Commercial Plastic Encapsulated Microcircuits for Naval Aviation Applications

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To determine the effects of uncontrolled long-term dormant storage on plastic encapsulated microcircuits, the Applied Physics Laboratory evaluated 92 commercial samples, some as old as 28 years, from multiple manufacturers and technologies. The presumption is that if old parts have not degraded after 20 or 30 years of uncontrolled long-term dormant storage, then vastly superior current products will survive similar periods under similar conditions. Results from destructive physical analysis revealed that only two plastic encapsulated microcircuits, both 28 years old, exhibited corrosion. Regardless of age, C-mode scanning acoustic microscopy revealed delaminated areas in most parts, suggesting that this technique might not be a good method for screening plastic encapsulated microcircuits. No direct relationship was found between corrosion and moisture content. In addition, oxygen plasma etching was found to be a very effective method for performing destructive physical analysis on plastic encapsulated microcircuits.
(Keywords: Plastic encapsulated microcircuits, Naval aviation, Long-term dormant storage.)

BACKGROUND

In June 1995, the Navy's acquisition program office for F/A-18 aircraft chartered a team of experts to determine areas of risk associated with using plastic encapsulated microcircuits (PEMs) in F/A-18 equipment and to recommend risk mitigation strategies. To provide a wide knowledge base, the team included members from the Naval Air Systems Command; Naval Air Warfare Center, Aircraft Division, Indianapolis; Naval Air Warfare Center, Weapons Division, China Lake; McDonnell Douglas Aerospace; Honeywell, Inc.; and APL. The long-term dormant storage study discussed in this article is derived from the findings of the F/A-18 PEM Assessment Team.

Long-term dormant storage of PEMs in harsh environments is one of the last major issues to be addressed before using PEMs in naval aviation systems. Since many maintenance and servicing operations of Navy aircraft are performed onboard aircraft carriers, the solution to this problem is paramount.

According to a McDonnell Douglas report,[1] the actual flying experience for the Navy F/A-18 aircraft indicates a composite use rate of 38.6 h/month. Therefore, to achieve a 6000-flight-hour life goal, the F/A-18 will be in service for nearly 13 years (113,880 h). The actual flying time represents approximately 5.3% of the total aircraft life; the remaining 94.7% is divided between storage, handling, maintenance, servicing, and ground (or carrier deck) environment.[1]

Assuming a conservative 1.7 system-to-flight usage ratio, F/A-18 system use can be estimated as 65.6 h/month (personal communication, S. Donaldson, PMA-265, NAVAIR, 25 May 1995). Therefore, the actual system usage time represents approximately 9.0% of the total aircraft life. Assuming this information is applicable for most naval aviation applications, nonoperational activities consume the remaining 91.0% of the total aircraft life under conditions similar to those for military missiles: uncontrolled long-term dormant storage in harsh environments.

Even spare components, boards, and systems in storage on aircraft carriers can be subjected to severe environmental stress. Extremely high humidity, salt-laden air, and severe ambient temperature excursions are among the worst of many other factors encountered. All these stresses have the potential to deteriorate both operating and nonoperating electronic systems.

DISCUSSION

Traditionally, the Navy has considered PEM reliability to be unsatisfactory for long-term dormant storage.[2] However, recent studies have shown that PEMs can withstand the typical missile environment in long-term dormant storage for up to 20 years.[3] Hundreds of articles and reports either praise PEMs or forbid their use in high-reliability applications.

One of the predominant failure modes regarding long-term dormant storage of PEMs is internal galvanic corrosion.[4] Hesitant PEM users expect corrosion on the die's metallization. We define metallization as a deposited or plated thin metallic film used for its protective or electrical properties.[5] This metallization is used both for interconnection on the die and to define a place for the attachment of bond wires.[5] Corrosion becomes more severe as modern product metallization lines become narrower, the separations between metallization lines become closer, and bond pads become smaller.[6,7] These smaller dimensions create a greater susceptibility to corrosion failures. PEM manufacturers resolved this greater potential for corrosion by using a passivation on top of the die surface. Passivation is defined as the formation of an insulating layer directly over a circuit or circuit element to protect the surface from contaminants, moisture, or particles.[5] In modern PEMs, the uncovered metallization features are reduced to bond pads. The physical dimensions of bond pads in modern PEMs are similar to the dimensions of the exposed (uncovered) metallization patterns in older PEMs. This provides the basis for the presumption of this study.

For galvanic corrosion to occur in PEMs, the following elements are necessary: a bimetallic couple (most often gold–aluminum, present in the gold bond wire to the aluminum metallization pad), free (mobile) ionic contamination (usually chlorine, potassium, bromine, and/or sodium), and moisture (diffused from the atmosphere), to form an electrolyte. All elements listed, except ionic contamination, are present in most PEMs.

We can identify two sources of ionic contamination: Traditionally, the encapsulant material was the main source of ionic contamination internal to the PEM. However, the present generations of molding compounds are considered ion-free since the typical ionic residue level in today's parts is less than 10 parts per million (ppm).[8] The second potential source is incidental contamination, external to the PEM. This contamination can be from sources such as the atmosphere, human handling, and cleaning agents.

The ionic transport of incidental ionic contamination to the die surface is still the subject of intense debate. The addition of up to 80% silicon fillers to produce the epoxy novolac encapsulant used today in most PEMs allows for limited ionic mobility. The encapsulant material manufacturers reacted to this limited ionic mobility by adding an "ion getter," or scavenger. The incorporation of alkali- and halide-ion gettering agents into the epoxy molding compound makes migrating ions in the epoxy unavailable for dissolution into any diffused or accumulated water in the package.[5] Therefore, ionic contamination transfer throughout the epoxy encapsulant is unlikely.

Delamination between the epoxy and the lead frame, typically a consequence of their different coefficients of thermal expansion, provides an entrance for moisture into the package. This moisture can transport ionic contamination to form an electrolyte, and, therefore, corrosion can result.[9] To mitigate this problem, we recommend the use of a conformal coating. Parylene and urethane conformal coats have been widely used to provide additional protection to assembled circuit boards from potential incidental contamination and moisture ingress through handling.[3,10-12]

Besides corrosion, the formation of intermetallic compounds between the gold bond wire and the aluminum die pad (gold–aluminum intermetallic, also called "purple plague") is a source of concern. The interface of aluminum and gold will form intermetallics after prolonged exposure to high temperatures because of the different interdiffusion rates of the compounds.[13] The formation of intermetallics is a predictable function of time and temperature and will always occur between gold and aluminum.[14] Thermal cycling, as well as the presence of contaminants (such as bromine in flame-retardant epoxies and residual chlorinated impurities) and moisture, further enhances the formation of intermetallics.[13] A host of catastrophic wire-bond failures may result from this mechanism.[13] An example would be the formation of the Kirkendall voids that will cause the bond to lift.[14] Significant void formation will start to occur after 10,000 h at +150°C.[14] The only way to eliminate this problem completely is to use a monometallic system, which is not available with PEMs.[13] Thus, users of the parts must compare intermetallic formation curves with the mission temperature profile to ensure that intermetallic formation will be controlled.[13]

EVALUATION

The purpose of this evaluation was to determine if uncontrolled long-term dormant storage affects the reliability of PEMs for naval aviation applications, such as the F/A-18 aircraft. This investigation is based on the assumption that if old parts have not degraded after 20 or 30 years of uncontrolled long-term dormant storage, then the vastly superior current products will survive similar periods under similar conditions. To conduct our study, we developed a seven-step testing flow:

1. External visual inspection
2. Radiographic inspection
3. Electrical testing at room, rated-high, and rated-low temperatures
4. Moisture content (as measured by weight change after a high-temperature bake)
5. Electrical retest (for any part rejected at step 3)
6. C-mode scanning acoustic microscopy
7. Destructive physical analysis

This sequence of tests includes basic physical, mechanical, and electrical tests to determine the overall quality of the parts, as well as their resistance to the effects of long-term dormant storage. The results from testing were reduced to a spreadsheet database and subjected to manipulation, producing the different perspectives and figures used in this report.

EXPERIMENT POPULATION DESCRIPTION

The samples used for this evaluation were selected on the basis of the following criteria: First, we evaluated only PEMs. Second, we evaluated only PEMs that were never installed on boards, to eliminate from the study those variables associated with board assembly and normal usage. Third, we evaluated only parts that clearly exhibited the manufacturing date (i.e., date code). These criteria eliminated most available PEMs for evaluation. We reduced the population to 92 commercial parts, including a few control samples from recent vintage. Reconstructing the storage conditions for most selected PEMs is impossible. However, we know that the storage conditions were not an ideal laboratory environment concerning moisture and electrostatic discharge protection. Therefore, the storage conditions are considered uncontrolled.

Figure 1 presents an age profile of the evaluated parts, showing an average age of approximately 16 years. Figure 2 gives the quantity of parts evaluated from each manufacturer. Of the 92 parts, 65 were analog, 21 were digital, 2 were special function (data communications chip and frequency synthesizer), and 4 were of unknown classification and manufacturer. Package style information is given in Fig. 3. All evaluated parts except one are plastic dual-in-line packages. A single small-outline integrated circuit was evaluated as a control sample.

EVALUATION RESULTS

Results from external visual inspection, following MIL-STD-883 (Test Methods and Procedures for Microelectronics), method 2009, suggest that long-term dormant storage will have a deleterious effect on the

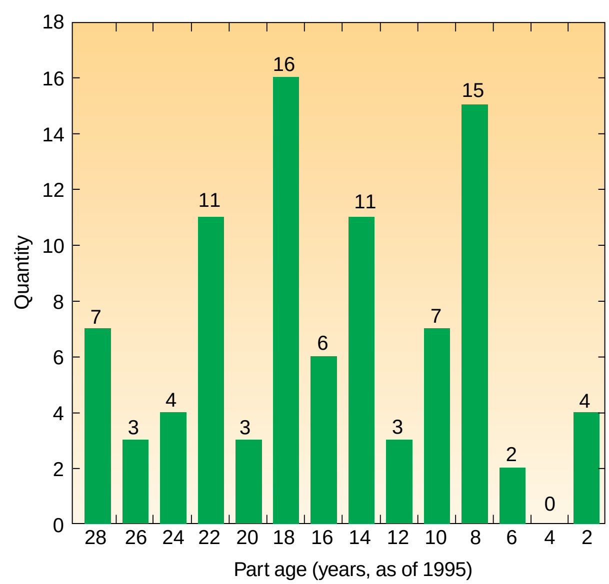


Figure 1. Age distribution of evaluated parts. The average age was approximately 16 years. The oldest part exhibited a date code of 6716 (manufactured in the 16th week of 1967).

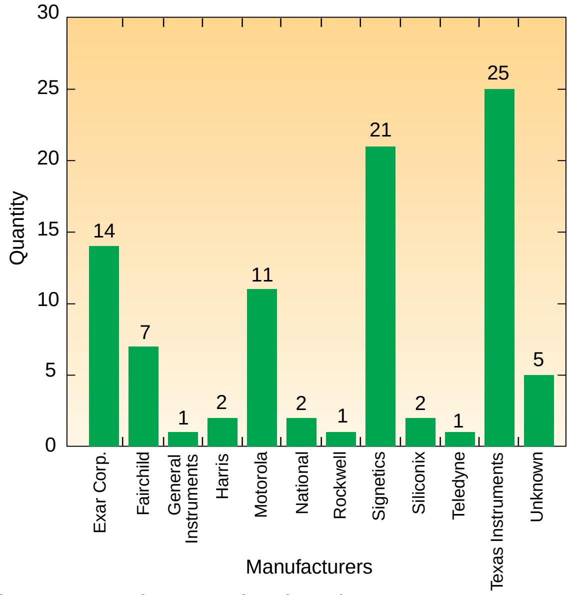


Figure 2. Manufacturers of evaluated parts.

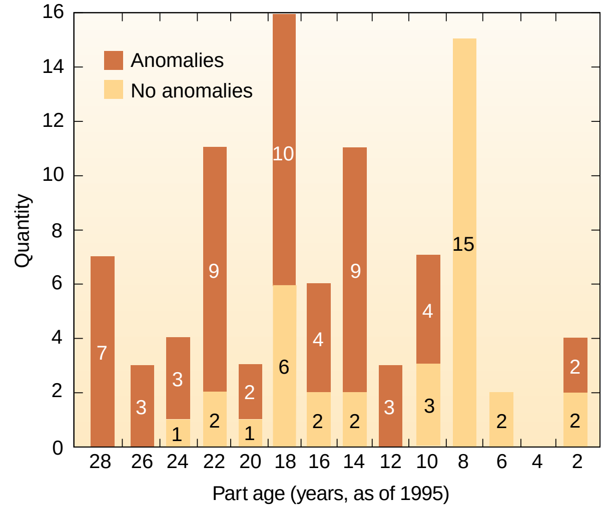


Figure 4. Results from external visual inspection of parts. Long-term dormant storage has a deleterious effect on the cosmetic appearance of plastic encapsulated microcircuits.

cosmetic appearance of PEMs. Of the 92 samples inspected, only 36 parts had no visual inspection defects. Figure 4 shows the quantity of parts that exhibited anomalies vs. no anomalies by part age. The leading failure modes were lead finish damage (27 cases), twisted leads (23 cases), and contamination from unknown sources (12 cases).

We performed radiographic inspection using MIL-STD-883, method 2012. Of the 92 samples inspected, 68 parts met the MIL-STD-883 criteria. The failure modes detected were inadequate die attach, misalignment, void in molding compound, wire crossing wire (worst offender, 11 cases), and foreign material in encapsulant. None of the failures were a consequence of long-term dormant storage; rather, they were a result of manufacturing and workmanship flaws. Figure 5 presents the quantity of parts that exhibited anomalies vs. no anomalies by part age. Note the improved quality (across all evaluated parts and manufacturers) of the more recently manufactured parts. Figure 6 provides a typical example of the failure mode "wire crossing wire." Eleven parts exhibited this failure mode. The bond wires presented in Fig. 6 are not in direct contact.

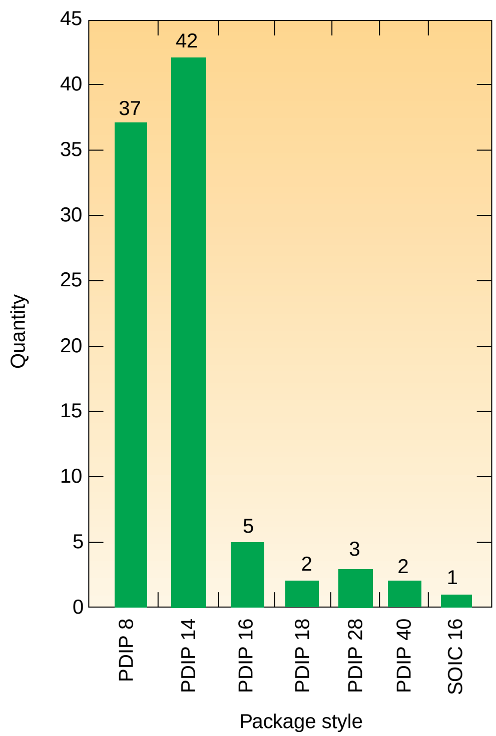


Figure 3. Package style distribution of parts. All parts except one were plastic dual-in-line packages (PDIPs). A single small-outline integrated circuit (SOIC) was evaluated as well.

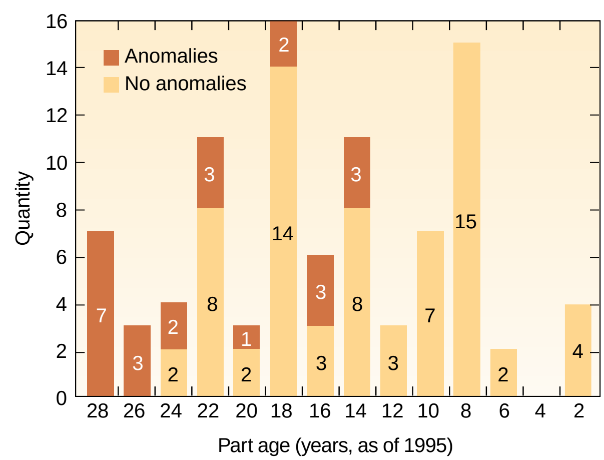
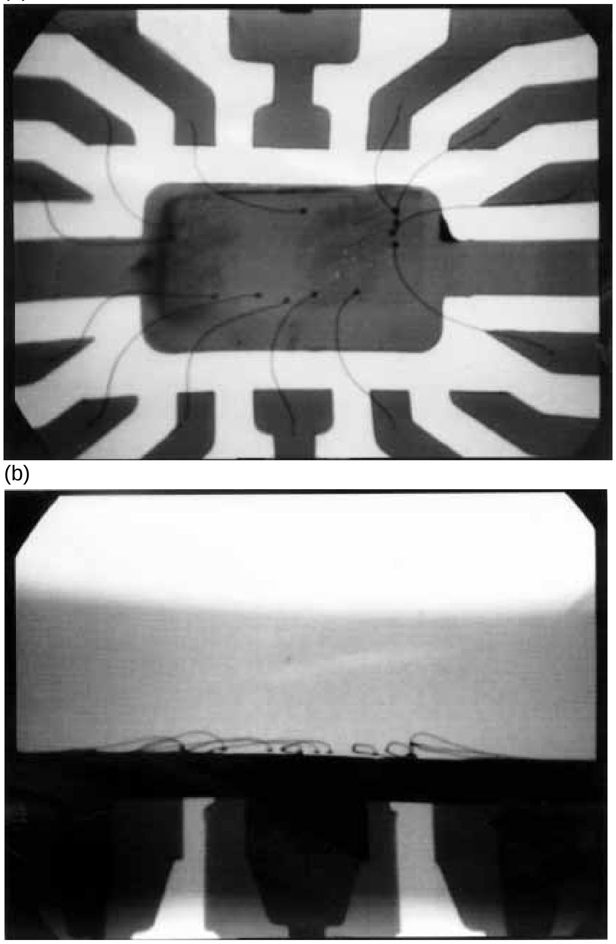


Figure 5. Results from radiographic inspection of parts. Note the improved quality of the more recently manufactured parts.

(a)



(b)

Figure 6. "Wire crossing wire" example. This failure mode was the worst offender. These bond wires are not in direct contact, but they are in very close proximity. (a) Top view. (b) Side view.

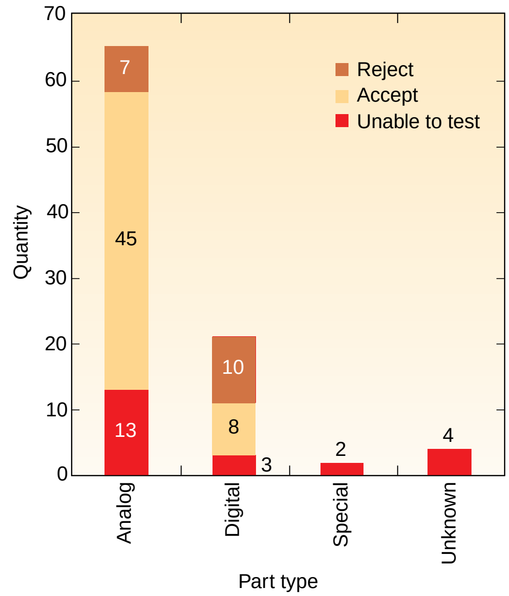


Figure 7. Results from electrical testing of parts at room temperature. Of 92 parts, 53 were accepted, 17 were rejected, and 22 were unable to be tested. Results at high and low temperatures were consistent with this figure.

However, their close proximity could be a cause of electrical rejection due to leakage currents.

Whenever a suitable automated test equipment program was available, we subjected the parts to electrical testing at room, rated-high, and rated-low temperatures (Fig. 7). Because we do not know if any parts that failed electrical testing were functional on their original manufacturing date, and because of the 17 parts that failed, 9 exhibited the failure mode "wire crossing wire" during radiographic inspection, we minimize the value of the information provided by the electrical testing of those parts. However, for parts that passed electrical testing, we gained confidence that they were good parts when manufactured and remained good during dormant storage. The results of electrical testing at rated-high and rated-low temperatures do not add any value to this discussion. High- and low-temperature testing was performed only in digital parts, and their behavior is consistent with the test results at room temperature.

To detect molding voids, cracks, and delaminated areas, Reber and Palmer[15] suggest the following nondestructive screen: (1) Weigh the dry packaged parts to 1-mg accuracy, (2) soak them in a saturated pressurized environment, (3) blow the surface dry, (4) weigh the parts, and (5) dry the parts thoroughly. The change in weight of uniformly good parts should form a tight distribution. Parts that show excessive weight gain should be rejected.[15] The change in weight is directly proportional to the amount of moisture absorbed. Since the parts under study were stored under uncontrolled conditions for a long period, we assumed that they were already saturated with moisture. We used an inverse method. We obtained the moisture content by weighing the parts to 1-mg accuracy, baking them for 24 h at 125°C, and weighing them again to 1-mg accuracy. We then calculated the change in weight loss (as a percentage of the initial measurement).

The weight of all parts (before the bake) ranged from 6080 mg to 150 mg; the average was approximately 1036 mg. The part that exhibited the highest delta weight loss (0.67%) was the single 16-pin small-outline integrated circuit (Fig. 8), the smallest and lightest part (149 mg after the bake) of the entire population. This is the only evaluated part at risk for popcorning, which is the package cracking caused by high moisture content that vaporizes and expands rapidly during elevated temperature processes. The resulting force can cause package delamination, internal cracks, bond damage, or, in severe cases, external package cracks. This is commonly referred to as the "popcorn effect" or popcorning, due to the audible pop that the package makes

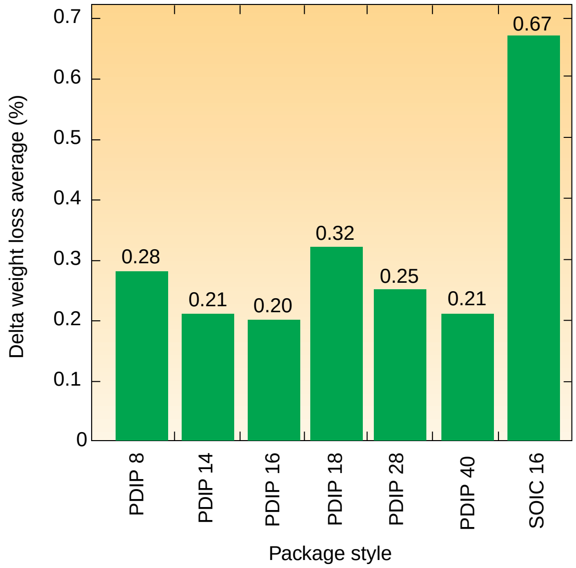


Figure 8. Delta weight loss of parts due to moisture desorption during high-temperature bake. The average weight loss of plastic dual-in-line packages (PDIPs) was 0.25%. (SOIC = small-outline integrated circuit.)

as it cracks.[13] Parts packaged as small-outline integrated circuits are especially at risk because usually they are exposed to high-temperature infrared reflow or vapor phase during final board assembly. This failure mechanism is an assembly concern and is easily prevented by proper component storage and handling or by subjecting the parts to a bake prior to board assembly. The behavior of this small-outline integrated circuit, as a factor of moisture content, should be investigated further. Finally, the delta weight loss for most parts was between 0.13% and 0.33%. These results confirmed our assumption that the parts were moisture laden.

The parts rejected at initial electrical testing (at any temperature) were subjected to retest at room, rated-high, and rated-low temperatures. One analog part (16 years old), which was a failure at initial electrical testing, passed at room temperature after the bake (see Fig. 9). In addition, one digital part (24 years old), which originally passed electrical testing at room temperature, was rejected at low temperature (and therefore was retested) and passed at high temperature. Then, at retesting, the digital part failed at room temperature, failed at low temperature, and passed at high temperature. Again, we minimize the value of the information provided by these electrical tests.

All parts being investigated were subjected to C-mode scanning acoustic microscopy. Of the 92 parts inspected, 84 parts exhibited some degree of delamination (see Fig. 10) ranging from small delamination to 100% delamination on top and/or bottom of the die paddle or die surface. Only eight parts passed C-mode scanning acoustic microscopy inspection without remarks. Figure 11 presets some typical examples of delaminated areas on both old and recent vintage parts. Figure 12 suggests that most parts, despite their age, are likely to exhibit some degree of delamination. These data suggest that C-mode scanning acoustic microscopy

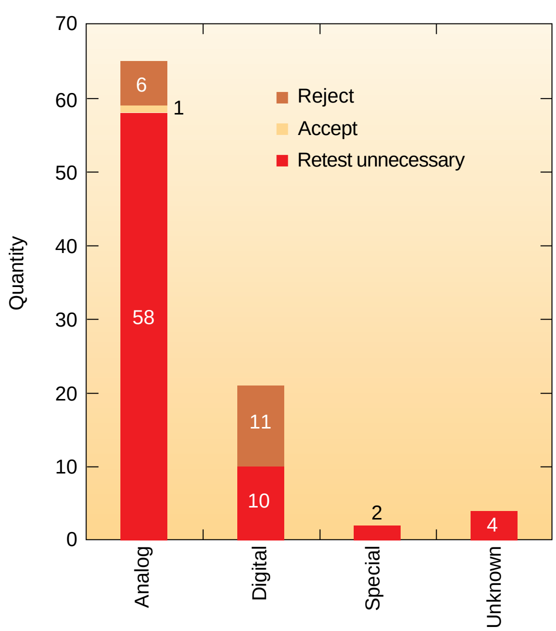


Figure 9. Electrical retest of parts that were rejected at initial electrical tests. One analog part, which was a failure at initial electrical testing, passed at room temperature after the high-temperature bake. Of 92 parts, 1 was accepted, 17 were rejected, and 74 did not require retesting.

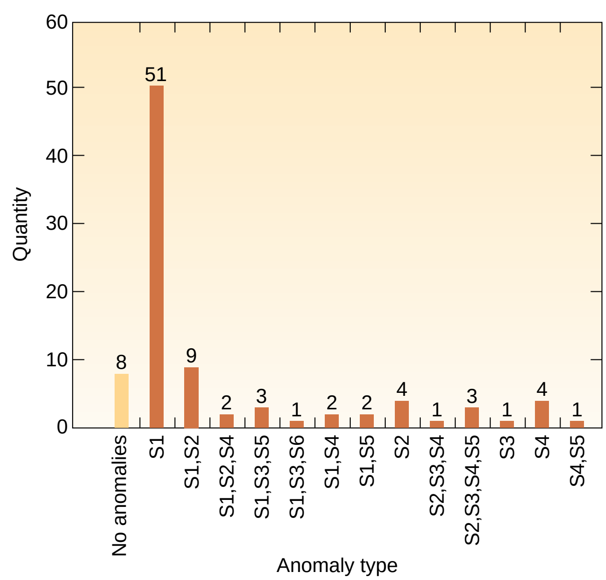


Figure 10. C-mode scanning acoustic microscopy results showing types of anomalies. Most parts exhibited some degree of delamination. (S1 = small delamination, S2 = void in die attach, S3 = 100% delamination on bottom of die paddle, S4 = void in molding compound, S5 = 100% delamination on top of die paddle, S6 = delamination on top of die surface.)

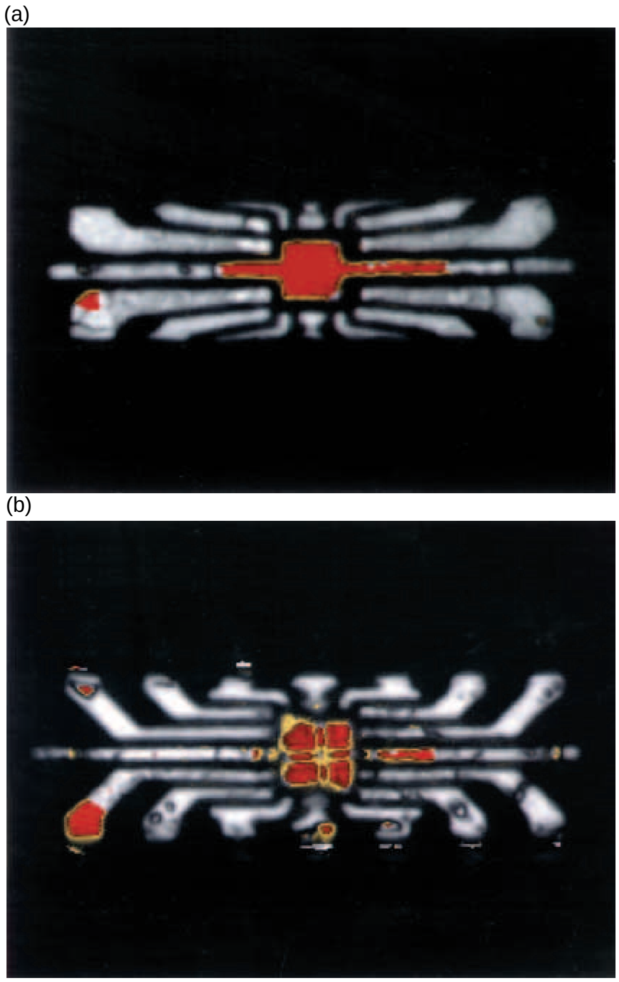


Figure 11. Examples of C-mode scanning acoustic microscopy results. (a) 100% delamination on bottom die paddle. (b) 100% delamination on die surface.

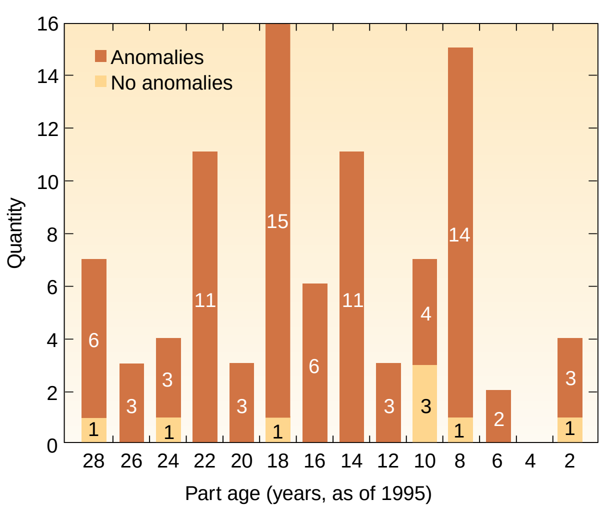


Figure 12. C-mode scanning acoustic microscopy results by part age. Regardless of age, most parts exhibited delamination. Therefore, the value added by using C-mode scanning acoustic microscopy for screening plastic encapsulated microcircuits is questionable.

is not a good method for parts screening, although it might be valuable for other purposes.

All parts were subjected to destructive physical analysis. The physical decapsulation was accomplished using an oxygen plasma etching system (see Ref. 16). This method, as shown in Fig. 13, proved to be highly effective in exposing the die without damaging the surface or the bond wires. In some parts, a chemical rinse using fuming nitric acid was done to complete the process.

Of 92 parts evaluated, 8 parts were rejected following MIL-STD-883 criteria, as shown in Fig. 14. Two parts were rejected for corrosion (failure mode D3), possibly a result of long-term dormant storage. One part with failure mode D1 (bond pull reject) passed electrical testing at room, low, and high temperatures. Therefore, this rejection was probably a bad bond to begin with and not a consequence of long-term dormant storage. Another part exhibited failure mode D1 (bond pull reject)

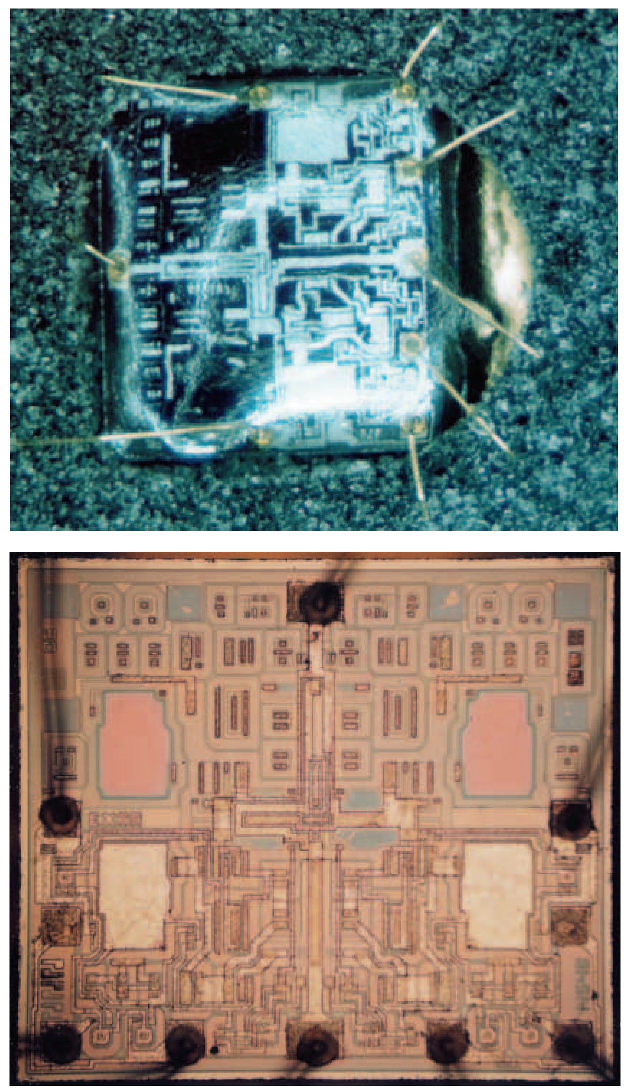


Figure 13. Oxygen plasma etching is a very effective method for exposing the die surface and the bond wires.

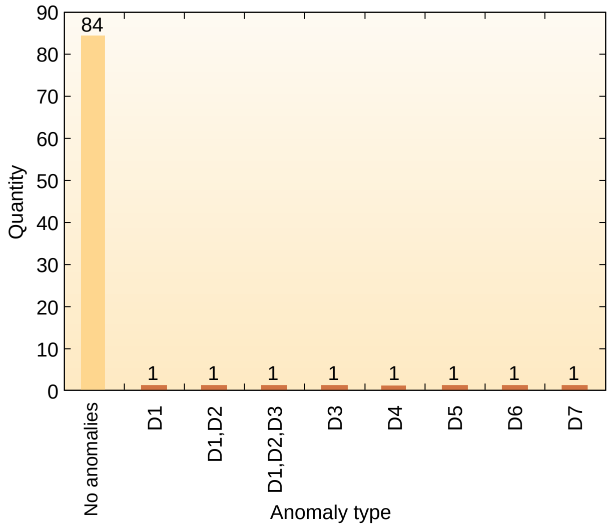


Figure 14. Destructive physical analysis results showing types of anomalies. Only two cases of corrosion occurred, both in parts that were 28 years old. (D1 = bond pull reject, D2 = intermetallics, D3 = corrosion, D4 = lifting of glass, D5 = void in metallization, D6 = oxide void, D7 = misaligned bond.)

with D2 (intermetallics). This part passed electrical testing at room temperature, and no corrosion was evident. Therefore, this part survived long-term dormant storage with some deterioration. The relation between the failure mode D4 (lifting of glass) and long-term dormant storage is debatable. We believe that failure mode D4 is not a consequence of long-term dormant storage but rather a consequence of a workmanship flaw and the oxygen plasma etching. In addition, failure modes D5 (void in metallization), D6 (oxide void), and D7 (misaligned bond) are manufacturing flaws that were present at the part's production date. Therefore, of eight rejected parts, six are not a consequence of long-term dormant storage. Finally, all rejected parts were 18 years or older, as shown in Fig. 15.

CONCLUSIONS

This evaluation provides evidence that long-term dormant storage is not a risk when using PEMs in naval aviation applications. Results from destructive physical analysis revealed only two cases of corrosion in PEMs, and both were on parts 28 years old. Recent improved processing technology will further minimize corrosion as a failure mode.

Regardless of age, C-mode scanning acoustic microscopy revealed delaminated areas in most parts, suggesting that this technique might not be a good method for PEM screening. No direct relationship was found between corrosion and moisture content. In addition, this study demonstrated that oxygen plasma etching is a very effective method for performing destructive physical analysis of PEMs.

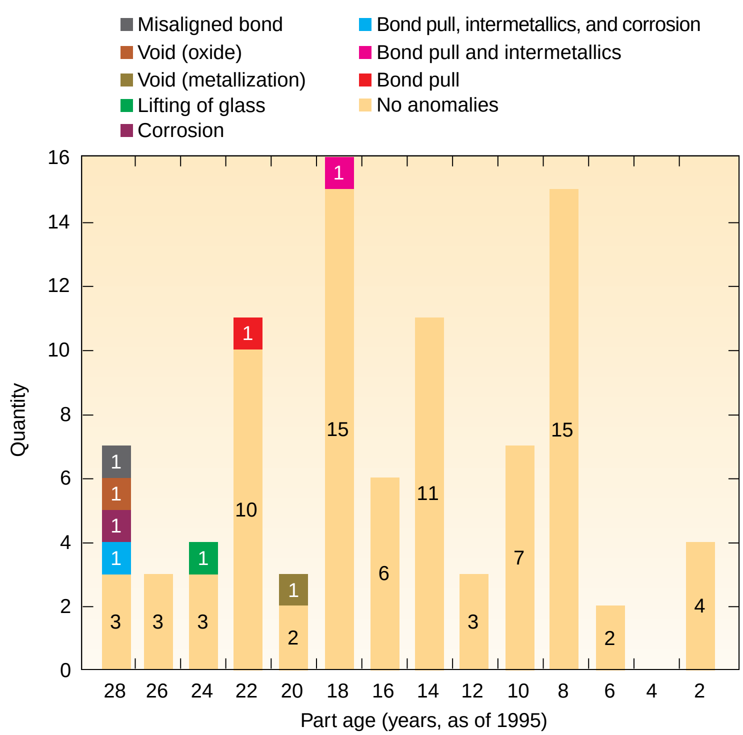


Figure 15. Destructive physical analysis results by part age. Regardless of failure mode, all parts noted for defects during destructive physical analysis were 18 years or older.

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