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MANUFACTURING PROBLEMS WITH PRINTED CIRCUIT BOARDS AND HOW TO AVOID THEM

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ABSTRACT

Low temperature exposure and specifically thermocycling of completed printed circuit boards often produce broken solder joints which are electrically either circuit interruptions or noisy joints. Glass-sealed components frequently crack or start to leak and finally fail. Printed circuit board and component materials with drastically different temperature behavior, compactly assembled without elastic media, are recognized as the major cause of failure. Stress relief loops, strong solder joints, and soft conformal coating plastic are suggested to prevent thermal stress and vibration failures.

INTRODUCTION

The conventional mounting of components to printed circuit (PC) boards no longer suffices since testing and exposure to preflight environments and severe flight conditions in space demand extended capabilities of electrical equipment. Forces from temperature changes and vibrations have broken many solder joints and glass-seals of components. The solder joint begins to crack at the heel of the clinched wire and progresses with time along both sides of the lead wire toward the terminating end. Cracking has occurred both in the solder material and in other cases between the solder and the component lead wire. The latter case was frequently observed at weldable materials, Nickel and Kovar.

FAILURE ANALYSIS

Experiments and theoretical analysis have clearly shown the causes of damage. A simple mathematical study reveals unexpectedly high stresses. Consider the mechanism of thermal mismatch of materials used in an assembly as shown in Figure 1. The temperature of the

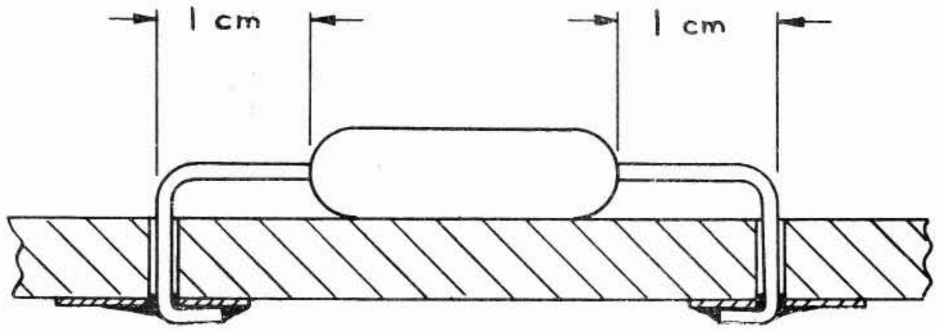

FIGURE 1. COMPONENT MOUNTING IN THE USUAL FORM

various parts in the force loop is of considerable difference during soldering; e.g., the lead wires may have had a temperature of 200°C when the solder started to solidify while the epoxy PC board was near room temperature. Thus, shortly after soldering, when cooled to 25°C, the lead wires and the component body are under tension; because of the temperature difference, the epoxy board did not shrink like the lead wires.

Copper also has a temperature expansion coefficient three times larger than the epoxy fiberglass board. When cooled in a low temperature test, the stresses further increase. By using dimensions and data from actual design, the difference of expansion or contraction can be calculated as follows: The expansion or contraction of the component body made of glass need not be considered because glass and epoxy boards have about the same expansion coefficient. The length differences between lead wires and board are of interest. The total lead wire length in horizontal direction is 2 cm. The thermal expansion coefficient is listed in Table 1.

The difference in length from +60°C to -60°C is

$$\Delta l = l \times (\beta \text{ copper} - \beta \text{ epoxy board}) \times \Delta t^{o}$$

$$= 2 \times ((16.5 \times 10^{-6}) - (5 \times 10^{-6})) \times 120 \text{ cm}$$

$$= 3 \times 10^{-3} \text{ cm } (0.0012 \text{ in.}).$$

The length difference of 3×10^{-3} cm causes stress forces in all mechanical members of the force loop. Wires and glass body are under tension, the PC board is under compression, and the solder joints may be under shear stress or tension. The cross-sectional dimension and moduli of

TABLE I. DATA OF MATERIAL

	Thermal Expansion $^{o}C \times 10^{-6}$	Mod. Elasticity kg/cm^2	Tensile Strength kg/cm^2
Amine Cured Epoxy	90	3.1×10^4	600
G 10 ⊥ to Board	60	13.3×10^4	
G 10 = to Board	$5 \div 10$	12.6×10^4	3000
Glass, Pyrex Corning	3.2	66.5×10^4	70
1538 Urethane	200	25 at 25°C 140 at 0°C 910 at -50°C	210
Copper	16.5	110×10^4	1260
Kovar Alloy A	5.5	140×10^4	5420
Nickel	13.3	210×10^4	3220
Solder 60/40	25	30×10^4	530

elasticity of the elements involved are used to tentatively calculate the forces. For simplification, we assume that the elastic deformation of the PC board is zero, because of its very large cross-section as compared to the lead wires and the glass body wall.

The stress σ is calculated as

$$\sigma = \frac{\Delta l}{l} \times E$$

$$= \frac{3 \times 10^{-3}}{2} \times 1.1 \times 10^{6}\ kg/cm^2$$

$$= 1.6 \times 10^{3}\ kg/cm^2.$$

The tension force F in the lead wire of 0.05 cm diameter or 0.002 cm^2 cross-section A is

$$F = \sigma \times A$$

$$= 1.6 \times 10^{3} \times 0.002\ kg$$

$$= 3.2\ kg\ (approx.\ 7\ lb).$$

From this calculation, which used some simplification, we conclude that low temperature can cause forces which the solder joint may not withstand. The glass body may fail even if the solder joint is strong enough to hold the force. When low temperature cycling is applied, the fatigue forces surely break the solder joint if it has not already failed during the first low temperature exposure. The previous calculations were made without considering the effects of the conformal coating. Broken solder joints caused by thermal stress have been experienced in uncoated boards as well as in coated ones. The coating makes the mathematical treatment of the problem more complicated and is not performed because of time and uncertainty.

Since we have investigated forces acting parallel to the PC board plan, we will now consider the thermal mismatch forces acting perpendicular to the board surface. Figure 2 shows a transistor mounted in a commonly used method.

The lead wires are threaded through the PC board holes, clinched, and soldered. In spite of the clinching, the spacer is mostly loose. Thus far, no stresses in the solder joints are indicated. After conformal coating is applied to fill all looseness with plastic, the polymerization at $+60^{\circ}C$ solidifies the coating. At that temperature, the

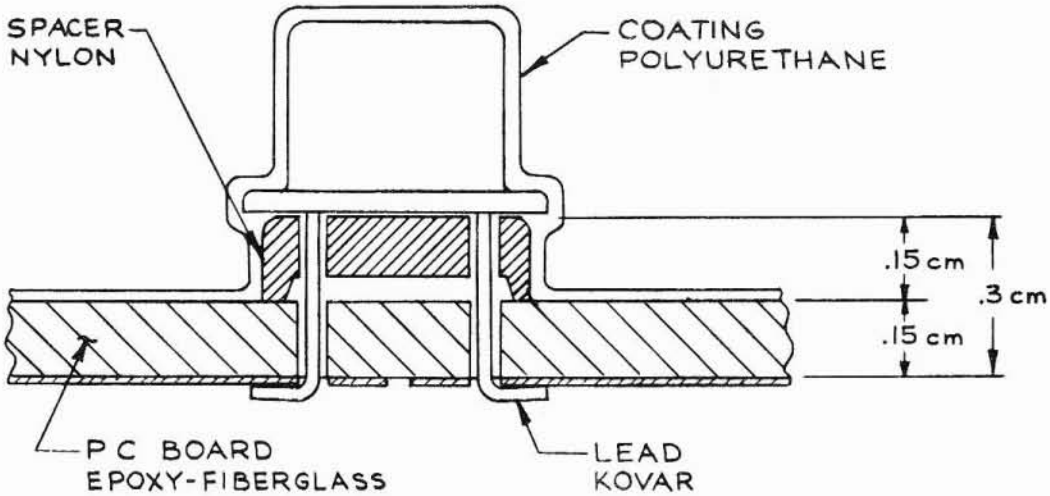

FIGURE 2. TRANSISTOR MOUNTING

system is still free of stress. When cooled to room temperature (25°C), all plastics, the nylon spacer, the polyurethane coating, and the epoxy board shrink much more than the Kovar lead wires; the results are compression of the wires and stress to the solder joints. The forces are possible because of the excellent bond strength of the conformal coating plastic. Still higher forces result from the low temperature exposure of -60°C.

The following calculation shows the change in dimensions and consequent stresses caused by thermal mismatch of the materials in a temperature range from +60°C to -60°C.

1. Polyurethane contraction:

$$\Delta l_p = l \times t \times \beta$$

$$= 0.15 \times 120 \times 200 \times 10^{-6} \text{ cm}$$

$$= 0.0036 \text{ cm.}$$

2. Epoxy board contraction:

$$\Delta l_E = 0.15 \times 120 \times 9 \times 10^{-5} \text{ cm}$$

$$= 0.0016 \text{ cm.}$$

3. Kovar lead wire contraction:

$$\Delta l_K = 0.3 \times 120 \times 5.5 \times 10^{-6} \text{ cm}$$

$$= 0.0002 \text{ cm.}$$

The total is $\Delta l = \Delta l_p + \Delta l_E - \Delta l_K$

$$= 0.005 \text{ cm } (0.002 \text{ in.}).$$

The total change in length of 0.005 cm is mostly absorbed by the softest member of the stress loop, since the modulus of elasticity of polyurethane even at -60°C is still two to three magnitudes smaller than the one of epoxy and Kovar, and the vast difference of the force carrying area of the Kovar leads does not compensate for the difference in E. The force can be approximated as follows:

$$\sigma = \frac{\Delta l}{l} \times E_{polyurethane}$$

$$= \frac{0.005}{0.3} \times 600 \text{ kg/cm}^2$$

$$= 10 \text{ kg/cm}^2.$$

The transistor can diameter is 0.6 cm; its area is 0.28 cm^2. The force acting against the three solder joints is

$$F = \sigma \times A$$

$$= 10 \times 0.28 = 2.8 \text{ kg (approx. 6 lb).}$$

or if equally distributed 0.93 kg (approx. 2 lb) per solder joint.

Although somewhat higher than intelligent estimates, calculations of shrink forces are still in fair agreement with the tests which have demonstrated the weakness of the design thousands of times. The fact that not all solder joints do break is attributed to the bending of the lead wire as it goes from the horizontal direction perpendicular through the board (Fig. 1).

COMPONENT MOUNTING

The calculations indicated high stress forces caused by mismatch of materials under thermal cycling. It cannot be expected to find materials with identical thermal behavior, but even if we could, thermal stresses would occur because the component parts would have different temperatures; e.g., during hand soldering or electric load. Therefore, the only available solution is to form expansion loops to minimize the destructive forces. Loops for a number of components, materials, dimensions, and other parameters have been developed, manufactured, and tested by temperature cycling within a wide range and large number of cycles. In all cases, the design approach of using expansion loops was successful. It is realized that this approach takes additional manufacturing efforts but it does solve the problem. Examples in Figures 3, 4, and 5 show the typical new mounting using specially formed wires (loops). A component mounting guideline and specification as a joint effort of the Institute of Printed Circuits (IPC), Army (Picatinny Arsenal), and NASA (MSFC) is in preparation. IPC has been well aware of these problems and has organized special committees and working groups to study printed circuit problems, especially thermal forces on PC boards during manufacturing, testing, and operation. The goal is to improve the reliability by new information for component mounting, joining, and conformal coating.

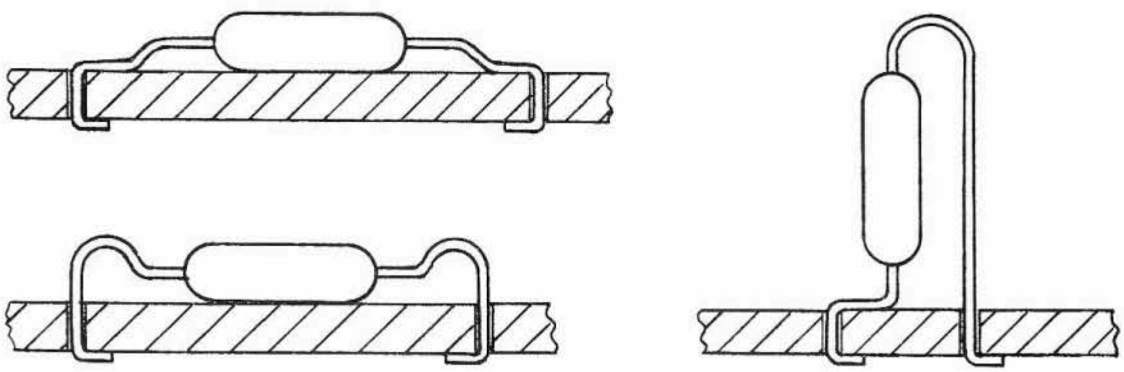

FIGURE 3. SUGGESTED CYLINDRICAL COMPONENT MOUNTING.

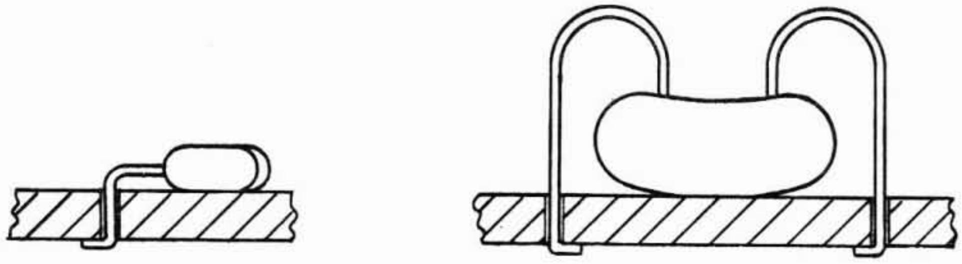

FIGURE 4. SUGGESTED CAPACITOR MOUNTING

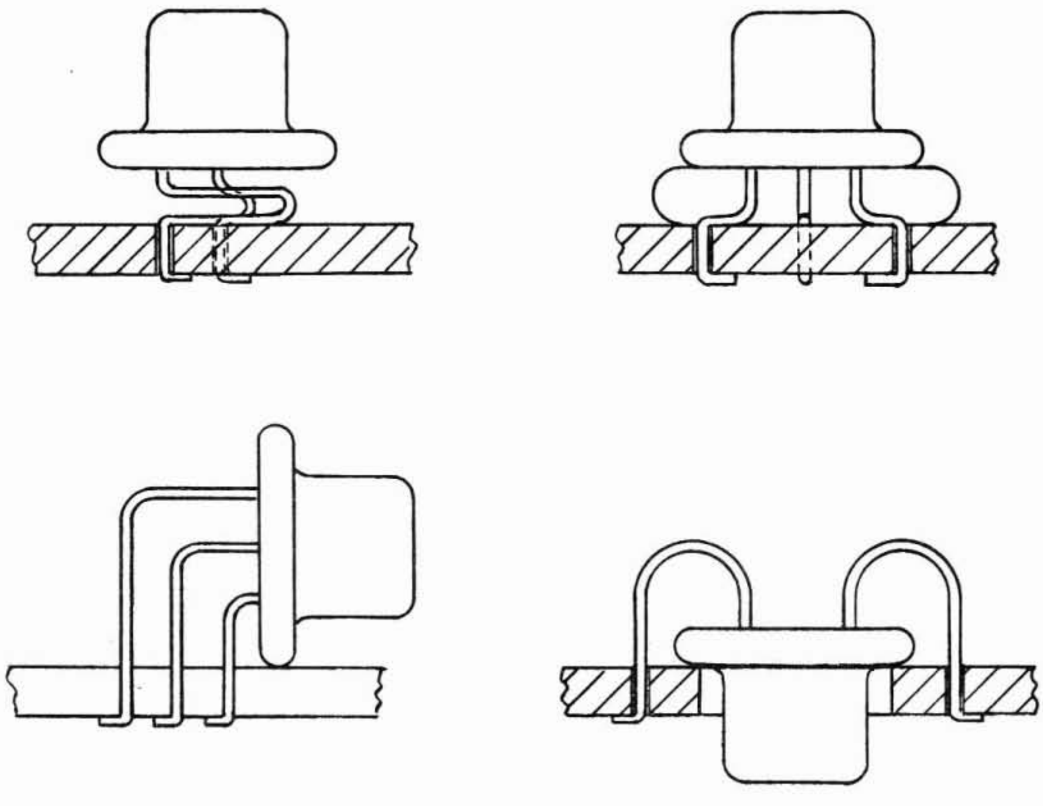

FIGURE 5. SUGGESTED TRANSISTOR MOUNTING

SOLDER PROBLEMS

As demonstrated by many tests, most weak or over-loaded solder joints break during the low temperature phase of the cycling because of excessive temperature strains. The failure mechanisms are well understood as demonstrated in Figures 6 through 10. As the printed circuit board and the conformal coating shrink in low temperature, the wire coming through the board to the solder pad is under compression. This compression force causes a bending moment to the solder joint which fatigues in time or breaks at the first cold cycle. The breakage begins at the edge of the joint where the highest force occurs. The strength of the solder material is very limited and the strength of the solder joint is especially weak when a minimum amount of solder is applied. The conditions become worse when a component lead is made of Nickle or Kovar, which are not as easy to solder as copper.

The technique of soldering has been exceptionally good whenever it was used in its realm of possibilities. The use of corrosive flux has been practically discontinued, and materials that are difficult to solder appear more frequently on printed circuit boards. Both facts result in weaker or less reliable joints. This is in opposition to the growing need for higher reliability for manned space flights under more severe conditions. The introduction of weldable leads into the electronic packaging technique brought about a difficult soldering problem. Much is said about the solderability of most any material, but the fact remains that certain materials are more difficult than others to join by soldering. When "hard to solder" (weldable) materials must be soldered, the leads should be ultrasonically presoldered. As this is not possible, or at least it is dangerous, in most cases of semiconductive components, extreme care and high skill for soldering are mandatory. Another prerequisite for accomplishing reliable solder joints is the elimination or drastic reduction of stresses to the joints, by the proper design and manufacturing approach such as the component lead-forming to expansion loops.

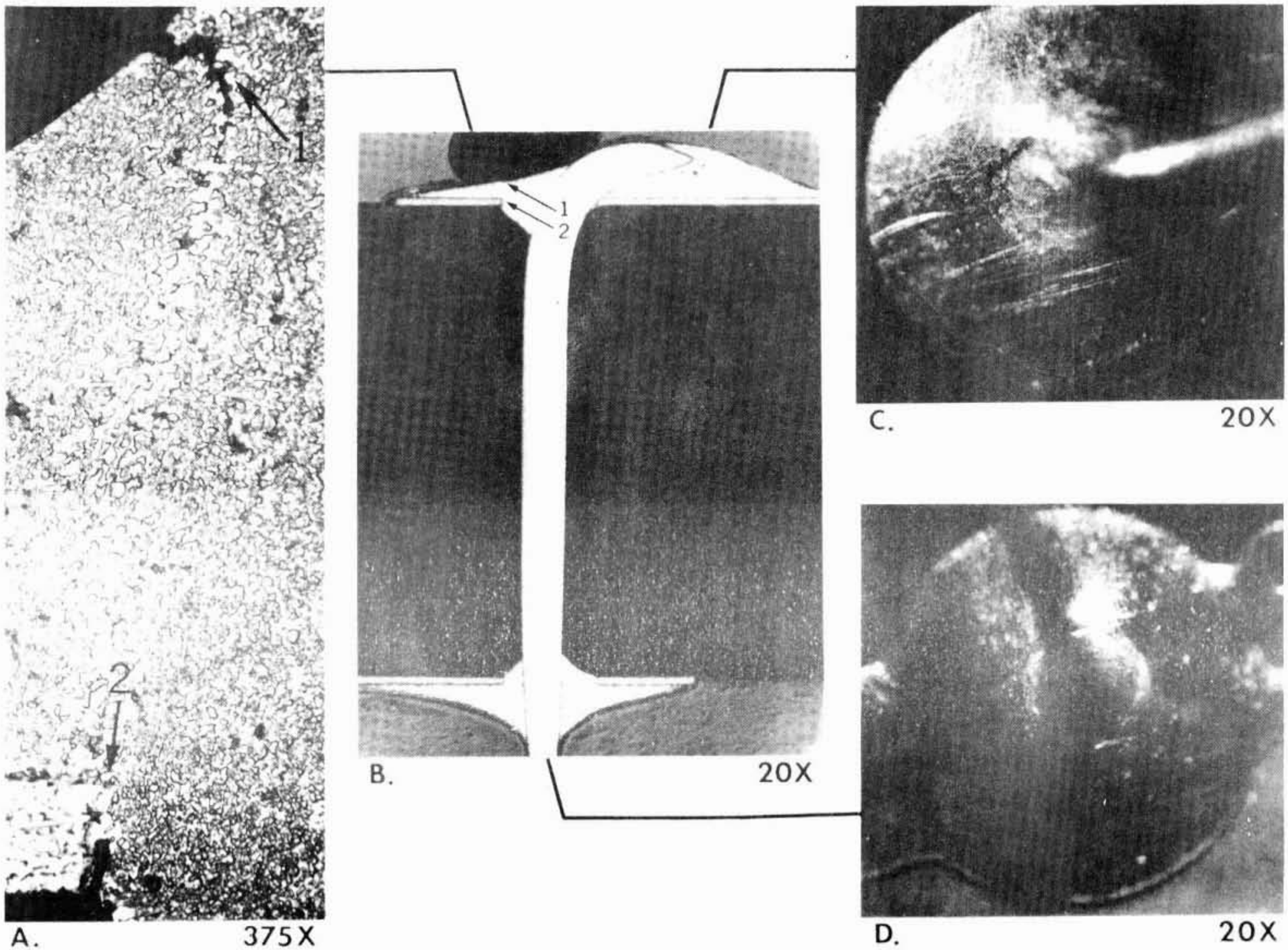

FIGURE 6. COMPONENT LEAD SOLDER CRACK

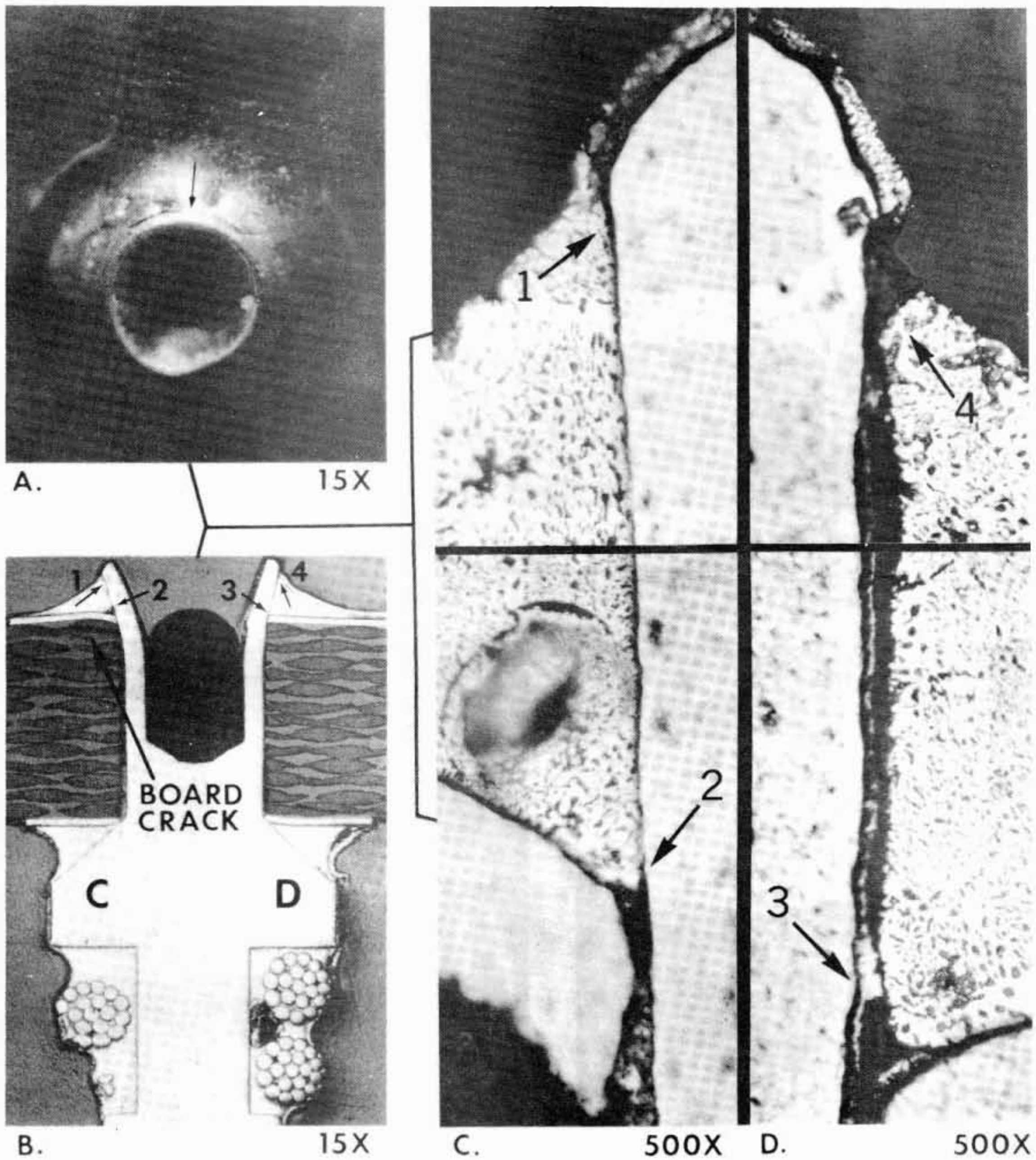

FIGURE 7. INTERFACE CRACK IN TERMINAL JOINT

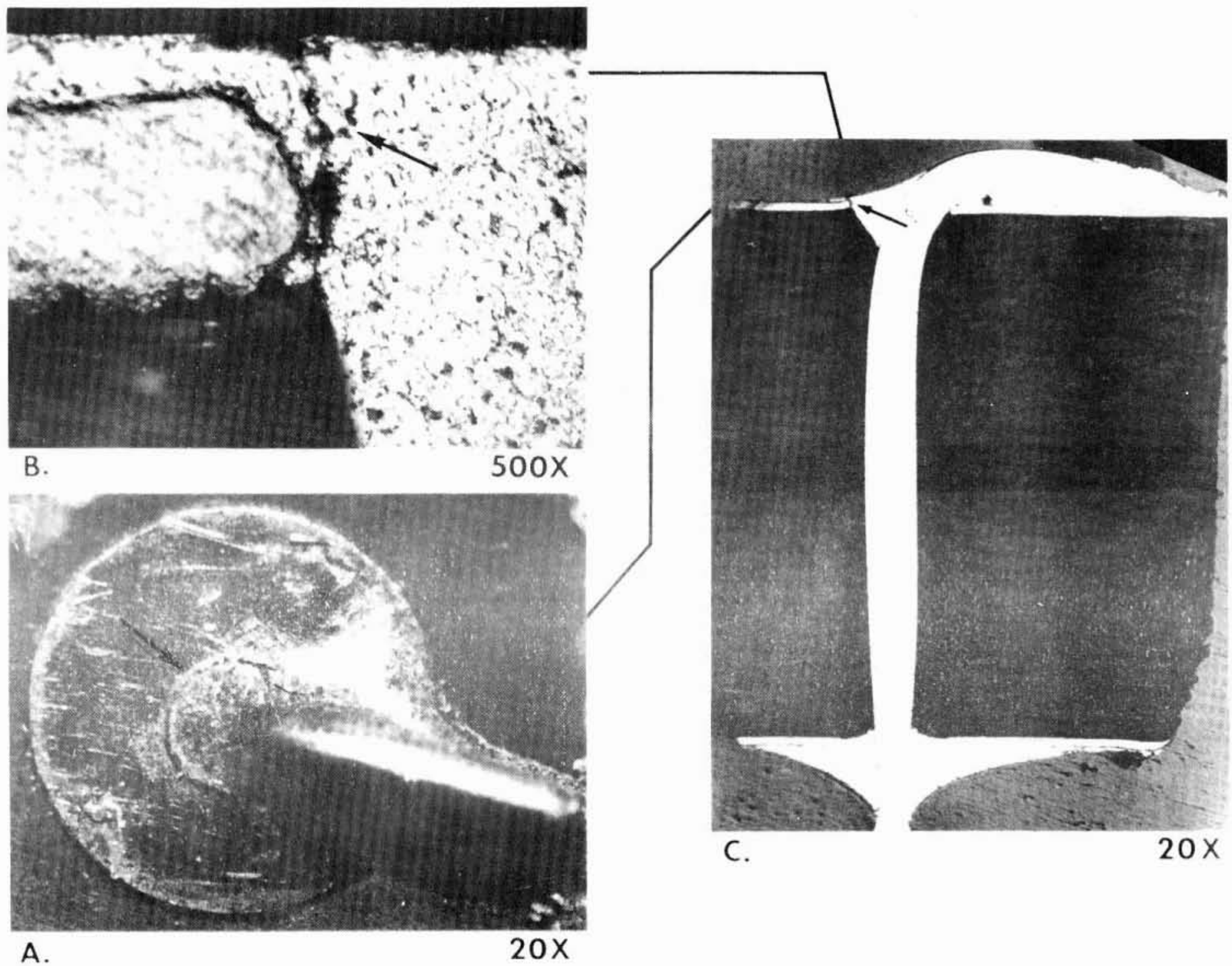

FIGURE 8. CRACK IN SEVERLY BRIDGED ZONE

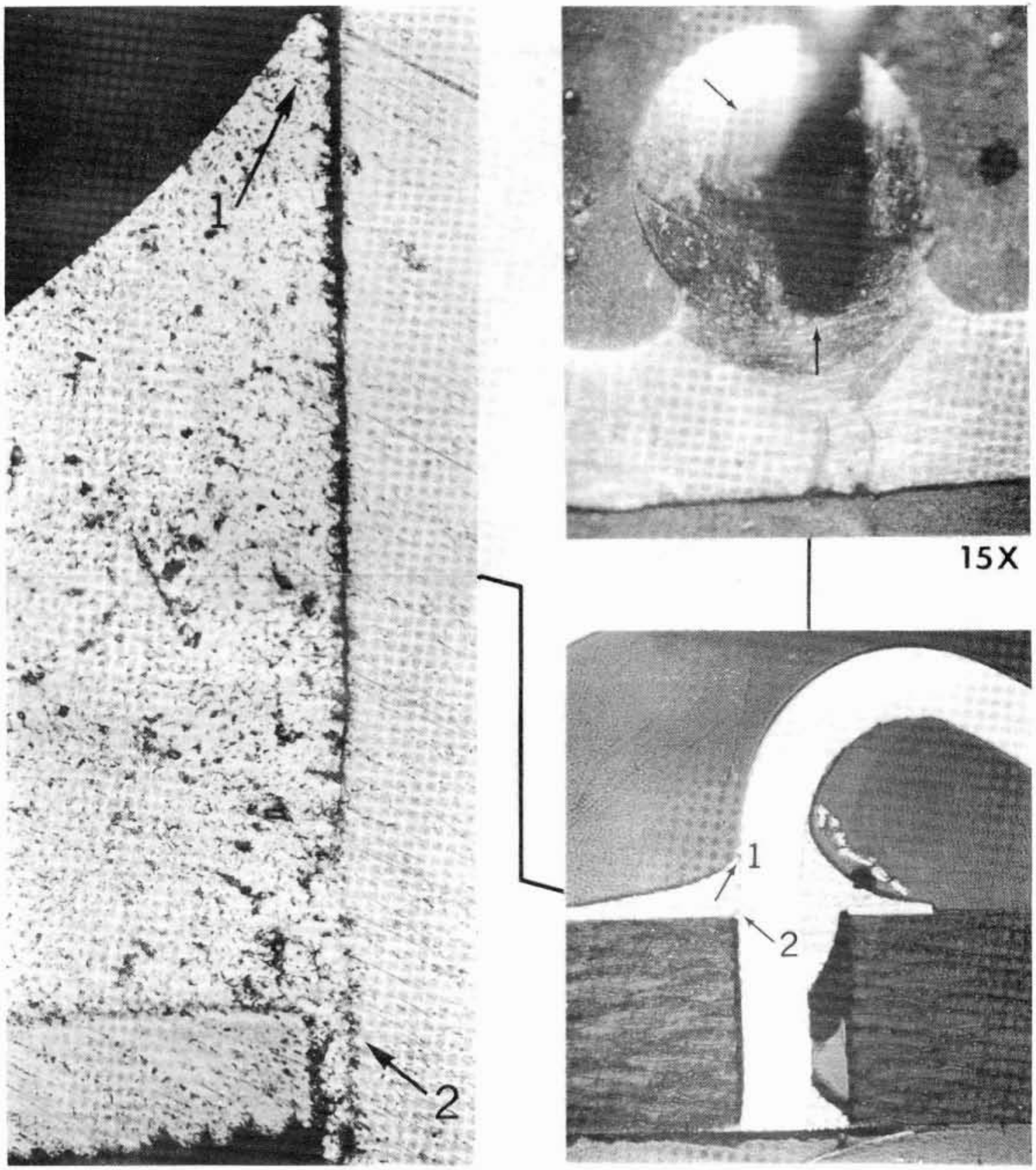

FIGURE 9. INTERFACE CRACK IN COMPONENT LEAD JOINT

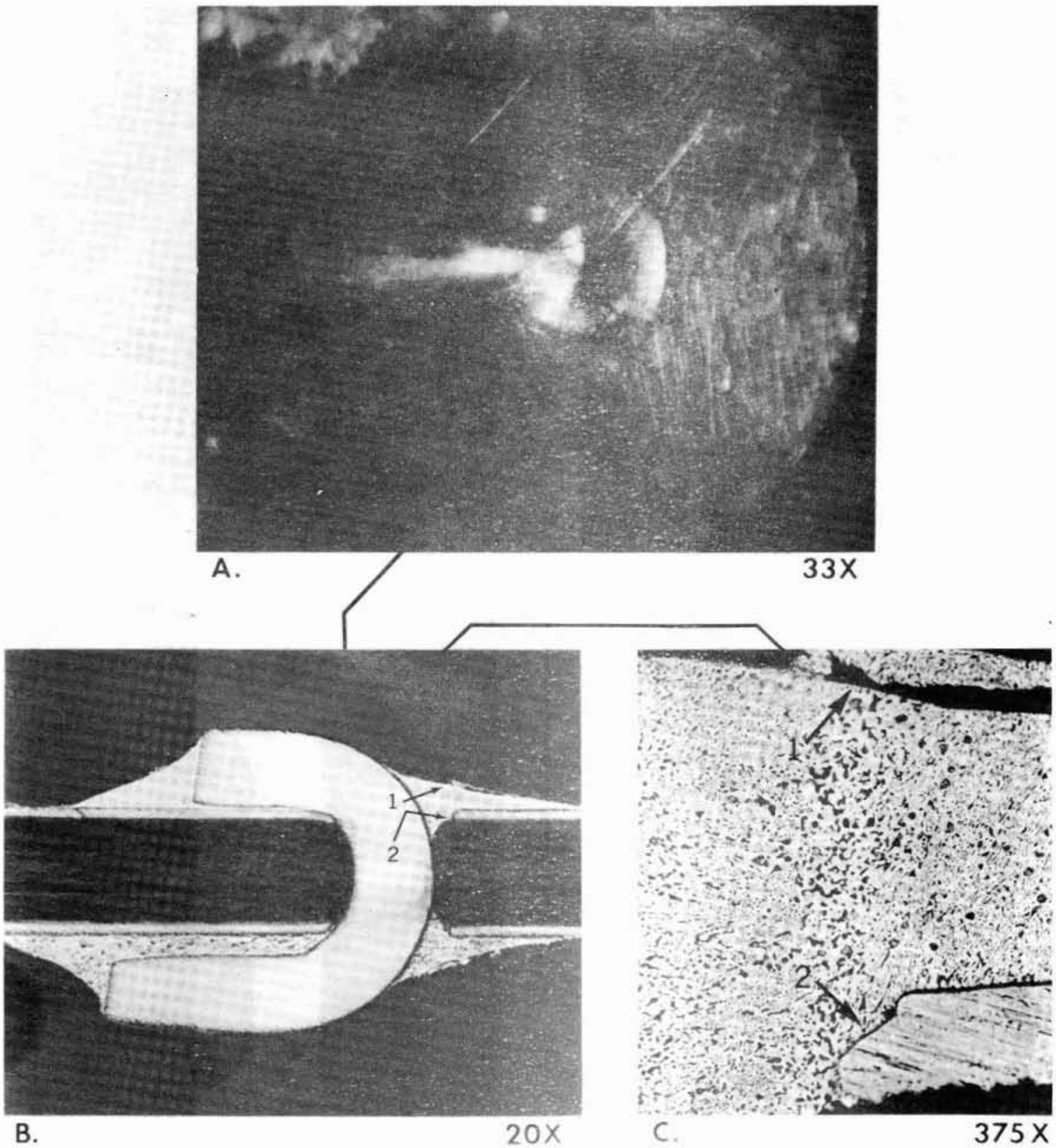

FIGURE 10. MICROSTRUCTURE COARSENING IN COMPONENT LEAD SOLDER

CONFORMAL COATING

The original purpose of conformal coating is still valid, yet a lot of disadvantages and dangers have been discovered and losses have been experienced, especially in severe temperature cycling. An example is the three cracked diodes shown in Figure 11. The coating was supposed to provide environmental protection against contamination of many kinds and to give mechanical support against acceleration forces. It was soon discovered that heavy coating of epoxy or polyurethane had considerable influence on the tuning of sensitive high frequency circuits, and the compression and tension forces acting against glass-seals and other components became more and more unbearable, as the range of temperature cycling increased. The first change from the original thick epoxy conformal coating was to thin polyurethane coating. Pure polyurethane without solvents maintains, even under very low temperature, a certain amount of flexibility, while epoxy becomes extremely hard. The latest testing has revealed that the application of a thin coat, about 5 mils, measured at a flat surface, forms fillets sufficiently strong to support most components against vibration. Heavy components should be fastened by locally applying a small amount of flexible epoxy such as X 81.

The mechanism of breaking glass-seals of components was studied experimentally in a series of tests using short pieces of glass tubing of different wall thicknesses and diameters; different amounts of coating and sizes of fillets were also applied. When uniformly and completely imbedded, the glass tubing never cracked. Thus the heavy shrink forces of the plastic material never crushed the glass or exceeded the compressive strength. The nonuniform imbedding caused by the fillets between the PC board and the component body produces the dangerously high tension forces. After switching from hard epoxy to soft polyurethane, PR 1538, the glass tubing samples under test did not fail. Further efforts are underway to find conformal coating plastics with still less hardening and smaller shrinkage at low temperature.

Meanwhile, besides the use of very thin and soft coating, plastic sleeves can also be used to prevent glass-seal cracking. The sleeve eliminates the bond to the glass; therefore, no forces can act on the glass. When plastic sleeves are used, their compatibility with polyurethane must be checked to assure proper polymerization.

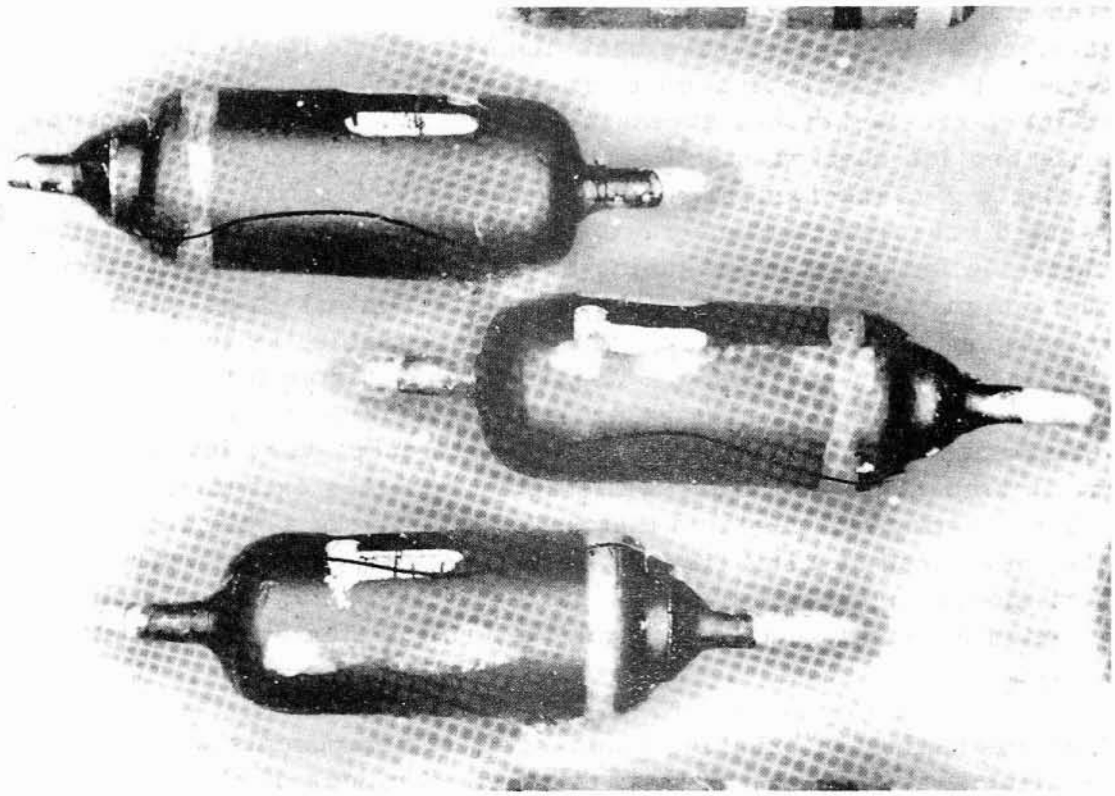

FIGURE 11. CRACKED DIODES

Outgassing of Plastics

In some of the orbital flights, the astronauts observed undesirable deposits on the spacecraft windows. More detailed studies revealed gas formation around the spacecraft during flight. This cloud of gaseous material has a degrading effect to all optical equipment because it limits the observing quality and falsifies the spectroscopic experimental results. The gas clouds and deposits are believed to originate from the plastic materials used in manufacturing the spacecraft. An extensive drive is underway to eliminate plastics with high weight loss in vacuum and to restrict the volume of others with low outgassing values to the minimum amount. Much plastic material is used in electronic packaging, wire insulations, PC boards and their coating, cordwood modules, etc., and some of these plastics will have to be replaced by more suitable ones. The limitation of permissible outgassing of plastics will have a strong impact in manufacturing and will cause many changes. The requirements for low thermal expansion, softness at low temperature, electrical values, etc. must receive proper attention when new materials are selected to avoid the present problems of solder joint and glass-seal breakage.

CONCLUSIONS

Much information is gained from environmental testing and theoretical studies in the field of thermal stress on PC boards. The seemingly small changes in dimension at changes of temperature were long under estimated in their consequences till very costly and time consuming repairs became necessary. Repair procedures, new component lead forming, component mounting, and coating prescriptions evolved. Reliability of PC boards has been vastly increased.

The big task is to convince the designers and manufacturers of the need for these improvements and to implement them.

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