Reliable Application of Plastic Encapsulated Microcircuits for Small Satellites

by

William M. Ash III* and Eric J. Hoffman**

The Johns Hopkins University Applied Physics Laboratory
Laurel, Maryland

ABSTRACT

Advances in electronics technology– more than in any other field– have enabled small satellites to perform important missions. But electronics (and its associated software) still represents the principal cost driver for many satellites. A key to reducing the cost of flight electronics– as well as improving reliability– is to fly the most recent, most capable integrated circuits (ICs).

The most desirable, state-of-the-art ICs for lightsat applications usually appear first in plastic, non-hermetic packages. Use of these plastic-encapsulated microcircuits (PEMs) for high reliability space hardware has traditionally been forbidden because of the perceived reliability risk due to moisture penetration, contamination, internal damage from thermal cycling, and other concerns. Yet the reality of today's aerospace market is that many desirable ICs will never be made available in hermetic packages.

Fortunately, over the last decade, manufacturers have significantly improved the reliability of PEMs. The Applied Physics Laboratory (APL) examined the use of PEMs for spaceflight application, taking into account reliability, board design, parts storage, fabrication, thermal, radiation, contamination, failure analysis, and other issues important to lightsat designers.

This paper summarizes APL's findings and outlines the conditions under which *some* PEMs can be safely used in space. Case studies are cited to show that, paradoxically, use of a slightly less reliable plastic part can sometimes improve the overall reliability of small satellite subsystems.

INTRODUCTION

Flight electronics and software can account for 30-50% of the cost of a small satellite. A key to reducing these costs is to fly the most capable, most highly integrated ICs possible.

To be considered flightworthy, ICs must exhibit adequate radiation hardness for the orbit and mission scenario (total dose, single event upset, and latchup resistance) and must be available in an acceptable temperature range and reliability level. An important aspect of the reliability level is the suitability of the package for spaceflight. Package issues include lead material and finish, means of heat removal, and– most importantly– protection of the die and wire bonds.

In a typical hermetically sealed IC, the die is mounted in a ceramic or metal cavity, bonded to the outside leads, backfilled with inert gas, and sealed with a metal or ceramic cover. In a plastic-encapsulated microcircuit (PEM), a plastic encapsulant (typically epoxy novolac) is molded in intimate contact with the die, wire bonds, and lead frame. Figure 1 contrasts the two types of IC construction.

PEMs have been widely used in consumer and industrial electronics with great success. The automotive industry, for example, installs 2.7 million PEMs *per day*. But space programs have traditionally forbidden their use, demanding instead hermetically packaged parts. Despite the advantages PEMs offer in terms of availability, performance, cost, size, and weight, the perception– not totally unfounded– was that

*Senior Staff Engineer, Space R&QA, Member AIAA
**Space Dept. Chief Engineer, Assoc. Fellow AIAA

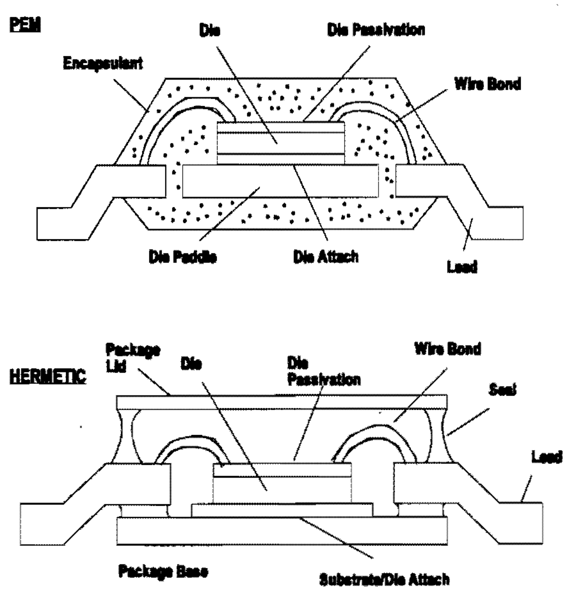

Figure 1. PEM vs. hermetic construction

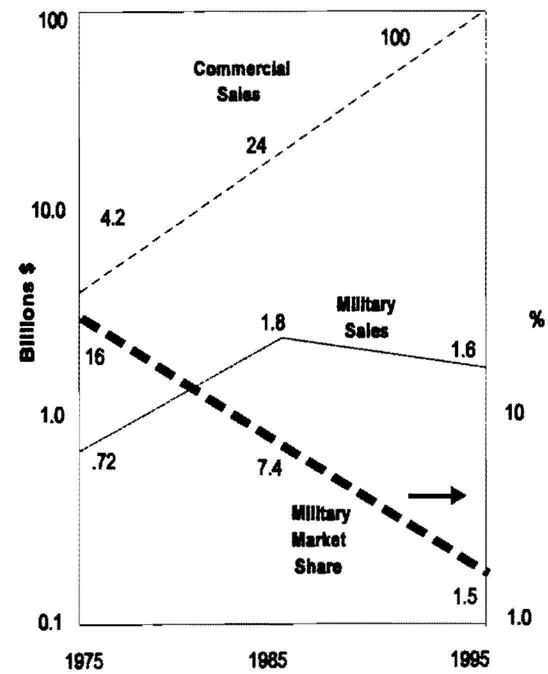

Figure 2. Declining hi-rel IC sales[1]

they were simply not reliable enough for space. Even today's best molded plastic packages are permeable to moisture, making them vulnerable to certain cracking, corrosion, and contamination failure modes for which hermetic ICs have no counterparts. In a poorly designed PEM process, the plastic itself can be a source of contaminants. Because the plastic has total contact with the bond wires and die, molding stresses or mismatched coefficients of thermal expansion (CTE) can induce bond failure or even die cracking under temperature cycling. The generally lower thermal conductance of PEMs exacerbates the problem, especially when high power ICs are used in the vacuum of space.

Despite these concerns, in recent years a convergence of market pressures and process improvements has forced a number of space organizations to re-examine the suitability of PEMs for flight. As Figure 2 shows, declining military and space budgets have caused many manufacturers to drop or cut back their hi-rel, hermetic package IC lines. By 1995, such parts are expected to represent only about 1-2% of the total IC market. For the satellite electronics designer, this means a greatly restricted choice of parts; use of lower performance, obsolete parts; or the expense, delay, and reliability

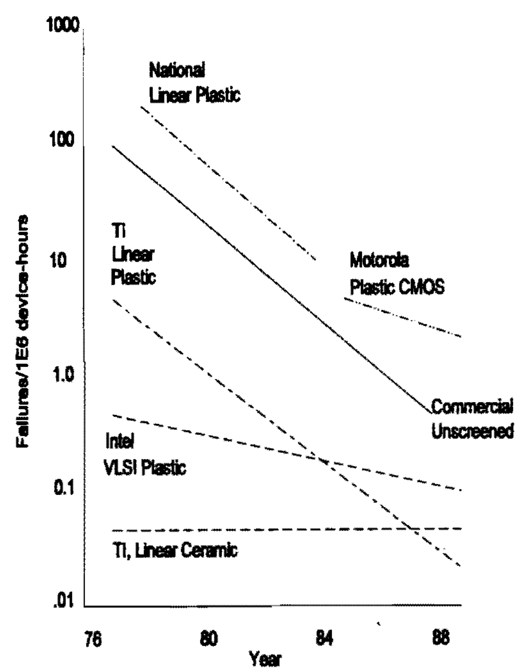

Figure 3. Microcircuit reliability improvement trends[2]

risk of hermetically packaging die using custom packaging houses.

Fortunately, the declining availability of hermetic ICs has been accompanied by substantial improvements in plastic packaging technology. Improved understanding of the physics of failure, advances in passivation and molding techniques, tighter process controls, and better methods of accelerated testing have improved the reliability of hermetic and non-hermetic parts alike (Fig. 3).

The improvement has been most dramatic, however, for PEMs. The declining failure rate of ICs in general has made the failure rates of the interconnects (solder joints, multilayer boards, connectors, welds) relatively more important. The reduction in interconnects brought about by use of highly integrated circuits is therefore of great benefit. Often, the most highly integrated part is available only in a plastic package.

PEMs have already flown in space in a limited way. Small quantities have flown for short durations and in non-critical systems. Does that make PEMs "space qualified?" No. For long term reliable use in space, a more rational examination must be undertaken– one which considers the peculiarities of PEMs and their interaction with the spaceflight environment.

In 1993, the Johns Hopkins Applied Physics Laboratory Space Department conducted a comprehensive examination of the suitability of PEMs for high reliability spaceflight applications[3]. We set out to answer a specific set of questions dealing not only with the reliability of the piece part itself, but with the broader system issues of board design, parts storage, radiation, thermal design, and every other aspect we considered important to achieving reliable operation in orbit. A summary of these findings is given below in question-and-answer format.

QUESTIONS (AND ANSWERS) FOR SPACE APPLICATION OF PEMS

1. Do PEMs sufficiently prevent outside contaminants from entering through the packaging material or along lead paths?

Here, "contaminant" refers not only to process introduced residues, mobile ionics, and board fabrication solvents, but also to general ambient moisture. Of course, only a hermetic part can, by definition, prevent contaminant ingress. However, a well designed PEM can control the amount and rate of contaminant ingress to the internal structures (lead frame, wirebonds, die pads, and die surface). Also, ingress is a time, temperature, and species specific process and therefore is very dependent on the external environment. Special note should be taken of the fact that moisture ingression actually stops (and reverses) in the vacuum of the space environment.

There are generally three paths that contaminant ingress can follow: 1) bulk diffusion through the encapsulant itself[4] ; 2) ingress along the leadframe, which worsens if the encapsulant has delaminated; and 3) package cracks/microcracks. Delamination and cracking are viewed as package failures.

The effects of ingress manifest themselves as different failure modes depending on the type of contaminant and the structure under question. Moisture participates in a number of adverse reactions and is considered to be the primary cause of device failure[5]. Moisture can move directly to metal structures either on the die surface or at bondwire/leadframe interfaces and participate in corrosion. One particular point to keep in mind, however, is the difference between molecular moisture and liquid moisture. Moisture is always present in the bulk encapsulant as molecular moisture. If sufficient delamination or voiding has occurred, this molecular moisture can then form the more dangerous liquid moisture inside the package.

Moisture also facilitates the transport of other contaminants (e.g., ionics) to sensitive die areas and aids in the formation of intermetallics at the bond pad interfaces. Moisture can also simply collect in the encapsulant and at the package's internal interfaces and flash to steam during high temperature processes such as wavesoldering. This effect, termed "popcorning," immediately compromises package integrity.

A useful way to view an encapsulated device, as opposed to a hermetic device, is to picture the packaging system as a "defense-in-depth" in which the bulk encapsulant is the first line, followed by any die overcoats (such as polyimides) and then the die surface passivation. Die passivation, the quality of which has traditionally been an unequivocable part of military specification product, has taken on a rediscovered importance in commercial designs. Unfortunately, the hermetic part, while being for all intents and purposes initially impervious to moisture, provides nothing to prevent ingression directly to the die passivation if the seal becomes breached. This "leveling factor" is often displayed in many of the hermetic versus encapsulated reliability tests[2].

A well-designed PEM encapsulated with a correctly composed epoxy novolac mixture can provide sufficient protection from contamination ingress for a long term spaceflight application. This protection is a primary concern for any successful product, and its capability is routinely proved by the propensity of industry data. A battery of tests, including Temperature-Humidity-Bias (THB), 85°C at 85% relative humidity (RH) testing (85/85), Highly Accelerated Stress Testing (HAST), and autoclave (pressure cooker) tests, have been developed to evaluate this characteristic of PEM designs.

For example, general automotive qualification includes sample temperature cycling and thermal shock, 85°C/85% RH testing, life testing, high temperature reverse bias, and autoclave testing in its subgroups (see also Question 12). Other studies, such as the works of Condra (board level temperature cycling and THB)[6]; Villalobos (1000 temperature cycles from -65°C to +150°C; 9240 PEM samples with .44% failures versus 1848 ceramic units with .38% failures); and Lidback (1000 temperature cycles from -65°C to +150°C; 133,747 PEM samples with .083% failures versus 46,473 ceramic units with .099% failures) show empirically that there is no significant difference in mechanical reliability between the technologies[2]. These results are continually being re-confirmed in an ever-growing database.

2. Are PEMs susceptible to contamination from the packaging material itself?

The exact composition and processing of the encapsulant material are very important in minimizing contamination. The amount and type of available contaminants are of key concern in the design of novolac encapsulants. This is a major factor in the long term performance of a design and a primary concern in reliability qualification. Many of the device test methods such as HAST, THB, and life test were specifically designed to evaluate device contaminants.

Low total ionic content in the base mixture is a key factor for highly reliable PEMs. Brominated flame retardants in the encapsulant, which are frequently encountered, also introduce failure causing contaminants. Their presence in an encapsulant should alert the user not only to the additional ionic content, but also to the increased possibility of intermetallic formation at the bond/die-pad interface. Solid long-term reliability and lot specific data are needed for products that have questionable ionic levels or these products should be avoided.

Additional protection from mobile ionics may be provided by ion "scavengers" or "getters." These encapsulant additives, which are generally hydrated metal oxides, "tie up" free ionic impurities so they cannot proceed to the die surface or other sensitive structures (wirebonds, etc.). Caution is recommended, however, as the introduction of a getter may cause additional problems with aluminum corrosion[7].

It is recommended that devices used in high reliability applications have low total ionic content (10 to 30 ppm). The usage of ionic scavengers must be reviewed on a case-by-case basis.

3. Is outgassing of the packaging material a concern for space use?

All evidence reviewed to date indicates that outgassing of the epoxy novolac encapsulants will not be a problem for space flight applications. Evaluations of plastic encapsulated parts performed for NASA RP 1124, *Outgassing Data for Selecting Spacecraft Materials*, demonstrate results that are well within the 1.0% Total Mass Loss and 0.1% Collectable Volatile Condensible Material requirements that are usually specified for flight use. PEMs recently evaluated at APL for flight application were found to have acceptable outgassing characteristics.

While it has also been conjectured that moisture and contaminants that the encapsulant has absorbed could be released in vacuum, we know of no reports specifically demonstrating this. This effect, if it exists, could be minimized by suitable handling and processing procedures.

4. Are PEMs susceptible to stress-induced die or wire bond failures due to coefficient of thermal expansion (CTE) mismatch?

Since all contiguous structures are in intimate contact, PEMs by their very nature are sensitive to CTE mismatch. Manufacturers must take great pains to correctly match the die, passivation and overcoats, leadframe design, and encapsulant mix.

The encapsulant mix, in which silica is added to the epoxy matrix, is varied until suitable characteristics (of which CTE is but one) are obtained. The best manufacturers use thermo/mechanical Finite Element Analysis to evaluate their designs.

CTE mismatch can cause mechanical damage to the die in the form of cracking or metallization disruption and has been known to also cause wire bond failure. CTE mismatch can also lead to delamination and package cracking with the resulting loss of encapsulant integrity. Prudent device manufacturers go to great lengths to understand their products' performance over temperature and so must the high reliability user.

5. Are PEMs more susceptible to radiation effects due to the absence of the metal cover? Will spot radiation shielding be more difficult to add?

The metal cover that is used in many hermetic package types is so thin (~ 15 mils of Kovar) that it provides little shielding value anyway, so its absence is not noticed. Most applications rely on the inherent total dose hardness of the die itself, independent of the package type. Single event effects, such as Single Event Upsets (SEU) and latchup due to cosmic rays, are generally not attenuated by package type or shielding (with the notable exception of solar proton SEU), so one must rely again upon inherent device hardness to these phenomena. For a device that has good single event resistance, but needs improved total dose protection, additional tantalum spot shielding can be added to PEMs in the same manner as is presently used for ceramic packages.

6. Are special handling and fabrication processes required for hi-rel space application of PEMs? Are special board conformal coating materials or processes needed?

The high reliability PEM user must pay particular attention to the ambient moisture levels (including dewpoints during environmental testing) to which the parts are exposed. Storage in dry nitrogen and the use of qualified desiccants are recommended.

Bakeouts, which are already widely used to prevent popcorning in commercial surface mount applications, are useful to drive off moisture absorbed by the encapsulant. However, these must be implemented prudently as they can accelerate the formation of intermetallics and other undesirable reactions.

PEMs do enjoy a benefit over glass-sealed hermetic packages: Glass-seals can be broken both during handling and after board installation. If this happens, the hermetic part then has *less* protection than an equivalent PEM.

Certain PEMs have shown that they can perform well with either parylene or urethane conformal coats[6]. Flight conformal coats are widely used to provide additional protection to assembled circuit boards from handling and extraneous materials. Compatibility of the coat must be evaluated not only with the encapsulant, but also with the device's marking ink.

7. Will PEMs used in space require additional thermal derating and/or new heat removal techniques?

PEMs do have greater junction-to-case thermal resistance (Θ_{JC}) than ceramic packages and must be applied within their space derated characteristics. Typical values for high reliability ceramics are 20 to 30 °C/watt, while comparable PEMs run at more than twice those values (80 °C/W). Leading manufacturers put additional effort into designing leadframes and heat spreaders that adequately remove heat from the device.

PEMs do have an advantage in that heat can egress out through the leads because of the nature of the die paddle/lead frame structure. Hermetic parts do not have this path (except through the wire bonds) and must conduct excess heat through the case. Other than that, it is not anticipated that "new" heat removal techniques will be needed; spacecraft designers will still be able use the same heat removal techniques that are presently used. However, there may be a more frequent need for heat removal structures when using PEMs, especially in the convectionless vacuum environment. These techniques are already well known, such as bonding copper or aluminum heatsinks to the board or package.

From a thermal standpoint, the electronics designer must realize that PEMs are not necessarily "drop-in" replacements for ceramic/metal devices.

8. Will PEMs require different board-stiffening techniques?

PEMs should actually perform better under board flexure than hermetic parts. A PEM's weight is approximately 2/3 that of an equivalently sized hermetic part; 6 grams versus 9 grams for a 40-pin dual-in-line package (DIP). A plastic encapsulated leaded chip carrier and its solder joints are much more forgiving of board flexure than, say, a side-brazed ceramic DIP (see Case Study II). These advantages in weight and board flexure tolerance combine to produce board designs that are more suited to the demands of spaceflight environments. Furthermore, if board-stiffeners can be eliminated, circuit board designs will have easier routing and better packing density.

9. Does the use of PEMs require new storage and re-test procedures?

PEMs for high reliability applications must be stored in a dry ambient. Typical PEMs will absorb more than the safe moisture level of 0.11% (NASA Parts Program Office suggestion) by weight after approximately 130 hours in a 30°C/60% RH manufacturing environment[8]. Protection is best guaranteed by either dry nitrogen storage, moisture barrier bags with suitable desiccant, a strictly controlled low humidity environment, or a combination of all three. Once boards and assemblies are populated with PEMs, they should also be stored under dry conditions. Any environmental testing, such as temperature cycling, that involves dew-point transitioning must have strict humidity control. Shelf life is not presently viewed as an issue, based on the large number of documented device-hours, as long as the above mentioned requirements are met.

Never forget that a PEM, unlike a hermetic part, "remembers" its recent environmental storage history as far as contaminant ingress is concerned.

10. What is the current position of peer space organizations regarding use of PEMs in hi-rel applications? What waivers would be required against standard NASA Performance Assurance requirements?

NASA is presently reviewing PEMs as non-standard parts application requests (NSPARs). The NASA/GSFC Parts Project Office is planning to evaluate the inclusion of acceptable PEMs into NASA standard parts programs for Grade 2 space applications[8]. Previously, the most widely held viewpoint was "Why would anyone want to use a PEM when there are traditional Grade 1 and 2 parts available?" This attitude has changed due to advances in encapsulation technology and continued market pressures.

JPL has been performing extensive evaluations on a large memory PEM for use on its Mars/Pathfinder program. NRL's Clementine program made extensive use of PEMs and successfully accomplished its primary mission objectives. Honeywell Space Systems Division has been sponsoring a "Best Commercial Practices Consortium" to review and evaluate the possibility of using non-traditional microcircuits in high reliability applications. The viewpoints of many industry organizations have been extremely favorable toward properly qualified PEMs.

The Department of Defense (DoD) has taken a leading role in the utilization of PEMs in high reliability applications. Not only are PEMs seeing increased usage in avionics, munitions, and communications applications, but the DoD, in a landmark policy reversal, now requires justification for using a military specification (and therefore "hi-rel") part versus commercial units, rather than vice versa[9]. DoD has been looking at PEMs for a number of years and the transition away from traditional practices is being to take hold.

11. What procedures should be used to qualify a PEM for space use?

PEMs must be qualified as any other space flight part would be. The user must realize and provide for the specific attributes of the technology and the manufacturing techniques involved. The procedures of MIL-STD-883, *Test Methods and Procedures for Microelectronics*, are recommended as the point of departure and should be employed as applicable. Of course tests such as hermeticity, Particle Impact Noise Detection (PIND), and constant acceleration do not apply to a solid, non-cavity PEM, but the other procedures such as temperature cycling, burn-in, radiography, and performance over temperature are excellent PEM screens.

MIL-I-38535, *General Specification for Integrated Circuits (Microcircuits) Manufacturing*, already provides for the qualification of PEMs, and the Defense Electronics Supply Center (DESC) is presently in the process of qualifying manufacturers. HAST, THB, and other high volume/low defect procedures go a long way to supporting a high reliability qualification. Add in standard military life testing and extended temperature cycling, and the high reliability space flight user can be assured of the flightworthiness of his PEM qualifications.

The areas to pay particular attention to are: encapsulant composition; part design, including CTE matches; manufacturer production practices; in-line testing; and reliability/quality assurance programs.

12. How consistent (between manufacturers and from lot to lot) are the packaging techniques? Once a part number is qualified, what lot testing must be done to confirm the flight lot is still reliably manufactured?

Leading manufacturers, especially those employing statistical process control, will have excellent lot-to-lot consistency for all device characteristics. Other manufacturers may have poor consistency, quality, and reliability.

Probably the best endorsement for PEMs is from the automotive manufacturers, who provide some of commercial industry's most stringent requirements. Motorola's Automotive Industrial Electronics Group (AIEG) buys PEMs only from suppliers who have qualified their product to AIEG internal qualification procedures. These procedures are designed to simulate worst case "under-the-hood" conditions. For example, automotive qualification includes sample temperature cycling for 1000 cycles, thermal shock (liquid-to-liquid) for 500 cycles, 85°C/85% RH testing for 1000 hours, life testing for 1000 hours, high temperature reverse bias for 1000 hours, intermittent operational life testing for 20,000 cycles and autoclave ("live" steam) testing for 96 hours. The number of rejects allowed for all these tests is *zero*. AIEG indicates that most vendors pass these tests without any problem, indicating a broad, industry-wide ability to meet or exceed the harsh automotive standards[2].

13. Can Destructive Physical Analysis (DPA) of failed parts and of incoming lots be reliably performed?

The ability to discover latent manufacturing defects and root causes of device failures is a key feature of a high reliability product assurance program. Destructive Physical Analysis (DPA) and Failure Analysis (FA) are therefore important and must be possible for a technology to be flightworthy. Fortunately, DPA/FA procedures have been developed for PEMs which provide surprisingly good probability of successful evaluations.

Novolac PEMs can be decapsulated with a simple milling operation followed by exposure to fuming nitric acid. While not as easy as simply "popping-the-top" on many ceramic packages, this procedure can be completed in a matter of minutes. Hot sulfuric acid is also reported to work, but may be less desirable due to safety considerations. After decapsulation has been accomplished, standard evaluation procedures, including bond pull and die shear, can be performed in most circumstances.

The investigator does run the risk of losing certain surface information, however. This should be anticipated and must be taken into account in an analysis. Therefore, when performing failure analysis, more attention must be paid initially to non-invasive techniques (such as performance over temperature, high temperature reverse bias testing, and stabilization bakes) in order to attempt to infer surface-related information prior to decapsulation.

14. Finally, are properly qualified plastic parts reliable enough for use in hi-rel flight hardware? Are there some ways in which plastic parts may have a reliability advantage over traditional hermetic parts?

Herein, we have examined a number of factors that contribute to the reliability of a PEM. Items such as a device's design, manufacture, and its application determine these characteristics. For each of these factors, be they material, environmental, quality assurance, or fabrication, it has been shown that it is possible for a manufacturer of high reliability spaceflight systems to include properly qualified and controlled PEMs in his products.

PEMs actually display certain features that make them attractive for spaceflight application, such as robustness under acceleration and vibration environments due to their monolithic structure. It has also been demonstrated that present day PEMs can be as reliable as hermetically packaged units.

Electronic systems can realize a boost in their overall reliability if their parts count can be lowered by using more capable PEMs in place of less highly integrated ceramic units. It is also good to keep in mind that integrated circuits today represent a small fraction of system reliability problems. Other items such as connectors and boards have much higher failure rates[2].

CASE STUDY I: THE SOLID-STATE RECORDER

The solid-state data recorder (SSR) provides an excellent illustration of the important enabling role that PEMs can play for small satellites. Spacecraft often require mass data storage. On low-earth orbit (LEO) missions, the recorder may accumulate data continuously throughout the orbit and then dump it quickly during a short pass over a ground station. A LEO recorder is therefore almost continuously in use. In deep space missions, particularly flybys, the recorder is used in the opposite way to capture high-rate data and play it back slowly over data-rate-limited links.

Early space missions were satisfied with a few megabits of storage, but today's missions need from 0.5 gigabit (Gb) up to 1000 Gb and beyond. Given the exceptional density of magnetic recording, the traditional solution to the mass storage problem has been the mechanical tape recorder; hundreds have been flown. But the disadvantages of tape recorders are well known. Crammed with delicate moving parts (each 1Gb recorder on a recent small APL satellite contained 1800 *non*-electronic parts and 3700 parts overall), tape recorders are hard to design for launch survival and long life. They have definite wearout mechanisms, such as tape and head wear, negator spring cycles, and bearings. The recorders usually must be hermetically sealed and operated over a restricted temperature range. Weight and power consumption tend to be high. Data access is serial and often plays back in reverse, complicating mission operations. Only a narrow range of record and playback data rates can be accommodated. Recorders couple angular momentum, reaction torques, and jitter to the spacecraft. Most importantly, the serial, single-string nature of tape recording makes it all but impossible to design a tape recorder to "degrade gracefully." The limited lifetime of tape recorders has led to their being flown in redundant pairs, triples, and even pentuples.

Solid-state alternatives to moving media recording exist, and in fact predated tape recorders in space. SSRs using magnetic bubbles, ferroelectrics, and many other technologies have been prototyped, but the most practical storage device today is the high density CMOS (complementary metal oxide semiconductor) random access memory (RAM) chip. RAM ICs can store data either as the latched state of a flip-flop (static RAM, or SRAM) or as small charges held in on-chip capacitors (dynamic, or DRAM). DRAMs are more dense but need continual refreshing because the charge leaks off.

In the late '80s, as flightworthy 64 and 256 Kb SRAMs became available, spaceborne SSRs became practical. A "flightworthy" RAM must be immune to single-event latchup and have a single-event upset (SEU) rate low enough to be correctable by a reasonable coding scheme. The density of both SRAMs and DRAMs increases every year, approximately doubling every 1.5 years. One of

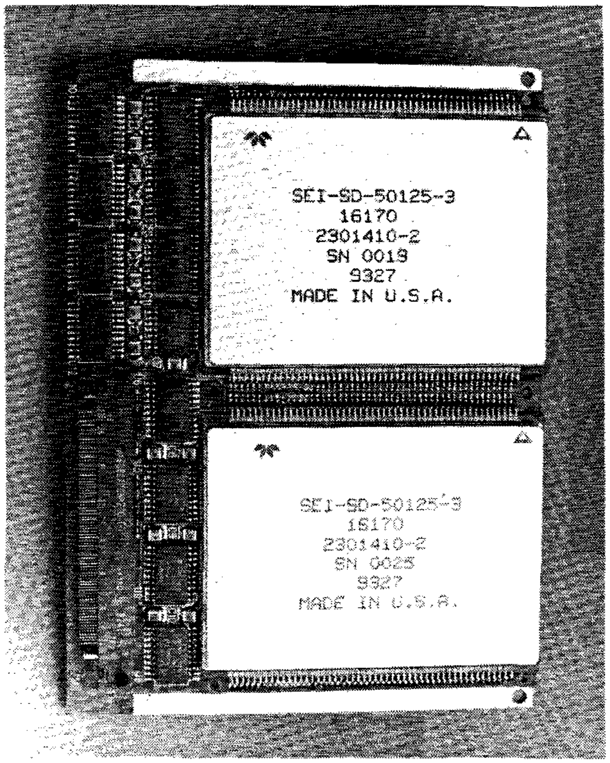

Figure 4. Clementine Memory Modules

the first DRAM-based SSRs to fly was the 2 Gb recorder provided by SEAKR, Inc. for NRL's Clementine spacecraft. That recorder used 704 4 Mb DRAMs, custom-packaged in 16 large, hermetic multi-chip modules with 44 die each. One of its eight memory boards (352 Mb) is shown in Fig. 4.

APL's Advanced Composition Explorer (ACE) and Near Earth Asteroid Rendezvous (NEAR) spacecraft require 0.5 to 1.0 Gb SSRs. The ACE recorder must operate through unusually high particle fluxes. NEAR is severely constrained in weight and schedule. Fortunately, an IBM 16 Mb DRAM has been tested and found to be unusually resistant to SEU. With this part, SEAKR will be able to meet our SSR requirements with just 44 to 88 DRAMs (including overhead for error correction and graceful degradation) and a total recorder weight of 3.3 lbs. A 352 Mb engineering model memory board also from SEAKR populated with PEM DRAMs is shown in Fig. 5.

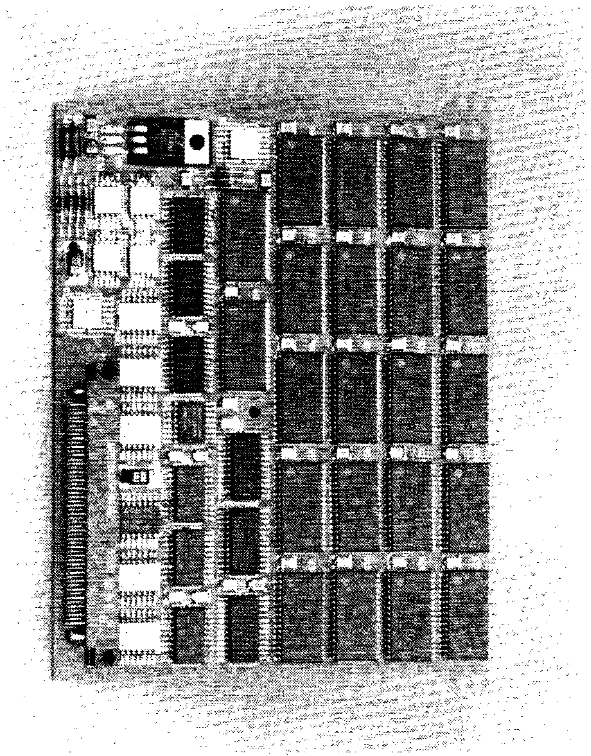

Figure 5. 352 Mb PEM Board

It is important to note that the IBM DRAM *is not available in a hermetic package*. Therefore, had APL not been able to qualify PEM packaging for ACE and NEAR, we would have had to resort to custom hybridization of die having 1/4 the capacity, à la Clementine. For NEAR, particularly, there was simply no schedule time for this, nor extra weight to accommodate either the 4:1 density reduction or a mechanical tape recorder. So in a sense, PEM DRAMs are an enabling technology for NEAR, the first of NASA's Discovery missions.

For ACE and NEAR, PEMs provide a reliability gain as well. SSR memory modules provide the ideal test bed for qualifying PEM usage in space, because SSRs are typically designed with spare memory segments to allow for graceful degradation. The failure of no single PEM DRAM can disable the entire SSR. Had the Clementine SSR been able to use the 16 Mb PEM DRAMs, the reduction in parts count and elimination of the large hybrids would, in our analysis, have reduced the failure rate from 655 to 361 FITs*, a factor of two improvement**.

CASE STUDY II: BOARD PACKAGING

In this case study we will show that PEMs can sometimes lead to better net board level reliability than comparable hermetic parts. We will show that even if PEMs are slightly less reliable on a part versus part basis, in many instances, once the parts are installed on boards, lead interconnect reliability and other factors can nullify any hermetic reliability advantage.

PEMs can be easier to install than hermetics in certain situations. Leadforming is a prime example. Any glass sealed hermetic component that requires leadforming runs the risk of seal cracking. Should that occur, the part will eventually fail due to ingress of ambient moisture. PEMs, which do not have brittle glass seals, are immune to this type of failure. In fact, glass seals have been known to fail due to mutual collisions when shipped inside of IC tubes.

Some organizations attempt to surface mount side-brazed DIPs (SBDs) with varying levels of success. In order to do this, one might try to put a single "L" bend into the SBD lead, while maintaining a .060" board-to-part clearance. At that point, there is not enough lead length in the standard lead to make a double (i. e., compliant) bend. Another alternative would be to make double bends for butt solder joints, but these also have reliability risks due to their small footprints. In order to perform any sort of leadform with a SBD, the user must come up with a practical and reliable scheme and be able to implement it with buildable tooling. PEMs, due to the position that they have obtained in the commercial industry, come in the sorts of packages (leaded chip carriers, single bend DIPs, etc.) that are most in demand and therefore the easiest to install.

The soldering operation is another point of consideration, especially since many ceramic devices come finished with gold. In this instance, the first thing that must be done to prepare for soldering is to remove the gold plating. Any more than 5% gold in the final joint will cause embrittlement; with its associated failure modes. Most PEMs, however, will come with a hot solder dipped finish (for cost reasons), which is acceptable as long as the units are stored properly. Also note that there is no discernable difference between the quality of machine solder joints for hermetic ceramics and PEMs[10].

In addition to ease of installation, these and associated attributes allow PEMs to perform better mechanically at the board level than some hermetic package types. A board populated with PEMs is 1/3 lighter, smaller (taking advantage of small outline packages), and more flexure compliant than a similar board populated with hermetic packages composed of metal, ceramic, and their associated glass frit seals.

Side brazed DIPs, with their straight leads, have much less board compliance than PEMs. If the part dissipates too much heat, it may need to be bonded to the board for heat sinking. In this case, the SBD must have its leads spring socketed in order to give some measure of stress relief for thermal expansion and mechanical compliance. This need for socketing dramatically increases the board level failure rate. A similar part in plastic that requires board bonding for heat sinking would not need socketing, due to its inherent lead compliance.

For example, let's examine a 28-pin SBD that normally has a failure rate of 10 FITs, compared to a 28-pin PEM that has been awarded a failure rate of 100 FITs, or ten times as much. Now, each spring contact socket pin has a failure rate of about 80 FITs[11] and if each solder joint is rated at .07 FITs we have:

PEM on board:

$$\lambda = 100 + 28(.07) = 102 \text{ FITs}$$

SBD in sockets:

$$\lambda = 10 + 28(.07) + 28(80) = 2252 \text{ FITs}$$

*A FIT is one failure in 10^9 device-hours.

**Based on MIL-HDBK-217E and DRAM failure rates

Therefore, the side brazed DIP in spring sockets can never be as reliable as the PEM. But without the socketing, the SBD runs the risk of cracking solder joints, lead brazes, and seals. Sockets also wear out: the springs eventually fatigue and are subject to contamination.

Although it may seem counterintuitive, we have shown that there are quite a few factors that can make a quality PEM more desirable at the board level than a comparable "high reliability" hermetic part. Much of this, of course, is due to the dramatic improvement in PEM reliability which has been driven primarily by the automotive industry. If a PEM can work reliably in a car's engine compartment, it can be made to function reliably in a space flight application. Keep in mind, though, that each part must be qualified on a case-by-case basis.

SUMMARY

APL's internal study concluded that the best of today's PEMs can be used in spaceflight application with little penalty when compared to hermetically packaged parts, *provided proper qualification, screening, storage, design, and fabrication processes are implemented.* Important reliability differences exist between part manufacturers, and among part numbers from a single manufacturer. A program for qualifying, procuring, and screening PEMs for space use must recognize and deal with these differences.

PEMs may require changes to board design, thermal design, parts control, and fabrication. Heat sinking may be required more frequently for PEMs. Outgassing, radiation shielding, and vibration susceptibility are not impediments to PEM use.

Because PEMs are permeable, storage discipline- from the time the part is manufactured until it arrives on orbit- is especially important to long term reliability. Particular attention must be paid to controlling humidity so that only a minimum amount of moisture is introduced to the encapsulant.

With proper care and attention to these details, many PEMs can be safely flown. The principal benefit PEMs offer is increased availability. But PEMs also cost less at the piece part level, and additional program savings can accrue from the shorter procurement cycle times. To maintain long term reliability, however, some of these savings must be reinvested in additional qualification, procurement, screening, storage, and inspection costs that are particular to PEMs.

Using a more advanced PEM to replace a number of less highly integrated hermetic ICs can reduce board area and weight. The reduction in parts count and interconnects made possible by flying the latest ICs can often improve overall reliability, as the SSR case study showed. Many PEMs also exhibit an increased robustness toward board level CTE mismatches (when compared, for example, to side-brazed ceramic DIPs) that can also enhance board-level reliability. DPA and failure analysis, once almost impossible with PEMs, can now be done with some success.

We therefore conclude that properly qualified and applied PEMs can be used in high reliability spaceflight applications.

ACKNOWLEDGEMENT

We would like to thank the APL PEM team (most notably Matt Bevan, Kedong Chao, Guy Clatterbaugh, Jim Kinnison, Binh Le, and Bruce Romenesko) for their effort on our internal study. Ed Hakim of the Army Research Laboratory, Scott Anderson of SEAKR Engineering, and Jerry Meunch of Odetics, Inc. contributed useful data. Ron Burek, Harry Charles, Howard Feldmesser, and Andy Moor also contributed helpful ideas and suggestions. We also thank Ken Burns and Virginia Stephens for helping to assemble this paper.

REFERENCES

[1]Ed Hakim, presentation notes, Army Research Laboratory, Ft. Monmouth, NJ (29 Jul 1993).

[2]Pecht, M. G., et al., "Plastic Packaged Microcircuits: Quality, Reliability, and Cost Issues," *IEEE Trans. on Reliability*, Vol. 42, No. 4 (Dec 1993).

[3]W. M. Ash III, ed., *High Reliability Space Flight Application of Plastic Encapsulated Microcircuits: A*

Feasibility Study, JHU/APL internal report SOR-3-94009, JHU/APL, Laurel, Md (Feb 1994).

[4]L. T. Nguyen et al., "Molding Compound Trends in a Denser Packaging World: Qualification Tests and Reliability Concerns," *IEEE Trans. on Reliability*, Vol. 42, No. 4 (Dec 1993).

[5]A. H. Kumar and B. Ozmat, "Package Sealing and Encapsulation" in *Microelectronics Packaging Handbook*, R. Tummala and E. Rymazewski, eds., Van Nostrand Reinhold, New York, p. 728 (1989).

[6]L. Condra, et al., "Comparison of Plastic and Hermetic Microcircuits under Temperature-Humidity-Bias", *IEEE Trans. Components, Hybrids, and Manufacturing Technology*, Vol. 15, pp. 640-650 (Oct 1992).

[7]CALCE EPRC, *Plastic Encapsulation of Microelectronics: Materials, Processes, Tests, Reliability, and Applications*, Univ. of Md, College Park, Md (In Press).

[8]G. Rose and N. Virmani, "Fundamentals of Plastic Encapsulated Microcircuits (PEMs) for Space Application," Space Parts Working Group, Los Angeles (3 Mar 1994).

[9]W. J. Perry, "Specifications & Standards- A New Way of Doing Business", Memorandum for Secretaries of the Military Departments, The Secretary of Defense, Washington, DC (29 Jun 1994).

[10]H. Feldmesser, private communication, JHU/APL, Laurel, Md (Jul 1994).

[11]W. K. Denson, *Reliability Assessment of Critical Electronic Components*, RL-TR-92-197, ITTRI, Rome Laboratory, Griffiss AFB, NY, p. 4-85 (Jul 1992).