microscope

The fatigue crack in the joint propagates as the structure is stressed cyclically. Such cracks can be seen sometimes in solder fillet between the parts, but the motion of such cracks in the gap cannot be followed by conventional means. These cracks do not show up in x-rays because there is no change in the total thickness of solder. However, the ultrasonic microscope can detect such cracks. Figure 1 is a photo of a sample which has shown a large increase in thermal resistance after thermal cycling. The silicon cracked into two parts early in the cycle test and each part is still holding to the base by only a small part of the area. Cracks appear to have propagated inward from several parts of the edge.

The Thermal Resistance Increase as a Measure of Thermal Fatigue

Measuring the thermal resistance is a powerful method to follow the progress of the fatigue crack, particularly if the solder joint is in the thermal path between a silicon chip and the heat sink. It has been used extensively in the power electronics industry as a measure of the quality of the solder joints in power device packages.

Figure 2 illustrates the thermal resistance increase in a power device consisting of 2 solder layers, when thermally cycled. An increase in the thermal resistance of as much as 10X can often be obtained after only a few hundred cycles. Actually the fatigue crack area is still quite small; however, because of its positive temperature coefficient, the device current tends to concentrate just above the fatigue crack, leading to a greatly amplified signal. Further, measurement of the transient thermal impedance of such a device during thermal cycling can give information about the actual location of the fatigue crack in the device package. This is illustrated in Figures 3a and 3b, which contrast the shape of the transient thermal impedance curves when the fatigue crack occurs in either of the two solder layers in the package.

Testing for Fatigue Suppression by the Thermal Resistance Technique

We have recently reported[1] that solder fatigue can be greatly accelerated if thermal cycling occurs in a corrosive environment, such as moist air. The success, of lack of it, of various encapsulation techniques can be easily tested by following the thermal resistance of the solder joint as a measure of the fatigue crack propagation. This is illustrated in Fig. 4. We have also reported[1] on the importance for the fatigue life of forces applied in the direction perpendicular to the shear plane in which the solder plastically deforms. Again the thermal resistance of the solder joint is a sensitive measure of the effect of Z forces on the fatigue life, as illustrated in Fig. 5. The same effect is observed when making the thermal measurement under pressure, as indicated in Fig. 6.

Method to Estimate Solder Fatigue

This method is based on the device geometries and thermal expansion coefficients, the expected application of the device, i.e., the number and severity of the thermal excursions, and N-S plots. The procedure is summarized in Table I.

Table II gives the parameters which determine time to failure due to solder fatigue for an application of a power device containing three solder joints which involves three different types of thermal cycles. While this method has not been tested against field experience, it probably is capable of identifying the most fatigue prone joint in any given design.

Isothermal Displacement Cycling

Experimental Procedures

Thermally cycling devices provides a good overall view of the device fatigue behavior, but unfortunately this type of testing does not provide information on the nature of solder fatigue per se. Therefore, to get such information, highly controlled, low cycle fatigue tests are being run on solder layers. Low cycle fatigue data exists in the literature but for the most part these tests were run on bulk tensile or bend specimens, (2,3) which are orders of magnitude thicker than the layers of solder used to hold things together. In our experiments the solder exists as a 0.005-0.010 layer which bonds two halfs of the test assembly together. This layer is then tested in fully reversed shear. An important feature of these tests is the close control of the test variables. Displacement and loads as small as 5 microinches and 0.8 lbs. are typically resolved, with displacement limits as small as 25 microinches being employed in the control of the test. Such high resolution is required because thin layers rather than bulk specimens are being studied. With a 0.007" thick layer a displacement of 25 microinches produces a shear strain of only 0.00357 or 0.357%. While working with a thin layer produces experimental difficulties, such an approach is considered more appropriate because it more closely models the solder layers of real devices.

The tests have been run in a servohydraulic testing machine with the specimen and grips enclosed in a chamber. The temperature of this chamber is controlled to within ± 0.2°C and tests have been run at -50°C, +35°C and +150°C. The chamber is usually purged with flowing N_2 gas during the test but other enviroments (such as wet N_2, wet or dry air) can also be employed and are planned to be employed.

Figure 7 shows a series of typical load-displacement hysteresis loops obtained in a test on type 60/40 solder tested at 35°C in dry N_2. Two types of loops are shown. Those marked ε_T utilize the signal directly from the displacement transducer and display the total displacement. Those marked ε_p utilize a modified displacement signal. Using an analog computer a signal which is equal to the load, P, times a constant is subtracted from the total displacement signal. This constant is adjusted so that when the specimen is cycled elastically the resultant P-$\mathcal{E}$ signal is made a vertical line. Thus the computer can be made to subtract the elastic signal leaving only the non elastic displacement, which is used in the P-$\mathcal{E}_p$ curves. The use of the plastic strain computer is necessary because when testing a thin layer it is impossible to measure only the displacement of the layer. The need to attach the extensometer to something and the requirement that these attachments be robust enough not to deform during handling or testing means that the extensometer must be placed at some distance from the solder layer. It therefore measures some of the elastic strain of the test assembly in addition to the elastic and non-elastic strain of the solder layer. Since the loads employed are too low to produce non-elastic displacements in the test assembly, the plastic strain computer yields a signal which is proportional only the non-elastic displacement of the solder layer (hereafter to be referred to as the plastic strain $\mathcal{E}_p$).

The encorporation of non-solder displacements in the total displacement signal gives rise to the apparent elastic nodules being low. The total strain is defined as the total displacement divided by the specimen thickness, i.e.,

$$\Delta\mathcal{E}_T = \frac{\Delta_{EA} + \Delta_{ES} + \Delta_{PS}}{t_s}$$

where Δ_{EA} = elastic displacement of the assembly

Δ_{ES} = elastic displacement of the solder layer

Δ_{ps} = non-elastic displacement of the solder layer

t_s = thickness of the solder layer

The shear modulus Y is measured as

$$Y = \frac{\frac{P}{A}}{\frac{\Delta_{EA} + \Delta_{ES}}{t_s}} = \frac{P t_s}{A(\Delta_{EA} + \Delta_{ES})}$$

where P is the load and A is the area of the solder layer. If only the displacement of the solder layer was being measured $\Delta_{EA} = 0$ and Y should be on the order of 2-3 x 10^{-6} psi. The measured values of Y are actually about 0.15 x 10^{-6} psi which means that for the test assembly being used and the position of the extensometer, $\Delta_{EA} = 16 \Delta_{ES}$. This large difference stems from the fact that the solder thickness is only about 0.007" while the distance between the extensometer measuring points is on the order of 0.300" (Δ_{EA}/Δ_{ES} is not just .3/.007 because the cross sectional area of the assembly is larger than that of the solder layer).

The plastic strain is given by:

$$\Delta \varepsilon_p = \frac{\Delta_{ps}}{t_s}$$

where Δ_{ps} the non-elastic displacement is determined from the hysteresis loop or plastic strain computer (i.e., it is the displacement which is not linearly proportional to the load, divided by the solder thickness).

The distinction between $\Delta\varepsilon_T$ and $\Delta\varepsilon_p$ is especially important in deciding on how to control or limit the cycling. If $\Delta\varepsilon_T$ is chosen as the parameter upon which to limit the cycling (i.e., the parameter used to signal when to reverse the direction of loading) the incorporation of non-solder elastic strains can lead to experimental errors. The solder experiences a strain which is actually less than $\Delta\varepsilon_T$ (the solder does not experience the elastic assembly displacement but in measuring $\Delta\varepsilon_T$ some of this displacement is incorrectly ascribed to the solder layer). The plastic strain is unaffected by the elastic assembly displacements since these are subtracted out by the plastic strain computer. Thus one can measure the plastic strain being imposed upon the specimen but one must calculate the elastic strain of the solder. If $\Delta\varepsilon_T$ is incorrectly defined as the solder total strain (elastic + plastic strain), then an error results, the relative magnitude of which depends upon the magnitude of the plastic strain in the solder layer.

Using limits of $\Delta\varepsilon_T$ presents an additional problem. As the load drops, due to crack growth or cyclic softening, the elastic strain also drops. Since the total strain limit is being kept constant the plastic strain of the specimen must increase to compensate for the decrease in the elastic strain. Since $\Delta\varepsilon_T$ contains the large contribution of Δ_{EA}, the increase in Δ_{ps} will be much larger than it would be if Δ_{EA} were not included in $\Delta\varepsilon_T$. The way around these problems and the approach followed in these experiments is to strain cycle with Δ_{ps} limits and to correlate the data with respect to $\Delta\varepsilon_p$ instead of $\Delta\varepsilon_T$. Fortunately it is usual to correlate low cycle fatigue data with respect to the plastic strain.

In all of the experiments described here ramp loading and unloading was employed. When a preset limit of $+\varepsilon_p$ was reached the cross head reversed until the other limit of $-\varepsilon_p$ was reached, where upon the crosshead reversed again. The cycling was fully reversed with the positive and negative shear displacements being the same(i.e. $|+\varepsilon_p| = |-\varepsilon_p|$ And $\Delta\varepsilon_p = +\varepsilon_p - (-\varepsilon_p) = 2\varepsilon_p$)

Figure 7 shows typical P-ε hysteresis loops for this cycling. All of the tests were run with a period of 3.2 - 3.8 sec. (i.e., at a frequency of ~ 1/3 Hz), at 35°C. Almost all the tests were run in dry N_2, a few however were run in lab air, with no significant difference between the results.

Two types of solders were tested types 60/40 (60 Sn, 40 Pb) and 151 (92.5 Pb, 5 Sn and 2.5 Ag). The test assemblies were prepared as follows:

1. The areas to be soldered were prewet with solder using flux (the areas were defined by being on raised portions of the assembly blocks with a Si on the surrounding area. The area being soldered was 0.1" x 0.5" with the direction of shear being in the 0.5" direction.

2. The half of the assembly blocks were then rewet, this time with a 0.003-0.004" solder layer, also using flux (in step 1 only a very thin layer of solder was applied with care being taken to insure that all the test assembly area was wet with solder).

3. The solder of two test assembly blocks was then reflowed to make the final joint. The assembly blocks were separated by spacers which defined the thickness of the solder layer. When the solder was melted in this reflow step the solder area were not directly above one another, but were displaced. Then after the solder melted the blocks were slid into the correct alignment. This was done to prevent entrapped gas bubbles. This entire operation was performed in a box containing N_2. After the blocks were aligned the entire box and assembly was slid off the hot plate where the melting was achieved, on to a cold plate where the solder solidified. The times and temperatures were monitored and controlled during this entire operation, so that the process could be as repeatable as possible.

The test assembly was then bolted into the test grips. The bottom grip utilized a woods metal alignment system. During the assembly operation this grip was free to move, after assembly the grip was frozen in place. This allowed the test specimen to be inserted in as stress free a manner as possible. Without such an approach the solder layer can be severly strained during insertion in the grips.

Preliminary Experimental Results and Discussion

This program is still ongoing so only some preliminary results will be discussed here. Tests have been run at -50°C, +35°C, and +150°C with cycling frequencies of from 3×10^{-5} to 3.3×10^{-1} Hz. We shall only discuss tests run at 35°C and 3.3×10^{-1} Hz.

Figure 7 shows an example of the hysteresis loops which were recorded periodically during each test. In addition a continuous record of the load and strain was made on strip chart recorders. The load record was particularly interesting. In most LCF tests cited in the literature the maximum load either increases or decreases due to cyclic hardening or softening and then reaches a plateau, which is followed by a decrease in load due to crack nucleation and propagation. These tests on solder differed in that there was no plateau of constant load. The load either started dropping after the first 1/4 cycle as in figure 1 or there was at most only one or two cycles of load increase followed by a continuous decrease in the maximum load (this latter behavior was typical at -50°C for both the 60/40 and 151 solders). It is believed that this load drop was due to cracking of the solder and that the load drop can be used as a crude measure of crack propagation (ultrasonic microscopy on interrupted tests are planned to determine the exact correlation between the load drop and the cracking of the solder layer).

Figures 8 and 9 show the drop in load as defined by $\phi = 1 - \Delta p/\Delta p\ max$, where Δp is the load range for any cycle and $\Delta p\ max$ is the maximum load range observed during the test. As can be seen $\ln \phi = A \ln N + B$. All the ϕ-N curves are not as well behaved as that of figures 2 and 3. In some there are tails at large and small values of ϕ. However between $\phi = .1$ and $\phi = .9$ there is good linear behavior. At -50°C there is a significant break in the ϕ vs. N curve even in the $\phi = .1$ to .9 range.

Work is ongoing to convert the ln ϕ vs. ln N curves to crack growth curves and from these define the LCF in terms of crack propagation. The other approach, and the one currently being employed is to define the fatigue life in terms of the number of cycles for the load to drop a given amount and then correlate this life with the $\Delta\varepsilon_p$ employed in the test. This is done in figures 10 and 11 where the lines for $\phi = .1$, .5, and .9 are shown vs. $\Delta\varepsilon_p$. There is considerable scatter in the $\phi = .1$ data, which is not surprising since this data is most subject to variations in the nucleation rate and cyclic hardening or softening effects. There is much less scatter in the ϕ = .5 or 0 = .9 data.

Figures 10 and 11 illustrate that both solder exhibit Coffin-Manson type behavior, i.e., $N_f = C\,\Delta\varepsilon_p^{-(1/\alpha)}$. The 60/40 solder has a Coffin-Manson fatigue exponent, α, of about 0.6 which is typical. The exponent for the 151 solder is $\approx$0.8. This data illustrates that while both solders exhibit typical LCF behavior it is a mistake to assume that both have a Coffin-Manson exponent of 0.6. Tests run at -50°C and +150°C are showing that α is a function of the cycling temperature. Tests run at frequencies other than 1/3 Hz are showing a significant influence of the cycling frequency on the life with the life decreasing as the cycling frequency decreases.

REFERENCES

1. "Semiconductor Chip Design Constraints Imposed by Package Limitations." C.A. Neugebauer, Tech. Digest, IEDM, Dec. 5, 1983 (pg. 5.1).

[2] R.N. Wild, Welding J., V. 51, pp 521S-526S (1972).

[3] H.S. Rathore, R.C. Yih and A.R. Edenfeld, J. of Testing and Evaluation, V. 1, pp 170-178 (1973).

TABLE I

PROCEDURE TO ESTIMATE FATIGUE LIFE

1. IDENTIFY THOSE DEVICES WHICH ARE THE MOST FATIGUE PRONE.
2. OBTAIN THE GEOMETRY OF EACH SOLDER JOINT IN THE SUSPECT DEVICE STRUCTURE.
3. OBTAIN THE CONDITIONS UNDER WHICH THE DEVICE IS EXPECTED TO BE USED.
4. CALCULATE THE THERMAL RESISTANCE OF EACH PACKAGE COMPONENT.
5. CALCULATE THE TEMPERATURE INCREASE ABOVE AMBIENT AT EACH INTERFACE UNDER POWER DISSIPATION.
6. CALCULATE THE STRAIN EXCURSION PER CYCLE FOR EACH SOLDER LAYER.
7. CALCULATE THE CYCLES TO FAILURE USING THE COFFIN-MANSON RELATION.
8. DIVIDE N_f BY THE NUMBER OF SUCH CYCLES WHICH THE DEVICE IS EXPECTED TO ENDURE DURING ONE YEAR; THIS GIVES THE PRELIMINARY TFF.
9. IDENTIFY THE MOST FATIGUE PRONE JOINT; IT HAS THE SHORTEST PRELIMINARY TFF.
10. FROM THIS PRELIMINARY TFF SUBTRACT THOSE PORTIONS OF THE FATIGUE DAMAGE CONTRIBUTED BY ALL OTHER STRAIN EXCURSIONS.

TABLE II

PARAMETERS WHICH DETERMINE
TIME TO FAILURE
DUE TO SOLDER FATIGUE

A. Slow ambient and average power cycle, 1 cycle/day required

Parameter	Solder joint 1	Solder joint 2	Solder joint 3
ΔT_U, °C	41.1	41.1	41.1
ΔT_L, °C	41.1	41.1	41.1
T_{max}, °C	100	100	100
ϵ, %	0.88	1.3	5.1
N_f, cycles to failure	$2 \cdot 10^6$	$7 \cdot 10^5$	$6 \cdot 10^4$
n_A, cycles per year	365	365	365
Years before failure	5500	1900	160

B. Power cycles of 1 min duration, 240 cycles/day required

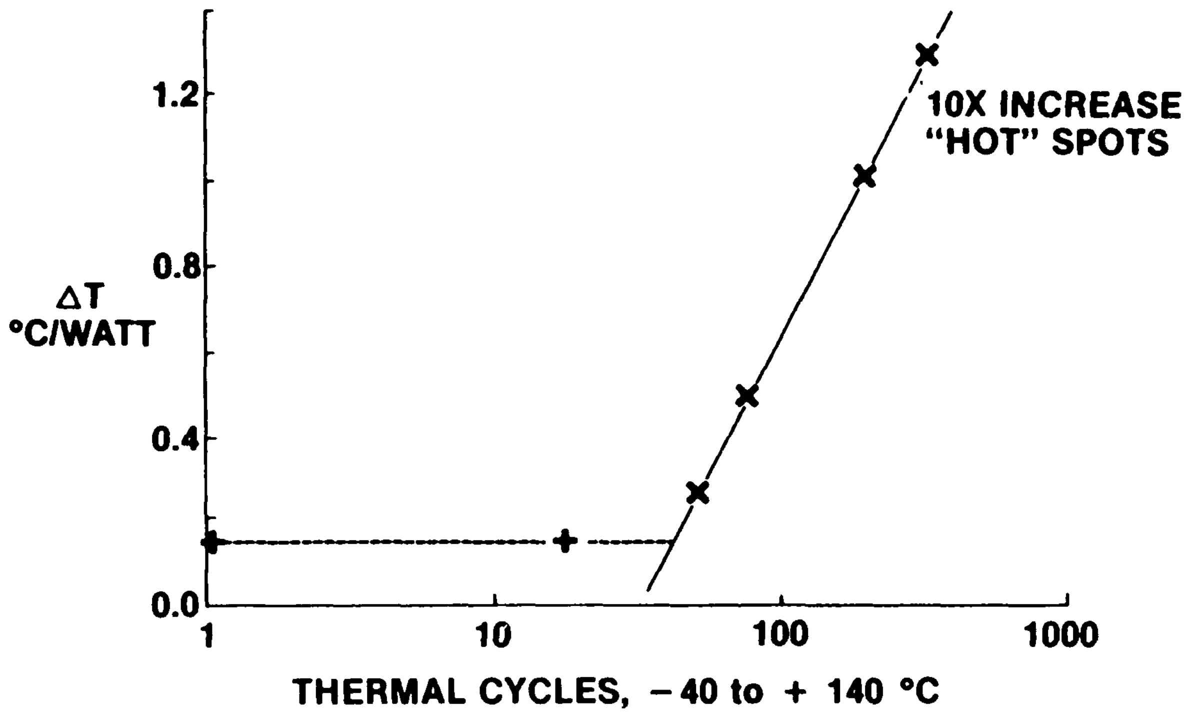
Parameter	Solder joint 1	Solder joint 2	Solder joint 3
ΔT_U, °C	20.6	19.0	15.8
ΔT_L, °C	20.6	17.4	14.7
T_{max}, °C	83	81	78
ϵ, %	0.44	0.51	2.3
N_f, cycles to failure	$3 \cdot 10^7$	$2 \cdot 10^7$	$4 \cdot 10^5$
n_B, cycles per year	87,000	87,000	87,000
Years before failure	340	230	4.6*

C. Power cycles of 5 min duration, 16 cycles/day required

Parameter	Solder joint 1	Solder joint 2	Solder joint 3
ΔT_U, °C	30.9	28.5	23.7
ΔT_L, °C	30.9	26.1	22.1
T_{max}, °C	99	97	92
ϵ, %	0.66	0.77	2.6
N_f, cycles to failure	$7 \cdot 10^6$	$3 \cdot 10^6$	$2 \cdot 10^5$
n_C, cycles per year	5900	5900	5900
Years before failure	1200	510	34

* Most fatigue prone

Fig. 1 An ultrasonic microscope image of a solder bond region after severe thermal cycling.



LARGE TEMPERATURE RISE WITH THERMAL CYCLING. IS ONLY 10% OF THE SOLDER LAYER CONDUCTING?

Fig. 2 Thermal resistance increase in a power device during thermal cycling. The increase is large because hot spots form in the silicon chip just above the fatigue crack.

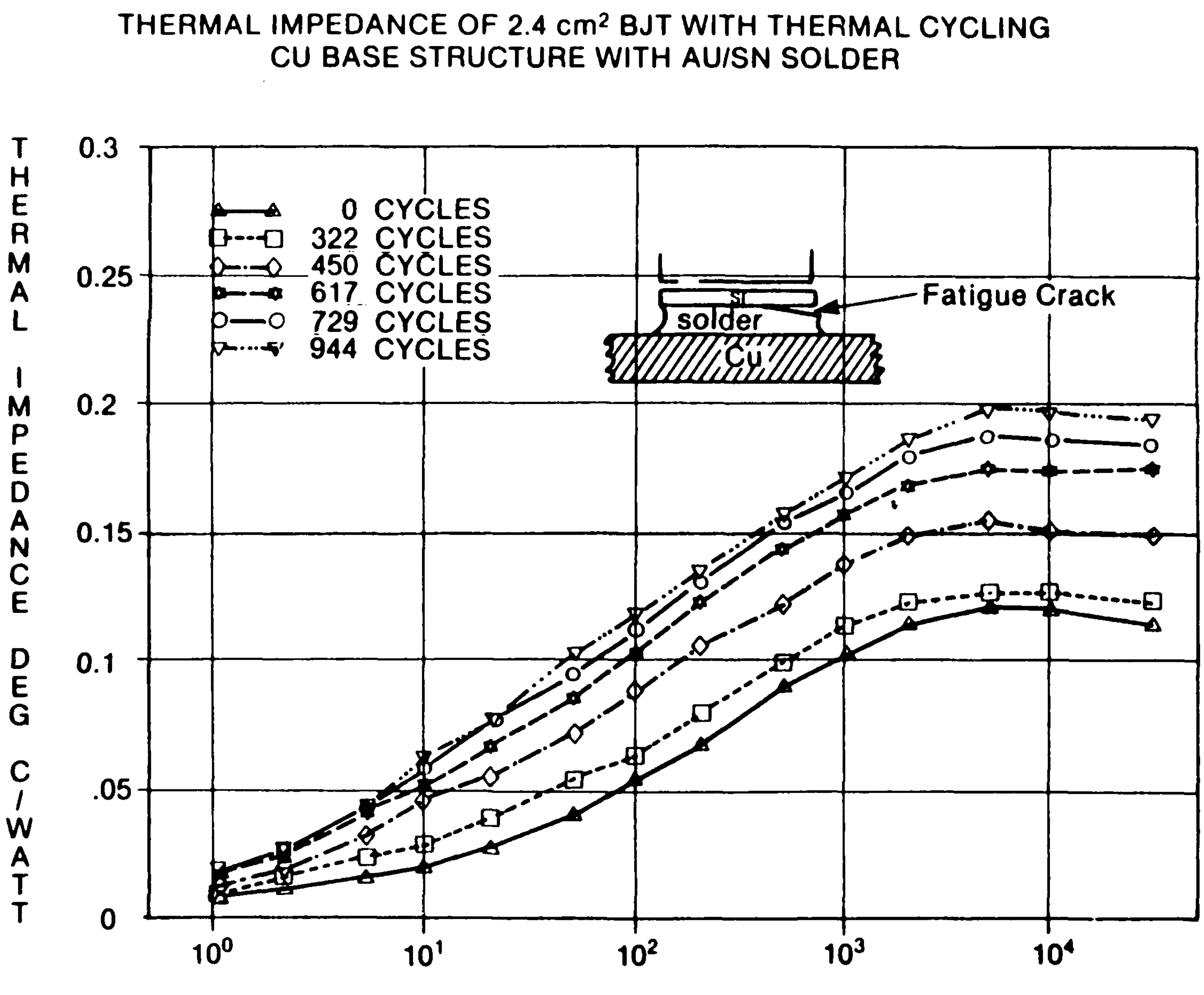


Fig. 3a Thermal impedance increase of a bipolar junction transistor with thermal cycling. The shape of these curves, and their rate of change on cycling, can be interpreted as chip delamination.

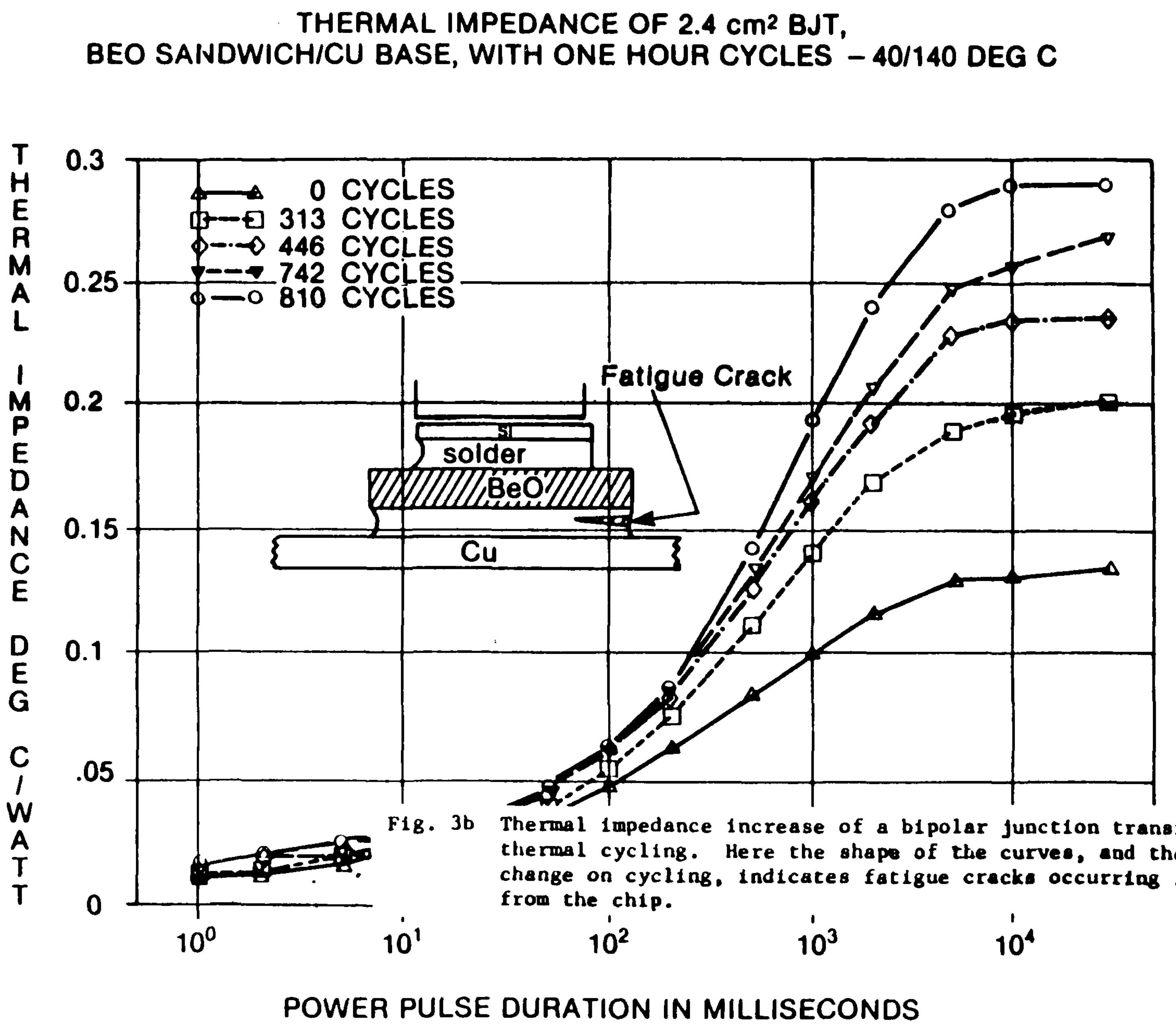


Fig. 3b Thermal impedance increase of a bipolar junction transistor with thermal cycling. Here the shape of the curves, and their rate of change on cycling, indicates fatigue cracks occurring further away from the chip.

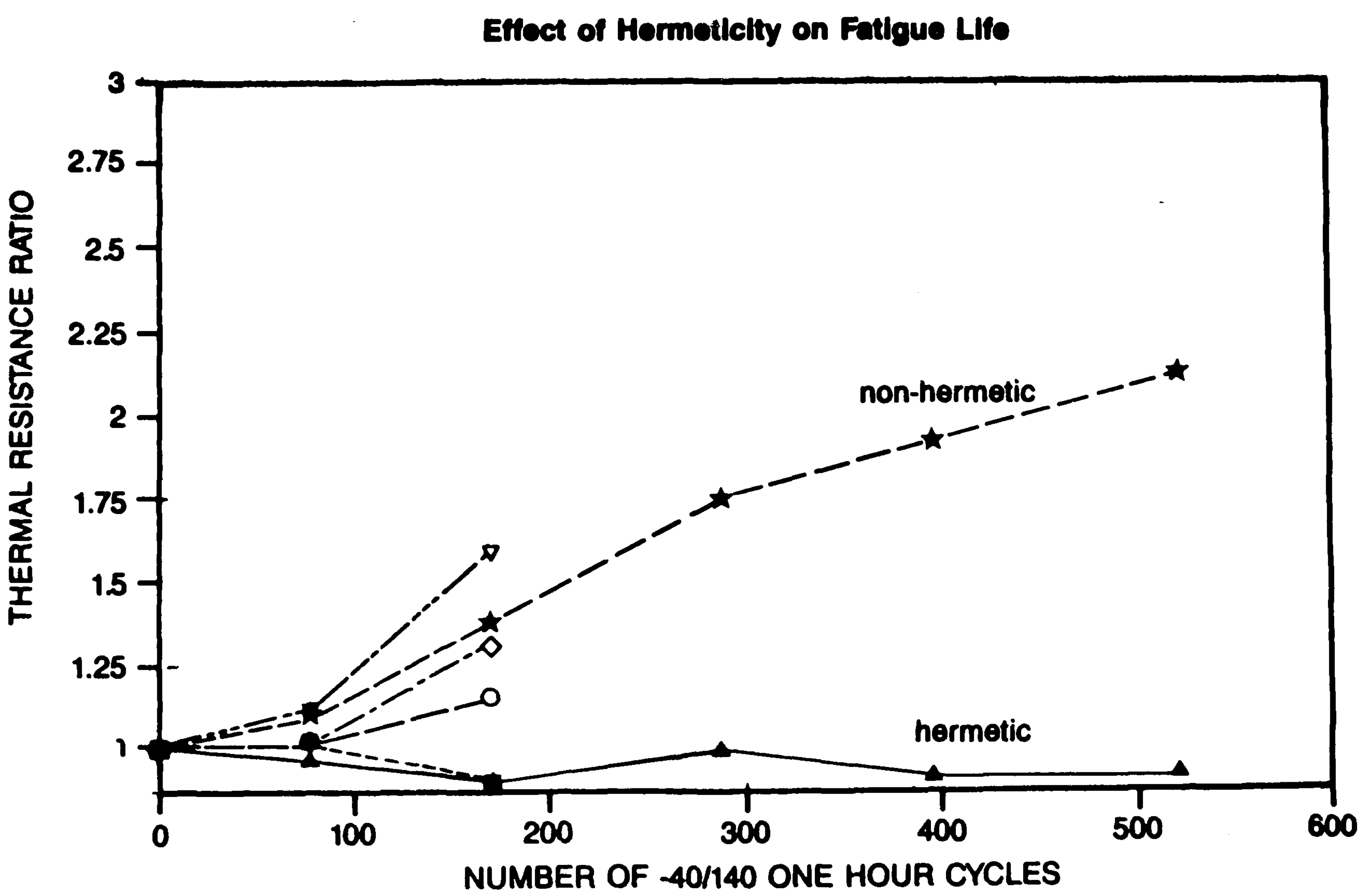


Fig. 4 Effect of Hermeticity on Fatigue Life.

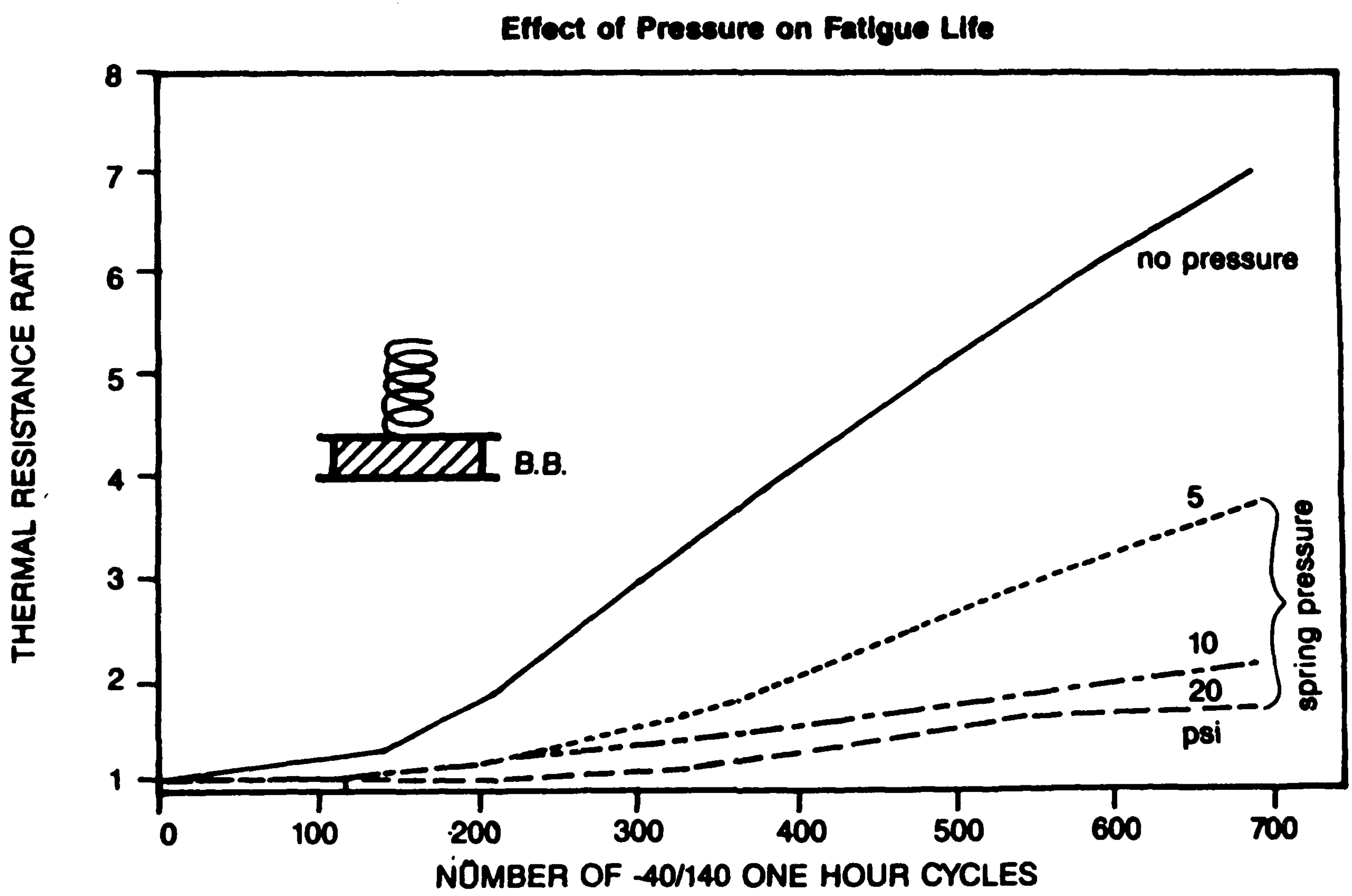


Fig. 5 Effect of Pressure on Fatigue Life.

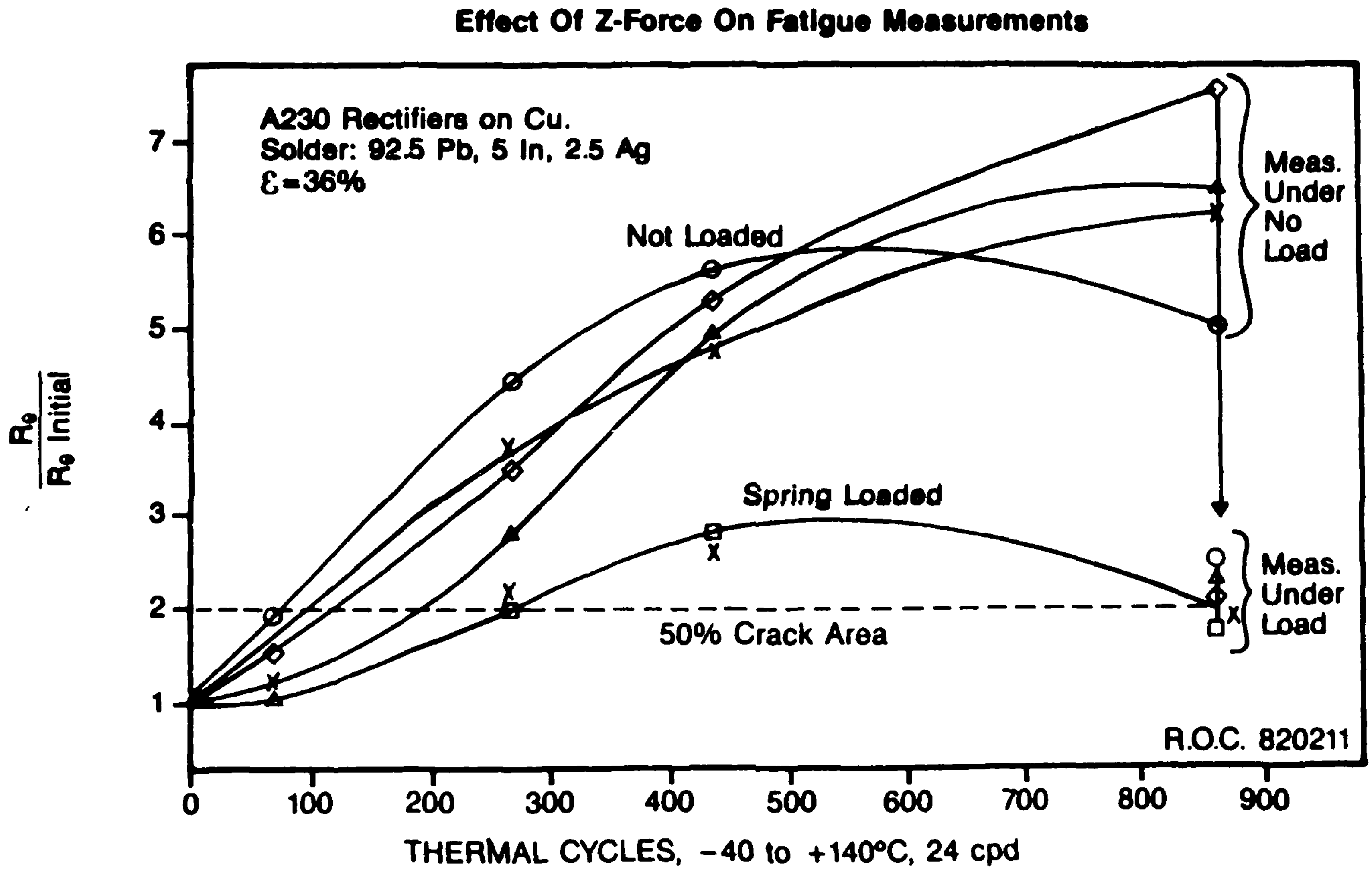


Fig. 6 Putting pressure on the solder joint after thermal cycling compresses the fatigue crack and decreases the thermal resistance.

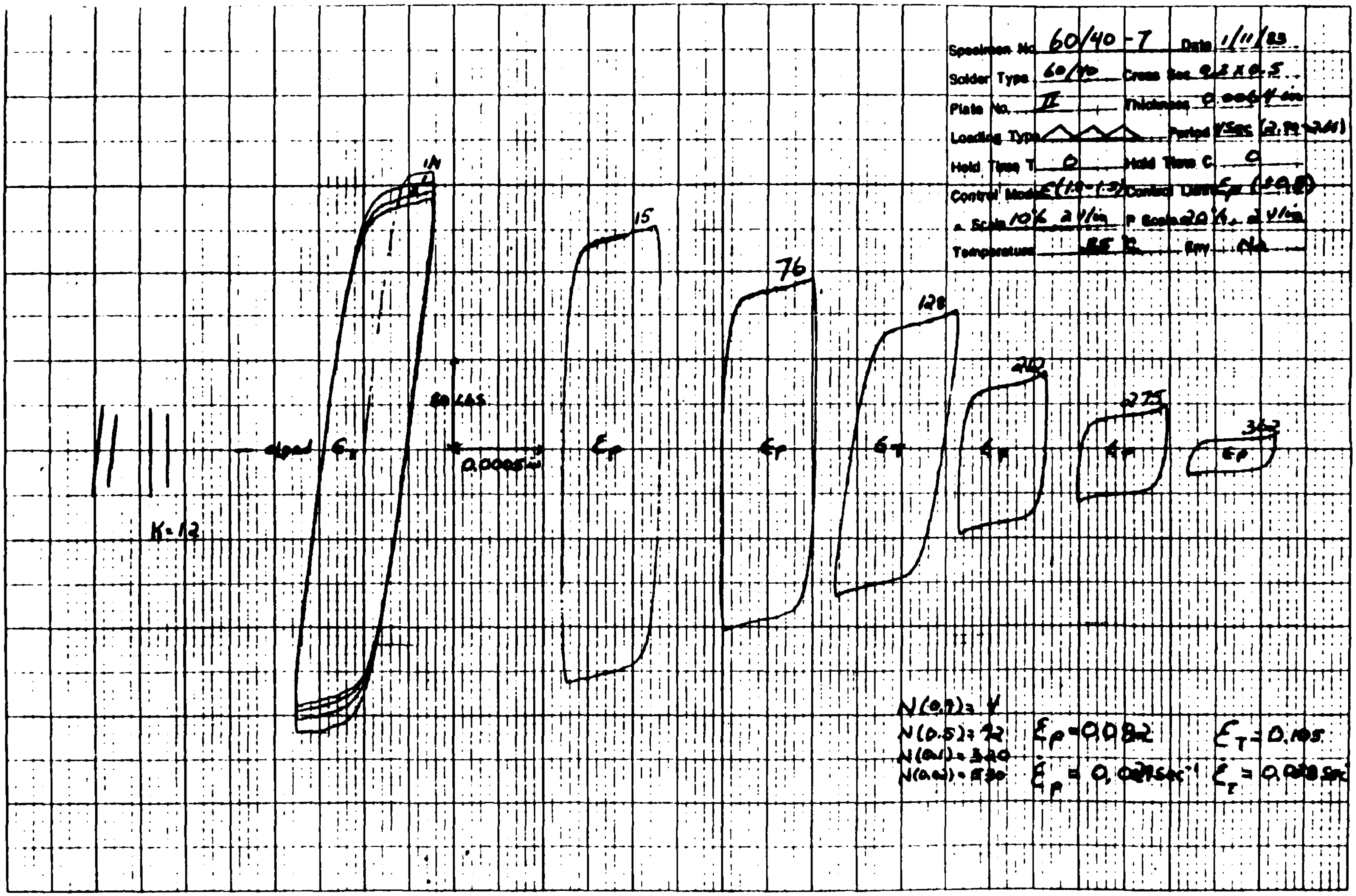


Figure 7 - Hysteresis loops (60/40 specimen cycled at 35°C

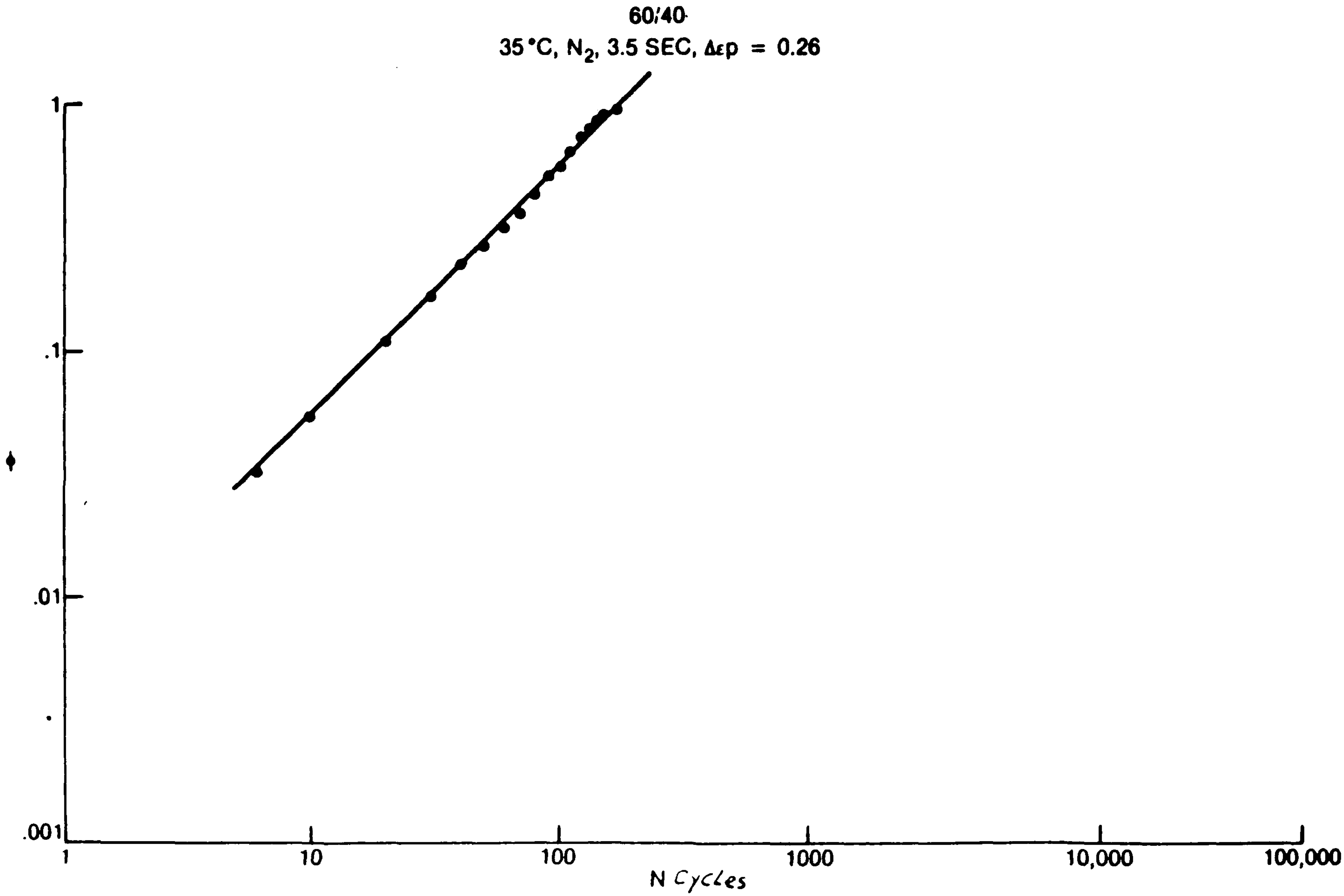


Figure 8 – ϕ vs. N for type 60/40 specimen, cycled at 35°C

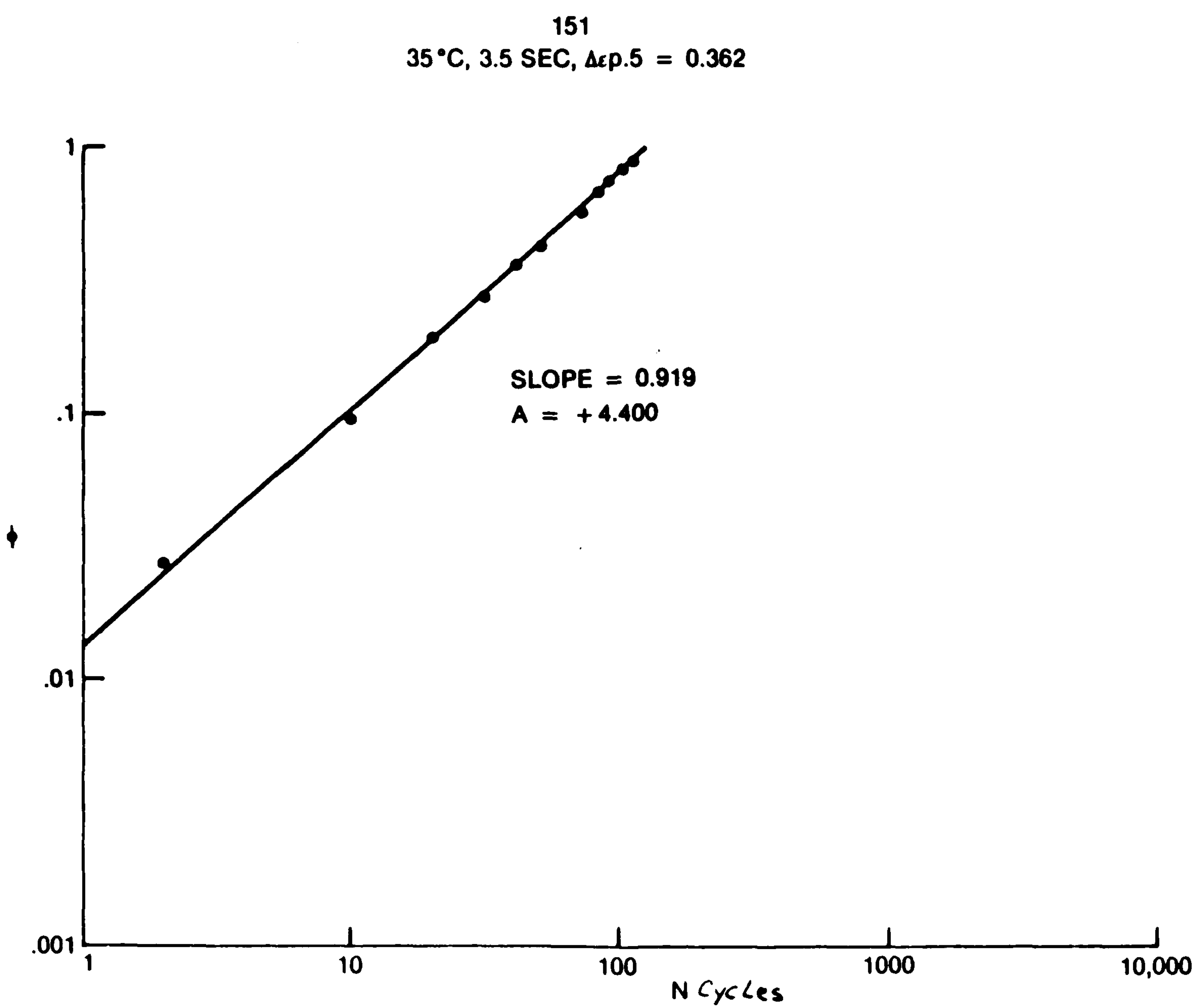


Figure 9 - ϕ vs. N for type 151 specimen, cycled at 35°C

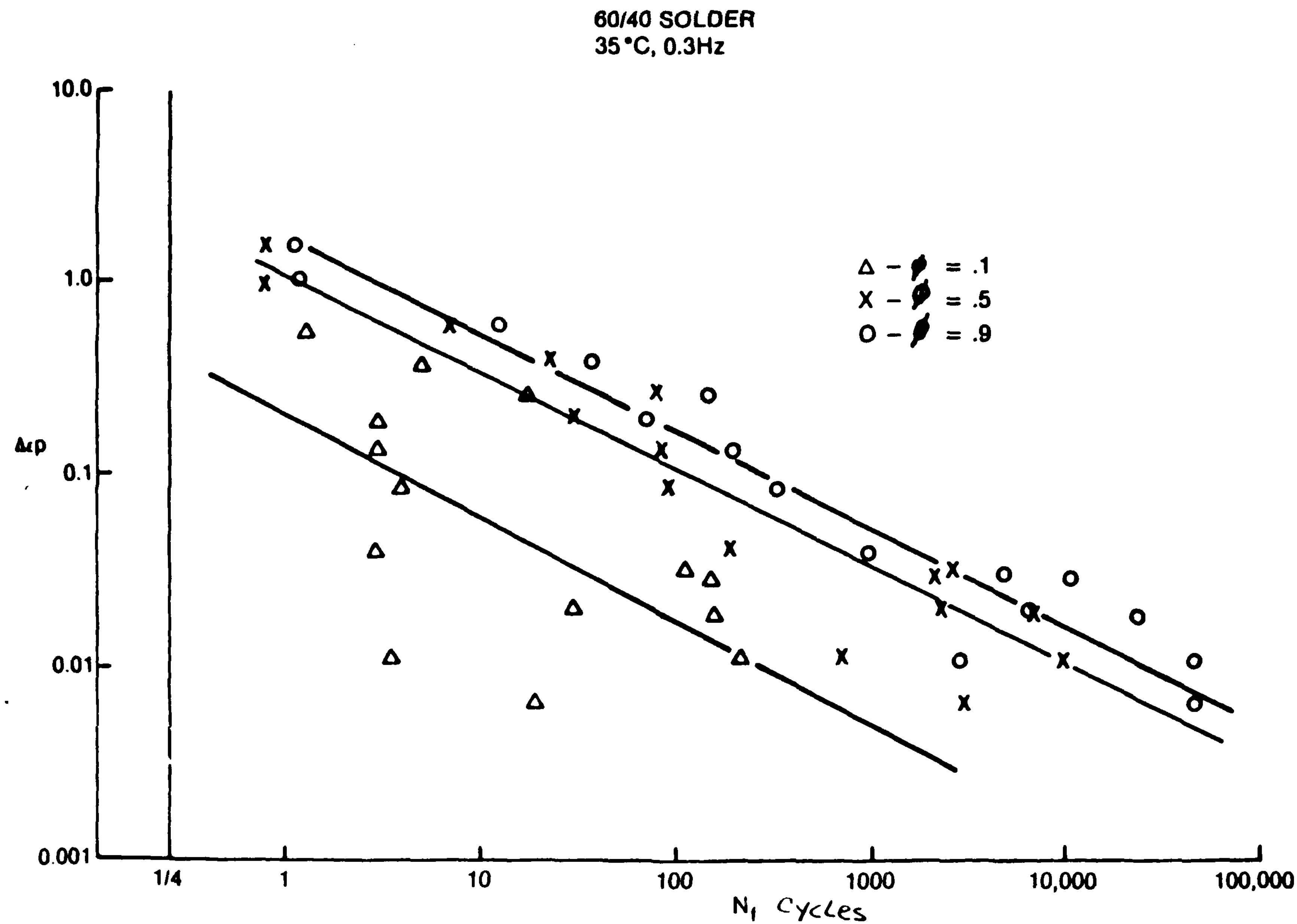


Figure 10 – $\Delta\varepsilon_p$ vs. N_f (defined at O = .1, .5 and .9) for type 60/40 solder, cycled at 35°C

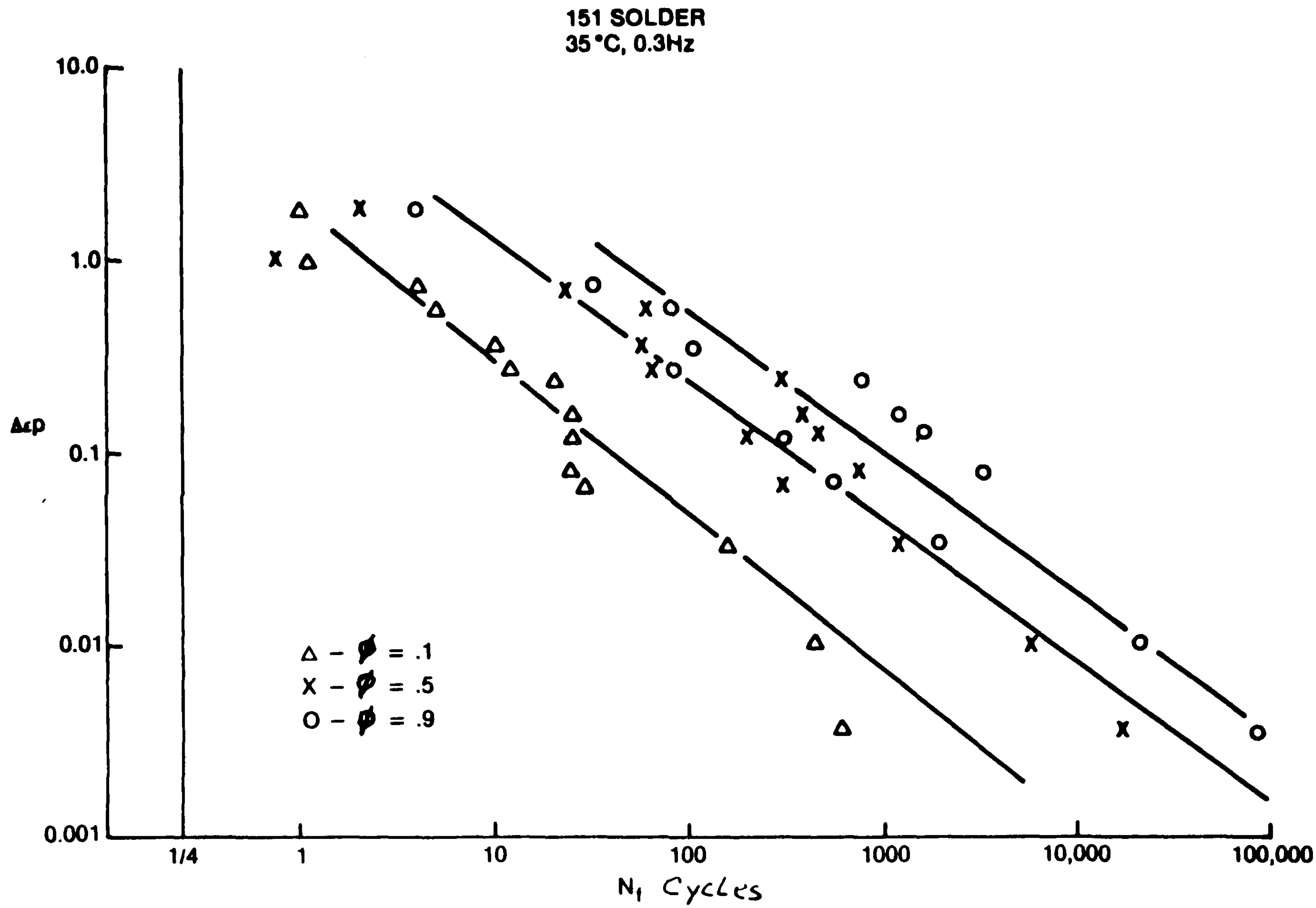


Figure 11 - $\Delta\varepsilon_p$ vs. N_f (defined at ϕ = .1, .5 and .9) for type 151 solder, cycled at 35°C

THERMALLY-CYCLED SOLDER SLEEVE* SCREEN TERMINATIONS

BY

P.J. JONES AND R.W. GRAY

RAYCHEM S.A.

SAINT-OUEN L'AUMÔNE,
FRANCE

*RAYCHEM TRADE MARK.

THERMALLY-CYCLED SOLDER SLEEVE * SCREEN TERMINATIONS

by

P.J. JONES and R.W. GRAY

RAYCHEM S.A.

Saint-Ouen l'Aumône
FRANCE

SUMMARY

*Solder Sleeve * screen terminations have been subjected to thermal shock cycles between the minimum and maximum rated temperatures of -65°C and 150°C. Microscopical examination revealed no thermal fatigue after 200 cycles despite the presence of microvoids, the growth of intermetallic layers and the coarsening of the phase structure of the solder. By 400 cycles some intermetallic cracking was detectable. All joints passed an electrical performance specification intended for use with much less severe tests. Differences between Solder Sleeve * results and those reported for printed circuit board joints are discussed and explained in terms of material and geometric differences.*

* *RAYCHEM Trade Mark.*

1. INTRODUCTION

1.1. Solder Sleeves*

A Solder Sleeve * device is a product that simultaneously solders and insulates a soldered joint, such as the cable screen termination (Figure 1.). The Solder Sleeve * consists of a heat-shrinkable outer jacket which contains a pre-fluxed solder preform together with two rings of heat-fusible thermoplastic. Upon heating the device, the jacket shrinks down, the solder melts and flows around the conductors to be joined (thus creating the solder joint) while the fusible inserts melt and seal the joint area. See Figure 2.

Under visual examination of such soldered joints, the presence of microvoids is typically observed within the solder mass. At the surface of the solder these appear as quasi-spherical dimples. The voids can vary in size between $\sim$10 and 100 μ. Their formation probably arises from a combination of several events including (1) evaporation of the flux solvent (2) volatiles created after flux reaction and (3) air entrapment during shrinkage of the device.

Despite the fact that millions of such Solder Sleeve * terminations continue to operate satisfactorily throughout the world, the question has been raised whether these voids effect the long-term reliability of the soldered joint. The concern stems from the possibility of cracks being initiated from such voids, especially when the joint is exposed to thermal stresses during accelerated thermal cycling of long duration between extremes of temperature. If such cracks spread to the entire conductor-solder surface then joint failure would ensue.

* RAYCHEM Trade Mark.

1.2. Previous work

There is extensive work reported in the literature on thermal cycling of soldered joints, however this is overwelmingly on joints made by component leads passing through holes in printed circuit boards. Berkebile (1) examined cracks that arose on PCB connections and concluded that the main cause of cracking was the difference in thermal expansion between the glass-epoxy board and lead metals ; he also concluded that the main stress raiser was the edge of the hole and recommended the use of stress relieving longer leads together with lap joints. Bang and Beal (3,4) cycled integrated circuits in plated-through-hole joints using a range of tin/lead solders from Sn 40 to Sn 70. They found that coarsening of the grain structure led to intergranular cracks at the pin/solder interface, which is the highest radial stress region, and confirmed the results of Zakraysek (2) that the eutectic alloy (Sn 63) is the worst in this respect. The increased propensity of the eutectic to crack has also been confirmed in the same geometry by other authors (5,6). The effect of adding thermal insulation either by the use of foamed encapsulants (7) or by using silicone sleeving on component leads (8) is to lessen the thermal shock during cycling and gives a considerable improvement in the tendency of plated-through-hole joints to crack.

In view of the considerable difference in geometry between plated-through-hole joints and the lap type of screen termination joint that one obtains with a Solder Sleeve * device, it is interesting to note that Dunn (9,10,11) compared the performance of the lap joints obtained with "Flat-Packs" to those of clinched and normal plated-through-hole joints. Whilst the latter types failed, no cracks were found for the lap joints. He concluded that the lap geometry isolates the joint from the largest thermal mismatch, that is between the lead and the thermal expansion of the PCB in its thickness direction, and that the form of the lead gives some bending stress relief. Some micro-porosity was also found in these "space quality" joints but no general connection was found between this porosity and cracking (11).

* RAYCHEM Trade Mark.

1.3. Purpose of this study

The objective of the work described in this paper is to determine the behaviour of thermally cycled Solder Sleeve * joints under conditions that might be expected to initiate solder cracking. The experimental conditions were extremely severe, namely cycling between the lower and upper temperature limits of the product (-65° to + 150°C) with very rapid temperature changes. Further, the normal eutectic solder alloy (Sn 63) was used with its apparent higher cracking susceptibility.

2. EXPERIMENTAL

2.1. Joint preparation

The product selected for this study was a D 144-00 Solder Sleeve * installed as a lap joint terminating the screen of a small size (24 AWG) screened cable to a 24 AWG wire. Both conductors were tin-plated copper. Cable preparation, Solder Sleeve * installation (using an infra-red heater) and joint inspection were made according to the recommended Raychem procedure (RPIP 540-01).

Thermal cycling

The test rig for the thermal cycling comprises two chambers. The cold chamber is cooled by liquid nitrogen injected into a forced circulation stream ; the hot chamber is heated by a hot-air blower, the impeller of which forces air over an electrical heating element before being passed into the chamber proper. The temperature in both chambers is regulated to within 5°C. The sample holder is moved between chambers by a drive unit mounted on rails and has doors mounted on it to seal each chamber on entry. A monitoring thermocouple is installed on the sample holder. The transfer of samples from one chamber to the other takes about 10 seconds.

* RAYCHEM Trade Mark.

The literature reveals numerous different thermal cycling conditions. The lower temperature chosen here was - 65°C, the same as Bang (3), this, being the minimum operating temperature for the Solder Sleeve * device. Again, to ensure the severity of our tests the upper temperature was taken as + 150°C, being the maximum operating temperature for D 144-00 Solder Sleeve * devices. The dwell times were 30 minutes each at the extreme temperatures with transfer time between then of ~10 seconds. Thus the cycle conditions adopted here are essentially those in MIL. STD 202F Method 107 D Test condition F. The only difference is that the MIL. specification allows up to 5 minutes at 25°C between transfer. Our rig transferred much more rapidly in accordance with the wish to have an even greater degree of thermal shock.

2.3. Electrical tests

The electrical quality of the soldered joints was monitored by measuring the voltage drop as a function of the number of thermal cycles. The Solder Sleeve * Specification RT 1404 requires that the voltage drop across the joint should not exceed that of an equivalent length of the grounding wire by more than 1mV on installation or 1.5mV after exposure to specified tests, including thermal cycling.

The voltage drop was measured from one side of the joint on the screen to the other side on the grounding wire at 1 Amp. D.C. current. This distance was fixed at 18mm and for the ground wire used the voltage drop was 0.89mV over this distance. For the current source a FARNELL AT-26 stabilized supply was used, the voltage drop being detected using knife edges connected to a KEITHLEY IEEE-488 voltmeter.

2.4. Visual examination

Samples were potted in epoxy resin and then sectioned using a diamond saw. Care was taken to avoid artefacts appearing during polishing such as scratches or those due to differential abrasion. The samples were polished using successively finer grades of diamond paste down to 1 μm followed by a final polish

* RAYCHEM Trade Mark.

using 0.05 µm alumina powder. Cleaning between polishing stages was performed ultrasonically using iso-propyl alcohol. These samples were used for direct optical microscopy using a Nikon microscope.

For examination by scanning electron microscopy the polished faces were rendered conductive with a thin evaporated carbon coating. A Cambridge Stereoscan S600 was used, together with an X-ray fluorescence analyser for elemental analysis.

3. RESULTS

3.1. Microscopy

Figures 3 show typical SEM micrographs for uncycled joints. Fig. 3 a is a general view for a section polished parallel to the conductors. Note the presence of several micropores as mentioned in the introduction (§ 1). Fig 3 b shows at higher magnification a perpendicularly polished section, again revealing micropores of irregular shape and size. The dark and light domains are respectively the tin-rich and lead-rich solder phases. Fig. 3 c is at higher magnification again, together with an elemental line scan for the elements copper and tin along the region delineated by the horizontal line. To the left, the large dark feature is a strand of a copper conductor. Note, the fluctuating tin signal, which indicates the tin concentration variation as the 'line' crosses alternately the tin-rich and lead-rich domains. From the region where the tin and copper signals overlap it is possible to estimate the thickness of the intermetallic layer around the conductor. Figures 4, 5 and 6 (a, b and c) show typical micrographs for joints cycled for 100, 200 and 412 cycles, respectively. In each case a) is a general view, b) a close-up near a pore and c) is an elemental line-scan near a conductor. From many such line scans it is possible to estimate the average size of the discontinuous lead-rich phase and the thickness of the intermetallic layer. The results are shown in Table 1.

TABLE 1 Average dimensions estimated from microscopy

No of cycles	Lead-rich domain size	Intermetallic thickness
0	~ 1 µm	0 - 1 µm
100	~ 4 µm	~ 2.5 µm
200	~ 6 µm	~ 3 µm
412	~ 10 µm	~ 3.5 µm

3.2. Electrical measurements

The measured voltage drop of the solder joints are summarized in Table 2. Note, the voltage drop due to an equivalent length of ground wire is 0.89mV, and this should be subtracted from these values to obtain the net effect of the joint area itself.

TABLE 2 Voltage drop results (millivolts)

No of cycles	Average ⊕	Standard Deviation	Minimum	Maximum
0	0.78	0.06	0.61	1.08
100	0.92	0.19	0.62	1.44
200	0.94	0.20	0.66	1.45
412	1.20	0.50	0.67	2.44

⊕ Averages over for 18 samples each.

4. DISCUSSION

For joints cycled up to 200 times - 65° to + 150°C, examination of the micrograpns revealed no sign of cracking, despite the presence of irregularly shaped microvoids. Even for the most severe case of 412 cycles there is no evidence of cracking in the eutectic solder mass. However, a few cracks were detected in the intermetallic zone (see figure 6 b). By contrast, Dunn (9) identified well-defined cracks in eutectic solder joints to PCBs cycled up to as low a temperature as 100°C. Similar results were found by Becker and Denlinger (5), that cracking was initiated after 200 cycles up to + 125°C. Thus the absence in the present study of any cracks for 200 cycles up + 150°C, and only some intermetallic cracking after 412 cycles, must indicate lower thermally induced stresses in the current screen termination joints compared to the above cited PCB joints. The reasons for this lower stress are two-fold. Firstly, the PCB joints experience larger thermally induced stresses because of the high ($\sim 40 \times 10^{-6}$/°C) expansion mismatch between glass-epoxy board and copper, whereas in the Solder Sleeve * joint the mismatch is only between solder and copper being $\sim 8 \times 10^{-6}$/°C. Secondly, the geometry of the plated-through-hole joint means that radial expansion of the PCB material is concentrated at the solder fillet, and as Dunn (9) pointed out, for a lap joint

* RAYCHEM Trade Mark

where the stress concentration is far lower (even on a PCB) cracking is much less likely.
The coarsening of the lead-rich phase and the growth of intermetallic (Table 1) are well known to occur in tin/lead alloys as a result of diffusional processes at elevated temperatures. Thermal cycling per se would not be expected to accelerate intermetallic growth, and if the elapsed time at 150°C is used to calculate an approximate growth rate the results agree reasonably with values published in the literature.

The results of voltage drop measurements (Table 2) are all within the accepted performance requirements of 1.5mV over the ground wire (ie 2.4 mV). Thus there is no deterioration electrically of the Solder Sleeves* joints up to ~400 thermal shock cycles, confirming the results of SEM examination. The reason for the slight upward drift in the average voltage drops (consistent though less than the experimental error) is possibly due to non-uniform current distribution arising from slight oxidation of the shield and ground wire leads as a result of the elapsed exposure (~ 200 hours) at 150°C.

It should be pointed out in conclusion that Solder Sleeve * devices are not designed or supplied for service conditions that involve such extensive and severe thermal treatment. Nevertheless, it is significant that eutectic solder joints do in fact survive such treatment.

4. CONCLUSIONS

- Screen termination Solder Sleeve * joints are not prone to thermal fatigue even with eutectic solder after 200 thermal shock cycles from minimum to maximum rated temperature (-65 to + 150°C).

- Some intermetallic cracking is observed in the intermetallic zone after ~400 cycles,but microvoids themselves do not contribute to crack growth under these cycling conditions.

- Differences between these joints and those reported on printed circuit boards are due firstly to the absence of high expansion coefficient board materials and secondly to the low stress of a lap joint.

- Electrical performance, as measured by voltage drop, remains satisfactory and confirms the absence of general thermal fatigue damage.

* RAYCHEM Trade Mark.

5. REFERENCES

1. M.J. Berkebile - "Investigation of solder cracking problems on PCB's" NASA Technical Memorandum NASA TMX - 53653 (1967)

2. Zakraysek - "The effect of temperature & stress on tin-rich solder alloys" Welding Journal - 50 (1971) 12 - 522s-527s.

3. E.R. Bangs and R.E. Beal - "Solder cracking study" - IIT Research Institute Final Tech. Report RADC-TR-75-67 - Rome Air Centre (1975)

4. E.R. Bangs and R.E. Beal - "Effect of low frequency Thermal Cycling on... soldered joints" Welding Journal - 54 (1975), 377s-383s.

5. Becker and Denlinger - "Improved solder alloy for P.C.B. application" Welding Journal - 57 (1978), 292s-297s-, PT 10.

6. D.M. Jarboe - "Thermal fatigue evaluation of solder alloys" U.S. Dept. of Energy - Report BDX-613-2341 - BENDIX (1980).

7. Munford - "The influence of several design ..... solder joint cracking" IEEE trans. on parts, hyb. & Pack. Vol Ph P11 N° 4 (1975) 12 - 296-304.

8. D.M. Jarboe - "Stress relief technique for reducing thermal fatigue....". U.S. Dept. of Energy - Report BDX 613-1655 BENDIX (1978).

9. B.D. Dunn - "The resistance of space quality joints to thermal fatigue" European Space Agency - Report ESA STM-207 (1978).

10. B.D. Dunn - "IBID" Part 1 - Circuit World - 5 - (1979) 4, 11-17.

11. B.D. Dunn - "IBID" Part 2 - Circuit World - 6 - (1979) 1, 16-27.

ACKNOWLEDGEMENTS

The authors wish to thank Raychem Corporation for the permission to publish this paper. The work involved many staff from both Raychem S.A., Pontoise and Raychem Ltd, Research Laboratories, Swindon, for which the authors are very grateful.

Figure 1.

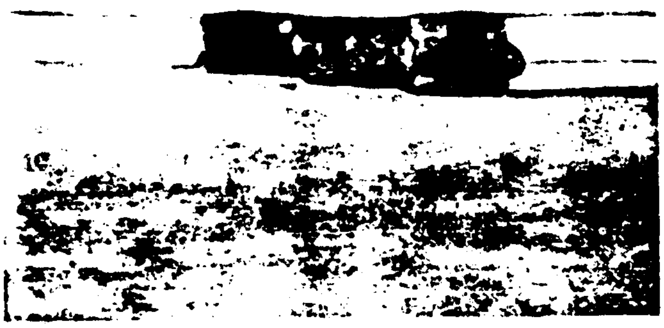


Figure 2.

UNCYCLED JOINTS

Scale

Fig. 3 a — 36:1

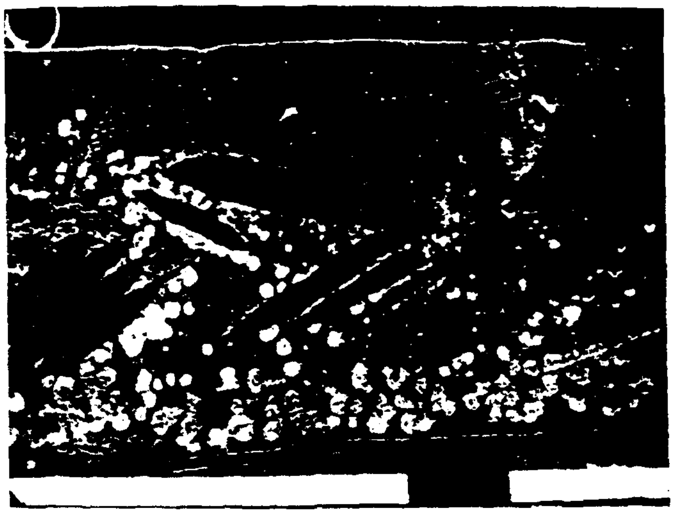


Fig.3 b — 1450:1

g. 3 c — 3000:1

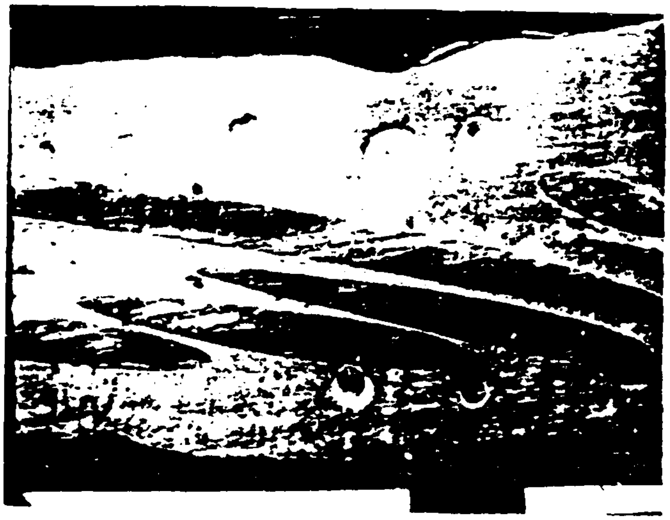
_Sn

_Cu

100 CYCLES

Scale

Fig. 4 a

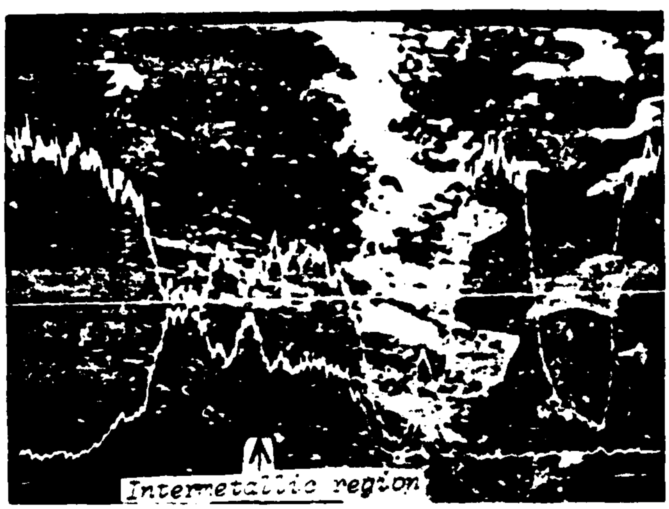


36:1

Fig. 4 b

1450:1

Fig. 4 c



3000:1

Sn

Cu

200 CYCLES

Scale

Fig. 5 a

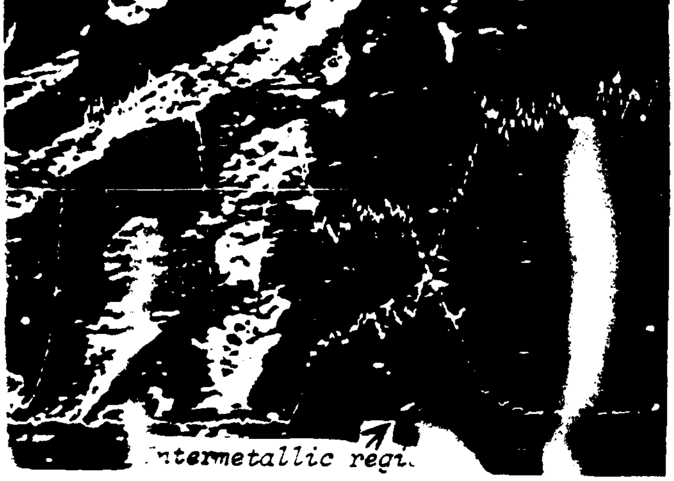
36:1

Fig. 5 b

1480:1

Fig. 5 c

— Cu



3000:1

— Sn

412 CYCLES

Scale

Fig. 6 a

36:1

Fig. 6 b

1450:1

Fig. 6 c

— Cu

3000:1

— Sn

CAUSES OF COMPONENT SOLDERABILITY PROBLEMS

Roy Yenawine

Texas Instruments
Dallas, Texas

CAUSES OF COMPONENT SOLDERABILITY PROBLEMS

Roy Yenawine, Ph.D.
Barbara Waller
Rick Howarth
Joan Dunnigan
Bill Russell
Texas Instruments, Inc.
Dallas, Texas

ABSTRACT:

This paper is a review of the causes of component solderability problems as seen by the Texas Instruments Equipment Group. Two types of causes are considered. The first is the system by which component lead solderability is described in MIL SPECS, contractural requirements, and in TI documentation. Seldom are all three of these factors in agreement. Often one or more of the three are internally inconsistant. The second type of cause of solderability problems is found on the component lead itself. These metallurgical solderability problems are reviewed in detail for the various families of components. Finally, solutions for these component lead solderability problems are proposed.

INTRODUCTION:

In a mature company many problems tend to appear and reappear in cyclical fashion. Each time the problem becomes severe, it is attacked and pushed back down into the background. Component solderability is one of those problems that stays down in the background only to erupt into a major problem every year or two. This cycle is dramatized by the "Chicken Little Effect" in which everyone rediscovers the minor solderability problems that have always existed. Cycles such as these usually mean that the primary cause of the problem has been ignored while only the symptoms have been attacked.

There are several levels of approach to this problem. The highest level of approach is (or was) that of Bell Labs. Bell defines the lead in a Bell specification and then inspects the parts in the vendor's factory. Bell does not have a large inventory of unsolderable parts.

The next level might be the IBM approach. IBM defines the lead clearly, negotiates aggressively with its vendors, and then 100% tins the parts on receipt. IBM rarely has an inventory of unsolderable parts and even those that sneak in are quickly tinned. This system insures that manufacturing managers at IBM know exactly what they are paying to have perfect solderability at the assembly level.

The third level includes companies such as the Texas Instruments Equipment Group (TI-EG). TI has been performing solderability testing for more than 20 years. Some credit for this testing is due to the requirements of the NWC Shrike Program. TI tests all incoming parts to MIL-STD-750, Method 2026.2 and then retests all parts leaving the warehouse that are to be used in the NWC programs (Harpoon and HARM) to the full requirements of MIL-STD-202, Method 208. If parts fail these tests, TI retins those parts that are in critically short supply and returns the rest to its vendors. TI may have a large inventory of unsolderable parts on hand at any time and be involved in the negotiation process with various vendors. However, the Harpoon reject rate on the assembled boards, measured immediately after the flow solder machine, is in the range of 4 defects per 10,000 solder joints, so the system usually works.

Further down the scale are the companies that test using RA or RMA fluxes and those that do not perform solderability testing at all. These companies perform a very valuable service by buying all of the poorly solderable parts rejected by those companies mentioned previously.

This paper is directed to those companies who, like TI, are caught between loose component specification (vendor) requirements and tight system (customer) requirements. The Bell Labs and IBMs are in firm control and need no help. The companies who have weak or no incoming testing have probably never noticed that there was a MIL-SPEC conflict and, thus, see no need for help.

The goal for all companies is to perform solderability testing in the most cost effective fashion. This paper is a review of the causes of solderability problems ranging from those arising from the Government MIL-SPEC system to the individual solderability problems resulting from human error. Of necessity, the examples cited are from the Texas Instruments Equipment Group which has a reasonably cost effective approach.

MILITARY ASSEMBLY SPECIFICATIONS:

Government specifications for solder joint quality seem to be relatively uniform. The Navy, as represented by NWC and WS6536, is very exacting. No military customer will knowingly accept an inferior solder joint. Although the three services readily accept LTPD and AQL levels in specifying the solderability of components, they seem to be loath to accept the LTPD or AQL concept as applied to assembly solder joints.

The requirements of the various assembly MIL-SPECS as shown in Table 1 tend to be more rigorous than the component specifications. The assembly specifications usually cite MIL-STD-202, Method 208, while some component specifications, most notably microelectronic and semiconductor parts, cite less severe tests. This is often a result of the agency controlling the specification and the companies with which they interact.
The agencies in charge of system reliability are more concerned with part performance than with part availability. the Navy, for example, places requirements in WS6536 that in their judgement will produce the most reliable system. The Navy would prefer

that all component specifications produce parts that could be soldered with very high yield with the RMA flux allowed in WS6536. However, the Navy cannot unilaterally change component MIL-SPECS that are used by the other services and that are controlled by DESC or the other services.

DESC, on the other hand, deals much more often with the component manufacturers and feels a responsiblity to keep cost low and availability high. As a result, assembly requirements often are more rigorous than component specifications. The major assembly documents in use at Texas Instruments are MIL-STD-454, WS6536, MIL-STD-46843, MIL-P-45743, and MIL-S-46844. The requirements are summarized in Table 1. Appendix A contains the exact wording of the applicable paragraphs.

TABLE 1: SUMAMRY OF ASSEMBLY SPEC SOLDERABILITY REQUIREMENTS

ASSEMBLY DOCUMENTS	COMPONENT TYPE		
	SEMICONDUCTORS	MICROELECTRONICS	MISC COMPONENTS
AIR FORCE:			
MIL-STD-454 (Electronic Equipment)	MIL-STD-750 Method 2026.3	MIL-STD-883 Method 2003.2	MIL-STD-202 Method 208
NAVY:			
WS6536 (Electronic Equipment)	MIL-STD-202 Method 208 within 120 days or pretin	MIL-STD-202 Method 208 within 120 days or pretin	MIL-STD-202 Method 208 within 120 days or pretin
ARMY:			
MIL-P-46843 (PWB Assemblies)	MIL-STD-202* Method 208	MIL-STD-202* Method 208	MIL-STD-202* Method 208
MIL-S-45743 (Hi-Rel Manual Soldering)	MIL-STD-202 Method 208	MIL-STD-202 Method 208	MIL-STD-202 Method 208
MIL-S-46844 (Machine Soldering)	MIL-STD-202 Method 208	MIL-STD-202 Method 208	MIL-STD-202 Method 208

*When Required by Contract

Where assembly documents are concerned, the requirements are generally consistent and strict. The only document not directly requiring that all components be solderable to MIL-STD-202, Method 208, MIL-STD-750, Method 2026, or MIL-STD-883, Method 2003 for all components (excluding boards) is MIL-P-46843, where the requirement applys only where referenced in the individual contract.

Table 2 lists the actual solderability requirements in the MIL-STDS referenced in these specifications:

TABLE 2: MIL-STD SOLDERABILITY TESTS

TEST CONDITIONS	MIL-STD-202 METHOD 208	MIL-STD-750 METHOD 2026.2	MIL-STD-883B METHOD 2003.2	MIL-STD-883C METHOD 2003
AGING	Steam Aging 60 Min. +5 or -0	Not Required	Steam Aging 60 Min.Minimum	Steam Aging 60 Min.Minimum
FLUX	R Flux	R Flux	R or RMA	R or RMA
FLUXING	Immerse 5-10 S. Drain 10-60 S.	Immerse 5-10 S. Drain 10-60 S.	Immerse 10-60 S.	Immerse 10-60 S.
SOLDER TEMP	230 +/-5 C	230 +/-5 C	260 +/-10 C	245 +/-10 C
DIPPING	Immerse 1+/-1/4 IN/S Dwell 5+/-1/2 S (Dipping Device)	Immerse 1+/-1/4 IN/S Dwell 5+/-1/2 S (Dipping Device)	Immerse 1+/-1/4 IN/S Dwell 5+/-1/2 S (Dipping Device)	Immerse 1+/-1/4 IN/S Dwell 5+/-1/2 S (Dipping Device)
EVAL	10 X Mag. 95% Coverage	10 X Mag. 95% Coverage	10-20 X Mag. 90% Coverage	10-20 X Mag. 95% Coverage

Note that the MIL-STD-883C revision coming into use next month changes the soldering temperature to 245 +/- 10 C and raises the coverage to 95 percent. This will bring MIL-STD-883 closer to the requirements of MIL-STD-202 and MIL-STD-750.

Very strict requirements on a few systems have a large effect on solderability tests for all components. The logistics that would be required to stock commonly used parts separately for each program in order to take advantage of the more relaxed requirements are too expensive to be worthwhile. Thus, the most rigorous assembly solderability specification tends to become the one to which components will be tested at incoming inspection. Further, the incoming management much prefers to test all parts to one common test. As a result, the most severe assembly specification (WS6536 for TI) often tends to become the engineering basis for all components.

COMPONENT MIL-SPEC SOLDERABILITY REQUIREMENTS:

The common solderability requirements are shown in Table 2. It would be best if there were only one solderability test, but requirements in the various standards are beginning to converge. MIL-STD-883C would be an excellent test to use on all components if only pure rosin (R) flux were used.

Table 3 shows a list of various component types and the MIL-STD containing the solderability requirement most commonly applied as well as the test procedure used. The anomalies would be amusing if they were not so serious. The IC, which is the single most common part on most modern PWB assemblies, has much less stringent requirements than the less expensive transistors and axial leaded components. Even common bus wire must be more solderable than the IC. The reasons for these oddly weak solderability specifications lies in the strength of the component manufacturers and their trade organizations. IC manufacturers exert a greater influence on the MIL-SPEC guardians than do the resistor or wire manufacturers. In many cases, it appears as if individual component types have obtained dispensations from solderability requirements that relate to some past difficulty in making a part rather than to the solderability requirements compatible with using the part.

TABLE 3: COMPONENT SOLDERABILITY REQUIREMENTS

DEVICE	MIL-STD	EXCEPTIONS & NOTES
Microelectronics	MIL-STD-883, Method 2003.2	
SC Devices	MIL-STD-750, Method 2026.2	
Large SC Devices	MIL-STD-750, Method 2026.2	Dwell 10+/-1 S.
Resistors	MIL-STD-202, Method 208	
Capacitors	MIL-STD-202, Method 208	
Switches, Relays	MIL-STD-202, Method 208	
Transformers	MIL-STD-202, Method 208	
Jacks	MIL-STD-202, Method 208	
Bus Wire	MIL-STD-202, Method 208	
Magnet Wire	J-W-1177	Solder 360-430 C Exam at 1X
Chip Capacitors	MIL-C-55681	SN62 Solder (2% Silver)

TEXAS INSTRUMENTS SPECIFICATIONS:

The conflicts among MIL-SPEC requirements are generally easily understood once they are presented in summary form on a Figure or Chart. However, a large company tends to have a complex system of requirements that can hide many flaws. Those flaws lie quietly and cause no problem until an unsolderable part arrives at incoming. Only then do they become visible.

The purchased part is described by a part drawing or specification that in many cases is required by contract to duplicate the relevant MIL-SPEC, and by special clauses in the purchase order. In many cases there is also a general specification in addition to the specific part specification. Requiring better solderability than that specified by the MIL-SPEC can make the part a "special" (or nonstandard) part rather than a "MIL-SPEC" part. This can make the part more expensive and less available. Some Parts Engineers believe that such a nonstandard part requires customer approval for each program on which it is used. One of these three documents can as easily as not loosen solderability requirements by providing special tests that are not as rigorous as the MIL-SPEC requirement.

At TI, once a part is received its testing is governed by an Incoming Quality Procedure (IQP) that tells an inspector what tests to perform and the required sample size. Quality Operating Instructions (QOI) describe the specific test procedures, and the part specification lists the required performance. Table 4 lists the internal documents and the approximate number of each type. Thus, there are tens of thousands of opportunities for error, and they may only be found when parts cannot be soldered acceptably at the assembly level.

TABLE 4: INTERNAL SOLDERABILITY DOCUMENTS

TYPE	MINIMUM NUMBER
PURCHASE ORDER CLAUSES	70
PART SPECIFICATIONS	45,000
GENERAL PART SPECIFICATION	27,000
IQPs	60,000
QOIs	161

GOVERNMENT-INDUSTRY ACTION:

While most of the MIL-SPECS have been relatively quiet, the MIL-SPEC controlling solderability of integrated circuits has been in a state of flux that promises to improve component solderability once the semiconductor industry learns how to reflow or tin-lead dip ICs. The learning process has been painful for both users and manufacturers.

The requirement for reflowed or solder dipped leads on DIP ICs that was self activated in MIL-M-38510 in December of 1982, has been the tool that raised the attention (and pain) level of the semiconductor industry to the solderability problems that are so prominently displayed at this and other similar forums.

DESC action is continuing to tighten the specifications in MIL-STD-883 until they differ from those of MIL-STD-202 only in allowing the more active flux. The active stance of the manufacturers as seen in the JEDEC 13 Committee is now being countered by a stronger stance in the user Electronics Industries Association (EIA) G12 Committee. This will help to give DESC-RADC freedom to require excellent component lead solderability.

There were many industry and joint industry/government meetings that focussed on component solderability in 1983. The NWC Soldering Symposium of February set the tone for the year with several strong papers on component solderability. The EIA G12 Committee met twice with the DESC representatives in attendance and unanimously voted for R flux, 95% coverage, and aging requirements for MIL-STD-883C. The JEDEC JC-13 (SC manufacturers) Committee met twice and voted overwhelmingly to keep solderability requirements on ICs at the present lax levels. A solderability symposium at the Westinghouse facility in Lima, Ohio, emphasized the specification discrepancies and the general nature of solderability problems. A joint military/industry meeting sponsored by Jim Raby at the Indy Electronics facility in Mantecca, California, focussed on the processing and lead finish changes needed to provide high manufacturing yield to both users and manufacturers of ICs.

The year of 1984 promises to be as active with three major meetings in August.

TEXAS INSTRUMENT'S COURSE OF ACTION:

TI is participating actively in the drive to consolidate the MIL-SPECS in one rigorous set of requirements, such as the new MIL-STD-883C with water white rosin flux.

The internal system within TI is policed by a corrective action loop that was formalized after the military/industry meeting at Mantecca in the spring of 1983 when it became apparent that a large percentage of the ICs manufactured in 1983 would be poorly solderable. The IC solderability problems resulted from the semiconductor industry's belated attempt to learn how to reflow tin plated leads and from their reluctance to commit to solder dipping component leads after burn-in.

Programs being supported by TI range from very old RADAR systems to high technology space and weapons systems. Some systems were designed before the common use of the IC, and thus have low density component loading and can use RA flux. Other programs have very dense IC packing and allow only RMA flux. A few subsystems allow only R flux. The large majority of these components come from common stock. Thus, the incoming solderability test must assure that parts drawn to be used on NWC programs will pass the stringent MIL-STD-202, Method 208, test.

This incoming requirement has created strong conflict when a lot of ICs manufactured to MIL-STD-883B was rejected to the tighter MIL-STD-202 test. In most cases the vendor complaints were obvious negotiating ploys since most experts believe that the large majority of parts failing MIL-STD-202 tests would also fail the MIL-STD-883B tests. Since TI could not use parts failing MIL-STD-202, and vendors were reluctant to accept parts that had not specifically failed to meet the requirements of MIL-STD-883B, a system was set up to review and retest all rejected lots in the Equipment Group Analytical Laboratory. The purpose of this testing effort was to analyze the solderability failure causes; to provide data, pictures, and written analyses to be used in negotiating the return of poorly solderable parts to the vendor. They were also to evaluate the next generation of tests on questionable parts.

Table 5 summarizes the 133 component failures that were retested in the lab out of 43,000 lots received by TI during a seven month period ending in January, 1984. Note that ICs make up 46% of the failures. This resulted from the industries last minute efforts to learn to reflow electroplated tin on IC leads by December 1, 1982, and from their efforts to optimize the solder dipping process in 1983. Note that the remaining failures were common non-IC components not at all affected by the new requirement to reflow or solder dip IC leads. Among other facts, it was learned that aging does affect component leads having exposed intermetallic compounds. It was found that the probability that a part will pass the MIL-STD-883B tests after failing the MIL-STD-202 tests is very low. It was also learned that lot variance had a large effect on testing integrity, so testing by date code was set up. TI tested parts drawn from the warehouse as well as those entering the warehouse, and the data shows that significant solderability degradation does not occur in a warehouse which is air-conditioned.

TABLE 5: PARTS EVALUATED

DEVICE	NUMBER OF LOTS RETESTED	% OF TOTAL
Microcircuits	61	45.9
Diodes	23	17.3
Transistors	31	23.3
Resistors	6	4.5
Capacitors	4	3.0
Terminals	3	2.3
Miscellaneous	5	3.8

COST EFFECTIVENESS OF THE TI SYSTEM:

The cost savings associated with a reject rate at the solder machine of 4 parts per 10,000 can only be compared to what it would be if parts were not inspected at incoming, which is information that TI does not intend to develope. The low level of incoming rejection in the face of a uniformly stringent incoming solderability test is simply a reflection on the intelligence of most of TI's vendors. Intelligent vendors do not ship poorly solderable components to a customer with tight solderability requirements so long as there are other customers who will pay the same amount for the parts and who do little or no testing. In fact, companies which tin 100% of the parts instead of testing must be prized customers.

The costs of the TI system are not high. The incoming solderability test adds little to the cost of other incoming tests that are required by contract. The cost of having a laboratory analysis of each failed lot is more than counterbalanced by the shortened RTV (return to vendor) cycle and the time previously wasted by professionals in the Procurement Assurance and Purchasing departments in negotiation with the vendor. The largest cost of rejecting unsolderable lots of parts is the interest paid on the money that remains in the hands of the vendor until he agrees to take the parts back.

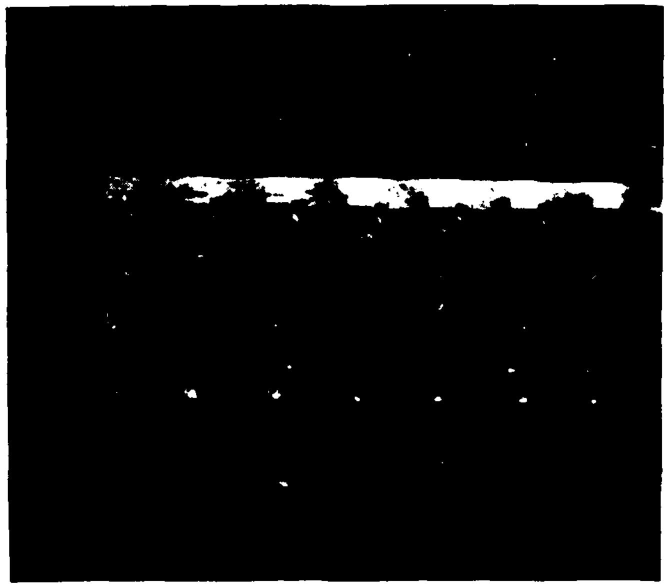
CURRENT SOLDERABILITY PROBLEMS:

The first section of this paper has dealt with the bureaucratic causes for the continuing component solderability problems. This section will review some examples of the solderability problems found in the last six months in a review of all incoming solderability rejects and will suggest some solutions.

Many solderability problems are simple process problems of a transient nature such as those seen in the less expensive components and those components manufactured by small companies who are often dependent on even smaller subcontractors for services such as electroplating. Some problems are endemic because of common practices or material selections. The worst of the problems that are common to a whole industry are those of exposed intermetallic compounds on the surface of integrated circuit leads. The lack of semiconductor industry sensitivity to the need for more solderable component leads caused the industry to be caught unaware when the requirement for reflow or solder dip went into effect in December of 1982. As a result, half of the solderability rejections in 1983 were for poor integrated circuit solderability resulting from poorly planned reflow processes.

The following Figures are a small representative sample of the 133 solderability rejections from the last 7 months of 1983 that were studied and documentated in the Equipment Group Analytical Laboratory.

AS RECEIVED



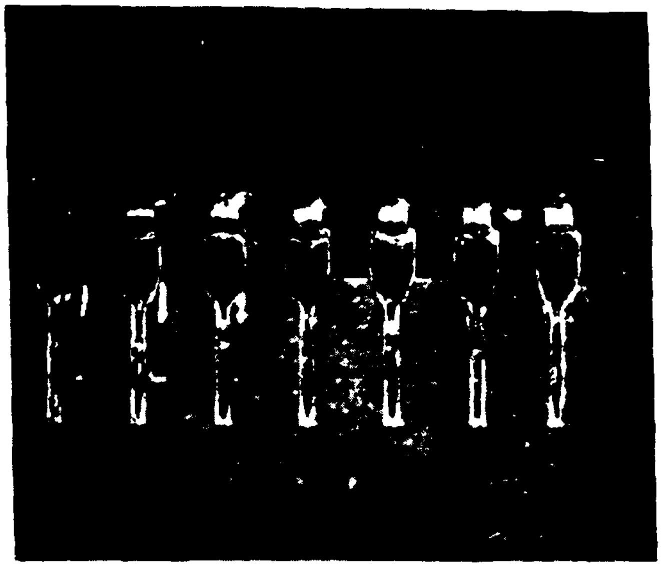
SOLDER TESTED

PROBLEM: Very thin tin on the as-received lead

SOLUTION: Require a thicker tin coating over minimal intermetallics

(1000X)

(1000X)



AS RECEIVED

SOLDERED AT 232°C

PROBLEM: Tin completely converted to intermetallic at the lead edge by burn-in on a very thin tin coating.

SOLUTION: Burn-in bare leads and tin or solder coat the leads only after cleaning off the burn-in oxides.

(1000X)

EDGE OF LEAD (1000X)

(1000X)

PROBLEM:

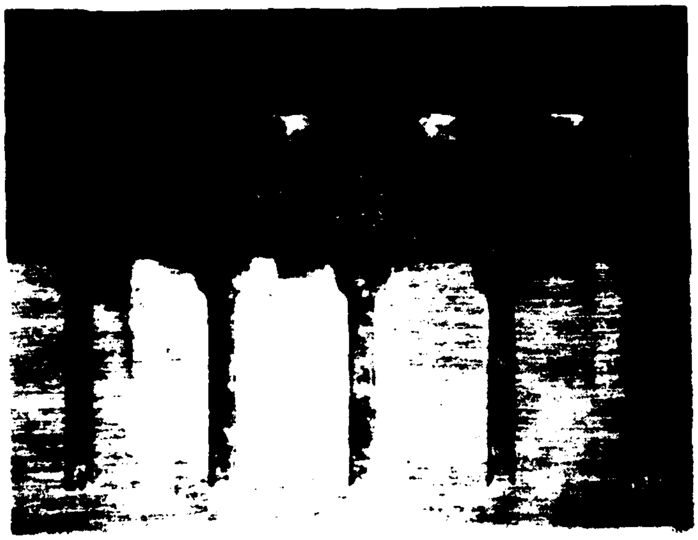
Poorly solderable substrate dewetting.

SOLUTION:

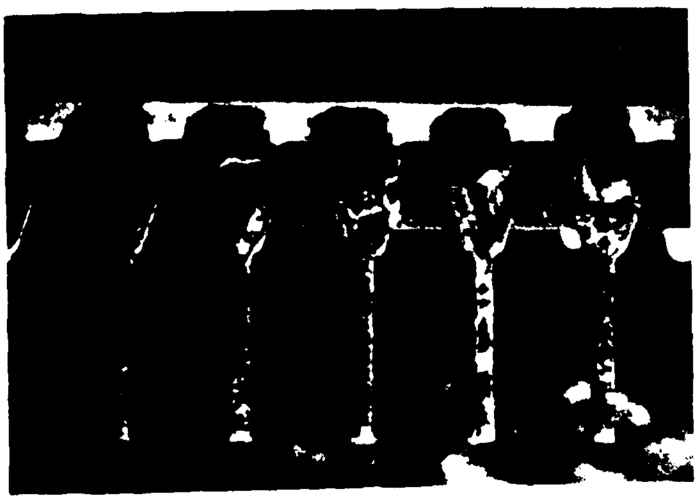
Strip and chemically clean the leads before solder dipping.

(1000X)

PROBLEM: Alloy 42 dewetting on IC leads from three different manufacturers.



SOLUTION: Solder dip cleaned leads after burn-in.



BEFORE AGING AFTER 24 HOUR AGING

PROBLEM:

Parts with exposed intermetallic compounds tend to become less solderable with exposure to assembly baking.

SOLUTION:

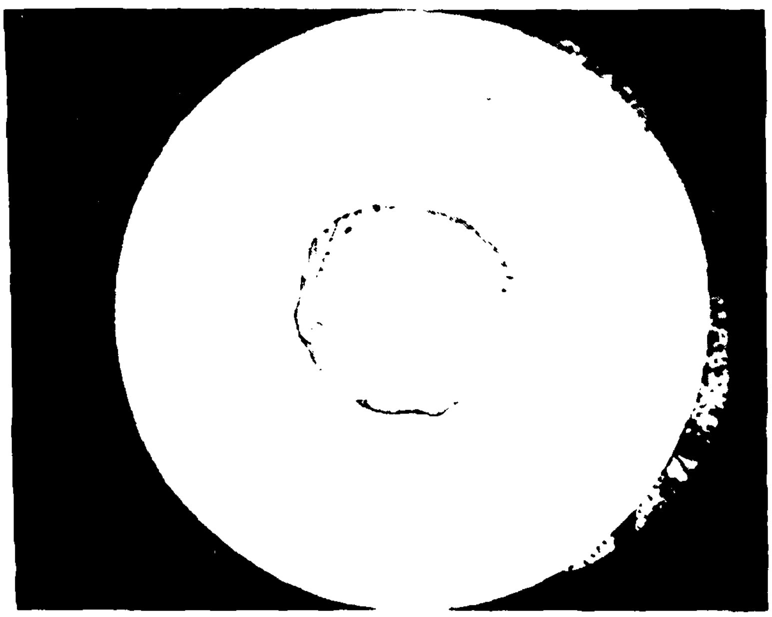
Perform 16 to 24 hour steam aging to reject lots that have marginal solderability and will be degraded by pre-soldering baking operations.

AS RECEIVED SAMPLE

AFTER 24 HOUR AGING

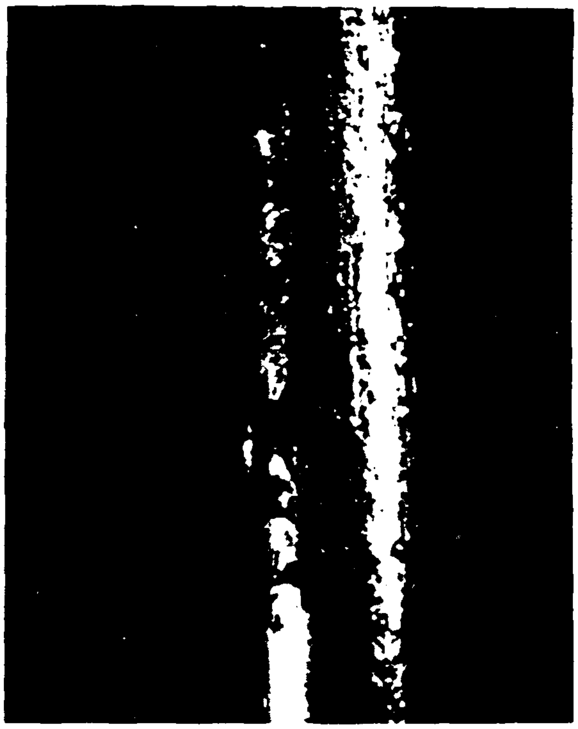
PROBLEM: Dewetting on a transistor lead.

SOLUTION: Perform the steam aging test on transistors to catch marginal lots.



MICROSECTION OF LEAD (50X)

CONTROL (RMA FLUX)



AGED 24 HOURS (RMA FLUX)

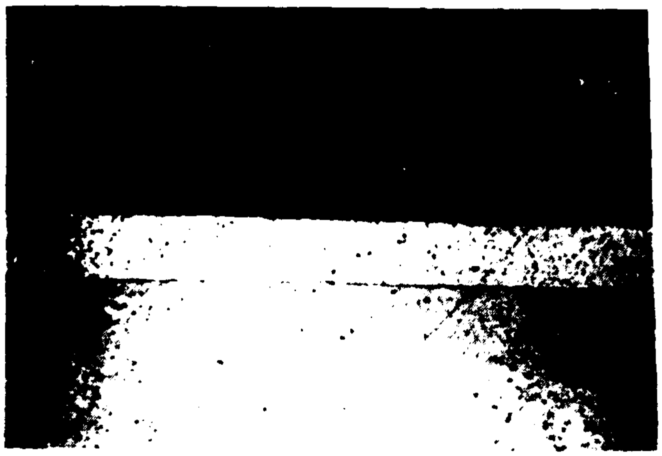
PROBLEM: Thin tin plating on diode leads totally converted to intermetallics by burn-in.

SOLUTION: Apply the tin to the cleaned lead after burn-in.

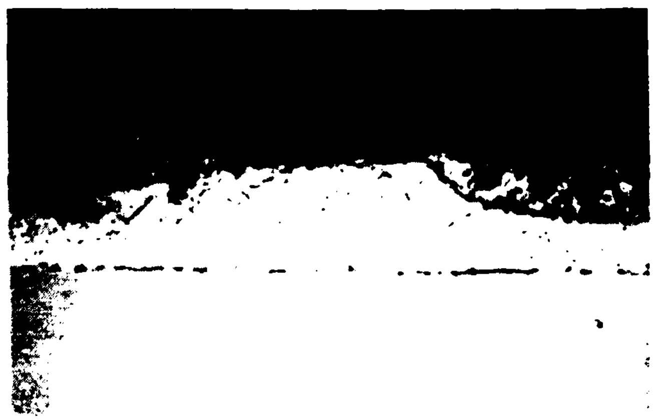
MICROSECTION OF THE LEAD (1000X)

PROBLEM: Silver plated diode leads

SOLUTION: TI drawing changed to require tin-lead plating



AS RECEIVED



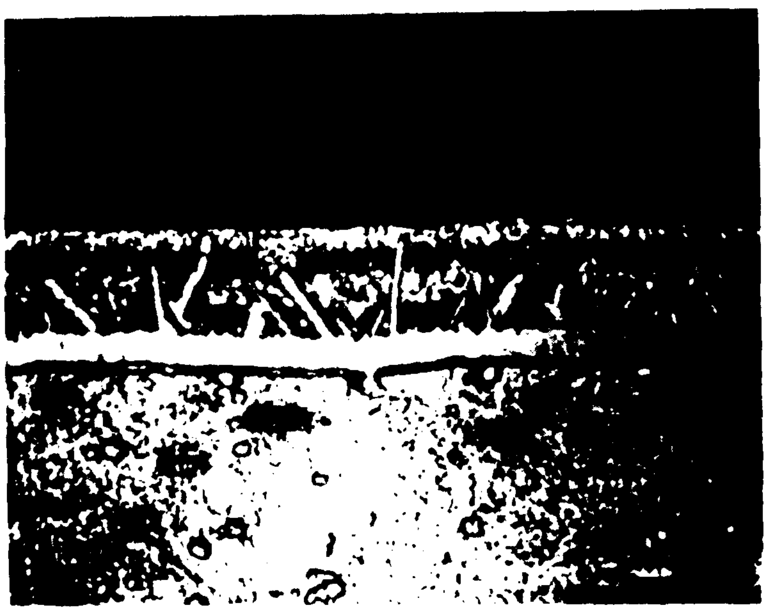
AFTER SOLDERING

PROBLEM:

A thin or intermittent copper barrier over the beryllium-copper substrate allowed beryllium to migrate to the surface and oxidize.

SOLUTION:

Test at Incoming to verify a sufficient copper or nickel barrier over the beryllium-copper.



PROBLEM:

Intermetallic compounds formed while firing the enamel coating on a capacitor with nickel plated beryllium-copper leads and prevented solder wetting.

SOLUTION:

Apply the solder after the enamel firing step.

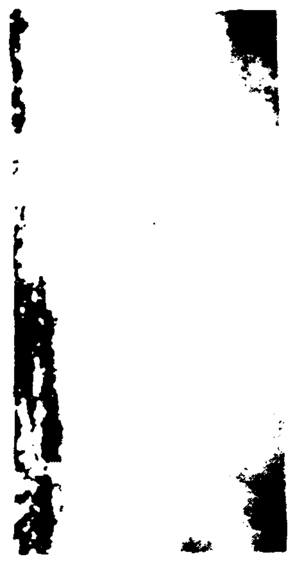
PROBLEM:

Baking of the component lead during the curing of the capacitor body caused extensive growth of the copper-tin intermetallics. Thin solder coating resulted in an almost pure lead surface in the top lead. Even very heavy solder overcoating is washed away during tinning and solderability testing.

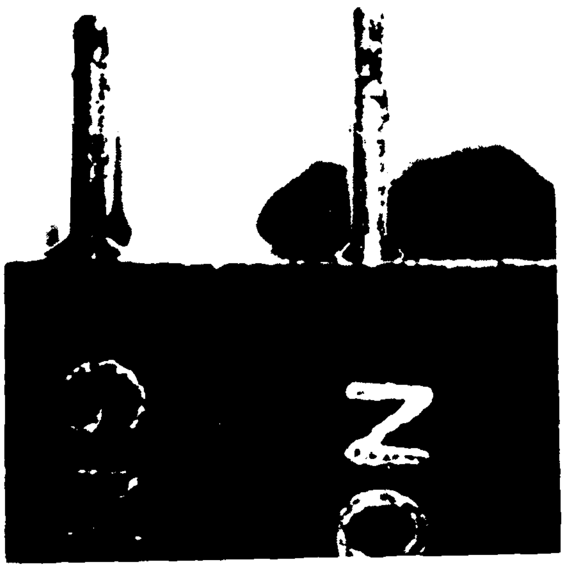
SOLUTION:

Perform all thermal processing on components before adding the tin or solder finish.

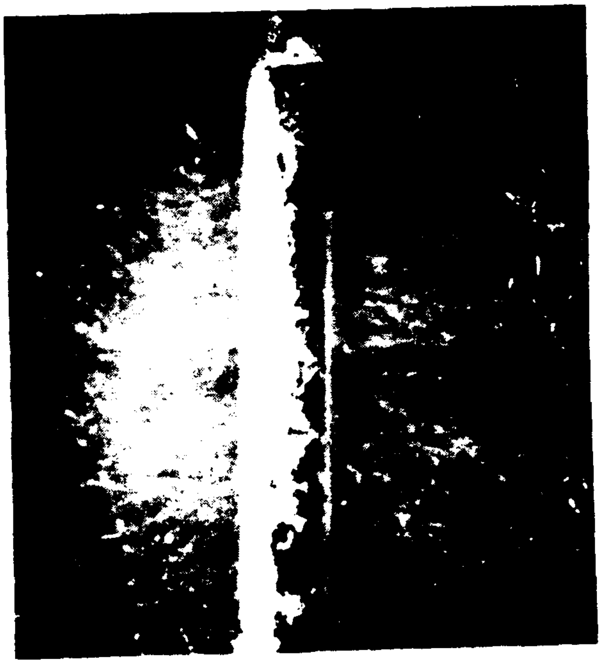
UNAGED QUARTZ CRYSTAL



24 HOUR AGED QUARTZ CRYSTAL



OSCILLATOR



RECTIFIER

PROBLEM: Oscillator, Rectifier, Crystal dewetting due to intermetallic formation. Note the effects of aging on solderability of the quartz crystal.

SOLUTION: Tin or solder should not be applied to the leads until thermal treatments are complete.

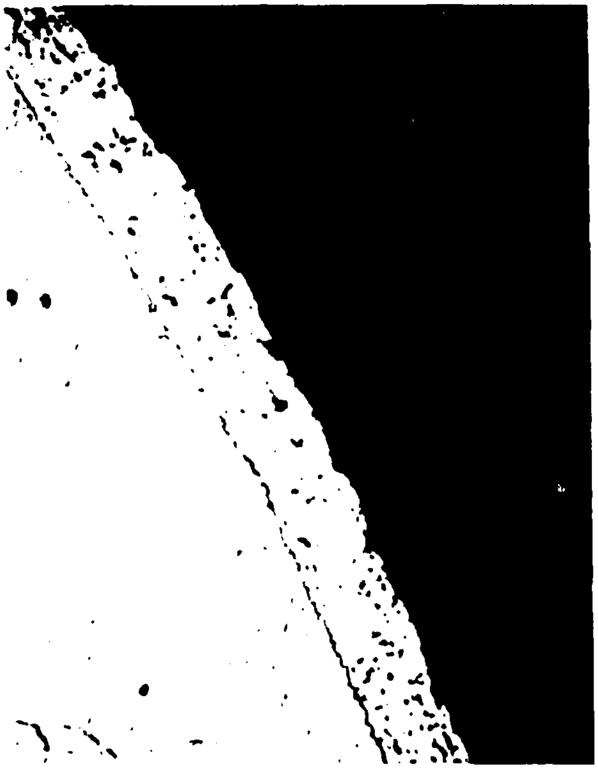
AS RECEIVED SAMPLE

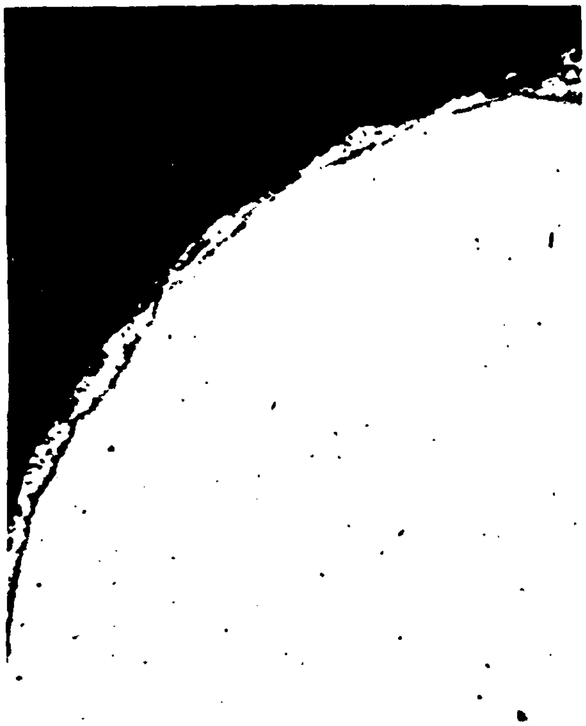
PLATING AFTER REFLOW

OUTGASSING DEWETTING

PROBLEM: Outgassing of electroplated tin-lead during reflow.

SOLUTION: Specify solder dipped leads.



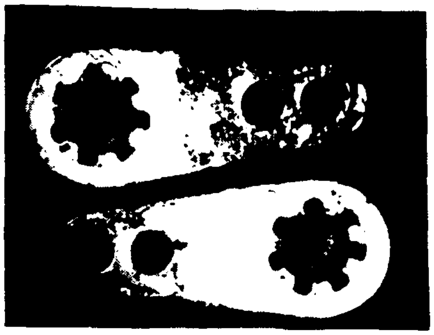


OUTGASSING (160X)

OUTGASSING (160X)

OUTGASSING (160X)

OUTGASSING (160X)



AS RECEIVED (1000X)

TINNED (1000X)

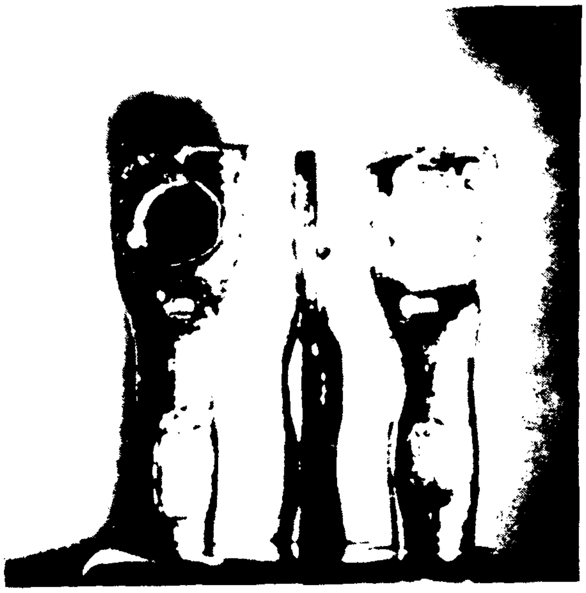
PROBLEM:

Tin Plate so thin that it converts to intermetallic very rapidly.

SOLUTION:

Apply thicker tin plate.

TRANSISTOR



PROBLEM:

Nickel surfaces tin poorly with RMA fluxes.

TERMINAL

SOLUTION:

Forbid nickel leads or coatings on engineering drawings.

LUG

CONCLUSIONS:

There is one major flaw in the assembly-component MIL-SPEC system that is seriously and adversely affecting component solderability at the incoming and assembly levels. The laxity of MIL-STD-883B in comparison with the requirements for system quality and even the requirements of far less expensive components covered by MIL-STD-750 and MIL-STD-202 is presently a major cause for component rejections. This results in extended negotiations, parts shortages, 100% tinning, the resultant damage occurring after the last electrical and hermeticity test, assembly touch up and loss of reliability for those companies with weak incoming inspection systems.

The transition to MIL-STD-883C with its more stringent inspection criteria in March of 1984 will not close the largest and most damaging loophole in MIL-STD-883B since RMA flux will still be allowed for testing. Every paper on fluxes points out one or several QPL RMA fluxes that are more active than allowed by MIL-F-14256 and it is to the semiconductor manufacturer's advantage to know which RMA flux is most powerful. With the wide range of QPL RMA fluxes available, the system manufacturers will often be using a less effective flux on the manufacturing line than the IC vendors are using to test components. The system manufacturer who is audited to verify the cleanliness of the assemblies, and is allowed to use only QPL RMA flux, and is expected to achieve 100% yield off the flow solder machine is at a great disadvantage in comparison with the parts suppliers.

There is a strong drive to bring MIL-STD-883C in line with MIL-STD-202 at a test temperature of 245 degrees C.

Although there are MIL-SPEC anomalies other than MIL-STD-883, the MIL-SPEC system does not seem to be a large cause of solderability problems with components other than integrated circuits. The internal documentation system used by an electronic system manufacturer has the potential to cause many solderability problems by allowing the purchase and acceptance of poorly solderable components.

In conclusion, MIL-STD-883C must be upgraded to require use of R (water white rosin) flux for solderability testing of ICs.

The most powerful tool to correct component solderability problems is to reject the inferior parts on receipt and return them immediately to the vendor along with proof of failure and recommended corrective action.

APPENDIX A

COMPARISON OF MAJOR ASSEMBLY DOCUMENTS SOLDERABILITY REQUIREMENTS

MIL-STD-454 is an Air Force document which states in it's Scope, "This standard covers the common requirements to be used in Military Specifications for electronic equipment." With regards to solderability, this documents states the following in Paragraph 4.3, "Wire and part leads, with or without attached terminals, shall meet the solderability requirements of Method 2026.3 of MIL-STD-750 for semiconductors, Method 2003.2 of MIL-STD-883 for microelectronics, and Method 208 of MIL-STD-202 for other electrical and electronic component parts."

WS6536 is a Navy document which states in it's Scope, "This specification defines the approved materials, methods, and inspection standards for producing the quality of electrical soldering workmanship necessary for use on guided missiles, aircraft, shipboard, weapons, ground vehicle equipment, and program critical ground support equipment." There are five paragraphs in this document which define the solderability requirements of the various components used. The applicable paragraphs read as follows: Paragraph 3.3.5, "Terminals. Terminals shall be tin or tin-lead plated or coated and shall meet the solderability tests specified in MIL-STD-202, Method 208. Cleaning prior to lead attachment shall be required." Paragraph 3.3.6, "Wire. Solderability shall be in accordance with MIL-STD-202, Method 208." Paragraph 3.3.7.1, "Printed Wiring Boards, Type 1, 2, 3. Except as specified herein, PWB design and construction shall be in accordance with MIL-STD-275 and MIL-P-55110, including solderability." Paragraph 3.3.8, "Flexible printed wiring. Flexible printed wiring shall conform to MIL-P-50884 (including solderability)." Paragraph 3.3.10, "Solderability for external leads. External leads shall satisfy the solderability tests specified in MIL-STD-202, Method 208, within 120 days prior to being soldered into an assembly. Semiconductors or microelectronics whose detail specification requires solderability in accordance with MIL-STD-750, Method 2026, or MIL-STD-883, Method 2003, or modules having the aging requirements of MIL-STD-202, Method 208, may be omitted. In lieu of the 120 day solderability requirement, component leads may be pre-tinned with a solder coating (fused hot solder coated) process to a minimum thickness of 0.0001 inch of the lead."

MIL-P-46843 is an Army document which states in it's Scope, "This specification covers the production of printed wiring assemblies designed in accordance with MIL-STD-275 or MIL-STD-1495 as applicable and consisting of printed wiring boards on which separately manufactured component parts are mounted." The requirements stated in this document with regards to solderability are the following: Paragraph 3.5.4.1, "Solderability of component leads and wires: Component leads and wires shall be sufficiently solderable to meet the requirements of this specification cited herein. Gold plated conductors to be soldered shall have the gold plating removed by double dipping using materials specified in MIL-S-45743 or other nonmechanical process prior to assembly. Other leads and wires may be tinned prior to soldering. When required by the contract or purchase order, the solderability shall be tested in accordance with EIA Standard RS-178-A or MIL-STD-202, Test Method 208." Paragraph 4.5.1.1, "Prior to release into production process, if required by contract or purchase order, or if required to meet the solderability requirements of this specification including subtier solderability specifications, each lot of components shall be inspected in accordance with EIA Standard RS-178 or MIL-STD-202, Method 208." Prior to February 26, 1979, the document read as follows, "All component leads and wires shall meet the solderability requirements of EIA Standard RS-178-A or MIL-STD-202 Test Method 108. Test shall be performed within 30 days of production unless leads are pretinned...."

MIL-S-45743 is an Army document which states in it's Scope, "This specification covers soldering, high reliability electrical and electronic connections with manual soldering apparatus as applicable to guided missile and certain aerospace equipment requiring extraordinary control of the soldering environment and techniques. It is not applicable to general soldering requirements." With regards to solderability it states the following: Paragraph 3.4.3, "Solderability. All surfaces to be soldered that do not conform to the solderability requirements of MIL-STD-202, Method 208, and all printed wiring circuits that do not conform to IPC-S-801 shall be re-tinned or replated to provide solderability conforming to MIL-STD-202 or IPC-S-801 requirements as applicable.

MIL-S-46844 is an Army document which states in it's Scope, "This specification covers machine soldering processes for printed board assemblies used in electrical and electronic equipment." With regards to solderability it states the following: Paragraph 3.4.3, "Solderability. All surfaces to be soldered that do not conform to the requirements of MIL-STD-202, Method 208, and all printed wiring circuits that do not conform to IPC-S-801 shall be re-tinned or replaced to provide solderability conforming to MIL-STD-202 or IPC-S-801 requirements as applicable."

FLUX EVALUATION II

Rick Howarth/Barbara Waller

Texas Instruments
Dallas, Texas

FLUX EVALUATION: II

Roy Yenawine, Ph.D.
Rick Howarth
Barbara Pulliam
Joan Dunnigan
Ed Tomczyk
Texas Instruments, Inc.
Dallas, Texas

ABSTRACT:

This paper compares data from several traditional flux evaluation tests to rank and better understand 120 fluxes that are currently in use in American industry. A quantitative view is taken of several normally qualitative tests, and several new tests are performed to better understand the behavior of the fluxes and the relationship of this behavior to the traditional flux evaluation methods.

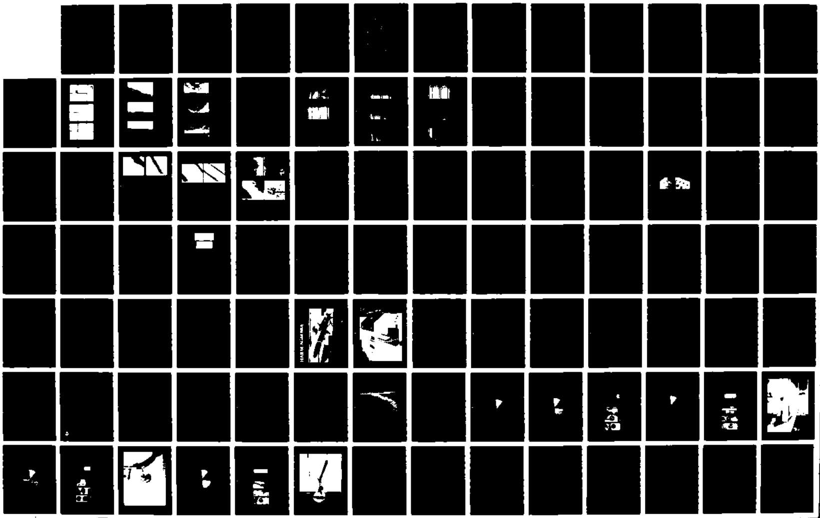
INTRODUCTION:

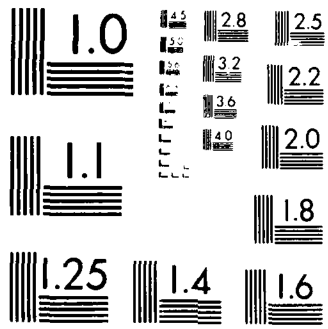
The search for the best available flux never ends, or, at least, it should never end. The task is not simple for several reasons. First, as shown clearly in the paper this group presented here three years ago, the different lead materials seen in electronic assemblies respond best to different fluxes. Second, new fluxes appear and old fluxes change. Third, assembly processes and inspection criteria change. The purpose of this study was to evaluate 120 fluxes representing a reasonable cross section of those available in the United States, using the more common MIL-SPEC tests and several new tests or modifications of older tests. Objectives were to rank the fluxes for potential use within the Texas Instruments Equipment Group or by TI's vendors and subcontractors, and to evaluate the tests that might be used in academic study of fluxes, qualification of individual fluxes for use on specific programs within the Equipment Group, and developement of incoming tests for fluxes to be used in production.

Although the previous paper presented by this laboratory demonstrated that fluxes are often more effective on some lead finishes than on others, this study has been limited to oxidized copper surfaces as described in MIL-F-14256. This constraint may seem odd in an industry in which bare copper surfaces are seldom subjected to flux and solder, but it is a reasonable starting place since the only MIL-SPEC relating to fluxes uses bare copper and since this study would have been far too large if lead finish had not been restricted. The rejection of a flux based on a test or specification other than the one to which it is ordered can be a very frustrating experience for both the vendor and the purchaser. Thus, if possible, the incoming test should be taken from MIL-F-14256.

AD-A197 600 SOLDERING TECHNOLOGY PROCEEDINGS OF ANNUAL SEMINAR (8TH) HELD ON 22-23 FEBRUARY 1984(U) NAVAL WEAPONS CENTER CHINA LAKE CA FEB 84 SBI-AD-E900 566 2/3

UNCLASSIFIED F/G 13/5 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

FLUX SELECTION:

Flux selection is simple only in a very strict environment in which the military customer severely restricts assembly flux choices. Some space programs allow only R (water white rosin) flux. Naval Weapons Center (NWC) and MICOM programs tend to allow only RMA (rosin - mildly activated) fluxes. Air Force programs often allow RA (rosin - activated) fluxes. The Navy is conservative because their failures tend to occur far from home and because their equipment operates under nasty conditions. The Army (MICOM) is conservative because Army equipment must be able to operate under any condition in which men can operate. Air Force equipment (and men) must lead a soft life.

Even within this strict military environment these rules may be broken or modified. NWC has at least considered use of RA flux on very tightly controlled programs after extensive evaluation. The Air Force has allowed use of a non-MIL-SPEC non-rosin flux on a specific system in which the actual PWB assembly and assembly process were all designed to accommodate the active flux. In addition to actual PWB assembly processes, every military electronic system supplier uses components that are tinned using very active fluxes and must be able to advise his suppliers and subcontractors on the best fluxes to use in tinning parts. Thus, it is no longer safe for a military electronics supplier to remain ignorant of the broad variety of non-MIL-SPEC fluxes available today.

The vendors known to the Equipment Group Analytical Lab were asked to submit any fluxes that they wished to see evaluated for inclusion in the study. The fluxes used by the Texas Instruments Equipment Group were all represented. One hundred and twenty fluxes were submitted and fully tested. Because many of these fluxes are not marketed for military use and because the tests designed for use with rosin fluxes are applied to fluxes that are vastly different from rosin fluxes, the flux name and vendor are hidden behind a code. The manufacturers whose fluxes are included are Alpha, Cobar, Fry, Gardiner, Gyrex, Hi-Grade, Kenco, Kester, Lonco, Multicore, RFE, and Superior. Table 1 shows the fluxes by name and type.

TEST SELECTION:

The impetus for this study is partly dissatisfaction with MIL-F-14256 tests as either evaluation or incoming tests. The wetting balance was also held in low esteem as an incoming test because of the large number of samples usually required to obtain a statistically satisfactory test result. However, these are the tests that exist and have some legal sanction. It was hoped to find some correlation between their results across the broad range of fluxes tested. At least one quantitative test was sought that could be used as an incoming test. To be truthful,

ROSIN FLUXES

ALPHA 100
GARDINER 1035
GARDINER 1135
HIGRADE 341
KENCO 240

ROSIN MILDLY ACTIVATED FLUXES

ALPHA 4011
ALPHA 611
ALPHA 620
ALPHA 625
COBAR 210-35
FRY RB-RMA-35
FRY-RB-RMA-25
GARDINER 1235
GARDINER 1425
GARDINER 1435
HIGRADE 535
KENCO 313
KENCO 365
KENCO 373
LONCO 106A35X
LONCO 106A35XMIL
MULTICORE 5381
RFE 201-20

ROSIN ACTIVATED FLUXES

ALPHA 2861
ALPHA 711
ALPHA 711 MIL
ALPHA 711-35 MIL
ALPHA 711-FS
ALPHA 806 MIL
ALPHA 809
ALPHA 815
ALPHA 815 MIL
ALPHA 816-35
ALPHA 820-25
ALPHA TL33M
COBAR 302-20
FRY RB-RA-25
FRY RB-RA-25M
GARDINER 2035
GARDINER 2135
GARDINER 2235
GARDINER 2425
GARDINER 2535
GARDINER 2635
GARDINER 2735
GARDINER 2835
HIGRADE 3519
HIGRADE 3527
KENCO 452
KENCO 465
KENCO 875
KENCO 882
KESTER 1773
LONCO 7733 TA
LONCO 9000
MULTICORE 366A-25
RFE 200-35
RFE 240-35
RFE 501-20

WATER SOLUBLE ROSIN FLUXES

COBAR 425
COBAR 425-SP
LONCO 35 W8
RFE 2630
RFE 2631-S
RFE 2632-S
RFE 2640

WATER SOLUBLE RESIN FLUXES

ALPHA 4118
ALPHA 4242
ALPHA 870-25
ALPHA 871-25
ALPHA 872-25
COBAR 353
LONCO 20 WSM 2
LONCO 35 WSM

WATER SOLUBLE ORGANIC ACID FLUXES

ALPHA 250HF
ALPHA 850-25
ALPHA 850-33
ALPHA 855
FRY T760
FRY T761
GARDINER 5117
GARDINER 5132
GARDINER 5310
GARDINER 5425
GARDINER 5735
GYREX #1
GYREX #2
HIGRADE 7922
KENCO 125
KENCO 147
KENCO 183
KENCO 192
KESTER 2211
KESTER 2331
LONCO 3355 HB
LONCO 3355-11
LONCO 3355-ST
LONCO 3366-11
LONCO CF-430
RFE 301-16CG
RFE 301-26
RFE 301-40CG
SUPERIOR 30
SUPERIOR 45
SUPERIOR 50
SUPERIOR 90

ORGANIC ACID FLUXES

HIGRADE 2001
HIGRADE 2002
HIGRADE 2002-M

SYNTHETIC ACID FLUXES

ALPHA 880
LONCO 212

SYNTHETIC RESIN FLUXES

ALPHA 4209
MULTICORE XERSIN2016

NO NAME FLUXES

FRY 502-35
FRY 552-35

TABLE 1 SUMMARY OF FLUXES EVALUATED

it was hoped that the MIL-F-14256 tests would be self consistent and that the ranking would not be dependent on the wetting balance.

The MIL-F-14256 tests performed are listed in Table II with the majority of tests performed exactly as required by MIL-F-14256. A brief explanation of each test listed in Table II follows.

TABLE II: MIL-F-14256 TESTS

TESTS	TEST REQUIREMENTS R & RMA	RA
Solids Content	15% Minimum	15% Minimum
Chloride & Bromide	Pass/Fail	Not Applicable
Effect on Copper Mirror	Pass/Fail	Not Applicable
Dryness	Dry/Tacky	Dry/Tacky
Spread Factor	80 Minimum	80 Minimum
Solder Pool	Pass/Fail	Pass/Fail
Resistivity of Water Extract	100,000 ohm-cm, Minimum	50,000 ohm-cm, Minimum

SOLIDS CONTENT. A weighed sample of flux (approximately 6 grams) was heated in a circulating air oven until the solvent was evaporated. The flux was heated and weighed repeatedly until the weight remained constant. The percent of residual solids content was then calculated.

SPECIFIC GRAVITY. The specific gravity was determined by pouring 40 milliliters of flux into a graduated cylinder and measuring the specific gravity using a Tromner balance.

CHLORIDES AND BROMIDES. A drop of flux was placed on a piece of silver chromate test paper. The test paper was examined for a color change which indicated the presence of chlorides or bromides.

EFFECT ON COPPER MIRROR. The copper mirror test was performed by placing 0.05 milliliters of the test flux and 0.05 milliliters of the control flux (rosin and isopropyl alcohol) on a copper glass slide and placing it in a 25 degrees C dust free container for 24 hours. At the end of 24 hours the flux residue was cleaned from the slide and the slide was visually examined. The test flux failed the test if there was any complete removal of the copper film.

DRYNESS. The dryness of the flux residue was determined by placing a solder ring and 0.10 grams of flux on an oxidized copper coupon. The samples were then placed in a 205 degrees C oven for six minutes. The coupons were cooled for 1/2 hour and then dusted with chalk powder. The ability to remove the chalk from the surface of the flux by light brushing was an indication of the dryness.

SPREAD FACTOR. The spread factor was run exactly like the dryness test with the exception that the height of the solder ring was measured after melting. By applying a formula which included the solder height, the percent spread factor was calculated.

SOLDER POOL. The solder pool test was run similarly to the dryness and spread factor tests. The test coupon was cleaned copper that had been oxidized for 5 minutes at 315 degrees C. The most important variation from the MIL-SPEC was in the evaluation of the results. Instead of a visual inspection, a metric planimeter was used to calculate the area of the solder pool.

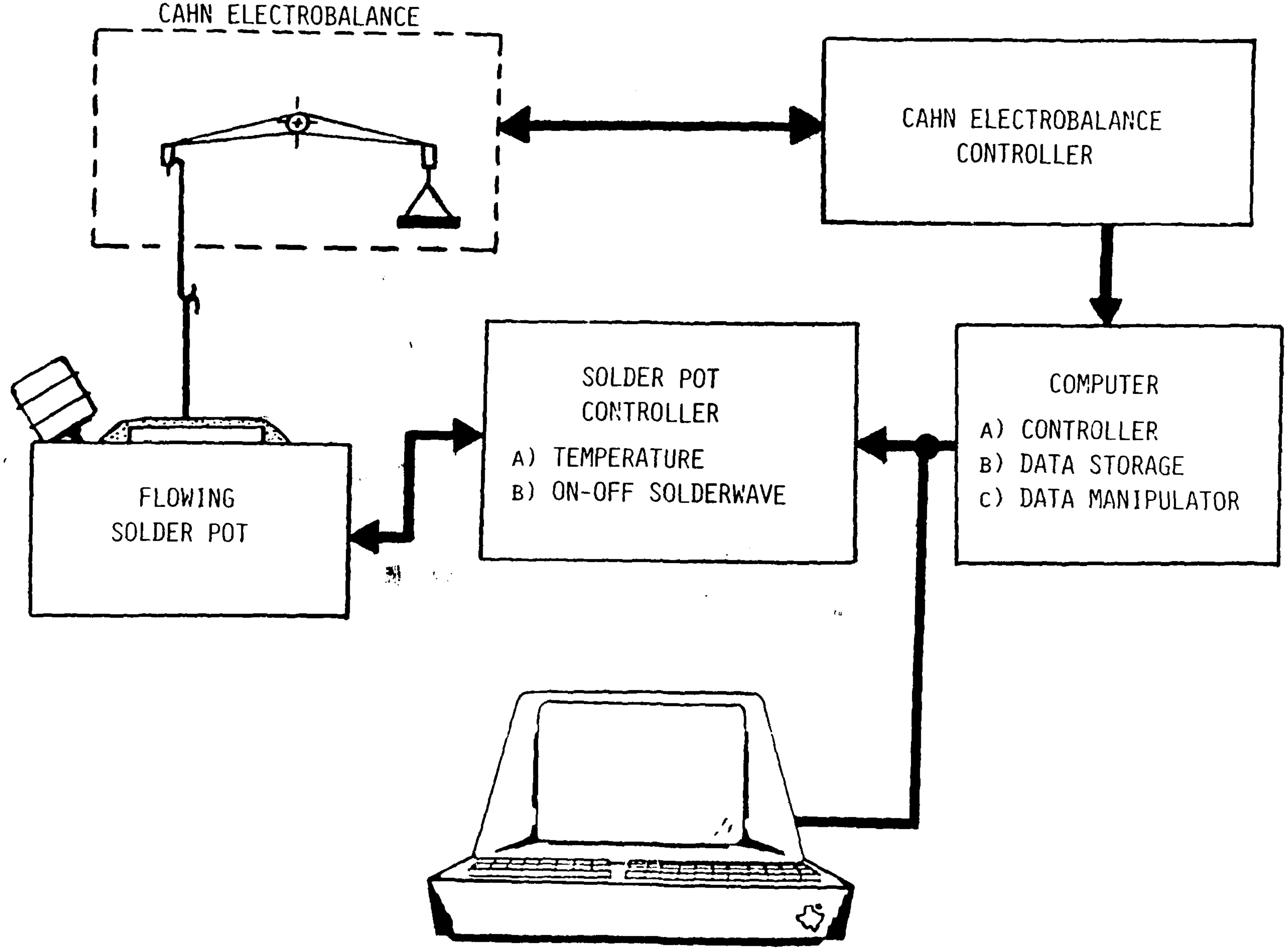
RESISTIVITY OF WATER EXTRACT. The water resistivity was measured by placing 0.1 milliliters of flux in a beaker of distilled water. The water was heated to the boiling point and then quickly cooled to 25 degrees C. The water resistivity was then measured using a conductivity bridge and cell. The resistivity was stated as the average of three tests.

Two additional non-MIL-F-14256 tests were conducted to better quantify the activity of each flux. These tests were the copper dissolution and the wetting balance test. A description of each test method follows.

COPPER DISSOLUTION. The copper mirror test is a pass or fail test that does not extend usefully into the active flux region. Therefore, a copper dissolution test was created to extend the concept of the copper mirror test to the more active fluxes. The test sample was a bundle of 20 mil copper wire weighing approximately 3 grams. These bundles provided measurable weight loss for active fluxes. Each pre-weighed bundle was placed in a beaker containing 30 mils of flux. The beaker was then covered and baked for 24 hours at 80 +/- 5 degrees C. The bundle was cleaned and reweighed and the weight loss was recorded as a percent of the total initial weight.

WETTING BALANCE. The last test performed was the wetting balance test. The wetting balance system consisted of a Model 2000 Cahn Electrobalance set up over an Electrovert WDC flowing solder pot. Both were attached to a TI 990 Computer and a Printronix 300 Printer (Figure 1). The Cahn Electrobalance is a very sensitive and low inertia instrument capable of withstanding the solder testing environment and providing accuracy far beyond solderability testing requirements (10 mg full scale). The use of the flowing solder pot provided a continually fresh surface that did not distort the curves. The solder pot was run with a peanut oil cover. The surface was wiped within 10 seconds

FIGURE 1


CAHN ELECTROBALANCE
CAHN ELECTROBALANCE CONTROLLER
SOLDER POT CONTROLLER
A) TEMPERATURE
B) ON-OFF SOLDERWAVE
COMPUTER
A) CONTROLLER
B) DATA STORAGE
C) DATA MANIPULATOR
FLOWING SOLDER POT

prior to each test because it was noted that even a flowing solder surface developed a thin oxide surface. The 20 mil copper wire samples were cleaned and oxidized as described by John Rizzo, Boeing Aerospace Company, "Evaluation of Flux Activity and Pot Life Using Wetting Balance Techniques," 1983 NWC Conference. The samples were submersed at a rate of 1 in/sec to a depth of 0.2 inch. Twenty samples were run for each flux type.

DATA TREATMENT:

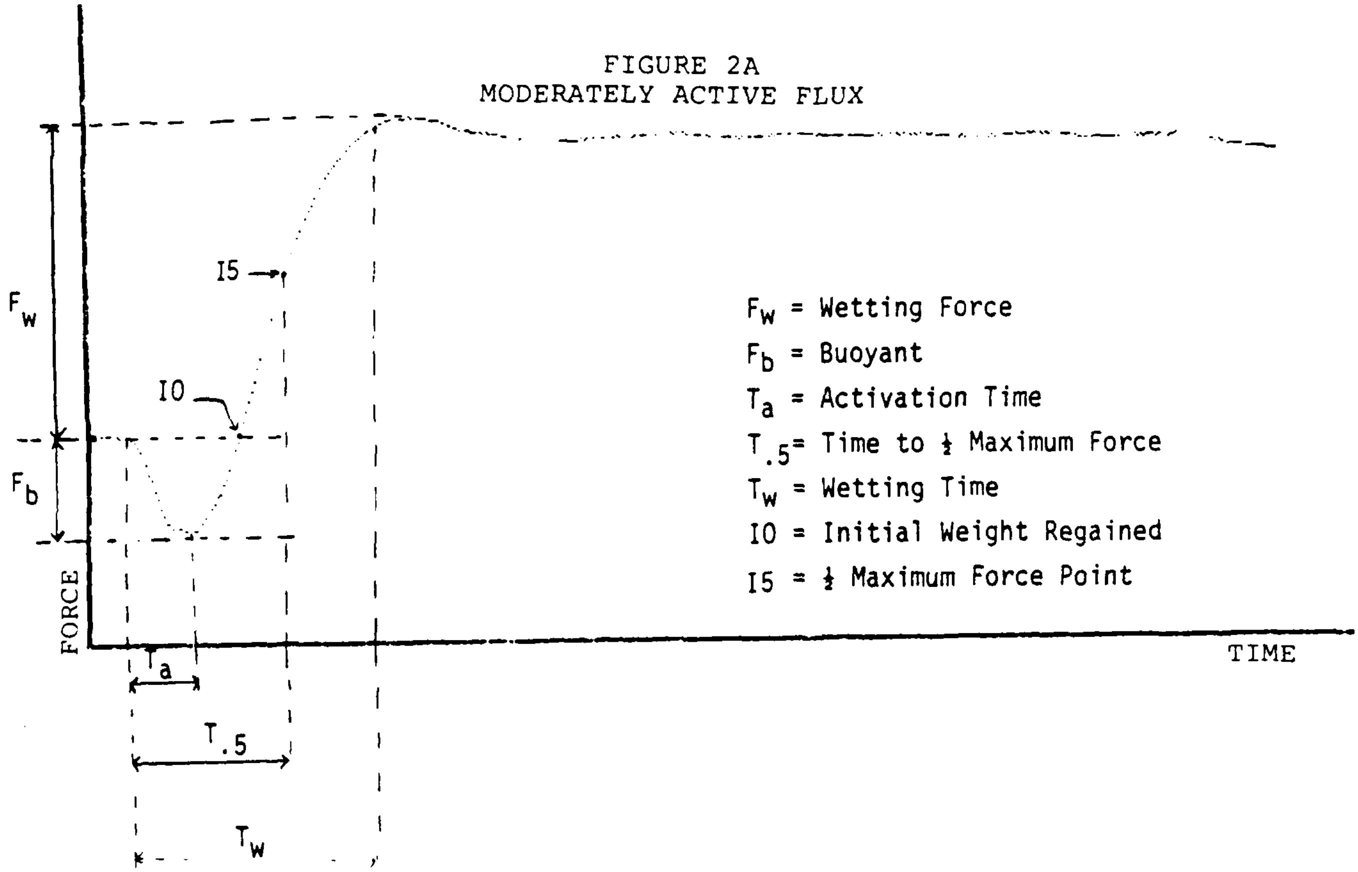
The data from all tests other than the wetting balance was simply averaged from the three tests run at each condition. The wetting balance data from twenty samples per flux was fully calculated for each flux and then combined for each flux.

Typical force vs time curves, reduced data and data summaries are shown in Figure 2. It becomes immediately apparent that the only way to manipulate such a large amount of data is with a computer. In writing a program to summarize the force vs time curves and reduce the data, it was necessary to identify specific points on each curve to act as flags in the calculations. The choice of these flag points is critical in reducing the data accurately and uniformly. A glance at Figures 2A through 2E provides some appreciation for the complexity of this programming task since widely varying curve shapes must be accommodated.

The major sections of the force vs time curves are diagrammed in Figure 2A and only a few words of explanation are necessary. The wetting time (Tw) is defined as the total time from initial contact of the fluxed lead with the solder until the slope of the curve (over 8 points) reaches an arbitrarily set value. This value must be reached after point Io and can be changed to be more or less sensitive to slope changes. It should be noted that the point on the curve corresponding to the set slope is not necessarily the same as the maximum force point. The initial slope is the slope at which the curve passes through the initial weight again, or Io, and is calculated over the points from Io to Io+10. In order to get some feeling for the general shape of the curve, the average slope was calculated between Io and Is.

A flux index was defined as the maximum wetting force divided by 20 times the time it took to achieve 50% of the maximum wetting force. This ratio has practical significance in that a flux with a large maximum wetting force but long time to 50% of the force would not be suitable for use on flow soldering lines. Similarly, a flux that has a rapid wetting rate but only a small maximum force would be considered unsuitable for use in flow soldering. In both cases, the flux index value would be small. This index proved to be sensitive enough to provide a unique ranking of the fluxes. Figures 2A through 2E are examples of typical forces vs time curves of fluxes ranging from inactive to extremely active.

FIGURE 2A
MODERATELY ACTIVE FLUX



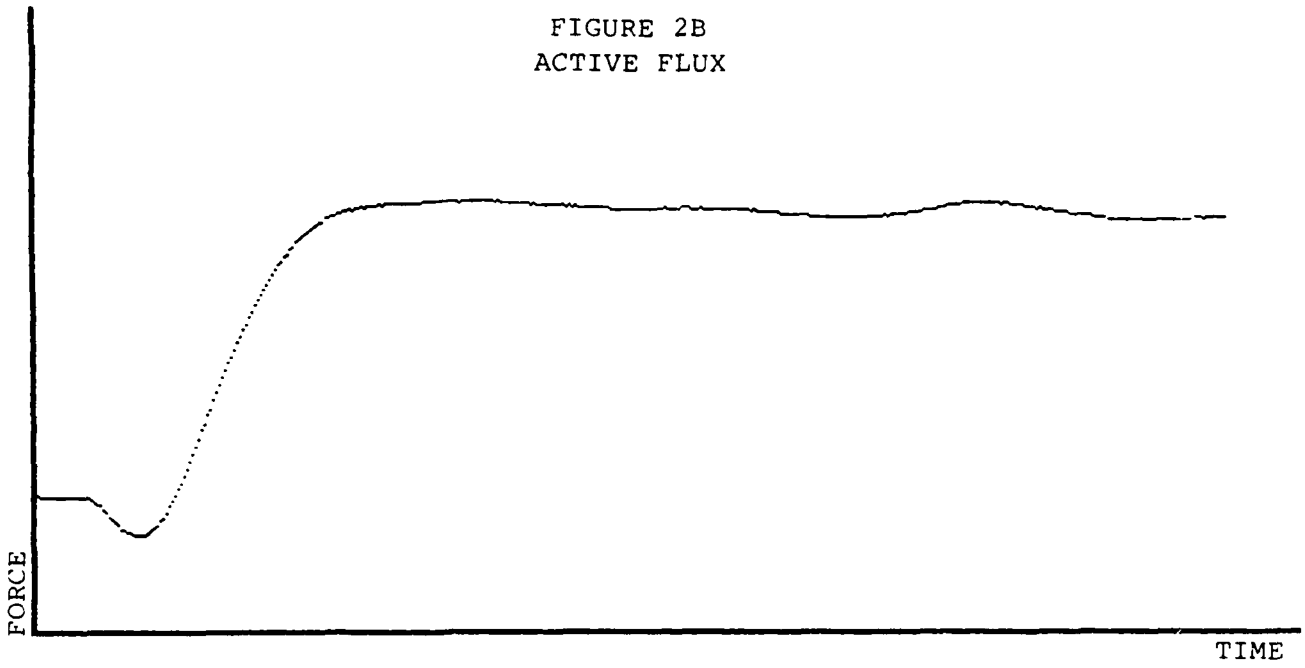
REDUCED DATA FOR SAMPLE SHOWN ABOVE:

Activation time was 0.5750 seconds.
Wetting time was 2.3500 seconds.
Initial weight was 32.8164 milligrams.
Maximum weight was 82.2710 milligrams.
Minimum weight was 17.0696 milligrams.
Buoyant force was 15.7468 milligrams.
Wetting force was 49.4546 milligrams.
Wetting rates:
    at initial weight was: 57.143 milligrams per second.
    average slope was: 62.255 milligrams per second.
Time to 50 % of wetting force was 1.3750 seconds.
Rate at 50 % of wetting force was 49.524 mg/second.
I1 = 11 I2 = 34 I0 = 51 I5 = 66 I3 = 105

SUMMARIZED DATA FOR 20 SAMPLES:

Parameter	Minimum	Maximum	Median	Average	Std_Dev	Units
Activation	0.5500	1.1750	0.7750	0.7638	0.1561	seconds.
Wetting time	2.3250	8.1750	5.1500	4.9425	1.8111	seconds.
Wetting force	16.4916	50.2177	43.8665	42.9395	7.2693	milligrams
Buoyant force	[illegible]	27.1957	17.1673	18.7508	4.7698	milligrams
Initial rate	4.9817	57.3374	19.6337	29.2275	17.2384	mg / sec.
Average rate	5.5352	63.0862	[illegible]	28.6215	19.2416	mg / sec
50 % time	1.3500	7.2000	2.7500	2.8513	1.3701	seconds.
50 % rate	3.8075	52.2508	13.8705	21.1624	16.3450	mg / sec
FLUX INDEX	1.2216	0.6975	1.5951	1.5060		mg / sec

FIGURE 2B
ACTIVE FLUX



REDUCED DATA FOR SAMPLE SHOWN ABOVE:

Activation time was 0.4500 seconds.
Wetting time was 2.3750 seconds.
Initial weight was 21.0867 milligrams.
Maximum weight was 68.1562 milligrams.
Minimum weight was 15.0671 milligrams.
Buoyant force was 6.0195 milligrams.
Wetting force was 47.0696 milligrams.
Wetting rates:
    at initial weight was: 41.709 milligrams per second.
    average slope was: 46.203 milligrams per second.
Time to 50 % of wetting force was 1.2500 seconds.
Rate at 50 % of wetting force was   38.681 mg/second.
I1 = 17 I2 = 35 I0 = 47 I5 = 67 I3 = 112

SUMMARIZED DATA FOR 20 SAMPLES:

Parameter	Minimum	Maximum	Median	Average	Std_Dev	Units
Activation	0.3250	0.7250	0.4500	0.4625	0.0965	seconds.
Wetting time	1.7000	3.3500	2.4250	2.4350	0.4361	seconds.
Wetting force	30.2277	48.3475	43.8461	42.5769	5.3006	milligrams
Buoyant force	3.7351	11.3370	5.9544	5.9310	1.6507	milligrams
Initial rate	32.3321	49.1230	40.1465	39.9755	3.6372	mg / sec.
Average rate	37.7436	50.0466	44.1731	43.9702	3.2354	mg / sec.
50 % time	[illegible]	1.5700	1.2250	1.2538	0.1370	seconds.
50 % rate	[illegible]	41.5110	[illegible]	[illegible]	3.8560	mg / sec
FLUX INDEX	[illegible]	[illegible]	3.5773	3.3960		mg / sec.

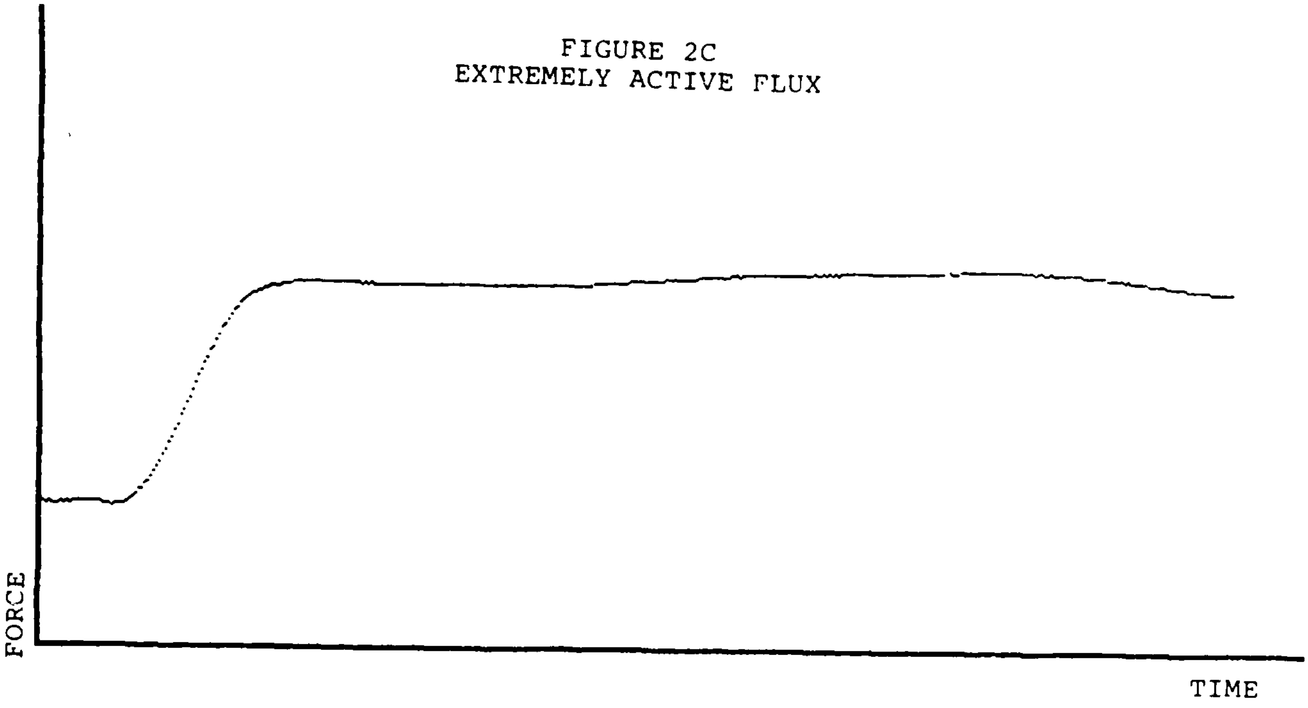


FIGURE 2C
EXTREMELY ACTIVE FLUX

REDUCED DATA FOR SAMPLE SHOWN ABOVE:

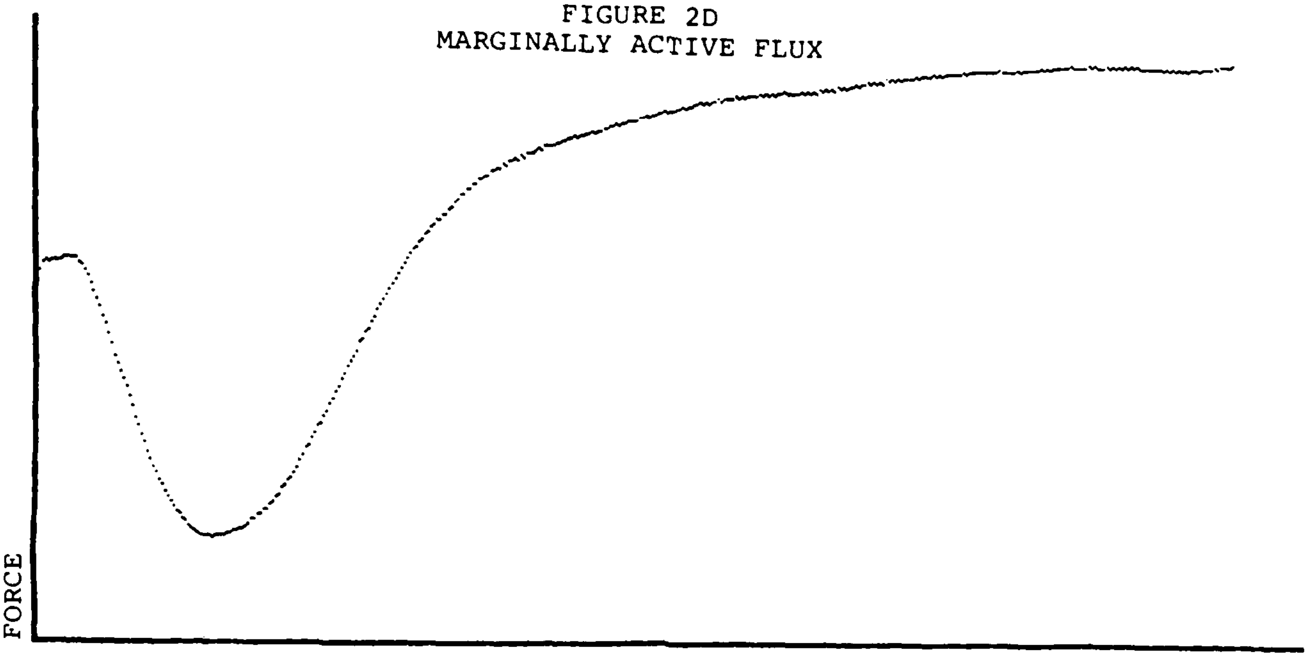
```
****** PLEASE NOTE THAT T_ACTIVATE IS 0.0 ******
****** AND WILL EFFECT T_WET & T_.5       ******

   Activation time was  0.0000 seconds.
   Wetting time was  1.6750 seconds.
   Initial weight was  22.4257 milligrams.
   Maximum weight was  59.8778 milligrams.
   Minimum weight was  22.0024 milligrams.
   Buoyant force was  0.4233 milligrams.
   Wetting force was  37.4521 milligrams.
   Wetting rates:
       at initial weight was:      9.963 milligrams per second.
       average slope was:     28.291 milligrams per second.
   Time to 50 %  of wetting force was  0.7000 seconds.
   Rate at 50 %  of wetting force was    35.458 mg/second.
 I1 =  16 I2 =  16 I0 =  25 I5 =  52 I3 =  83
```

SUMMARIZED DATA FOR 20 SAMPLES:

Parameter	Minimum	Maximum	Median	Average	Std_Dev	Units
Activation	0.0000	0.5000	0.2500	0.2233	0.1759	seconds.
Wetting time	1.4500	3.7250	1.9[illegible]0	2.1350	0.6001	seconds.
Wetting force	33.4554	59.1168	39.4831	42.1605	7.1140	milligrams
Buoyant force	0.1832	3.0769	1.1396	1.3828	0.8892	milligrams
Initial rate	8.1074	37.3138	21.5873	20.8058	7.1377	mg / sec.
Average rate	25.1447	44.3008	30.6206	32.3374	4.5501	mg / sec.
50 % time	0.8000	1.5250	1.0250	1.0925	0.2140	seconds
50 % rate	13.6569	46.8364	34.3834	33.0989	6.8631	mg / sec.
FLUX INDEX #	4.1819	3.8765	3.3520	3.8571		mg / sec

FIGURE 2D
MARGINALLY ACTIVE FLUX

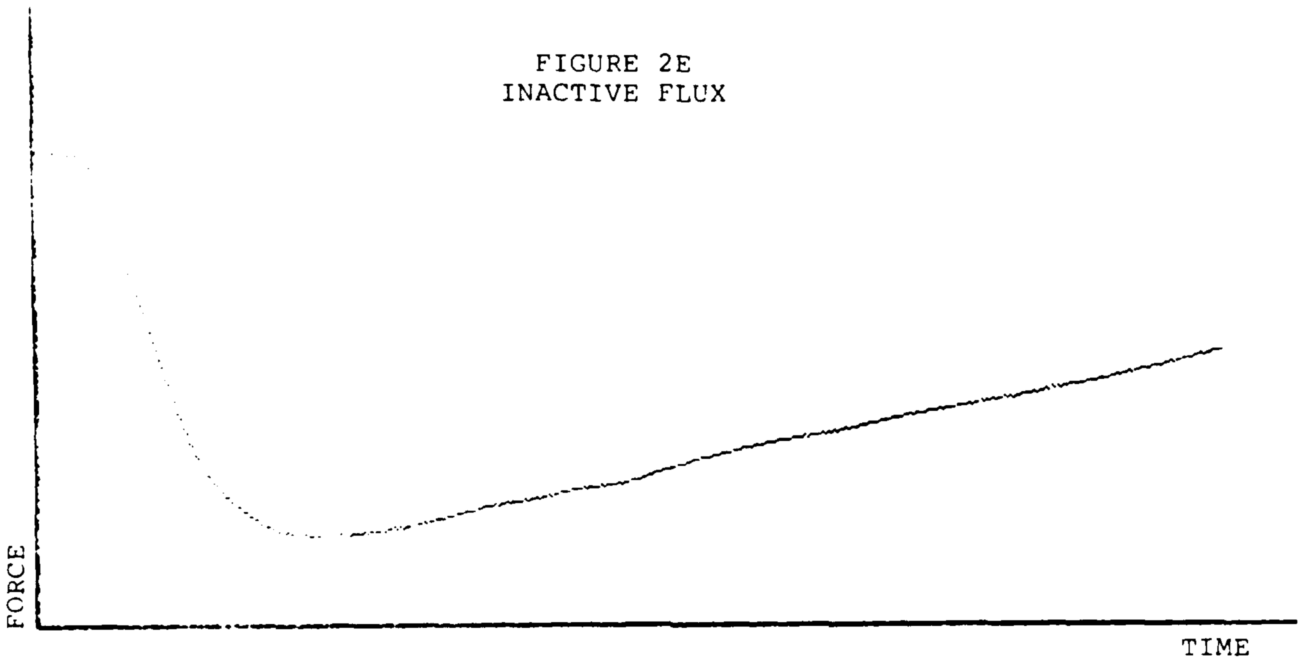


REDUCED DATA FOR SAMPLE SHOWN ABOVE:

Activation time was 1.1750 seconds.
Wetting time was 5.4000 seconds.
Initial weight was 60.0936 milligrams.
Maximum weight was 90.9401 milligrams.
Minimum weight was 16.5812 milligrams.
Buoyant force was 43.5124 milligrams.
Wetting force was 30.8465 milligrams.
Wetting rates:
    at initial weight was: 23.248 milligrams per second.
    average slope was: 18.085 milligrams per second.
Time to 50 % of wetting force was 3.6500 seconds.
Rate at 50 % of wetting force was 8.889 mg/second.
I1 = 12 I2 = 59 I0 = 123 I5 = 158 I3 = 228

SUMMARIZED DATA FOR 20 SAMPLES:

Parameter	Minimum	Maximum	Median	Average	Std_Dev	Units
Activation	0.5500	1.6000	0.8250	0.9350	0.3094	seconds.
Wetting time	2.0250	6.5750	3.0000	3.7600	1.4976	seconds
Wetting force	30.8465	53.3903	43.3374	43.6516	4.2991	milligrams
Buoyant force	11.3472	49.7558	22.3850	27.0150	11.5229	milligrams
Initial rate	13.2845	73.1623	37.8998	45.1526	19.1105	mg / sec.
Average rate	14.1014	78.5880	37.5091	46.9153	22.1335	mg / sec.
50 % time	1.2750	4.6250	2.3000	2.5500	1.0585	seconds.
50 % rate	3.8889	60.8546	32.4298	36.5030	18.9938	mg / sec.
FLUX INDEX #	2.4193	1.1544	1.3842	1.7113		mg / sec



REDUCED DATA FOR SAMPLE SHOWN ABOVE:

Activation time was 2.1500 seconds.
Wetting time was 3.7000 seconds.
Initial weight was 74.4566 milligrams.
Maximum weight was 43.0036 milligrams.
Minimum weight was 13.9438 milligrams.
Buoyant force was 60.5128 milligrams.
Wetting force was -31.4530 milligrams.
Wetting rates:
at initial weight was: 9999.990 milligrams per second.
average slope was: 9999.990 milligrams per second.
Time to 50 % of wetting force was +9.999900000000e+002 seconds.
Rate at 50 % of wetting force was 9999.990 mg/second.
I1 = 13 I2 = 99 I0 = 160 I5 = 159 I3 = 161

SUMMARIZED DATA FOR 20 SAMPLES:

Parameter	Minimum	Maximum	Median	Average	Std_Dev	Units
Activation	1.3500	2.5750	1.7500	1.8200	0.2749	seconds.
Wetting time	3.7000	9.6250	8.7750	8.3588	1.5682	seconds.
Wetting force	-31.4530	28.8889	10.6797	7.0549	15.6425	milligrams
Buoyant force	32.6902	63.0443	55.6573	53.0463	8.4212	milligrams
Initial rate	3.9072	9999.9900*	10.4518	3505.4470	4889.4977	mg / sec.
Average rate	4.1514	9999.9900*	9.2796	3505.3616	4889.5617	mg / sec.
50 % time	4.7500	999.9900*	7.7750	305.2095	466.6577	seconds.
50 % rate	1.4652	9999.9900*	6.9353	3004.1142	4698.8541	mg / sec.
FLUX INDEX #	-0.6622	0.0029	0.1374	0.0023		mg / sec.

*DEFAULT VALUE. INITIAL WEIGHT NEVER ACHIEVED.

INDIVIDUAL TEST RESULTS:

The following paragraphs summarize the results of the individual tests that were performed. No attempt is made in this section to correlate the data of one test with that of another. Data correlation will be addressed in the next section. All test results are summarized in Appendix A.

DRYNESS. Although a MIL-SPEC requirement, this test has little practical significance for manufacturers assembling PWBs which must pass stringent cleanliness requirements for removal of flux residues such as WS6536. This dryness test would be of greater interest to commercial manufacturers who might wish to leave the residues on the PWBs.

CHLORIDES AND BROMIDES. The MIL-SPEC requirement concerning chlorides and bromides is only applicable to R and RMA fluxes. These fluxes are allowed to show no evidence of chlorides and bromides being present. All of the R fluxes tested passed this test. However, of the 18 RMA fluxes tested, only 9 passed and 2 of the fluxes that failed this test are currently QPL approved. Not surprisingly, only 3 of the 36 RA fluxes passed this test, and no organic acid, synthetic acid, synthetic resin, water soluble rosin or water soluble resin fluxes passed. It is worthy of note that 3 of the 32 water soluble organic acid fluxes did indeed pass. It would appear that the majority of fluxes available (with the exception of R fluxes) contain chloride or bromide activators, regardless of the flux type.

RESISTIVITY OF WATER EXTRACT. The resistivity of water extracts for R and RMA fluxes must be at least 100,000 ohm-centimeters and at least 50,000 ohm-centimeters for RA fluxes. Again, all of the R fluxes met the MIL-SPEC requirements. One of the 5 QPL approved RMA fluxes failed this test and in general 6 of the fluxes classified as RMA by their manufacturers failed to meet the 100,000 ohm-centimeter minimum. All of the QPL approved RA fluxes that were tested passed, but in general only a third of the RA fluxes were able to meet the MIL-SPEC requirements. The remaining fluxes (water soluble organic acid, organic acid, synthetic acid, water soluble resin, water soluble rosin and synthetic resin) were all well below the 50,000 ohm-centimeter minimum resistivity limit of the MIL-SPEC.

EFFECT ON COPPER MIRROR. Flux types R and RMA fail MIL-SPEC requirements if they cause any complete removal of the copper film on a copper mirror. This requirement does not apply to RA fluxes. Of all the R and RMA fluxes tested, only one RMA flux removed the copper film (and it was not QPL approved). By contrast, the large majority of the other flux types tested failed this test. It seems that this test would be a good tool for identifying type R and RMA fluxes.

DISSOLUTION OF COPPER. This non-MIL-SPEC test was devised as a quantitative version of the copper mirror test. There is a general correlation between the two tests. Although there are wide variances within a given flux type, the fluxes that failed the copper mirror test usually showed faster copper dissolution rates. In general, the acid fluxes dissolved significantly more copper than other flux types and the average dissolution rate for the remaining rosin and resin fluxes (excluding type R) were roughly similar.

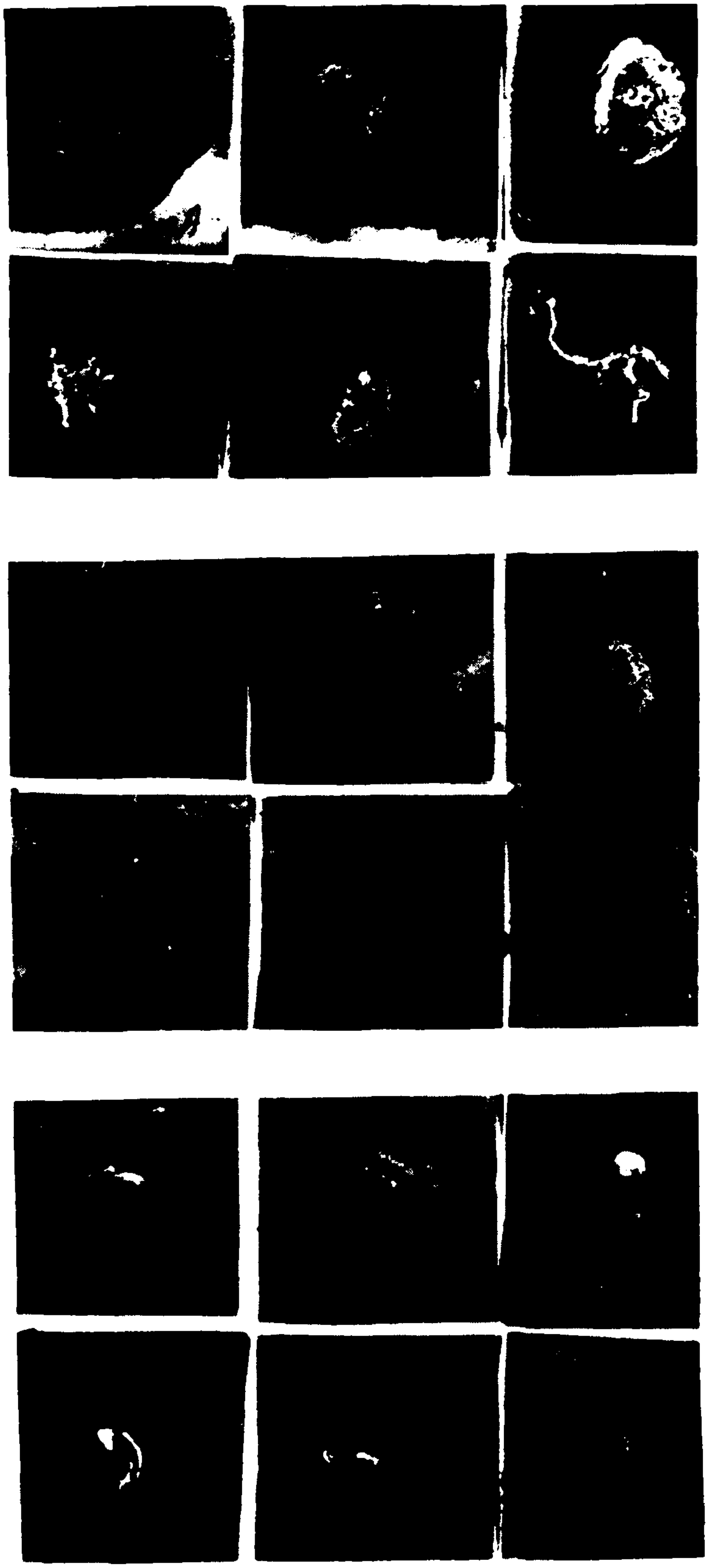
SOLIDS CONTENT. The MIL-SPEC requires a minimum of 15 percent solids by weight for R, RMA and RA type fluxes and only 7 of these fluxes failed to meet this requirement. Of these 7 that failed, none were QPL approved. The non-MIL-SPEC flux types were divided equally between those that had at least 15% solids by weight and those that did not with the proportion remaining fairly constant within flux types.

SPECIFIC GRAVITY. Although not specified in the MIL-SPEC, this test is the one most commonly used at Texas Instruments as a process control tool on the flow soldering line. The water soluble organic acid fluxes showed greater variance between fluxes than did the other flux types but, in general, the specific gravity values for the various flux types were centered around 0.15-0.17.

SPREAD FACTOR. The MIL-SPEC establishes a minimum spread factor of 80 for R, RMA, and RA fluxes. Obviously, this requirement is easily met with all types of fluxes since only 3 of all those tested failed, and even the failed fluxes had spread factors of 75 or greater. The majority of the fluxes had spread factors between 90 and 95. The photographs in Figure 3 illustrate the vastly different appearance of the various coupons after the test. Although the test was designed for rosin based fluxes, many of the water soluble acid and resin fluxes performed well. The microsections shown in Figure 4 demonstrate the relative fluxing ability of an R, RMA and RA flux quite dramatically as evidenced by the wetting angle of the solder at the copper-solder interface. Extreme cases of non-wetting are shown in Figure 5.

SOLDER POOL. The solder pool test outlined in the MIL-SPEC is a qualitative test which was modified to obtain a quantitative comparison of the fluxes. As expected, the area of the solder pool was smaller for R type fluxes with a median value of 81 millimeters squared. The remaining flux types had median values near 140 millimeters squared except for the organic acid fluxes where the median area was 273 millimeters squared. The variance between fluxes within a type group were greater than the variances from type to type, therefore, it would be hard to distinguish between flux types based on this test.

WETTING BALANCE. This is the best quantitative tool for comparing fluxes. The advantages of this test over other methods include the use of precise instrumentation sensitive to small variations between fluxes, computerized data gathering and manipulation, and the fact that the test does relate to some



RMA TYPE FLUX

WSOA TYPE FLUX

RMA TYPE FLUX

SA TYPE FLUX

WS ROSIN TYPE FLUX

RMA TYPE FLUX

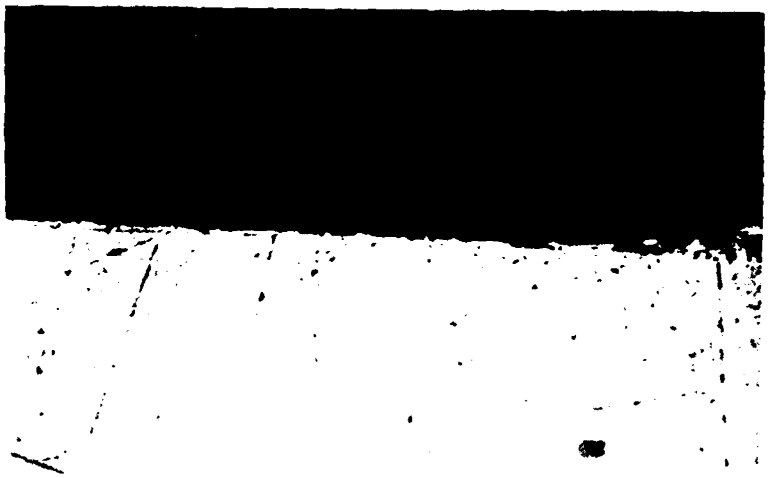
FIGURE 3
VARIATION OF SPREAD FACTOR TESTS

R TYPE FLUX

(800X)

RMA TYPE FLUX

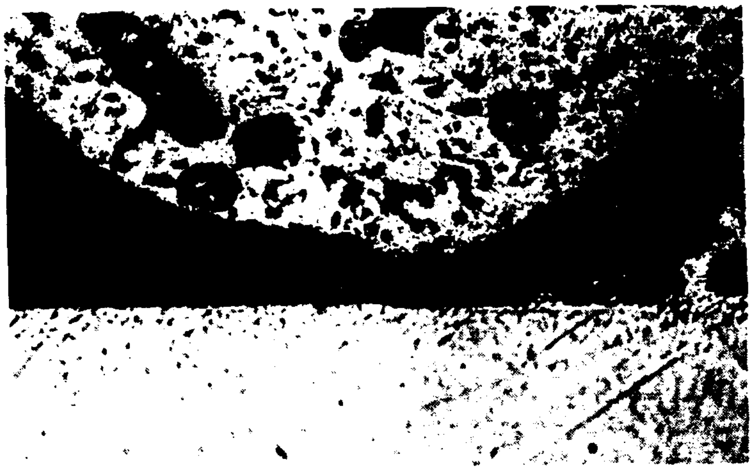
(800X)



RA TYPE FLUX

(800X)

FIGURE 4
SPREAD FACTOR MICROSECTIONS
INDICATING WETTING ANGLE



WS RESIN TYPE FLUX

(800X)

WSOA TYPE FLUX

(120X)

WS ROSIN TYPE FLUX

(500X)

FIGURE 5
SPREAD FACTOR MICROSECTIONS
INDICATING EXTREME NON WETTING

degree to the assembly soldering process. The drawbacks of this testing are the large sample sizes required for repeatability and the caution that must be exercised in using a computer to manipulate data from very dissimilar traces. The data for individual fluxes was reproducible and was handled without trouble by the computer program. Many refinements to the program were required to be able to handle the broad range of curves seen from the slowly acting R fluxes to the very fastest water soluble fluxes. The chosen flux index proved to be an excellent way to combine the wetting speed and wetting force into one index that accounted for the fact that some fluxes wetted very quickly to very low maximum wetting forces while other fluxes wetted to high wetting forces but did so very slowly.

Figures 2A through 2E are summarized in Table 3.

TABLE 3

	INACTIVE	MARGINALLY ACTIVE	MODERATELY ACTIVE	ACTIVE	EXTREMELY ACTIVE
INDEX	----	.845	3.597	3.765	4.161
Ta	2.15	1.175	0.575	0.450	0.000
Tw	3.70	5.40	2.35	2.375	1.675
Ts	----	3.65	1.375	1.25	0.90
Fw	-31.453	30.8465	49.4546	47.0696	37.4521
Fb	60.5128	43.5124	15.7468	6.0195	0.4233
Mave	----	18.085	62.255	46.203	28.291
MIo	----	23.248	57.143	41.709	9.963
MIs	----	8.889	49.524	38.681	35.458

As illustrated in Table 3, the various slope measurements do not reflect the relative activity of the fluxes and appear to be greatly influenced by the specific points used to calculate the value. It is interesting to note that while the wetting force does not follow a trend from inactive to extremely active fluxes, the buoyant force does follow this trend. The various time measurements all show good correlation with flux activity with the possible exception of wetting time. As discussed earlier, the point on the force vs time curve at which the Tw measurement is made is determined by a change in the slope of the curve. The curve of the inactive flux, although relatively constant in slope, does go through an inflection point great enough to trigger the Tw measurement. In this case, the Tw value for this flux is falsely low. The index described earlier proves to be a sensitive measure of flux activity and correlates precisely in Table 3.

TEST CORRELATION EVALUATION:

Correlation between the various types of tests is general and reveals only the most obvious of trends. Figures 6A-I are the summaries of the tests performed in this study.

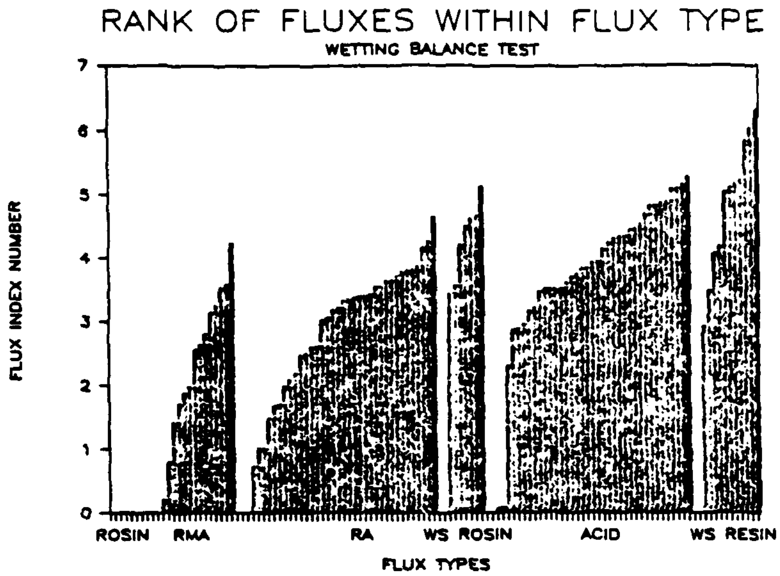


FIGURE 6A

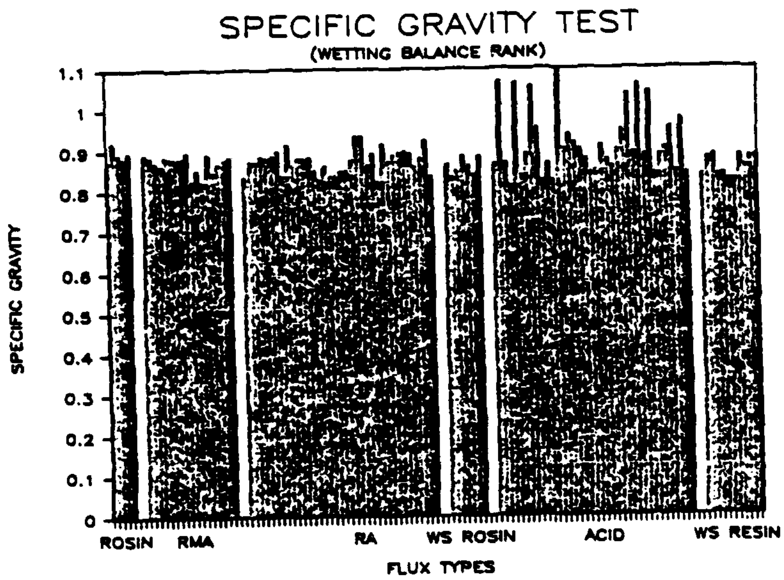


FIGURE 6B

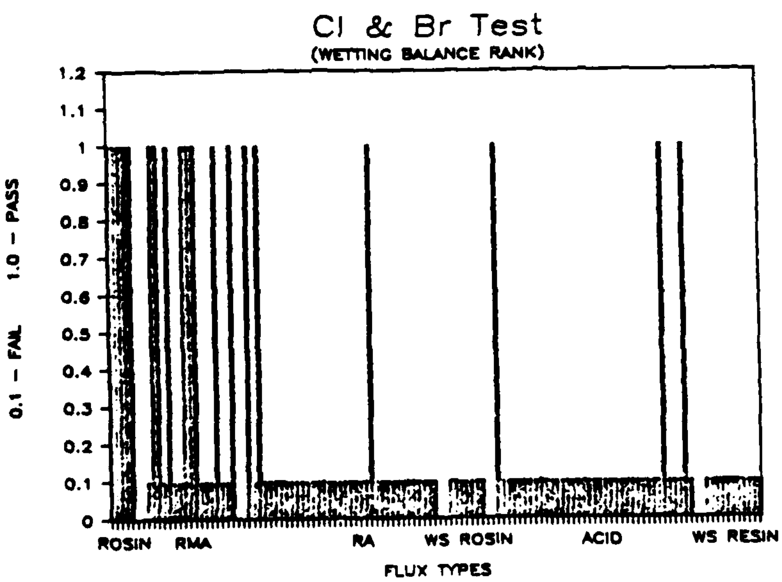


FIGURE 6C

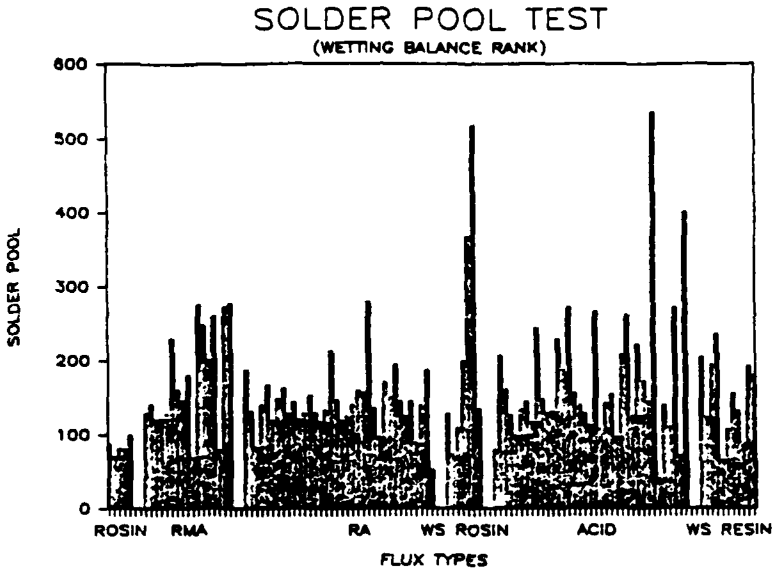


FIGURE 6G

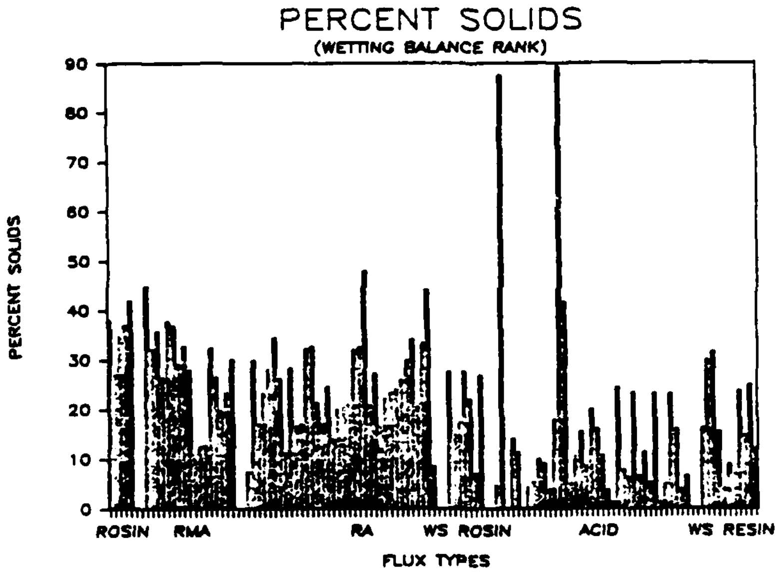


FIGURE 6H

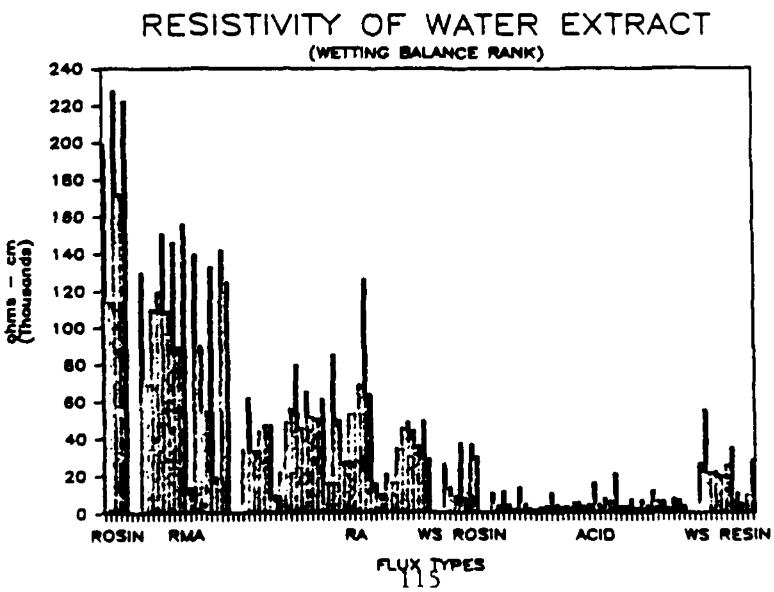


FIGURE 6I

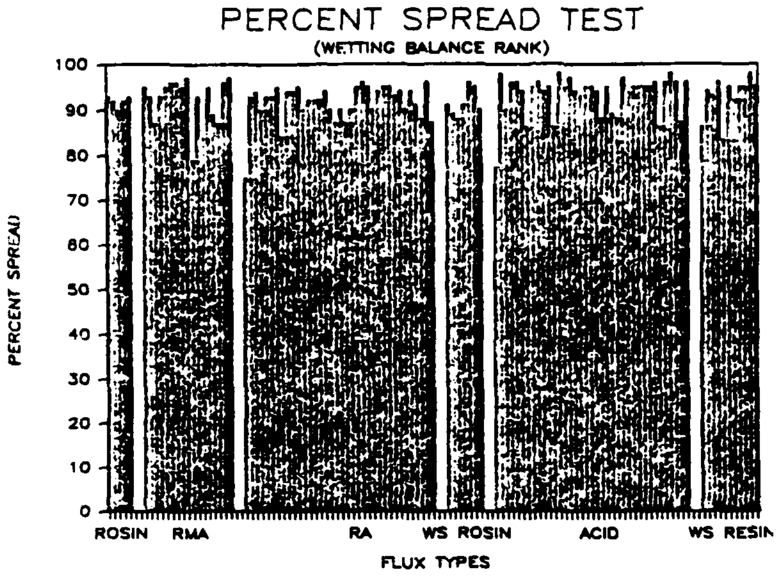


FIGURE 6D

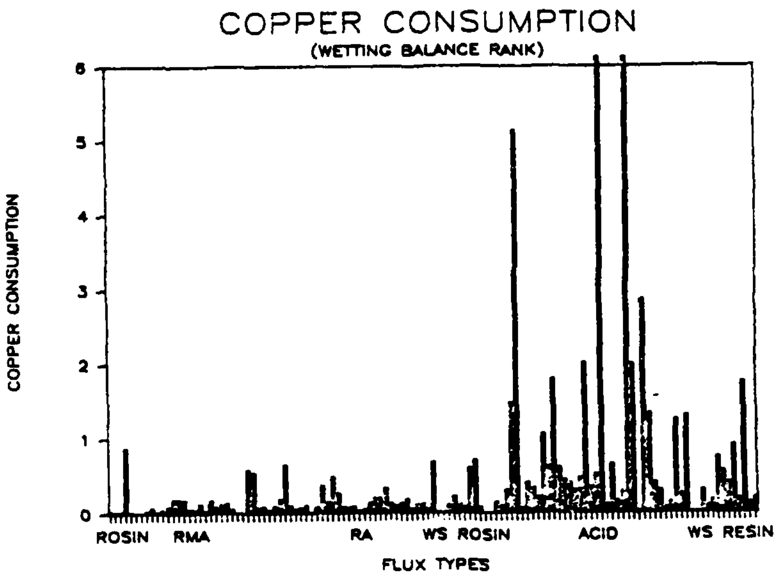
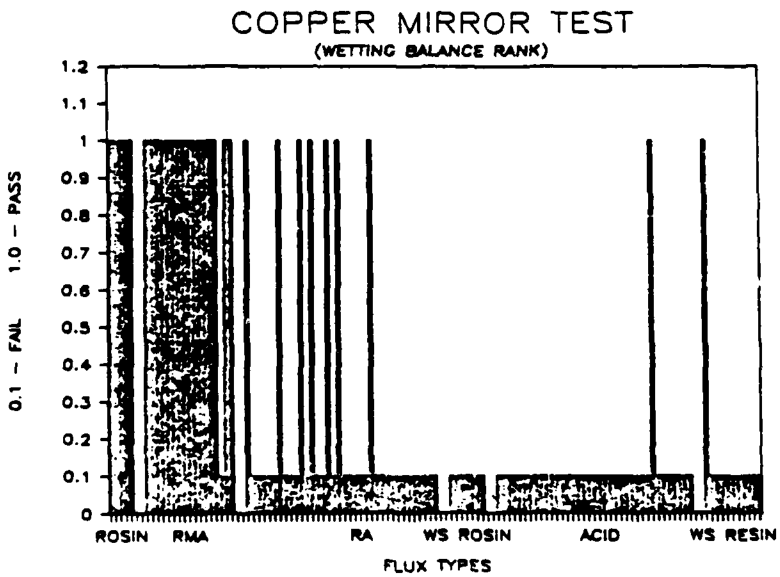


FIGURE 6E



FICURE 6E

TABLE 4

TEST SUMMARY BY FLUX TYPE

TYPE		Cl & Br	COPPER MIRROR	SPECIFIC GRAVITY	SOLIDS (PERCENT)	POOL (MM^2)	SPREAD FACTOR	EXTRACT RESISTIVITY (OHM-CM)	COPPER DISSOLUTION (% CHANGE)	WETTING BALANCE INDEX
ROSIN	MAXIMUM	P	P	.9199	41.9	99	93	228,000	.88	.0202
	MEDIAN	P	P	.8913	37.0	81	92	172,333	.02	.0115
	MINIMUM	P	P	.8961	27.0	70	90	114,000	.01	.0023
	(MIL-F-14256)	(P)	(P)	(NA)	(15MIN)	(NA)	(80MIN)	(100,000 MIN)	(NA)	(NA)
RMA	MAXIMUM	P	P	.8949	44.9	277	97	156,000	.19	4.2391
	MEDIAN	F	P	.8802	29.3	145	93	151,000	.07	1.9929
	MINIMUM	F	F	.8210	11.0	69	79	13,400	.01	.0018
	(MIL-F-14256)	(P)	(P)	(NA)	(15MIN)	(NA)	(80MIN)	(100,000 MIN)	(NA)	(NA)
RA	MAXIMUM	P	P	.9342	48.1	280	96	126,333	.68	3.8848
	MEDIAN	F	F	.8717	23.4	140	93	45,667	.10	3.1879
	MINIMUM	F	F	.8209	7.5	52	75	9,400	.01	.0019
	(MIL-F-14256)	(NA)	(NA)	(NA)	(15MIN)	(NA)	(80MIN)	(50,000 MIN)	(NA)	(NA)
WS ROSIN	MAXIMUM	F	F	.8845	27.8	517	96	37,700	.71	5.132
	MEDIAN	F	F	.8609	22.2	135	91	26,200	.13	4.5060
	MINIMUM	F	F	.8317	7.3	73	88	7,967	.08	3.4650
ACID	MAXIMUM	P	P	1.100	89.3	536	98	21,067	11.80	5.2707
	MEDIAN	F	F	0.8913	9.2	145	95	5,400	.40	3.9397
	MINIMUM	F	F	0.8119	0.0	40	77	1,763	.04	.06690
RESIN	MAXIMUM	F	P	.8842	31.8	237	98	55,667	1.76	5.1673
	MEDIAN	F	F	.8580	15.6	156	95	25,867	.30	4.1814
	MINIMUM	F	F	.8220	4.2	65	83	5,290	.08	2.9376

The extreme variation in performance within the flux type groupings points out the lack of correlation of most properties within flux types. It may not be assumed that a very corrosive flux is any better than a far less corrosive flux if the ability to wet a given lead is the criteria for acceptance. Table 4 is a summary of the performances of the various types of fluxes. Only the most general of trends may be seen, and the data spread within each flux type generally exceeds the data spread of the median values for every type tested.

It is clear from the summarized test data that the wetting balance test is the only test useful for ranking purposes. The MIL-SPEC tests then allow the fluxes that perform best in the wetting balance tests to be evaluated to see if they meet the requirements of MIL-F-14256. Table 5 shows summary data of three fluxes currently used at Texas Instruments as well as a flux which out performed the majority of samples tested. As can be seen from this Table, Alpha 620 meets the requirements of an RMA flux as specified in MIL-F-14256 and yet still ranked as one of the best fluxes evaluated. This flux is much more active than our currently used RMA flux and even performed better than our presently used RA flux. Comparing the results of the solder pool test, Alpha 620 was the best of the RMA fluxes with only 5 of the 120 fluxes performing better in this test. The wetting balance test provided the most revealing comparison of these fluxes. Of the 31 RA fluxes tested only 2 performed better than Alpha 620 and of the 55 non-rosin fluxes tested. Alpha 620 out performed half of the samples.

Table 5 is a summary of the nine tests performed during this study and indicates the wide range of value obtained for each flux type.

TABLE 5: REPRESENTATIVE MILITARY FLUX PERFORMANCE COMPARISON

FLUX TYPE	WETTING INDEX	PERCENT SOLIDS	Cl Br	SOLDER POOL	PERCENT SPREAD	COPPER MIRROR	WATER EXTRACT	COPPER CONSUMPTION
R	0.02	P	P	99	93	P	222,333	.01
RMA	2.0	P	P	180	97	P	156,000	.05
RA	3.4	P	F	160	95	F	53,833	.03
*RMA	4.2	P	P	277	97	P	125,000	.05

*Alpha 620

CONCLUSIONS:

The wetting balance test is the only test among those studied that is a worthwhile tool for quantitative evaluation of a flux or for an incoming test measuring fluxing effectiveness.

An index consisting of the wetting force above the initial (or zero) force divided by 20 times the wetting time to the first maximum was found to be an excellent index for comparing the fluxing ability of electronic assembly fluxes.

The tests in MIL-F-14256 are not good measures of the ability of a flux to induce solder wetting of a lead. They are only tests of conformance to a MIL-SPEC.

FUTURE WORK:

Two studies must follow this work. The first study is a repetition of the wetting balance study on the lead materials in common use in the electronics industry. The second study is that of correlation of wetting balance data with flow soldering data for selected fluxes.

APPENDIX A

(CON'T.)

FLUX TYPE	WETTING BALANCE	PERCENT SPREAD	COPPER MIRROR	WATER EXTRACT	COPPER CONSUMPTION	SPECIFIC GRAVITY	SOLIDS CONTENT	Cl & Br	SOLDER POOL
RA	3.4254	95	0.1	58000	0.03	0.9342	32.7	0.1	160
RA	3.4254	96	0.1	69500	0.05	0.9330	48.1	0.1	157
RA	3.458	95	1	126333	0.14	0.8625	20.9	1	280
RA	3.5625	90	0.1	64000	0.21	0.8904	27.3	0.1	136
RA	3.5667	94	0.1	15833	0.21	0.8209	16.8	0.1	97
RA	3.659	95	0.1	9867	0.34	0.9140	22.4	0.1	171
RA	3.6693	95	0.1	20667	0.13	0.8700	23.4	0.1	151
RA	3.7085	93	0.1	16133	0.1	0.8860	24.1	0.1	195
RA	3.7981	94	0.1	34767	0.14	0.8928	26.0	0.1	145
RA	3.8212	90	0.1	45667	0.19	0.8956	30.1	0.1	125
RA	3.8352	94	0.1	48867	0.06	0.8900	34.3	0.1	145
RA	3.8848	91	0.1	44167	0.11	0.8579	21.2	0.1	89
RA	4.1722	88	0.1	36166	0.12	0.8790	33.5	0.1	140
RA	4.2747	96	0.1	49500	0.05	0.9235	44.3	0.1	187
RA	4.6615	87	0.1	28667	0.68	0.8340	8.5	0.1	52
WS ROSIN	3.465	91	0.1	26200	0.1	0.8631	27.7	0.1	128
WS ROSIN	3.5795	89	0.1	13600	0.22	0.8317	15.0	0.1	73
WS ROSIN	4.2174	88	0.1	8900	0.13	0.8478	17.4	0.1	109
WS ROSIN	4.506	91	0.1	37700	0.08	0.8840	27.8	0.1	199
WS ROSIN	4.6211	96	0.1	7967	0.61	0.8609	22.2	0.1	368
WS ROSIN	4.6805	95	0.1	36833	0.71	0.8390	7.3	0.1	517
WS ROSIN	5.132	90	0.1	30133	0.08	0.8845	26.9	0.1	135
ACID	0.0669	77	0.1	10433	0.15	0.8642	4.7	1	80
ACID	0.0782	98	0.1	4100	0.1	1.0670	87.5	0.1	207
ACID	2.3254	90	0.1	11333	0.31	0.8665	0.0	0.1	161
ACID	2.885	96	0.1	3900	1.48	0.8119	14.2	0.1	127
ACID	2.9163	96	0.1	1763	5.14	1.0634	11.4	0.1	99
ACID	2.9824	94	0.1	13233	0.07	0.8367	0.0	0.1	135
ACID	3.1913	86	0.1	4733	0.41	0.8893	4.4	0.1	145
ACID	3.2448	95	0.1	2000	0.33	1.0550	5.5	0.1	117
ACID	3.4901	96	0.1	1933	0.21	0.9511	10.1	0.1	244
ACID	3.5279	94	0.1	3133	1.06	0.8220	9.2	0.1	148
ACID	3.5319	95	0.1	3967	0.63	0.8643	4.0	0.1	130
ACID	3.5326	86	0.1	10633	1.8	0.8235	18.0	0.1	132
ACID	3.5571	98	0.1	4510	0.61	1.1000	89.3	0.1	230
ACID	3.6416	95	0.1	2817	0.44	0.9020	41.8	0.1	189
ACID	3.7339	97	0.1	3533	0.4	0.9371	5.1	0.1	273
ACID	3.7708	94	0.1	5400	0.31	0.9163	10.5	0.1	156
ACID	3.8486	93	0.1	5600	0.48	0.9000	15.6	0.1	141
ACID	3.8591	95	0.1	3720	2.02	0.8760	8.6	0.1	129
ACID	3.9397	95	0.1	4533	0.35	0.8410	20.1	0.1	113
ACID	3.9606	94	0.1	16067	0.52	0.8492	16.1	0.1	267
ACID	4.1583	88	0.1	5166	11.8	0.9088	10.7	0.1	108

APPENDIX A

TEST RESULTS

FLUX TYPE	WETTING BALANCE	PERCENT SPREAD	COPPER MIRROR	WATER EXTRACT	COPPER CONSUMPTION	SPECIFIC GRAVITY	SOLIDS CONTENT	Cl & Br	SOLDER POOL
R	0.0023	93	1	199333	0.03	0.8744	38.0	1	87
R	0.0044	92	1	114000	0.01	0.9199	27.0	1	70
R	0.0115	90	1	228000	0.02	0.8913	34.9	1	81
R	0.0119	92	1	172333	0.86	0.8819	37.0	1	81
R	0.0202	93	1	222333	0.01	0.8961	41.9	1	99
RMA	0.0018	95	1	130000	0.03	0.8880	44.9	0.1	129
RMA	0.0018	93	1	69333	0.07	0.8821	32.2	1	140
RMA	0.0018	87	1	110333	0.01	0.8678	35.8	1	120
RMA	0.2063	93	1	119667	0.04	0.8600	26.5	0.1	121
RMA	0.7978	95	1	151000	0.09	0.8845	37.8	1	128
RMA	1.4322	96	1	109000	0.19	0.8812	37.0	0.1	229
RMA	1.736	96	1	146333	0.18	0.8802	29.3	0.1	160
RMA	1.8995	95	1	89667	0.17	0.8811	32.8	1	145
RMA	1.9929	97	1	156000	0.05	0.8949	27.9	1	180
RMA	2.5741	79	1	13400	0.05	0.8254	11.0	1	69
RMA	2.6538	93	1	139667	0.12	0.8510	12.6	0.1	275
RMA	2.8139	84	1	90000	0.03	0.8210	12.7	0.1	247
RMA	3.1544	95	1	54666	0.17	0.8910	32.4	0.1	201
RMA	3.2648	89	1	133000	0.08	0.8467	26.5	1	260
RMA	3.5475	87	0.1	19167	0.11	0.8681	19.7	0.1	79
RMA	3.6081	96	1	142000	0.13	0.8770	23.4	0.1	273
RMA	4.2391	97	1	125000	0.05	0.8830	30.2	1	277
RA	0.0019	75	1	34233	0.58	0.8319	7.5	1	187
RA	0.7323	93	0.1	62100	0.54	0.8718	30.0	0.1	131
RA	1.0277	94	0.1	33333	0.07	0.8717	17.1	1	83
RA	1.0277	90	0.1	43933	0.08	0.8848	23.3	0.1	140
RA	1.506	93	0.1	47333	0.04	0.8819	28.2	0.1	167
RA	1.695	93	0.1	47167	0.09	0.8858	34.6	0.1	119
RA	1.7118	95	1	9400	0.19	0.8964	26.3	0.1	149
RA	1.9994	84	0.1	21800	0.65	0.8361	11.2	0.1	163
RA	2.0978	94	0.1	49000	0.1	0.9120	28.4	0.1	129
RA	2.1993	94	0.1	56233	0.05	0.8610	16.5	0.1	144
RA	2.4909	[illegible]	1	80000	0.07	0.8803	17.0	0.1	120
RA	2.5202	90	0.1	45667	0.1	0.8809	32.3	0.1	129
RA	2.6223	92	1	65667	0.01	0.8823	32.8	0.1	153
RA	2.6296	92	0.1	51666	0.08	0.8495	21.3	0.1	129
RA	3.0348	92	0.1	50833	0.37	0.8256	17.1	0.1	117
RA	3.0771	94	1	61667	0.15	0.8596	24.6	0.1	133
RA	3.1879	90	0.1	16033	0.49	0.8369	14.0	0.1	213
RA	3.232	87	1	85333	0.27	0.8386	20.0	0.1	147
RA	3.3402	90	0.1	50067	0.08	0.8479	20.4	0.1	119
RA	3.3776	87	0.1	27400	0.07	0.8489	21.0	0.1	125
RA	3.396	90	0.1	53333	0.09	0.8752	32.3	0.1	141

APPENDIX A

(CON'T.)

FLUX TYPE	WETTING BALANCE	PERCENT SPREAD	COPPER MIRROR	WATER EXTRACT	COPPER CONSUMPTION	SPECIFIC GRAVITY	SOLIDS CONTENT	Cl & Br	SOLDER POOL
ACID	4.2546	95	0.1	8000	0.11	0.8753	3.7	0.1	143
ACID	4.3173	89	0.1	6600	0.65	0.8577	1.2	0.1	155
ACID	4.344	88	0.1	21067	0.16	0.8990	24.5	0.1	97
ACID	4.3466	97	0.1	3520	0.29	0.9483	7.8	0.1	209
ACID	4.4349	94	0.1	3590	6.04	1.0342	6.5	0.1	263
ACID	4.463	95	0.1	7533	2	0.8913	23.6	0.1	126
ACID	4.5247	95	0.1	2313	0.04	1.0594	6.7	0.1	223
ACID	4.6865	95	0.1	6833	2.88	0.8870	11.5	0.1	173
ACID	4.8293	95	1	4217	1.33	1.0411	5.4	0.1	145
ACID	4.8324	96	0.1	12133	0.4	0.8395	23.4	0.1	536
ACID	4.875	86	0.1	6683	0.3	0.8869	1.4	1	40
ACID	4.8979	96	0.1	6467	0.07	0.9023	5.0	0.1	140
ACID	5.0824	98	0.1	2653	0.14	0.9518	23.2	0.1	110
ACID	5.1004	96	0.1	7633	1.25	0.8437	16.1	0.1	273
ACID	5.1574	87	0.1	6700	0.25	0.9741	4.0	1	71
ACID	5.2707	96	0.1	3670	1.3	0.8380	6.6	0.1	400
WS RESIN	2.9376	86	1	26833	0.3	0.8351	16.3	0.1	205
WS RESIN	3.4884	94	0.1	55667	0.09	0.8767	30.1	0.1	123
WS RESIN	4.0702	93	0.1	21433	0.17	0.8831	31.8	0.1	196
WS RESIN	4.1814	96	0.1	22000	0.75	0.8333	15.6	0.1	237
WS RESIN	5.0321	83	0.1	20367	0.56	0.8365	4.2	0.1	65
WS RESIN	5.1025	95	0.1	25867	0.41	0.8220	9.0	0.1	107
WS RESIN	5.1673	92	0.1	35166	0.91	0.8230	7.2	0.1	156
WS RESIN	5.2278	95	0.1	10500	0.19	0.8825	23.9	0.1	132
WS RESIN	5.8402	95	0.1	5290	1.76	0.8580	14.9	0.1	90
WS RESIN	6.0375	98	0.1	9667	0.13	0.8810	25.1	0.1	193
WS RESIN	6.3291	95	0.1	28150	0.19	0.8842	12.2	0.1	179

THE MECHANISMS OF SOLDERABILITY

AND SOLDERABILITY RELATED FAILURES

by

John A. DeVore
General Electric Company
Syracuse, New York

Mr. DeVore is a Senior Metallurgist for the General Electric Electronics Laboratory. He has been on the laboratory staff for 25 years. Mr. DeVore graduated from the Michigan Technological University in 1959 with a B.S. in Metallurgical Engineering.

Mr. DeVore's major work is failure analysis and all aspects of soldering and solderability. Emphasis has been placed on defining the basic mechamisms related to soldering.

THE MECHANISMS OF SOLDERABILITY AND SOLDERABILITY RELATED FAILURES

Introduction

In today's manufacture of electronic equipment, the philosophy is to do it right the first time. This has been proven to be not only the most cost effective way to produce hardware but also the way to the most reliable hardware.

A major impact factor to doing it right the first time is the solderability of component leads and printed wiring boards. Poor solderability results in questionable rework which adds cost and detracts from reliability.

Solderability is defined as the ability to solder easily. In more scientific terms, this means that full metallurgical wetting must be complete within the time of the soldering operation (hand or machine) which is usually 1-3 seconds. In order to assure that solderability is high it is necessary to understand both the mechanisms of both good and bad solderability. This understanding can then be used to correct solderability faults properly. Properly because the cause is attacked and not the symptom.

There are only three basic mechanisms of solderability. These are wetting, non-wetting and dewetting. This paper will describe each in both scientific and lay terms giving typical symptoms and causes. Based on this information and the use of a technique described in a prior paper[1], it is possible to describe corrective action.

Wetting

The first mechanism to be described is wetting. Since better than 99% of the solders (based on annual tonnage) used in the electronics industry are either tin based or tin containing, the discussion will be held to these alloys. Non-tin containing alloys will follow the general reactions but will be different in reaction rate and reaction product composition.

Wetting as related to solders is a metallurgical reaction process. It results in a smooth layer of solder which is firmly adherent to the base metal. Figure 1 shows a well wet base metal surface. Very few defects in the solder surface are seen at this magnification.

While the surface appearance gives some indication of whether the base metal is well wet or not, it does not describe wetting in the way which results in understanding of the mechanism. This is better shown in a metallographic cross-section such as shown in Figure 2.

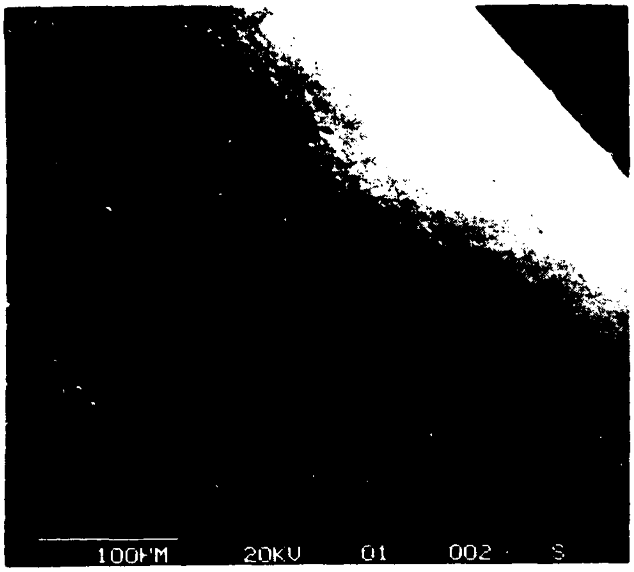


Figure 1 - Surface of well wet base metal.

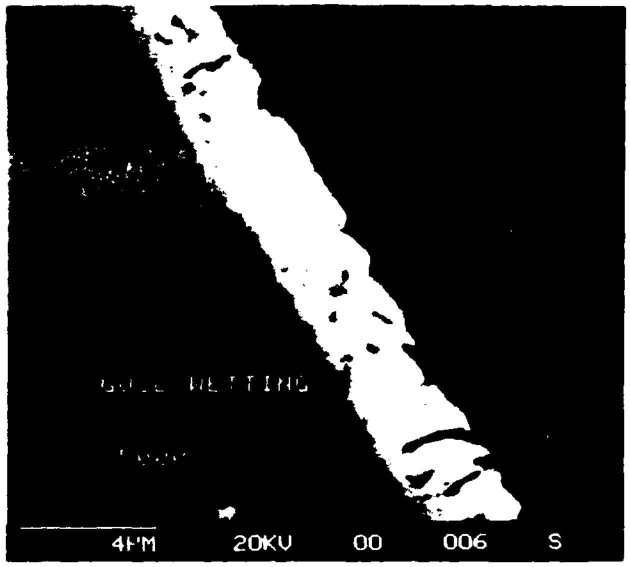


Figure 2 - Metallographic section of well wet surface (BSE image).

The photograph shows copper on one side of the interface and solder on the other side. At the interface is the metallurgical reaction product formed when the molten solder contacted the copper. It is composed of two materials known as intermetallic compounds. These compounds are Cu_3Sn (nearest the copper) and Cu_6Sn_5 (nearest the solder). Their rate of formation is exponential with respect to temperature and approximately linear with respect to time. The compounds can form by solid state diffusion. The rules of formation are similar to those governing liquid-solid reactions. Tin forms similar compounds with other base metals such as nickel and iron as well as their alloys.

In order to have good wetting intermetallic formation must be fast and complete. Therefore, the interface must be clean at the time of formation and must stay clean during formation. If this clean condition is not met, then one of the other two mechanisms of solderability will rule.

Non-Wetting

Non-wetting is the simplest of the two mechanisms contributing to poor solderability. It is the opposite extreme from wetting and results from the presence of a physical barrier between the base metal and the solder. Figure 3 shows a photograph of non-wet area on copper. The dark areas are the non-wet copper. The base metal has been exposed and there has been no intermetallic formation. The solder shows a negative wetting angle which is characteristic when the non-wetting mechanism is operating. Without intermetallic formation, there can be no wetting.

A similar non-wetting can occur on the surface of an alloyable coating on the base metal if it is resistent to the fluxes used or the soldering conditions. Such things as epoxy deposits or oxide deposits, especially on gold, will cause this type of defect.

Dewetting

Dewetting is the least understood of the solderability mechanisms. Wetting and non-wetting are the two extremes of solderability. Dewetting is a mechanism which represents all the shades of gray between the two extremes.

Visually, dewetting is most often manifested by the solder on the surface pulling back into irregular mounds. In reality, this pulling back can vary from barely observable to that where the base metal is almost exposed between the mounds. Modern solderability specifications treat dewetting as a single condition and do not provide any guidance as to where the mechanism, if operating, will begin to affect solder joint quality.

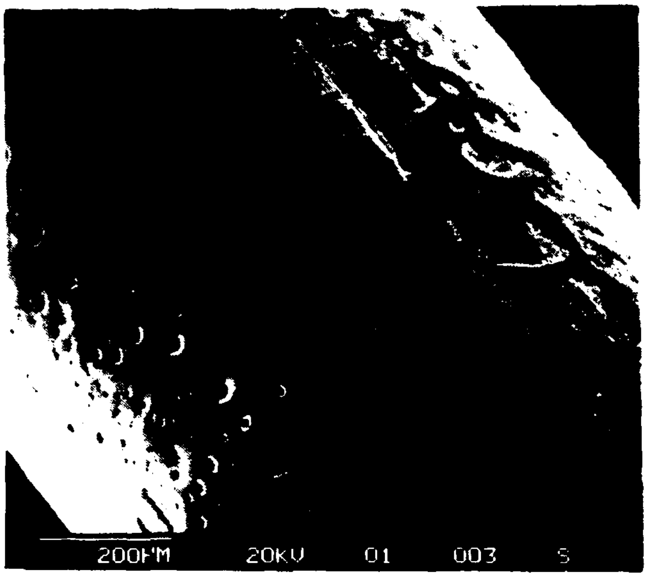


Figure 3 - Non-wetting.

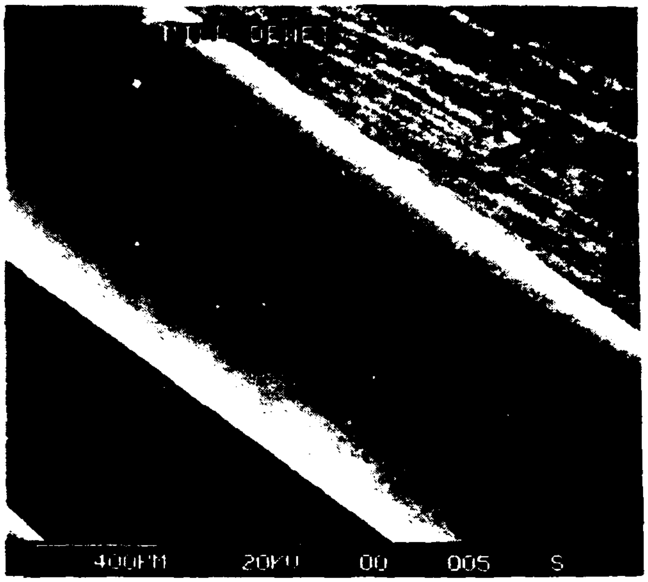


Figure 4 - Mild dewet surface.

Figure 4 shows a surface which is mildly dewet. At this level, the dewetting is not usually visible under normal solderability inspection magnifications.

In 1973, work in our laboratory resulted in the definition of the mechanism causing dewetting[2]. This has now been fully proven and expanded to cover all degrees of dewetting.

All dewetting is the result of gas evolution during exposure of the part being soldered to molten solder. The source of the gas is the thermal breakdown of organics or the release of water of hydration from inorganics. A common component of these released gases is water vapor. Water vapor at soldering temperatures is highly oxidizing and results in either oxidation of the surface of the molten solder film or of some subsurface interface, typically the intermetallic surface at the molten solder interface.

Figures 5 and 6 show the effect of this gas release on the mildly dewet surface. The voids shown are typical of all dewet surfaces.

Greater amounts of gas release will result in more voids and exposed intermetallic. Figures 7 and 8 show a middle range dewetting condition. At this level, it is easily visible during solderability examination.

The degree of dewetting is dependent upon the amount of gas released, the composition of the gas and the location of the gas release. The greater the amount, the higher in water vapor and the deeper the location of the contamination, the more severe will be the dewetting. Small amounts of gas released from a surface film or from co-deposited organics in an alloyable coating will result in slight mounding with evidence of gas release. If the dewetting causing gas release is from the co-deposited organics in the base metal or from heavily embedded particles in the base metal, then dewetting will be more severe in that the surface of the intermetallic will be oxidized as well as the surface of the solder film. Once the intermetallic is oxidized, it will become

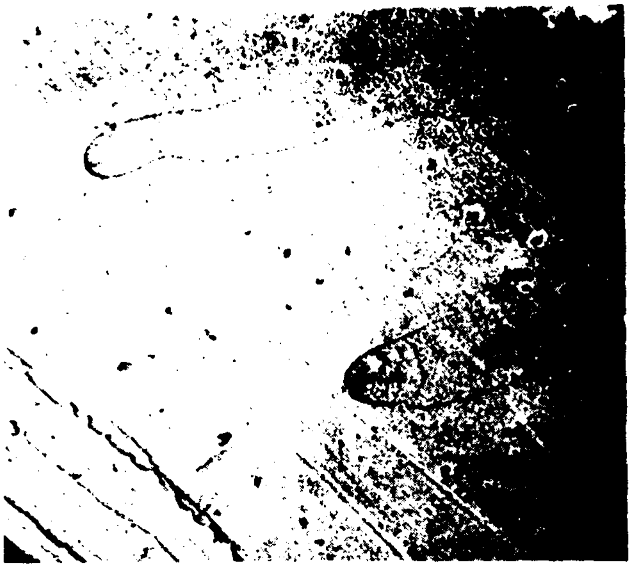


Figure 5 - Mildly dewet surface.

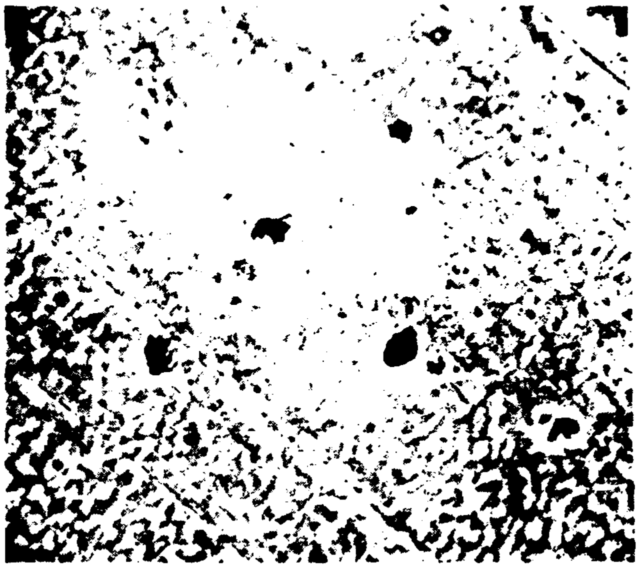


Figure 6 - Detail of gas voids in mild dewetting.

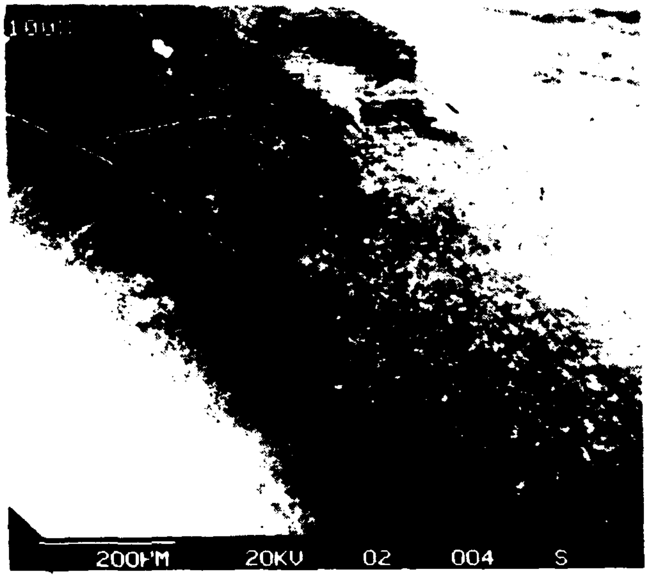


Figure 7 - Moderate dewetting.

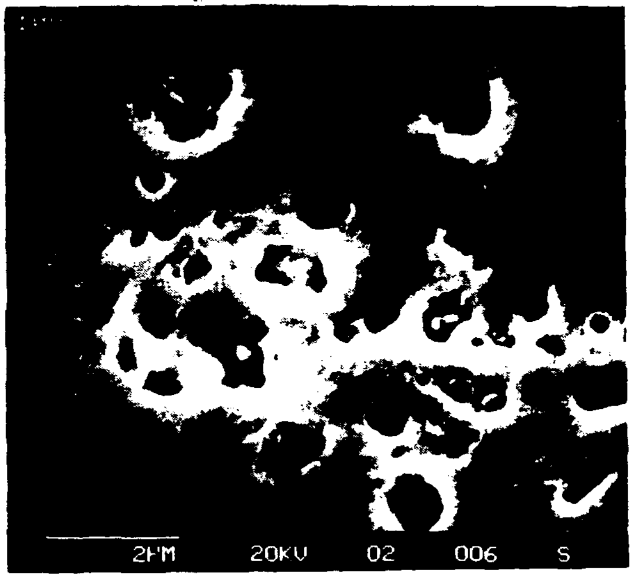


Figure 8 - Gas voids in moderate dewetting.

a non-wetting surface and will be exposed. Gas released from heavy co-deposited organics in an alloyable coating can also result in passivation of the intermetallic surface.

It has often been observed that higher soldering temperatures and longer dwell times result in more severe dewetting. This most often happens when the source of the gas release is from the base metal. The increased reaction rates produce a more vigorous release. The longer dwells increase the release time. Both result in an increased release volume.

Effect of Solderability Mechanisms on Solder Joints

The mechanisms of solderability have a significant effect on the properties and visual appearance of solder joints. Obviously, full wetting is the desired operating mechanism. With full wetting, a solder joint will have its maximum properties (strength, fatigue resistance, electrical conductivity, etc.) and best appearance (positive, low contact angles). Non-wetting and dewetting result in reduced properties and poorer appearance.

Non-wetting produces the most significant effect on solder joints. With non-wetting, there is no bond between the solder and base metal. This reduces the effective soldered area. Entrapped non-wet areas are classed as a film defect with small radius ends. These are very detrimental in fatigue environments as they represent strong stress risers.

The effect of dewetting on solder joints is directly in proportion to the degree of dewetting. Severe dewetting can result in property reduction similar to non-wetting as the defects in the joint are similar. Mild dewetting may have little reduction in properties over a fully wet joint. In addition, due to its mechanism, results in gas voids in solder joints. The amount and size of the voids is again dependent on the degree of gas release. The effect on properties is mainly in fatigue resistance. Voids act as stress risers and may reduce fatigue life by at least one-half.

Detection of Operating Mechanisms

The basic methods used to detect the operating solderability mechanisms are solderability tests. Using visual or optical criteria to determine the mechanism is relatively easy for full wetting and most non-wetting conditions. Non-wetting on base metals which have the same color as solder is sometimes difficult. Nickel and nickel-iron alloys are good examples of these. The wetting balance shows non-wetting easily as a reduced wetting force. Since a full intermetallic is developed under both wetting and dewetting conditions, the presently used criteria do not work very well. Both conditions result in a short wetting time and a high wetting force. Visual examination must be used to see if the surface dewet.

Lack of knowledge of the dewetting mechanism has prevented using the wetting balance to its full potential. Previous attempts to use the method to define dewetting has failed due to a misconception of the dewetting mechanism or an inaccurate view of it. It is felt that this has been due to trying to match curve indications to the symptoms rather than the actual cause[3].

In the wetting balance test, wetting time is based on the ease of intermetallic formation. The major input to wetting force is the height of the meniscus which is based on the degree of wetting. Since dewetting is based on gas evolution, neither of the above indications relate to the mechanism. The closest relation to the mechanism is the condition of the meniscus in terms of surface tension. This is best measured at the time of sample withdrawal when the meniscus is fractured. The gas evolution and release which causes dewetting also causes oxidation of the meniscus surface. The worse the oxidation, the higher will be the withdrawal force. The gas release can also be seen in the curve, especially in the area of the knee. This is manifested by an uneven curve. It is not, however, as good an indication as the withdrawal force. Figure 9 shows a normal curve from a sample with full wetting. Figure 10 shows a curve from a sample which mainly exhibits dewetting.

Based on knowledge of the mechanisms of solderability and of the wetting balance, it is possible to use the instrument and describe the solderability characteristics as a single number. Using the formula $\dfrac{\text{Wetting Force @ 2 sec}}{\text{End Point Force}} \Big/ \text{Wetting Time}$, all three mechanisms can be described for a sample. It has been our experience that a resultant number of 5 or 6 represents minimum good solderability. This is based on a wetting time of 0.6 sec, a wetting force at 2 seconds ofd 275 MN/M and an end point force of 100 MN/M.

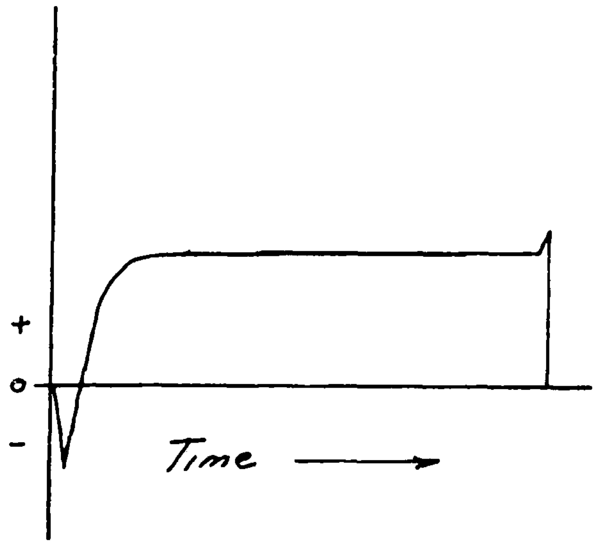


Figure 9 - Wetting balance trace showing good wetting.

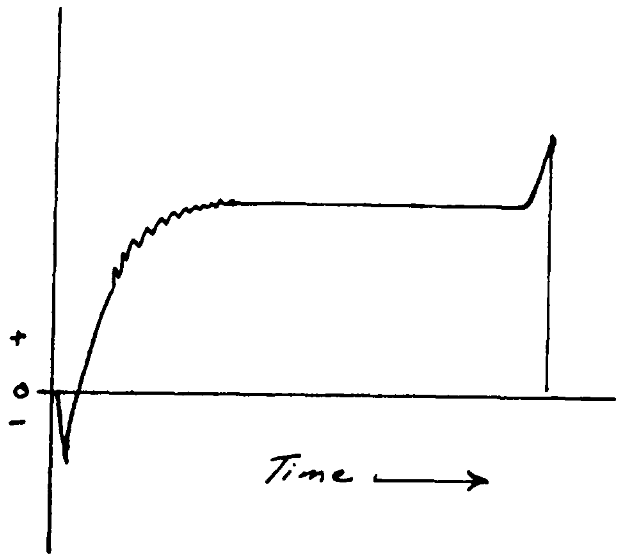


Figure 10 - Wetting balance trace showing effect of dewetting.

Summary

1. There are three basic mechanisms of solderability. These are wetting, non-wetting and dewetting.

2. Wetting is the result of clean molten solder contacting a clean base metal. This results in a metallurgical reaction which goves a continuous, unbroken intermetallic compound bond between the two.

3. Non-wetting is the result of the presence of a barrier which prevents solder from contacting the base metal. No metallurgical reactions result between the solder and the base metal.

4. Dewetting is the most complex of the solderability mechanisms. Dewetting occurs in all degrees dependent on the amount and composition of the gas evolution and release. The results of the dewetting mechanism operating can be seen visually as solder pullback. However, in its more mild forms, it is difficult to detect visually and is best detected by the use of the wetting balance.

References

1. Solderability Defect Analysis, J.A. DeVore, Sixth Annual Soldering Technology Seminar, China Lake CA, February 1982.

2. Dewetting of Solder on Copper Surfaces, J.A. DeVore, IPC Annual Meeting, Miami Beach FL, April 1974.

3. Wetting Balance Solderability Testing, J.A. DeVore, General Electric Workshop on Solders and Solderability, October 1983.

830TP0079-1

SOME COMPONENT LEAD SOLDERABILITY ISSUES

By
R. N. Wild
International Business Machines Corporation
Owego, NY 13827

Prepared For Presentation at
8th Annual Soldering Technology Seminar
Navy Weapons Center
China Lake, CA

February 23, 1984

IBM
Federal Systems Division
Owego, NY 13827

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

Some Component Lead Solderability Issues

by
R. N. Wild
International Business Machines Corp.
Owego, NY 13827

Eighth Annual Soldering Technology Seminar

Navy Weapons Center
China Lake, CA

ABSTRACT

This paper will discuss some serious component lead solderability and IC solder joint degradation problems that were shown to be related to inadequate specifications and manufacturing controls of component lead plating parameters.

Over the last two years, the above solderability and solder joint degradation problems have led to extensive work in trying to better understand component plating and solderability issues as they relate to both military manufacturing and reliability. This included various solderability evaluations and a series of tests relating various component lead finishes to manufacturing defects.

These evaluations have shown that many of these basic solderability problems are related to:

- Inadequate or inconsistent lead cleaning and plating parameters.
- Extensive, and in some cases, inadequate component burn-in and tin reflow procedures.
- Excessive and/or inadequate component storage parameters by both manufacturers and users.
- Weak and/or conflicting DoD specifications.
- Reluctance of many users to return defective parts to manufacturers.

We believe that many of these problems can be reduced by pretinning components leads as a final component finish and by requiring components to meet much more critical plating and solderability tests than presently required.

1.0 INTRODUCTION

Many erratic and persistent component solderability problems over the last several years have resulted in IBM Owego pretinning nearly all incoming components to improve both component shelf life and to reduce solderability problems during hardware assembly. This pretinning, although expensive and time consuming, appeared effective in overcoming most plating and solderability problems, including plating outgassing problems found with bright tin platings and some other matte tin plating deposited with improper processing or bath controls.

2.0 EXPERIENCE AND HISTORY

A review of our component procurement, testing and pretinning (solder dipping) practices was initiated approximately two years ago due to experiencing an increasing amount of component lead solder delamination (flaking) being found on some military IC flatpack leads after pretinning and forming of the flatpack leads for surface mounting of the components (Figure 1).

Typical Formed Leads No Flaking

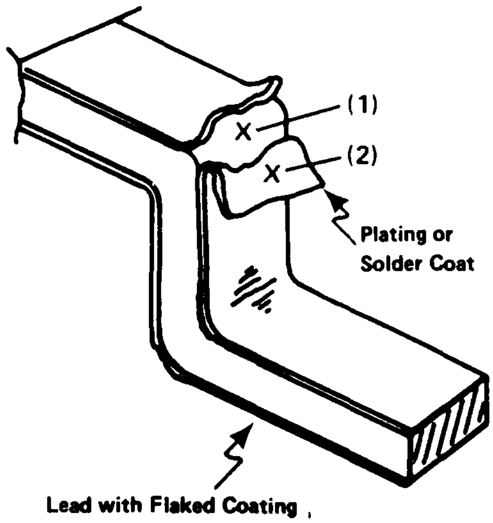
Typical Leads Exhibiting Flaking

Figure 1. Solder Flaking from IC Flatpack Leads

The severity of solder flaking was found to vary from one IC (flatpack) manufacturer to another, and from different date codes of a manufacturer. An increase in thickness of the solder coating (or the tin plate on the leads), or a reduction in the radius of the lead forming bend also increased the propensity for flaking of the lead coating. The as-received tin plated leads would also flake on lead forming, but not as severe as the thicker and stronger SN63 solder dipped coatings.

Most of the components exhibiting flaked leads were originally acceptable to the applicable military specifications for both solderability and plating adhesion. There were some dewetting problems in the areas of worst case flaking; however, our primary concern with the flaking of these leads was the mechanical strengths of the surface mounted solder joints. Subsequent analysis showed a substantial strength reduction with some of these solder joints which required corrections.

Briefly, the basic cause of the flaked and weak component lead conditions [1] was found to be related to inadequate component tin plating parameters, where there was excessive co-deposition of plating organics in the tin plating and at the tin to Alloy #42 component lead interface. Component aging at high burn-in temperatures with these entrapped plating organics degraded the tin plate to Alloy #42 interface bond, probably by diffusion reactions (Figure 2).



Typical Surface Analysis:

1) Substantial carbon, some tin, little evidence of oxidation
2) Carbon, then Tin-Nickel-Iron (intermetallics) separated from lead surface)

Note:
- o Carbon, not oxidation was major contributor to weak lead to solder interfaces (Three major suppliers)
- o Metallographic analysis cannot resolve defects on unformed lead interfaces. Thin non-uniform intermetallic layer, found on weak leads.

[Weakest joints shows darker lead surface in flaked area. Also analysis shows highest carbon content on weakest leads.]

Figure 2. Microprobe and Auger Analysis — Weak Lead Interfaces

3.0 COMPONENT SOLDERABILITY ISSUES

Solderability is a difficult property to measure and to define accurately. The major purpose of solderability testing is to determine how well the lead or metal is wetted by solder with the major goal being to determine whether or not proper solder joints can be made in manufacturing. The present cost of touch-up or rework of defective solder joints in industry, due to various solderability problems, is considered extremely expensive. Maintaining proper solderability of components and boards on the manufacturing line is also becoming very important, especially with the goal of both the military and many manufacturing groups in obtaining "0" defect solder joint defects and the trend in industry toward automation of the various manufacturing lines, especially soldering operations.

As previously mentioned these solderability issues are difficult enough without having various conflicting military solderability specifications that the manufacturers or users must meet (Table I). The test parameters of the three most commonly used solderability specifications (Table II) show conflicts in test temperature, flux type, artificial aging and degree of acceptable solder coverage. DoD is presently trying to standardize to a single specification as shown in Table II. We generally support the proposed DoD solderability specification (Table II) except for the recommended use of an "RMA" flux, which we strongly believe should be an "R" type flux so that actual solderability of the part is determined, not that the part is made solderable by the use of more aggressive RMA fluxes. We also urge the use of a more realistic artificial steam aging test [2] so that military users can be assured of maintaining an acceptable level of solderability after a reasonable period of time in storage prior to use on the manufacturing line.

Table I. Five Solderability Specifications in Effect

Specification		Type Hardware
1) MIL-STD-202F (Army)	—	Electronic - electrical component/ parts
2) MIL-STD-750C (Navy)	—	Semiconductors
3) MIL-STD-883 (Air Force)	—	Micro electronics
4) MIL-STD-1311	—	Electronic tubes
5) MIL-STD-1344A	—	Electrical connectors

Table II. Some Specification Comparisons (1)

Specifications	MIL-STD-202	MIL-STD-750	MIL-STD-883
• Temperature °C	230 ± 5 °C	230° to 260 °C ± 5 °C	260 ± 10 °C
• Flux	R(2)	R	R or RMA
• Aging	1 hr steam	Optional	1 hr steam
• Coverage (%)	95	90	90

Notes: 1) All have insertion and retraction rates of 1.0 in/sec, dwell time of 5.0 ± 0.5 sec

2) Wire can use RMA flux

3) New DOD proposed solderability standard would be:
- Temp. — 245 °C
- Flux — RMA (strongly believe should be "R" flux)
- Aging — 1 hr steam (strongly believe should be 12 to 24 hour aging)
- Coverage — 95%

4.0 SOLDERABILITY TESTING

As a result of the previously mentioned solderability and lead flaking problems, an internal solderability task group was assembled to address the various solderability issues in Owego. These included:

- Implementation of more critical and more accurate Receiving and Inspection solderability testing with strong efforts made to return defective product to the procurement source.

- Working with component manufacturers to more clearly define or impose more stringent procurement limits on component lead finish and solderability requirements.

- Optimization of both pretinning and component solderability rework parameters.

- Providing guidelines for both component handling and storage environments.

- Working with the military on optimization of component plating and solderability specifications.

4.1 RECEIVING AND INSPECTION SOLDERABILITY TESTING

Solderability testing in Owego has been improved substantially by; 1) extensive personnel training sessions, 2) use of semi-automated test equipment, and 3) by the use of clear guidelines on both solderability test methods and accept/reject criteria. We found that close support by various groups was necessary in order to maintain this consistent and accurate solderability testing.

We conduct solderability testing to the applicable military solderability procurement specification (Table II), but in addition we have been testing to the new proposed DoD solderability specification, except that we use "R" flux in place of RMA flux. We have also been gathering data on the IPC recommended 24 hour steam aging test [2] that is designed to be more representative of one year component aging. An example of this solderability testing is shown in Table III. This table shows accept/rejects for some typical components over a four month time period.

Table III. Some 1983 Solderability Test Data(1)
(Receiving Inspection)

Type Components	Rejects(2)		
	Rejects	Orders	Percent
• Resistors	18	742	2.43
• Capacitors	4	368	1.09
• Diodes	12	132	9.09
• Transistors	10	134	7.46
• IC flat packs (3)	113	641	17.63
• IC DIPS	21	185	11.35
• Hybrid circuits	6	112	5.36
Summation	184	2314	≈ 8%

Notes: 1) Solderability test parameters:
- Temp. = 145°C
- Flux = R
- Coverage = 95%
- Aging = none

2) Rejects with 24 hour steam aging was 24.8%
3) Early 1983 rejects were averaging 43.3%

The most significant solderability problems were found to be ICs, diodes and transistors. Poor results with the present tin reflow requirements of MIL-M-38510 were a significant contributor to the solderability problems with ICs (more discussions on this subject will follow). Overall solderability rejects showed an average of about 8.0 percent which is considered very high for efficient manufacturing of military product.

As shown in Table III, total solderability rejects with the IPC task group recommended 24 hour steam aging test was about 25 percent. This, I believe indicates marginal solderability with a substantial portion of incoming components. This would provide doubt on the storage life capability of those components rejected to this aging test.

Our extensive effort to return defective parts back to the procurement source is showing benefits. An example is IC flatpack (Table III) which was averaging over 40 percent rejects earlier this year. With component manufacturing corrections, rejects are now down to about 18 percent with further improvements expected as the marginal product is used up. Similar improvements would be expected with most components if the component users would be more diligent in returning problem components back to the procurement source. There is essentially few or no real incentives for the component manufacturer to correct or maintain tightly controlled plating or solderability parameters if the users use or correct this defective product.

4.2 PLATING OUTGAS TEST

A tin reflow outgas test (Figure 3, Reference 1 and Table IV) implemented in Owego to detect excessive entrapped component plating organics, shows that about 3.0 percent of tin or tin-lead plated components still exhibit what we consider to be excessive plating organics that can contribute to both component solderability and storage problems [1,3] and to the weak solder joint problems discussed in Section 1.0. These plating conditions should not be considered acceptable for military product. MIL-M-38510 presently sets a maximum organic limit for platings to be 0.05 percent carbon. An accurate measurement for carbon limits is generally done by combustion carbon analysis. Controls on carbon content must apply to all DoD plating specifications.

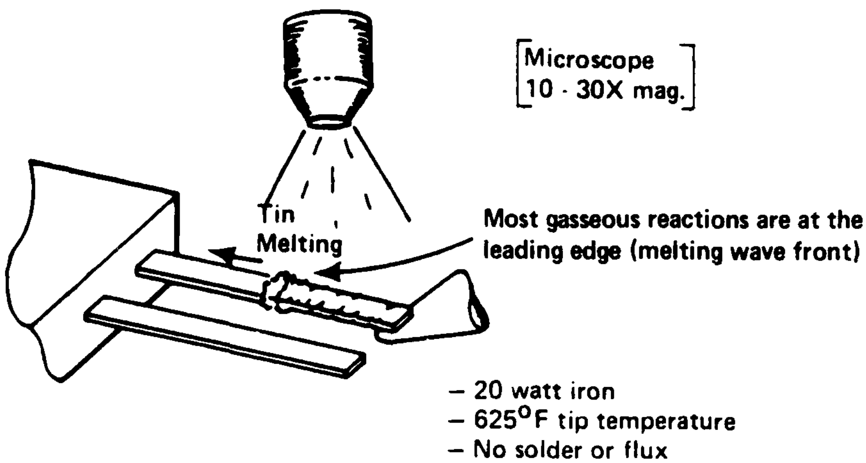


Figure 3. Tin or Tin-Lead Plating Outgassing Test

Table IV. Tin and Tin-Lead Plating Outgas Test

- **Four months test results**
  - **40.0% no test (gold plate, tin reflowed, etc.)**
  - **25.6% shows slight outgassing**
  - **3.2% shows medium outgassing**
  - **0.2% shows severe outgassing**

Notes: 1) Outgassing is determined by reflowing tin plate and observing outgassing eruptions at ~ 20x magnification

Combustion carbon analysis would be difficult for some manufacturers due to a lack of proper equipment. The plating reflow test as conducted by Owego is very rapid and simple to conduct; however, results are subjective and to a degree operator dependent. A better test to establish the organic limits in both tin and tin-lead plating, especially for plating lines may be the organic detection test defined by D. A. Luke of LeaRonal (UK) Limited [3]. In brief, the test is as follows:

- Plate a sample of deposit onto a stainless steel plate and remove the non-adherent foil. Wash and dry the foil and weigh.
- Fuse the tin or tin-lead alloy in glycerol at about 200°C (for a few seconds).
- Wash, dry and weigh the resultant bead of tin or tin-lead and calculate occluded organic matter as a percentage of weight loss.

Note: D. A. Luke of LeaRonal has established a weight loss limit of 0.1% to represent a properly controlled plating process that should not exhibit solderability or storage problems.

This LeaRonal organic plating limit test may be valuable for inclusion in MIL-M-38510 to help control plating parameters.

5.0 Component Lead Finish Effects

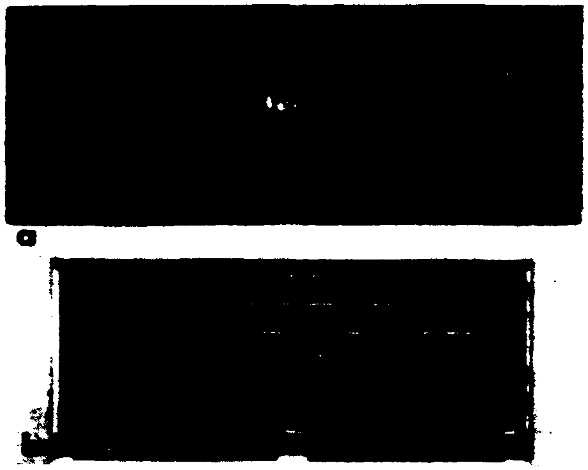
This series of tests was conducted to relate various component lead finishes to actual manufacturing defects on a military line. A very large number of the test components were provided by two major IC manufacturers (about 4000 parts with different lead finishes) and a portion from in-house stock. The component lead finishes included:

- Tin Plated Leads ONLY
- Tin Plate and Burned-In Components
- Tin Plate and Reflowed (per MIL-M-38510)
- Pretinning of Above Conditions (by Owego)
- Pretinning by IC Manufacturers

The test matrix included about 18,000 flatpack solder joints and about 25,000 DIP solder joints. Typical hardware (Figure 4) were assembled with above special components using set identical soldering parameters for all components with no corrections provided for the different lead finishes. Again, this evaluation was to establish effects caused by the different lead finishes only, thus great care was taken to insure proper solderability of the multilayer board (MLB) assemblies and to ensure there were no changes in processing with the different assemblies.

5.1 Pretinning Procedures

The pretinning (solder dipping) procedure used by Owego (Table V) on supplied ICs was the same type robotic tinning procedures used on the manufacturing line. These tinning procedures provided a smooth continuous solder coating on the IC leads which was suitable for the specific soldering applications.



a) Typical dip page assemblies (~ 50 pages) assembled using standard wave soldering techniques

b) Typical flat pack page assemblies (~ 19 pages) assembled using robotic reflow soldering techniques

Figure 4. Special Test Assemblies

Table V. IC Pretinning Parameters

• Solder:	Eutectic 63/37 SnPb		
• Solder temperature:	495°F ± 10°F (257°C)		
• Solder pot parameters:	Dynamic solder wave		
• Flux:	Alpha 611 (RMA)		
• Tinning parameters:		FPs	DIPs
— Insertion rates (inch/second)		1.0	1.0
— Dwell times (seconds)		3.5 to 4.0	5.0
— Retraction rates (inch/second)		0.2	1.0

Note: Above tinning parameters removes original lead finish and replaces it with a fresh solder coating that has been proven excellent for both high density solderability and extended storage

5.2 Solderability Testing

Special solderability tests were conducted on each of the different test groups of ICs used in this investigation. These included three different types of tests including MIL-STD-883, the new proposed DoD tests (but with "R" flux), and the proposed DoD test but with 24 hour artificial steam aging. Three different series of tests were conducted to compensate for both testing and inspection variables.

The results, (Table VI) showed similar results with MIL-STD-883 with 1.0 hour steam aging and the new proposed DoD solderability standard test, but conducted with "R" flux. The added 24 hour steam aging test showed an increase in solderability rejection rates. Again, that may have implications as to questionable storage parameters for some of these lead conditions. The greatest number of solderability rejects were, however, found on reflowed and burned-in products; almost no rejects were found with pretinned products.

Table VI. Some Solderability Test Comparisons[1]

Three different tests conducted:

	1) MIL-STD-883	2) DOD Special	3) DOD Special
	• 260°C • RMA flux • 90% coverage • 1 hour steam aging	• 245°C • R flux • 95% coverage • no aging	with 24 hour steam aging
• Total tests	27	26	27
• Specimens/test	3-4	3-4	3-4
• Percent rejects (test groups)	25.9%	26.9%	40.7%

Notes: 1) • Average of three repeated tests (different times) for each of nine different test cells

• Substantial variations found with some tests believed due to sample size and subjective nature of tests

5.3 Hardware Inspection and Results

All solder joints were inspected at 25X and 7X magnifications in the Materials Laboratory using a single well-qualified laboratory specialist in order to maintain repeatability for all inspections. Inspection requirements (Figure 5) were to document both poor or negative wetting conditions and actual rejectable solder joint conditions. The results (Tables VII and VIII) show extremely high rejectable or questionable solder joint conditions on both reflowed and burned-in components. These tests also show very noticeable component soldering improvements with pretinning (solder dipping) as a final lead finish. Inspection at the normally used 7X magnification would reduce the observed defects by about 50 percent.

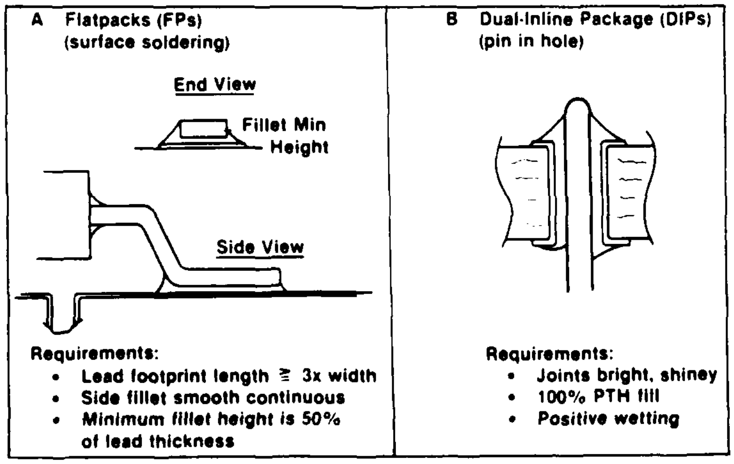


Figure 5. Solder Joint Requirements

Table VII. Flatpack Lead Finish vs. Solder Defects[1]
(Robotic Reflow Soldering[2])

Test Group	Lead Finish Parameters	Solderability Test[3] Results	Defective[4] Joints (%)
1	Tin plated lead only	Good to excellent	6 0
2	Tin plated and pretinned (63/37 SnPb)	Excellent	2 9
3	Tin plated and reflowed	Poor	54 9[5]
4	Tin plated, reflowed and pretinned	Good	17 1
5	Tin plated and burned-in (145° C for 168 hrs.)	Good	12 3
6	Tin plated, reflowed burned-in and pretinned	Good	3 8

Notes:
1) Total test matrix included ~18,000 solder joints
2) Robotic mounter was set for standard product with no corrections provided for different lead finishes
3) Three different solderability tests conducted
4) Joints inspected at 25x magnification
5) Inadequate tin reflow

Table VIII. DIP Lead Finish vs. Solder Defects
(Wave Soldered[1])

Test Cells	Component Lead Finishes	Solderability[2] P W	Rej.	Cond.
1	Tin plated leads only	14 7	0 21	F-G
2	Tin plate and pretinned (63/37 SnPb)	0 30	0	G-E
3	Tin plated and reflowed (MIL M-38510)	34 25	0 30	F
4	Tin plated reflowed and pretinned	0 56	0	G
5	Tin plated and burned-in	17 62	2 70	F
6	Tin plated, burned-in and pretinned	1 51	0	G
7	Tin plated burned in and reflowed	33 92	0 18	F
8	Tin plated, burned-in, reflowed and pretinned	2 43	0 10	G
9	Tin plated, burned-in solder dipped (by manufacturer)	0 85	0	G
10	Bare leads, burned-in and solder dipped	0 15	0	G

Notes:
1) Set wave soldering parameters with no corrections provided for different lead finishes (~ 25,000 joints)
2) Soldered conditions.
   - P W = % leads showing poor wetting on component side of MLB
   - Rejected joints (%)
   - Overall solder joint conditions
     — E = Excellent, G = Good, F = Fair

These tests also show that even with the more aggressive wave soldering test that hardware showing acceptable as-received solderability conditions (Groups 1 and 5) still showed marginal soldering conditions. Thicker MLBs would of course be more sensitive to these effects (higher melting tin plate and burn-in effects). These tests although limited, also show excellent results with product which was solder dipped by the IC manufacturer, (Tests 9 and 10). This includes product burned-in with bare leads then cleaned and solder dipped

6.0 SUMMATION

The extensive solderability and plating evaluations over the last two years show that most solderability problems are created by:

- Improper and/or inconsistent lead cleaning and plating parameters even by some of the largest component manufacturers.

- Component burn-in operations (135° to 200°C) which can be very detrimental to lead finishes.

- Excessive or improper storage environments by both manufacturer or users.

- Lead contamination issues (minor but important).

- Others

  - Inadequate or improper solderability testing (important but not considered a major type defect).
  - Conflicting and in some cases weak military and/or procurement specifications.

7.0 ADDED COMMENTS

The present industry practice of providing components with tin and/or tin-lead platings as a final finish must be questioned if we are to be successful in reducing solder joint defects, especially on automated soldering lines. Our pretinning experience, plus the evaluation discussed in this paper shows the detrimental effects of both component reflow and the various component burn-in procedures and the advantages of providing components with a "properly" solder dipped finish.

The serious loss of component solderability on tin reflowed hardware by both manufacturers supplying these test components is believed related to component lead oxidation reactions during the specific reflow operations. One manufacturer used vapor phase as a reflow technique while the other used an oven to reflow the tin plating. Both of these operations degraded the tin reflowed components to where they were not solderable, even to MIL-STD-883.

7.1 Special Reflow Experiment

IBM Owego reflowed the tin plate on the as-received "tin plated" parts (in Test 1, Table VII) in hot oil at 470°F for both 10 seconds and another group of specimens for 10 minutes without any loss in lead solderability including testing to the proposed DoD solderability specification with "R" flux and including 24 hour artificial steam aging. This test strongly suggests oxidation as being the primary cause of the loss of solderability, not intermetallic formations due to temperature exposure.

8.0 RECOMMENDATIONS

We strongly urge both industry and the military to work together to create needed changes in both lead finishes and specifications to resolve present solderability issues. Some suggestions are:

- DoD must produce a single more critical military component solderability specification that is technically correct and not a compromise on issues.

- Tighter and more consistent plating, burn-in and processing controls are needed for the manufacturing of military components over that of commercial hardware.

- The present tin reflow requirements of MIL-M-38510 has created real problems for both the component manufacturer and the users (believed related primarily to reflow techniques). These issues should be reviewed (task team) for possible improvements; some possibilities:

  - We, the military users, would prefer a final-controlled solder dipped lead finish over either reflowed tin or a plated finish for military product.

  - If relief is provided for the present tin reflow requirements of MIL-M-38510, it should only be done with implementation of substantially more critical plating, processing and solderability controls than now exist.

  - Tight plating and solderability controls must apply to all DoD specifications and components.

9.0 REFERENCES

[1] Report (830TP0001) on "Plating Effect on Component Solderability and Solder Joint Strengths," by R. N. Wild of IBM Owego, NY.

[2] IPC Task Group Report by D. Schdenthaler - Chairman, Entitled; "Accelerated Aging for Solderability Evaluation."

[3] Solder on a New Range of Tin Lead Plating Processes (Synopsis) by D. A. Luke, LeaRonal (UK) Limited.

10.0 ACKNOWLEDGEMENTS

For J. Lake and R. Jereb for component preparation and test product assembly. To K. Taylor and H. Allegrucci for data collection, metallography, solderability testing and inspections.

VAPOR-PHASE SOLDERING
A USER'S REPORT

Patrick Nicholson

Aerojet
Azusa, California

VAPOR-PHASE SOLDERING--A USER'S REPORT

Vapor-Phase Soldering is a process whose time has come. Right now, there are three areas where people in the business of electronic assembly need help:

o Flex-Print Harness Soldering--usually done by hand; high probability of delamination.

o Surface-Mount Components--no good method for mass soldering, rather than one-at-a-time.

o Special Configurations--flat plates; inaccessible joints--no fast, easy way to solder them.

THE CONVENTIONAL METHODS ALL HAVE PROBLEMS:

o Focused Infrared is non-repeatable; it tends to burn the board.

o The Hot Bar Technique only works for flat-packs; it does one at a time.

o Oven Soldering is slow and likely to form intermetallics or oxidize parts, so they can't be soldered, later.

o Laser Soldering does one at a time, and tends to burn the board. Laser Soldering has promise in areas where Vapor Phase won't work, however.

ADVANTAGES OF VAPOR-PHASE SOLDERING

1. It's a Mass Process. Whether you use a batch or flow-through machine, the whole board will be soldered at one time, and the flow-through is high.

2. Precise control of temperature. The boiling fluid determines the vapor temperature--you CAN'T overheat!

3. Fast, uniform heating--independent of part geometry. Every part touched by the vapor is heated--and heated at a uniform rate.

4. An oxygen-free atmosphere. As soon as a part enters the fluorcarbon atmosphere, oxygen is excluded--so there can be no oxidation! Flux-free soldering is possible.

5. It's a forgiving process. A fixed temperature, an oxygen-free atmosphere--it's not an easy process to screw up...but it can be done!

DISADVANTAGES

1. STARTUP COSTS:

(1) Initial cost of the machine--typically $10,000 to $60,000 or more, depending on the model.

(2) Fluorocarbon costs. FC-70 costs about $500 a gallon--it will cost several thousand dollars to charge up a large machine.

(3) Installation costs. Venting is required. Special electrical wiring is required to handle an 18 or 36 KVA machine. Unless your machine has a built-in water-cooling capability (an extra-cost option), you will have to provide an external system.

2. Operating Costs:

(1) Maintenance--filtering, filter replacement, occasionally draining and cleaning the machine. Not a large expense.

(2) Fluorocarbon. At $500 a gallon, a large machine can boil off a lot of dollars, if not well managed. Expect high losses when you start a new operator. If it doesn't taper off--you have the wrong operator.

3. Control Problems (the result of not being able to see inside the machine):

(1) How fast should the elevator run?

(2) How long should the part dwell at temperature?

(3) Is the primary vapor up to temperature?

(4) Is the solder on my workpiece molten?

(5) Is something wrong?

The answers to these questions will come come with experience.

*******NEWS FLASH!*******

YOUR'RE LIKELY TO FAIL ON YOUR FIRST ATTEMPT!

WE DID...

VAPOR PHASE SOLDERING IS NOT MAGIC--IT DOESN'T CURE

VPS USERS REPORT

PROBLEMS IN YOUR PROCESS.

More specifically, these are the problems that caused my failure:

(1) Several of our parts slipped out of position--if parts are not self-fixturing, they must be fixtured.

(2) We got de-wetting and poor wetting--surfaces to be joined must be highly solderable. Vapor-Phase soldering does not make oxidized parts solderable. If you use old parts that have been knocking around in your desk drawer for months, as we did--don't expect good results!

(3) We had assemblies where the solder ran down the trace, leaving the solder joint dry. The solderable area must be limited in some way (solder mask, for example).

(4) We couldn't tell how long to leave the parts inside the machine (you can't see inside). An experienced operator can guess pretty close (our vendor rep obviously wasn't experienced); otherwise, you will have to make Mass vs Time charts for any given machine, to be able to predict dwell time reasonably closely.

(5) Finally--and most important: we got spatters, solder balls and consistently poor wetting. Solder cream used must be fresh, oxide-free, and inherently high quality--not an old jar that had been kicking around in the desk drawer for months. You can't get good joints with bad solder!

OBVIOUSLY, VAPOR PHASE IS NO PANACEA--YOU HAVE TO CONTROL THE PROCESS.

But, at the time...we didn't know what caused our failure, or what to do about it. What we DID know, was that "educated guesses" wouldn't solve the problem.

WE AT AEROJET CHOSE TO RUN AN R & D PROGRAM

THIS WAS THE PROBLEM TO BE SOLVED:

CRITICAL MICROWAVE ASSEMBLIES--both leadless chip components and planar antennas--had to be assembled in a repeatable manner at a high rate. Vapor Phase Soldering appeared to be the most likely solution.

THE PROBLEM:

1. Leadless chips. Chips .050 to .120 on a side are commonly used in Microwave assemblies. We had always installed them manually. But, if we were to be able to use any of the pick and place machines coming on the market, we HAD to convert to machine soldering.

2. Location problems. Line length is critical in Microwave. By using a computer-controlled pick and place machine to place the parts, and a vapor-phase machine to solder them, we could improve the repeatability of location.

3. Fillet size critical. The solder fillet on very small parts becomes an integral part of the component. Solder screening or plating and Vapor Phase soldering could achieve the desired consistency.

4. Effects of gold plating. Gold-plated parts or boards will have gold-contaminated solder joints. Vapor Phase soldering has no washing action. Therefore, it is essential to know HOW MUCH gold a solder joint can tolerate, before embrittlement becomes a problem.

ANTENNA SOLDERING: SPECIAL PROBLEMS:

1. Flat surfaces--our antenna is a flat Duroid circuit board soldered to a cylindrical support ring. The problem is to make a continuous solder joint with no voids or flux entrapment.

2. Continuous solder joint--to achieve proper performance at Microwave frequences, a continuous, non-interrupted ground connection was required, all the way around the antenna.

3. No flux entrapment--with two flat surfaces, flux entrapment is difficult to avoid. Thanks to the oxygen-free atmosphere of Vapor Phase, we were able to solder without flux.

4. Tooling required--the antenna had to be properly located, and kept flat during soldering. The result was a tool weighing considerably more than the antenna--about 5 pounds. Because all the soldering was around the periphery, it worked out very well.

*******HERE'S WHAT WE NEEDED TO KNOW*******

1. Which solder cream works best?

2. What is the optimum dwell?

3. What effect does gold have?

4. How do we avoid intermetallics?

HERE'S HOW WE FOUND OUT:

1. Measurements, not opinions. We looked for a way to know what was going on inside those solder joints, rather than guessing.

2. Visual inspection inadequate. You can't tell how many gas bubbles, or voids or intermetallics you have in a joint, unless you make a cross section.

3. Metallurgical analysis is required--nobody can tell by looking what variation in alloys or what intermetallics form inside a solder joint. S.E.M. (Scanning Electron Microscope) analysis is the answer.

SOLDER CREAM SELECTION

1. Solder spread test. A controlled amount of solder was placed on clean copper (in our case, copper clad Duroid). After solder cream application, the Duroid was lowered into the machine and allowed to dwell 2 minutes. The amount of spread was a measure of the effectiveness of the flux. This test also shows up splatters and solder balls.

2. Solder ball test. A controlled amount of solder cream was placed on bare alumina, which was then allowed to dwell 2 minutes in the Vapor Phase machine. The evaluation involved observation of spatters and solder balls; it is basically an evaluation of the solder's ability to wet itself.

3. Application techniques. Our initial tests were run using hand application. It quickly became obvious that solder screening or plating was required for repeatability. We chose screen printing.

4. Final solder cream selection. We tested 7 vendors, and evaluated the following considerations:

(1) Solder spread test
(2) Solder ball test
(3) Price
(4) Availability.
(5) Support

With the above considerations in mind, we selected Multicore SN62 Vapor Phase Solder Cream.

PLATING CONSIDERATIONS

1. Antenna Support Ring was brass. We had a problem with the zinc migrating through the plating and contaminating the solder joints.

2. A barrier material was needed--the common ones are: nickel and copper. We chose copper because of its excellent compatibility with brass. After trying several plating thicknesses, we settled on .0005 copper.

3. Is solder fusing necessary? In general, fusing improves solderability. But in soldering our antenna to the support ring, fusing caused the solder to agglomerate, resulting in irregular thickness. We settled on a plating thickness of .0003, unfused.

DWELL TIME STUDY

1. Samples at intervals from 2 to 10 minutes were taken. The purpose of this study was to find out what TIME as a variable does to the solder joint. It is a matter of common knowledge that the number of intermetallics formed is directly proportional to time at temperature. We wanted to find out what the limits are.

2. Bare copper substrate--G10 circuit board material was used for this test. All tests were run by soldering leadless chips to the substrate, using Multicore SN62 solder cream.

3. Gold-plated substrates--G10 was plated with 50 millionths of gold, in order to evaluate the effect of gold in the solder joint.

RESULTS--WHAT WE LEARNED:

1. Dwell must be kept short. In fact, minimum dwell is mandatory. Intermetallics are already evident at 2 minutes. With longer dwell times, the alloy tends to dissociate, resulting in a bad appearance and microcracks.

2. Intermetallic formation is indeed proportional to dwell time. By the end of 10 minutes, we had intermetallic crystals that extended from one end of the fillet to the other, seriously reducing the flexibility of the joint. Such intermetallics are responsible for failures under thermal shock or thermal cycling.

3. Rapid cooling of the solder joint is preferred, in order to minimize intermetallic formation.

EQUIPMENT MODIFICATION MAY BE REQUIRED

Elevator controls on machines as delivered normally do not have the flexibility to achieve the ideal profile:

1. A prompt withdrawal from the primary vapors, probably within 1 minute for small circuit boards without fixtures.

2. A relatively long dwell in the secondary vapors to allow cool-down.

OTHER CONCLUSIONS:

VPS USERS REPORT

DESIGNING ASSEMBLIES FOR VAPOR PHASE:

1. Part Geometry: Vapor Phase is forgiving, but no area intended to be soldered may be masked from the vapors.

2. Substrate Material: Any substrate material that can stand the vapors can be used. If leadless chips or chip carriers are to be installed, a good match of coefficient of expansion is required to avoid stress failure of the solder joints.

3. Pad size and shape: Because surface-mounted parts tend to "skate" on liquid solder, it is important that pads be consistent in size, so that the parts will self-center. A "pads only" design is preferred, so solder doesn't run down the trace, leaving the component dry.

4. Component size and shape: As is the case for pads, consistent contact areas are required for self-centering.

5. Solderability: Most critical! A good, solderable material or surface finish must be specified. In many cases, a barrier material (nickel or copper) must be added over the base material to avoid contamination bleed-through, or excessive intermetallic formation.

6. Plating or surface finish. The prime consideration is a high degree of solderability. In general, fused tin or fused tin-lead worked the best for us.

7. Solder alloy and flux. There is a world of difference between manufacturers as to how flux or solder cream will perform. Run your own tests. SN62 is usually preferred for soldering to leadless chips, because the silver content reduces silver scavenging from silver-palladium metalization.

TOOLING CONSIDERATIONS

1. Size and weight of tools must be considered when determining dwell time, because the tools are heated along with the part. The total must be within the capacity of the machine. Not to mention that the total must not exceed the capacity of the elevator--otherwise, you will have to fish it out of the tank...like we did!

2. Tension and force. There must be enough tension on the assembled parts to ensure follow-up as the solder melts. Otherwise, you will get two separate parts with a nice reflowed surface--but no assembly!

3. Masking, entrapment. Vapor Phase heats by vapors, right? Therefore, if parts are masked by tooling,

they won't heat. On the other hand, if the tool or part entraps fluorcarbon, it will be dragged out of the machine. At $500 a gallon, this can be expensive.

4. Base material. The tool must be a good thermal conductor, capable of repeated excursions into a 419 degree environment, without distortion.

5. Surface finish. THE TOOL MUST NOT BE SOLDERABLE! In addition, it must be able to withstand the assault of the small amount of hydrochloric and hydrofluoric acid that forms in the primary vapor. Keep in mind that the parts to be soldered come out quickly, but the tools receive repeated doses.

PROCESS CONTROLS

1. MEASURE AND TEST to make sure you get what you specify. Solder alloy and trace contaminants, plating material, plating thickness--check at receiving! Check EVERY batch! You'll be surprised how often materials are out of specification.

2. Solderability. How do you check for it? You can get a feel by observation. If you want an objective measurement that permits measuring and comparing batch to batch, I recommend a solderability tester, such as the Hollis Meniscograph or Multicore Wetting Balance. Make sure you get a set-up including a printer or plotter, so you get a permanent record.

3. Shelf life. Substrates, components, solder cream--all tend to oxidize with time. Solder cream should normally be refrigerated, but check the supplier's recommendations. Don't accept solder cream without a date stamp. Chip components with palladium-silver metalization had better be stored in a nitrogen dry-box. Finally, enforce a FIFO inventory system on all solderable materials.

4. DOCUMENT YOUR PROCESS. Even the best operator will sometimes forget. And even the best may leave--or get promoted--or get pregnant. Good, clear documentation simplifies the training problem.

* * * *

*******IN SUMMARY*******

* * * *

1. VAPOR PHASE IS A FAST, SAFE, REPEATABLE PROCESS.

2. VAPOR PHASE IS A CLEAN AND FORGIVING PROCESS.

VPS USERS REPORT

3. THE PROCESS MUST BE DEVELOPED AND DOCUMENTED.

4. SURFACES TO BE SOLDERED MUST BE HIGHLY SOLDERABLE.

5. VAPOR PHASE IS THE ONLY REASONABLE ANSWER FOR SURFACE MOUNT COMPONENTS.

****

TRY IT! YOU'LL LIKE IT!

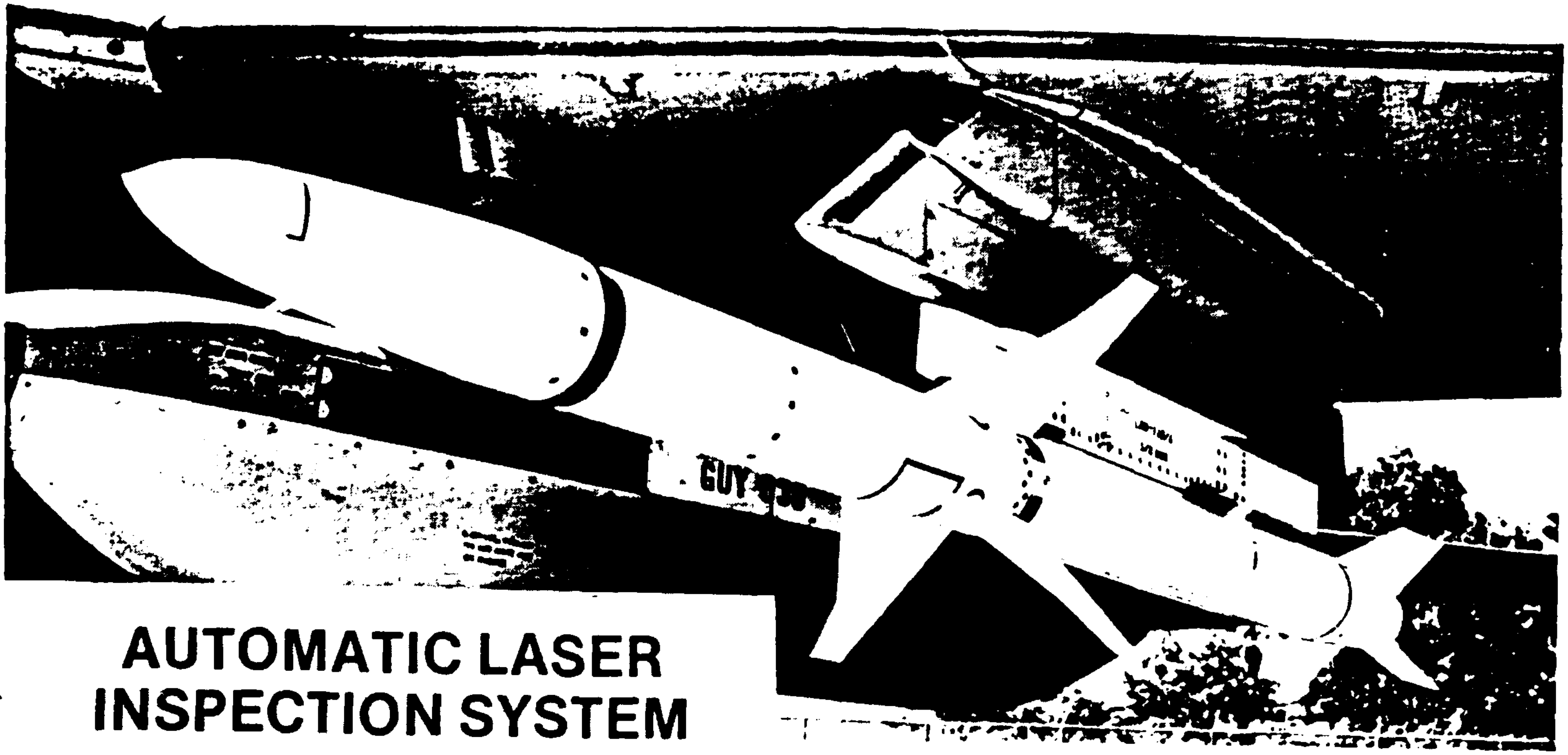
P.K. Nicholson
TAMS DIVISION
DEPT. 2221 MANUFACTURING ENGINEERING
X 2108

AUTOMATIC LASER INSPECTION SYSTEM

Mr. Fred Henley

Texas Instruments
Lewisville, Texas

HARM AGM 88A

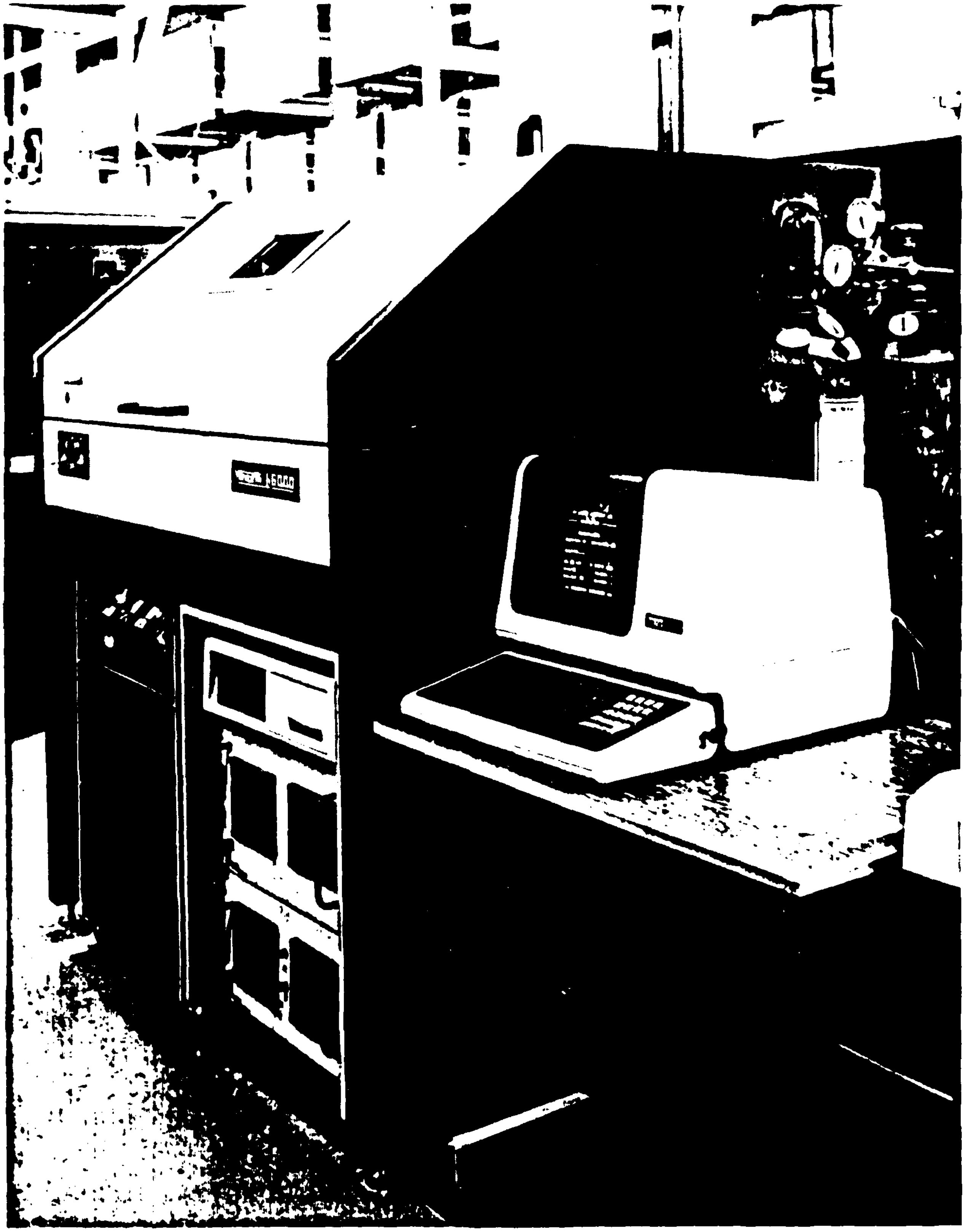


AUTOMATIC LASER INSPECTION SYSTEM

BY

FRED HENLEY
QA ENGINEERING
DEFENSE SUPPRESSION DIVISION
EQUIPMENT GROUP

TEXAS INSTRUMENTS



AUTOMATIC LASER/INSPECT CRITERIA STUDY

INTRODUCTION

The primary objective of the Laser/Inspect Study Program was to demonstrate the feasibility of Printed Wiring Board Solder Joint Inspection by use of a Quantitative Laser Heating and IR scanning technique. The program's secondary objective included the development of a procedure to establish a WS6536D compatible thermal acceptance criteria for individual solder joints and validation of that procedure. Miscellaneous program objective included establishing programming expertise, creating a data link between the Digital Equipment LSI-11 computer in the inspection system and the mainframe system for data reduction, storage, and manipulation. The program culminated with a factory demonstration of the inspection procedure and techniques as applied to testing of PWB's during the actual manufacturing process.

SYSTEM METHODOLOGY

The Laser/Inspect is an automatic solder joint inspection system. This system uses laser energy for detecting defective solder joints. A defective joint is one that is either electrically nonfunctional or whose life expectancy could be reduced because of a defective condition within the mechanical strength characteristics of the joint. Typical visual solder defects include dewets, surface voids, bridges, cold solder, residual flux, solder impurities, and poor lead contact on surface mounted components.

Defective solder joints using the Automatic Laser/Inspect System are found by analyzing the thermal signature of each joint. The thermal signature consists of a series of measurements taken by the infrared detector which shows the solder joint's ability to absorb and dissipate the Laser Applied Energy in a determined period of time. Once a PWB solder joint has been inspected and the signature analyzed by the computer a printout of defects only or results of all solder joints may be obtained as needed on the system printer. This printout of defects only provides objective evidence of Hardware Acceptability or information necessary for rework.

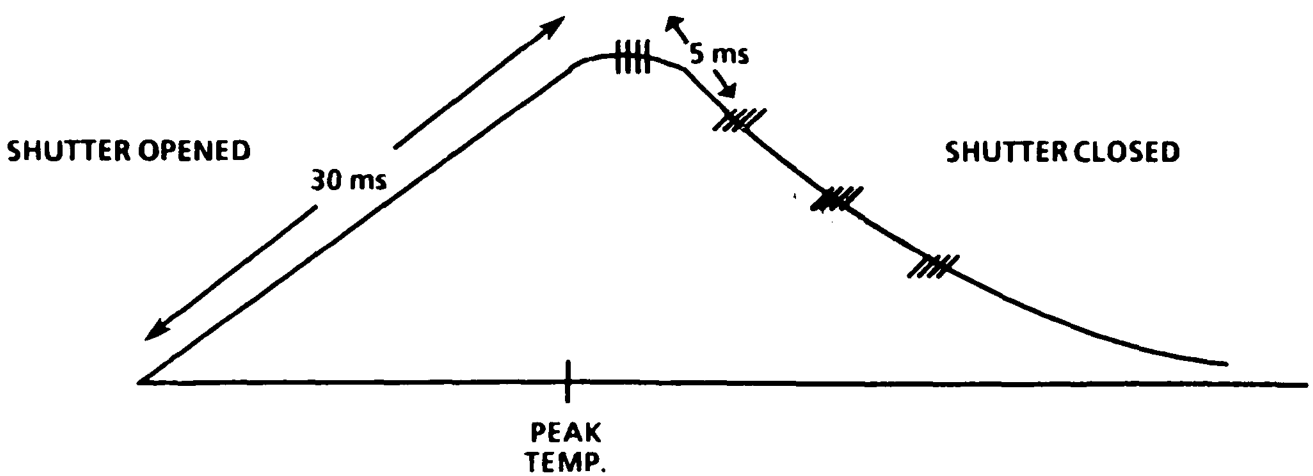
Inspection of a circuit board takes place by placing a PWB onto its specially designed test fixture which is placed on the X-Y Table of the Laser/Inspect. The PWB part number must be entered into the system computer which has been preprogrammed to select the X-Y Coordinates of the plated through holes on that PWB. The system computer will then control the movement of the X-Y Table under the injection head. Once a solder joint is positioned under the injection head the IR Detector makes the current temperature of that solder joint the baseline (zero) starting point. Once this starting point has been established. The shutter opens for 30 milliseconds allowing the laser to apply thermal energy to an individual solder joint. While the joint is heating, the IR detector monitors the rise in temperature. If the temperature rises too rapidly toward the saturation point (3900 units) the shutter closes to prevent damage to the board and/or joint. After the heating time is complete the shutter closes and the IR detector takes the first series of measurements. Four readings are taken simultaneously and averaged to obtain the peak thermal temperature. Three cool down temperatures are obtained in the same manner, once every five milliseconds, taking 45 milliseconds per joint for inspection. These temperature readings make-up what is is referred to as the thermal signature for an individual solder joint. A typical inspection sequence for an individual solder joint is shown in figure 1.

The detection system transmits the analog signals to the computer and creates a database for each individual solder joint. Once the database has been created analyzation of the peak thermal temperature may be performed by using the "Profile Calculation" made in the system computer.

The method of calculation can be chosen from three areas; blanket, median, and statistical. Choosing the blanket method the Accept/Reject threshold and tolerance can be chosen on an overall level. In the median method the median of all values for a specific solder joint is calculated and used as the Accept/Reject threshold. The Accept/Reject threshold and tolerance in the statistical method are obtained from the mean and standard deviation of the specified data file. Once the calculations have been made they are included in the main file on the Winchester disk. It is from this file that comparisons are made to find defective solder joints.

There are three possible categories for a solder joint's thermal reading - defective, acceptable, and burn prevention. Both the defective and the acceptable conditions are determined by comparing their peak thermal temperature to what is expected for that joint plus a tolerance limit. Acceptable solder joints fall within the prescribed limit unlike defective joints. Defects such as bridges will have peak thermal temperatures that fall below normal whereas voids, cold solder, non-wetting, and foreign substances will cause the peak thermal temperature to be above normal. The third condition, burn prevention, occurs when the solder joint heats too rapidly toward the detector's saturation point (3900 units). When this occurs the shutter is disabled so that additional thermal energy cannot be applied. This condition is caused by gross solder defects and foreign substances such as flux residue that tend to "burn" off the surface.

INSPECTION SEQUENCE



DSD

EQUIPMENT GROUP

FIGURE 1

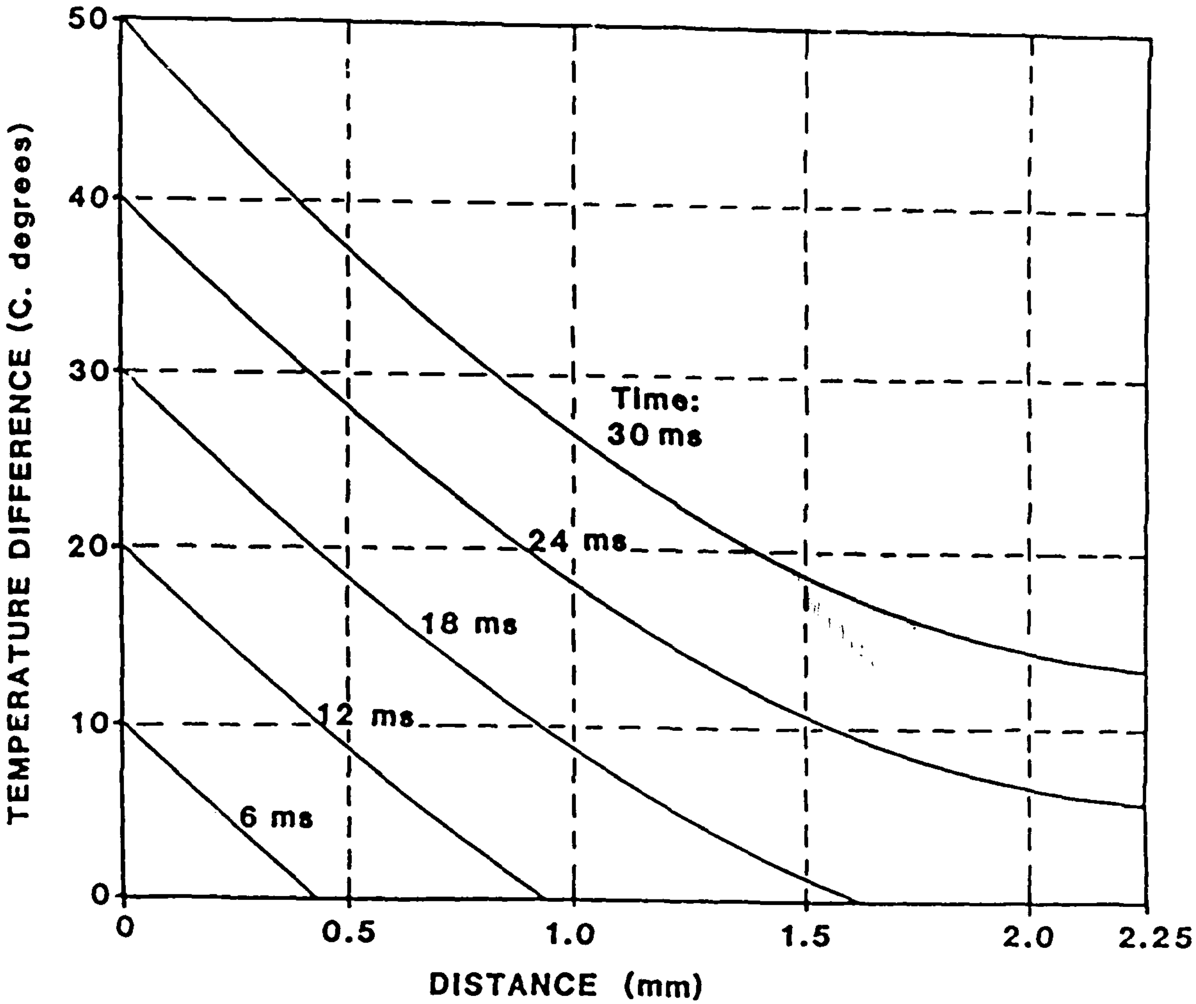


Fig. 1.a HEAT PENETRATION IN A SOLDER JOINT

TEST SEQUENCE

The primary objective of the test sequence is to validate a technique of Laser Inspection that will apply to any individual solder joint on "HARM" Printed Wiring Boards in the Manufacturing Environment of WS6536D. There are two steps to the implementation plan of this test sequence:

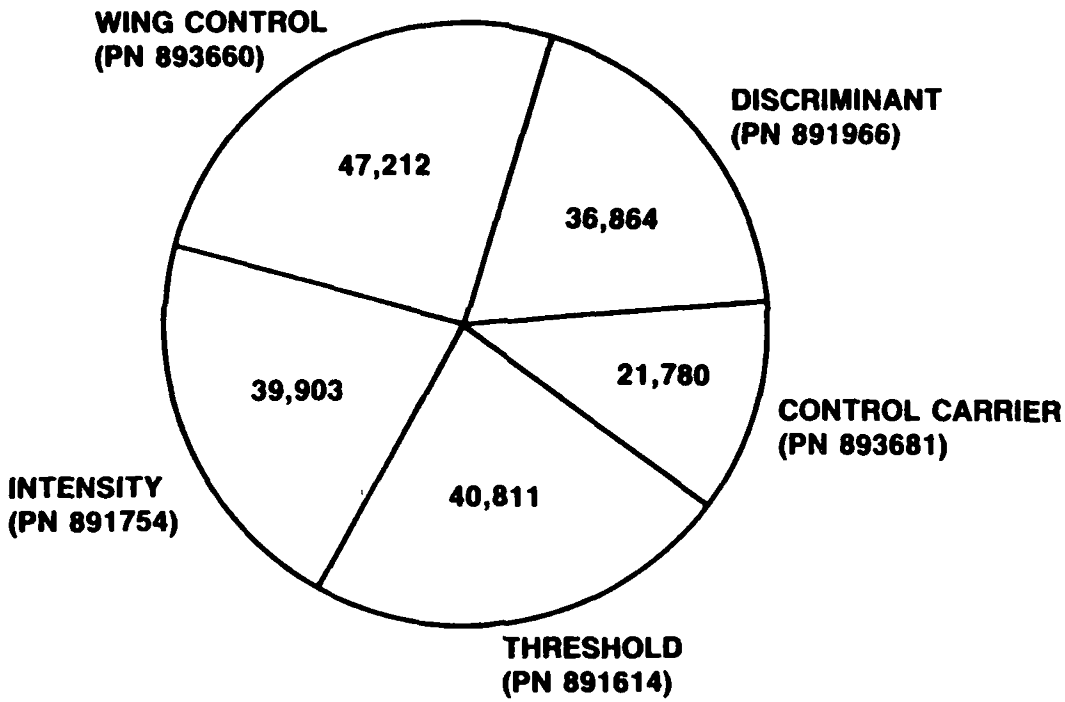
1. Develop a production procedure.
2. Validate that production procedure.

The Laser/Inspection Production Procedure was developed by obtaining and analyzing a statisically significant quantity of Printed Wiring Boards (PWB's) of the same part number. The procedure also included laser scanning each solder joint on each PWB, obtaining peak thermal temperatures, and performing "Profile Calculation". "Profile Calculation" is a software program used to statistically determine the accept-reject thermal limits for individual solder joints. Once these operations have been performed the Laser/Inspect System is ready to evaluate PWB's of the same part.

Validation of the Production Procedure was accomplished by

1. Identifying "HARM" PWB's that would represent every possible component within the missile and every typical PWB configuration (five unique part numbers. See figure 2).

HARM PRODUCTION PRINTED WIRING BOARDS
(43 PER PART NUMBER)



**186,570
TOTAL SOLDER JOINTS
EVALUATED**

FIGURE 2

2. Following the Production Procedure (obtain quantity of PWB's, Laser Scan, and perform Profile Calculation).

3. Quality Control Inspection of the PWB's for conformance to WS6536D/HARM Requirements.

4. Correlating all QC noted and Laser System noted defects, and grouping as follows:

   QC Accept - Laser Reject

   QC Accept - Laser Accept

   QC Reject - Laser Accept

   QC Reject - Laser Reject

5. Microsectioning two PWB's of each of the five production part numbers (Laser Test Boards) to correlate QC results, laser readings and actual condition of the solder joints.

6. Fine tuning the "Profile Calculation" statistical package as necessary to correlate thermal readings and solder joint visual characteristics/integrity.

7. Implementing Laser Inspection Procedure for Production PWB's.

Five unique part number Printed Wiring Boards were utilized for the study sequence. Two from the control section - control carrier and wing control and three from the guidance section - discriminator, threshold, and intensity. These boards represented the typical component and board configurations within the missile.

Prior to any of the testing done for the criteria study, a test for the repeatability of the system was performed. One PWB was scanned by the Laser/Inspect five times then a comparison was made. The comparison printout (figure 3) lists each component and the readings for each time the PWB was scanned. A mean and standard deviation is calculated for each pin of the component. By looking at the standard deviations shown on the printout, the data, hence the system, is proven to be repeatable.

The selected boards were flow soldered and cleaned of all foreign material by the aqueous cleaner. Figure 4 demonstrates how critical cleanliness is to the effectiveness of the Laser System. Boards were scanned by the Laser System and a profile calculation for each part number performed. An "error only" list was printed for each PWB scanned. Quality control inspectors then inspected the PWb's for conformance to the required Solder Specification WS6536D/HARM. All visually nonconforming solder joints were documented on the Assembly Work Order Troublesheets. Photo copies of individual troublesheets were taken for each part number scanned and this data was compared to the Laser/Inspect System error list for each board.

HARM LASER/INSPECT REPEATABILITY

DATE: 10/17/83 COMPONENT R127 PIN COUNT = 2 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1614D1

PIN#:	1	2
5028	31	31
5028A	31	34
5028B	34	35
5028C	36	34
5028D	31	37
STD/DEV :	2	2
AVERAGE :	32	34

DATE: 10/17/83 COMPONENT R128 PIN COUNT = 2 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1614D1

PIN#:	1	2
5028	35	34
5028A	42	34
5028B	37	34
5028C	39	31
5028D	37	35
STD/DEV :	2	1
AVERAGE :	38	33

DATE: 10/17/83 COMPONENT C1 PIN COUNT = 2 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1614D1

PIN#:	1	2
5028	94	32
5028A	94	30
5028B	99	40
5028C	89	38
5028D	103	29
STD/DEV :	5	4
AVERAGE :	95	33

DATE: 10/17/83 COMPONENT C2 PIN COUNT = 2 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1614D1

PIN#:	1	2
5028	102	42
5028A	106	40
5028B	113	48
5028C	113	51
5028D	110	44
STD/DEV :	4	4
AVERAGE :	108	45

DATE: 10/17/83 COMPONENT VR7 PIN COUNT = 2 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1614D1

PIN#:	1	2
5028	77	76
5028A	80	73
5028B	80	78
5028C	80	72
5028D	81	73
STD/DEV :	1	2
AVERAGE :	79	74

FIGURE 3

After being inspected by Quality Control the Production PWB's continued on to the next operation. The two PWB's per part number that were designated to go through destructive testing stopped after first look QC. A review of the error list and Quality Control visual rejects supplied the information necessary to select ten solder joints per board to be microsectioned from the four chosen categories.

Microsectioning of the solder joints was performed by the Process Engineering Lab. The technician first photographed the component and etch side of the solder joint while the PWB was still intact. Each solder joint to be sectioned was cut out of the Printed Wiring Board and mounted in clear polyester compound. Reference designators and pin counts were etched into the side of the sectioning compound. At this point the technician was ready to start the microsectioning of the solder joint. Sectioning started at the outside of the barrel inward to the lead in increments of approximately .005". If a defect (e.g. void, non-adherence of the solder to the barrel wall or lead, foreign material, etc.) was identified at any increment under 10X magnification a photograph was taken to preserve the observation and then the incremental sectioning was continued. When the sectioning had progressed to the point where 1/2 of the plated through hole was sectioned a photo was taken to show evidence of the solder condition around the lead (e.g. Good continuous wetting, etc.). Sectioning would proceed through the lead toward the remaining barrel wall. If a defect was identified under 10X magnification a photo was taken. The technician used intervals of 1/3, 1/2, and 3/4 for sectioning of the solder joints and the documentation of physical characteristics found within that joint.

FREQUENCY DISTRIBUTION

CONTAMINATION CAUSES AN UPWARD
SHIFT OF THERMAL READINGS

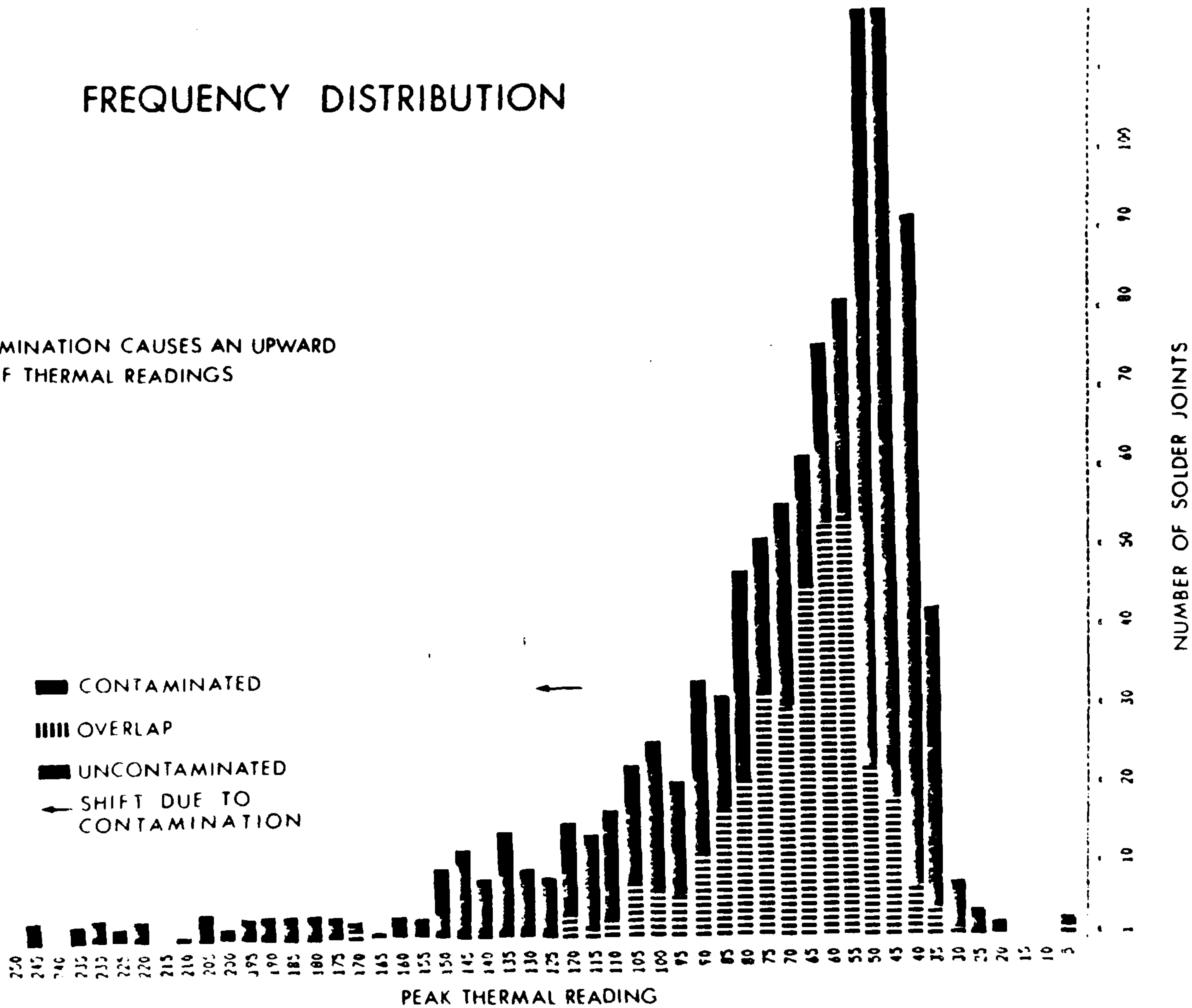
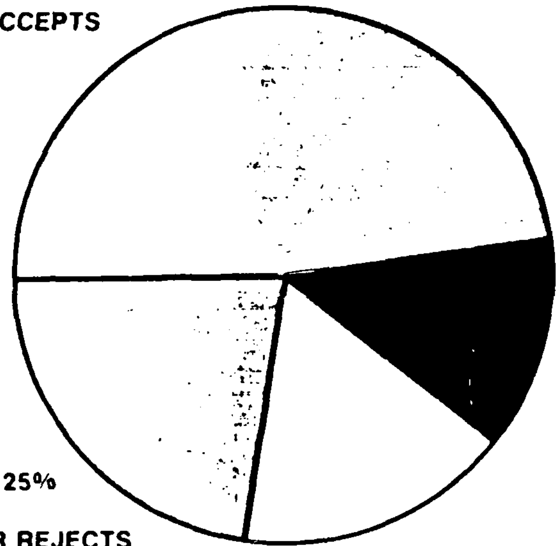


FIGURE 4

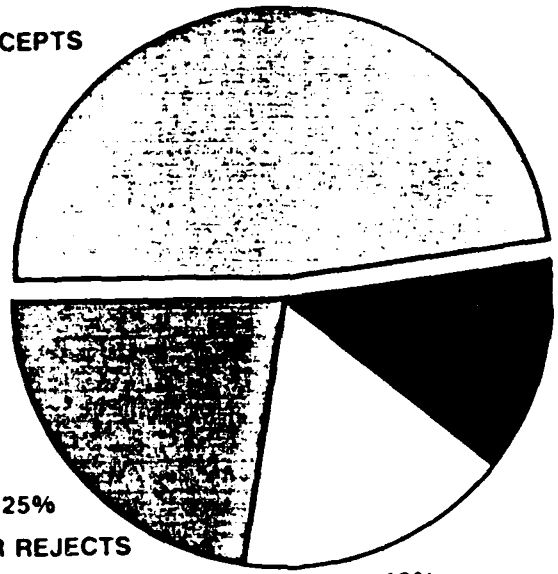
HARM MICROSECTIONS OF SOLDER JOINTS FROM PRODUCTION BOARDS

HARM PRODUCTION PRINTED WIRING BOARDS



104
TOTAL SOLDER JOINTS
MICRO-SECTIONED
BY CATEGORY

HARM
PRODUCTION PRINTED WIRING BOARDS

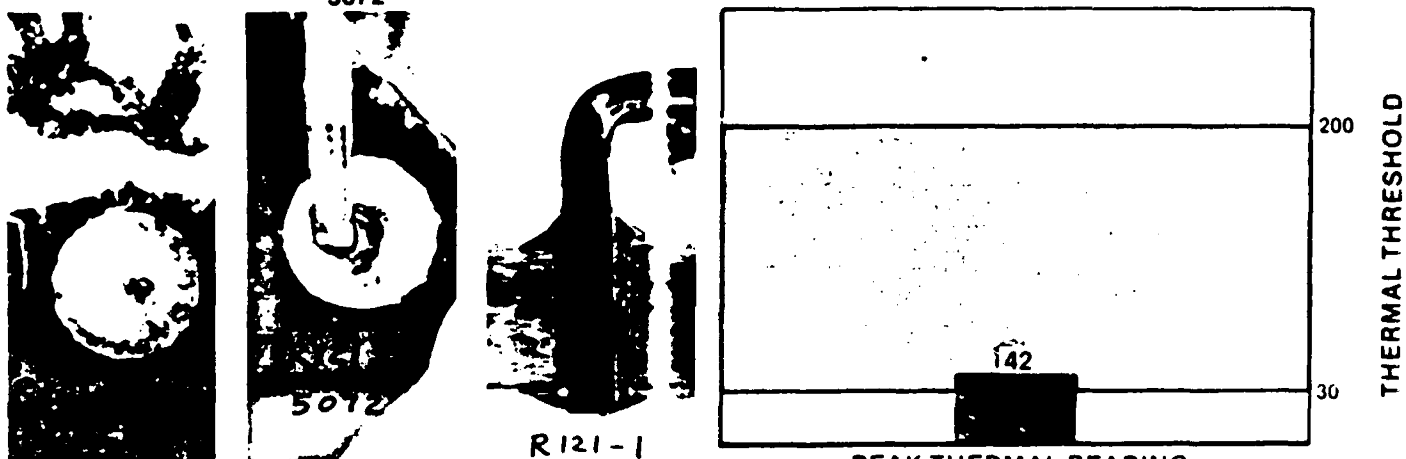


104
TOTAL SOLDER JOINTS
MICRO-SECTIONED
BY CATEGORY

HARM LASER INSPECTION SYSTEM

CROSS SECTION RESULTS

R121-1
5072



ETCH SIDE

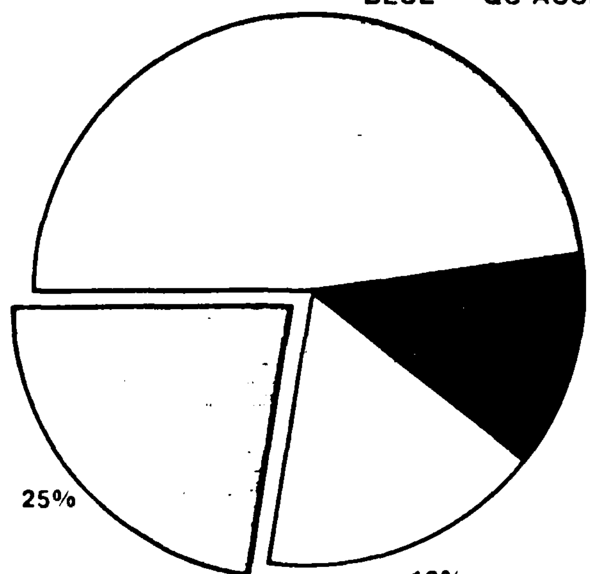
COMPONENT SIDE

FULL CROSS SECTION

PEAK THERMAL READING

- QUALITY CONTROL ACCEPT LASER/INSPECT ACCEPT
- 99.6% SOLDER THERMAL VOLUME
- GOOD SOLDER FILLET

HARM PRODUCTION PRINTED WIRING BOARDS

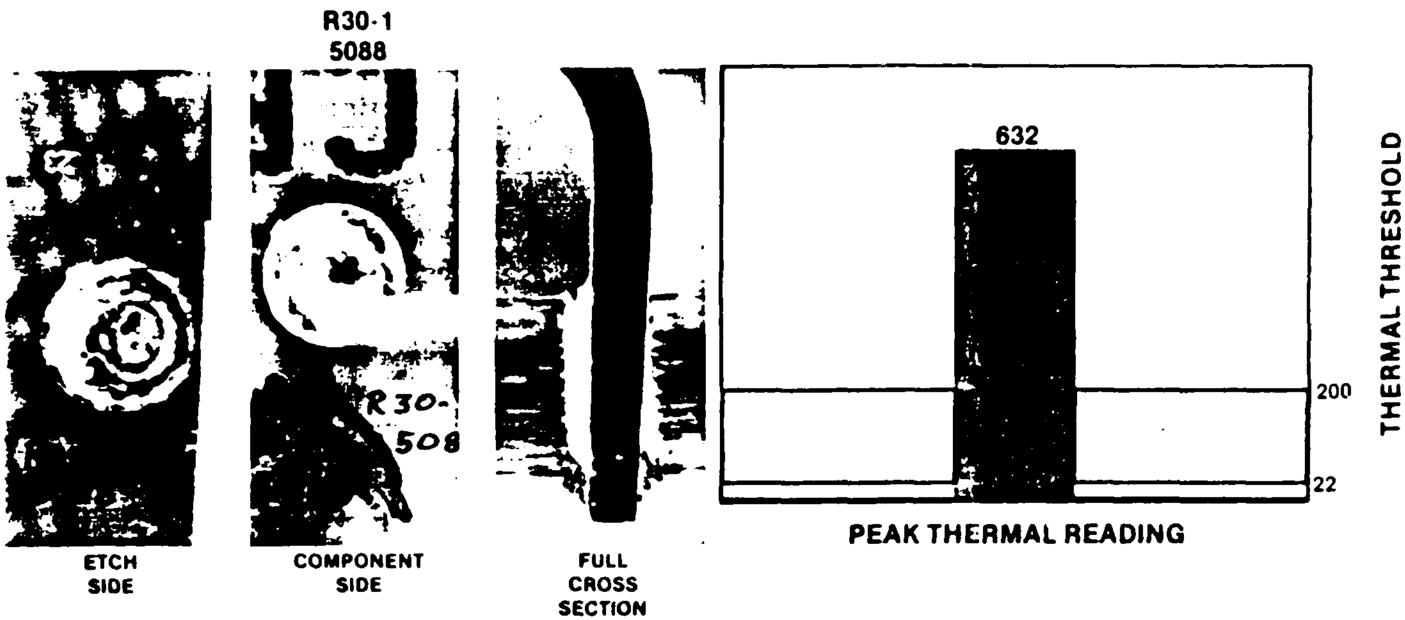


LASER REJECTS
SMALL PERCENTAGE GOOD
JOINTS BUT DOES NOT
ACCEPT BAD JOINTS

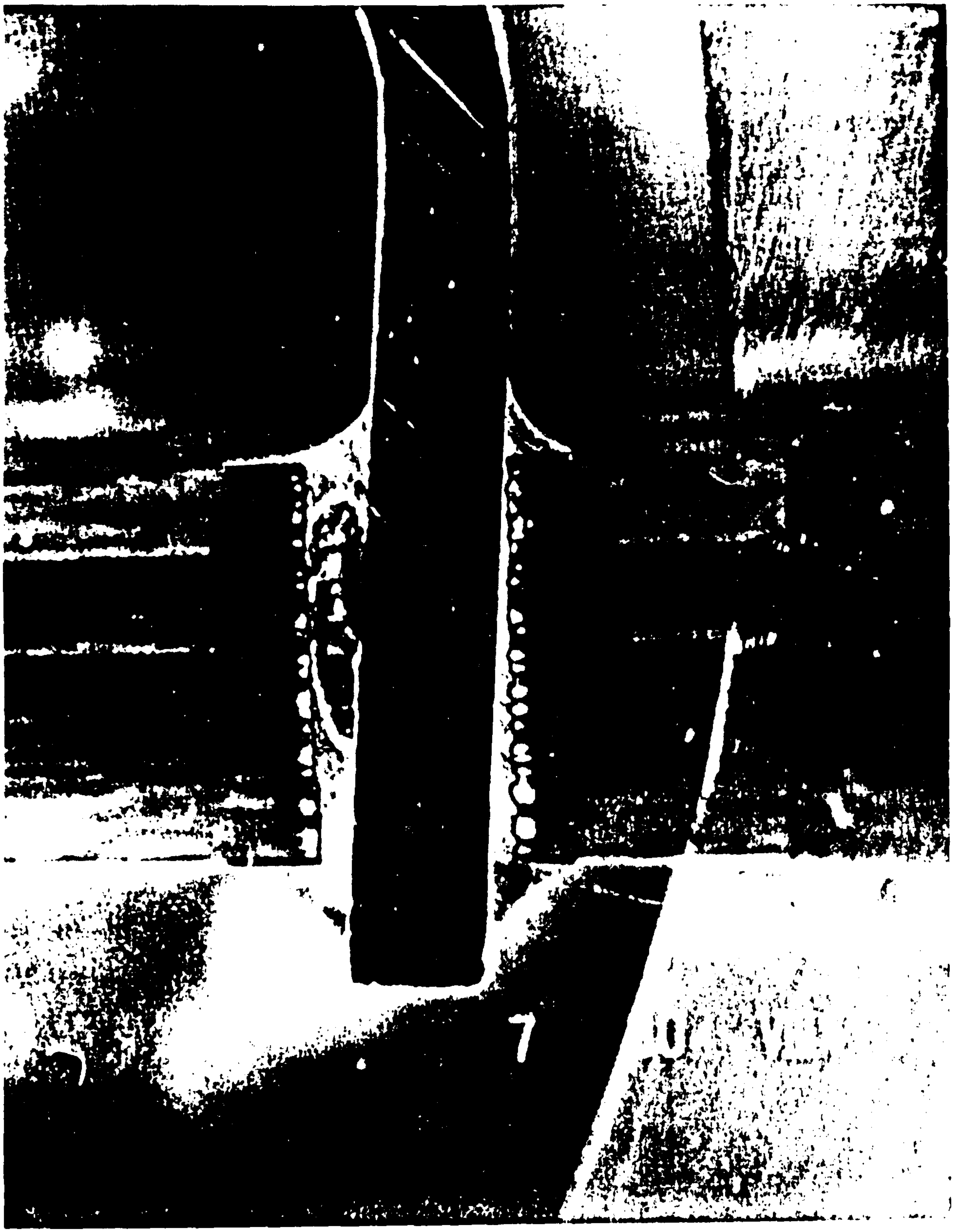
104
TOTAL SOLDER JOINTS
MICRO-SECTIONED
BY CATEGORY

HARM LASER INSPECTION SYSTEM

CROSS SECTION RESULTS

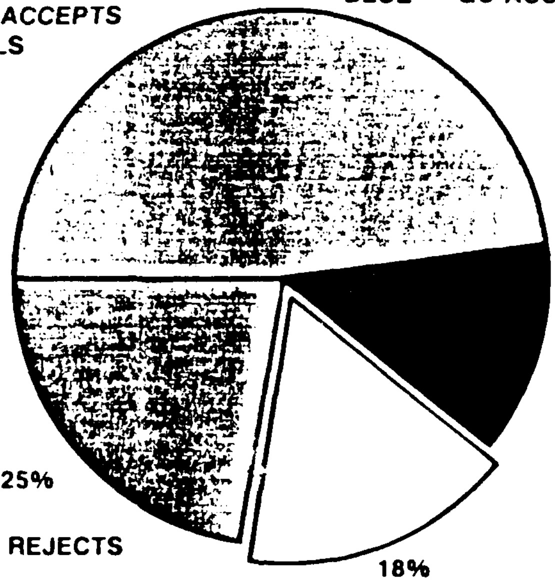


- QUALITY CONTROL ACCEPT LASER/INSPECT REJECT
- 61% SOLDER THERMAL VOLUME
- VISUALLY ACCEPTABLE THERMALLY REJECTABLE


7

HARM PRODUCTION PRINTED WIRING BOARDS

CORRELATION —
LASER CONSISTENTLY REJECTS
DISCREPANT JOINTS, BUT ALSO ACCEPTS
DEWET AND INSUFFICIENT CALLS
BY QC ON TOP SIDE JOINTS



104
TOTAL SOLDER JOINTS
MICRO-SECTIONED
BY CATEGORY

HARM LASER INSPECTION SYSTEM

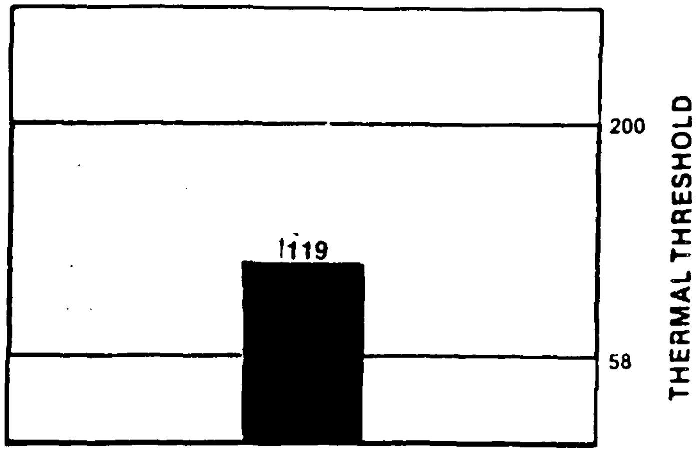
CROSS SECTION RESULTS

AR8-1
5072

ETCH SIDE

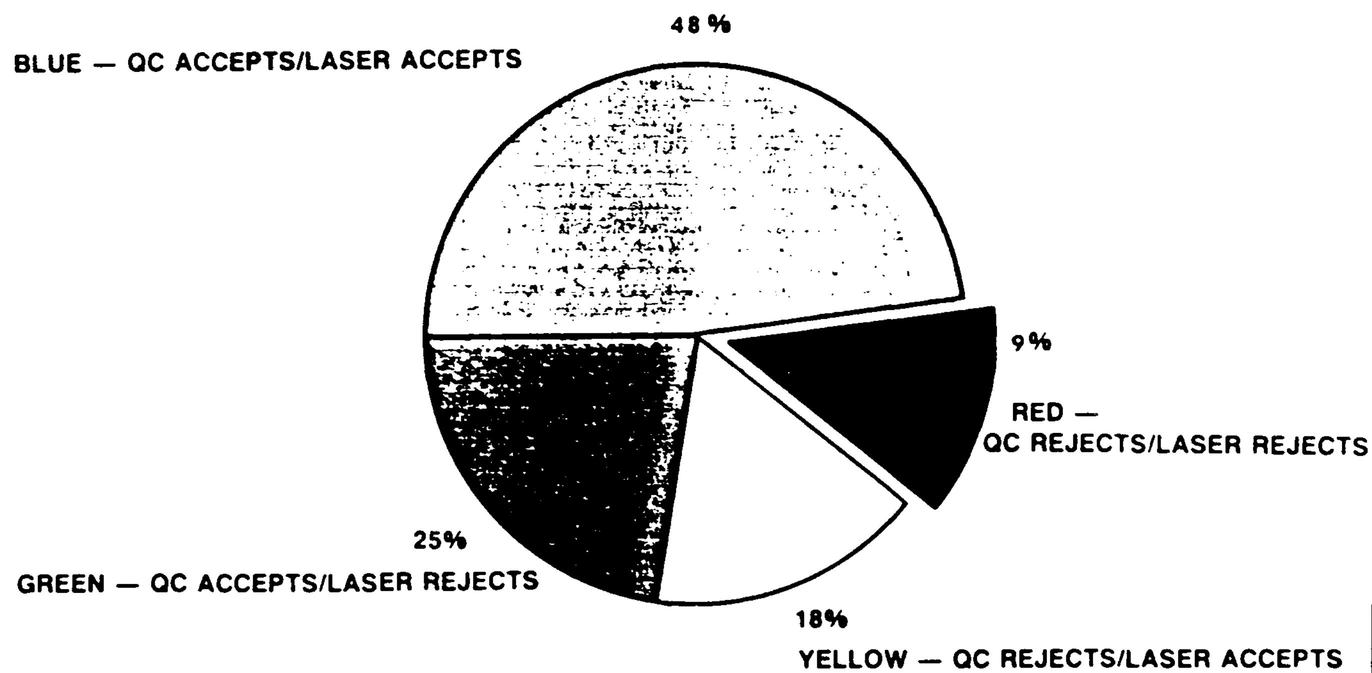
COMPONENT SIDE

FULL CROSS SECTION



- QUALITY CONTROL REJECT LASER/INSPECT ACCEPT
- 99.5% SOLDER THERMAL VOLUME
- VISUALLY REJECTED BECAUSE OF A DEWET ON COMPONENT SIDE

HARM PRODUCTION PRINTED WIRING BOARDS



104
TOTAL SOLDER JOINTS
MICRO-SECTIONED
BY CATEGORY

HARM LASER INSPECTION SYSTEM

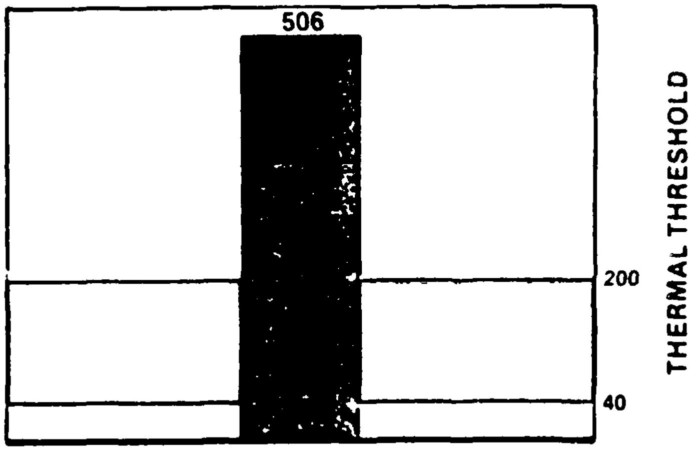
CROSS SECTION RESULTS

Q3-2
5072

ETCH SIDE

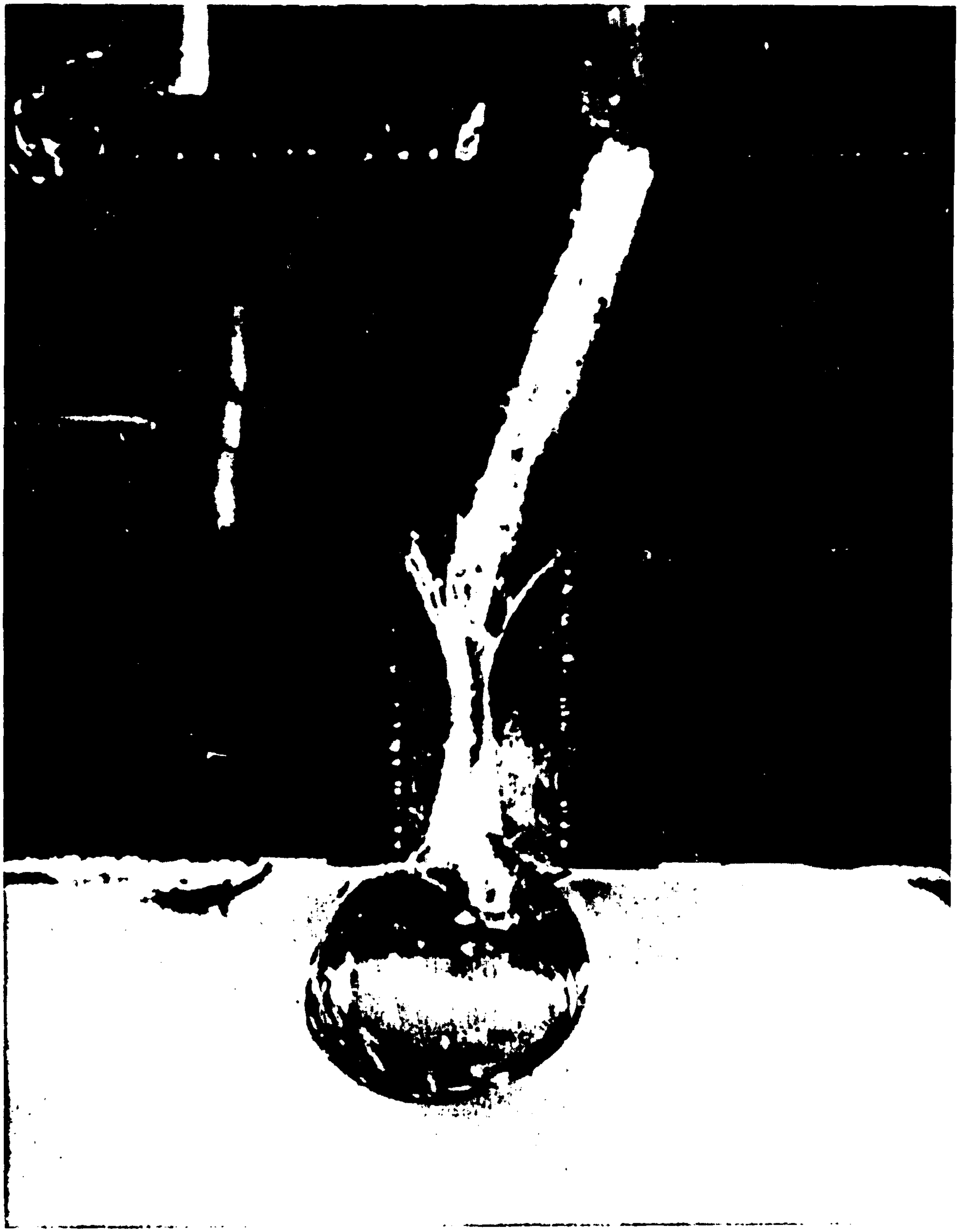
COMPONENT SIDE

FULL CROSS SECTION



PEAK THERMAL READING

- QUALITY CONTROL REJECT LASER/INSPECT REJECT
- 68% SOLDER THERMAL VOLUME



PROCESS CONTROLS

For tighter Process Controls of Lead Configuration Bent Leads are the solution. Bent Component Leads remove the large variation caused by heating the lead instead of the solder volume. With this variation eliminated the thresholds and tolerances tighten, thereby significantly decreasing the possibility of rejecting an acceptable solder joint. An experiment was performed on a Printed Wiring Board that had straight through lead components. The board was scanned in its original Lead Configuration then six components (Q2-Q4, U23, U33, and U13) were modified to simulate the auto inserted (bent) leads and rescanned. Results of this experiment are shown in figure 5. The Straight through Lead Component's (5031-18) peak thermal reading had a range of 2080 and the Bent Lead Components (Auto-IC) had a range of 77.

METAL CASE COMPONENTS STRAIGHT-THROUGH LEADS VS BENT LEADS (SIMULATED AUTO INSERT)

DATE: 10/14/83 COMPONENT Q2 PIN COUNT = 3 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1966D1 Q

PIN#:	1	2	3	
5031-18	349	335	351	STRAIGHT-THRU
AUTO-IC	53	52	41	BENT LEAD

DATE: 10/14/83 COMPONENT Q3 PIN COUNT = 3 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1966D1 Q

PIN#:	1	2	3	
5031-18	197	147	46	STRAIGHT-THRU
AUTO-IC	43	39	43	BENT LEAD

DATE: 10/14/83 COMPONENT Q4 PIN COUNT = 3 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1966D1 Q

PIN#:	1	2	3	
5031-18	19	1799	8	STRAIGHT-THRU
AUTO-IC	32	45	39	BENT LEAD

- REDUCTION OF DEFECTS BY 4 WITH BENT LEADS.

DUAL IN-LINE STRAIGHT-THROUGH LEADS VS BENT LEADS (SIMULATED AUTO INSERT)

DATE: 10/14/83 COMPONENT U23 PIN COUNT = 16 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1966D1 U

PIN #:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
5031-18	103	435	380	128	198	217	144	152	206	732	268	861	196	1142	980	1704	STRAIGHT-THRU
AUTO-IC	52	53	77	107	58	64	63	49	45	46	50	54	79	61	51	72	BENT LEAD

DATE: 10/14/83 COMPONENT U33 PIN COUNT = 14 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1966D1 U

PIN#:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
5031-18	73	554	333	328	742	389	841	2088	1368	1295	854	465	1075	802	STRAIGHT-THRU
AUTO-IC	53	50	51	61	39	53	83	39	45	52	40	46	46	60	BEND LEAD

DATE: 10/14/83 COMPONENT U13 PIN COUNT = 14 VANZETTI SYSTEMS LASER/INSPECT MASTER PROFILE: 1966D1U

PIN#:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
5031-18	70	542	374	373	307	238	54	111	621	392	109	307	689	163	STRAIGHT-THRU
AUTO-IC	30	35	40	87	40	44	53	48	42	48	42	40	49	53	BENT LEAD

- REDUCTION OF DEFECTS BY 32 WITH AUTO INSERTION.

Q — METAL CASE COMPONENTS

U — DUAL IN-LINES

FIGURE 5

RECOMMENDATIONS

To fully utilize the Laser/Inspect System it is necessary to maintain stringent Process Control such as lead configuration, cleanliness of the Printed Wiring Boards and method of component installation. Presently the Laser/ Inspect has demonstrated it performs 100% Fail Safe Inspection which has been verified by the microsections of the production laser test boards. The rejection of an acceptable solder joint does sometimes occur but can be eliminated by Process Controls.

LEAD INGESTION HAZARD IN HAND SOLDERING ENVIRONMENTS

Elisabeth R. Monsalve

Safety and Occupational Health Specialist
Safety Program Office
Naval Weapons Center
China Lake, California 93555

Presentation for

Eighth Annual Seminar
Soldering Technology and Product Assurance
22, 23 February 1984
Soldering Technology Branch
Product Assurance Division
Engineering Department
Naval Weapons Center
China Lake, California 93555

INTRODUCTION

Amid advancing soldering technology and the proliferation of automated techniques, hand soldering remains a mainstay in a number of electronics applications.[1] Hand soldering with an iron, and pretreatment of components by pot tinning are very much in evidence in a research and development facility like the Naval Weapons Center, where many and varied one-of-a-kind electronic component prototypes are produced.

Soldering, more specifically hand soldering and pot tinning used in electronics applications, has not traditionally been considered a high lead hazard operation or occupation. Eminent toxicologist Elkins characterized the overall lead hazard in soldering operations as "minor."[2,3] As late as 1977, in a comprehensive monograph on lead, the World Health Organization (WHO) did not include soldering *per se* in its listing of lead hazardous industries/operations.[4] Automobile radiator repair, which does involve a heavy form of soldering, was rated as highly hazardous. The Lead Industries Association (LIA) asserts in a soldering safety manual[5] that there is relatively little general hazard, or hazard from lead fume, in soldering operations because of the low temperatures involved (650-900°F). The manual cites extensive air sampling data confirming lead levels below the current Occupational Safety and Health Administration (OSHA) action level of 0.03 mg/m^3 (30 μg/m^3). However, the potential hazard of lead ingestion was alluded to briefly in a statement regarding the importance of "good personal hygiene habits" and the prohibition of smoking, eating, and drinking in lead exposure areas. In assessing the lead hazard associated with the use of low melting point lead alloys (200-600°F) to construct radiotherapy shielding, no significant lead fume was detected. Handling procedures to minimize ingestion were recommended.[6]

The National Institute of Occupational Safety and Health (NIOSH) does list "solderer" as an occupation in which lead exposure may occur; the type of soldering and nature of the potential exposure are not qualified.[7,8] Yet in four separate health hazard evaluations of industrial hand soldering and pot tinning environments from 1974 to 1980, almost all airborne lead samples were below detection limits, blood-lead indices were well within normal range, and it was determined that no health hazard from lead appeared to exist.[9-12] One of the studies does suggest a potential lead ingestion hazard in a recommendation regarding close attention to worker hygiene, including prohibition of eating or smoking in the workplace.[9]

In 1978, OSHA promulgated a stringent revision of the Occupational Exposure to Lead Standard that governs over 120 operations involving the use of lead and includes hand soldering.[13,14] In the contracted technical feasibility study[15] for the Standard, however, "electronics" was categorized as an industry in which lead exposures were almost exclusively below the then proposed 0.1 mg/m^3 (100 μg/m^3) permissible exposure limit. Lead exposures were futher described as very low.

Western Electric Company, in a biological study to support the exclusion of hand soldering operators from the OSHA Lead Standard,[16] maintains that solderers' airborne lead exposures have been demonstrated to be "extremely low." Forty long-term hand solderers were found to have blood-lead indices comparable to a control group of office workers with no known exposure to lead. In justifying the biological monitoring methodology of the study, environmental air measurements are dismissed as limited because lead exposure may also occur by means of skin absorption or ingestion.

Burgess[17] describes potential health hazards to soldering operators as "minimal," stating that flux may represent the most significant potential hazard. Temperatures routinely used are considered too low to generate significant fumes, although handling of dross dust may be a source of exposure to lead. Most interestingly, Burgess admits that his position should be reconsidered in light of the present 0.50 mg/m^3 (50 μg/m^3) OSHA permissible exposure limit for lead.

Elaborating on Burgess' theme, the 1978 OSHA revised Lead Standard represents a substantial conservative evolution in scientific thought and increasing regulation in regard to the hazards of lead. The Standard revises the permissible exposure limit to lead in air downward threefold from 0.15 mg/m^3 (150 μg/m^3) to 0.05 mg/m^3 (50 μg/m^3) and mandates biological monitoring of lead workers and strict control of workplace exposures. Much of the research upon which the standard is based demonstrates subtle or subclinical toxic effects of lead in workers at relatively low levels previously considered to be "safe."[14] Although actual exposures to lead may not have increased and may actually be decreasing due to improved awareness and technology,[3,7,8] increasing knowledge of the toxicology of lead dictates a continuing reassessment of the hazard it presents. The potential hazard associated with even low-level exposures to lead may indeed have implications for solderers.

The toxic effects of inorganic lead in man have been known since ancient times and numerous toxicological investigations span over 150 years.[3] Lead is a cumulative poison whose effects on the hematological, neurological, and renal systems are well documented. Classic signs of frank poisoning in adults such as intestinal colic, anemia, brain dysfunction, convulsions, upper extremity weakness, wrist drop, and kidney failure are rarely seen in the United States today.[3,7,8] Of more relevance to this investigation is a discussion of newer findings of more controversial subclinical effects of lead at low levels of exposure.[18-25]

Subclinical effects of lead are physiologic changes undetectable except by increasingly sophisticated biological monitoring techniques. They appear much earlier than the signs and symptoms of overt disease. Many medical researchers feel that these changes are "critical effects," the precursors of disease, early manifestations on a continuum. Exposures that induce subclinical critical effects must be reduced to prevent occupational illness. Others, often industry representatives, argue that the clinical significance of these early changes is dubious; there is not enough evidence to demonstrate that these changes represent or lead to a material impairment of health.[14,26]

To place subclinical toxicological findings in perspective, an attempt must be made to characterize "low" levels of exposure. The measurement of lead exposure and human response to exposure are, in themselves, a complex and controversial issue beyond the scope of this discussion. The advantages, disadvantages, and predictive relationships between biological monitoring indices and environmental sampling data have been weighed extensively.[14,27] It is noteworthy that OSHA, in Solomon fashion, has required both environmental and biological monitoring in the Lead Standard. The toxic effects of lead exposure are generally discussed in the context of blood lead levels, although this is only a measure of recent or continuous exposure. Blood lead may be misleading because of the cumulative nature of this poison and the variability of human response to it.[16,22,27,28] Other biological indices, such as red blood cell protoporphyrins measured as zinc protoporphyrin (ZPP), may be more accurate and useful in assessing levels of toxicity because they estimate total body burden and *response* to exposure. A recent estimate of mean blood lead level in adults in the United States is 13 to 14 μg/dl (deciliter).[29] Traditionally, lead-related disease was not thought to occur at blood levels below 80 μg/dl.[14,18,30] The Lead Standard requires that blood lead levels be kept below 50 μg/dl. WHO recommends an upper limit of 40 μg/dl for adult workers.[31] Substantial recent research demonstrates overt clinical and subclinical toxic effects at blood levels as low as 40 to 60 μg/dl.[18-25,32,33]

It has long been known that lead has an effect on the blood-forming system at relatively low levels; this information is the basis for laboratory diagnosis of lead absorption and poisoning. In the absence of the anemia of frank poisoning, these findings are thought by some to be reversible subclinical effects of unknown significance. Others argue that these alterations reflect the "general toxicity of lead in the entire body."[14] Of perhaps more dramatic concern are reports of potentially nonreversible subclinical changes in the human nervous system and human reproduction.

There are an increasing number of disturbing reports describing nervous system changes in asymptomatic workers at "safe" levels of exposure as low as 50 μg/dl. Decreased nerve conduction velocities have been shown to be an early indicator of lead-induced neurological damage.[18,20] Subsequent research strongly suggests that changes in neurobehavioral patterns in asymptomatic lead workers may be an even more sensitive indicator of toxicity at low levels of exposure. Deficits in visual reaction time and auditory function have been reported in workers with a mean blood lead of 46 μg/dl.[20] Visual intelligence and visual motor tasks were found to be significantly affected in a group whose blood lead levels were 32 ± 11 μg/dl and had never exceeded 70 μg/dl.[21] Based on findings of decreased psychological performance test scores at low levels of lead absorption indicated by low ZPP, it has been concluded that even non-occupationally exposed groups, with environmental exposures to lead in air, food, and water, may be at risk for central nervous system dysfunction.[23] A very recent work in progress describes deteriorating neurobehavioral function in verbal concept formation, visual/motor performance, memory, and mood with increasing lead intake in workers with blood-lead levels as low as 40 to 60 μg/dl. The report concludes that central nervous system abnormalities occur well before peripheral nervous system disruption at lower blood levels (<60 μg/dl) and shorter periods of exposure (<6 months).[25]

Lead exposures at low or safe levels are also being reassessed in regard to effects on reproduction and the unborn. OSHA concluded that lead severely affects the reproductive capability of males and females; all workers planning pregnancies should keep their blood-lead levels below 30 μg/dl. Blood-lead levels apparently as low as 30 to 40 μg/dl may result in decreased fertility in men.[19] Fetal exposure is the critical issue in assessing occupational lead exposures in women because lead readily crosses the placental barrier, and lead in the umbilical cord blood correlates well with that in the blood of the mother. Given the Center for Disease Control lead poisoning limit of 30 μg/dl for children, this same limit should apply to women who are or are likely to become pregnant. Since the blood/brain barrier in the newborn is relatively immature, and central nervous system growth is very dramatic during fetal life, there is at least as much, if not more, concern for the fetus as the child.[34,35] This upper limit for women of 30 $\mu g/dl$ is also recommended by the WHO.[31].

The question of a health hazard from lead in hand soldering and pot tinning environments appear to be moot. The literature suggests that there is little, if any, exposure to airborne lead because of the low temperatures involved.[1,5,6,36,37] The possibility of lead ingestion is briefly mentioned,[1,5,6,9,16,37] but the potential hazard has neither been explored nor quantified. One factor contributing to this dearth of attention may be methodological difficulties. More likely is the notion that the necessity to avoid ingestion is axiomatic; the means are obvious and easy.

In the production soldering environment, the rationale for good hygiene may be accepted by employees without quantitative justification. The prohibition of eating, drinking, smoking, and cosmetics applications and the use of gloves and handwashing are compatible with quality control; therefore, they are further reinforced. Hygiene regulations may be relatively easy to enforce despite lapses caused by subtle, inadvertent human habits. "Clean" areas for eating, drinking, and smoking are generally designated and accepted.

In the less regimented and structured milieu of a research and development facility, or even of the home hobbyist, soldering and pot tinning are performed in many types of settings. These areas may be used for other functions throughout the workday and may be the employee's only workspace. In these circumstances, hygiene regulations may seem unduly restrictive and problematic. A rationale supported by data may be very desirable.

In light of research suggesting significant toxicity, especially neurological and reproductive, at low lead levels previously considered to be safe, it was felt that a study to explore a potential lead ingestion health hazard in soldering environments was needed. Study objectives were twofold:

1. To confirm the absence of airborne lead in soldering and pot tinning environments at levels significant to constitute an inhalation hazard or source of surface contamination.

2. To determine the presence or absence of removable lead contamination on accessible surfaces in amounts significant to constitute an opportunity for a lead ingestion hazard.

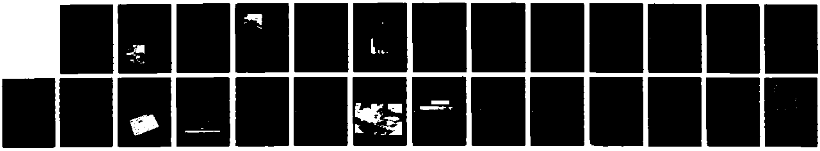
EXPERIMENTAL DESIGN

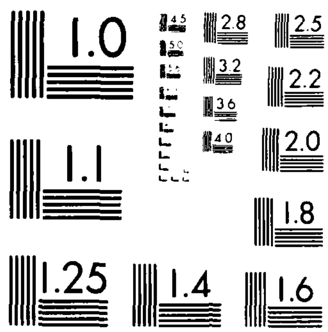
SAMPLE SELECTION

Rough estimates suggest that there are 500 to 600 separate electronics-type soldering and tinning environments, i.e., work areas for one operator, scattered throughout most operations at the Naval Weapons Center. Areas and operators were selected on the basis of interest, cooperation, and availability and were felt to represent a range of overall typical activities. A majority of the samples were collected at soldering class laboratory sessions held at the Center on an ongoing basis. The soldering laboratory is a somewhat idealized setting in which hygiene and quality control measures are strictly observed. It was felt that potential environmental

AD-A197 600 SOLDERING TECHNOLOGY PROCEEDINGS OF ANNUAL SEMINAR (8TH) HELD ON 22-23 FEBRUARY 1984(U) NAVAL WEAPONS CENTER CHINA LAKE CA FEB 84 SBI-AD-E900 566 3/3

UNCLASSIFIED F/G 13/5 NL




1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

contamination itself, however, would still be of interest and not differ significantly from less ideal settings. All soldering operations employed a temperature-controlled hand soldering iron (e.g., Thermo-Trac, Weller) set at approximately 700°F. Eutectic solder (63% tin, 37% lead) was used with mildly activated rosin (RMA) flux.

Wipe samples for the control group were taken from working surfaces in the general vicinity of the soldering area, i.e., the same large room or building, when it was determined that soldering had not and was not being performed on or near that surface. Several control samples were taken from work surfaces in various rooms of a building where soldering was never performed.

Air samples were collected during actual soldering operations. Wipe samples were taken at times when soldering may or may not have been in progress. No attempt was made to correlate air and wipe sampling. Each surface wipe sample characterizes a separate soldering environment. The air samples separately measure 13 of these environments.

AIR SAMPLING

All air samples were collected on 37 mm 0.8 μm millipore AA mixed cellulose ester membrane filters connected to a Bendix BDX 44 Super Sampler pump (Figure 1). The sampling pump was set for an airflow of 2.0 liters per minute and was calibrated before and after sampling to assure volume. All sample cassettes but one were positioned approximately 6 to 16 inches above the soldering work. It was felt that source zone samples would be less intrusive than samples placed on the operator. In addition, source zone samples should represent the "worst condition" because of their proximity to the fume generation point and their continuous exposure, even when the operator temporarily left the area. The one exception is a personal sample, collected at operator request with the sampling cassette attached to the operator's collar (Table 1).

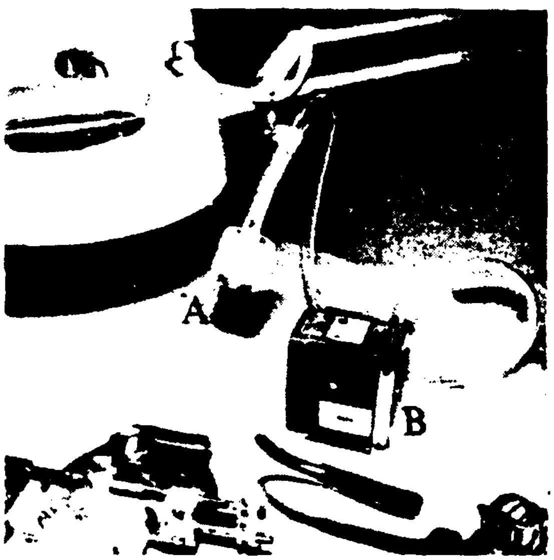


FIGURE 1. Air Sampling Train. Cassette 6 to 16 inches above soldering work (A). Pump unit (B).

TABLE 1. Air Sampling Results.

Sample no.	Pb $\mu g/m^3$	Sample no.	Pb $\mu g/m^3$
1	none detected	8	none detected
2	none detected*	9	none detected
3	none detected	10	none detected
4	none detected	11	none detected
5	none detected	12	2μg
6	none detected	13	2μg**
7	none detected		

*Personal sample.
**Pot tinning sample

Sampling time ranged from 120 to 147 minutes and sample volume ranged from 216 to 300 liters. Potential lead fume generation was not expected to be and was not constant during the period sampled since the soldering performed was transient and very sporadic. Although this is not inconsistent with the nature of hand soldering in electronics applications, it might be expected that more actual soldering might have occurred during the sampling period in a production environment. Whether or not potential constant or average fume levels could increase is debatable, but unlikely, because of the temperatures involved. The time period sampled represented the minimum required by the analytical method and included or exceeded the solderer's actual soldering exposure for that day. Residual fume in the air after soldering had ceased might be expected to be included in a number of samples. In those cases where the operator's soldering activity for the day exceeded the period sampled, it was not expected that potential exposure during the unsampled periods would differ significantly. The tinning pot sampled is an exception, in that any fume generation would be expected to be relatively constant.

Mechanical ventilation was not employed in any soldering or pot tinning environment sampled. Natural ventilation often included airflow from air conditioning systems and was felt to be good.

All samples were analyzed by atomic absorption spectrophotometry with a limit of detection of 1 μg.

WIPE SAMPLING

Sampling for surface contamination was performed using essentially the OSHA wipe sampling technique.[38] It consists of wiping a 100-cm^2 surface with a 7-cm Whatman 42 filter paper moistened with water. Care was taken to minimize artifactual lead contamination and sampling error by using hospital supply sterile distilled water. The background lead in the filter paper as specified by the manufacturer was 0.2 μg/g, an amount considered to be insignificant for the study purpose. The sampler wore a fresh disposable vinyl glove for each sample. Standardization of the size of the surface area wiped was attempted using a vinyl template, cleaned prior to each use (Figure 2).

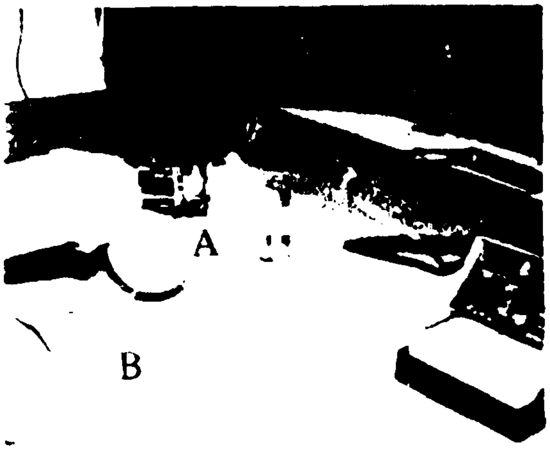


FIGURE 2. Wipe Sampling Equipment. Whatman 42 filter moistened with water (A). 100-cm^2 surface area outlined by vinyl template (B).

Wipe samples for the experimental group were taken from an area of the work table or bench directly accessible to the solderer. Types of surfaces included bare wood, Formica, Masonite, and soft vinyl mats. Control group wipes came from desk or table surfaces of "woodgrain" vinyl, Formica, or painted metal.

Samples were also taken from solderers' hands. Only in the classroom were vinyl disposable gloves worn and samples were taken from the gloved hand in these instances. Bare skin or gloved, samples were obtained by wiping the lateral and palmar surfaces of each finger from palm to tips and the palm itself. Each sample includes both the right and left hand, and the sampler attempted to perform the wiping in the same fashion for each sample.

Field blanks were submitted with each sample batch. All samples were analyzed by atomic absorption spectrophotometry with a limit of detection of 1 μg.

There is little guidance or precedence for the assessment of surface lead contamination by wipe sampling or any other methodology. Attempts to use wipe sampling in the assessment of the health hazard presented by beryllium surface contamination and resuspension[39] and radiation surface contamination[40] resulted in the conclusion that the method is strictly qualitative, i.e., may determine the presence or absence of contamination. OSHA policy[38] tends to support this conclusion by stating that wipe sampling is used to document the presence of a hazardous substance and may not support a citation, but is rather complementary to all other available evidence about a hazard and requires case-by-case professional judgement. In addition, there are no published OSHA standards or guidelines by which to evaluate results.

Wipe sampling has been used "semiquantitatively" to evaluate household lead surface dust as a source of lead exposure in children.[40,41] In the absence of standards, the findings were treated somewhat quantitatively by comparing them with findings in control samples and "before and after" samples and arbitrarily labeling the samples as "high" and "low." Both of these studies, as well as this investigation, test hypotheses with a common element—that a significant quantity of removable lead surface contamination is present to provide an *opportunity* for a lead ingestion hazard. The "opportunity" hypothesis does not require the testing precision necessary to prove actual ingestion of specific amounts of lead to correlate lead exposure with absorption and effect, or to compare results with standards. Therefore, for the purposes of this study, wipe sampling was selected as a useful, semiquantitative, exploratory technique.

In using wipe sampling to assess a possible lead ingestion health hazard, some speculation about the nature of removable lead surface contamination is warranted. Since it has been theorized that temperatures used in hand soldering are too low to generate significant lead fume, it follows that the major vehicle for lead surface contamination is likely to be direct physical transfer from solder and dross to various surfaces. The contamination is likely to consist of lead oxides and oxycarbonates readily removed during contact with solder[1,37,42,43] and dust from dross.[17] Lead in these forms, if ingested in sufficient quantity, could be expected to produce toxic effects.[1,37,44,45]

RESULTS AND DISCUSSION

In 11 of 13 air samples (Table 1) collected during separate soldering operations, lead fume was undetectable. Fume levels in the remaining two samples were considered to be insignificant against an OSHA permissible exposure limit of 50 $\mu g/m^3$. The data substantially support the first study objective, to confirm that lead fume is not generated during soldering operations in amounts significant to constitute an inhalation hazard or source of surface contamination.

Given the expected range of sample values and the estimated population, the number of experimental and control surface wipe samples (Table 2) were considered to be adequate. The experimental soldering surface results were pooled and divided into 10-μg incremental bands. The control results were treated similarly (Figure 3). It can be seen that all of the soldering wipe results are under 100 μg and 80% are under 51 μg. All of the control values are less than 11 μg.

TABLE 2. Wipe Sampling Results.

Soldering surfaces				Control		Solderers's hands	
Sample no.	Pb $\mu g/100\ cm^2$	Sample no.	Pb $\mu g/100\ cm^2$	Sample no.	Pb $\mu g/100\ cm^2$	Sample no.	Pb $\mu g/100\ cm^2$
1	0	11	13	1	none detected	1	3
2	1	12	14	2	none detected	2	3
3	2	13	17	3	none detected	3	3
4	3	14	27	4	1	4	5
5	4	15	45	5	1	5	6
6	5	16	47	6	1	6	14
7	7	17	70	7	2	7	15
8	8	18	70	8	3	8	15
9	9	19	80	9	3	9	16
10	13	20	92	10	3	10	20
						11	32

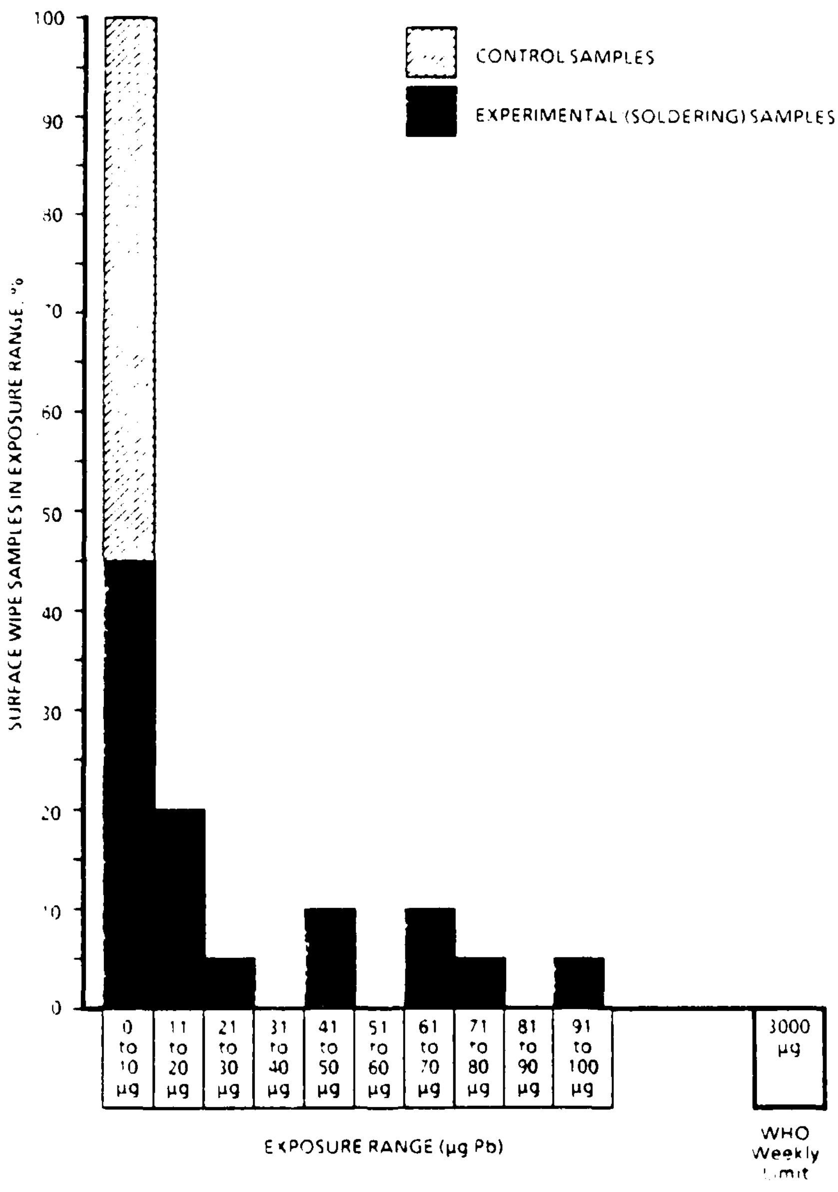


FIGURE 3. Percent of Surface Wipe Samples in Incremental Exposure Ranges.

There is a statistically significant difference between the experimental and control groups when the presence or absence of detectable lead is constructed as a binomial experiment. The null hypothesis that there is no difference between the lead surface contamination in soldering and nonsoldering environments can be rejected.

Wipe sample data from solderers' hands (Table 2) were not included in data analysis. The data are presented to highlight the lead ingestion opportunity presented by contamination on surfaces particularly accessible to the mouth.

The data do indicate measurable removable lead surface contamination in support of the second study objective of demonstrating opportunity for ingestion. In evaluating "opportunity," a number of unknowns and potentially confounding variables are encountered. The nature and quantity of the solderers' actual contact with contaminated surfaces and subsequent combinations of object hand-to-mouth activity were not assessed. This activity could be highly variable and unpredictable among individuals. In addition, the equivalency of wipe sampling in picking up lead contamination to real-world hand-object-mouth interfaces is unknown. Quantitation is further obscured in a number of ways. Intermediate objects capable of conveying lead (e.g., food, pen) could not be assessed. Surfaces and hands are treated as separate contributions. It was not possible to differentiate additive versus substitutive contributions to overall intake carried to the mouth. That is, the possibility exists that some surface contamination, by virtue of being removed from a surface, could become less available for ingestion and should be subtracted from overall potential intake possibilities!

In order to deal with this morass of variables, the assumption is made that all lead found in any single wipe sample was conceivably ingested. This assumption is felt to be a conservative overestimate appropriate to evaluating a health hazard.

Even if the amount of ingestible lead could be accurately known, assessing the data in regard to a health hazard is still very problematic. Although models[14,46] have been proposed, there is still no consensus regarding a predictive relationship between exposure to lead in air or by ingestion, and blood-lead levels. In addition, as previously discussed, blood-lead levels are controversial as an index of exposure versus actual toxic effect or response to exposure.

WHO[47] addressed a number of these variables in establishing a provisional maximal or tolerable overall weekly lead intake for an adult. It is believed that this concept of total lead intake provides the most useful and valid framework for interpretation of study findings in regard to a potential health hazard. The WHO recommended ceiling of 3 mg (3000 μg) per week takes into account the cumulative nature of lead poisoning. It presupposes that lead inhaled from the atmosphere will reduce the amount tolerable in food and water. Although in non-industrially exposed populations, lead in air contributes a much less significant fraction to the total than does food and water (200 to 300 μg/day). In highly urbanized polluted areas, intake of lead by inhalation may contribute as much as 100 μg/day.

It can be seen from simple calculations (Table 3), that after the "normal" weekly intake from air, food, and water is totaled, there exists a leeway of 200 to 900 μg. Thus, 200 to 900 μg of lead per week could be contributed from soldering before tolerable values were exceeded. Assuming that the solderer ingests a full wipe sample value (Table 2) on each of 5 days per week, it can be shown that acceptable intake levels could be marginally exceeded. Using a mathematical model,[46] ingestion of 20 to 30 μg of lead per day (mean wipe sample

TABLE 3. Calculation of Maximum Acceptable Lead Intake According to WHO Recommended Limit.

Source of Pb contribution	Total intake (μg)	
	Daily	Weekly
Food and water	200-300	1400-2100
Community air	100	700
	300-400	2100-2800
WHO recommended limit (5-day work week)	440-480	3000
Allowable contributions from all other sources including soldering (5-day work week)	40-180	200-900

value—Table 2) added to "normal" daily intake of 200 to 400 μg, could result in a blood lead level of 23 to 45 $\mu g/dl$. As previously stated, subclinical toxic effects of lead have been demonstrated at blood lead levels as low as 40 to 60 $\mu g/dl$, and 30 $\mu g/dl$ is the recommended limit for men and women of childbearing age. It should be emphasized that these calculations assume no other industrial lead exposures. They do not account for the presumably significant amount of lead that could be ingested during the practice, observed during the study, of holding solder wire in the mouth, using the mouth as a "third hand." The totals do not include the not uncommon off work lead exposures such as hobby soldering, spray painting, shot pouring, use of lead pigments in painting and ceramics, indoor target practice, etc. In the Naval Weapons Center rural desert environment, the figures probably overstate lead intake from community air pollution.

Given a magnitude in micrograms and relatively narrow tolerances, this delicate balance between lead absorption and poisoning could easily be upset by any exposures other than the "usual" in food, water, and air. It should also be noted that the WHO recommendation was made prior to most of the research on subclinical toxicity of lead at low levels of exposure and could be conceivably reduced even further in the future.

CONCLUSIONS

1. No significant inhalation hazard from lead fume exists in soldering and pot tinning environments. In addition, lead fume is not a significant source of surface contamination. The practical implications are that mechanical exhaust ventilation and physical isolation of soldering areas are not essential to prevent a lead hazard. (Irritating and/or toxic decomposition products of flux may require ventilation, however.) Lead contamination may be spread to adjacent areas by accumulation of dross dust and/or solderers' contaminated hands.

2. A low-order lead ingestion hazard exists in nonproduction soldering environments. This hazard may easily be substantially increased by such common practices as placing solder wire in the mouth, using the mouth as a "third hand." The hazard may also be increased by lead exposures outside of soldering, which may not be uncommon.

3. Reasonable hygiene measures in areas where soldering is performed are justified. Handwashing prior to eating, drinking, smoking, and cosmetics applications should be the cornerstone. Other worthwhile measures include the avoidance of food or cigarette placement on bare working surfaces, and routine wet cleanup of working surfaces after soldering.

ACKNOWLEDGMENTS

Thanks are extended to Jim Raby for his interest in the health of solderers, Linda Roush for statistical assistance, and Alice M. Parker for encouragement and material support.

REFERENCES

1. Manko, H. H.: *Solders and Soldering*. McGraw-Hill, New York, NY (1979).

2. Elkins, H. B.: *Chemistry of Industrial Toxicology*. John Wiley & Sons, Inc., New York, NY (1950).

3. Stokinger, H. E.: The Metals. In *Patty's Industrial Hygiene and Toxicology, Vol. 2A: Toxicology*, 3rd Revised Ed., G. Clayton and F. Clayton, Eds., pp. 1687-1782. John Wiley & Sons, Inc., New York, NY (1981).

4. World Health Organization: *Environmental Health Criteria 3: Lead*. Geneva (1977).

5. Lead Industries Association, Inc.: *Safety in Soldering: Health Guidelines for Solderers and Soldering*. New York, NY (1982).

6. McCullough, E. C. and D. H. Senjem: Airborne Concentrations of Toxic Metals Resulting from the Use of Low Melting Point Lead Alloys to Construct Radiotherapy Shielding. *Medical Physics*. 8:111-114 (1981).

7. O'Connor, B. M. and G. Christakis: *Ten Guides: Development of Occupational Disease Guides*, pp. 50-65. NTIS No. 80-194-053. NIOSH, Cincinnati, OH (1978).

8. Key, M. M. et al, Eds.: *Occupational Diseases: A Guide to their Recognition*, Revised Ed., pp. 361-363. DHEW (NIOSH) Publication No. 77-181, Cincinnati, OH (1977).

9. National Institute for Occupational Safety and Health: Health Hazard Evaluation Determination Report HE 79-148-716. DHHS (NIOSH), Cincinnati, OH (1980).

10. National Institute for Occupational Safety and Health: Industrial Hygiene Survey of the General Electric Company. NTIS No. 83-13-722-4. Cincinnati, OH (1978).

11. National Institute for Occupational Safety and Health: Health Hazard Evaluation/Toxicity Determination Report 73-180/183-159. DHEW (NIOSH), Cincinnati, OH (1974).

12. National Institute for Occupational Safety and Health: Health Hazard Evaluation/Toxicity Determination Report 76-105-368. DHEW (NIOSH), Cincinnati, OH (1977).

13. U.S. Department of Labor: Occupational Exposure to Lead: Final Standard (1910.25). *Federal Register*, V 43, N 220, pp. 52952-53014 (November 14, 1978).

14. U.S. Department of Labor: Occupational Exposure to Lead: Attachments to the Preamble for the Final Standard. *Federal Register*, V 43, N 225, pp. 54354-54509 (November 21, 1978).

15. D. B. Associates, Inc.: Technical Feasibility, Costs of Compliance and Economic Impact Assessment of the Proposed Standard for Lead for Selected Industries. USDOL (OSHA), Washington, D.C. (1977).

16. Barrett, C. D. and H. D. Belk: Blood Lead Study of Long Term Hand Soldering Operators. *JOM*. 19:791-794 (1977).

17. Burgess, W. A.: *Recognition of Health Hazards in Industry*. John Wiley & Sons, Inc., New York, NY (1981).

18. Seppäläinen, A. M. et al: Subclinical Neuropathy at "Safe" Levels of Exposure. *Arch Environ Hlth*. 30:180-183 (1975).

19. Lancrajan, I. et al: Reproductive Ability of Workmen Occupationally Exposed to Lead. *Arch Environ Hlth*. 30:396-401 (1975).

20. Repko, J. D.: The Effects of Inorganic Lead on Behavioral and Neurologic Function. DHEW (NIOSH) Publication No. 78-128, Cincinnati, OH (1978).

21. Haenninen, H. et al: Psychological Performance of Subjects with Low Exposure to Lead. *JOM*. 20:683-689 (1978).

22. Fischbein, A. et al: Health Status of Cable Splicers with Low Exposures to Lead: Results of a Clinical Survey. *AJPH*. 70:697-700 (1980).

23. Valciukas, J. A. et al: Lead Exposure and Behavioral Changes: Comparisons of Four Occupational Groups with Different Levels of Lead Absorption. *Am J Ind Med*. 1:421-426 (1980).

24. Feldman, R. G., N. L. Ricks and E. L. Baker: Neuropsychological Effects of Industrial Toxins: A Review. *Am J Ind Med*. 1:211-227 (1980).

25. Baker, E. L. et al: Occupational Lead Neurotoxicity—A Behavioral and Electrophysiologic Evaluation: 1) Study Design and Year One Results. *Brit J Ind Med.* In press.

26. Zielhuis, R. L.: Second International Workshop Permissible Levels for Occupational Exposure to Inorganic Lead. *Int Arch Occup Environ Hlth.* 39:59-72 (1977).

27. Lauwerys, R. R.: *Industrial Chemical Exposure: Guidelines for Biological Monitoring.* Biomedical Publications, Davis, California (1983).

28. Joselow, M. M. and J. Flores: Application of the Zinc Protoporphyrin (ZP) Test as a Monitor of Occupational Exposure to Lead. *Am Ind Hygiene J.* 38:63-66 (1977).

29. Mahaffey, K. R.: National Estimates of Blood Lead Levels: United States, 1976-1980. *New Engl J Med.* 307:573-579 (1982).

30. Waldron, H. A.: The Blood Lead Threshold. *Arch Environ Hlth.* 29:271-273 (1974).

31. World Health Organization: Report of a Study Group: Recommended Health Based Limits in Occupational Exposure to Heavy Metals. Technical Report Series No. 647. Geneva (1980).

32. Baker, E. L. et al: Occupational Lead Poisoning in the United States: Chemical and Biochemical Findings Related to Blood Levels. *Brit J Ind Med.* 36:314-322 (1979).

33. National Academy of Science: *Lead in the Human Environment.* Washington, D.C. (1980).

34. Bridbord, K.: Occupational Lead Exposure and Women. *Preventive Medicine.* 7:311-312 (1978).

35. Roels, H. A. et al: Invesitgation of Factors Influencing Exposure and Response to Lead, Mercury and Cadmium in Man and in Animals. *Env Hlth Perspectives.* 25:91-96 (1978).

36. Sittig, M.: *Handbook of Toxic and Hazardous Chemicals.* Noyes Publications, Park Ridge, NJ (1981).

37. Thwaites, C. J.: *Capillary Joining—Brazing and Soft-Soldering.* Research Studies Press, A Division of John Wiley & Sons, Ltd., Chichester, U.K. (1982).

38. U.S. Department of Labor (OSHA): *Industrial Hygiene Field Manual.* 77:8006, 8171-8172. Bureau of National Affairs, Washington, D.C. (1981).

39. Cohen, J. J. and R. N. Kusian: Significance of Beryllium Surface Contamination to Health. In *Surface Contamination*, Proceedings of a Symposium at Oak Ridge, Tennessee, June, 1964, pp. 345-348. Pergamon Press, New York, NY (1966).

40. Sayre, J. W. et al: House and Hand Dust as a Potential Source of Childhood Lead Exposure. *Am J Dis Child.* 27:167-170 (1974).

41. Sayre, J. W. and M. D. Katzel: Household Surface Dust: Its Accumulation in Vacant Homes. *Env Hlth Perspectives*. 29:179-182 (1979).

42. Browning, E.: *Toxicity of Industrial Metals*, 2nd Ed. Butterworth's, London (1969).

43. Lingane, J. J.: *Analytical Chemistry of Selected Metallic Elements*. Reinhold Publishing Corporation, New York, NY (1962).

44. Manton, W. I. and C. R. Malloy: Distribution of Lead in Body Fluids After Ingestion of Soft Solder. *Brit J Ind Med*. 40:51-57 (1983).

45. Walker, R. and R. Oliphant: Contamination of Potable Water From Lead-Based Solder. *Anti-Corrosion*. Pp. 13-15 (1982).

46. Dollimore, J. and M. H. Jagasia: The Toxicity of Ingested Lead—A Mathematical Theory. *Int Env and Safety*. Pp. 38-39 (August, 1982).

47. World Health Organization: Evaluation of Certain Food Additives and the Contaminants Mercury, Lead and Cadmium. Technical Report Series No. 505, FAO Nutrition Meetings Report Series No. 51. Geneva (1972).

Addendum to

Proceedings of

8th ANNUAL

SOLDERING TECHNOLOGY

ELECTRONICS MANUFACTURING

SUPPORT OFFICE

SEMINAR

22, 23 February 1984

ABSTRACT

"Soldering Systems for Surface Mounting"

Donald J. Spigarelli

The soldering technique to be used for surface mounting may be non-subjectively determined by understanding the specific type of surface mounting to be performed.

This paper will review a proposed specification of surface mounting; Type I - Total surface mounting, Type II - Mixed Technology, Type III - Underside attachment.

Mass soldering technology applicable to each surface mounting type will be discussed. Further, potential new developments in single systems for Type II soldering will be discussed.

INCREASING SOLDER JOINT RELIABILITY OF
LEADED SURFACE MOUNTED COMPONENTS

BY

JAMES H. DIERKE
GOVERNMENT SYSTEMS MANUFACTURING
CONTROL DATA CORPORATION
MINNEAPOLIS, MINNESOTA

INTRODUCTION

The increased demand for high density packaging has created an equal emphasis for increased solder joint reliability. Repairing a single solder joint is not a big problem, but in a system with 40,000 solder joints, solder joint reliability becomes a critical issue.

This article briefly discusses the steps taken by Control Data's Government Systems Manufacturing Division to increase their Solder Joint reliability of leaded surface mounted components used in the building of the AN/AYK-14 (V) airborne computer

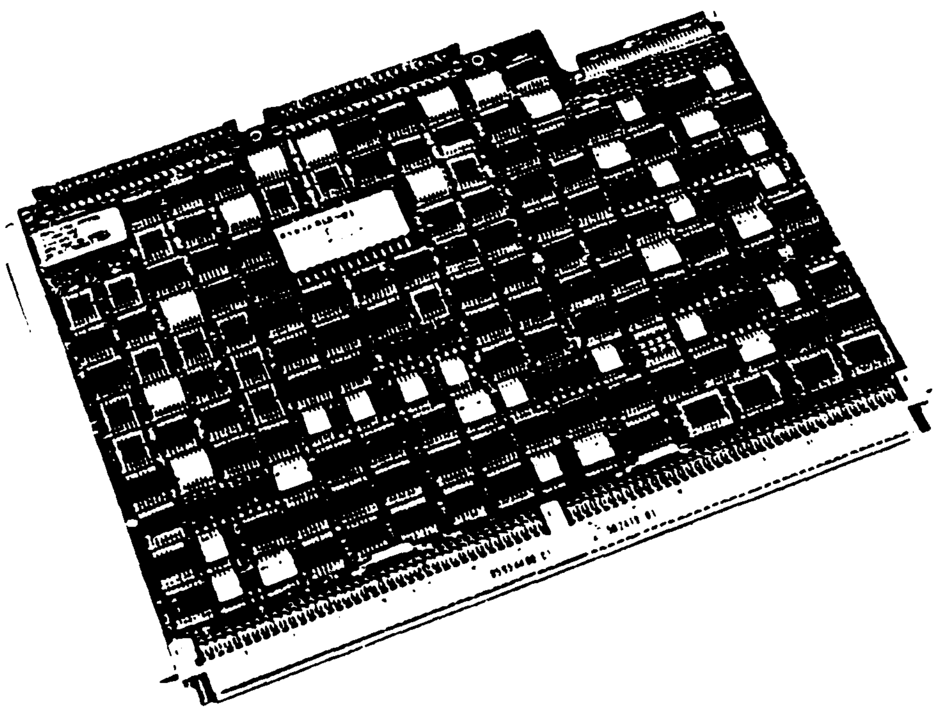


FIGURE 1
HIGH DENSITY AN/AYK-14 MODULE

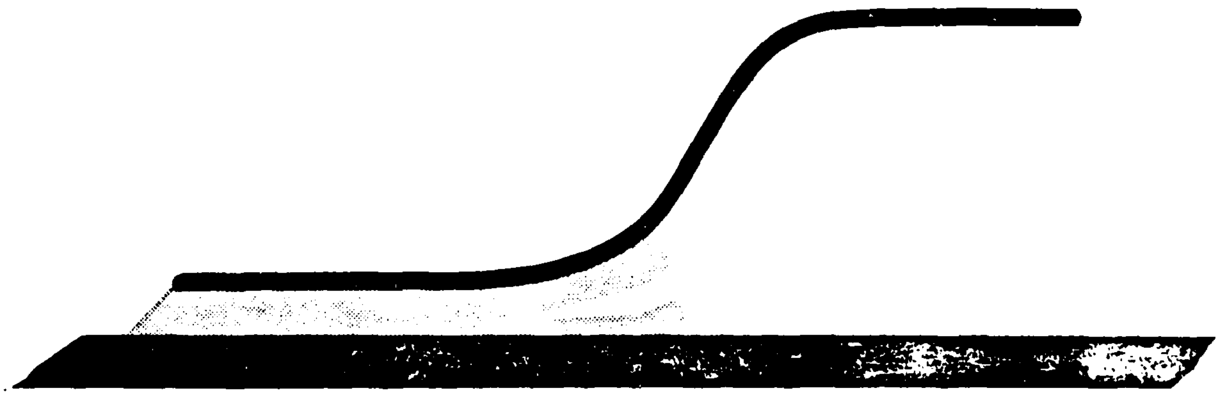
BACKGROUND - Cracked Solder Joints

When we began initial production of the AN/AYK-14 (V) computer we encountered an unacceptable rate of cracked or broken solder joints on the integrated circuits (ICs). Like most manufacturing problems, our high rate of cracked solder joints was due to a number of factors and required a series of step-by-step solutions, some which are still being implemented. Part of the problem was caused by the design itself. With the need to get the most functions in the least amount of space, all printed wiring boards (PWBs) were designed for maximum density. Since the AN/AYK-14 (V) is a military computer, high reliability is a requirement and the computer has to withstand extensive temperature (-55^{o}C to +125^{o}C), vibration, and environmental testing.

As part of the environmental testing, all assembled PWBs are subjected to a high temperature burn-in, with power-on, before going to electrical test. This is a common practice to "weed-out" any weak components. We didn't find many bad components, but did detect cracked and broken IC solder joints. The cracked solder joints would electrically test good, only to fail during vibration or thermal cycling later on.

Normally it's a fairly simple matter to resolder a cracked or broken solder joint, but these are high density PWBs, with 3000 to 5000 solder joint connections per PWB, with eight PWBs per computer system; or about 40,000 solder joints per system. As might be expected, the initial mean-time-between-failures was very low!

THE "PROBLEM"



CRACKED SOLDER JOINT

FIGURE 2

PROBLEM INDENTIFICATION

A complete study of the problem was made to determine where the cracked solder joints were first appearing in the production cycle and what could be done to improve the Solder Joint strength and thereby increase reliability.

The study showed that nearly 95 percent of the cracked solder joints appeared on IC leads, with only a small amount occurring on discrete components and connectors. The cracked solder joints first appeared after machine reflow soldering and increased in number as additional testing, such as high temperature burn-in, vibration, and temperature cycling, was performed. Once the cracked solder joints had been resoldered, by hand, no additional cracking normally occured. It was also discovered that the first prototype systems, which had been hand soldered, had no problem with cracked solder joints. Thus, our problem appeared to be caused during the mechanical reflow soldering process. How could this be? We were using the same machines to solder other types of PWBs, with no problem. What was different about these PWBs?

A CLOSER LOOK

An in-depth study showed that the AN/AYK-14 (V) system was very different from previous systems. Due to the high density packaging requirements of the AN/AYK-14 (V), the ICs were being formed with smaller feet, different tooling, and smaller pad design. Also, this system had to meet larger temperature and vibration ranges.

We focussed our attention on the basic IC joint design and on determining the factors that could affect the solder joint strength. Since the components are surface mounted, all forces are transmitted directly to the solder joint itself. Looking at the cracked solder joint, it was concluded that failures were occurring between the component lead and solder joint. This was a very important conclusion since it showed that the problem was with the solder joint and not the PWB.

CAUSES OF SOLDER JOINT FAILURES

The forces that a solder joint must withstand can be broken down into two broad categories: mechanical and thermal. Vibration testing falls into the mechanical category and burn-in into the thermal category. From the type of failures we were seeing, we knew that both types of forces were causing problems and that the solder joint had to be strong enough to sustain both. Generally, with systems that run at high temperature, the thermal forces are greater than the mechanical forces.

Since the problem with cracked solder joints only occurred with the machine soldered PWBs, and the pad, lead, and PWB material designs were correct and met Mil-Spec requirements, it was assumed that the cause of the problem was associated with the manufacturing process.

FIRST THINGS FIRST

The failed joints were carefully studied to determine if some cause of the failure could be detected visually. In many cases it was found that the lead was not placed on the pad correctly and that some part of the lead was actually off the pad. This condition weakens the joint strength because there is less contact area. This was a workmanship and tooling problem. With our old tooling the IC's were placed on the forming die by hand and visually aligned by the operator. If the IC's were not aligned parallel with the forming die they were formed skewed which meant that some leads were too long and wouldn't completely fit on the pad. The operators were instructed to make sure that the leads were parallel to the die before forming, but this was very difficult to control. New tooling was needed.

CLEAN, CLEAN, CLEAN

In soldering surface mounted components, the only mechanical strength is the solder joint itself. To make a good solder connection, the components being soldered must be cleaned of all oxides and have good solderability. To ensure good solderability, all IC leads are solder tinned before assembly. Our PWBs have .00075 to .001 inch tin-lead plating, which has been fused for better solderability. Even though our PWBs are washed in distilled water after coming from storage and then vapor degreased just before assembly, we still had a solderability problem.

Further visual inspection of the failed solder joints showed poor solder wetting, caused by excess oxides. This problem was corrected by using a more active flux. Type RA is the strongest flux allowed by Mil-Spec and use of this flux requires that you test the PWBs after cleaning, to be sure that all of the flux has been removed.

Switching to this more active flux reduced our cracked solder joint problem by about 25 percent. This was a good start, but we had a long way to go.

CRACKED SOLDER JOINTS BEFORE BURN-IN

As we got deeper into the cracked solder joint problem a strange phenomenon was observed. Many of our solder joints were cracking while they were sitting on the shelf waiting to go into burn-in. The only temperature the PWB assemblies had been exposed to was room temperature! We had to be doing something to the IC leads during our soldering operation that was placing a high mechanical stress on the solder joints--a stress that was great enough to crack, and even break, the joints.

Our mechanical relfow soldering process consisted of two U-shaped bars that came down onto the IC leads and forced them into contact with the PWB. The bars were energized until the solder was melted and reflowed. The bars were then de-energized and, with the bars still holding the IC leads in contact with the PWB, the solder joint was cooled.

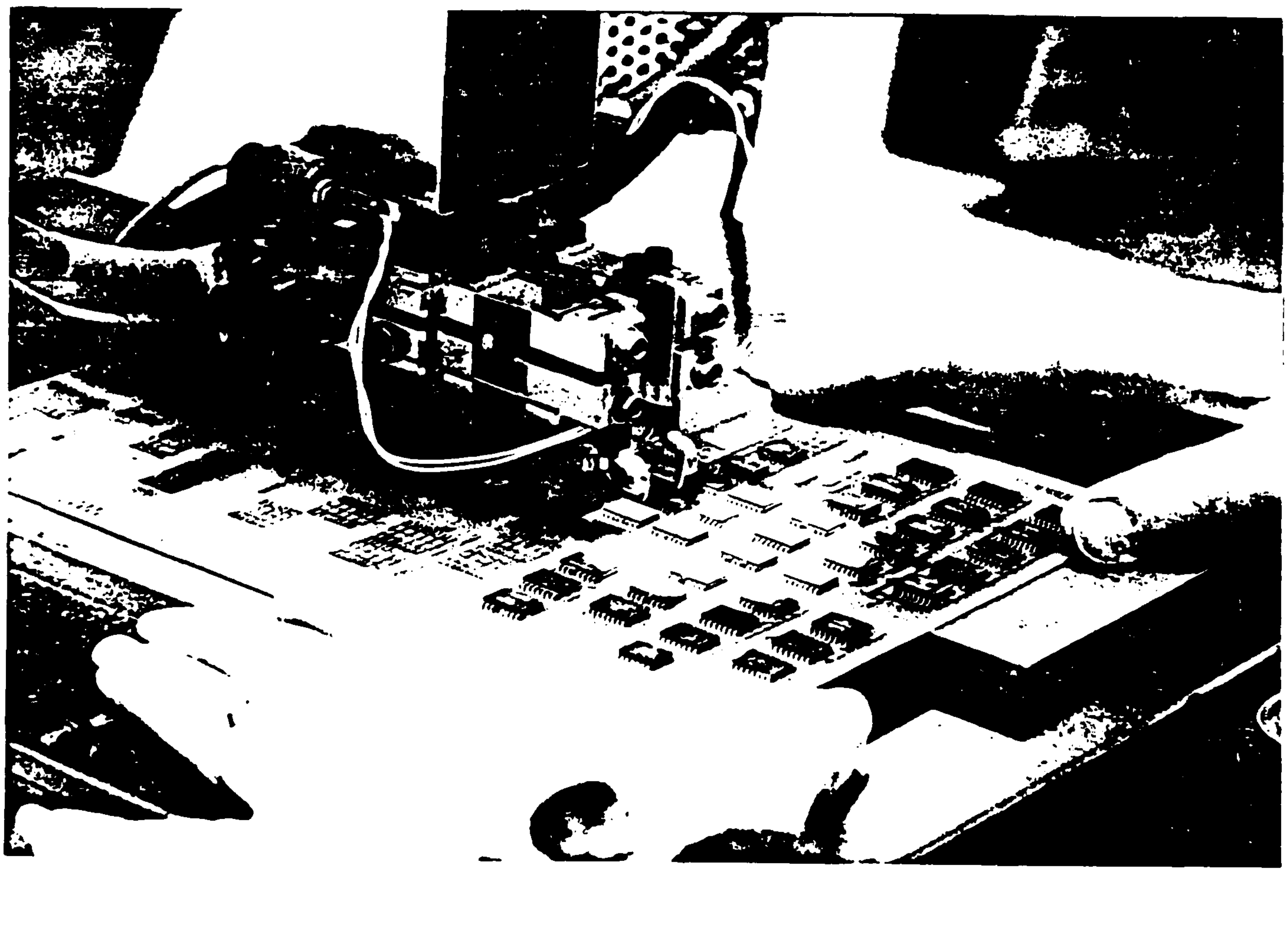


FIGURE 3
MECHANICAL REFLOW SOLDER MACHINE

Examination of the formed IC leads showed that the foot on the .006 inch thick IC lead was not being formed parallel to the soldering surface, but actually had a "toe down" condition.

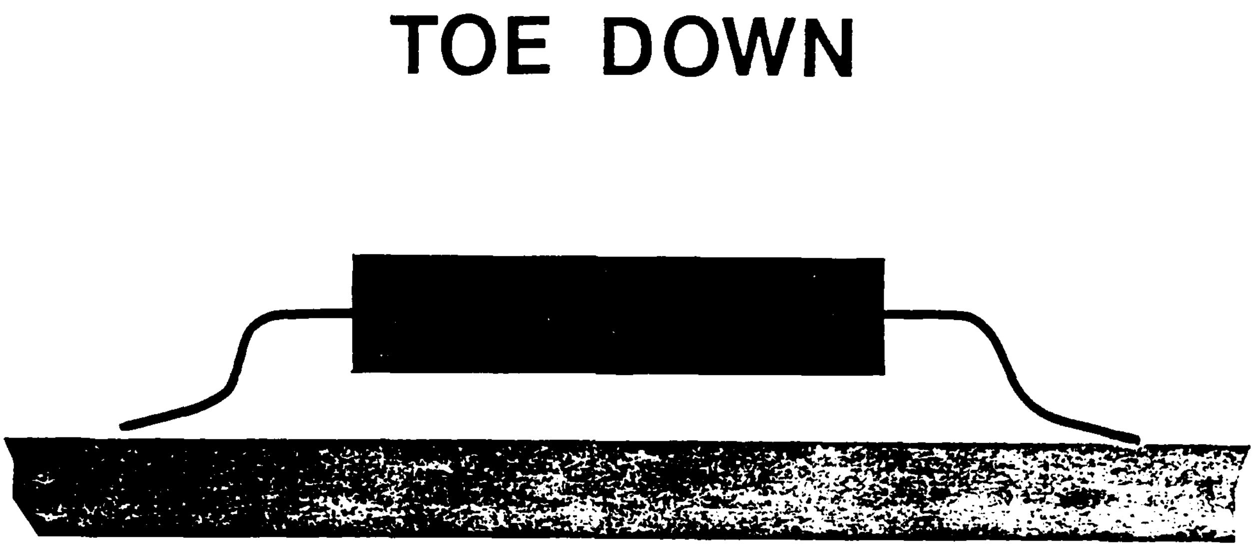


FIGURE 4
IC LEADS FORMED IN TOE-DOWN POSITION

Calculations showed that with a "toe down" condition of .003 inch or more, a force great enough to fracture the Solder Joint was created during the soldering operation. During the soldering operation the heater bars forced the IC leads flush to the PWB. If the leads were not properly formed, the effect of the resulting pressure was similar to trying to solder a compressed spring. This condition does not exist with hand soldering, where the IC lead is not forceably held in place during cooling.

This residual mechanical stress problem and the skew problem discussed earlier were both corrected with new IC forming tooling. Things were beginning to look better, the number of cracked Solder Joints had been reduced by 50 percent. The IC's were being placed on the pad properly, without skew, and the solder joints weren't cracking at room temperature. But we were still cracking solder joints during burn-in.

HIGH TEMPERATURE BURN-IN

Burn-in is used to remove weak components before testing. During the burn-in process, which is run at 230°F for 40 hours, the modules undergo higher thermal stresses than in normal operating conditions. These stresses are high enough to cause cracked solder joints.

HIGH TEMPERATURE BURN-IN CONT.

It isn't really clear exactly what happens when solder goes through thermal cycling (see "Development of Highly Reliable Soldered Joints for Printed Circuit Boards," Westinghouse Defense and Space Center August 1968) but if you have cracked Solder Joints after burn-in you can be sure that the thermal stresses were greater than the strength of the solder joint and you either have to reduce your burn-in temperature or increase your solder joint strength.

JOINT DESIGN FOR THERMAL STRENGTH

The actual forces generated by thermal expansion can be calculated. Our calculations showed that, with an IC lead width of .017" we must have an IC foot length of at least .046" to compensate for the thermal force.[1] The design was fixed at .035" and would have been very costly to change. We had to change the effective foot length without changing the actual length. Therefore, we increased the amount of solder in the joint area and modified our criterion for "excess solder" to a criterion termed "preferred solder". Of course, the amount was necessarily controlled such that the "excess" did not result in bridges and shorts.

INCREASING FOOT LENGTH

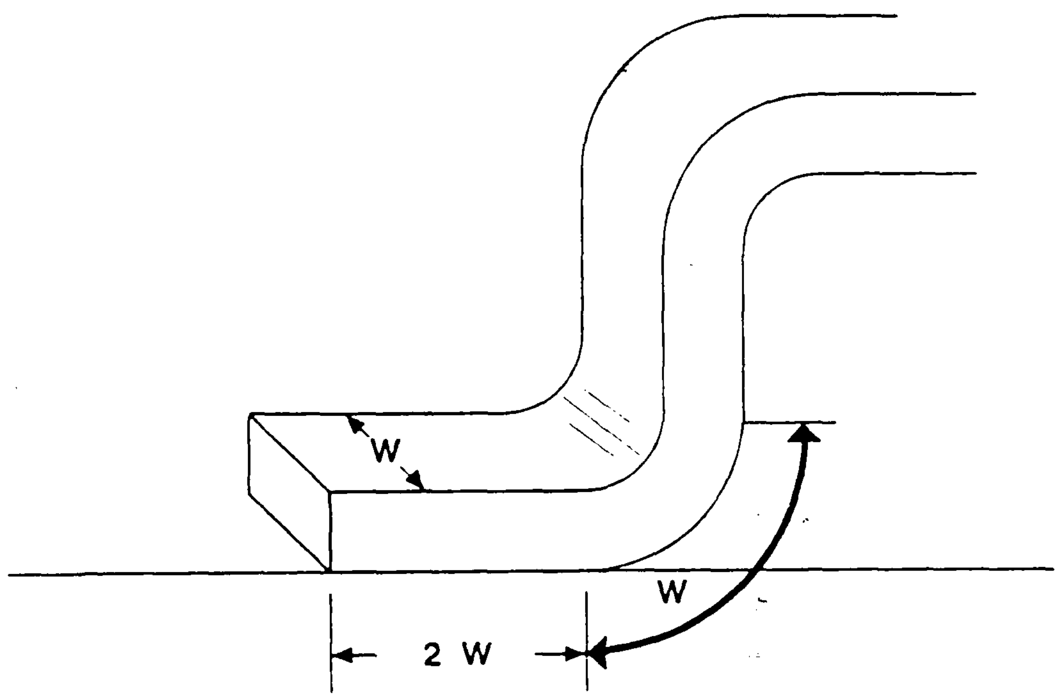


FIGURE 5
HOW TO INCREASE FOOT LENGTH

RESULTS

Careful attention to the forming operation, strict control of material solderability and increased solder in the joint area combined to solve the cracking problem. Over 40,000 solder joints were inspected before and after burn-in, vibration, and thermal cycling, without one cracked solder joint. At the present time we make 800,000 solder joints per month and average less than one solder joint failure. That's high reliability soldering!

[1] Calaculations are shown at the end of this paper.

CONCLUSION

In conclusion, let's briefly review the requirements and recommendations for eliminating solder joint cracking of surface mounted components.

1. Identify the problem - what components and where in the manufacturing process.

2. Eliminate misformed components due to workmanship, handling or poor tooling.

3. For good solderability, clean and pre-tin surfaces of components to be soldered .

4. Check high temperature - make certain that all manufacturing processes, baking, coating and etc., do not exceed design limits for the solder joint.

5. Make one change at a time - then check your result. Many processes are interrelated and making a change to one process may effect several others.

6. Establish written history of what corrective actions were taken and the results - don't try to remember - write it down!

7. Carefully control workmanship - a lead only half soldered onto a pad won't be reliable.

8. Don't solder-in mechanical stress - be sure that leads are formed so that they can be soldered into position without having to be forced during soldering.

9. Design for thermal strength - make sure that the component leads and PWB pads are designed for the thermal stresses found in manufacturing processes, even if the product isn't operated in a high temperatures environment.

10. Carefully control your manufacturing process - make sure that the process is being rigidly followed.

FORCES GENERATED BY THERMO EXPANSION

α_S = Linear coefficient of thermal expansion for 63/37 solder = 13.7×10^{-6} in./in./$^{\circ}$F

α_K = Linear coefficient of thermal expansion for Kovar IC leads = 5.33×10^{-6} in./in./$^{\circ}$F

ΔT = Change in temperature of solder joint between burn-in and room temperatures ($^{\circ}$F) $\Delta T = T_B - T_R$

E = Modulus of elasticity of solder = 31×10^{6} lb/in^2

T_R = Temperature of room - 70°F

T_B = Temperature of burn-in - 230°F

$\gamma_S = (\alpha_S - \alpha_K)\Delta T$ in./in. = Solder strain

$$\Delta T = T_B - T_R$$

$$= 230 - 70$$

$$= 160^{\circ}F$$

$$\gamma_S = (\alpha_S - \alpha_K)\Delta T$$

$$= (13.7 - 5.33)\, 10^{-6} \times 160$$

$$= (8.37 \times 10^{-6})\, 160$$

$$= 1339.2 \times 10^{-6} \text{ in./in.}$$

$\sigma_S = \gamma_S \times E$ = Stress in Solder Joint

$$= 1339.2 \times 10^{-6} \text{ in./in.} \times 31 \times 10^{6} \text{ 16/in}^2$$

$$= 41{,}515 \text{ lb/in}^2$$

This load, or force, must be spread overthe cross sectional area of the joint. Using an IC lead thickness "t" of .006" and a lead width "W" of .017", the thermal force is:

$F = \sigma_s \times A$

$= \sigma_s \times t \times W$

$= 41{,}515\ lb/in^2 \times .006\ in. \times .017\ in.$

$= 4.23\ lb$ (thermal force)

The termal force is a shear loading of the solder joint and is carried by the soldered area; therefore, to find the required lead length to support the force:

$F = 4.23\ lb$ (thermal force)

$A = W \times L$ (shear area)

$W = .017\ in.$ (IC width)

L = IC Foot Length (inches)

$\sigma_s = 5400\ lb/in^2$ (shear strength of 63/37 solder)

$A = F/\sigma_s$

$= 4.23\ lb/5400\ lb/in^2$

$= .000784\ in^2$

$L = A/W$

$= .000784/.017$

$= .046$ in. foot length