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INVESTIGATION OF DISCRETE COMPONENT CHIP MOUNTING TECHNOLOGY FOR HYBRID MICROELECTRONIC CIRCUITS

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May 1975

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16. ABSTRACT

Until recently, most discrete electronic components have been electrically and mechanically connected into package assemblies using solder techniques. However, today's complex semiconductor microcircuits, ceramic components, and hybrid microcircuit assemblies possess physical and chemical characteristics which are adversely affected by high temperature solder and eutectic bonding processes. Therefore, organic materials such as adhesives are being used in microelectronic applications as a replacement for the metallurgical techniques.

The use of polymer adhesives for high reliability microcircuit applications is a radical deviation from past practices in electronic packaging. Therefore, Marshall Space Flight Center has conducted research programs to evaluate adhesives for use in microcircuit packaging. Bonding studies were performed using two gold-filled conductive adhesives, 10/90 tin/lead solder and Indalloy no. 7 solder. Various types of discrete components were mounted on ceramic substrates using both thick-film and thin-film metallization. Electrical and mechanical testing were performed on the samples before and after environmental exposure to MIL-STD-883 screening tests.

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INTRODUCTION

Until recently, most discrete electronic components have been electrically and mechanically connected into package assemblies using solder bonding techniques. Today's complex semiconductor microcircuits, ceramic components, and other leadless devices possess physical and chemical characteristics which are adversely affected by high temperature solder and eutectic processes. Therefore, organic materials are being used in microelectronic applications as a replacement for the metallurgical techniques. These uses include adhesive bonding of components for mechanical, electrical and thermal purposes, package sealing, substrate mounting and other applications.

The use of adhesives in lieu of eutectic bonding or other metallurgical attachment is highly desirable from the standpoint of both reliability and manufacturing. Organic adhesives can be processed and cured at lower temperatures (usually below 150°C); allow easy rework, removal, and replacement of components without subjecting the circuits to high temperatures; and, because of their low moduli of elasticity, allow stress dissipation without damaging the component, bond line, or substrate. This latter property is particularly important during temperature cycling or thermal shocking of circuits, especially in the case of larger components such as capacitors. Previous investigations have clearly delineated that solder joined capacitors are susceptible to catastrophic failures during temperature cycling and, consequently, it has been recommended that this assembly technique not be used for meeting the requirements of high reliability microcircuits.

MICROELECTRONIC PACKAGING

Assembly Techniques

In recent years, more and more electronics hardware has been designed into smaller packages. Not only are these subassemblies made smaller but generally they perform more electronic functions. Microelectronics, in addition to reduced weight and size, consume less power and are more reliable than the discrete counterpart. The standard printed circuit board, when used, contains discrete components with wire leads. These leads are soldered or welded into place on the board to form mechanical and electrical connections as shown in Figure 1.

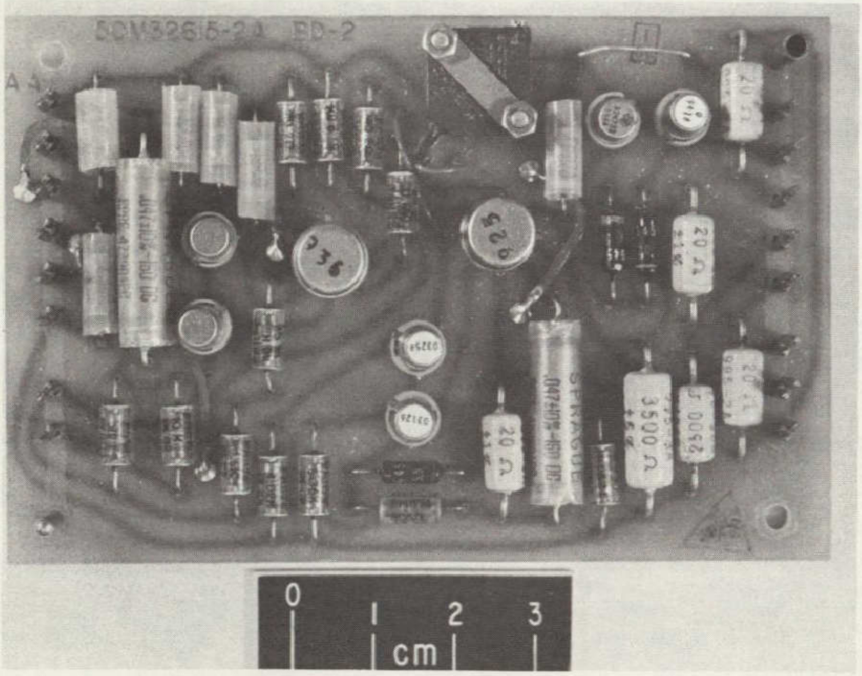


Figure 1. Conventional printed circuit board with leaded components.

Compared to printed circuit board assembly, greater packaging densities can be achieved with discrete monolithic integrated circuits and hybrid microcircuit assemblies as illustrated in Figure 2. As seen in this figure, discrete components must be mounted onto the base substrate using new bonding techniques because of the leadless configurations. In Figure 3, the component

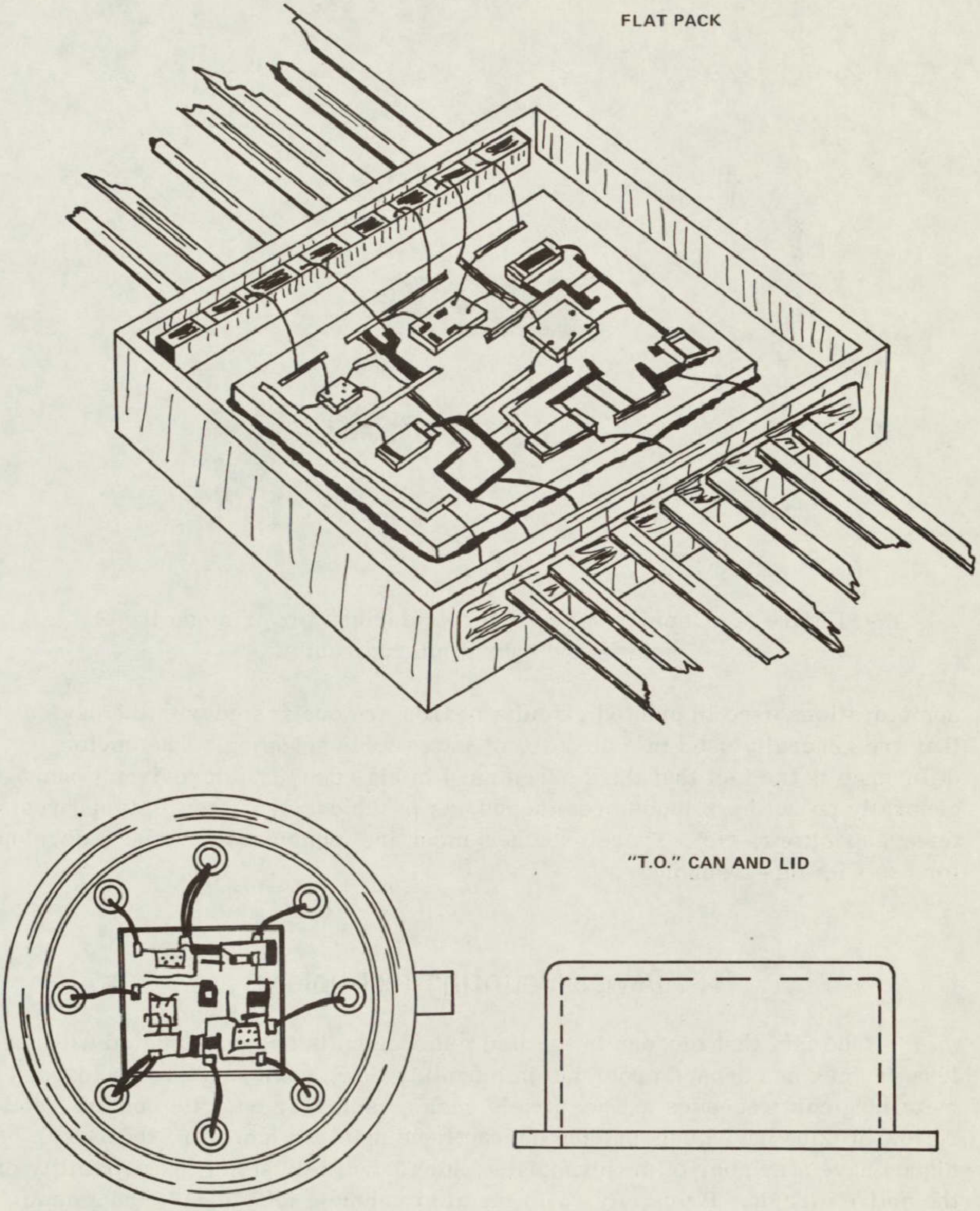


Figure 2. Monolithic and hybrid integrated circuit packaging technology.

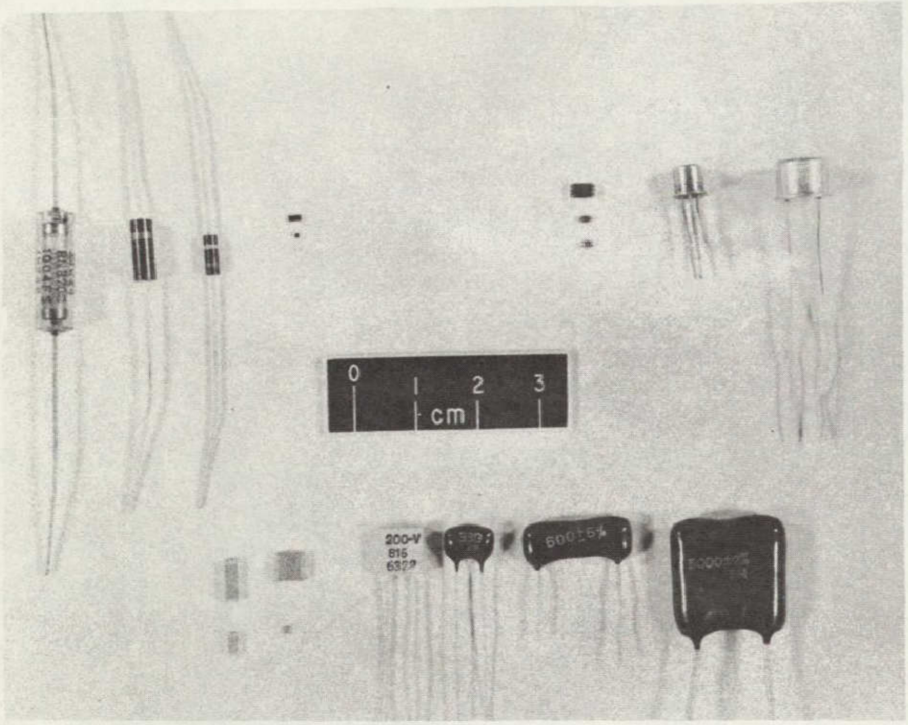


Figure 3. Comparison of discrete devices for printed circuit boards and hybrid microcircuits.

configurations used in printed circuits boards are contrasted with the devices that are generally used in microcircuit integrated packaging. The obvious difference is the fact that the devices used in high density microcircuit packages generally do not have leads preattached, as is the case with conventional resistors, capacitors, etc. Therefore, new mounting techniques have been developed for use with this technology.

Device Mounting Technology

The fact that modern integrated microcircuits are constructed with leadless devices has caused problems in mounting these components. Standard metallurgical processes and materials such as solders, eutectic bonding, and reflow brazing have been and are currently being used; however, these techniques have a number of disadvantages which adversely affect the reliability of the entire circuit. Primarily, with metal attachment techniques, the components are held rigidly to the substrate (usually ceramic), as shown in Figure 4.

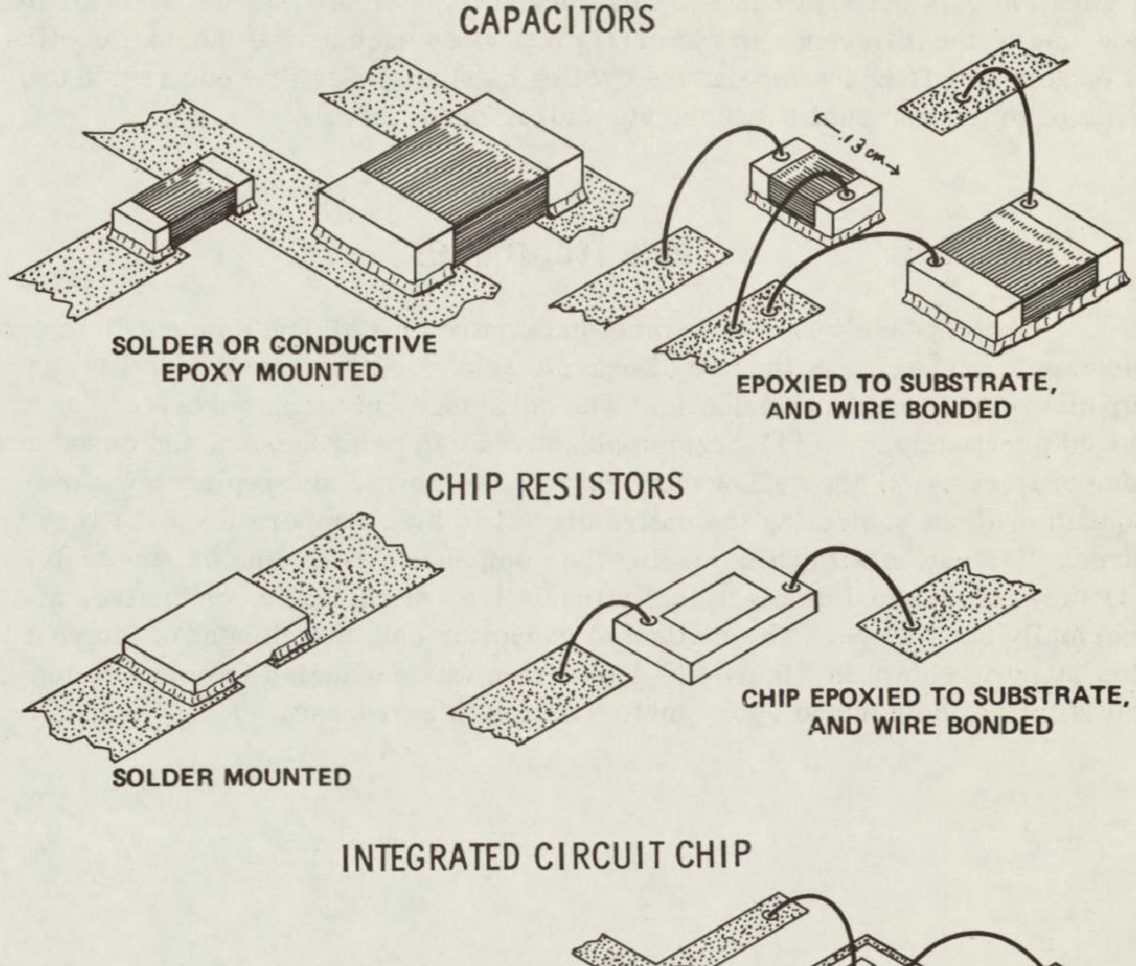


Figure 4. Discrete electronic components used in hybrid packaging technology.

A ceramic chip capacitor is shown soldered in place on a ceramic substrate. Because of the difference in material properties such as the thermal coefficient of expansion (TCE), temperature cycling causes stress that can result in damage to the component, substrate and/or bond line.

New Techniques

One relatively new and somewhat controversial development in microelectronic packaging is the use of organic adhesives instead of metallic materials for discrete component mounting. The advantages of using adhesives, as mentioned previously, are (1) organic adhesives can be processed and cured at low temperatures, (2) they allow easy rework, removal, and replacement of components without subjecting the entire circuit to high temperature, (3) they allow stress dissipation without damaging the component, bond line or substrate, and (4) they can be used as electrically insulative, electrically conductive, and thermally conductive. The method of capacitor chip attachment of interest to this study is shown in Figure 5. A program was conducted to compare the reliability of solder and epoxy materials for this process.

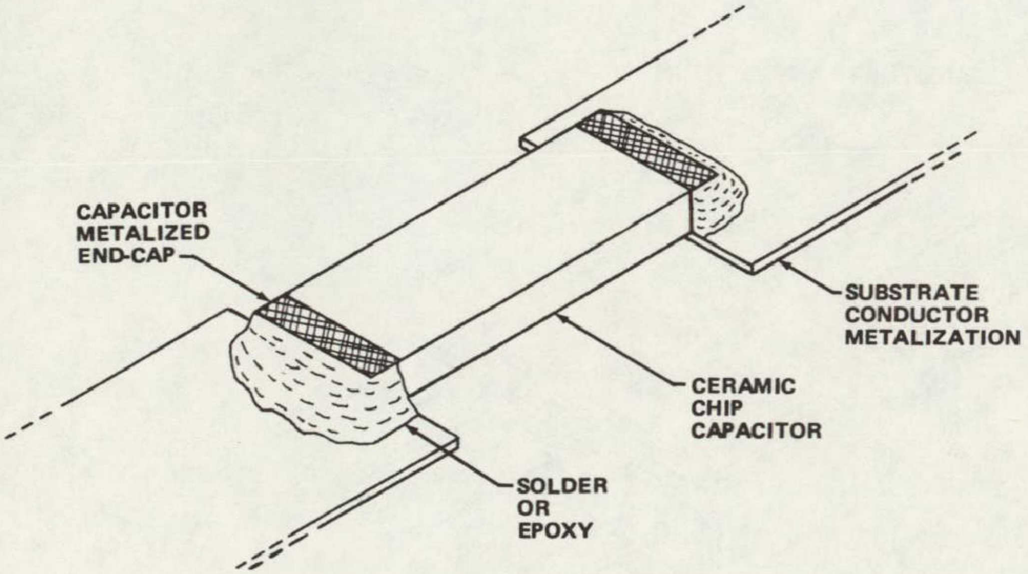


Figure 5. Conventional capacitor attachment method.

RESEARCH AND DEVELOPMENT PROGRAMS

Reliability Considerations

Increased experience with adhesives and confidence in their performance have reached the point where they are being used in commercial, military, and aerospace applications. However, few investigations have been conducted to develop adhesives specifically meeting the very stringent requirements for long-term, high reliability space applications. George C. Marshall Space Flight Center (MSFC) has conducted studies directed to the identification and investigation of such problems that could result from the use of adhesives and to the development of suitable evaluation tests to qualify the various adhesives, thereby forming the basis for guidelines and specifications for electrically conductive and insulative adhesives for hybrid microcircuits. To generate an adequate data base to verify the validity and establish the sensitivity of the selected tests, an indepth evaluation was made of selected state-of-the-art adhesives representative of the major classes presently proposed for use in hybrid microcircuits. Properties of these materials considered to be important for microcircuit use were studied in detail and included chemical composition, outgassing, corrosivity, weight loss, mechanical and thermal properties, and other factors. Both in-house research at NASA and contract-sponsored work have been performed.

Adhesive Investigations

Adhesives currently used in hybrid microcircuits can be classified into the two very broad categories: electrically insulative and electrically conductive. In many circuit assemblies, both types are used. The various uses to which adhesives have been put include the following:

1. Electrically Insulative.
    a. Bonding substrates to packages.
    b. Lidding.
    c. Reinforcing edge connectors.
    d. Protecting fine wire leads.

e. Molding or sealing packages.

f. Bonding chip components (e.g., capacitors, resistors, semiconductors, etc.) to substrates.

2. Electrically Conductive.

a. Bonding semiconductor die to substrates.

b. Repairing conductor lines.

c. Attaching capacitors to bond pads.

d. Providing ohmic contact of connectors or lead frames.

Of these, the most important and common uses are bonding substrates (usually an alumina ceramic) to the base of metal or ceramic packages, using an electrically insulative adhesive, and attaching semiconductor die and chip capacitors to conductor pads on substrates using an electrically conductive adhesive.

Insulative Adhesives. A comprehensive investigation was carried out to identify those properties of electrically insulative adhesives to ensure the requirements of long-life and high reliability. Results of this work have been described in other reports and will only be summarized here.

Advantages and limitations of the polymeric types of adhesives such as phenolics, polyurethane, polyamides, polyimides, silicones, epoxies, and cyanoacrylates were considered in choosing the most promising chemical type(s) for electronic applications. Based on many considerations, it was concluded that the epoxies are the most appropriate type for use in microelectronics. Commercial manufacturers of adhesives for this application have concentrated development efforts on the epoxy series. A comprehensive test program was conducted with 14 different adhesives selected from at least 5 different manufacturers. Variables of the test program consisted of using several adhesive types such as paste, preform solids, etc., cured with five different agents: primary/secondary amine, tertiary amine, anhydride, anhydride heterocyclic amine, and boron trifluoride. The adhesives were placed on the common microcircuit metallization systems and cured, then environmental tests were performed. Results of this work are reported in NASA TM X-64789.

The program described for insulative adhesives was very detailed and comprehensive and, therefore, only a summary of the conclusions are presented here as follows:

1. Bond Strength — The bond strength of most insulative epoxies is adequate, even after environmental testing and aging. Thermal cycling, between -55°C and 150°C, is the most likely test to affect strength and usually not before 100 cycles.

2. Outgassing — This is a very important test and should be performed on materials before selection for specific applications. Outgassing was measured at 150°C after cure for the epoxies and showed nonmeasurable quantities for some materials to significant amounts of organic vapors from others.

3. Corrosivity — Of the adhesives tested, only the anhydride cured adhesive and tertiary amine cured adhesive appear to be suitable for use on the aluminum and gold metallization systems. The other types of adhesives caused discoloration of varying degrees.

4. As a general design rule, it is best never to place adhesives over two or more metallization lines that are operating at different electrical potential. This is to avoid electrolytic corrosion of the metal lines.

5. A properly screened and qualified insulative adhesive can be used for mechanical attachment of discrete components in high-reliability applications.

Conductive Adhesives. Several investigations have been conducted to evaluate conductive epoxies. In order to obtain meaningful information, metallic conductive systems (solders and eutectics) were included in the research programs. The objective of this work was to determine the long-term reliability of conductive epoxy systems for microelectronic packaging compared with conventional metal systems. Since the combined efforts are extensive in scope, only a summary is included here. The parameters of these investigations include development and evaluation of several conductive epoxy systems by comparison to metallic attachment methods and materials. Microelectronic discrete components such as semiconductor chips and capacitor chips (from various manufacturers) were mounted on substrates and environmental tests were performed. Results of this work are reported in NASA TM X-64908.

STUDY PROGRAM

Background

This study is a followup of an investigation performed previously by MSFC and reported as "Investigation of Mountain Discrete Chip Components for Hybrid Microelectronic Applications." In the previous investigation, both active and passive devices were mounted to thick- and thin-film metallized substrates using bonding systems which included two solders (10/90 and 63/63/2Ag), a gold filled conductive epoxy, and three nonconductive epoxies (Epon 828, Hysol 0151, and Ablestick 517). Briefly, the results of that study showed the nonconductive epoxies to be superior in strength to the conductive epoxy and solders. The conductive epoxy and 10/90 solder proved so difficult to work with that satisfactory test specimens could not be fabricated, thereby making it impossible to evaluate these two systems.

In this study, 10/90 tin/lead solder, two gold filled conductive epoxies, and Indalloy no. 7 solder were evaluated. The components were limited to chip capacitors and leadless inverted devices (LIDs).

Test Conditions

This investigation was intended as a screening study of several industry methods used in mounting chip capacitors and LIDs to space flight hardware. Test methods involved those required for Class A hardware per MIL-STD-883. Tests included the following:

1. High temperature storage (72 hours at 150°C).
2. Temperature shock (15 cycles, -65°C to 150°C).
3. Temperature cycling (500 cycles, -65°C to 150°C).
4. Mechanical shock (10 000 g's, 3 axes, 2 directions each axis).
5. Constant acceleration (20 000 g's, 3 axes, 2 directions each axis).
6. Vibration (70 g's, 3 axes).
7. Sequential (serial exposure of the tests listed above).

Substrate/component/bonding system variables included the following:

1. Thick- and thin-film metallized substrates.
2. Kemet and MDI capacitors and Frenchtown LIDs.
3. Two types and sizes of capacitors, two sizes of LIDs.
4. Three bonding systems including two gold epoxies, 10/90 solder and Indalloy no. 7 solder.
5. ATC capacitors, one type and size bonded with 10/90 solder only.

Visual inspection plus mechanical and electrical testing were conducted on specimen before and after environmental exposures. The conductive epoxy was satisfactory in most catagories and was superior to the solder, which cracked and caused components to fail mechanically and electrically.

Variables Matrix

The variables used in this test program are listed below:

Component	Materials
Substrate	Al_2O_3 Ceramics
Components	(1) Capacitors (2) Ceramic 1C Carriers
Conductor Metallization	(1) Thick-Film Gold (2) Thin-Film Gold
Solders	(1) 10% tin, 90% lead (2) 50% lead, 50% indium
Epoxy Adhesives	(1) Epoxy, Gold Filled, H-44 (2) Epoxy, Gold Filled, 58-1

The discrete components were mounted on ceramic substrates and environmentally tested as described in the test conditions. Examples of some test patterns with components attached are shown in Figures 6 through 11.

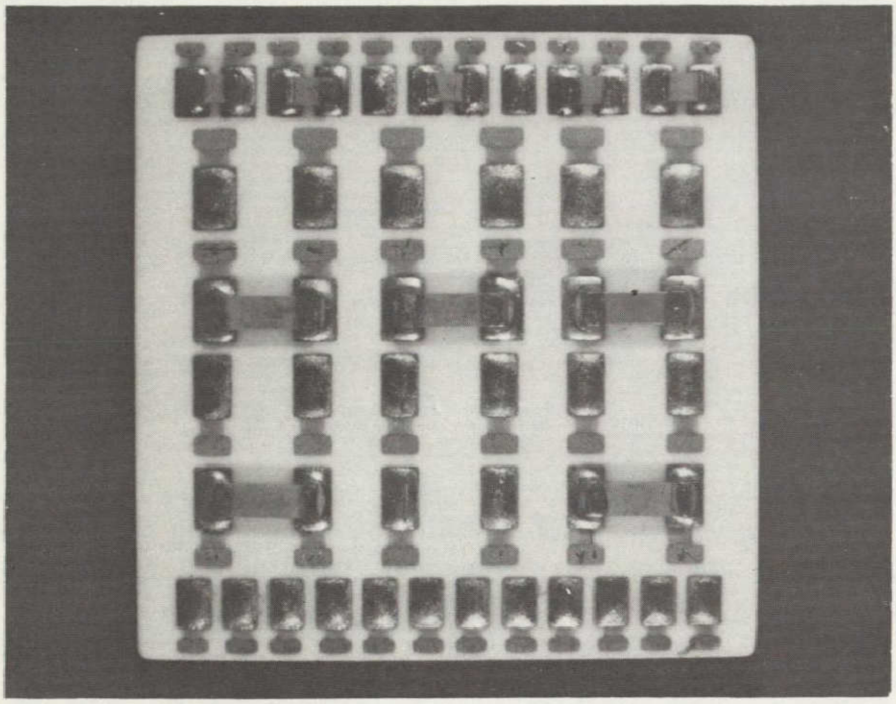


Figure 6. Pt/Au thick film, 10/90 solder — Kemet capacitors.

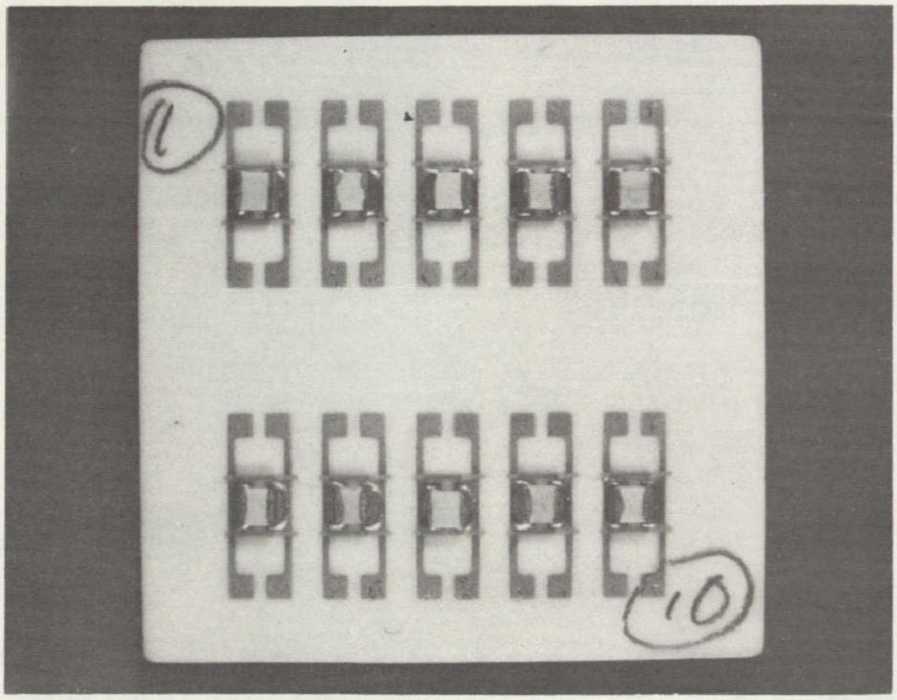


Figure 7. Pt/Au thick film, 10/90 solder — ATC capacitors.

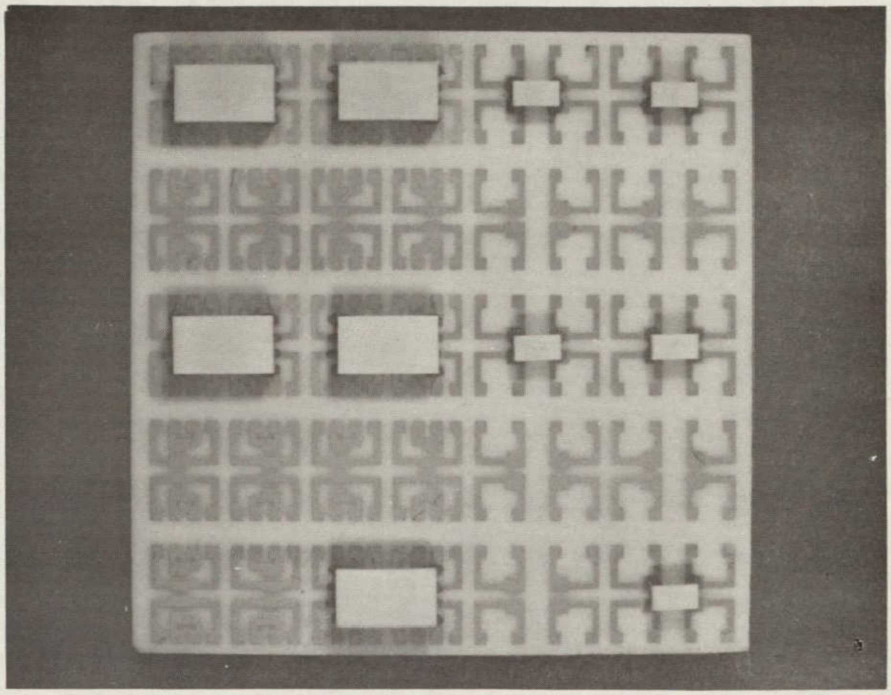


Figure 8. Thin film substrate, epoxy.

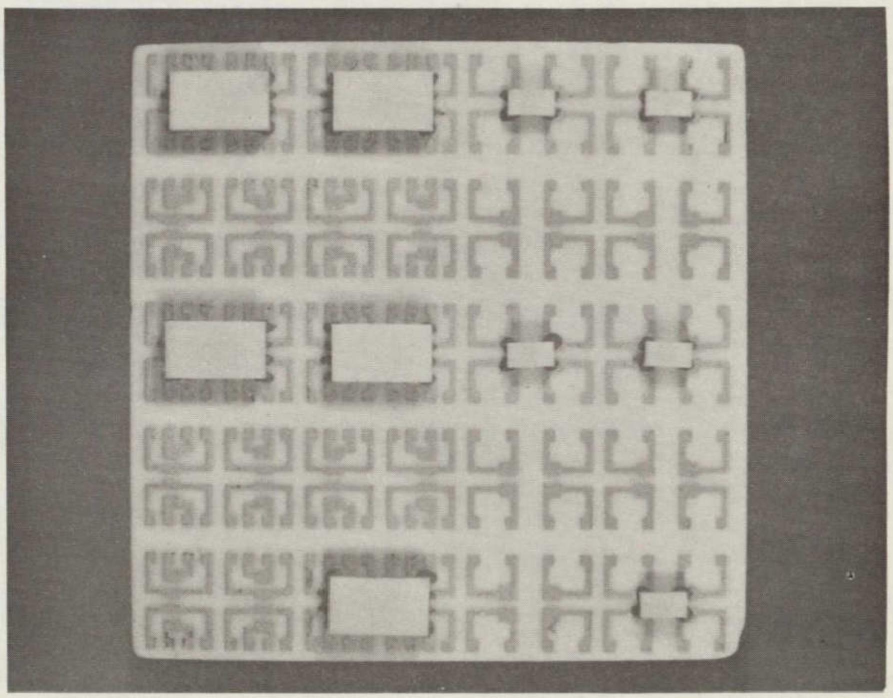


Figure 9. Thick film substrate, epoxy.

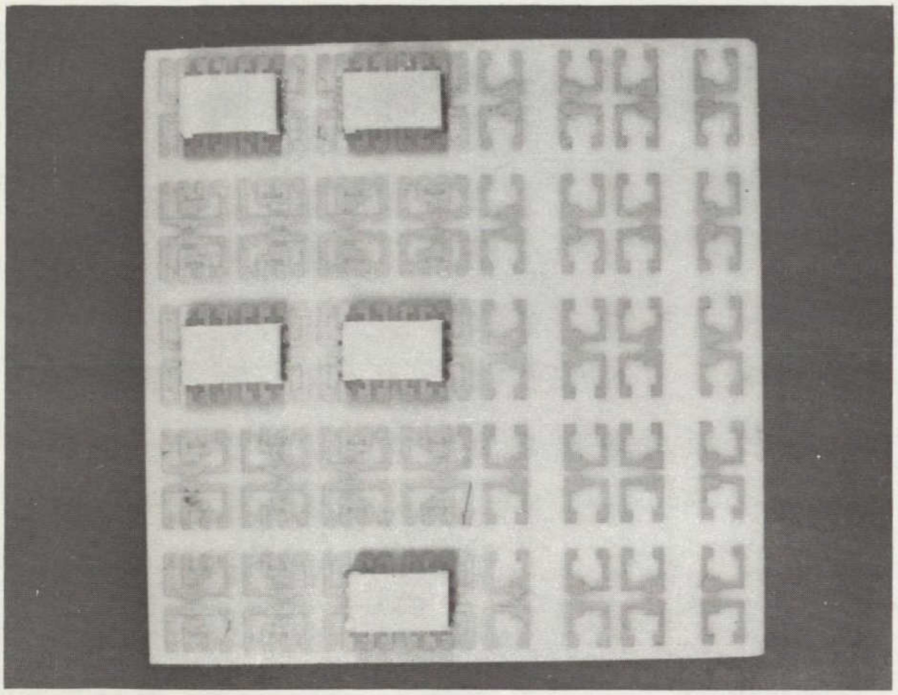


Figure 10. Thin film substrate, Indalloy no. 7 solder.

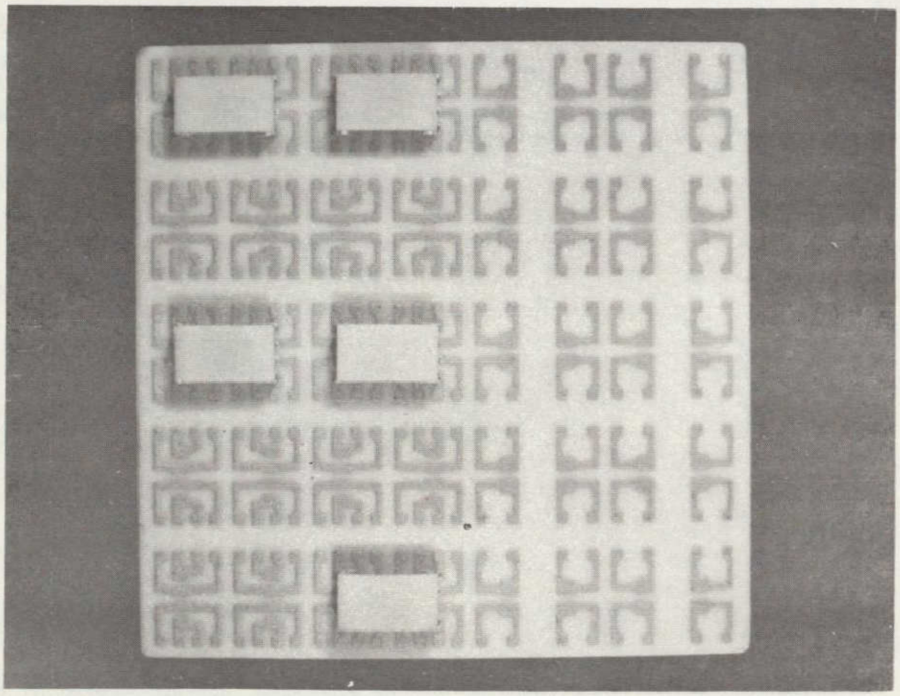


Figure 11. Thick film substrate, Indalloy no. 7 solder.

TEST PROGRAM

Environmental Exposure Sequence

The test substrates were subjected to MIL-STD-883 (Method 5004) Class A screening requirements. The following tests were performed in sequence:

1. Internal Visual (precap) — Method 2010, Condition A.

2. Stabilization Bake — Method 1008, Condition C (High Temperature Storage) — 24 hour (both minimum).

3. Thermal Shock — Method 1011, Condition C.

4. Temperature Cycling — Method 1010, Condition C (minimum).

5. Mechanical Shock — Method 2002, Condition F (one shock-Y_1 or Condition B, five shock-Y_1).

6. Constant Acceleration — Method 2001, Condition E (centrifuge).

(Other non-environmental tests are included in the screening procedure. These pertain to electrical function of the microcircuit).

Details of Test Methods

The testing program for this study was designed to incorporate most of these tests. Thermal condition C (-65°C to +150°C) was used, but tests were of longer duration to induce failure, if possible. Thus, high temperature storage was extended to 72 hours at 150°C. Temperature cycling was extended to 500 cycles from -65°C to 150°C and thermal shock was 15 cycles over the same range. Freon type liquids provided the shock media of -65°C to +150°C.

Mechanical shock was conducted in accordance with Method 2002, Condition E. Accelerometers could not be calibrated above 10 000 g, Z_1 and Z_2 directions were executed. It is believed that this sequence constitutes a more severe test exposure than either one Y_1 shock at 20 000 g or five Y_1 shocks at 1500 g, as required under Class A screening.

Constant acceleration was conducted in accordance with Method 2001, Condition D, 20 000 g level.

Vibration was also incorporated at Test Condition C Level, 70 g from 20 Hz to 2000 Hz.

Also included in this study was a parallel plan to determine the effects of these tests on chip capacitor and LID attachments. Each test was applied individually to each substrate combination lot. Following the completion of the individual tests, another lot of substrates was tested serially according to the sequence shown in Figure 12.

TEST RESULTS

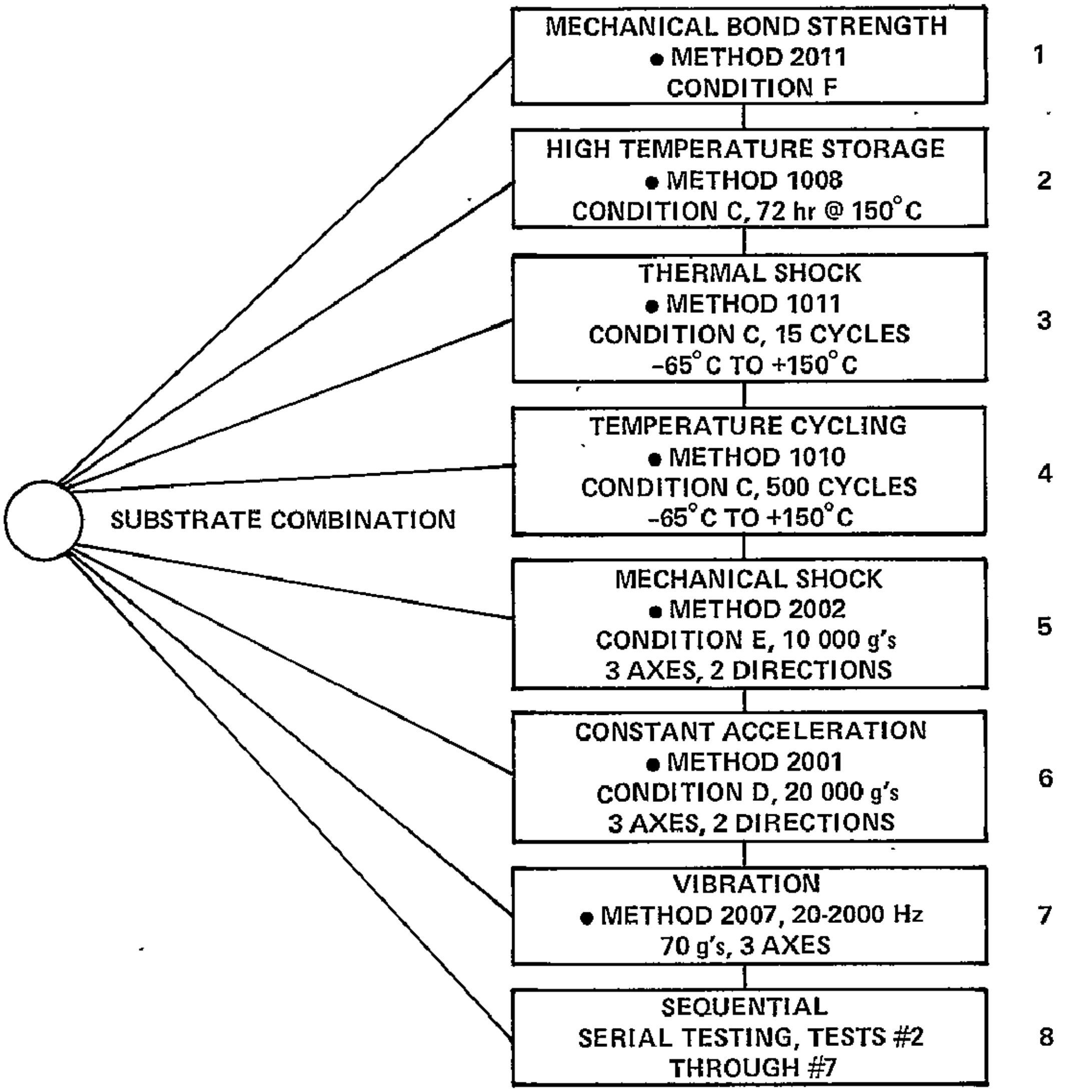
Only a summary of the test results is included in this report.

Based on a relative rating of all the bonding systems used on both capacitors and LIDs the number of failures occurring during the individual and sequential exposures is as follows:

1. Best — Gold filled epoxy system (Ablebond 58-1 and Epo-Tek H-44).
2. Second — 10/90 solder system.
3. Third — Indalloy no. 7 solder system.

(Failure criteria used in rating the bonding system was defined in terms of visual and electrical results as reported in the next section.)

It is difficult to give an overall rating because the bonding systems behaved differently between capacitors and LIDs and especially between capacitor vendors. The results clearly showed that bonding systems should be evaluated against each component and each vendor supplying the component. In other words, a bonding system that works well with LIDs may not work well with capacitors and one that works with Brand A capacitor may not work with Brand B capacitor. Our testing showed a prime example of this situation wherein the conductive epoxies showed no fillet cracking when used with Kemet capacitors during the individual exposures and only one instance of fillet cracking during sequential exposures. Yet with MDI capacitors, the epoxies developed fillet cracks within 300 thermal cycles during individual exposures and within 50 thermal cycles during sequential exposures. This fact suggests that a difference in



1. EACH SUBSTRATE COMBINATION WAS EXPOSED TO THE CONDITIONS LISTED ABOVE BOTH ON AN INDIVIDUAL BASIS AND SEQUENTIAL BASIS.
2. MECHANICAL SHEAR TESTING WAS PERFORMED AT THE COMPLETION OF EXPOSURES #2 THROUGH #8 FOR COMPARISON WITH THE "AS FABRICATED" RESULTS OF CONDITION #1.

Figure 12. Serial testing sequence MIL-STD-883 mechanical and environmental test conditions.

thermal expansion coefficients may exist between Kemet's and MDI's dielectric materials. It has been shown that handbook values of thermal expansion coefficients for barium titanate are for reference only and that these values may change drastically depending on each vendor's particular formulation and mixing techniques.

In both individual and sequential exposures, thermal cycling caused the most failures among the bonding systems. Nearly all failures from thermal cycling involved fillet cracking. Impact shock as an individual exposure was second in causing failures in which most failures involved removal of the components from the substrate. During sequential testing the thermal environments, primarily thermal cycling, did the damage while the subsequent mechanical environments of impact shock, acceleration and vibration uncovered the damage by causing removal of the components from the substrates.

If one desired to develop a screen to determine bonding system/component integrity and compatibility, thermal cycling would have to be the nucleus. Temperature storage followed by approximately 100 thermal cycles followed by acceleration testing should constitute an adequate screen. Specific levels of exposure would be determined by end item usage. The levels used in this evaluation were out of reach of most any bonding system available and were not realistic for hybrid microcircuits. Such test levels were used only to ensure failures so that the various bonding systems could be compared and rated.

The ranking of bonding systems did not necessarily agree for individual and sequential exposures. Component removal which was always gross in sequential testing was primarily responsible for bonding system rating disagreement between the individual and sequential exposures. During sequential testing, the bonding system with the greatest brute strength characteristics, as measured by its ability to keep components from being removed from the substrate, was in general the system that showed the lowest failure rate. Probably the greatest benefit obtained from sequential testing was the determination of the system which had the greatest component retention strength.

Three variables among the many associated with each bonding system contributed significantly toward failures. They were (1) the type of substrate metallization used, thick film versus thin film, (2) the size of the component, and (3) the component supplier. Fillet cracking occurred earlier and became more severe on thick film than on thin film substrates. This trend held true on both capacitors and LIDs with both the epoxy and solder bonding systems. This trend did not necessarily follow for the sequential exposures. The size of the components appeared significant only with the epoxies in that the smaller sizes developed less fillet cracking and experienced less removals from the substrate than did the larger sizes. Component size made little difference in fillet cracking with Indalloy no. 7 solder. With 10/90 solder, however, component size did make a difference in that the larger components were less susceptible to fillet cracking.

The type of dielectric material involved, i.e., K1200 versus NPO versus porcelain, made little difference in the failure rates of the bonding systems. Kemet and MDI capacitors used K1200 and NPO, whereas ATC capacitors employed porcelain as the dielectric.

Failure Criteria

Failure criteria were based on visual and electrical results only. Shear test results were not used as failure criteria or in rating of the bonding systems. Shear testing proved to be unwieldy and produced results which were erratic and difficult to interpret. Most of the erratic shear results occurred with Kemet and ATC capacitors and LIDs, as will be explained later in the report. The shear test fixture was changed for MDI capacitors and the results were more consistent. Only the MDI shear results were considered valid.

Components and bonding systems exhibiting the following conditions were classified as failures:

1. Visual (40X magnification).
    - a. Bonding fillet cracking.
    - b. Component cracking.
    - c. Component removed.
2. Electrical
    - a. Capacitance deviation greater than ±5 percent of the original.
    - b. Joint dc resistance increase greater than 0.200 ohms.

Kemet and ATC Capacitor Results

Individual Exposures. A summary of all the failures that occurred during individual exposures among all the bonding systems is presented in Table 1.

The gold epoxies showed by far the least number of failures. Ablebond 58-1 showed the highest failure rate with all failures occurring as "joint resistance increases" during thermal cycling. Of the eight total resistance increase failures among all substrate combinations and bonding systems, seven involved Ablebond 58-1. Metallographic cross sectioning was performed on 2 of these high resistance joints after 500 thermal cycles and are shown in Figures 13 and 14. The cross sections showed no obvious causes for resistance problems. Figure 13 shows a slight separation between the gold plating and copper guard in the epoxy fillet area which should not, however, cause the problem. Since the bulk feature of the epoxy appears sound, the problem most likely stems from a bond line deterioration at the capacitor, which would be difficult to detect visually.

Epo-Tek H-44 had only one failure, a capacitor removed during impact shock, and was rated as the best epoxy system for Kemet capacitors. Figure 15 shows a cross section of an H-44 epoxy fillet after 500 thermal cycles.

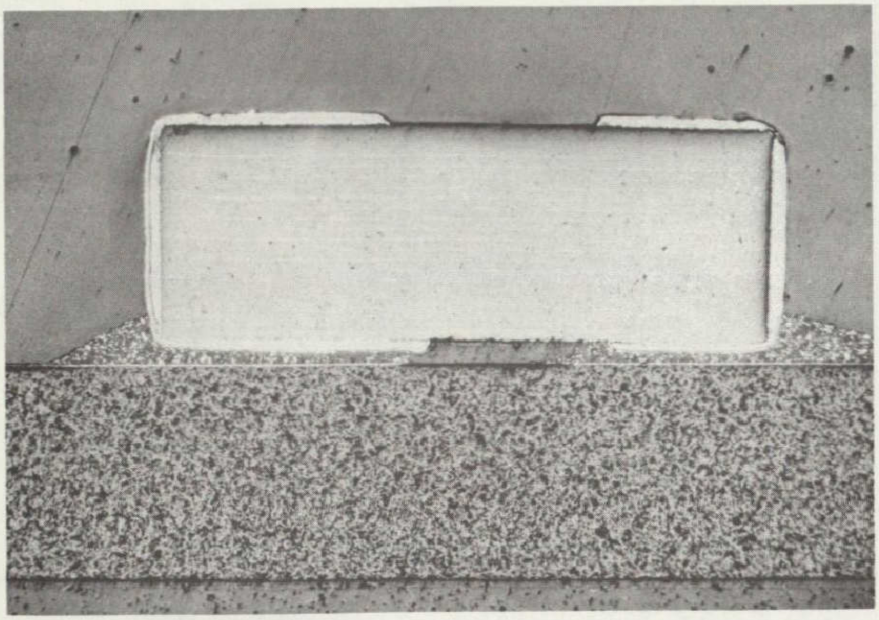
Solders. Indalloy no. 7 and 10/90 solders ranked third and fourth, respectively, behind the gold epoxies. The primary failure mode was fillet cracking during thermal cycling. Although the percentage of cracking between the two solders was equal during thermal cycling, Indalloy no. 7 cracked within 50 cycles whereas 10/90 showed more crack resistance and survived 300 cycles with Kemet capacitors and 200 cycles with ATC capacitors before cracking. With the Kemet capacitors, the 10/90 solder fillets cracked at the capacitor interface. This suggested that optimum wetting may not have been achieved possibly due to an inability to clean the electrodes thoroughly (all Kemet capacitors scheduled for 10/90 solder bonding was received with bare copper electrodes which were tinned in house). Kemet balked at tinning with 10/90 since it was not one of their standard alloys. As a precaution to ensure good wettability, all capacitors shceduled for solder mounting should be pretinned with the solder alloy by the capacitor supplier.

With ATC capacitors, 10/90 cracked in the bulk of the solder fillet near the bonding pad within 200 cycles. Solder wetting and filleting was good.

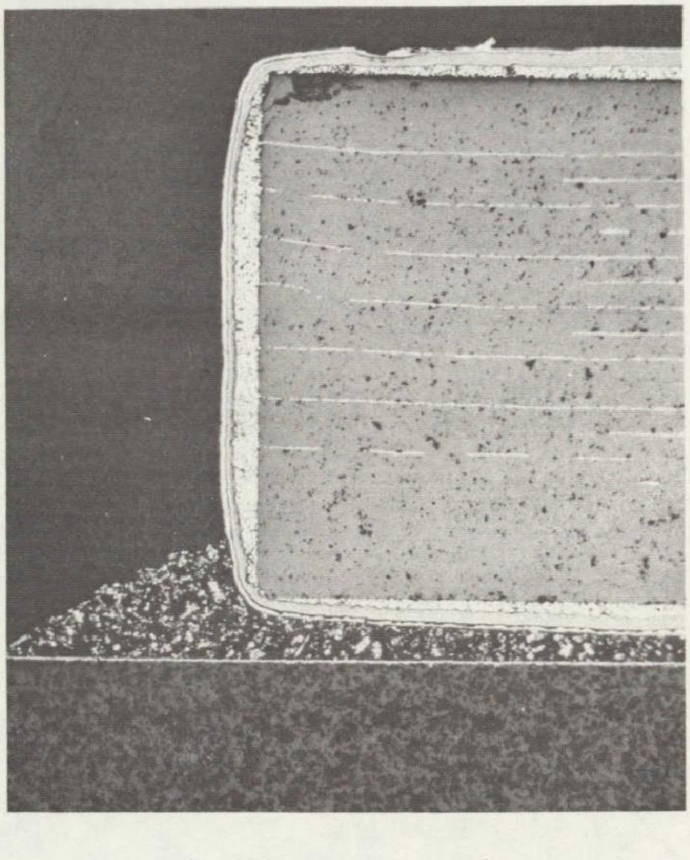
TABLE 1. INDIVIDUAL EXPOSURES TESTING SUMMARY (Kemet and ATC Capacitors)

			Visual Failures			Electrical Failures		
ATC No. of Caps	Kemet No. of Caps	Bonding System	Caps(w) Cracked Fillets	Caps Cracked	Caps Removed	Capac. Dev.	Joint Resistance Increase	Total Failure Percentage
	240	58-1 Epoxy	0	0	0	0	7	7/240 = 2.9
	240	H-44 Epoxy	0	0	1	0	0	1/240 = 0.42
	240	Indalloy no. 7 Solder	40	0	0	2	1	43/240 = 17.9
	120	10/90 Solder	20	0	0	5	0	25/120 = 20.8
60		10/90 Solder	10	0	0	0	0	10/60 = 16
Total			70	0	1	7	8	

Ranking: First, H-44 Epoxy	0.42% Failure
Second, 58-1 Epoxy	2.9% Failure
Third, Indalloy no. 7 Solder	17.9% Failure
Fourth, 10/90 Solder	20.8% Kemet Caps. Failure
	16.0% ATC Caps. Failure

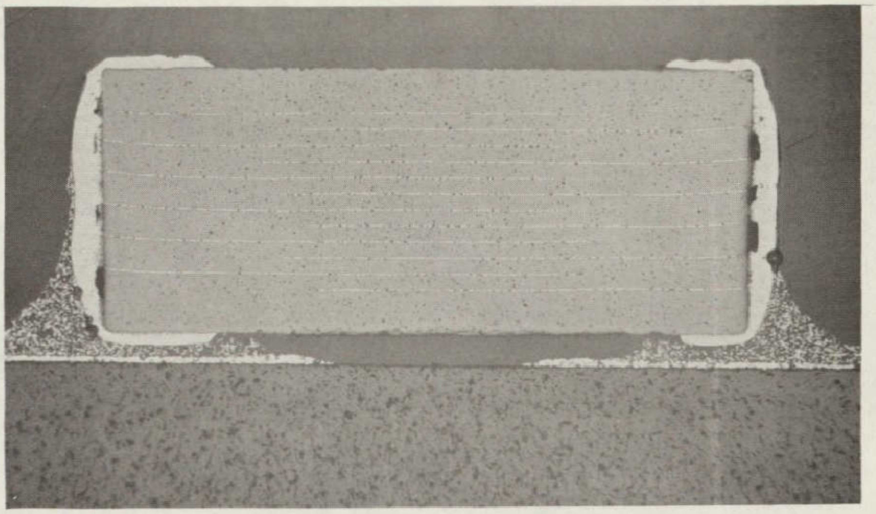


0805 size, NPO (40X magnification)

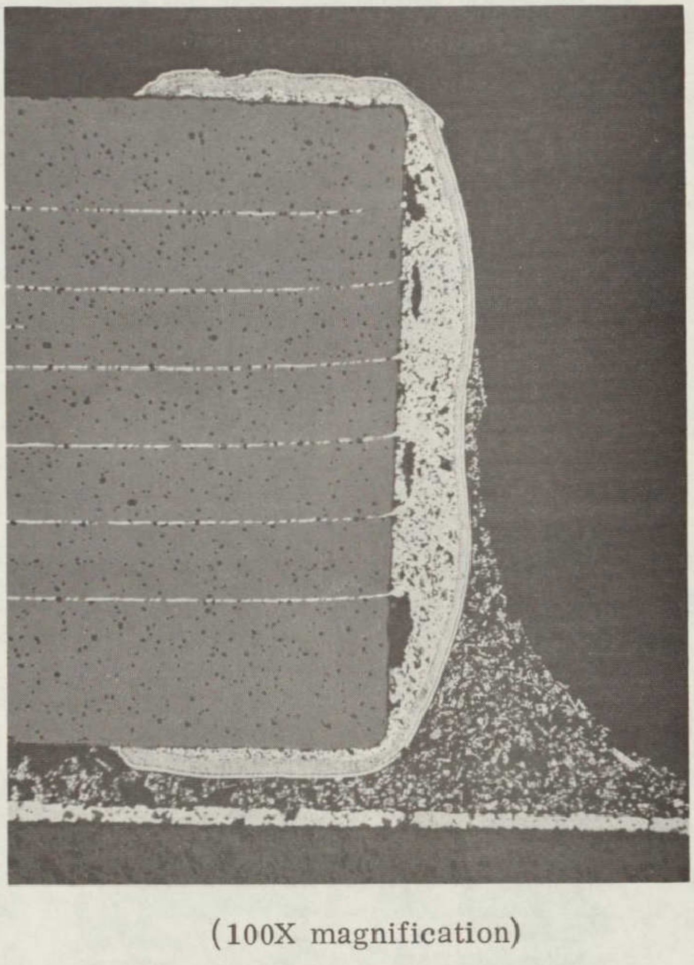


(100X magnification)

Figure 13. Ablebond 58-1 epoxy bonded Kemet capacitors to thin film substrates, dc resistance failure at joint (photographed after 500 thermal cycles).

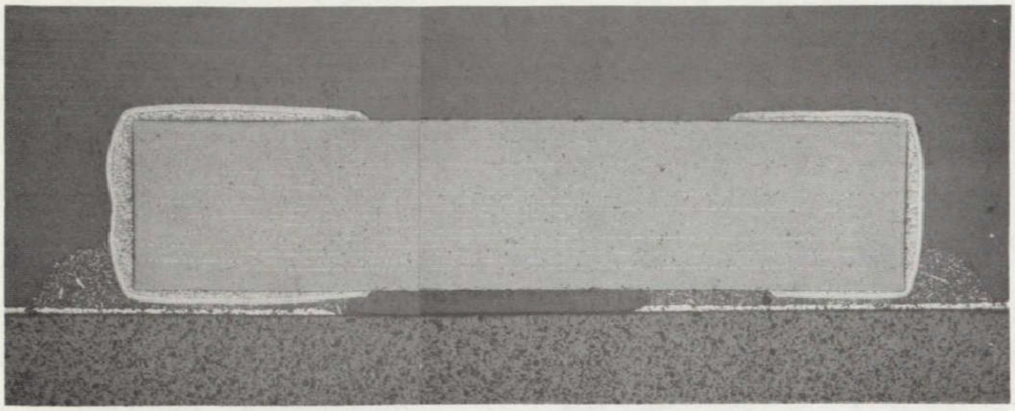


0805 size, K1200 (40X magnification)

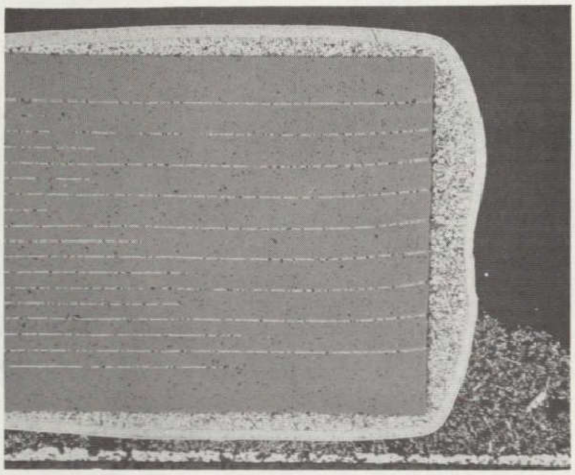


(100X magnification)

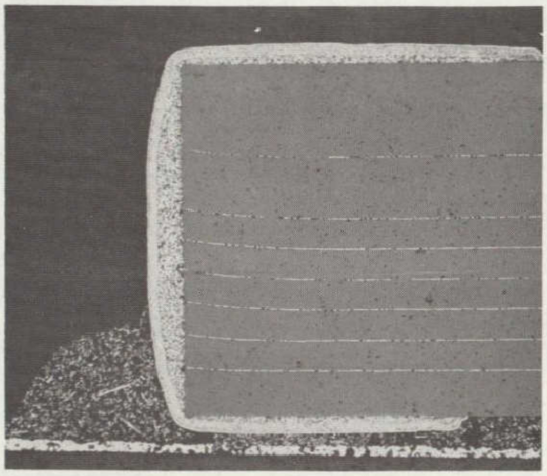
Figure 14. Ablebond 58-1 epoxy bonded Kemet capacitor to thick film substrate, dc resistance failure at joint (photographed after 500 thermal cycles).



1806 size, NPO (40X magnification)



(100X magnification)



(100X magnification)

Figure 15. Epo-Tek H-44 epoxy bonded Kemet capacitor on thick film substrate, no failure (photographed after 500 thermal cycles).

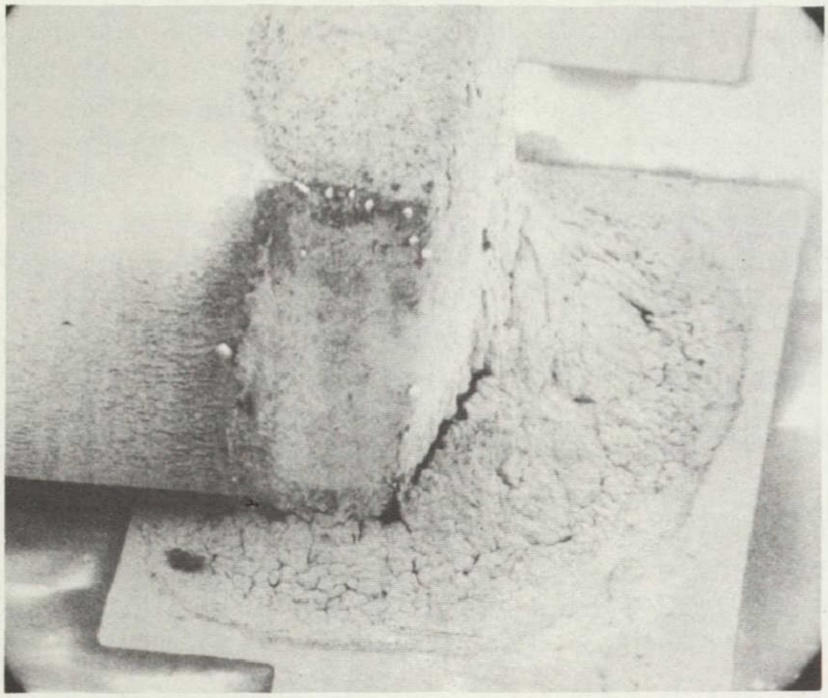
Photographs of Indalloy no. 7 solder fillet cracks resulting from thermal cycling are shown in Figures 16 through 19. The photos show the typical behavior pattern of Indalloy no. 7 on both Kemet and MDI capacitors during thermal cycling exposure. Note particularly the peeling of the substrate metallization from thick film substrates in photos 16b and 17b. Metallization lifting almost always occurred when the fillet extended to the edge of the substrate bonding pad. When the fillet stopped short of the pad edge, fillet cracking would occur along the base of the fillet as shown in Figures 17a and b. Also of particular interest is the crack location — on thick film the crack always occurred near the base of the fillet (Fig. 17a), whereas on thin film the crack occurred either near the top of the fillet or at the capacitor interface (see photo 16a).

On thin film substrates, Indalloy no. 7 fillets exhibited peeling from the substrate metallization within 50 thermal cycles as shown in Figure 19. The peeling effect relieved stresses in the fillets which extended fillet life through 200 cycles without fillet cracking. Although the Indalloy fillets did eventually crack between 200 and 300 cycles, it was proved that thin film substrates provided longer fillet life than did thick film substrates.

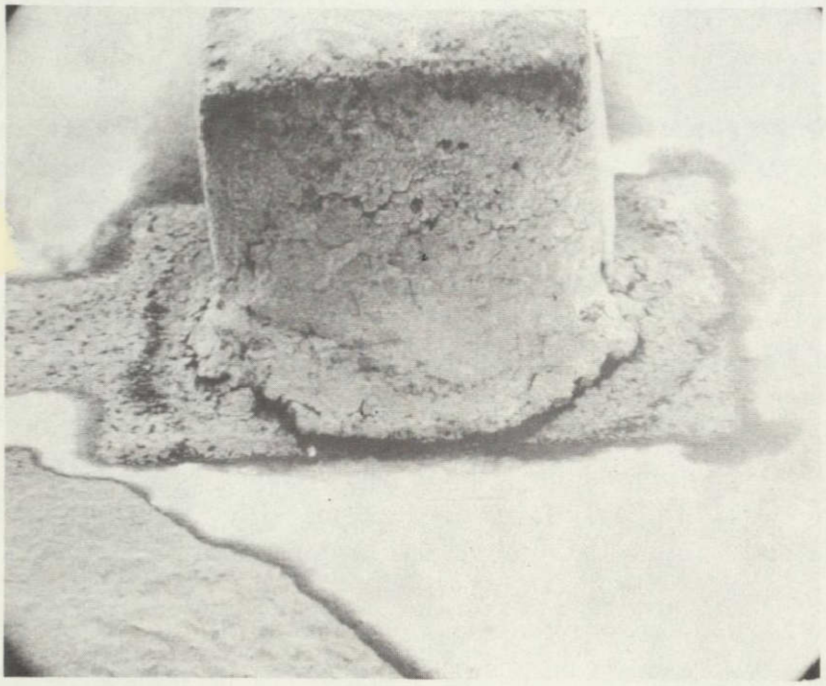
The secondary failure mode associated with solder was electrical in which seven capacitance failures and one joint resistance failure occurred. Five capacitance failures were with 10/90, while Indalloy no. 7 accounted for two capacitance and one joint resistance failure. Of the eight electrical failures, six occurred during thermal cycling, showing again the predominant effects of this exposure.

Two of the capacitance failures associated with 10/90 are shown in Figures 20 and 21. Figure 20 shows a transverse crack extending across the thickness of the capacitor near an electrode. Note the fractures in the ceramic immediately beneath the electrode metallization overlap area. The electrodes appear to be trying to pull a chunk of dielectric away from the main body of dielectric. It is suspected that the transverse crack was the result of the loading induced at these stress concentrated areas. Also obvious in Figure 20 is the formation of copper-tin intermetallics located in the fillet area. Note the spalling or separation of the intermetallics from the copper guard. Intermetallics bewteen tin-lead solders and copper when excessive cause brittle joints which are susceptible to early failure. Intermetallic formation can be minimized through maintaining the proper reflow conditions.

Figure 21 shows two defective conditions involving a 10/90 solder mounted capacitor. A void was observed along the center portion of the dielectric which involved three plates. The defect appears inherent to the capacitor

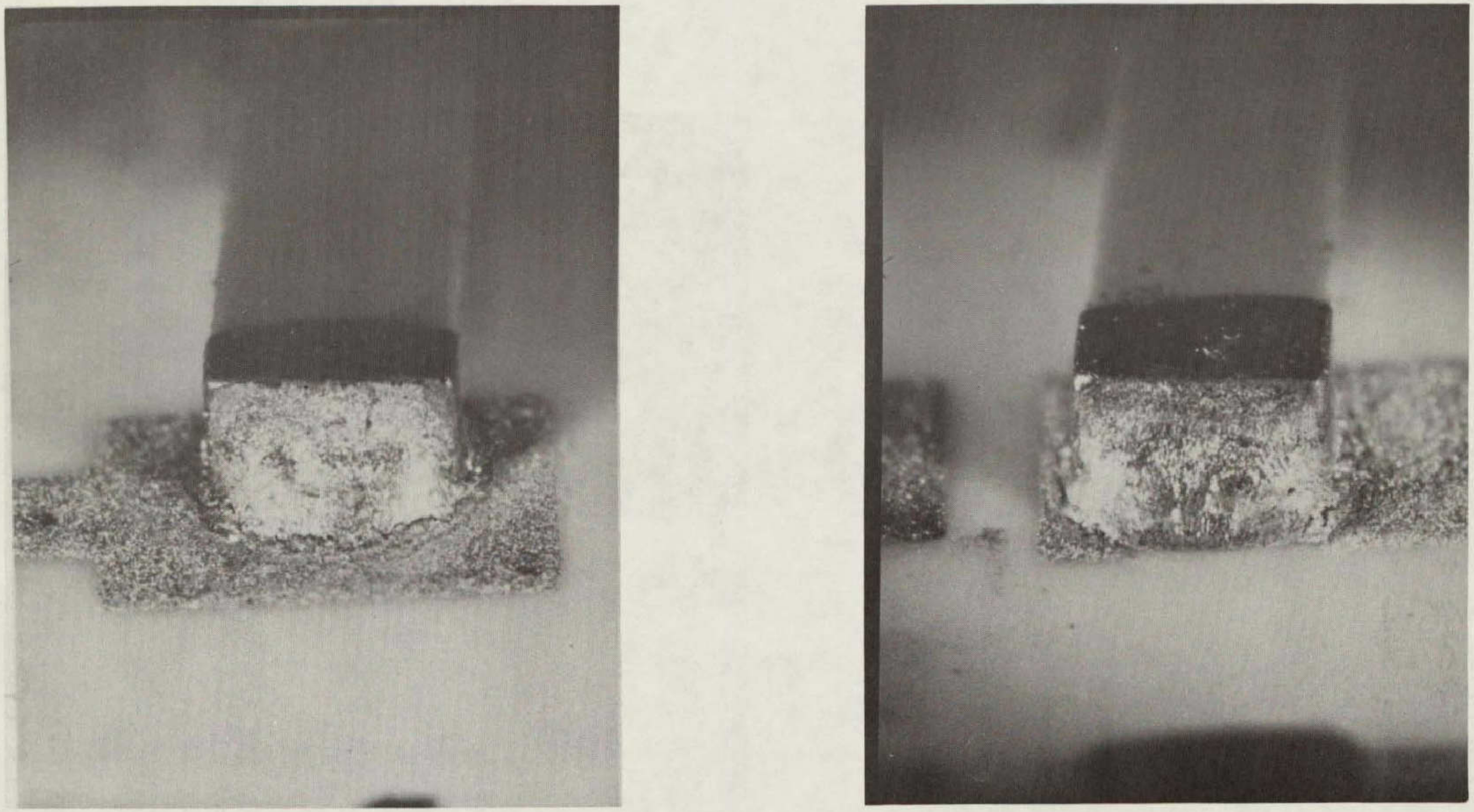


a. R25 size, NPO — Thin film substrate metallization (47X magnification).



b. R25 size, NPO — Thick film substrate metallization (32X magnification).

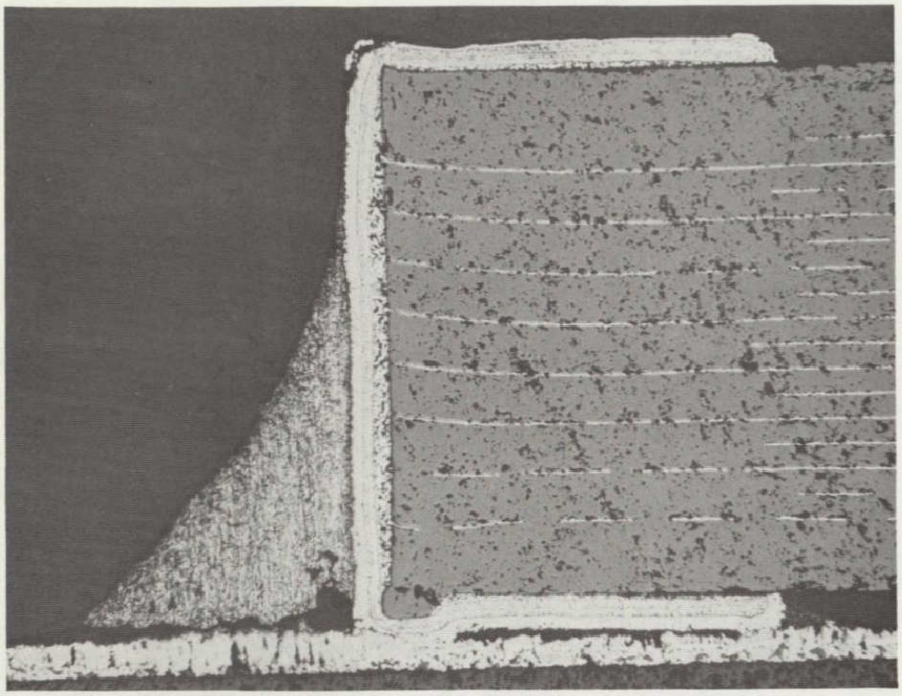
Figure 16. Indalloy no. 7 solder bonded MDI capacitors (photographed after 500 thermal cycles).



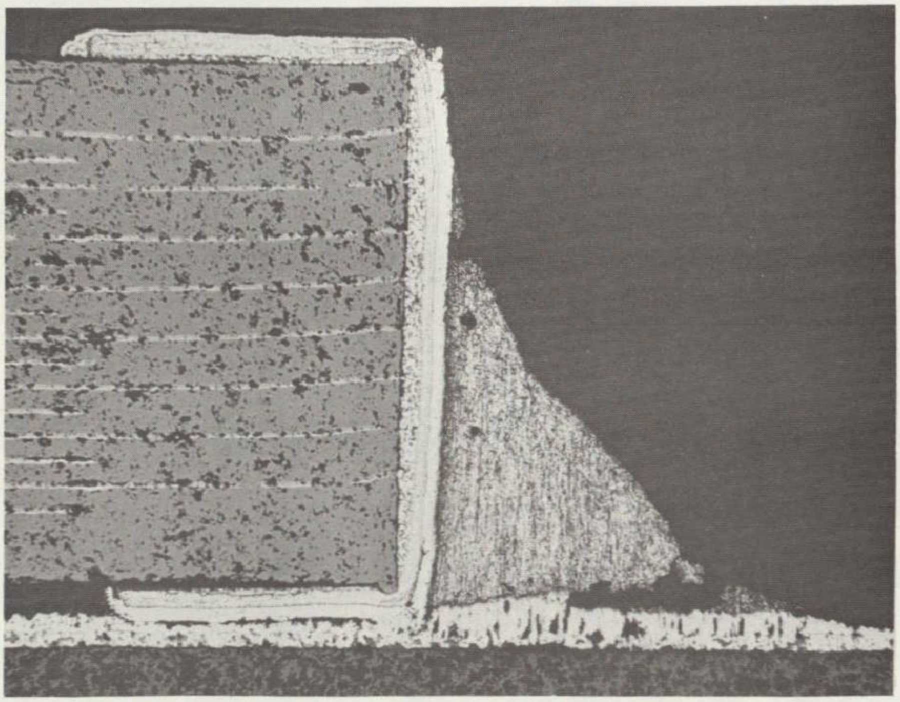
a. Fillet cracking at base of fillet on thick film. Typical when fillet stops short of bonding pad edge.

b. Bonding pad metallization peel from substrate. Typical when fillet bridges from capacitor to bonding pad edge.

Figure 17. Indalloy no. 7 bonded Kemet capacitors to thick film after 200 thermal cycles (1806 size, NPO, 25X magnification).

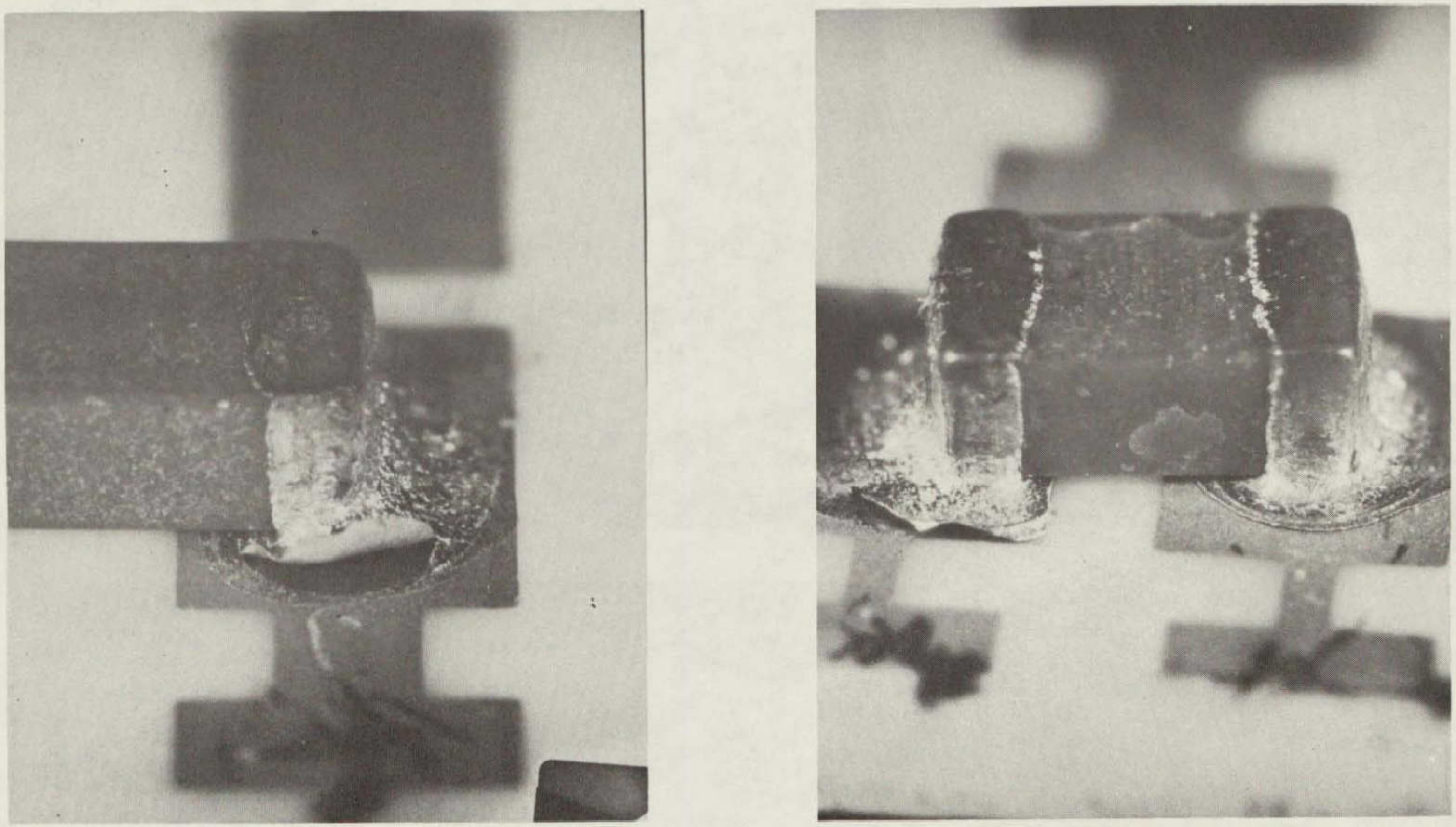


0805 size, NPO (100X magnification)



0805 size, NPO (100X magnification)

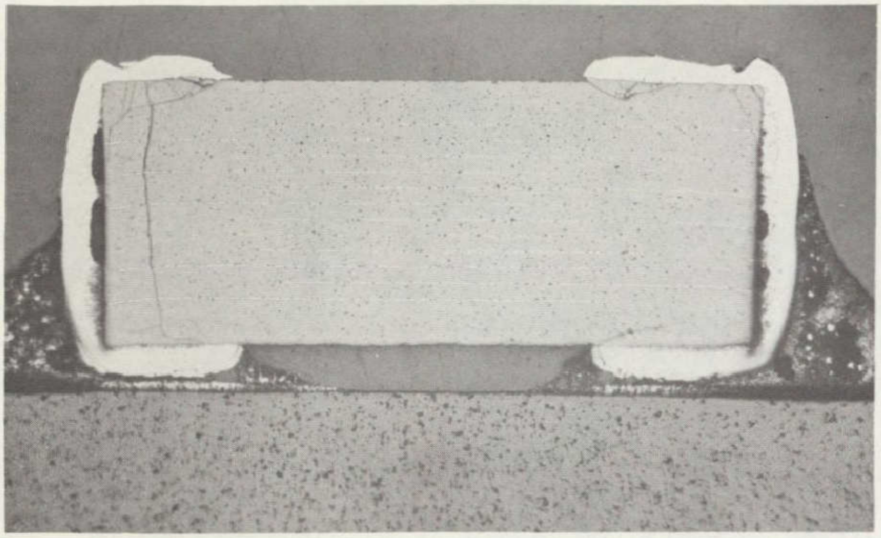
Figure 18. Indalloy no. 7 solder bonded Kemet capacitor to thick film substrate, fillet cracking after 200 thermal cycles.



1806 size, K1200

0805 size, K1200 (25X magnification)

Figure 19. Indalloy no. 7 solder, Kemet capacitor bonded to thin film substrate after 200 thermal cycles, solder peel.



0805 size, K1200 (40X magnification)

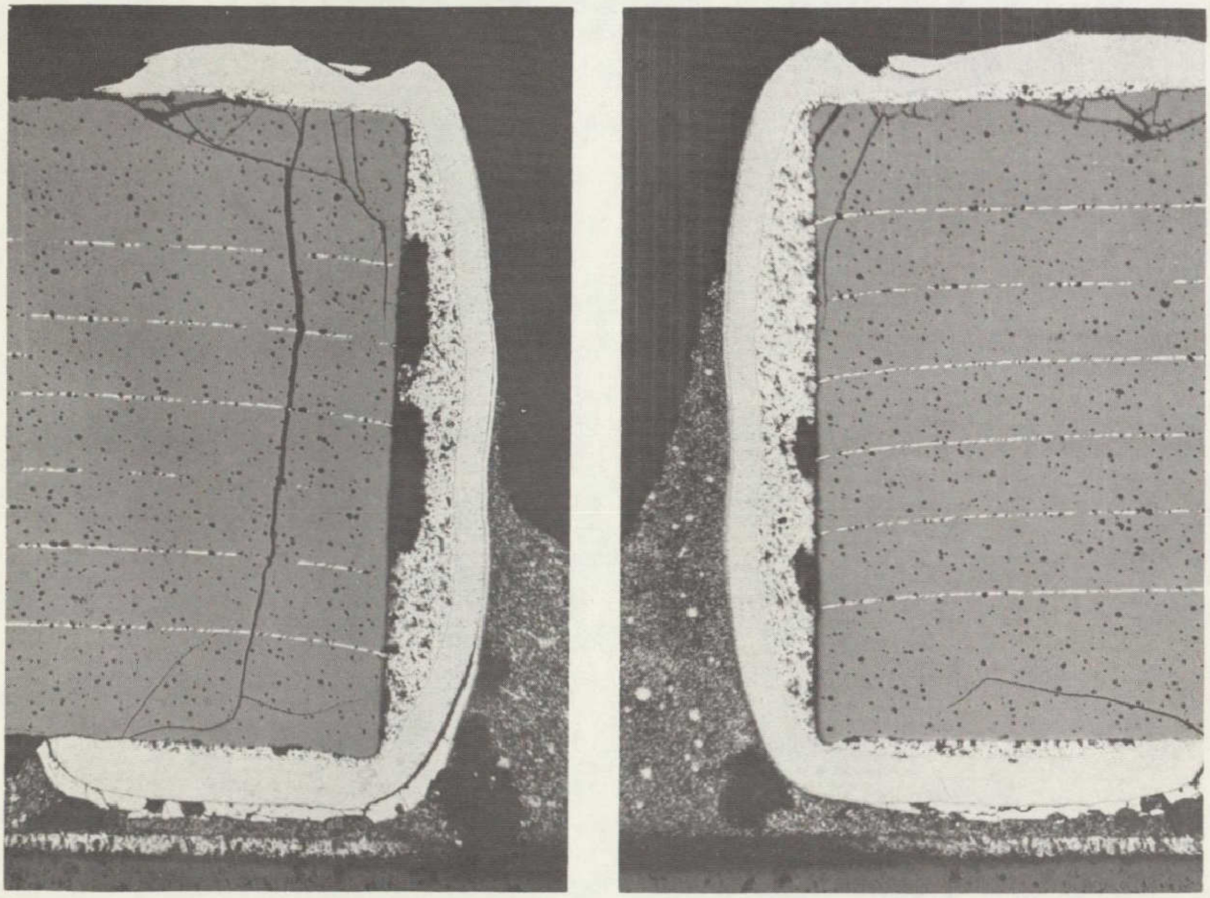
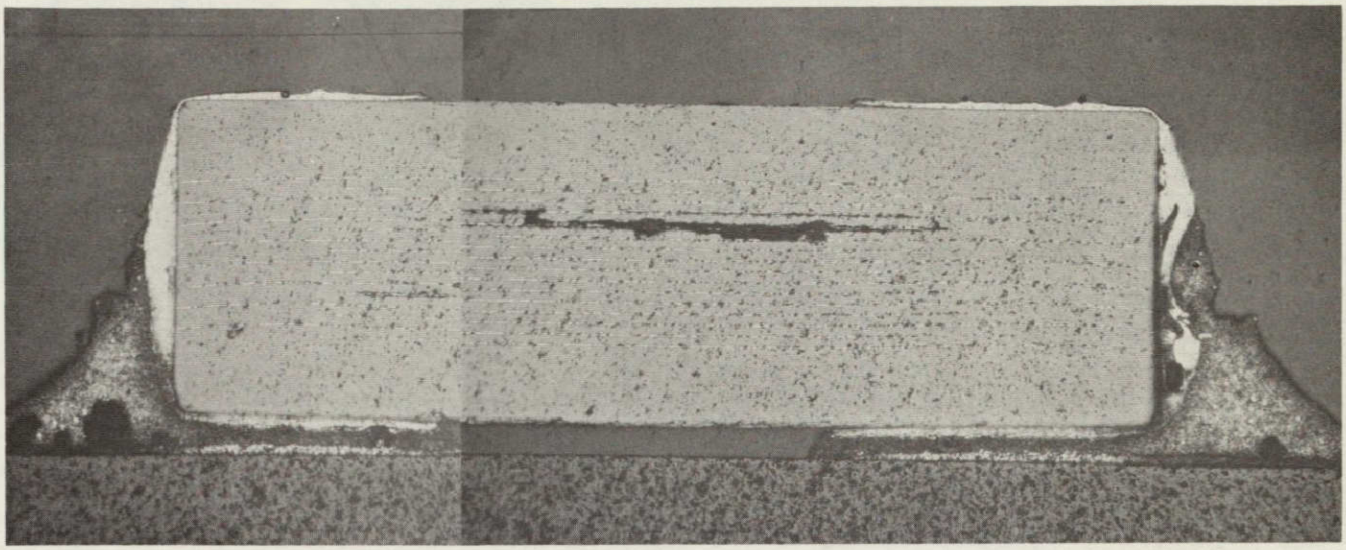
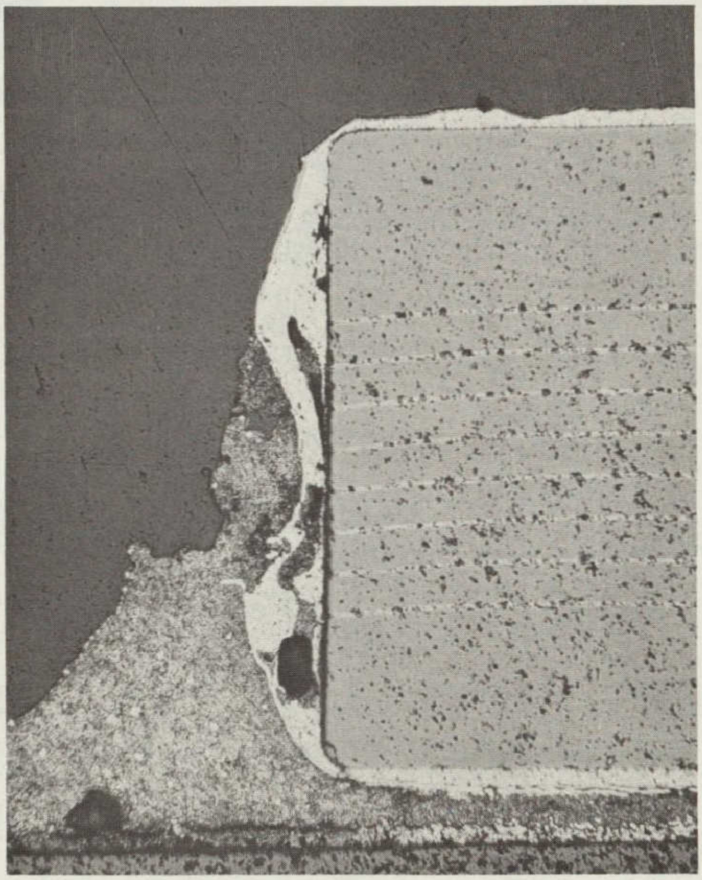


Figure 20. 10/90 solder bonded Kemet capacitor to Pt/Au thick film substrate, capacitance failure (photographed after 500 thermal cycles).



(40X magnification)



1806 size, NPO (100X magnification)

Figure 21. 10/90 solder bonded Kemet capacitor to Pt/Au thick film substrate, capacitance failure (photographed after 500 thermal cycles).

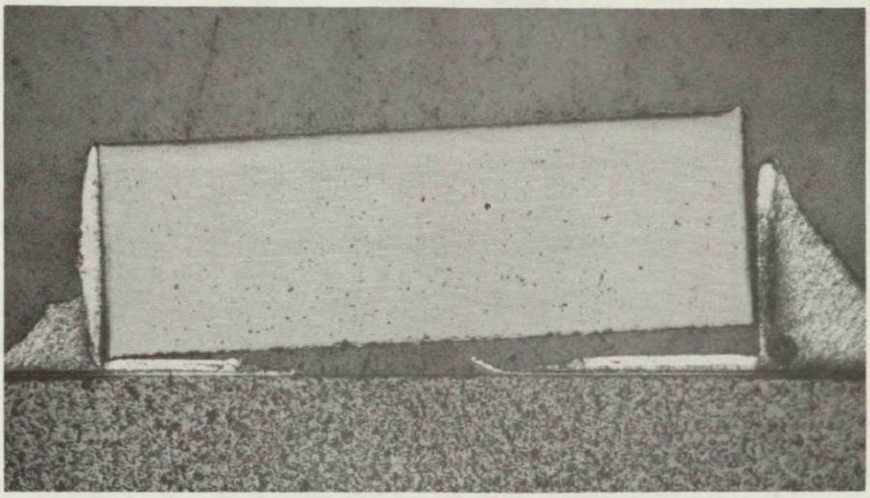
and probably did not contribute to the failure. The other condition found at one electrode involved a separation between the inner silver metallization and the capacitor plates. It appeared that the copper guard was either porous or non-uniform to allow solder penetration to the silver metallization. In fact, the copper guard could not be resolved in the main fillet area. It was faintly visible only along the top and bottom overlap areas. Solder penetration to the silver metallization may have contributed to the failure, but in any event the primary failure mode was judged to be the separation between the silver inner metallization and the capacitor plates.

Cross sections of two of the electrical failures that occurred in Indalloy no. 7 mounted capacitors during thermal cycling are shown in Figures 22 and 23. Figure 22 shows a capacitance failure caused by complete separation between the plates and the inner silver electrode metallization. Note again the absence of the copper guard.

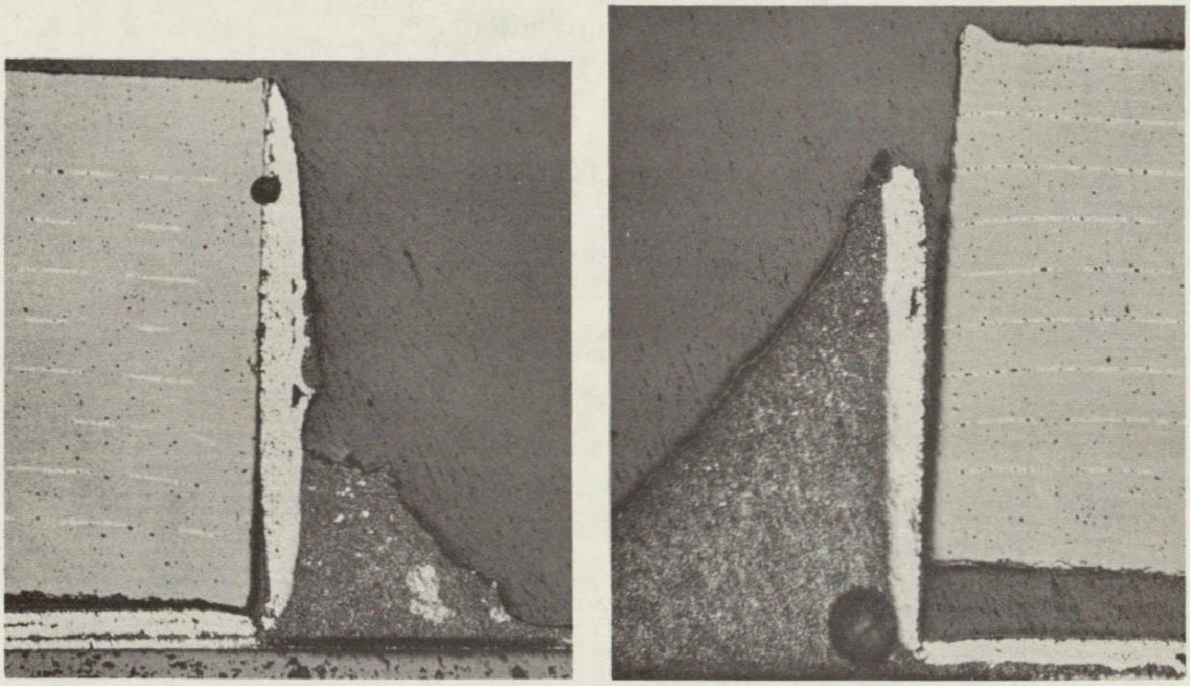
Figure 23 shows an Indalloy no. 7 mounted capacitor with a resistance increase failure. Again the copper guard was evident only as a thin and non-continuous strip along the top side of the electrodes. All traces of pure gold and copper disappeared along the ends and bottoms of the electrodes because of solder scavenging. The outer layer seen in the photograph is an intermetallic comprised of tin, copper and gold. Cracking occurred in the intermetallic layer and progressed through the solder causing separation of the larger portion of the fillet from the capacitor electrode which resulted in a high resistance joint.

Of the four electrical failures analyzed where solder was involved, three of the failures pointed toward electrode metallization defects. Poor bond strength between the inner silver electrode metallization and the capacitor plates plus thin and discontinuous copper guards were the type defects observed. Poor electrode adhesion and coverage were also noted on the following Kemet capacitor lots during incoming inspection:

Type	Size	Electrode Outside Metallization	Qty. with Electrode Peeling	Qty. with Electrode Separation at Corner	Total Lot Qty.	Lot No.	% Defective
NPO	1806	Copper	15	0	34	309HP	15/34 = 44
NPO	1806	Copper	1	0	32	241HP	1/32 = 3
NPO	0805	Gold	24	0	319	304HG	24/319 = 7.5
K1200	1806	Gold	0	73	319	223RP	73/319 = 23



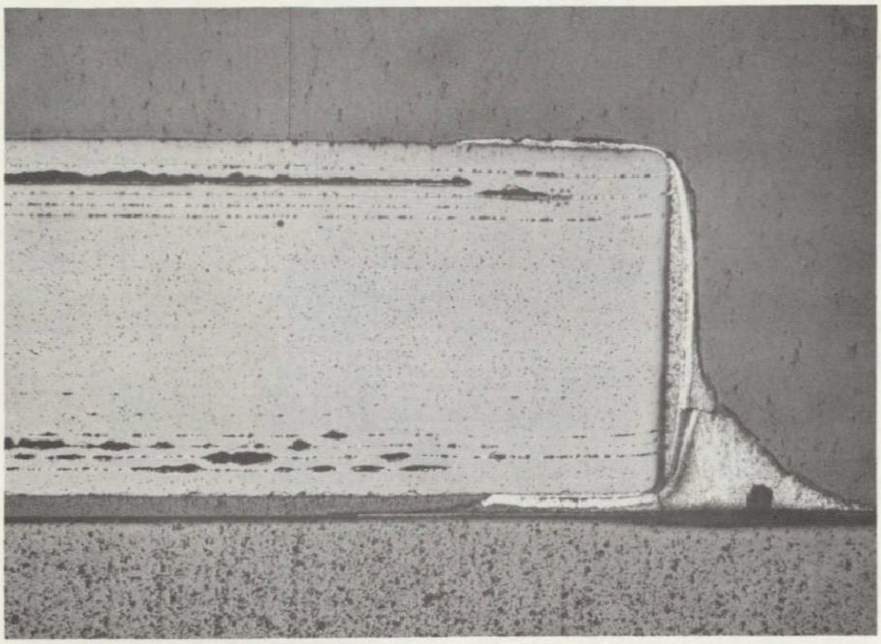
(40X magnification)



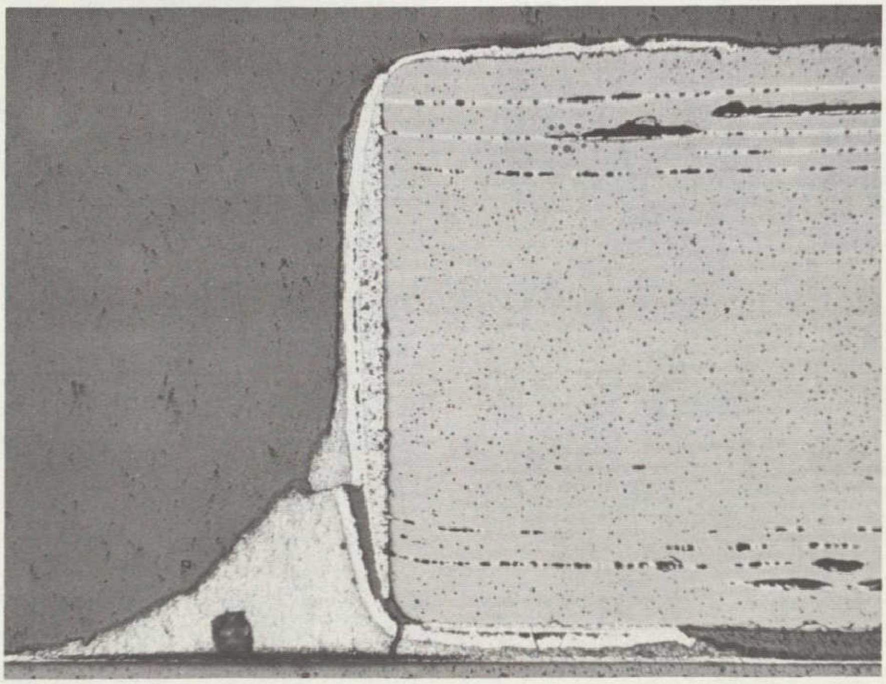
0805 size, NPO type

(100X magnification)

Figure 22. Indalloy no. 7 bonded Kemet capacitor to thin film substrate, capacitance failure (photographed after 500 thermal cycles).



(40X magnification)



1806 size, K1200 type (70X magnification)

Figure 23. Indalloy no. 7 solder bonded Kemet capacitor to thin film substrate, dc resistance failure after 300 thermal cycles.

Sequential Exposures. The sequential tests caused considerably more failures than did the individual exposures, especially in the category of capacitor removal. Thermal cycling, as shown in the individual exposures results, was again the environment that caused the most damage. Mechanical testing performed after thermal cycling caused a large percentage of capacitor removal due mainly to the effects of thermal cycling. Impact shock removed more capacitors than the combined totals of vibration and acceleration. A summary of results is shown in Table 2.

The gold epoxies showed the least number of failures. Ablebond 58-1 did not show the dc resistance increase problems that it experienced during individual testing. Ablebond 58-1 proved superior to H-44 primarily in the category of overall adhesive strength as shown by the fewer number of capacitors removed during mechanical testing.

Both epoxies developed fillet cracking within 100 thermal cycles. Cracking was limited, however, in that it was observed in only one capacitor with each type of epoxy.

Generally the epoxies showed good resistance to fillet cracking but they proved to be mechanically weak after thermal cycling.

Solders. As in the individual exposures, Indalloy no. 7 and 10/90 ranked third and fourth, respectively, behind the gold epoxies after sequential testing. Both solders developed fillet cracking within 50 to 100 thermal cycles. Indalloy no. 7 combinations followed almost the identical pattern of fillet cracking shown during individual thermal cycling. The 10/90 solder fillets, however, cracked considerably earlier during sequential thermal cycling than during individual thermal cycling. As explained earlier, 10/90 wetting to the capacitor electrodes was not considered optimum.

With ATC capacitors, bulk solder cracking occurred within 300 thermal cycles. Interest in the ATC capacitor was derived from the use of porcelain as the dielectric material and the ability to compare its thermal expansion characteristics with barium titanate. Porcelain provided advantages in this respect as both Kemet and ATC capacitors proved equally vulnerable to solder fillet cracking using 10/90.

The majority of electrical failures among all bonding systems that occurred during sequential testing were associated with Indalloy no 7. All capacitors exhibiting electrical failures were eventually removed from the substrate during mechanical testing and consequently no failure analysis could be performed.

TABLE 2. SEQUENTIAL EXPOSURES TESTING SUMMARY (Kemet and ATC Capacitors)

ATC No. of Caps	Kemet No. of Caps	Bonding System	Visual Failures			Electrical Failures		
			Caps(w) Cracked Fillets	Caps Cracked	Caps Removed	Capac. Dev.	Joint Resistance Increase	Total Failure Percentage
	40-11 =29[a]	58-1 Epoxy	1	0	19	1	1	22/29 = 76
	40-3 = 37[b]	H-44 Epoxy	1	0	36	1	0	38/37 = 102
	40-11 = 29[c]	Indalloy no. 7 Solder	40	0	25	4	6	75/69 = 108
	20	10/90 solder	15	0	7	1	1	24/20 = 120
10			10	0	1	0	0	11/10 = 110
Total			67	0	88	7	8	

a. 10 caps lost during thermal shock due to cracked substrate plus 1 lost due to handling.

b. 3 caps lost due to handling.

c. 10 caps lost during acceleration due to cracked substrate plus 1 lost due to handling.

Ranking:	First, 58-1 Epoxy	76% Failure
	Second, H-44 Epoxy	102% Failure
	Third, Indalloy no. 7 Solder	108% Failure
	Fourth, 10/90 Solder	120% — Kemet caps. Failure
		110% — ATC caps. Failure

Both Indalloy no. 7 and 10/90 showed little resistance to fillet cracking during thermal cracking. But for a bonding system with brute strength, as measured by its ability to retain a capacitor to the substrate during mechanical testing, 10/90 proved superior to Indalloy no. 7 and to the gold epoxies.

MDI Capacitor Results

Shear Test. The intent of the shear test was to determine bonding fillet degradation through comparison of unexposed and environmentally exposed shear values. Results are given here for MDI capacitors. Table 3 shows a summary of all the failures that occurred during individual environmental testing for all bonding systems.

The gold epoxies showed the lowest failures of the bonding systems. The primary failure mode was fillet cracking during thermal cycling. This was a surprising result compared to the Kemet specimens where only two instances of fillet cracking were observed. Fillet cracking occurred in both types of epoxy and was observed at the 300 thermal cycle inspection interval. Ablebond 58-1 specimens showed a lower percentage of fillet cracks than did H-44 specimens. It was also observed that Ablebond 58-1 did not develop fillet cracks when used in any thin film substrate combinations. None of the cracks in either epoxy caused a change in dc electrical resistance of the joints.

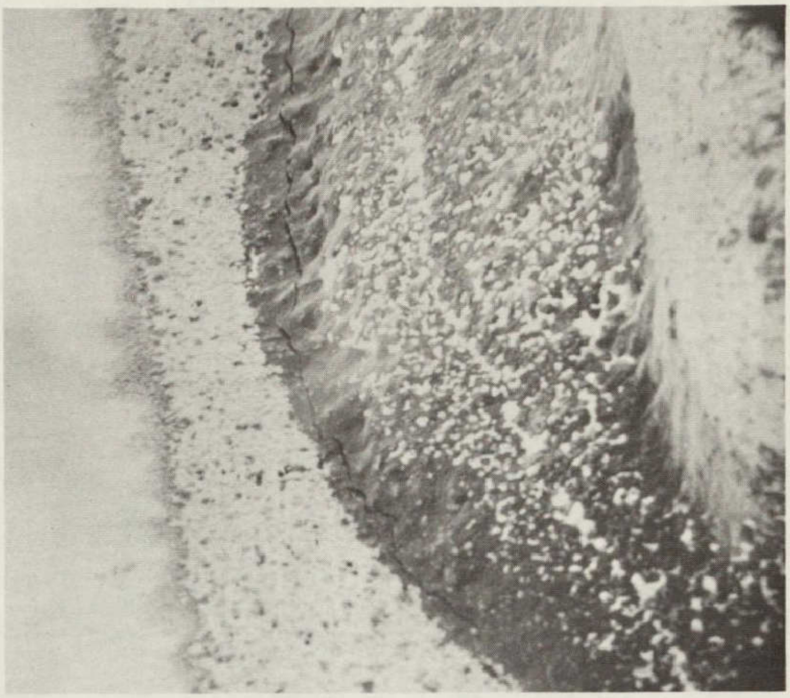
Photographs of typical epoxy cracks are shown in Figures 24 through 27. The smaller sized (R15) capacitors showed more resistance to fillet cracking as evidenced by the fact that most cracking occurred only during the last 100 of the 500 thermal cycles. Photos 24 and 25 show how H-44 fillet cracking on thick film substrate metallization was always located low in the fillet close to the bonding pad. (It was interesting that the crack locations in both epoxy and solder fillets were the same on thick film substrates.) The cracks propagated at a 90 deg angle from the epoxy surface until it reached the bonding pad. Once at the bonding pad, the crack propagated parallel with the bonding pad for approximately 30 to 40 percent of the fillet width. Cracking never progressed to the point of isolating the capacitor from the bonding pad, which explains why no dc electrical resistance increases were detected among the cracked fillets.

Figure 26 shows H-44 epoxy on thin film substrate metallization. Again, as reported earlier with solder fillets on thin film metallization, cracking occurred high in the fillet close to the capacitor electrode.

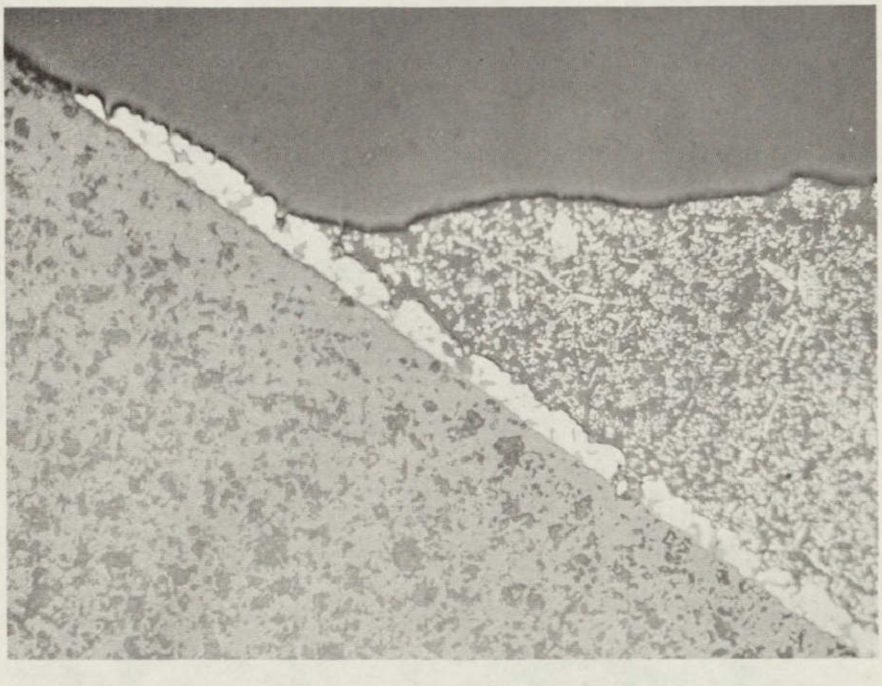
Figure 27 shows fillet cracking in Ablebond 58-1 on thick film substrate metallization. No Ablebond 58-1 fillet cracking occurred on specimens mounted to thin film substrates.

TABLE 3. INDIVIDUAL EXPOSURES TESTING SUMMARY (MDI Capacitors)

MDI No. of Caps	Bonding System	Visual Failures			Electrical Failures		
		Caps(w) Cracked Fillets	Caps Cracked	Caps Removed	Capac. Dev.	Joint Resistance Increase	Total Failure Percentage
240	58-1 Epoxy	6	1	2	0	0	9/240 = 3.75
240	H-44 Epoxy	15	3	5	0	0	23/240 = 9.58
240	Indalloy no. 7 Solder	45	0	1	5	0	51/240 = 21
120	10/90 Solder	12	2	0	0	0	14/120 = 11.6
Total		78	6	8	5	0	

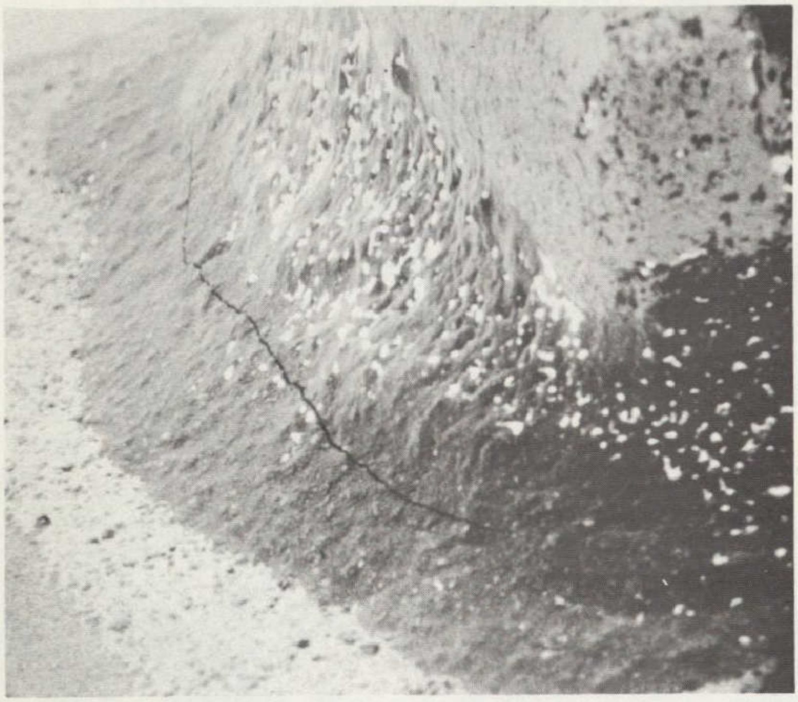


(100X magnification)

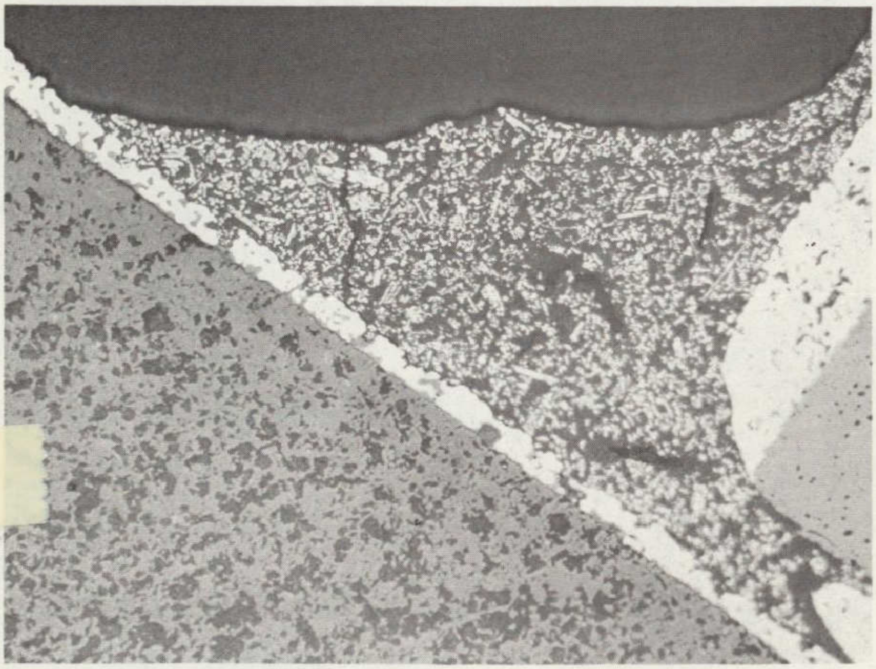


R25 size, K1200 type (160X magnification)

Figure 24. Epo-Tek H-44 epoxy bonded MDI capacitor to thick film substrate, fillet cracking (photographed after 500 thermal cycles).

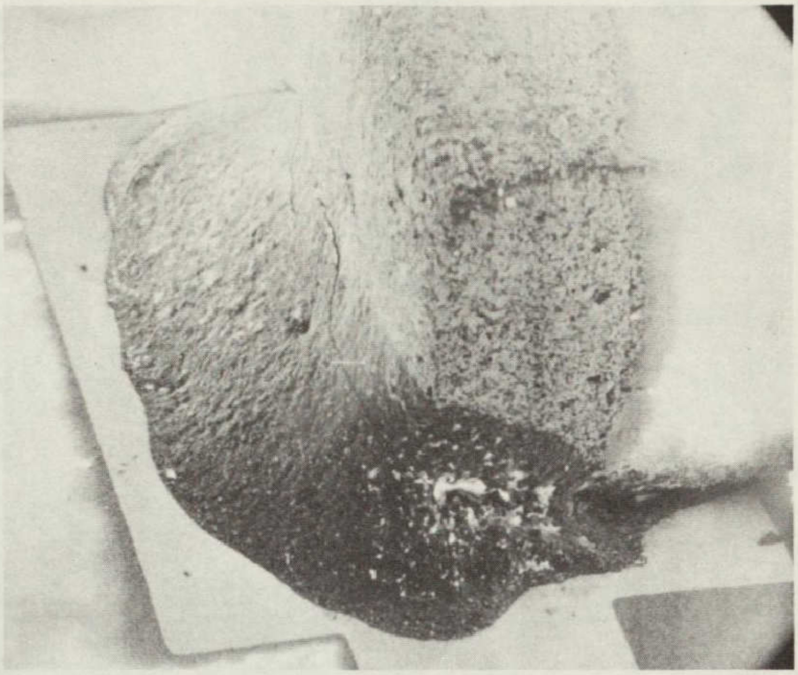


(95X magnification)

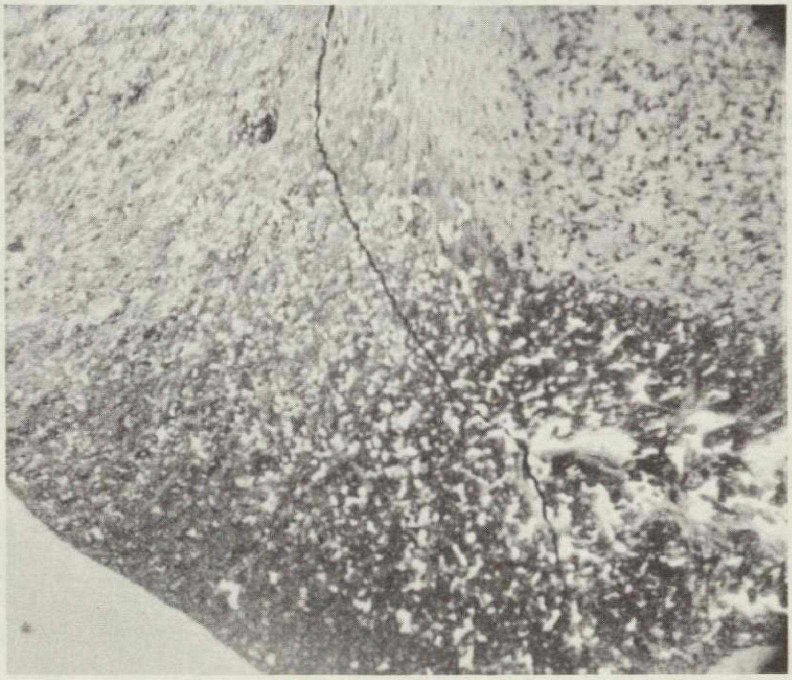


R25 size, K1200 type (160X magnification)

Figure 25. Epo-Tek H-44 epoxy bonded MDI capacitor to thick film substrate, fillet cracking (photographed after 500 thermal cycles).

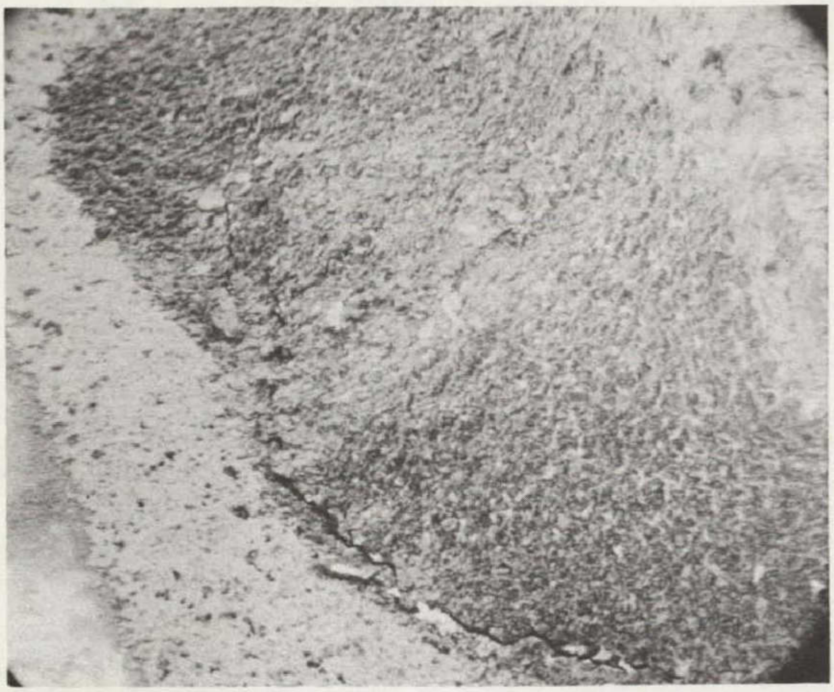


(48X magnification)

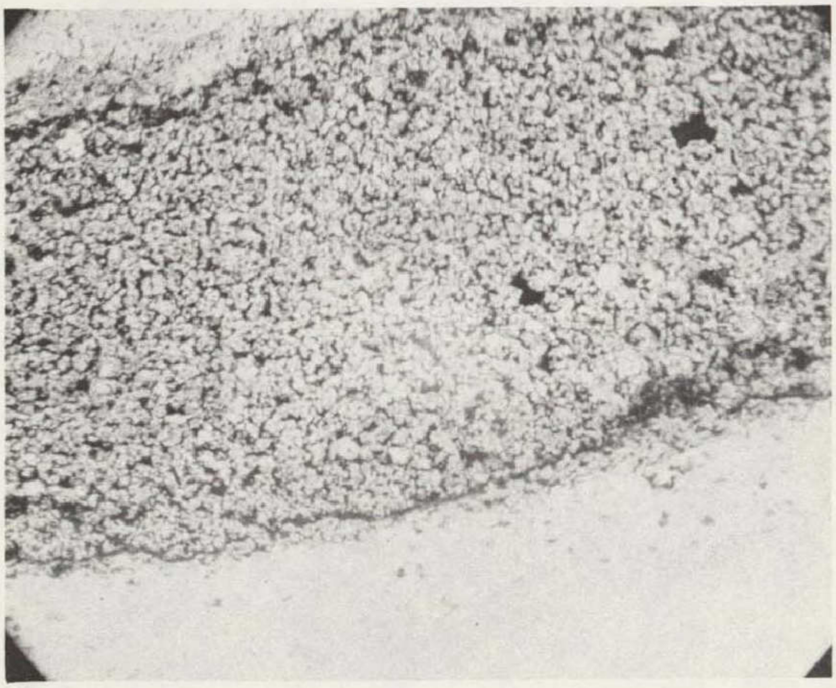


R25 size, NPO (95X magnification)

Figure 26. Epo-Tek H-44 epoxy bonded MDI capacitor to thin film substrate, fillet cracking (photographed after 500 thermal cycles).



R25 size, K1200 type (89X magnification)



R25 size, NPO type (130X magnification)

Figure 27. Ablebond 58-1 epoxy bonded MDI capacitors to thick film substrate, fillet cracking (photographed after 500 thermal cycles).

The two epoxies showed opposite surface textures; H-44 appears shiny and vitreous while Ablebond 58-1 appeared dull and grainy. This condition was noted on both Kemet and MDI capacitors and LIDs. For a comparison of surface textures, see Figures 26 and 27.

Dc Resistance Failures. There were no dc resistance failures. During impact shock testing, seven epoxy mounted capacitors were removed. In some instances the capacitor peeled from its electrodes, leaving the electrodes and epoxy intact with the bonding pad (see Figure 28). In other instances, large chunks of dielectric material and electrode metallization remained imbedded in the epoxy fillets after the bulk of the capacitor had been removed (see Figure 28b). Capacitor removal was therefore a result of capacitor fragility rather than the fault of the epoxy. Figure 29 shows typical examples of two capacitors which cracked and shattered yet remained attached to the substrate.

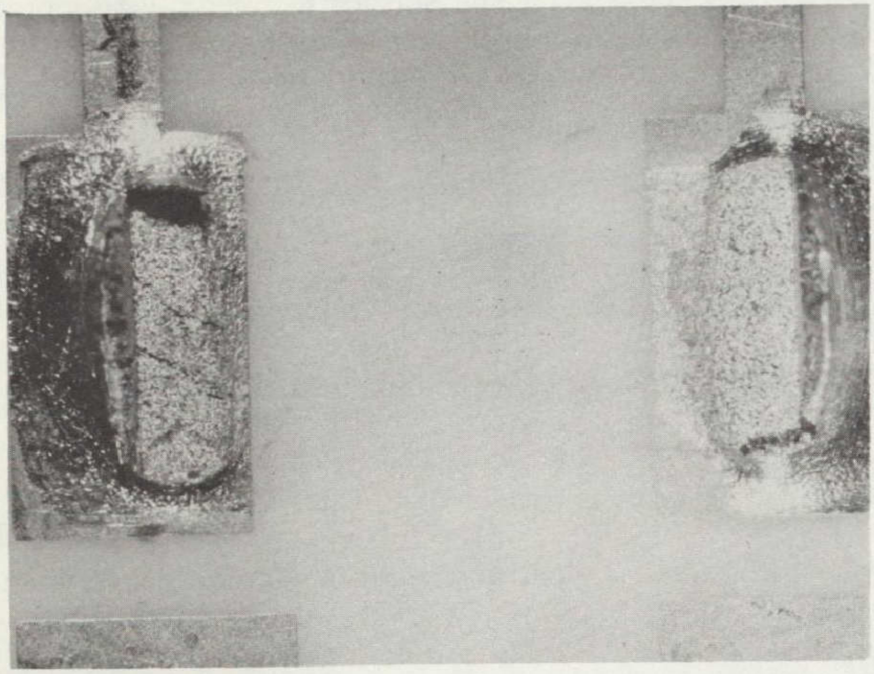
Epoxy. There were no electrical failures with any epoxy bonded specimens.

Solders. Of the two solders, 10/90 and Indalloy no. 7 ranked third and fourth, respectively, behind the epoxies. Fillet cracking caused during thermal cycling was the primary failure mode in both solders. Indalloy no. 7 cracked within 50 cycles, whereas 10/90 required 200 cycles. After 500 cycles, Indalloy no. 7 specimens showed 100 percent fillet cracking whereas 10/90 specimens showed 60 percent.

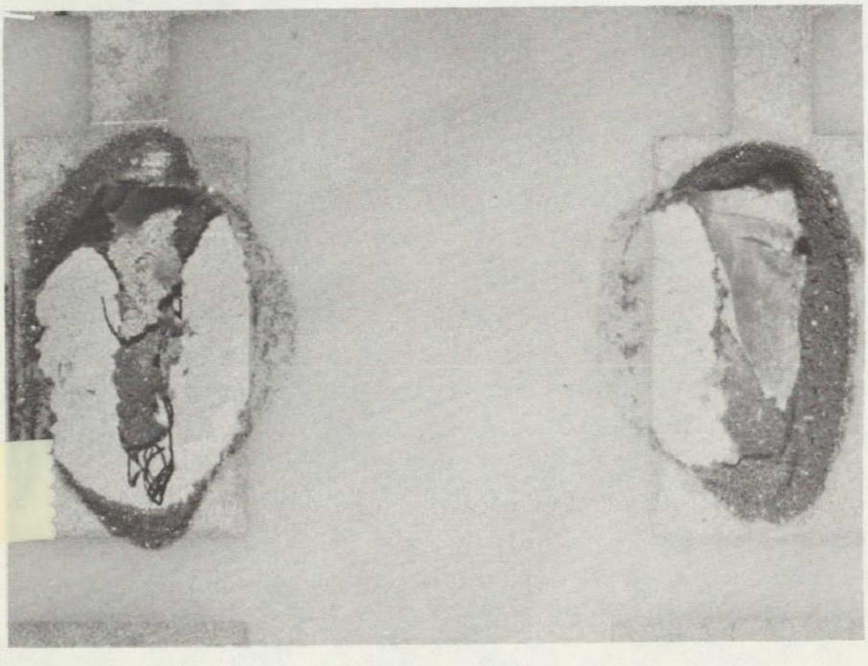
One combination with 10/90 involving K1200 type and R25 size capacitors survived 500 cycles without fillet cracking. Figure 30 shows an example of the 10/90 fillets after 500 thermal cycles. There was evidence of considerable stressing (orange peel) but no definite crack line was observed. Figure 30b shows an example of the smaller size capacitor after 500 cycles where considerable solder cracking developed. The larger fillets associated with the larger size capacitor proved more crack resistant primarily because of the greater solder mass involved.

Indalloy no. 7 fillets showed slightly more crack resistance on thin film than on thick film. The type, magnitude and location of Indalloy no. 7 fillet cracking with MDI capacitors on both thick and thin film substrates was identical to that experiences on Kemet capacitors (see Figures 16, 17, 18 and 19).

There were five electrical failures, all capacitance deviations, associated with the solders. All failures involved Indalloy no. 7 and occurred during impact shock, acceleration and thermal cycling. No failure analysis was performed.

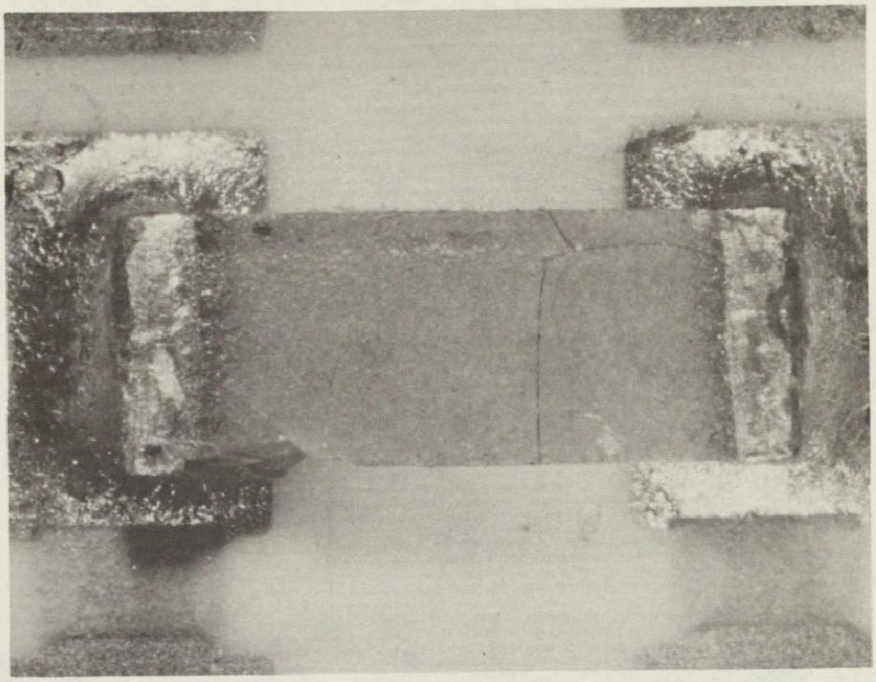


a. R25 size, NPO, electrodes peeled from capacitor body (20X magnification).

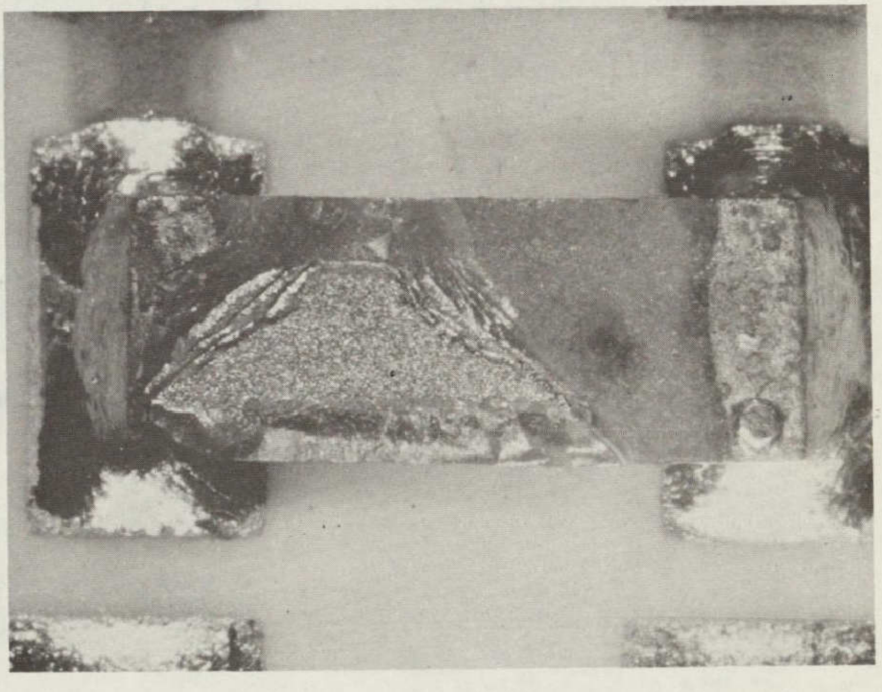


b. R25 size, NPO, electrodes peeled, capacitor chip out, epoxy fillet peel (20X magnification).

Figure 28. Failure modes exhibited with MDI capacitor after impact shock.

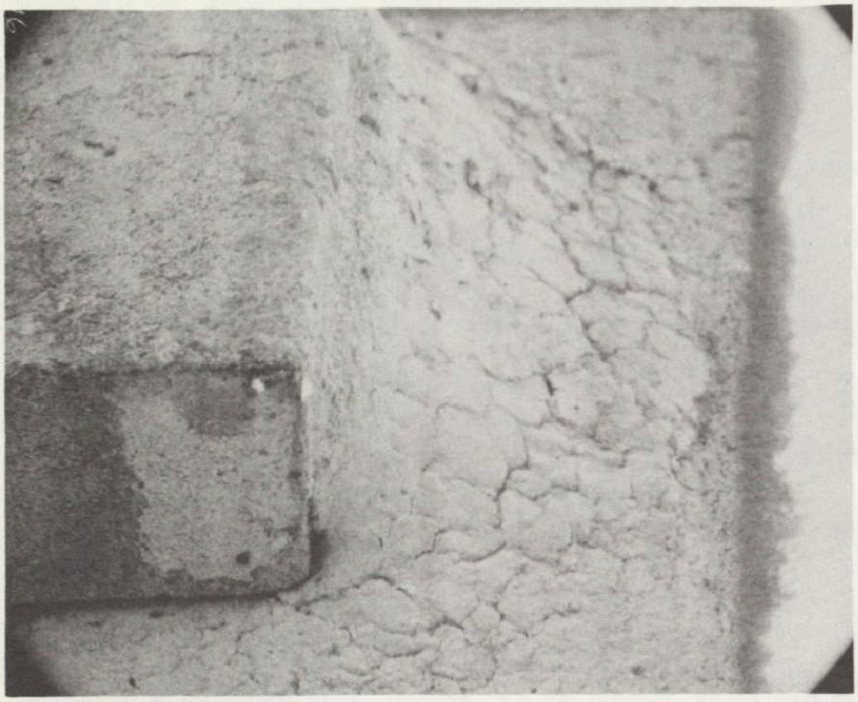


a. R25 size, K1200, capacitor cracked (20X magnification).

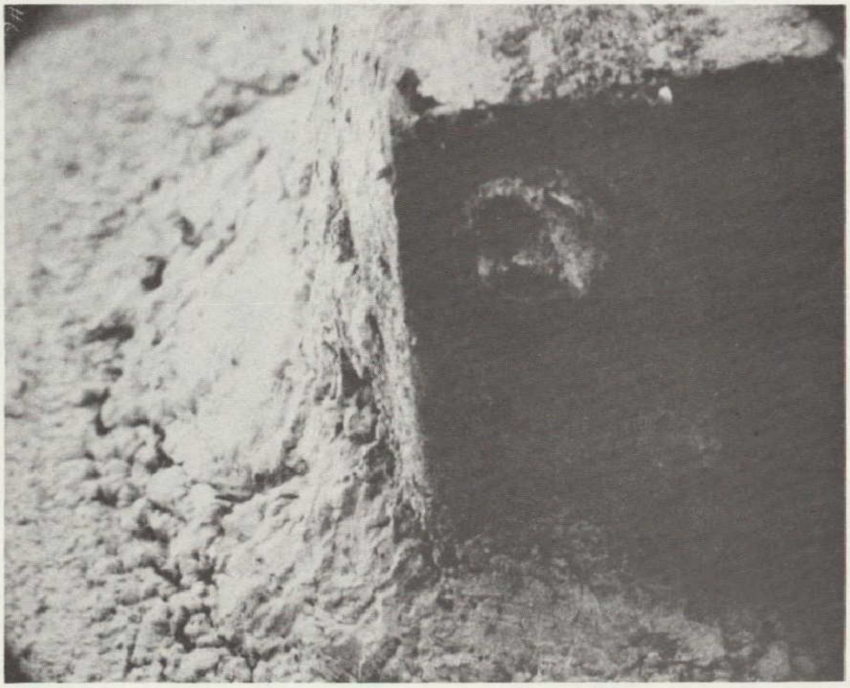


b. R25 size, K1200, capacitor shattered (20X magnification).

Figure 29. Failure modes exhibited with MDI capacitor after impact shock.



a. R25 size, K1200, solder crazing (67X magnification).



b. R15 size, K1200, solder cracking (99X magnification).

Figure 30. 10/90 solder bonded MDI capacitors to Pt/Au thick film substrate (photographed after 500 thermal cycles).

Sequential Exposures. A summary of results for sequential exposures is shown in Table 4.

The failure rates from sequential testing were considerably higher than with individual testing. Again, thermal cycling plus impact shock proved the most damaging environments.

Gold Epoxies. The gold epoxies ranked second and third behind 10/90 solder. High percentages of fillet cracking from thermal cycling plus capacitor removal during impact shock accounted for their ranking behind 10/90 solder. Fillet cracking in both epoxies occurred within 100 thermal cycles and the percentage of cracking through 500 thermal cycles was approximately equal. With respect to overall adhesive strength preventing capacitor removal during mechanical testing, Ablebond 58-1 proved superior to Epo-Tek H-44.

There were two substrate combinations using the epoxies that survived all sequential testing without failure. They were as follows: (1) Ablebond 58-1 with R25 size, K1200 type on thin film substrate metallization and (2) Epo-Tek H-44 with R15 size, NPO type on thick film substrate metallization.

One electrical failure, a "dc joint resistance increase," occurred with Ablebond 58-1. This was the third incidence of a dc resistance problem with Ablebond 58-1. To recap briefly, resistance problems first occurred with Kemet capacitors during individual thermal cycling, second with Kemet capacitor during sequential thermal cycling and now, third, with MDI capacitor during sequential thermal cycling. The one thing in common among all incidences was thermal cycling.

Generally, the epoxies showed poor resistance to fillet cracking (thermal cycling) and equally poor adhesive properties during mechanical testing (primarily impact shock).

Solders. Of the two solders, 10/90 ranked first and Indalloy no. 7 ranked last among the four bonding systems. Indalloy no. 7 fillets continued to follow their early cracking trends by cracking within 50 thermal cycles on both thick and thin film substrates.

The 10/90 solder fillets survived at least 200 cycles with cracking occurring only on the small R15 size capacitors. The two combinations of 10/90 with the larger size R25 capacitors survived 500 cycles without fillet cracking.

TABLE 4. SEQUENTIAL EXPOSURES TESTING SUMMARY (MDI Capacitors)

MDI No. of Caps	Bonding System	Visual Failures			Electrical Failures		
		Caps(w) Cracked Fillets	Caps Cracked	Caps Removed	Capac. Dev.	Joint Resistance Increase	Total Failure Percentage
40	58-1 Epoxy	17	0	10	0	1	28/40 = 70
40	H-44 Epoxy	13	0	26	0	0	39/40 = 97.5
40	Indalloy no. 7 Solder	39	1	40	3	0	83/40 = 207
20	10/90 Solder	6	0	0	3	0	9/20 = 45
Total		75	1	76	6	1	

Ranking:	First, 10/90 Solder	45% Failure
	Second, Ablebond 58-1 Epoxy	70% Failure
	Third, H-44 Epoxy	97.5% Failure
	Fourth, Indalloy no. 7 Solder	207% Failure

The 10/90 solder continued to show its brute strength characteristics through impact shock, acceleration, and vibration testing by not allowing any capacitor removal. This single factor is the strongest asset of 10/90 and was responsible for its high ranking among the bonding system.. In contrast, Indalloy no. 7 solder allowed 100 percent capacitor removal during the mechanical environments.

Solder accounted for six out of the seven electrical failures among the four bonding systems. Three failures involved 10/90 and three involved Indalloy no. 7. All failures were capacitance deviation greater than ±5 percent of the original capacitance value. Five of the six failures occurred during thermal cycling and one during impact shock.

None of the failures were analyzed because the three Indalloy no. 7 mounted capacitors were removed during impact shock and the three 10/90 failures were purposely left for shear testing.

SUMMARY

1. The conductive epoxies and 10/90 solder produced satisfactory bonds for Class A hardware conditions only in certain substrate/component combinations. Indalloy no. 7 solder was totally unsatisfactory as a bonding system.

2. A bonding system should be evaluated against each particular substrate/component combination to be used and more importantly against each component supplier. For example, in this study, the conductive epoxies proved compatible with Kemet capacitors but developed fillet cracking when used with MDI capacitors.

3. Generally the MIL-STD-883 levels of testing for Class A hardware is considered too severe for hybrid microcircuits especially in the mechanical testing categories. Substrate breakage was frequently encountered due to the high test levels.

4. Thermal cycling and impact shock proved to be the most effective tests in determining the mechanical and electrical characteristics of the bonding systems and components. Thermal cycling plus impact shock or acceleration should, therefore, be the nucleus of any screen testing.

5. The conductive epoxy bonding systems had fewer failures than did 10/90 and were rated the best of the systems evaluated.

6. Ablebond 58-1 epoxy provided better adhesive properties and was more crack resistant compared to Epo-Tek H-44 epoxy. Ablebond 58-1 did, however, show the potential of having electrical resistance problems.

7. Epo-Tek H-44 was superior to Ablebond 58-1 only in that is showed no electrical resistance problems and in that it exhibited a smoother, finer grained texture.

8. The 10/90 solder, although prone to fillet cracking during thermal cycling, provided the greatest strength among all the bonding systems relative to its ability to prevent component removal during mechanical testing.

9. Sequential exposure testing was substantially more severe than the individual exposures. Only one substrate combination with each epoxy and one with 10/90 solder survived all the sequential exposures without failures. The greatest benefit derived by the sequential exposures was the determination of which system had the greatest overall strength relative to retaining the components.

10. The type substrate metallization, the component supplier, and the size of the components were the primary contributors toward the survival of each bonding system. The type of dielectric material K1200 versus NPO made no difference.

11. Thin film substrate metallization prolonged bond fillet life in both capacitors and LIDs and in both the epoxy and solder systems.

12. MDI capacitors were more vulnerable to cracking and shattering during mechanical testing than were Kemet capacitors.

13. MDI capacitors were uniform in workmanship from lot to lot. Kemet, however, showed variations in workmanship from lot to lot in the areas of electrode metallization peeling and splitting.

14. The ATC capacitors with porcelain dielectric offered no advantages over barium titanate in regard to bond fillet cracking.

CONCLUSIONS

The test program described in this report represents only a summary of the investigations conducted to date on bonding systems for discrete electronic components. Since the use of adhesive in place of soft metals is becoming prominent for high reliability applications, studies to prove this suitability in space-flight avionics hardware were required. Marshall Space Flight Center has been actively conducting research and development in this area. In general, adhesives, when selected and properly qualified are acceptable and, in some cases, more reliable, than the traditional solder techniques. Test procedures and qualification criteria are being developed at MSFC and will be proposed as NASA/industry standards for this technology.

APPROVAL

INVESTIGATION OF DISCRETE COMPONENT CHIP MOUNTING TECHNOLOGY FOR HYBRID MICROELECTRONIC CIRCUITS

By Salvadore V. Caruso and J. O. Honeycutt

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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