INTERCONNECTION TECHNOLOGY

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INTERCONNECTION TECHNOLOGY

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Prepared by W. P. Beck, D/842, under PDO 6984696

Internal, electrical, subassembly techniques were developed to improve interconnections. In these studies, solderability was determined for thin-film metallization systems. There was a cost comparison of welding and soldering flatpacks. Assembly times of Ampere sockets were compared to assembly times of bifurcated terminals. Multiple-leads were reflow soldered to printed circuit boards. Multiple-leads were thermocompression bonded to thin-film substrates, and packaging concepts for hybrid microcircuits and other related feasibility studies were part of the work performed during 1969-1972.

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CONTENTS

Section	Page
SUMMARY	6
DISCUSSION.	10
SCOPE AND PURPOSE	10
ACTIVITY.	11
<u>Welding Versus Soldering.</u>	11
<u>Thin-Film Solderability</u>	16
<u>HMC Interconnection Lead Bonding.</u>	21
<u>Ampere Sockets Opposed to Bifurcated Terminals.</u>	39
<u>Interconnecting Stacked Substrates.</u>	39
<u>Flexible Circuit Application Study.</u>	42
<u>Multiple-Lead Reflow Soldering.</u>	46
ACCOMPLISHMENTS	52
REFERENCES.	53
APPENDICES	
A. EQUIPMENT COSTS	54
B. FABRICATION COST LIST	55
DISTRIBUTION.	58

ILLUSTRATIONS

Figure		Page
1	Standard Hours Fabrication Versus Board Size . .	17
2	Standard Hours Attachment Versus Number of Integrated Circuits Attached	18
3	Standard Hours Board and Integrated Circuit Attachment Versus Integrated Circuit Attachment and Board Size.	19
4	Lead Frame Schedule.	25
5	Thin-Film Thermocouple Calibration	26
6	Thermocouple Calibration	27
7	Bond Time and Force Calibration.	28
8	Lead Frame Calibration	30
9	Bond Wedge and Head Temperature Measurement. . .	31
10	Bonding Head Temperature	32
11	Interface Temperature Versus Time (5-Mil). . . .	33
12	Interface Temperature Versus Time (10-Mil) . . .	34
13	Lead Pull Test Failure Modes	35
14	Lead Frame Bond Envelope	36
15	Lead Strength Versus Deformation Lead Frame Soldering.	37
16	Lead Flexure Test Results.	38
17	Fatigue Testing of 5- by 5-Mil Lead Frames . . .	39
18	Longitudinal Deformation to Decrease Stress at Edge of Bond Zone.	40
19	Ampere Socket Method	41
20	Bifurcated Terminal Method	42
21	Assembly Sequence, First Step.	43

22	Assembly Sequence, Second Step.	44
23	Assembly Sequence, Third Step	45
24	Assembly Sequence, Fourth Step.	46
25	Seven Probe Tool.	48
26	Staggered PCB Lands	49
27	Temperature Versus Distance Along Electrode . .	50
28	Center Electrode Temperature Versus Current . .	51

TABLES

Number		Page
1	Attachment Times.	13
2	Printed Circuit Board Fabrication Times and Scrap Rates	14
3	Average Time and Scrap Rates for Printed Circuit Board Fabrication From November 1969 to February 1971	15
4	Solder and Weld Defect Information.	16
5	Solderability Spread Factors.	20
6	Solderability Results	22

SUMMARY

The project was conducted to develop interconnection techniques for application to present and future electronic assemblies - especially those using hybrid microcircuits (HMCs). Project work included:

- Determination of the relative costs of welding opposed to the soldering of HMC packages;
- Evaluation of the solderability of thin films including definition of solderability tests;
- Establishment of a thermocompression (TC) bonding schedule to attach gold plated copper leads to thin film gold conductors;
- Determination of relative assembly times for Ampere sockets and bifurcated terminals to interconnect ceramic substrates;
- Determination of a means of interconnecting stacked, open-faced substrates within tight packaging restraints and demonstrating its feasibility by fabricating a model;
- Evaluation of a flexible circuit to replace a problem printed circuit board for enhancement of visual inspection of solder joints; and
- Development of a process to reflow solder, in a single operation, all or half of the ribbon leads from an integrated circuit (IC) or HMC package to a printed circuit board (PCB).

There is no significant cost difference between parallel-gap welding and reflow soldering when both the costs of IC attachment and PCB fabrication are considered. Nickel clad boards required for parallel-gap welding are approximately twice as expensive as the copper-clad boards used for reflow soldering. The visual defect rate of solder joints is higher than the defect rate for weld joints, while the equipment costs for welding are higher than those for soldering equipment.

A lead frame evaluation comparing two copper alloys, CDA194 and CDA725, for suitability to both reflow soldering and parallel-gap welding was partially funded by this project. The evaluation has been completed and a separate report, BDX-613-501, has been published. Stamped lead-frame material of copper alloy CDA194, 0.005- or 0.007-inch (130 to 180 μm) thick and plated with 50 to 100 microinches (1.27 to 2.54 μm) of nickel and 100 to 150 microinches (2.54 to 3.81 μm) of gold evolved as best suited to the two

attachment methods. Material makeup was most critical to the welding operation. An important result of the study was that copper alloy can be welded to copper clad PCBs with reasonable tolerances on machine settings, although with not as great a tolerance as with nickel clad boards.

Methods were developed to determine solderability criteria for various thin-film metallization systems. The tests involve solder spread, solder lifting and measurement of the solder contact angle.

The use of HMCs in electronic assemblies requires that the HMCs be easily interconnected to other circuitry in the electronic assembly. The Energy Research and Development Administration (ERDA) HMCs that are designed by Sandia Laboratories, Albuquerque and produced at Bendix Kansas City use thin (0.13 mm) gold plated copper-alloy leads to provide the needed interconnections. Work on this project characterized bonding force, time, temperature, and substrate support during bonding and related these characteristics to bond quality. Both single-lead and multiple-lead bonding were studied, and multiple-lead bonding was later implemented into Bendix HMC production. Bond envelopes that graphically illustrate the range of machine parameters were developed to yield acceptable bonds for the materials used. Machine control settings were correlated to actual parameters and a thin-film thermocouple was developed to measure the temperature at the interface between the thin-film gold conductor and the gold plated copper lead during bonding.

Preliminary work to evaluate the fatigue strength of 0.13, 0.20, and 0.26 mm thick leads indicates that unloaded 0.13 mm thick leads can survive up to 16 flexures per Mil Std 883 Method 2004 Condition B. Plating the leads with nickel and 2 μ m gold reduces the unloaded flexure strength by at least 50 percent. Leads 0.26 mm thick survived fewer unloaded flexures than did 0.13 mm thick leads; however, during tests with a 250 g load applied, the 0.26 mm thick leads survived more flexures than the 0.13 mm thick leads. Additional work is needed to improve flexure strength of TC bonded interconnecting leads. Tool configurations, lead thickness, plating, and lead width are recommended variables for future study.

A time study was made for two methods of interconnecting alumina substrates to PCBs. One method used Ampere sockets while the other used bifurcated terminals. The 120 interconnections were made in 5.3 hours using Ampere sockets; 6.1 hours were needed using bifurcated terminals.

Open face hybrid substrates, stacked one above the other, were studied for a practical and reliable means of interconnection within a 0.050 inch (1.27 mm) gap around the periphery of the substrates. The alumina substrates were 1.050 inches square

(2.667 cm square) by 0.025-inch (630 μ m) thick with as many as 60 interconnections to each substrate. A model was built to show the feasibility of the selected method of interconnection.

Because of the inability to adequately inspect solder joints made to the printed circuits on the underside of the 1443287-3 interconnect board, a feasibility study was conducted to determine if printed flexible circuits would allow visual inspection of these solder joints. This study consisted of fabricating three versions of printed flexible circuits that could possibly replace the interconnect board. The boards were fabricated and analyzed, and the fabrication costs were compared to the fabrication costs of the interconnect board. This study concluded that the interconnect board can be replaced by a printed flexible circuit (6984696-2) and that the solder joints can be 100 percent visually inspected to assure good electrical connections. If this application of flex circuit is pursued, then solder methods and the effects of stress should be investigated.

Reflow soldering was studied to develop processing for soldering all leads of an IC or a hybrid to a PCB in one operation. The scope of the study included the soldering parameters and the equipment design to efficiently and reliably solder multiple lead devices to PCBs. Processes considered were infrared reflow soldering and pulse heated electrode soldering. Infrared reflow soldering and pulse heated electrode soldering were investigated for soldering a single side and both sides of a multiple lead package. In addition, a literature search for other multiple lead soldering techniques was conducted.

A pulse heated multiple lead soldering head was designed with rigidly positioned wire loops. This design failed because all circuit leads were not uniformly contacted; hence, uniform solder joints were not obtained. The head was redesigned to allow for limited movement of each electrode to compensate for varying lead heights. Because of the spacing of the leads [the electrodes were 0.050 inch (1.3 mm)] the electrodes were staggered to allow placement of the electrodes in the body of the soldering head. Each electrode was spring loaded and electrically heated. A PCB test pattern was designed to correspond to the staggered electrode head configuration.

The electrode head failed because of the inability to electrically insulate the electrodes from the body of the head and maintain electrode movement. However, the staggered electrode pattern not only allowed more room for electrode placement but allowed more flexibility in lead placement; thus, alignment was not as critical as compared to conventional IC lead alignment.

A Development Associates Control (DAC) model MDS soldering system using a continuous tantalum electrode was evaluated. The electrode

holds seven leads on each side of the device in soldering position; the electrodes are then pulse heated for reflow soldering of the pretinned circuit leads. Preliminary work with the DAC system was encouraging, which led to the purchase of a Paul Dosier Associates Model 2001B place and solder machine. A decision to terminate the project work prevented optimization of the process, but multiple lead soldering by pulse heating was found feasible as a production operation.

DISCUSSION

SCOPE AND PURPOSE

This project was guided by the problems common to past and present electronic assembly operations and those expected in future electronic assemblies, especially those associated with HMC thin-film technology.

In addition to developing or adapting newer methods of interconnection, such as lead-frame bonding, reflow soldering, and flexible circuits, comparisons of costs and of intuitive advantages of the newer interconnections against the older methods were made.

A cost study of parallel gap welding versus reflow soldering of IC flatpacks was made. The study included attachment times and cost and scrap rates for the required PCBs, visual defect rates and equipment costs. The flatpacks used gold plated kovar ribbon leads. Other work evaluating copper leads for weldability and solderability was done on a special order and partially funded by this project.

Solderability of HMC thin films requires a criterion for comparison of solder joint quality. Three solderability tests are proposed and developed to show feasibility.

The Sandia Laboratories, Albuquerque, defined HMC technology as based on the reliability of gold-to-gold TC bonds.¹ The leads that interconnect the electronic circuitry inside the HMC to external circuitry require a gold-to-gold TC bond at the interface between the gold conductors in the HMC and the lead.

A reliable lead bonding process requires that the variables affecting bond quality be evaluated and their limits established so that the needed bond quality is obtained. Bonding time, force, temperature, and the effects of substrate flatness on bond quality were studied. Prior work at Sandia Laboratories, Albuquerque, by resident Bendix technical personnel had determined how substrate and lead cleanliness and tool configuration affect bond quality. The goal of this work was to define the set of parameters that result in bonds of adequate quality and to define the process capability for TC bonding of 0.13 mm thick leads. The leads evaluated were 0.13 mm thick, 0.38 mm wide annealed CDA194 alloy, which were plated with a nickel flash and 2×10^{-6} m of gold. These leads were TC bonded to 3×10^{-6} m of gold that was evaporated onto 0.2×10^{-6} m of chromium² and were obtained in strips so that several leads could be bonded simultaneously.

Ceramic substrates were attached to a printed circuit "mother" board via Ampere sockets and bifurcated terminals. The two attachment methods were compared in terms of speed of assembly.

Different methods of interconnecting stacked substrates within tight space restraints were considered. The most promising was selected, and a model was constructed to show the feasibility of that method. No prior work had been done, but other interconnecting schemes had been studied.

A printed flexible circuit was fabricated to facilitate the visual inspection of all solder joints. The flex circuit had the same maximum physical dimensions as the 1443287-3 interconnect board. The 1443287-3 is a production PCB that requires blind solder joints to be made to circuit paths on one side of the board. Many of the techniques used to fabricate this flex circuit had been acquired from previous development work on flexible cables.

A process study was made of reflow soldering multilead ICs and hybrids to PCBs. The objective was to determine the soldering parameters and equipment design for efficiently and reliably soldering multiple lead devices to PCBs. Two principal areas of investigation were infrared reflow soldering and pulse heated electrode soldering in addition to other methods as revealed by a literature search. All multiple lead soldering methods were to be considered for soldering each side of a device. Machine parameters for an optimal solder connection, rework capabilities, efficiency, and operator training fundamentals were to be derived.

Established methods of welding flatpack leads produce highly reliable interconnections but severely limit rework capabilities and are time consuming because only one lead is welded at a time. Established methods of soldering flatpack leads yield a more reworkable interconnection but, like welding, are time consuming. A method was needed to interconnect in one operation all the leads of a multiple lead device to a printed wiring board. Because soldered interconnections can be reworked, multiple lead attachment by soldering seemed the obvious solution. Several methods had been pursued in the past without success, including Process Development Order 6984681, *Infrared Reflow Soldering*. Concurrently, Process Development Order 6984701, *Flatpack Installation by Single-Probe Reflow Soldering*, investigated the Browne single-probe soldering system and achieved significant success in improving the reliability of the interconnection and the efficiency of the process, when compared to the existing methods of solder interconnection.

ACTIVITY

Welding Versus Soldering

Welding Versus Soldering Cost Study

To determine the cost difference between reflow soldering of ICs and parallel gap welding, these areas were considered:

- Attachment times,
- Cost and scrap rates for nickel-clad circuit boards and copper-clad printed circuit boards,
- Visual defect rates, and
- Equipment costs.

Each area was considered separately and then attachment times and PCB information were combined to show their relationships. In this study, consideration was only given to soldering and welding the flatpacks that have leads mounted on the surface of the boards.

Attachment Times

Attachment times were derived from production records for reflow soldering of 14-lead ICs to nickel-clad PCBs and for the parallel gap welding of similar packages to nickel-clad boards. The operations studied included the preforming of flatpack leads; cleaning of flatpacks; tinning leads; and soldering, welding, and cleaning of boards after attachment.

Several operations common to the two processes were considered to require the same amount of time. These operations included lead preforming, lead clipping, cleaning of flatpack leads, and spray cleaning the boards before the flatpack attachment.

Table 1 shows the operations and the times required to attach 14-lead ICs by parallel gap welding and by soldering.

There is little difference in attachment time between parallel gap welding or soldering with the Browne machine. Because of the lead preparation and cleanup operations required for soldering, welding is significantly faster than soldering.

Cost Scrap Rates

Several PCBs of similar size and complexity were compared in cost and scrap rates. Three large copper-clad boards (approximately 15 in.² (97 cm²)) from an electronic timer were compared with three similar nickel-clad boards from a radar assembly. Also, a small copper board [approximately 1.4 in.² (9.7 cm²)] and a small nickel board from a radar assembly were studied.

Tables 2 and 3 summarize the information on PCBs. The information on sales and scrap for the boards was obtained from Production Control; standard hours were obtained from Methods Engineering.

Large nickel boards require twice the fabrication time as do similar copper boards (1.658 hour versus 0.8170 hour). The scrap rate of large nickel boards is 35.7 percent as compared to 34.1 percent for copper boards.

Table 1. Attachment Times

Operations	Reflow Soldering With DAC Machine	Reflow Soldering With Browne Machine	Parallel Gap Welding With Hughes Machine
Preform Flatpack Leads	0.225	0.225	0.225
Clean Flatpack Leads	0.330	0.330	NA
Tin Flatpack Leads	0.684	0.684	NA
Clean Flatpack Leads	0.330	0.330	0.330
Clean Board	0.258	0.258	0.258
Solder or Weld	2.772	1.348	1.194
Clean Board	0.064	0.064	NA
Totals per Flatpack Standard Minutes	4.663	3.239	2.007
Standard Hours	0.078	0.054	0.003

Fabrication times for small nickel boards are 1.5 times that required for small copper boards. In this case, the reject rate for nickel boards is 6 percent higher than copper boards.

Soldering and Welding Defect Rates

Quality histories were studied to determine the difference in the visual defect rate of soldering as compared to welding flatpacks. The histories on soldering flatpacks included the period from

Table 2. Printed Circuit Board Fabrication Times and Scrap Rates

Assembly	Board Area		Standard Hours Per Board	Sales*	Scrap*	Percent Scrap*	Material Cost
	(in ²)	(cm ²)					
Nickel-Clad FR45							
Radar	15.90	102.6	1.64551	1762	861	32.8	11.77
Radar	15.55	100.3	1.47718	1761	840	32.3	11.77
Radar	16.26	104.88	1.85238	1533	1112	42.0	11.77
Radar	1.47	9.48	0.32567	717	271	27.4	1.32
Copper Clad FR45							
Timer	20.19	130.23	0.78780	1370	637	31.7	1.21
Timer	14.45	93.20	0.82541	870	443	33.7	1.21
Timer	11.9	76.8	0.83785	742	436	37.0	1.32
Radar	1.34	8.64	0.23659	694	189	21.4	0.08
*Quantities are for November 1969 to February 1971							

Table 3. Average Time and Scrap Rates for Printed Circuit Board Fabrication From November 1969 to February 1971

Board Type	Standard Hours	Percent Scrap
Large Nickel	1.6583	35.7
Large Copper	0.8170	34.1
Difference	0.8413	1.6
Small Nickel	0.32567	27.4
Small Copper	0.23654	21.4
Difference	0.09906	6.0

January 1, 1969 to January 1, 1971. Fifteen percent of the solder joints included in this information are discrete component solder joints. The weld data includes only the defect information from welded flatpack assemblies (Table 4).

The defects included in Table 4 are all visual defects that can be attributed to the soldering or welding process. This includes the generation of solder splashes, flux residues, solder joint defects, weld joint defects, and misaligned leads.

The average defect rate for parallel gap welded flatpacks is 2077 joints per defective joint, which is better than the 1399 joints per defective joint for reflow soldered flatpacks.

Equipment Costs

The equipment costs for two soldering machines, the DAC and Browne and the Hughes parallel gap welder are given in Appendix A. The purchase price of the Hughes equipment is twice that of the Browne machine, but when calculated as a cost per attached flatpack, the difference is not great.

Combined Costs

A model has been developed to compare the costs of soldering and welding. Two items, the cost of PCB fabrication (Figure 1) and the cost of IC attachment (Figure 2), are considered individually and in a combined form (Figure 3).

Table 4. Solder and Weld Defect Information

Weld Assembly	Joints Inspected	Total Defects	Joints Per Joint Defective	Joints Per Assembly	Percentage Of Defective Joints
1	134874	38	3549	254	0.028
2	94696	34	2785	266	0.036
3	71442	73	978	294	0.102
Total	301012	145		814	
Average	100337	48.3	2077	271	0.05

Solder Assembly	Joints Inspected	Total Defects	Joints Per Joint Defective	Joints Per Assembly	Percentage Of Defective Joints
1	15308	8	1913	356	0.052
2	14520	10	1452	363	0.069
3	13560	13	1043	339	0.096
Total	43388	31		1058	
Average	14462	10.3	1399	352	0.07

For this model, it is assumed that only ICs are attached to the board. If any other component types are soldered into eyelets, then the curve would shift upward by a constant amount.

Reflow soldering with the Browne machine shows a small time advantage over parallel gap welding. When the higher visual defect rate of soldering is considered, there is no significant overall difference between parallel gap welding and reflow soldering with the Browne machine.

Thin-Film Solderability

To support the solderability criteria, three separate tests were proposed and demonstrated. The tests involved solder spread, lifting, and measurement of the solder contact angle.

The solderability spread test proved to be relatively simple. It appeared to be reliable and gave a relative measure of the solderability of the materials involved.

Figure 1. Standard Hours Fabrication Versus Board Size

A solderability spread experiment was performed by D/842-2. The equipment used included a hot plate, a thermocouple for monitoring hot plate temperature, a substrate with chrome-gold metallization, solder preforms and soldering flux, and a micrometer. The testing procedure prepared the substrate with solder flux. The solder preform was then placed on the substrate. Next this substrate was placed on the hot plate until the solder melted. The experiment provided the following parameters: temperature [480°F ±10°F (249°C ±12°C)], solder (Alpha 60/40 preforms), flux (Nonactivated Rosin), and time (5 seconds after the start of melting).

The interpretation of test results produced the fact that the relative solderability is determined by the spread factor. The percentage of spread factor equals

$$\frac{D-H}{D} \times 100$$

Figure 2. Standard Hours Attachment Versus Number of Integrated Circuits Attached

where the diameter (D) of an equivalent sphere has the same mass as the solder preform and where the maximum height (H) of the solder is on the substrate. The following calculations for an equivalent sphere were made for the solder spread test demonstration. The solder preform was a disc with a diameter of 300 mils (7.62 mm) and a height of 17 mils (0.43 mm).

$$(\text{Disc}) \quad V = \pi R^2 H = 0.0012 \text{ in.}^3 \quad (0.77 \text{ mm}^3)$$

$$(\text{Sphere}) \quad V = \frac{4}{3} \pi R^3$$

$$R^3 = \frac{3V}{4}$$

Because the masses and the densities are equal, the volumes are equal. Substituting the volume of the disc:

Figure 3. Standard Hours Board and Integrated Circuit Attachment Versus Integrated Circuit Attachment and Board Size

Radius = 66 mils (1.68 mm)

Diameter = 132 mils (3.35 mm)

Spread Factor Percentage = $\frac{D-H}{D} \times 100$.

For one sample,

H = 18.3 mils (0.46 mm), and

S.F. = $\frac{0.132 - 0.018}{0.132} \times 100 = \frac{0.114}{0.132} \times 100 = 86.4$

The spread factor of 86.4 percent corresponds to a relative solderability of from good to very good. Table 5 shows the data for three samples.

Table 5. Solderability Spread Factors

Sample	Height		Diameter	Spread Factor Percentage
	(mils)	(mm)	(D-H)/D	
1	18.3	0.46	1137/1320	86.14
3	18.5	0.47	1135/1320	85.98
4	16.4	0.42	1156/1320	87.58

It should be noted that the substrates used were 4500Å (0.45 x 10⁻⁶ meters) chrome-gold on glass. The spread test was previously used on other types of materials with different solderabilities.

For the lifting test, one sample from the solderability spread test was used. The second sample was examined and it was found that the solder was easily removed with a sharp instrument. It was noted that the solderability was dependent on the time that the substrate remained at an elevated temperature. In the solderability spread test, the second sample was left on the hot plate for approximately 10 seconds while the other three samples were heated for only 5 seconds after the solder had begun to melt. Because of the increased time, the second sample was rendered unsolderable when all the gold was removed by the solder. None of the other spots could be lifted with a sharp instrument.

For the third test, measurement of the solder contact angle, one sample was examined with the scanning electron microscope. A vertical photograph was made at 100X and the angle of contact was measured with a protractor. The fourth sample from the spread test was used, and the solder contact angle was 14.7°.

Data for the fourth sample:

$$H = 16.4 \text{ (0.42 mm)} \quad \frac{D-H}{H} = 1156/1320$$

Spread Factor = 87.5 percent

Contact Angle = 14.7°

Any contact angle less than 60° is acceptable for solderability. However, the optimum solderability is generally obtained with a contact angle between 15° and 30°.

Experimental Data

The experiment outline has been followed with data being taken from the thin-film materials shown in Table 6. In the experiment, 99.5 percent alumina substrates with a surface roughness of 10 microinches (254 nm) and Number 611 Milors nonactivated rosin flux were used. The chrome and gold thickness in part A were 1000Å (0.10×10^{-6} meters) each.

<u>Material</u>	<u>Average Spread Factor Percentage</u>
Chrome-Gold on unglazed ceramic	89.318
Tantalum-Chrome-Gold on unglazed ceramic	87.615
Chrome-Gold on glazed ceramic	87.226
Chrome-Copper on unglazed ceramic	91.42

In addition to the above test, two samples of gold (not chrome and gold) on glazed ceramic were examined. Because of poor film adherence, the gold was immediately "absorbed" by the solder, and the ceramic was exposed. These samples were then unsolderable.

It should be noted that in some cases there are large variations in the solder heights. These variations are caused by inconsistent timing of the solder melting time. However, it should also be noted that the solder spread factors all fall within a few percent of each other, indicating that the solder melting time is not critical as far as the spread factor criterion for solderability is concerned. This point was also demonstrated by the lifting test.

HMC Interconnection Lead Bonding

The use of HMCs in electronic assemblies requires that the HMCs be easily interconnected to other circuitry in the electronic assembly. The ERDA HMCs that are designed by Sandia Laboratories, Albuquerque, and produced at Bendix Kansas City use thin (0.13 mm) gold plated copper-alloy leads to provide the needed interconnections. The leads are attached to 3 µm gold conductors on the HMC by TC bonding. The other ends of the leads are then attached into the electronic assembly by soldering, a common method of assembling electronic components. Thermocompression bonding of gold-plated copper leads to thin-film gold conductors represents a new technology requiring characterization before production use.

Table 6. Solderability Results

Sample	Height		Diameter	Spread Factor Percentage
	(mils)	(mm)	(D-H)/D	
Chrome-Gold			Unglazed Ceramic	
1	22.6	0.51	0.1094/0.132	82.88
2	10.2	0.26	0.1218/0.132	92.27
3	16.3	0.4	0.1157/0.132	87.65
4	9.9	0.25	0.1221/0.132	92.50
5	11.5	0.29	0.1205/0.132	91.29
Tantalum-Chrome-Gold			Unglazed Ceramic	
1	15.0	0.38	0.1170/0.132	88.64
2	16.2	0.41	0.1158/0.132	87.73
3	16.3	0.41	0.1157/0.132	87.65
4	17.9	0.45	0.1141/0.132	86.44
Chrome-Gold			Glazed Ceramic	
1	16.8	0.43	0.1152/0.132	87.27
2	18.5	0.47	0.1136/0.132	86.06
3	17.4	0.44	0.1146/0.132	86.82
4	16.1	0.41	0.1159/0.132	87.80
5	15.6	0.40	0.1164/0.132	88.18
Chrome-Copper			Unglazed Ceramic	
1	7.0	0.18	0.1250/0.132	94.69
2	15.0	0.38	0.1170/0.132	88.64
3	9.9	0.25	0.1221/0.132	92.50
4	13.4	0.34	0.1186/0.132	89.85

Schedules for TC bonding are based on the fundamental physics of the process. This philosophy justifies the determination of an optimum combination of bonding parameters rather than a characterization of a particular machine.

Thermocompression bonding is a technique that welds material through the application of pressure and heat. It is a solid state weld in that neither weldment material changes state (materials are not melted) during welding. Because the temperatures used are well below the melting point of weldments, very little diffusion exists and the technique is an example of the intimate contact theory.

The theory of intimate contact states that free energy is associated with all surfaces; and if two surfaces are brought into contact, the energy at their interface will decrease. Furthermore, the energy, such as force, required to rupture the interface is equivalent to the decrease in surface energy that occurred during the formation of the joint. Thus, to create a bond, weldments must simply be placed in contact. A weld would be created by this process, but the strength of the resulting joint would be poor because the free energy of practical surfaces is low and practical surface roughness will not permit contact over an appreciable area. Thermocompression bonding relies on the application of force and heat and time to remove contaminants and to achieve conformity of weldment surfaces.

Bond integrity results from large deformation required to break up brittle surface contaminants and to disperse them. The bond then results from intimate contact of the weldments. There is no transport of matter other than by flow; the interface appears as one continuous boundary or as a line of grain boundaries. Thermocompression bonding is deformation bonding in that the dominant mechanism is the application of sufficient pressure to create plastic flow and, therefore, intimate contact.

Temperature has other important influences on bond quality. First, it facilitates plastic deformation because the ductility of metals increases with the temperature increase. Second, temperature decreases the elasticity of metals, and in this way, temperature helps prevent bond rupture during elastic recovery after the bond force has been relaxed. Finally, temperature increases the mobility of the surface contaminants and thus increases surface free energy.

Bond time is important only to the extent that finite masses with finite mobilities require time to become heated and to flow. It has been shown that gold-to-gold bonds require approximately 0.1 second for sufficient flow and dispersion of weldments and contaminants.² The characterization of bonding equipment indicates the required time for material heatup.

Bond time can be determined by the characterization curves for bond interface temperatures.. To obtain a repeatable process, the interface temperature should reach an equilibrium value.

It should be noted that bond time is dependent on the thermal properties of the bonding system. Therefore, major changes in the bonding head or in the substrate support can change the optimum bond time. In addition, a change in the thickness or width of leads will change the required bond time.

Interface temperature, as a function of tool temperature, is determined during machine characterization. The result, combined with the previously determined bond time, reduces a four-variable-problem (bond time, force, substrate temperature and tool temperature) to the two-variable-problem of bond force and interface temperature.

To determine the bond force and interface temperature combinations that yield acceptable mechanical strength, a number of bonds are made at various force and temperature settings, and the resulting bonds are tested. The minimum and maximum bond forces that will produce acceptable bonds as a function of interface temperature are determined. A key that is helpful in determining these forces is to recall that at forces below the minimum, pull strength is low and the failure mode is typically bond delaminations; at forces greater than the maximum, pull strength is low and deformation is excessive. An additional helpful characteristic is that as interface temperature is increased, both maximum and minimum bond force will not increase but will decrease or remain constant.

A plot of bond force and interface temperature that yields acceptable bonds can be made as shown in Figure 4. The optimum point is the set of machine values that provide the greatest assurance that the bond parameters will not move outside the enclosed region of Figure 4 as a result of normal machine control variations or tolerances.

Thin-Film Thermocouples

Determining the temperature at the interface between the surfaces being bonded is fundamental to investigating TC bonding. It is difficult to measure the interface temperature with commercial sensors because the bond area is typically 1.16 mm^2 . Thin-film thermocouples were developed to facilitate interface temperature measurement.

The thermocouple junction is approximately the same size as that of the bond area, and the thermocouple, being a thin film, inherently has an extremely fast response time. The thermocouples are produced by vacuum depositing chromel and alumel through a mask. The calibration setup for a thin-film thermocouple is shown in Figure 5. Figure 6 shows the electrical characteristics of a

Figure 4. Lead Frame Schedule

thin-film thermocouple as a function of the junction temperature. The figure also shows characteristics of a bulk chromel-alumel thermocouple as stated by *The Handbook of Chemistry and Physics*. From the slopes of these lines it is apparent that the Seebeck coefficients for thin-film thermocouples are approximately 10 percent less than that of bulk thermocouples, but that the output of the thin-film thermocouples is sufficient for temperatures in the range of interest (approximately 200°C).

In addition to the output characteristics, the stability and repeatability of thin-film thermocouples were measured. Three thermocouples were baked at 350°C for 19.5 hours. During this test the thermocouples were continuously monitored. The output of the thermocouple did not vary more than +0.1 millivolts, which is within the measuring accuracy of the monitoring voltmeter. Manufacturing repeatability was measured by producing several thermocouples in each evaporation run and noting the differences in output characteristics from run-to-run and within a single run. It was found that thermocouples produced in a single evaporation run had identical electrical characteristics, but that run-to-run variations required a calibration of at least one thermocouple from each evaporation run.

Figure 5. Thin-Film Thermocouple Calibration

Characterization of Lead Bonder

Lead bonding has three dominant machine parameters. These are bond force, time, and temperature. All three of these parameters were determined and plotted in terms of bonder settings. Bond time and temperature were reduced to a single parameter: bond interface temperature. A K & S lead bonder was used for this evaluation.

Figure 6. Thermocouple Calibration

An additional parameter that influences the yield is the material that supports the substrates during bonding. The support material is significant because it influences the thermal response (at the bond interface) and because its elastic properties prevent substrate fracture during bonding. Kapton appears to have both the thermal and elastic properties required.

Bond time and force were calibrated by placing a dynamic load cell under the bonding head (Figure 7) and cycling the machine. A typical load cell output is shown in Figure 8. It should be noted that the width of the pulse at maximum amplitude is defined as bond time and that the amplitude of the pulse is defined as bond force. Using this technique, bond time and force were determined as a function of bonder settings.

Figure 7. Bond Time and Force Calibration

Figure 7 Continued. Bond Time and Force Calibration

Bond wedge and head temperatures were determined by monitoring a 1-mil ($25.4\ \mu\text{m}$) thermocouple attached on the wedge and by monitoring the head temperature with the controller thermocouple (Figure 9). The controller thermocouple is cemented deep inside the bonding head. Figure 10 illustrates head and wedge temperatures for various controller settings. The large thermal lag between wedge and head temperature should be noted. The head is machined from Inconel 718.

Interface temperatures were measured using thin-film, chromel-alumel, thermocouples. A lead was aligned during bonding so that the bond zone coincided with the junction of the thermocouple. Figure 11 shows the dependency of the interface temperature on head temperature and bond time. The difference in thermal response for different substrate support materials can be seen by comparing Figure 11, in which mica was used as substrate support, and

Figure 8. Lead Frame Calibration

Figure 12, in which a set of leads or a lead frame, was used. At times in excess of 10 seconds, quasi-equilibrium exists and bond time can be neglected. The substrate (or HMC) is not heated in lead bonding.

Thermocompression bonding of gold weldments requires an interface temperature of at least 200°C, which is obtained for a head temperature of 600°C with a 10 second bond time. The maximum usable head temperature is 675°C. Above this maximum, the tool is red hot and can be easily damaged. Therefore, the range of head temperatures (for example, interface temperature) for lead bonding schedule development is 625°C to 675°C.

Bond Schedule Definition

The criteria established for TC bonding of leads to gold thin-film conductors dictated a minimum of 0.34 kg strength for a 90° pull (Figure 13) of any individual lead and a minimum average

Figure 9. Bond Wedge and Head Temperature Measurement

pull strength of 0.45 kg for all leads bonded during any one bond cycle. The data used to establish those criteria indicated that deformation of the lead in the bond area of 35 to 55 percent of the original lead thickness seemingly gave higher strength and more reliable bonds.³ A bond envelope (Figure 14) was developed against those criteria for substrates from ten different chrome-gold evaporation lots and six different lead plating lots. The

Figure 10. Bonding Head Temperature

Figure 11. Interface Temperature Versus Time (5-Mil)

Figure 12. Interface Temperature Versus Time (10-Mil)

larger bond envelope, an envelope which can be obtained and which can allow up to 61 percent deformation, prompted further investigation of bond strength versus bond deformation.

Average 90° bond pull strength was determined as a function of lead deformation in the bond zone. As seen in Figure 15, failures at the bond heel occur at higher pull strengths while the lead-to-evaporated gold interface failures (TC failures) occur at lower pull strengths. Pull strengths of less than 0.45 kg occurred at deformations less than 35 percent. However, the heel-failure trend, although it has increasing deformation, shows that 65 percent deformation would more than adequately meet the 0.45 kg average-strength criteria.

Figure 13. Lead Pull Test Failure Modes

The number of flexures, which a lead can withstand before a fracture, is also of interest. During HMC processing and testing, leads are subjected to small flexures. Maximizing the number of such flexures will reduce the rework and the possible scrapping of HMCs that had developed fractured leads. Lead fatigue tests were made on three sizes of leads per Mil. Std. 883, Method 2004, Condition B except that flexing was continued until the lead fractured. Unplated and plated leads were tested. The average number of flexures until the lead fractured is summarized in Figure 16 for each lead size and plating condition. Thicker leads showed better flex resistance under load. This is attributed to greater tensile strength with a larger cross-sectional area. Thinner leads showed better flex resistance without a load applied. This difference apparently was because of the flexure point shifting slightly each time the lead was flexed. It was concluded that unplated leads can be flexed more times than plated leads.

Further unloaded flex testing of plated leads was performed. Thirty-eight copper alloy, CDA725 leads were used. Nineteen leads were plated with 20.3 microns each of nickel and gold while the plating on the other lead frames was 55.9 microns each of nickel and gold. The average number of flexures before failure per lead is shown in the following test results.

Figure 14. Lead Frame Bond Envelope

	<u>90° Flex Arc</u>	<u>180° Flex Arc</u>
20.3μm Ni and Au	8.5	3.2
55.9μm Ni and Au	4.0	2.1

It is expected that nickel, being much harder than gold and copper, is the predominant factor in plated leads having reduced flex resistance.

A sample of 226 each 0.13 mm thick nickel/gold plated leads was bonded to gold conductors at different deformations and tested with a 30 degree flexure under a 200 gram load. Figure 17 shows the correlation of deformation with flexure resistance. At 65 percent deformation, a 0.13 mm lead can withstand about eight 30 degree flexures under a 200 gram load as compared to an unbonded lead that can withstand about 43 flexures. A range of 8 to 12 flexures can be expected over an allowable deformation range of 35 to 65 percent.

Figure 15. Lead Strength Versus Deformation Lead Frame Soldering

The deformation that results from lead TC bonding creates a line of stress concentration near the edge of the bond zone that directly contributes to decreasing flexure resistance with increasing deformation. The area of stress concentration could be appreciably reduced by rotating the bond wedge 90° to produce a longitudinal deformation instead of the standard transverse

Figure 16. Lead Flexure Test Results

pattern (Figure 18). Limited data indicate that a significant increase in flexural strength can be realized by this method. Several TC bonded leads flexed through 90° cycles until failure occurred. Five longitudinally bonded leads failed with an average of 10.2 flexures and with individuals ranging from 6 to 12 flexures each. Eight standard transversely bonded leads failed with an average of 2.75 flexures with individuals ranging from one to six flexures each. The 90° peel test on the longitudinally bond leads produced lead failures at 17 ounces (481.9 g). The failure mode was a separation of the lead at the periphery of the bond zone. Additional work regarding tooling needed to longitudinally bond multiple leads is needed before a decision on the longitudinal lead bond is made.

Other approaches to increase lead flexure resistance include elimination of the nickel between the CDA194 alloy lead and the gold plating, evaluation of the influence of lead width, and evaluation of the effect of bonding wedge geometry.

Figure 17. Fatigue Testing of 5- by 5-Mil Lead Frames

Ampere Sockets Opposed to Bifurcated Terminals

An estimate was made of the assembly time to electrically and mechanically interconnect six ceramic substrates to a mother PCB using two methods. The two interconnection methods were via Ampere sockets and bifurcated terminals as shown in Figures 19 and 20. For the study, each substrate had 20 terminals, 10 each on the opposite sides of the substrates. The estimated assembly time to attach 120 terminals was 5.3 hours for the Ampere socket approach and 6.1 hours for the bifurcated terminal approach. Thus, ten assemblies could be fabricated in 53 or 61 hours, respectively.

Interconnecting Stacked Substrates

The interconnection problem involved five hybrid substrates stacked one above another with a typical spacing between substrates of 0.060 inch (1.52 mm). It was the intent of this study to propose, within an initial set of packaging criteria, a feasible interconnection configuration to achieve production objectives of reliability, inspectability, and manufacturability.

Figure 18. Longitudinal Deformation to Decrease Stress at Edge of Bond Zone

The packaging criteria included:

- Alumina substrates, 1.050 inch (2.667 cm) square by 0.025 inch (0.64 mm) thick;
- Outside package dimension, 1.200 inch (3.048 cm) square by 0.572 inch (14.53 mm) high;
- Outer cover wall thickness of 0.020 inch (0.51 mm);
- 15 leads on each substrate side, on 0.050 inch (1.27 mm) centers;
- 14 package interface connections; and
- Copper alloy leads (0.005 by 0.015 inch) (0.13 by 0.38 mm) TC bonded to chrome-gold over tantalum-nitride metallization.

Initial packaging plans allowed a nominal 0.030-inch (0.76 mm) gap between the inside wall of the cover and the edge of the substrate for interconnections. Interconnection ideas considered were vertical stackings, flex circuits, PCBs, Diacon connections, lead lattice, metallized interconnect wafers, cascaded ribbons, and wire overlays. The wire overlay method was selected.

Figure 19. Ampere Socket Method

The wire overlay method uses grooved insulators. These insulators maintain lead separation, and they provide a guide that helps solder a Number 26 AWG wire to interconnect all in-line ribbon leads. The ribbon leads, which are TC bonded to the alumina substrates, are routed through windows in the insulator grooves. After all the hybrid leads are formed, the Number 26 AWG wires are placed over the ribbon leads and soldered.

A model of the wire overlay configuration was constructed to show feasibility. Figures 21, 22, 23, and 24 show the assembly sequence. The assembly was not difficult to make, and the only real problem encountered was the insertion of the substrates into the corner posts. Tooling could overcome this loading problem and could

Figure 20. Bifurcated Terminal Method

provide for consistent cutoff lengths for the leads. Leads and interconnect wires should be pretinned. No further work is planned on stacked substrates.

Flexible Circuit Application Study

6984696-1 was fabricated using two-mil (50.8 μm) Kapton polyimide film clad on both sides with 2.8 mils (71.1 μm) copper as the base laminate. Two-mil (50.8 mm) Kapton coated on one side with epoxy adhesive was used as the outside dielectric (coverlay). After the required holes were drilled in the base laminate panels

Figure 21. Assembly Sequence, First Step

and coverlay, the base laminate panels were prepared for etching. After the etching process, the eyelets were swaged in the holes and the composite circuit construction was laminated at 350°F (176.7°C) and at 500 psi (3.447 MPa) for 30 minutes. The swaged eyelets were cross-sectioned, and photos were taken to study the mechanical connection between the circuit and the eyelet.

6984696-2 was fabricated using two-mil (50.8 μm) Kapton film clad on both sides with 2.8 mils (71.1 μm) copper. One side of the circuit pattern was placed on a panel and the other side was placed on a separate panel. In both cases, the copper on the side of the panel that had no circuit pattern was completely

Figure 22. Assembly Sequence, Second Step

etched away. Each panel, containing one-half of the circuits, was laminated separately at 350°F (176.7°C) and at 500 psi (3.447 MPa) for 30 minutes.

6984696-3 was fabricated using the material and techniques as 6984696-1 except the swaged eyelets were replaced by plated-through holes. The plated-through holes were cross-sectioned and photos were taken to study the plating in the holes.

Results of Fabrication Techniques

Flex circuit 6984696-1 did not offer any significant advantages over the board. The eyelets that were used were too long. Cross sections of the eyelets revealed poor mechanical connections.

Figure 23. Assembly Sequence, Third Step

6984696-2 was two separate flexible printed circuits, each containing one-half of the circuitry contained on the original board. Each printed circuit was laminated separately as individual pieceparts. This allows installation of the flex circuits, one at a time. The first circuit can be installed and the solder connections can be visually inspected. If no discrepancies are noted, the remaining flex circuit can be installed and inspected. High temperature solder can be used on the first flex circuit and a low temperature solder on the second flex circuit. This will prevent the first solder joints from reflowing when the second connections are made.

6984696-3 was the version of the two-layer single flex circuit with plated-through holes. The plated-through hole circuits were an improvement over the eyelet circuits because the former eliminated the mechanical connections of the eyelets and the conductor paths. However, the problem of visual inspection would still remain with this version of the flex circuit.

Figure 24. Assembly Sequence, Fourth Step

Comparison of Fabricated Costs

A comparison of the fabrication costs of single and double layer interconnect boards (1443287) is based on a single lot of 100 parts. The cost list is in Appendix B.

Multiple-Lead Reflow Soldering

Infrared Reflow Soldering

Infrared reflow soldering was initially investigated on PDO 6984681. It was recommended that this process not be used by Bendix Kansas City Division. The process did not lend itself to

an adequate lead hold down method because the hold down fixture had to be translucent and the solder had to be heated by light. Leads were held in position by the force generated by flexing the angled preformed lead foot against the PCB. The fragile IC leads could not be preformed, tinned, and placed on the board without damaging the lead preform integrity. Too much time was consumed in attempting to align the leads before the soldering operation. The viewing of the soldering process was limited by the necessary machine design. The friction between the lead and the solder on the PCB pad kept the leads in alignment. When the solder reflowed, this friction was diminished and the lead would lose alignment.

A literature search and especially the findings from PDO 6984701 *Flatpack Installation by Single-Probe Reflow Soldering* revealed the pulse heated electrode method as a better area to investigate; consequently, infrared reflow soldering was not pursued further on this endeavor.

Pulse Heated Electrode Reflow Soldering

Several versions of pulse heated electrode soldering were considered. The first attempt used a hand-held soldering iron that used a loop of 0.020 inch (0.5 mm), diameter nichrome wire to hold and heat the lead for reflow of the solder. The wire, however, rapidly degraded because of the heat and the wire broke or bent. This version required a flux cored solder preform and an externally added flux diluted 50 percent parts by volume (PBV) with alcohol. Adequate coverage of the solder joint area was not achieved with undiluted flux unless an excessive amount was applied. Diluting the flux by 50 percent PBV lowers the soldering tip temperature and lessens the residue on the finished joint.

An extension of the wire loop method was the design of the multiple soldering head shown in Figure 25. The head had individual wire loops for simultaneously soldering all seven leads. This head was also compatible with a PCB that had a staggered pad arrangement (Figure 26). A larger pad area was provided, and greater head tolerance and larger wire sizes were allowed for the electrodes. The larger pad size alleviates some of the problems of lead placement accuracy encountered on prior multiple lead soldering. This multiple lead head design failed because it did not give uniform and adequate pressure on all leads. Nonuniform pressure resulted in inconsistent solder joint configurations and in insufficient heat conduction for solder reflow.

A second design of the multiple lead soldering head was similar to the first, but it was improved by allowing limited movement of the electrodes. However, this type also met with failure because it could not isolate the electrically heated electrode from the head and still maintain adequate electrode movement. The staggered

Figure 25. Seven Probe Tool

Figure 26. Staggered PCB Lands

lead frame pad layout was successful in alleviating the lead placement problem as well as allowing more room for a multiple lead soldering head.

The separate electrode for each lead method was abandoned, and a method that used a continuous tantalum electrode to hold and heat the leads during soldering was pursued. A Development Associates Controls Model MDS soldering system was purchased. The system employs two separate electrodes, one for each side of a fourteen lead IC. Each electrode has an independent power supply. Current, amplitude and time are controlled by the DAC system. The current heats the tantalum electrode to reflow the solder and to form a solder joint. The heated tantalum electrode oxidizes and forms a layer of insulation that prevents a voltage potential between leads of the solder device. Occasionally, this oxide would crack and break off leaving the oxide on the soldered joint. This residue was not difficult to remove.

The electrode temperature was determined for various time and current settings as shown in Figures 27 and 28. Actual temperatures can vary because of thermal load and electrode characteristics, but the sample serves to indicate the family of thermal curves. Electrodes tend to be hotter in their centers. This difference is less at lower current and time settings but probably would not degrade the completed solder joints.

Figure 27. Temperature Versus Distance Along Electrode

One lot of one-thousand-electrical-reject ICs was received as test soldering devices for the DAC machine. Bendix report BDX-613-501, *Parallel-Gap Welding and Reflow Soldering Lead Frames* stated that 50 microinches (1.27 μm) of gold plating was minimal for good solder wetting characteristics. A sample of 21 ICs was chosen and the gold thickness was measured. The gold thickness average was 151 microinches (3.8 μm) with a standard deviation of 18 microinches (0.45 μm). Because lead thickness affected previous attempts to multiple lead solder and because the cross-section dimension of the lead would affect the thermal load, the width and thickness of the lead were measured. The distribution of the gold thickness revealed a slight tendency of the gold to be thicker on leads 1, 7, 8, and 14 with thinner platings toward the

Figure 28. Center Electrode Temperature Versus Current

center leads of 4 and 11. This deviation was about 50 microinches (1.3 μm) and according to the above report should not affect the wetting characteristics of the lead.

The DAC soldering system was incompatible with larger multiple leaded devices. A literature search had revealed a promising pick and place machine manufactured by Paul Dosier Associates of Costa Mesa, California. The Dosier multiple lead soldering machine lifts a preformed, pretinned, multiple leaded device from a "nest," places it on the PCB, and then solders it. The soldered device was controlled by the orientation of the device in the nest, and location of the devices on the PCB was controlled by a pantograph table movement. This machine employed tantalum electrodes similar to the DAC soldering system. A Paul Dosier Associates Model 2001B and tooling for a typical production PCB were purchased. Several multiple leaded devices were soldered, and the process appeared feasible. The process was never optimized, however, because of priority programs.

ACCOMPLISHMENTS

It was shown for circuit packages with ribbon leads that parallel gap welding and reflow soldering offer similar costs for attaching the circuits to PCBs. The cost of reflow soldering can be reduced by soldering all circuit leads simultaneously. Although processing refinements are required before production use, the feasibility of multilead reflow soldering has been demonstrated.

Attachment of ribbon leads to hybrid microcircuits also lends itself to multilead attachments. A TC bonding schedule was developed and has been incorporated on the production line to simultaneously TC bond 19 leads. As a part of this work a thin-film thermocouple was developed to accurately measure the temperature at the bond interface.

Schemes for interconnecting hybrid microcircuits were studied. Ampere sockets were faster than bifurcated terminals for assembly of a hybrid assembly to a printed circuit "mother" board. Feasibility was shown for a method of interconnecting stacked hybrid substrates within a small perimetric clearance.

Although no follow-up work was performed, three tests were proposed and developed to determine the solderability of thin-film metalization systems. Spread factor evolved as the best indicator of solderability. Of the systems evaluated, copper-chrome on unglazed ceramic displayed greatest solderability.

Replacements for a PCB were fabricated using flexible circuits to improve the viewing of solder joints. A two layer, flex construction appeared to be a good replacement, but its fabrication costs are higher than those for the rigid printed circuit version.

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APPENDIX A
EQUIPMENT COSTS

Operation	Brand	Equipment	Cost	Total
Welding Station	Hughes	Power Supply	775.00	
		Voltage Regulator	185.00	
		Weld Head*	410.00	
		Scope	575.00	
		Scope Mount	125.00	
		Foot Pedals	85.00	
		Weld Table	25.00	
		Cables	17.50	
		Fiberoptic Light Source	132.00	
		Gage, Force**	37.50	
				2367.00
Soldering Station	DAC	Controller, Head Base and Optic Set***	1435.00	
		Soldering Tip Set	23.20	
		Fiberoptic Light Source	69.95	
				1528.15
Soldering Station	Browne	Standard Unit	995.00	
		Printed Circuit Board Laminate		
		Heater	200.00	
				1195.00

*Replacement electrodes \$15.00 per set.

**Force Gage - \$75.00 (1 used for every 2 welding stations)

***List price has increased in past year. New price estimate
\$2000.00

APPENDIX B
FABRICATION COST LIST

Interconnect Board (1443287-3)

Material:

0.052 inch (1.32 mm) thick orlon laminate w/0.0028 in. (71.1 μ m) thick copper, cladding on both sides; 36 square feet (3.35 square meters) required.	\$ 144.00
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Tooling

Dollars

Drill fixture	\$ 250.00
Photo tools	250.00
Contour fixture	500.00
Total tooling	<u>\$1000.00</u>

Labor

Hours

Stamp	1.0
Tooling holes	2.0
B. E. holes	2.5
Deburr	2.5
Vapor blast	3.0
Electroless copper	9.0
Electro copper	6.0
Deburr	2.5
Scrub	2.6
Clean	4.0
Resist	5.0
Expose	5.0
Develop	3.5
Examine	4.0
Tin-lead plate	5.1
Strip resist	4.0
Etch	8.0
A. E. drill	1.5
Contour	8.0
Deburr	13.0
Eyelet	4.0
Stamp	4.0
Clean	1.0
Total labor	<u>101.2</u>
(Total hrs)(rate) = (101.2)(\$4.23)	= \$428.08
Total cost per 100 parts	= \$1572.00

Printed Flexible Circuit (6984696-2)

Material:

0.002 thick Kapton w/0.0028 in. (71.8 μ m) thick copper cladding one side; 60 square feet (5.57 square meters) required.	\$ 252.00
0.002 thick Kapton w/adhesive one side; 120 square feet (11.15 square meters) required.	222.00
Fiberglas Reinforced Silicone Rubber; 8 square feet (0.74 square meters) required.	<u>48.00</u>
Total material	\$ 522.00

Tooling

Drill fixture	\$ 250.00
Photo tool	250.00
Contour die	650.00
Laminating plates	<u>125.00</u>
Total tooling	\$1275.00

Labor

	<u>Hours</u>
Stamp	2.0
Tooling holes	4.0
B. E. drill	5.0
C. L. drill	2.0
Deburr	5.0
Scrub	5.2
Clean	8.0
Resist	10.0
Expose	10.0
Develop	7.0
Examine	8.0
Etch	16.0
Strip	8.0
Solvent clean	2.0
Laminate	50.0
Blank contour	4.0
Stamp	8.0
Clean	<u>2.0</u>
Total hours	156.2
(Total hours)(rate) = (156.2)(\$4.23)	= \$ 660.73
Total cost per 100 parts	= \$2457.00

Printed Flexible Circuit (6984696-3)

Material

0.002 thick Kapton w/0.0028 in. (71.1 μ m) thick copper cladding; 30 square feet required, at \$4.30 square foot.	\$ 129.00
0.002 thick Kapton w/adhesive one side; 60 square feet required, at \$1.85 square foot.	111.00
Fiberglas Reinforced Silicone Rubber; 4 square feet required, at \$6.00 square foot.	<u>24.00</u>
	\$ 264.00

Tooling

Drill fixture	\$ 250.00
Photo tool	250.00
Contour die	650.00
Laminating plates	<u>125.00</u>
Total tooling	\$1275.00

Labor

	<u>Hours</u>
Stamp	1.0
Tooling holes	2.0
B. E. drill	2.5
C. L. drill	1.0
Deburr	2.5
Scrub	2.6
Electroless copper	9.0
Electro copper	6.0
Scrub	2.6
Clean	4.0
Resist	5.0
Expose	5.0
Develop	3.5
Examine	4.0
Etch	8.0
Strip	4.0
Solvent clean	1.0
Laminate	25.0
Contour	2.0
Stamp	4.0
Clean	<u>1.0</u>
Total labor	95.7
(Total hours)(rate) = (95.7)(\$4.23)	= \$ 404.81
Total cost per 100 parts	= \$1943.81

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J. A. Peters, D/842	25
T. A. Wiley, D/842	26
R. E. Kessler, D/865	27