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EVALUATION OF PLATED-THROUGH CONNECTIONS FOR PRINTED CIRCUIT BOARDS

by

George Voida

and

Norbert J. Eich

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ABSTRACT

The present report describes the evaluations conducted with plated-through connections produced by techniques used by some of the prominent fabricators of printed circuit boards.

The following topics are discussed in detail: (1) concepts of metallizing dielectric surfaces by "copper reduction" or "immersion deposition," (2) step-by-step processing techniques for producing quality plated-through connections, (3) environmental results of plated-through connections, (4) in-process and final inspection of plated-through interconnects, (5) Sandia Corporation specification for insuring quality of the through-connects, and (6) future applications of the plated-through technique.

Commercial suppliers who are qualified to produce high-quality plated-through connections are also listed.

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EVALUATION OF PLATED-THROUGH CONNECTIONS FOR PRINTED CIRCUIT BOARDS

George Voida and Norbert J. Eich
Sandia Corporation

Introduction

With the advent of complicated equipment, apparatus, and instrumentation for industrial, military, and space applications, renewed interest and emphasis are, of necessity, expressed in the reliability of electrical connections. In electrical and electronic assemblies in which thousands of electrical connections must be made, the failure of a single connection may prove extremely costly or even disastrous.[1] It is therefore understandable why manufacturers of aircraft, communication, missile, and computer assemblies and subassemblies have supported extensive and expensive programs for developing and evaluating electrical connections.

The evaluation program of plated-through connections at Sandia Corporation was instituted because of the unreliability of the existing interconnects in the electrical and electronic industries and because of the prevalent disagreements among users concerning the various types of interconnects. The program was not a comparison study of plated-through connections versus the existing types, but was aimed specifically at determining the stability of the plated feed-through as applied to Sandia Corporation apparatus.

The plated-through connection appeared particularly advantageous since the chemical techniques seemed inherently more promising for achieving reproducibility, uniformity, and the desired metal-dielectric adherence of the electroplated feed-through. Early development of the plated-through connection indicated that throughout fabrication systematized quality controls could be maintained to ensure ultimate connection reliability; whereas similar precise controls in the application of mechanical connections had not evolved even though the latter had been used for decades. Besides being comparatively easy to fabricate, the plated connection could readily be inspected with assurance and could be adequately tested without destruction.

Without the spontaneous response of the printed circuit manufacturers, it would not have been possible to develop the chemical and production processes so rapidly and to achieve the high state of reliability of the available plated-through connections.

Mechanism of Conductive Sensitizing of Dielectric Surface

The art of metallizing nonconductive surfaces with silver, copper, gold, nickel, iron, and antimony by immersion deposition has been practiced for a great many years and probably had its greatest impetus at various periods in history because of the demands for "silvering" of glass.

At the outset of the discussion, the terminology of "immersion deposition" should be clarified. In this process the particular nonconductive surface, whether it be glass, ceramic, quartz, cork, leather, wood, wax, or plastic, is covered with a film of the metal simply by immersion in an aqueous solution containing the specific metallic ions. The deposition does not require passage of an electric current but is initiated and enhanced by the chemical behavior of certain "seeding" agents which promote an affinity between the nonconductive surface and the metal ions. In the process the ions are reduced in the form of a continuous, adherent envelope over the nonconductive article.

As a general rule the chlorides, nitrates, or sulfates of the desired metal are used for preparing one of the constituent solutions used in the deposition process. The principal solution which contains the required metallic ions, however, does not function unless "seeding" or "nucleating" agents as already mentioned are also present.

In the present discussion only copper deposition will be considered, for reasons which will be explained later.

Some of the useful copper solutions which are mentioned in the literature are presented in their constituent parts in Tables I and II. Modifications of these solutions are used in practice today for production of plated-through connections. In most instances the production formulae are considered proprietary by the manufacturers who have developed and are using them.

TABLE I

Copper Solutions for Immersion Deposition
(Formaldehyde Method)[2]

Miscattilli Formula		Mass Production Formula*		Abramson Formula	
Solution 1		Solution 1		Solution 1	
Copper sulfate	4 gms	Copper bichloride	215 gms	Caustic soda (9%)	200 cc
Rochelle salts	15 gms	Zinc chloride	16 gms	Sucrose 100 g/L	200 cc
Caustic soda	9 gms	Gold chloride	4 gms	Nitric acid	0.5 cc
Distilled water	1000 cc	Water	1750 cc		
Solution 2		Solution 2		Solution 2	
Formaldehyde	200 cc	Rochelle salts	735 gms	Water	1250 cc
		Water	1650 cc	Formaldehyde	80 cc
		Solution 3		Solution 3	
		Caustic soda	335 gms	Copper sulfate	20 gms
		Lump sugar	380 gms	Glycerine	80 cc
		Water	1215 cc	Conc. ammonia	20 cc
		Glycerine	325 gms		
		Solution 4			
		Ammonium nitrate	9 gms		
		Formaldehyde (40% solution)	2100 cc		

*Three parts of water with one part of each of the 4 Solutions.

Each of these solutions contains caustic soda, an organic salt, and of course the reducing agent. The caustic soda probably initiates the chemical reaction by hydrolyzing the reducing agent. It probably also hydrolyzes the surface of the plastic, thus activating it so that the copper actually is chemically bonded with the dielectric. The surface conditioning of the dielectric is in some manner attributed to the caustic; and the tests, as will be illustrated, indicate the strong possibility of chemical as well as mechanical enhancement of copper-insulator adhesion.

TABLE II

Copper Solutions for Immersion Deposition
(Hydrazine Methods)[2]

Bamberger and Schweitzer Formula*		French Formula		Chattaway Formula	
Solution 1		Solution 1		Solution 1	
Copper sulfate	50 gms	Copper hydrate soln. (conc.) in conc. ammonia (0. 88)		Phenyl hydrazine	1 part
Conc. ammonia	100 cc			Water	2 parts
			(90 cc)		
Solution 2		Solution 2		Solution 2	
Hydrazine sulfate	19 gms	Hydrazine sulfate	60 gms	Copper hydrate soln. (conc.) in conc. ammonia	1 part
Water	1000 cc	Distilled water	1000 cc		
			(150 cc)		
Solution 3		Solution 3		Solution 3	
Caustic soda	20 gms	Potassium hydroxide	111 gms	Potassium hydroxide	10 parts
Water	1000 cc	Distilled water	1000 cc	Water	100 parts
			(88 cc)		

*Use one part of Solutions 1 and 3 and two parts of Solution 2.

The ammonia in these formulae forms complex ions with copper in the following manner and as a result may enhance the immersion deposition of the copper probably because the ionic potential of the copper is reduced:

$$Cu^{++} + 4NH_4OH \rightarrow Cu(NH_3)4^{++} + 4H_2O \ .$$

In addition to the formaldehyde and the hydrazine, alcohol, invert sugar, glucose, glycerine, sodium or potassium tartrate, and tartaric acids serve as the reducing agents in the copper deposition reaction. The copper of course is in ionic form, and it must be reduced to its metallic state as follows:

$$Cu^{++} + 2e^{-} \rightarrow Cu^{o} \ . \qquad (1)$$

The formaldehyde is probably decomposed to its constituent products as shown by the following reaction and as intimated by several investigators:

$$HCHO \rightarrow 2H^{+} + CO + 2e^{-} . \qquad (2)$$

These reactions present only an oversimplified explanation of the oxidation and reduction processes which actually occur but are sufficient for understanding the reasons why the copper is deposited out in its metallic state.

In some formulae platinum chloride may actually operate as the primary "seeding" constituent. The platinum deposits out as a film probably through a displacement reaction with polar groups on the dielectric surface. Then the nascent hydrogen which is formed in the decomposition of formaldehyde is attracted to the platinum because of its inherent affinity for the metal, and as a result the hydrogen accelerates the deposition of copper over the desired surface. Gold chloride operates just as effectively in promoting the immersion deposition of the copper.

If stannous chloride is employed, it, too, enhances the deposition of the copper and improves the adhesion. Fixation or deposition of the tin ions is produced by an exchange reaction with some of the polar groups on the plastic and the glass fibers. The polar groups act catalytically as the nuclei in promoting the deposition of tin, thus lending additional credence to the possibility of the formation of a chemical bond between the dielectric and the metal.

The properties of the surfaces on which the copper is immersion deposited are inconsequential as long as those surfaces are thoroughly cleaned. It is true, as mentioned above, that the polar properties of the dielectric may have a pronounced effect on the type of bond which is developed with the copper. It is quite possible that some of the plastics may develop secondary valence bonds with the copper to form the chemical type of bond earlier mentioned. Some tests have already been conducted by Sullivan and Eigler[2, 4] with immersion-deposited nickel on n- and p-type silicon. In these tests, when the metal was separated from the dielectric by spot-pull evaluations, fracture occurred through the silicon rather than along the nickel-silicon interface as would be the case if the metal were only mechanically adhering to the base material. As more experience is gained with immersion deposition in the printed circuitry industry, dielectric- or plastic-copper adhesion of this same quality will undoubtedly be developed.

The commercial sensitizers are multiple solution systems which must be freshly mixed and used within a few hours after mixing. During the sensitizing procedure the clad laminate must be agitated in the solution in a plane axial to the hole. Agitation causes a continuous flow of concentrated solution through the hole. The copper as a result forms a molecularly thin layer over the surface through the "immersion deposition" process. This process, or "copper reduction" as it is sometimes called, is the only sensitizing procedure acceptable for the preparation of Sandia Corporation printed wiring boards.

Premetallizing the Dielectric Surface

Before the immersion deposition solutions described in the previous section were developed, the dielectric surface was metallized prior to electroplating by several more direct methods. Most extensive use was made of silver, copper, and carbon paints.

The metallic paints were objectionable for a number of reasons, but primarily because they were applied manually. The paints could have been applied automatically, but the necessary masking and spraying techniques for doing so were not developed since the basic process did not appear feasible as a production operation.

The silver paint showed the greatest promise, but the metal exhibited migration or electrochemical transfer under certain environmental conditions and therefore was used only as an interim metallizing substance. Since the copper paints originally possess high electrical resistance and are subject to accelerated oxidation on processing and environmental exposures, they were not extensively employed in sensitizing operations. The carbon paints were used in production by a number of manufacturers but developed very poor adhesion with the dielectric surfaces, were permeated by electrolytes during the subsequent electroplating operations, and were extremely sensitive to thermal shock on soldering.

These premetallizing methods, because of the shortcomings enumerated, have been completely rejected as production processes and are not acceptable for producing plated-through connections for Sandia Corporation applications.

Preparation of the Dielectric Surface

Drilling, rather than punching, of the epoxy glass laminate is essential if a quality plated-through connection is to be produced. Speed of drilling, sharpness of drills, and experience of operators must be considered if delamination or separation of the glass ply interlayers is to be avoided. Lubricants should not be used under any circumstances since residual films on the hole surface would prevent adequate sensitizing and plating. Some manufacturers use a water spray system, probably with detergent and abrasive additives, both to expedite drilling and to minimize wear of drills. Excessive wear of drills is an industry-wide problem and is alleviated only by a systematic program of resharpening of the drills.

Operators must be trained in techniques of drilling in order to prevent gouging of the hole surface and separation of the glass plies.

Reaming is not necessary. It is a secondary and a costly step; furthermore, a slightly roughened surface resulting from drilling is desirable for developing mechanical interlocking between the sensitizer and the epoxy-glass surface.

Some manufacturers sand-blast the hole surface primarily to remove the adhering glass-fibers and to slightly roughen the surface to improve mechanical interlocking.

Since adhesion of the plated-through connection is dependent to some extent upon the bridge between the copper shell and the land, any steps taken to increase interfacial adherence through mechanical interlocking are advantageous.

In some cases cleaning is accomplished with a dilute solution of potassium hydroxide, followed by thorough rinsing in running water. If dust, oils, fingerprints, or other contaminants are deposited on the surface, cleaning must be repeated because effective deposition and good adherence of the metal cannot be achieved except on a chemically clean surface.

Solvent cleaning with trichloroethylene, naphtha, and methylated spirits may also be employed. Solvents, however, are to be used judiciously if deterioration of the plastics is to be prevented.

Punching is unsatisfactory because the glass plies are invariably separated during the operation, and electrolyte penetration and entrapment unavoidably result under these conditions.

The "Negative" and the "Positive" Processes for Producing Plated-Through Connections

The "negative" and the "positive" processes are distinguished from each other primarily by the sequence in which the printed wiring pattern is photographically exposed on the copper surface.

The differences and advantages of the two processes are outlined in detail so that the design and production development engineers may be aware of both the flexibility and the problems associated with the in-process procedures.

The "Negative Process"

1. Photoexpose the negative pattern on the copper.
2. Etch the copper in ferric chloride or some other suitable etchant.
3. Clean and dry thoroughly the printed circuit boards.
4. Remove the organic resist. (Note: The organic resist may be removed at this point, or after Step 10 as well.)
5. Drill holes either by "eyeballing" or with use of the drill jig.
6. Clean the board and holes thoroughly, as previously directed.
7. Immersion sensitize the holes.
8. Plug up holes with wax or some other suitable compound, to protect conductive film.
9. Remove immersion copper from surface by mild ferric chloride etching.
10. Remove the wax.
11. Interconnect all portions of the printed circuitry with silver paint (or other suitable conductive paints.)
12. Mask, Krylon spray, or silk-screen the paint over tie-ins to prevent deposition of the electroplates on them and thus facilitate their removal after the electroplating operation.
13. Electroplate the desired thickness of copper on the conductors and on the hole surfaces.
14. Electroplate a solderable material such as tin-lead or gold on the conductors and on the hole surfaces.
15. Thoroughly clean the electrolytes off the boards.
16. Remove the tie-ins.

The resist may be removed either after etching or after Step 10 after removal of the immersion deposit. In the "negative process," aside from the immersion sensitizing operation, application and removal of the wax sealant is probably the most critical step of the entire operation. The wax should cover the entire hole surface so the immersion deposit is not damaged during the mild etching operation of Step 9; then the wax should be removed with sufficient care so as not to disrupt the film mechanically. If the immersion deposit is insufficiently protected in these operations, opens could occur in the film and a faulty plated-through connection would result. Masking of the tie-in conductors in Step 12 is desirable so that metal build-up does not occur over them, and their subsequent removal can be expedited.

Exposure of the dielectric surfaces to the plating solutions is the most serious disadvantage of the "negative process." The insulation resistance of some of the epoxy-glass laminates in previous investigations has been degraded by the plating solutions.[6] Noticeable deterioration of the copper-laminate bond has also been observed; therefore with some base materials it may not be possible to use the "negative process" unless the surface is adequately protected with a suitable coating.

The "Positive Process" -- Because of its more direct approach the "positive process" has been almost universally adopted for mass production of plated-through connections. In this process several of the critical operations mentioned with the "negative" procedure are eliminated. There are a number of slight variations in the sequence of operations from manufacturer to manufacturer, but the procedure outlined below is essentially representative of the process.

1. All the necessary holes are drilled in the board by use of a drill jig.
2. The copper and hole surfaces are thoroughly cleaned.
3. The copper and hole surfaces are immersion sensitized.
4. The board is rinsed thoroughly in running water.
5. The copper surface is sanded to remove the immersion-deposited copper since this is not a suitable base material for developing good adhesion with the subsequent electroplated deposits.
6. The positive pattern is photoexposed on the copper. (The desired wiring pattern remains uncoated with resist as a result of this preparation.)
7. The desired thickness of copper is plated on the conductors and through the holes.
8. The solderable metal which will serve as the resist is then plated.
   a. If tin-lead is used, the subsequent etchant is chromic acid.
   b. If gold overplate is used, ferric chloride is used as an etchant.
9. The board is thoroughly rinsed in running water.
10. The photo resist is removed.
11. The unwanted copper is then removed by etching.

When the plated-through process was first introduced, the "negative process" was preferred because the organic resists were not chemically resistant to the plating solutions. Suitable impervious resists as well as milder plating solutions operating at much lower temperatures have since been developed.

During the sanding operation mentioned in Step 5, it is extremely important to prevent damage to the immersion copper deposit particularly where the film forms a bridge between the hole and the land.

The proper alignment and registration of the pattern to coincide with the drilled holes within the required tolerances is one of the most important features of the "positive process." In production this is expedited by using alignment holes or pins on the photo positive so that superimposition on the clad laminate is accomplished within ±0.005 inch or less.

The plated copper must be dense and of uniform thickness throughout the cross section of the hole. These properties may be readily achieved with recently developed solutions.[7] The build-up of nodules or excess copper thickness at the opening of the holes must be avoided since these thick sections may cause interference during insertion of component leads into the finished printed circuit boards.

The solderable overplate must be sufficiently dense and thick to protect the base copper during the etching operations. Tin-lead 0.0002 to 0.0003 inch in thickness and gold 75 to 100 millionths of an inch in thickness have been found adequate as resists. Before the development of the dense, fine-grained gold plating solutions, most printed circuit manufacturers insisted on using about 0.0002 to 0.0005 inch of silver under the gold to insure the etch-resist properties of the gold overplate. This precaution is no longer necessary in the industry because of recent developments in gold-plating solutions.[8, 9]

One of the manufacturers uses an underplate of nickel with the gold, but this is primarily for purported strengthening of the copper.[10] The present investigations indicate that the nickel does not sufficiently improve the mechanical properties of the plated-through connection to justify the additional cost.

When the electroplates are used as resists, the galvanic couple established with the base copper accelerates the dissolution of the latter during etching. As a consequence, pronounced undercutting of the copper conductors may result if the boards remain unnecessarily long in the etchant or if the etchant is substantially spent. Therefore the time in the etchant must be more carefully controlled than is normally required with the organic resists. It is claimed that, with a recently developed commercial acid gold solution, it is possible to minimize undercutting because of the lower potential difference existing between the acid gold and the copper. To date this particular claim has not been substantiated by any of the Sandia Corporation suppliers.

Visual inspection at each stage in the preparation of the plated-through connection must be performed. In this manner it can be determined whether adequate controls are maintained during drilling, sensitizing, plating, and overplating. A continuity test specimen should be produced with each group of printed circuit boards during the development, preproduction, and production stages of the process. By making resistance and current-carrying capacity measurements of these specimens, it can be established whether the process is under control and the plated connections conform to the requisite quality.

The Evaluation Program

The evaluation of the plated-through connections was commenced about a year and a half ago primarily because printed circuit modules for the APAR (Automatic Programming and Recording System) or the ADS (Automatic Data System) program had adopted this type of interconnection (see Figure 1). At that particular time, dependable production processes had not been developed; therefore, it was necessary to institute an evaluation program both to determine the quality of the interconnection as well as to select suitable suppliers.

From the very inception of the program, the manufacturers were impressed with the need to develop copper immersion or copper reduction techniques. They were informed that for eventual Sandia Corporation applications only this basic process would be acceptable, since the silver and carbon paint processes had already been found unsuitable for reasons stated previously in this report. The quality of the plated-through connections was determined through electrical, visual, and cross-sectioning examinations. Each of these procedures will be fully described in the next section.

Careful records were kept of the quality of the plated-through connections as received, the compliance with purchase order specifications, the promptness of delivery, the cost per printed circuit specimen, and the stability of the plated-through connections under the various test environments.

At first boards were evaluated only from suppliers who were immediately considered as sources of APAR modules. Later, however, the printed circuits of several other prominent suppliers were also included in the studies.

From these evaluations, information useful for design purposes, process testing, and inspection procedures was accumulated.

Testing of the Plated-Through Connection

1. The Continuity Pattern -- All the tests performed on the plated-through specimens were conducted using a printed circuit continuity test pattern containing 17 plated-through connections. This printed circuit board with its continuity test pattern is shown in Figure 2. Of these 17 plated-through connections, 15 are in series and connected to each other by lines forming a continuous electrical path through the printed circuit board. The pattern is alternately produced from one side of the board to the other by means of the plated-through connections. This pattern was selected because it can be conveniently used for resistance measurements, and also it provides several rows of holes suitable for sectioning. The plated-through connections were encapsulated, sectioned through the diameter of the hole, and microscopically examined, as will be described in later sections of this report. This continuity pattern was produced by various suppliers using their own production techniques for fabrication and has been used as a means for evaluating the quality of the plated-through connections from these suppliers.

A modified version of the continuity pattern which is used for production inspection and evaluation is composed of only six plated-through connections in series (see Figure 3). Tests may be performed on this test pattern to determine thickness of the plated-through copper, electrical resistance, current-carrying capacity, and other desired properties without destroying the principal printed circuit board. The test pattern may be located in any available space, such as in some unused portion on the printed circuit board, where it will either form a permanent part of the pattern proper or be conveniently removed as required. The test to be performed may be done at any time during the fabrication of the board, thus making it possible for a supplier or user of the board to perform the necessary test at any convenient time. This continuity pattern has been adapted for use on the printed circuit boards for certain electronic packages in the Sandia Corporation system and has proven satisfactory for in-process or preassembly testing of plated-through connections. Similar continuity patterns are being used by two suppliers for quality control of the plated-through connections during production. This test performed by these two suppliers is supplementary to the visual inspection which is the only one normally used by other manufacturers for in-process examination.

2. Resistance Measurements -- Resistance measurements of the continuity pattern were made using a Northrup Type S test set 5300 in a Wheatstone bridge circuit. The resistance measurements, made on the continuity patterns received from the various suppliers, varied in resistance from 15 to 50 milliohms. Because the contact resistance of the test set switch contacts and the resistance of the test leads are approximately the same as the value of the resistance of the pattern, it is difficult to make an accurate measurement unless proper interconnection is made between the meter and the pattern. Since many resistance measurements were required during the plated-through connection study, positive electric continuity between the pattern and the instrument were very rapidly made through small clamps soldered directly to the test leads. By this arrangement the resistance of the pattern could be read to within 1 to 2 milliohms of the exact value.

The resistance measurement was very useful for determining the quality of the plated-through connections before and after the various tests. Changes occurring in the plated connections as a result of soldering and unsoldering, current-carrying tests, thermal cycling, elevated temperature exposure, and shock and vibration tests were determined by the resistance measurements. The resistance of the individual plated-through connection was on an average less than 1 milliohm, and the resistance of the interconnecting line was on an average 4 milliohms. The cross-sectional area of copper in the plated-through connection was on an average 200 square mils, and the cross-sectional area of the connecting line was on an average about 500 square mils. The connecting line was about 20 times the length of the plated-through connection. This would partially account for the resistance difference of the plated-through connection and connecting line. The resistance measurement is a practical test because it indicates the approximate thickness of plated-through copper and also is an indication of the plating quality on any printed circuit board.

Continuity pattern resistance measurements in milliohms versus current in amperes at burnout were plotted and are shown in Figure 7. The curve on this graph indicates the maximum current which can be carried by the modified continuity test pattern without permanent change or damage resulting to the printed circuit board. There are inconsistencies between some of the resistance and burnout current measurements, and at the present time there are no valid explanations for these discrepancies. A graph of resistance versus the thickness of the plated-through copper was also plotted, but because of insufficiently accurate measurements, a satisfactory relationship could not be produced from the available data. The data in Table III may also be used for determining the line widths consistent with the desired current-carrying capacities of conductors of varying weights.

TABLE III

Cross-Sectional Area of Etched Lines

Line width (mils)	1-Ounce		2-Ounce		3-Ounce	
	Mils^2	Circular mils	Mils^2	Circular mils	Mils^2	Circular mils
25	33.75	43.0	67.50	86	100	127.5
31.25	42.1	53.7	84.2	107.4	125	159.5
40	54	68.7	108	137.4	160	204
50	67.5	86	135	172	200	255
62.5	84.2	103.5	168.4	207	250	318
75	107	137.2	214	273	300	382
87.5	118	150	236	300	350	445
100	135	172	270	344	400	505
112.5	154	196	308	392	450	572
125	168.5	215	337	430	500	638

3. Resolderability Tests -- In these tests wires of suitable diameter were soldered and unsoldered through the holes 10 times to simulate component replacement in a printed circuit board. The plated-through connection was brought to room temperature between the soldering operations. In this manner soldering as actually encountered in practice during repair operations was simulated. Since plated-through connections are to be used extensively in repairable boards, it is necessary to determine the resistance of the plated-through copper to thermal shock. Plated-through connections when soldered with a 25-watt iron may withstand considerably more than 10 soldering cycles, as exemplified by as many as 150 remakes in studies conducted by one supplier. Of course this resistance is predicated on copper plate about 1.5 mils or more in thickness. Future tests are to be conducted with 0.5-mil-thick copper plate, and also a combination of 1.5-mil copper with an overplate of 0.7 mil of nickel, as a completion of the thermal shock studies.

Until more data have been accumulated with soldering irons of different wattage, instructions should be issued for assembly and repair of printed boards with plated-through connections. After soldering, the plated-through connections are encapsulated, sectioned, and microscopically examined as described previously.

4. Cross-Sectioning Plated-Through Connections and Microscopic Examinations -- After the pertinent tests have been conducted on the plated-through connections, the board specimen is encapsulated in a clear epoxy resin and then properly sectioned through the diameter of the holes. The sectioned surface is suitably polished and examined under a microscope. This visual examination will reveal:

1. Whether hole has been drilled from one side or from both sides of the board, or whether it has been punched.

2. Whether delamination of the glass cloth plies has occurred.

3. The thickness, granular structure, density, pin-hole count, and buildup of the copper through the hole.

4. Whether electrolyte entrapment between the copper and the hole surface has occurred.

5. Effects of soldering on the plated-through copper and the base material.

6. Uniformity of plated-through copper in the holes and at the hole-land junction.

7. Effects of cleanliness and processibility on subsequent adhesion of the plated copper to the hole surface.

8. The exact diameter of the holes.

9. Registration of the pattern from one side of the board to the other.

10. Extent of oxidation of the plated-through connection as a result of exposure to high relative humidity and elevated temperatures.

5. Current-Carrying Capacity Tests -- Resistance measurements were made on five boards from each supplier prior to the current-carrying test. The boards were then connected to a low-voltage, high-current source in series with a carbon pile variable resistor. The current was increased in steps as follows:

5 amps for 1 minute
10 amps for 1 minute
15 amps for 1 minute
20 amps for 1 minute

After the last run of 20 amps for 1 minute, the board was allowed to cool and another resistance measurement made. The current was then immediately increased to 25 amps and thereafter increased in increments of 5 amps. Each of the currents was carried for a period of 30 seconds. The test was continued either until the printed conductor or the plated-through connection burned through, or until 50 amps had been carried for 30 seconds. The burnout current for the different continuity patterns varied from 15 amps to 40 amps. Individual holes and groups of two holes in series carried currents as high as 50 amps, and none of the through-connections tested burned out at currents less than 20 amperes. High temperatures produced by these currents actually softened and distorted the epoxy-glass laminates in the printed boards.

The initial resistance measurement or the current recorded at burnout is an excellent measure of the quality of the plated-through connection. Either one or both of these tests may be used as a practical production procedure for determining the quality of the through-plated copper.

6. Temperature Cycling Tests -- The continuity specimens were cycled from 165° to $-65^{\circ}F$. If the boards were separated so that adequate air circulation could occur, temperature equilibrium could be reached within a few minutes; however, they were maintained at each of the temperatures for an hour or longer.

Because of the difference in thermal coefficient of the plated connection and the base laminate, thermal cycling was considered a fast, practical method of determining the magnitude of stress which would develop between the two materials. It was anticipated that the relatively porous copper interconnect would separate at the hole-land juncture. The recommended use of nickel plate over the copper by one supplier is primarily to minimize and eliminate separation failure of this type.

Interconnects produced by the different manufacturers with plated copper about 1.5 mils thick satisfactorily withstood 50 or more thermal cycles without failure and without any significant changes in pattern resistance. Ordinarily if an interconnection fails, whether it is an eyelet, a fuzed eyelet, a stake, or a plated-through connection, failure will be manifested within 5 to 10 cycles, and thereafter the resistance increases very rapidly until it reaches an infinite value.

Plated-through interconnects which are produced under the controls outlined in this report will not fail on thermal cycling.

7. Elevated Temperature Exposure (250°F) -- Two groups of boards were exposed to 250°F for 1000 and 500 hours, respectively. Resistance measurements were made on each of the boards prior to exposure. Resistance measurements were made on the first group after 5, 10, 25, 50, 100, 250 and 500, and 1000 hours. Wires were soldered through all of the holes in this group to simulate the conditions that would be experienced with components mounted on the board. No appreciable resistance change was noted in any of these measurements. The second group of boards was tested after 500 hours exposure, and again no appreciable resistance was noted. The boards of both groups changed to a dark brown color after approximately 50 hours of exposure at 250°F.

Thermal expansion of the base laminate and the copper was initially considered significant enough to cause separation of the plated-through copper. This condition, however, was not manifested even after the prolonged exposures described above. Corrosive constituents which were released as out-gassing products from the base laminate at elevated temperatures tarnished the plating on the conductors. The gold plate was severely tarnished by the out-gassing products and resisted soldering except when excess flux was used. On the other hand, solderability of the tin-lead plating was not materially affected by the oxide formation, probably because the alloy plating readily melted, and the oxides were effectively floated away.

8. Exposure to High Relative Humidity -- The plated-through connections were unaffected by exposure to 95-percent relative humidity and room temperature. Stability of the connection was again determined by means of the resistance measurements before and after the test.

Specimens were also exposed to 95-percent RH and 165°F for 24 hours, but once again resistance values showed that the plated interconnect was completely stable in the environment. This test may also be used for determining the presence of entrapped electrolyte behind the copper plate. Entrapment is manifested by severe discoloration and oxide formation in the hole and the adjacent portions of the land.

9. Shock and Vibration Tests -- Two different groups of printed circuit boards with plated-through connections were shock and vibration tested to determine the detrimental effects of these tests. In the first group, four components (two resistors and two capacitors) were mounted on each board. The boards were shock and vibration tested in both directions on all three axes, with resistance measurements being recorded before and after each change in axis. Both leads broke on 7 capacitors, and one lead broke on 20 capacitors, but none of the leads was broken on any of the resistors. The mass of the capacitor was larger than that of the resistor and the mass center was located higher on the board than that of the resistor. This mass difference plus the smaller wire size of the capacitors would explain the high incidence of broken capacitor leads. There was no appreciable change in resistance in the first group of boards due to shock and vibration.

No components were mounted on the boards in the second group. An initial resistance measurement was made prior to the test and again at the completion of the test. The shock and vibration tests were much more severe than normally required by Sandia specifications. The shock was as high as 100 g's and vibration was as high as 30 g's. The electrical resistance of the continuity pattern did not change as a result of these tests.

10. Detrimental Effects of Elevated Temperature and High Relative Humidity on the Under-Surface of the Plated-Through Connector -- The effects of high relative humidity, elevated temperature, and electrolyte entrapment on the copper interface next to the laminate surface were of interest in this study. By removing the lands from both sides of the plated-through connections and pulling the plated-through copper shell from the hole, the surface is made available for visual examination. The plated-through copper may be removed by soldering a wire through the hole and then pulling on the wire with a tensile machine.

When available, three specimens from each supplier represented were tested. Specimens were extracted from printed boards which had not been environmentally tested, and also from boards which had been exposed to 250°F for 500 hours, exposed to 95-percent relative humidity and 165°F for 24 hours, or subjected to ten soldering and unsoldering tests. The surface of the recovered copper interconnect was then examined microscopically for voids, oxidation, and other detectable evidence of thermal, mechanical, or chemical damage. The accompanying enlarged photographs (see Figure 8) of the copper specimens show the difference in oxidation of one specimen from each of the three conditioning environments enumerated above. A fourth group of specimens (which were not photographed) consisted of the soldered and unsoldered samples which were almost identical in appearance to those exposed to the elevated temperature. The particular specimens photographed were selected because they exhibit greater contrast in oxidation of the copper.

The force in pounds required to pull the copper interconnects from different manufacturers' boards was determined by pull tests conducted with a Dillon tensile machine.

The plated interconnects produced in epoxy-glass laminate exhibited only slight decrease in shear strength as a result of the solderability test, whereas the plated-through shells in XXXP phenolic paper laminate retained no measurable adhesive strength after soldering. The interconnects in the XXXP printed circuits were produced with silver paint as the premetallizing agent, and therefore clearly illustrate the superiority of the copper reduction sensitizing process. The epoxy-glass specimens tested under the other conditioning environments exhibited no detectable decrease in shear strength as a result of the particular exposures.

11. Pull Tests on Plated-Through Connections -- This destructive test was devised as a means of determining the shear strength of the plated interconnect. When a No. 18 copper wire was soldered through the hole and a load of about 30 to 35 pounds was applied with the Dillon tester, the wire commenced to elongate, thereby nullifying the test.

A No. 16 wire was also used, but elongation likewise resulted at a loading of 50 to about 55 pounds. Since larger wires could not be soldered in these particular interconnects, the test was discontinued. It is obvious, however, that the shear strength of the plated interconnect exceeds 55 pounds or a loading which would never be approached in practice.

12. Thickness Requirements of the Plated-Through Connections -- In the present investigations, plated-through connections of 1.5 mils nominal thickness were evaluated. Of course, in some cases the thickness varied noticeably from manufacturer to manufacturer and was consistently on the high side of this nominal value.

For most applications, copper 1.5 mils thick would be more than adequate because in all tests burnout was not experienced until a minimum of 20 amperes was carried by the tested interconnect. Since in most printed circuit applications current-carrying requirements are considerably below this value, the plated interconnect could be less than 1.5 mils thick. Many of the manufacturers, however, prefer to deposit at least this much copper as a standard practice, and have admitted that the difference in cost of producing 1.5 mils and that of producing 2.0 or even 2.5 mils is negligible. From a reliability standpoint, therefore, it may be advisable to stipulate a minimum of 1.5 mils of copper plate since the price differential is negligible.

Since in some miniaturized packages it may be necessary to minimize the plating thickness because of hole diameter and space limitations, boards with plated-through connections with about 0.5-mil copper thickness have been ordered and will be evaluated in the very near future.

Reliability of Plated-Through Connections

During the past 5 years, there has been a great deal of controversy over the reliability of electrical connections through printed circuit boards. Comparisons have been made to show the superiority of one type of connection over another, and the various proponents of the different types have formulated strong cases for their specific interconnect. Usually the evidence has been extremely detrimental to the "unsatisfactory" connections whether sufficient supporting data were available or not.

The different interconnects can probably all be made reliable when produced under controlled conditions; but, unfortunately, when a number of specific mechanical operations are required to produce the connections, such as inserting, crimping, and soldering of an eyelet, too much depends on human judgment and machine variability. It is also impossible to write a specification to insure their reliability, since mechanical connections are extremely difficult to inspect for minute flaws which may subsequently contribute to failure.

In the production of plated-through connections, controls during copper deposition can be precisely maintained, as has already been demonstrated by the evaluations in Sandia Corporation and by those at any of several suppliers and users.

During and after processing, imperfections in a plated-through connection can be detected immediately by visual inspection; therefore, a high standard of quality is attained by a very positive and very rapid means of examination. The visual inspection may readily be supplemented by resistance measurements, current-carrying capacity measurements, and the other tests already described in this report. The high quality of the plated connection, therefore, is established because of the systematized controls practiced in fabrication and because of the thorough techniques adopted in inspection. Continuance of systematized production and inspection procedures is mandatory if this high incidence of reliability is to be repeatedly achieved.

Had similar fabrication and inspection techniques been developed for eyelets, stakes, feed-throughs or other electrical connections, perhaps the same degree of reliability achieved with plated-through holes would have been attained.

The composite properties of plated-through connections as produced commercially are tabulated in Figure 9.

Use of Plated-Through Connections in Various Electrical and Electronic Components

Use of the plated-through techniques has been made primarily in the printed wiring industry; however, the processes may be used with equal success in resistor, capacitor, relay, timer, microwave, etc. applications. The use of the plated connections is not recommended in printed boards less than 1/32 inch in thickness for Sandia Corporation applications; however, developmental evaluations conducted by General Mills, Inc. have illustrated that plated holes 10 mils in diameter may be successfully produced in a dielectric about 15 mils thick. The most detrimental effect on the stability of the plated connection in a thin supporting dielectric would be produced by the flexure properties of the latter.

Plated-through connections may be produced with equal reliability on glass, ceramic, quartz, or plastics; therefore the techniques are suitable for producing satisfactory metallic adhesion to high-temperature base materials. Versatile materials such as Fotoceram may acquire unexplored uses as a result of the advances in the plated-through technology.

It is also possible that by adoption of plated-through techniques, the difficult problems of interconnection and of individual component preparation in the microminiaturization developments may be solved.

Plated-through connections are used extensively in printed circuit boards for computer and various military applications. In both areas reliability has been a prime consideration, and apparently this has been most effectively achieved with plated-through connections.

Quality Control and Specification for Production of Plated-Through Connections

Most suppliers are using adequate controls in production for developing quality plated-through connections. Techniques in drilling, cleaning, sensitizing, and plating are very specific. The time, temperature, current density, agitation, solution concentration, diameter of the hole, and thickness, size, and shape of the printed circuit board are all important factors in the chemical processing of the plated connections and are the significant parameters in producing the desired plating thickness. Of course systematized visual inspection, as mentioned previously, is an indispensable tool for determining whether in-process quality is being attained.

The external, electrical, and microsectioning tests outlined in TR-145798 Test Requirements For Printed Wiring Board were devised for the XMC-656 package as supplemental to the control and inspection procedures used by the manufacturer. Plated-through connections may also be optionally produced with Drawing 400194; however, this specification does not require supplemental testing of the interconnects. In time it is anticipated that fabricators will develop more direct techniques for measuring the quality of the plated connections.

Future Studies with Plated-Through Connections

The following evaluations should be conducted in future studies with plated-through connections:

1. Suitability of plated-through connections in flexible laminates 1/64 inch or less in thickness.
2. Suitability of plated-through connections in ceramic and glass base materials of various thickness.
3. Suitability of plated-through holes in epoxy paper laminates.
4. Applicability of plated-through connections in microminiaturized packages.
5. Practicality of producing printed circuits by the additive process.
6. Determination of the optimum diameter of plated connections in boards of various thickness.
7. Determination of the minimum thickness of plated-through conductor which will withstand Sandia requirements.
8. Evaluation of the use of electroless nickel for anticipated applications at temperatures in excess of $500^{\circ}F$.
9. Re-evaluation of product of various approved suppliers periodically.
10. Periodic information from the approved suppliers on processing techniques.

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3. Sullivan, W. V., and Eigler, J. H., "Electroless Nickel Plating for Making Ohmic Contacts to Silicon," Journal of the Electrochemical Society, April 1957, Vol. 104, No. 4.

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6. Rinker, E. C., and Jahns, F. W., Jr., "Improved Baths Solve Lifting of Plated Circuit Foils," The Iron Age, June 19, 1958.

7. Sel-Rex Corp. Bulletin, Cu Sol Copper Plating Process.

8. Rinker, E. C., "Bright Gold Plating," Plating, August 1953.

9. Sel-Rex Corp. Bulletin 150B, Technical Data on Sel Rex Autronex Process, September 1958.

10. Geddy, George B., "The Tuf-Plate Hole for Printed Circuits," presented at IRE Meeting of Professional Group on Production Techniques on June 6, 1958.

Component side of board Reverse side of board

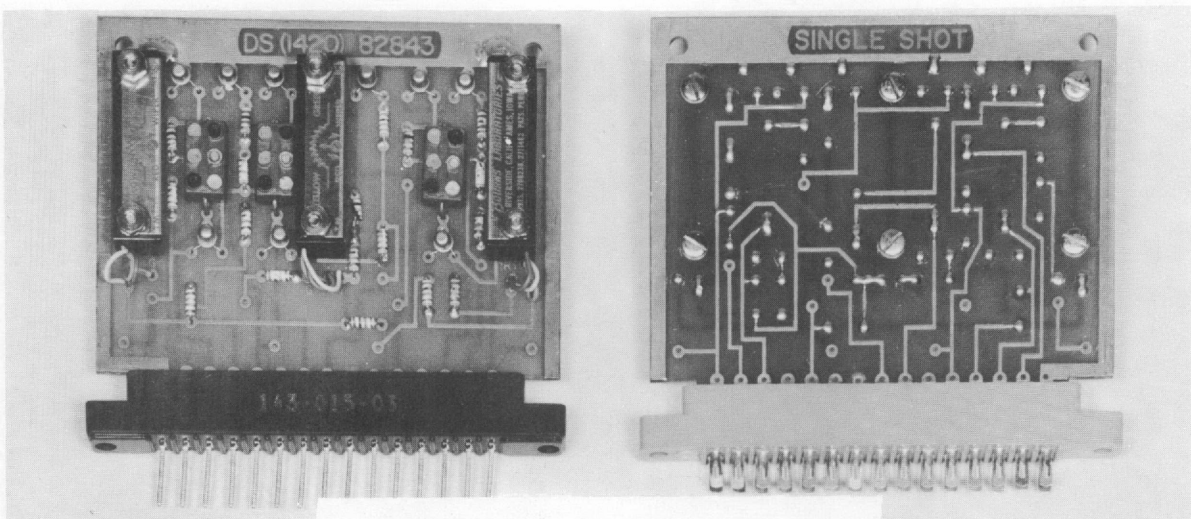


Fig. 1a -- Miniature connectors

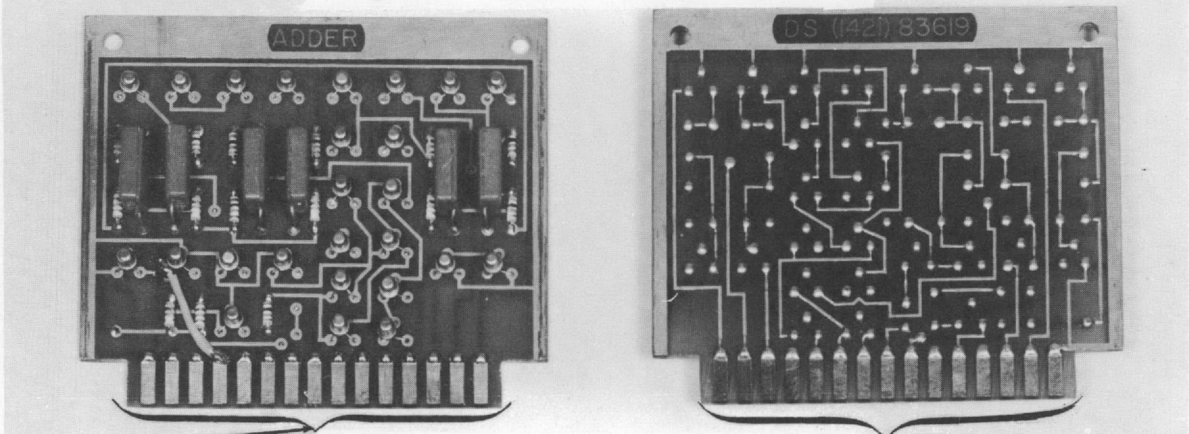


Fig. 1b -- Nickel-rhodium plate
Lead-tin plate on rest of circuitry

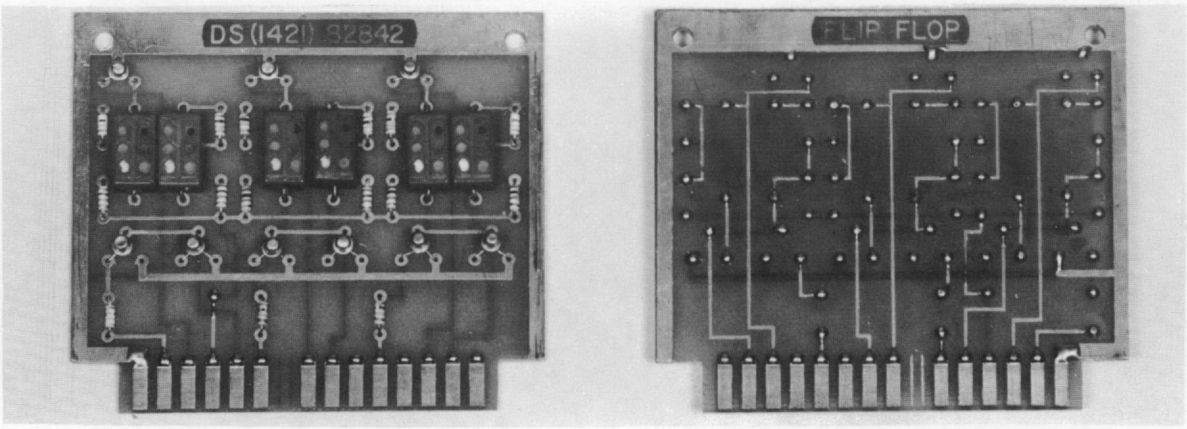


Fig. 1c -- (connections through the boards are plated-through holes)

Figure 1. APAR System Plug-In Units

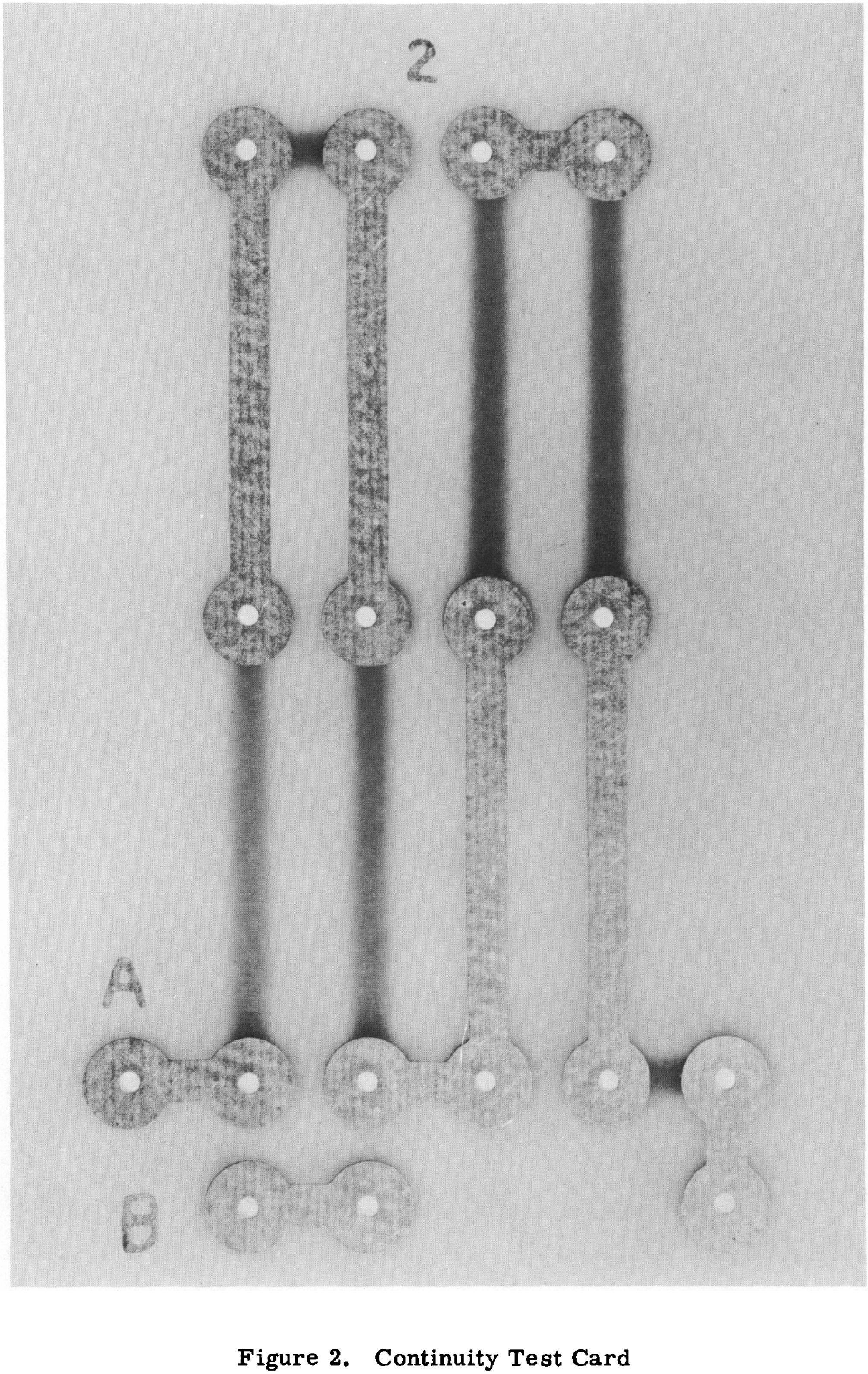


Figure 2. Continuity Test Card

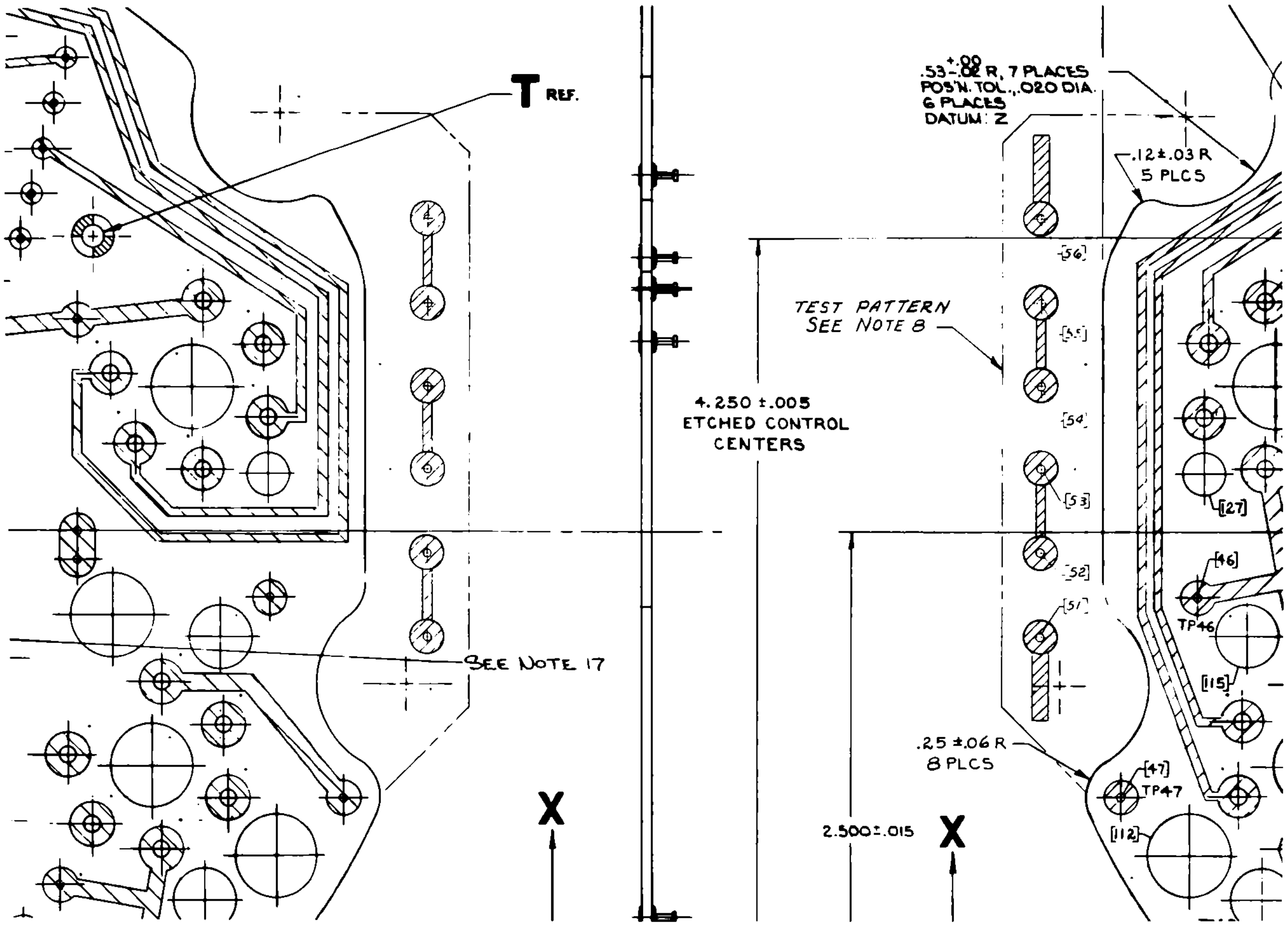
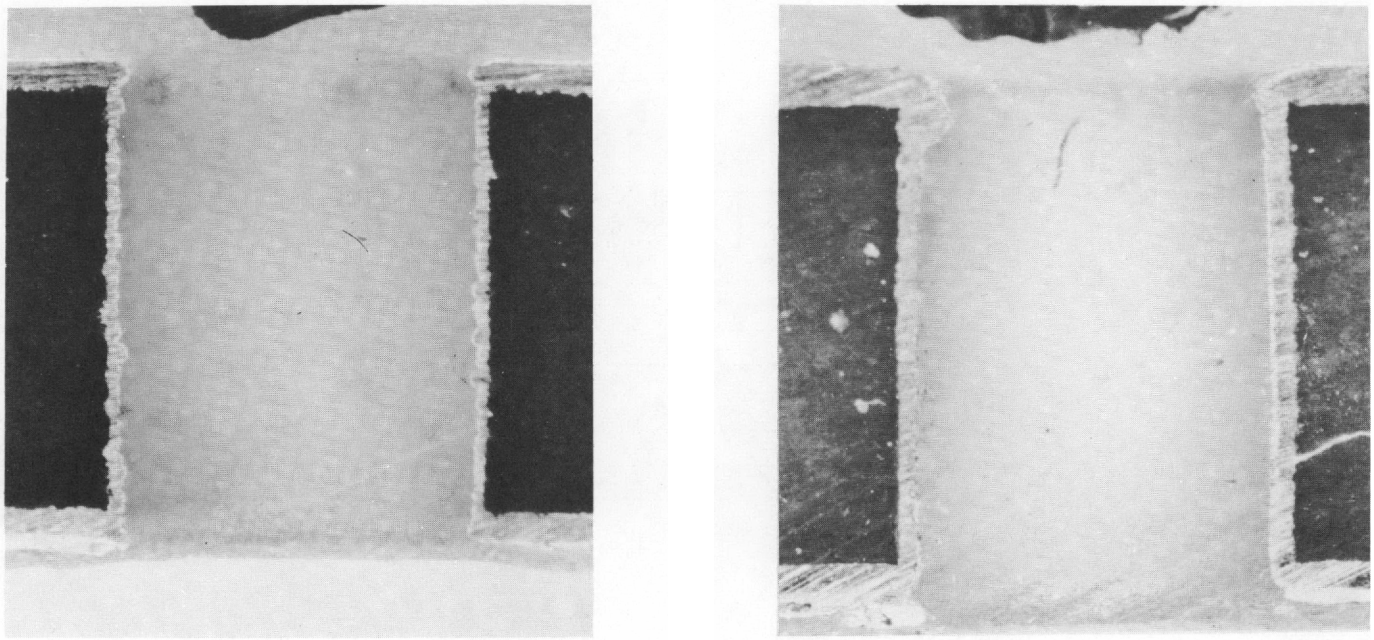
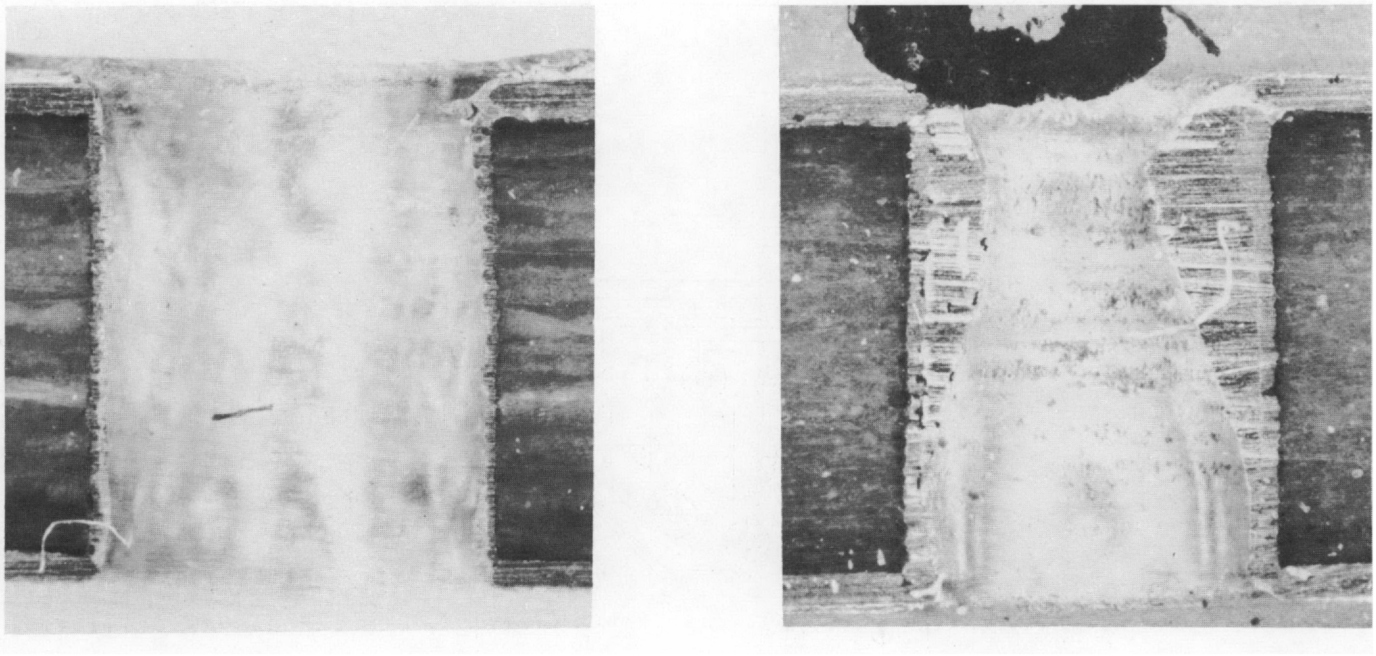


Figure 3. Continuity Card for Production Testing

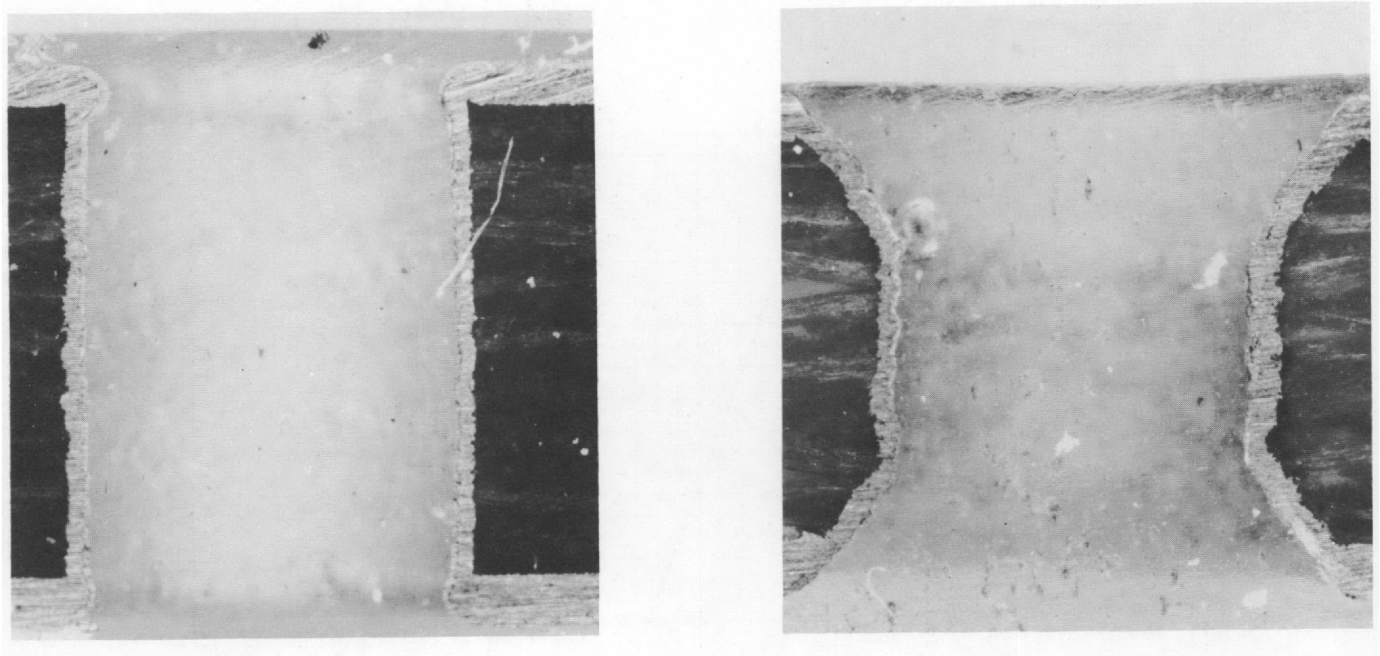


Unsoldered

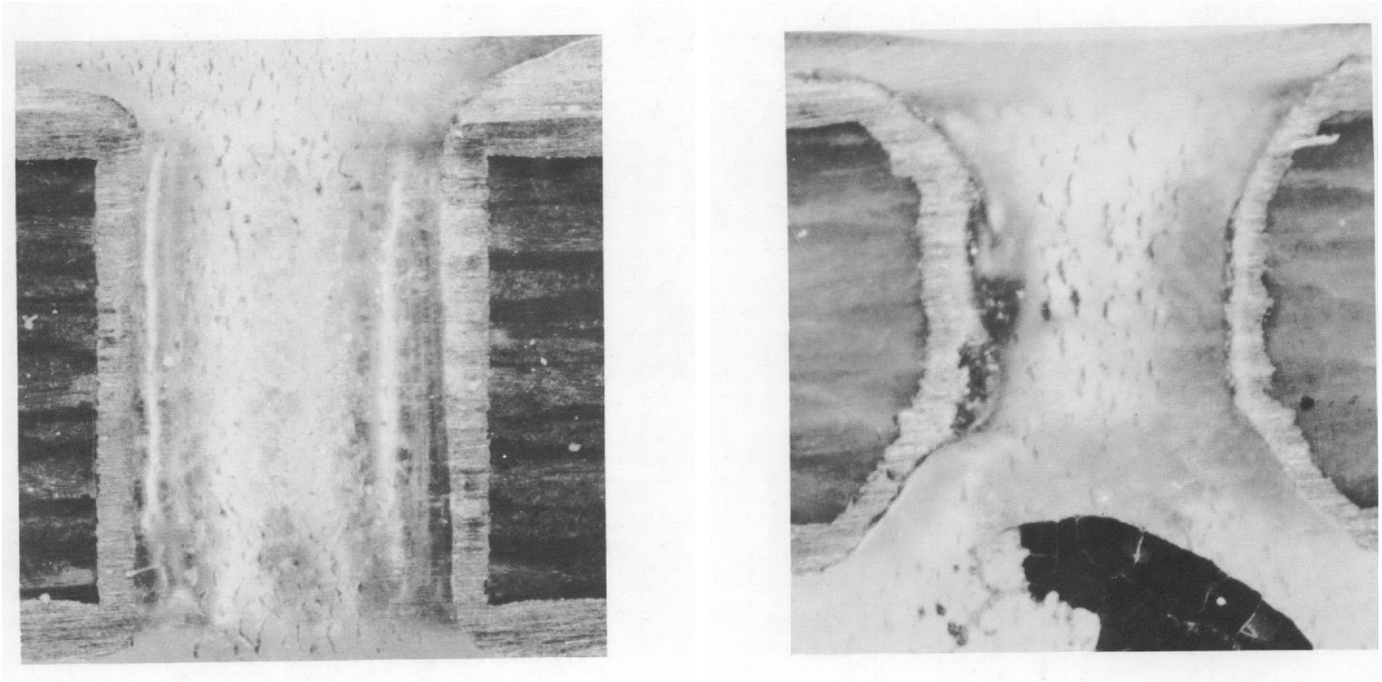


Soldered

Figure 4. Enlargements of Sectioned Plated-Through Connections



Unsoldered



Soldered

Figure 5. Enlargements of Sectioned Plated-Through Connections

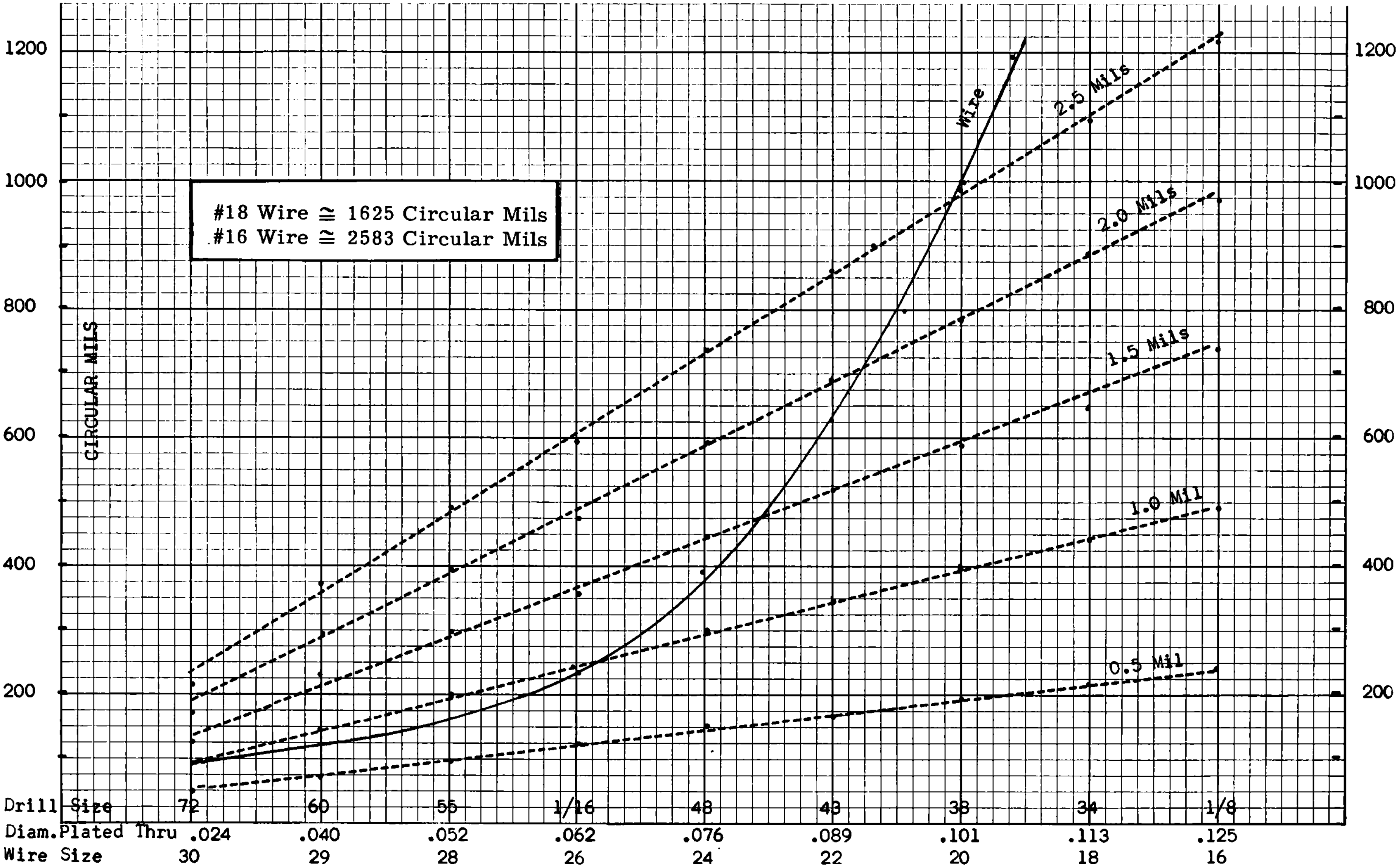


Figure 6. Comparison of Cross-Sectional Area of Standard Wire With Area of Plated-Through Connections of Various Thickness

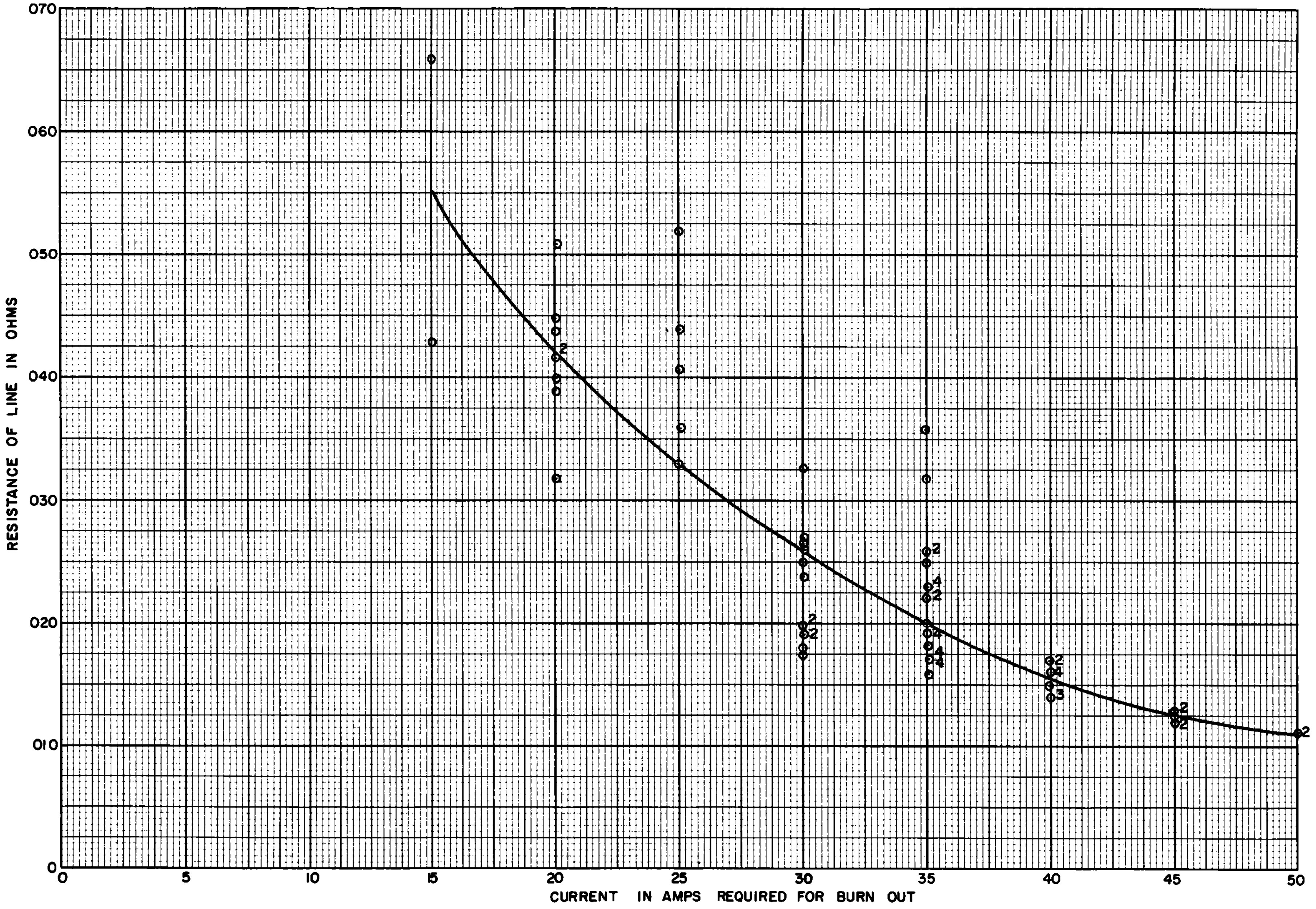


Figure 7. The Current-Carrying Capacity at Burnout Versus Resistance

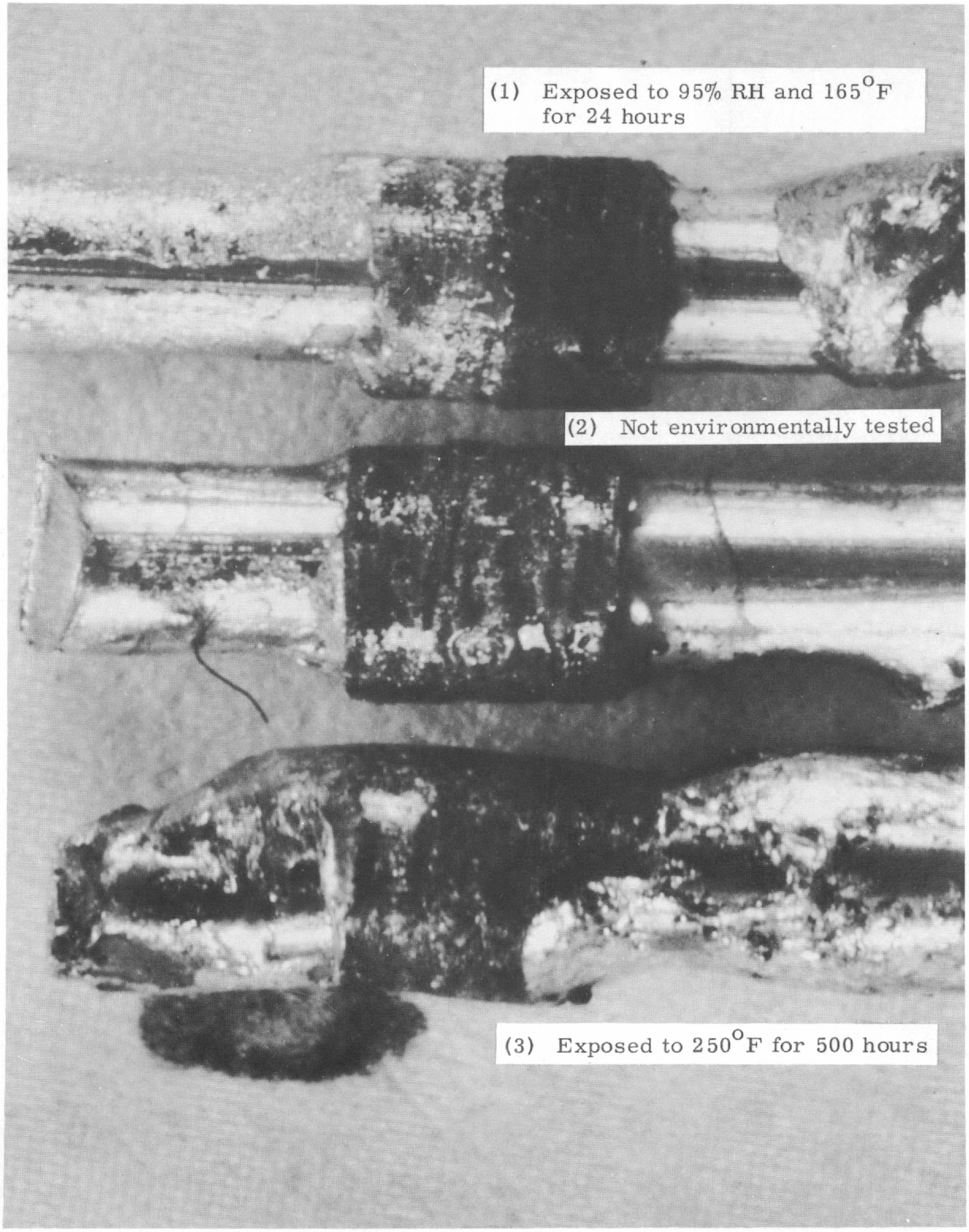


Figure 8. Recovered Plated-Through Connection

(1) Supplier	(2) $\frac{\text{No. of cards received}}{\text{No. of cards therm. cycled}}$	(3) Type of laminate 1/16-inch thick	(4) Sensitizing process	(5) Percent failures of received cards	(6) Average resistance / No more than 5 milliohms above average / % within range ±5 milliohms of average	(7) $\frac{\text{Thickness of plated-copper requested}}{\text{Thickness measured}}$	(8) Effects of soldering tests	(9) Type of surface plating	(10) Solderability of plating	(11) Solderability of plating after exposure to 250°F for 500 hours	(12) Effects of exposure to 250°F for 500 hours	(13) Current studies $\frac{\text{average resistance}}{\text{Current - Time to burnout}}$	(14) Time for delivery in days	(15) Cost per card in dollars
A	$\frac{48}{20}$	Epoxy glass	Colloidal copper	None	0.039 - 5 - 75%	$\frac{1.5}{1.2-1.9}$	None	Gold	Good	Good	Turned dark Very heavy tarnish		45	2.15
B	$\frac{48}{20}$	Phenolic	Colloidal copper	None	0.036 - 3 - 85%	$\frac{1.5}{1.2-1.9}$	Slight burning	Gold	Good	Good	Turned dark Very heavy tarnish		45	2.15
C	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.027 - 1 - 95% 0.034	$\frac{1.5}{1-1.5}$	Slight burning	Gold	Very good	Fair	Turned dark Very heavy tarnish	$\frac{0.021}{35 - 15}$	90	3.55
D	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.016 - 0 - 100%	$\frac{1.5}{2-2.5}$	None	Gold	Good	Fair	Turned dark Very heavy tarnish	$\frac{0.016}{35 - 20}$	45	1.30 $48 setup charge
E	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.023 - 0 - 100%	$\frac{1}{0.7-1.8}$	None	Gold	Very good	Good	Turned dark Very heavy tarnish	$\frac{0.017}{40 - 10}$	45	1.90 $25 setup charge
F	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.031 - 1 - 95% 0.041	$\frac{0.5}{1-1.3}$	None	Gold	Very good	Very good	Turned dark Very heavy tarnish	$\frac{0.024}{35 - 25}$	45	1.90 $25 setup charge
G	20	Epoxy glass	Silver paint	None	0.048 - 2 - 75% 0.056 0.069	$\frac{1.5}{1.5-1.8}$	None	Tin-lead	Very good	Good	Turned dark Slight tarnish	$\frac{0.038}{20 - 30}$	30	Gratis
H	$\frac{52}{20}$	Epoxy glass	Silver paint		0.035 - 0 - 100%	$\frac{1.5}{0.5-1.5}$	None	Tin-lead	Fair	Very good	Turned dark Slight tarnish		150	$575 total
I	$\frac{52}{20}$	Phenolic	Silver paint		0.068 - 7 - 40%	$\frac{1.5}{0.5-1.5}$	None	Tin-lead	Fair	Very good	Turned dark Slight tarnish		150	
J	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.035 - 1 - 90% 0.041	$\frac{1.5}{2-3.4}$	None	Gold	Very good	Poor	Turned dark Very heavy tarnish	$\frac{0.035}{35 - 10}$	60	2.40
K	$\frac{92}{20}$	Epoxy glass	Copper reduction	None	0.028 - 3 - 75% 0.071 0.035 0.036	$\frac{1.5}{2-3}$	Slight burning	Gold	Very good	Fair	Turned dark Very heavy tarnish	$\frac{0.045}{20 - 30}$	115	2.90
L	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.048 - 2 - 90% 0.070 0.055	$\frac{1.5}{2-2.5}$	None	Gold	Good	Good	Turned dark Very heavy tarnish	$\frac{0.045}{20 - 55}$	45	3.70
M	20	Epoxy glass	Copper reduction	None	0.033 - 2 - 90% 0.048 0.047	$\frac{1.5}{1.8-2.5}$	None	Gold	Very good	Poor	Turned dark Very heavy tarnish	$\frac{0.030}{25 - 20}$		1.60
N	20	Epoxy glass	Silver paint	None	0.034 - 0 - 85%	$\frac{1.5}{0.9-1.9}$	None	Tin-lead	Poor	Very good	Turned dark Slight tarnish		210	2.10
O	20	Phenolic	Silver paint	None	0.031 - 1 - 90%	$\frac{1.5}{0.9-1.9}$	Slight burning	Tin-lead	Poor	Very good	Turned dark Slight tarnish		210	2.10
P	$\frac{40}{20}$	Epoxy glass	Copper reduction	None	0.014 - 0 - 100%	$\frac{1.5}{1.8-2.2}$	None	Tin-lead	Fair	Very good	Turned dark Slight tarnish	$\frac{0.012}{45 - 30}$	30	4.45
Q	$\frac{40}{20}$	Phenolic	Copper reduction	None	0.016 - 0 - 100%	$\frac{1.5}{1.8-2.5}$	Slight burning	Tin-lead	Fair	Very good	Turned dark Slight tarnish	$\frac{0.014}{40 - 20}$	30	4.00
R	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.019 - 0 - 100%	$\frac{1.5}{1.8-2.8}$	None	Gold	Very good	Fair	Turned dark Very heavy tarnish	$\frac{0.015}{40 - 15}$	120	3.25 Photography $30/lot
S	$\frac{20}{20}$	Epoxy glass	Copper reduction	None	0.021 - 0 - 100%	$\frac{1.5}{1.8-2}$	None	Gold	Good	Fair	Turned dark Very heavy tarnish	$\frac{0.018}{30 - 30}$	60	5.00
T	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.024 - 0 - 100%	$\frac{1.5}{1.8-2.5}$	None	Gold	Very good	Fair	Turned dark Heavy tarnish	$\frac{0.018}{35 - 10}$	60	4.50
U	$\frac{80}{20}$	Epoxy glass	Copper reduction	None	0.025 - 2 - 90% 0.031 0.031	$\frac{1.5}{1.5-2}$	None	Gold	Very good	Fair	Turned dark Heavy tarnish	$\frac{0.020}{35 - 10}$	30	2.40

(4) Silver paint specimens were accepted prior to development of copper reduction process.
(6) Values above the plus 5-milliohm limit are listed.
(11) Solderability of tin-lead improved in all cases as a result of exposure to 250°F.

Figure 9. Data Sheet

No. of copies	Distribution
3	Aberdeen Proving Ground
1	ACF Industries-ERCO
1	Aerojet-General Corporation
1	Aerojet-General, San Ramon (IOO-880)
1	Air Force Ballistic Missile Division
1	Air Force Cambridge Research Center
1	Air Force Institute of Technology
1	AFPR, Boeing, Seattle
2	AFPR, Lockheed, Marietta
2	Air Force Special Weapons Center
2	ANP Project Office, Convair, Fort Worth
10	Argonne National Laboratory
1	Army Ballistic Missile Agency
2	Army Chemical Center
1	Army Rocket and Guided Missile Agency
1	Army Signal Research and Development Laboratory
1	Assistant Secretary of the Air Force, R & D
2	Battelle Memorial Institute
1	Booz-Allen Applied Research, Incorporated
4	Brookhaven National Laboratory
1	Bureau of Aeronautics
1	BAR, Aerojet-General, Azusa
1	BAR, Goodyear Aircraft, Akron
1	BAR, Grumman Aircraft, Bethpage
1	Bureau of Ordnance (Code ReS6a)
1	Bureau of Ships (Code 1500)
1	Columbia University (SOO-187)
1	Convair-General Dynamics Corporation, San Diego
2	Defense Atomic Support Agency, Sandia
1	Defense Atomic Support Agency, Washington
3	Defence Research Member
1	Denver Research Institute
1	Emerson Radio and Phonograph Corporation
1	Evans Research and Development Corporation
1	General Atomic Division
1	General Electric Company (ANPD)
1	General Electric Company, Philadelphia
1	General Electric Company, St. Petersburg
1	Goodyear Atomic Corporation
1	Jet Propulsion Laboratory
1	Knolls Atomic Power Laboratory
2	Los Alamos Scientific Laboratory
1	Martin Company
1	Massachusetts Institute of Technology (Ashby)
1	National Aeronautics and Space Administration, Cleveland
3	Naval Research Laboratory
1	Oak Ridge Operations Office
1	Office of Ordnance Research
1	USAF Project RAND
2	University of Calif., Livermore
1	Westinghouse Electric Corp. (Biondi)
6	Wright Air Development Center
325	Technical Information Service Extension, Oak Ridge
75	Office of Technical Services, Washington
483	