High-G Ruggedization Methods for Gun Projectile Electronics

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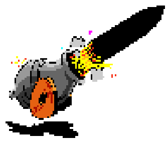
BIOGRAPHY

Jeff Burd is a principal engineer with L3 Interstate Electronics Corporation (IEC). He has specialized in gun ruggedized designs and testing since 1995 and is the project engineer for gun projectile programs. He is also currently working on IRAD projects for developing advanced packaging and security coating applications. Jeff graduated with a BSEE degree from California Polytechnic University, Pomona, California.

ABSTRACT

Design and test methods are presented for ruggedizing electronic assemblies to survive artillery gun fire G-forces. Typical peak set-back accelerations for a 155 mm gun projectile are 15,500 G's with a 9 msec pulse duration. Highly accurate guidance of artillery shells is now possible due to size and cost reductions in GPS receiver navigation electronics. Processes have been developed to attach components for high rate production at low cost. This report documents both GPS receiver board and demonstration test vehicles designs. Presented are the test program results including the successful designs for MCM's and crystal oscillators. IEC is a proven leader in high-G electronics ruggedization. The demand for miniaturized gun-hardened electronics will greatly increase in the future to power the military's autonomous munitions. Test component selection and design of experiment (DOE) testing are critical for a successful high-G ruggedization project.



INTRODUCTION

Since the earliest times of blackpowder cannons, the goal has been to accurately place a fired projectile onto the intended target. Improvements in accuracy have been made in both gun and projectile designs. As modern guns and military missions require increasing ranges, the miss distance of an unguided projectile becomes unacceptable. A means to navigate and control the projectile into the target is required.

Advancements in electronics and micro-electro-mechanical-systems (MEMS) have made it possible to place navigation and flight control into artillery projectiles. Electronic assemblies must now survive and operate through gun-fire accelerations exceeding 15,000 G's. The design and test methods for gun ruggedization are presented in this paper.

GUN RUGGEDIZED PRODUCTS

IEC's initial gun ruggedized design was a 6" square by 0.75" thick GPS receiver developed for a Navy 8" gun demonstration test shot (Figures 1, 9, 15). In May of 1996, an off-the-shelf production receiver was modified and shot at 8,000 G's (Figure 2.). The receiver was operational and tracking after seven seconds into the gun shot flight.

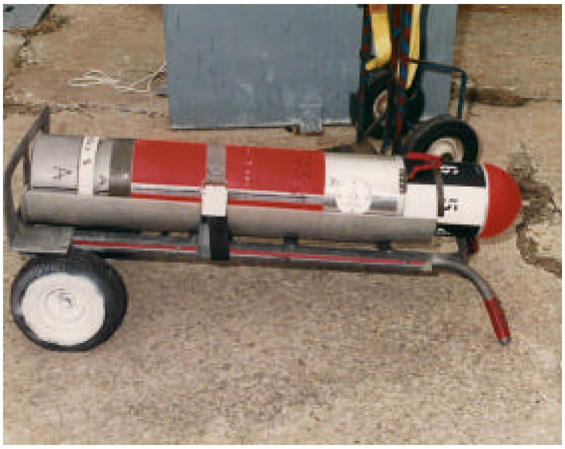


Figure 1. 8” canister containing the IEC GPS receiver.

Figure 2. 8” gun at NSWC Dahlgren, Va.

IEC is currently producing gun ruggedized GPS receivers (Figure 3)

Figure 3. Gun test shot at Yuma, Az. Test range.

HIGH-G ACCELERATION DEFINED

The term “high-G” refers to very high levels of acceleration in the thousands of “G’s”. For many applications it is useful to express acceleration in units of “G’s” where 1 G equals 32 ft-sec^2 at sea level. The applied force, due to acceleration, can then be calculated by multiplying the objects mass times the acceleration in G’s.   For example: A quarter, which weights .0125 pounds, would weigh 200 pounds under 16,000 G’s of acceleration.

Because gun accelerations (with the exception of spin) have very short durations, they can be classified as shock pulses, with a haversine pulse shape[1].

THE HIGH-G GUN ENVIRONMENT

There are four types of acceleration forces produced in a projectile during a gun shot. *Setback* acceleration is the largest force produced and is towards the rear of the gun opposite the direction of flight. *Setforward* acceleration occurs at the time of gun barrel exit and is caused by the “springback” decompression of the projectile structure. *Balloting* accelerations are due to imperfections in the gun barrel which result in lateral shocks to the projectile as it moves down the barrel. *Radial* accelerations are caused by gun barrels which are rifled to impart a spin to the projectile. A typical 155 mm projectile spin rate is 300 revolutions-per-second (rps) at barrel exit. The radial acceleration will result in centrifugal force which is proportional to the off-axis radius of the component.

Several factors affect gun accelerations and pulse durations; gun caliber, barrel length, powder charge amount, and projectile weight.

Some examples of gun fire shock and force load types are:

- Setback shock (8,000 - 16,000 G’s at 9-16 msec)
- Gun barrel exit set-forward shock (2,000 G’s at 1msec)
- In barrel lateral balloting shocks (200-5000 G’s < 1msec)
- Rifled gun barrel centrifugal forces (20-300 RPS)

DESIGN GOALS
A successful gun hardening program meets all system requirements at the lowest possible cost.

Design goals are:

- Mechanical survivability
- Adequate design margins
- Reduce electrical device parameter shifts
- Manufacturability
- Reduce costs
- Automated assembly processes
- Test program

The final goal is to develop a design which is repeatable in a low-cost production environment and meets all requirements with sufficient margins.

DESIGN PROCESS
Gun hardening design is a multi-step process consisting of the following:

- Identify the G-force requirements
- Prepare a preliminary component material list
- Component selection
- Mechanical analysis
- Component pretest screening
- Unit design for gun hardening
- Qualification testing

IDENTIFY G-FORCE REQUIREMENTS
The military customer will specify many of the gun forces expected. Live gun testing can be performed to measure specific forces. The system design specification should identify design margins to be used. A design margin of 1.25 to 1.5 times the expected force levels is typical for most designs. Qualification test levels may be two times or more the expected force levels depending on the test methods chosen. One example is to use a factor of two test margin when employing a centrifuge to test components.

PREPARE A PRELIMINARY COMPONENT MATERIAL LIST
Make a table of all major components in the design and candidate parts for final selection. Next, rank each part for it's expected shock resistance: low, medium, high. Use this table to prioritize which parts to test early in the design phase. The methods selected for testing and test results can all be summarized in this table for ease of reference.

COMPONENT SELECTION
Proper component selection is important to surviving gun shot forces at the lowest possible cost.

Discrete components (Resistors/Capacitors/Inductors): The smallest, lowest-height surface mount components should be used. Parts with a high-height to base-area-ratio may require adhesive attachment. Air-gap capacitors and air-wound inductors should not be used as the G-shock may change the components value.

Crystal based devices: Crystal devices can break and center frequencies will shift as a result of gun shock. Larger circular crystal disks require four-point mounting clips to survive and some manufactures will define an axis of orientation for gun shock. Stress-Compensated (SC) cut crystals are generally better than AT cut for reducing center frequency shifts. Center frequency shifts of less than 1 PPM can be achieved.

SAW oscillators are usually attached by a weak adhesive to allow for proper operation. This adhesive bond may be broken during a shot.

Integrated Circuit Packages: The gull-wing leads of surface mount IC's are designed for thermal expansion and are not well suited to shock loads. The force on the part is translated directly to the leads which are easily bent and torn from their solder pads. The larger the part the worse the retention capability. Adhesive applied under the part or at the edges, will be required.

Ball Grid Array (BGA) packaging is the package of choice. These packages tend to be thin, light-weight, and with many rigid solder ball attachments on the bottom surface. Applying an underfill material can further strengthen heavier devices.

MCM's and Hybrids: Commercial hybrid parts may contain internal components which will not survive gun fire. Wire bonds to bare die survive very high G-forces due to their short length and low mass. IEC has successfully tested flip-chip, CSP, and BGA packages on a MCM-L substrate package design (Figure 4) up to 36,000 G's without failure.

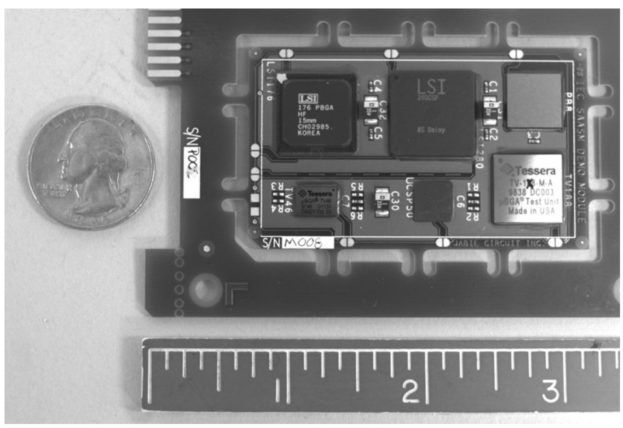


Figure 4. MCM-L test module.

MECHANICAL ANALYSIS

Mechanical analysis using Finite Element Modeling Analysis (FEMA) software can predict stresses and PC board deflections. This information can be used to place adhesive where required and plan test cases. Test results should be compared to the FEMA data (Figure 5.) to validate the mechanical model used.

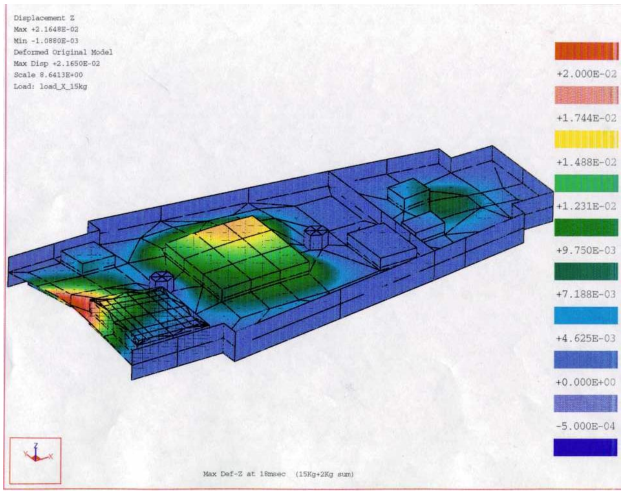


Figure 5. FEMA stress data plot.

COMPONENT PRETEST SCREENING

Identified high risk components should be tested early before being included on a new PC board layout. This will allow time for alternate part selection and testing or working with the part vendor to ruggedize the part design. It is useful to make a test board to mount the device onto, simulating a finished PC board layout. This test board can serve for both electrical test and mechanical fixture for high-G testing (Figure 6.). When the time comes for final board level testing, there won't be any surprises.

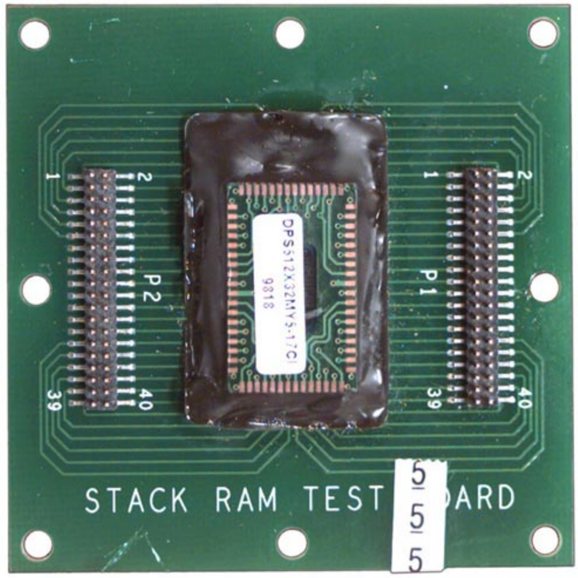


Figure 6. Example test board.

UNIT DESIGN FOR GUN HARDENING

The design of the printed circuit board (PCB) and supporting structure is critical to a gun hardened design. The PCB should be oriented parallel with the direction of setback acceleration. Although this seems contrary to logic, there is much less board deflection produced. It is board deflection which stresses larger area parts and will cause lead separation and part pop-off. Board size and thickness is also a consideration. Smaller, thicker boards will be stiffer and resist deflection. Placing larger components at the board edges (lowest board deflection) will reduce mass in the center of the board. All boards must be adequately supported to minimize board deflection, preventing damage from hitting adjacent structures. The board should have a metal stiffener support around the entire outer edge of the board. Additional stiffening may be required running through the center portions of the board to reduce deflection to an acceptable amount. (Figure 7)

Figure 7. IEC GPS receiver.

COMPONENT ATTACHMENT METHODS

The following categories describe various methods to attach components to a PC board. The order of methods presented reflects preference of use due to repeatability, cost, and strength.

Solder

Use solder for attachment whenever possible. It is most compatible with standard PWB processing methods. For metal can devices, solder the can to the PC board ground plane.

Adhesive

Use adhesive when required to hold heavier parts. The adhesive selected should be compatible with a low cost application process. The best case is to use an automated adhesive application dispenser (Figure 8). The dispenser is programmed to provide a controlled amount of adhesive in a repeatable pattern eliminating human errors for hand applications. The adhesive selected for this use should be a one-part, premixed type epoxy, which does not harden at room temperatures.

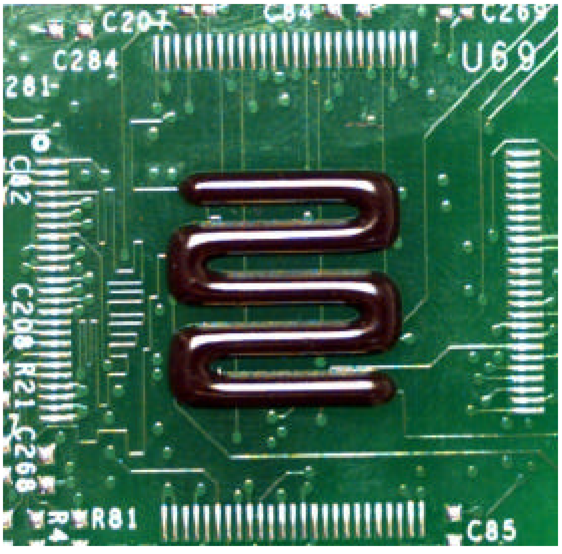


Figure 8. Epoxy dispensed under IC component.

MECHANICAL FASTENERS

Mechanical fasteners may be screws, bolts, straps, etc.,to hold a device in place. These methods may be larger, heavier, and more costly than using solder or adhesives. (Figure 9.)

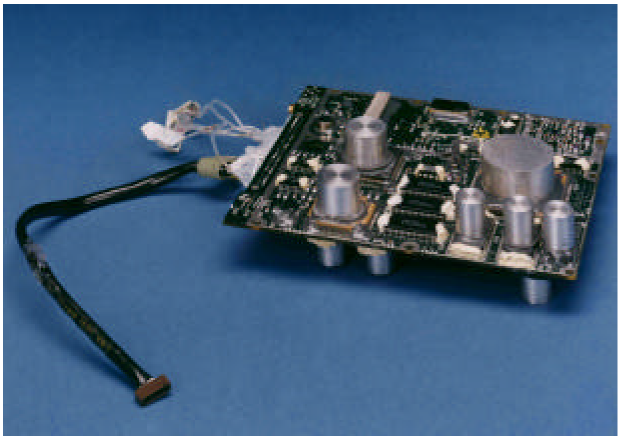


Figure 9. Demonstration GPS board showing metal pins to hold IC’s in place.

ENCAPSULATION AND POTTING

The method of gun hardening using an encapsulation material is usually the first concept that is put forward. This approach has many drawbacks; Once potted, an assembly can’t be easily tested, reworked, or allow for troubleshooting of a failure after a high-G test. The potting material adds weight to the assembly, which will increase the loading on the supporting structures. Differences in Coefficient-of-Thermal-Expansion’s (CTE’s) between the potting and other components may result in stress fractures and open circuits after repeated thermal cycles.

There are some applications where potting does offer an advantage. IEC used a two-part epoxy compound to encapsulate a lithium battery assembly (Figure 10). The batteries where wired together and placed into a metal housing which was then filled with epoxy. The epoxy supported the batteries and prevented deformation of the battery case. This assembly survived live gun fire testing at 14,000 G’s.

Figure 10. Encapsulated battery assembly.

ADHESIVE SELECTION
It is important that a reliable manufacturing process is developed for a design that uses adhesive attachments. The process should be one that does not require mixing or manual application of the adhesive.

Epoxies are a good selection due to their high PSI retention strength. The final selection should be made on both the bond strength, and the ease of application.

A one-part high temperature cure epoxy is the best choice for most applications. Mixing is not required and the epoxy does not set-up at room temperature. This type of epoxy can be used in automated adhesive dispensing equipment. The use of an automated system is preferred to obtain repeatable results.

QUALIFICATION TESTING

DESIGN-OF-EXPERIMENT (DOE)
Use DOE methods to set up controlled experiments using G-force as an independent variable. Use multiple test parts to establish variations in failure points, etc. When testing for device parameter changes use a sample from different production lots.

TEST PHASES
Testing should progress in phases from component level testing to module level (MCM), and finally to PC board and full-up unit assembly levels. By testing in phases problems can be found early and corrected.

COMPONENTS-> MCM'S-> BOARDS-> UNIT

Use lower cost testing methods early (shear, centrifuge), progressing to air gun / rail gun, and finally to the application gun firings. This will result in a high degree of design margin confidence at the lowest development cost.

STATIC -> DYNAMIC-> SHOCK-> GUN

TEST METHODS
A well planned test program is critical to a successful gun hardening project.

Testing can be grouped into three categories:
Static testing, constant acceleration load, and dynamic testing.

STATIC TESTING
Static testing consists of methods which apply a increasing force to the component under test until a failure occurs. This may be performed by using a commercially available pull-tester, or, one can be made using a load cell and digital meter.

IEC has designed and built such a tester using a 0-1,000 pound load cell and hydraulic jack to apply an increasing force to the device being tested. (Figure 11)

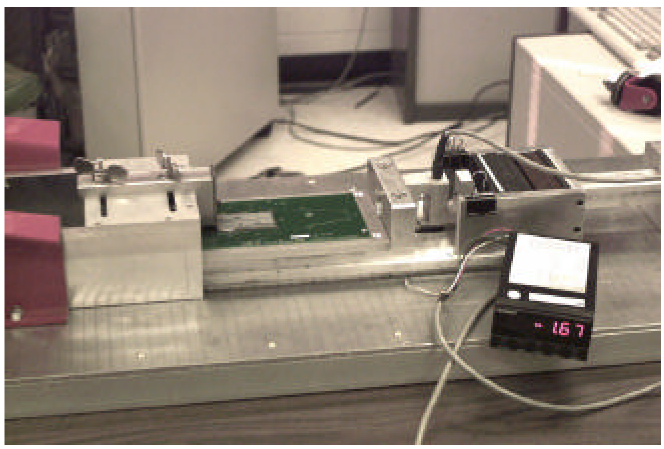


Figure 11. IEC shear tester.

This method is inexpensive and is useful for quickly testing many test samples. Different adhesive types, amount used, etc., can be compared under a controlled environment. The static tester may be placed into a large temperature chamber to conduct high and low temperature effects.

Different attachment modifications to the IEC tester will allow for shear, pull, or PC board bending evaluation.

CONSTANT ACCELERATION LOAD

Some electrical components have fragile internal structures such as exposed wire-bonds, crystals, hybrid devices, air-wound coils and air-gap capacitors, etc. These components are best tested on a centrifuge.

The centrifuge (Figure 12) produces a constant acceleration force on both external and internal structures of a complex assembly component.

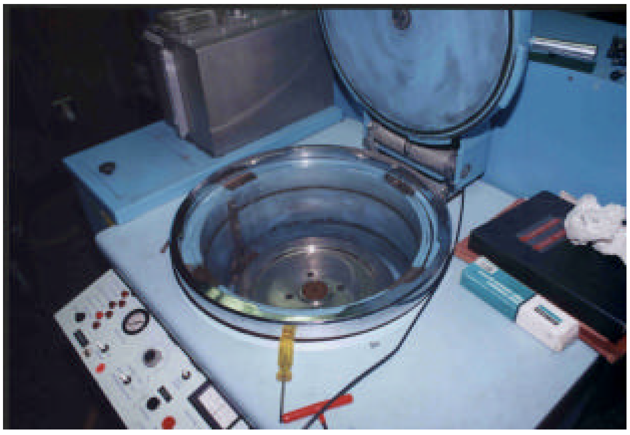


Figure 12. Centrifuge

IC screening type centrifuges typically produce over 30,000 G's of force. A limitation in their use is the small size of the device-under-test that can be accommodated, (less than 2.5 inches per side cube). Also, force increases at greater radius distance from the center hub, causing different G-forces on components on the test board.

$$G_{force} = Radius_{ft}(RPM*PI/30)^2 \;/\; 32ft\text{-}sec^2$$

A holding support fixture must be designed and built to hold the test specimens. Keep in mind the support structure must be strong enough to support the high loading levels.

The centrifuge is useful for testing at levels much higher than gun shot levels, testing to failure point, and demonstrating design margins.

DYNAMIC TESTS

Dynamic tests simulate both acceleration forces and short pulse duration's; shock tower, air gun, rail gun, and live gun.

Shock towers (Figure 13) operate with the test component attached to a mounting plate. The mounting plate is elevated and then dropped from a measured height (often accelerated by elastic cords). Pulse durations are typically short (0.1 msec) and achieving greater than 10,000 g's is difficult. Shock towers are good for simulating balloting shocks.

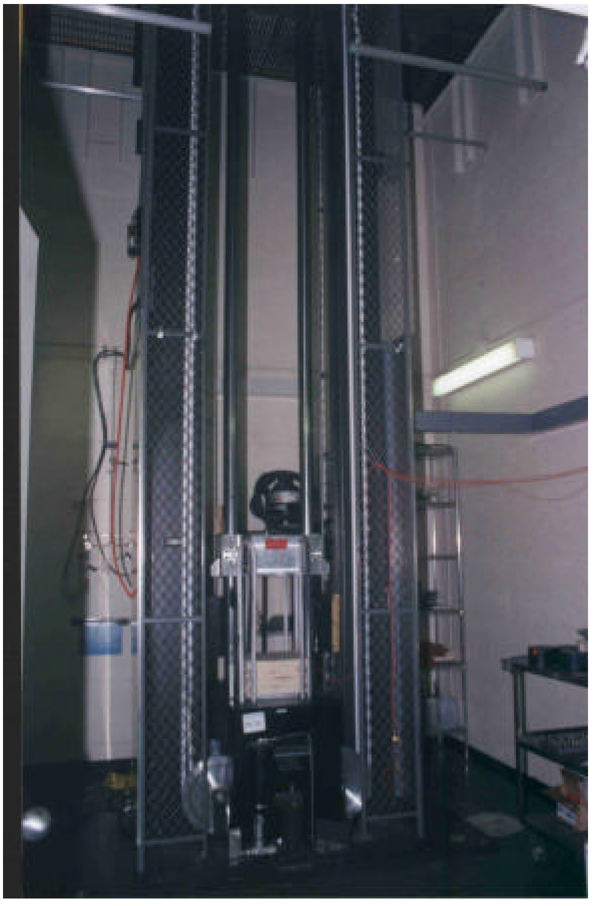


Figure 13. Shock tower

Air guns either employ compressed gas or a vacuum to accelerate a test cylinder down a tube. The NTS operated air gun (Figure 14) is a compressed air type. The shock pulse occurs at the time of the gas release, and the cylinder then decelerates in the 120' tube and returns to the starting breech position. NTS and IEC have successfully made modifications to the air gun system running a coax cable down the internal length of the air gun tube. This cable has been used to supply power and monitor oscillator frequency performance.

Figure 14. NTS air gun.

A rail-gun is an artillery gun which fires a test projectile horizontally into captivating rails. The projectile is decelerated gradually as it passes down the rail system, where 13 KG's at 9 msec pulse durations are possible.

The Navy utilizes an 8" gun (Figure 15) to fire a test canister which has a soft recovery parachute system. Components are mounted inside the "canister" projectile for testing up to 18,000 G's at a 16 msec pulse duration.

Figure 15. NAVY, NSWC Dahlgren, Va. ,8" soft recovery gun system.

FAILURE MECHANICS

Once a test program has begun the following types of failures may be seen:

Electrical:

- Shorts, opens (cracked traces)
- Crystals (center frequency shift)
- Parameter changes (R/L/C's)

Mechanical (External)

- Detached parts
- Cracks in parts and epoxy
- Lead bending and detachment

Mechanical (Internal)

- Hybrids, SAWs internal breakage
- Broken crystals
- Wire bonds broken
- Die, component detachment
- Substrates cracked (ceramic)

FAILURE DIAGNOSTICS

The following methods have proven useful for diagnosing high-G failures:

- X-ray equipment. Can show failure mechanisms hidden by adhesive and potting materials. (Figure 16)

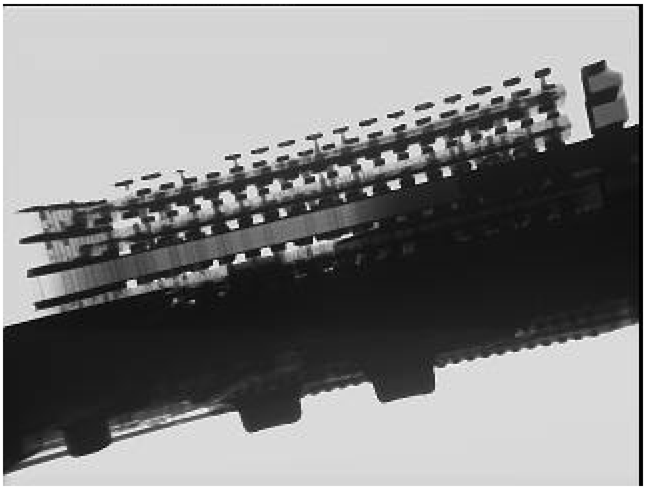


Figure 16. Example X-ray of electronic assembly.

- Acoustic Microscopy. Ultra-high frequency sound waves are used to show internal structures of a component. Very useful for finding delaminations in solder ball attachments, etc. (Figure 17)

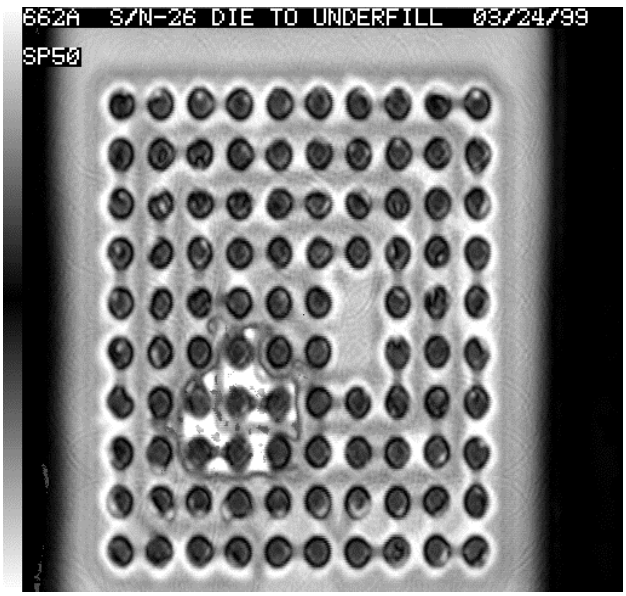


Figure 17. Example of Acoustic scan image.

- Infra-red cameras. Use to detect thermal differences between a good and failed device on a populated PC board.

LESSONS LEARNED

- Test components early before committing to final board layout.
- Less is better: use small BGA style parts, minimize adhesive use.
- Test in phases using various testing methods.

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Tony Boczon (540) 543-8813

L3-IEC: Jim Grace (714) 758-4216

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