

# **PARTICLE IMPACT NOISE DETECTION (PIND) COMBINES VIBRATION, SHOCK, AND ACOUSTICS FOR DETERMINING RELIABILITY OF ELECTRONIC COMPONENTS**

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**Abstract:** Particle Impact Noise Detection (P.I.N.D.) is a reliability screening technique that employs vibration, shock, and acoustics. As a requirement for MIL-STD883E, MIL-STD750, and MIL-STD39016, this test has helped the manufacturers of hermetically sealed electronic components greatly increase the reliability of their product by eliminating contaminants within the cavity over the past thirty years. Recent advancements in packaging methods have created significantly larger packages with increased weight and require improvements to the test equipment including advancements to the closed loop control of vibration, increased dynamic range of closed loop control of shock, and the addition of multiple crystal acoustic detection sensors. This paper will describe these advancements and their effects in helping the test systems to better handle the challenge presented by multi-chip modules (MCM), and Systems on Chip (SOC), and today's' larger hybrids circuits.

## **INTRODUCTION**

Small contaminants inside of electronic packages that contain a cavity will move in a dynamic environment and locate into a position, typical the bond wires, which could short out the part for a brief time during usage. Such a failure is critical for high dynamic stress environments and can pose a significant integrity problem in high reliability electronics applications. As early as 1960, government space organizations, electronic component manufacturers and end users employed PIND testing as a nondestructive test to determine the integrity of electronic components.

For the past thirty years, the PIND test with its series of mechanical shocks and vibrations has been employed by component manufacturers to screen electronic components. A significant trend in the modern manufacture of these components is to build larger and larger packages resulting in changing requirements for the venerable PIND test equipment.

## **DEFINITION OF PIND**

Particle Impact Noise Detection (PIND) is used to determine the integrity of electronic components by "listening" for the acoustic signals generated by impacts created by loose particles inside the cavities of electronic components such as transistors, integrated circuits, hybrids, diodes, relays, and switches.

The PIND test simulates dynamic environments such as aircraft landings and aerospace launchings by administering a series of mechanical shocks and vibrations to the device under test. These shocks and vibrations free particles adhering to the component cavity walls. The high frequency acoustic noise from the resulting impacts between the particles and the package interior are detected by a transducer on which the test component is mounted.

## **ALTERNATE TESTS FOR LOOSE PARTICLE DETECTION**

### **Vibration Testing**

In addition to the PIND test, there are two other procedures for conducting electrical monitoring during vibration for particle detection. These procedures are (1) monitored vibration with power applied to the device, and (2) Sinusoidal vibration with mechanical shocks applied at various intervals.[3].

The monitored vibration method is usually specified for testing power transistors and diodes. The technique uses a sinusoidal vibration either at a fixed frequency or a swept range of continuous frequencies. Power is applied to the device under test and a latching circuit is used to detect electrical anomalies or malfunctions in the device output functions. This test is not considered completely effective because in order to be detected a particle must occupy one of many specific locations at a specific time. This is lengthy and expensive, problems that get worse as the parts increase in size.

The sinusoidal vibration test is sometimes termed the *autonetics test*. It is similar to monitored vibration tests except that it subjects the device under test to shocks at frequent intervals.[3]. These shocks serve to dislodge particles that may be adhering to cavity walls and allows them to freely move about the cavity.

As with the monitored vibration test the sinusoidal vibration test is considered ineffective; correlation of data on devices identified as containing particles and the results of analysis on the devices were poor. [3]. Analysis of defects that passed sinusoidal vibration tests indicated that many contained particles. Additionally, the imposed mechanical stresses are believed to generate particles. This test is also considered impractical due to high cost, limitation of available test equipment, and the time and cost of designing and implementing the driving and monitoring circuitry.

### **Radiographic Monitoring**

Radiographic tests can be effective in detecting large loose or affixed particles as well as manufacturing process deficiencies. It is inexpensive and very easily performed. Some of the draw backs of X-ray testing of electronic components include: some conductive particles are invisible to X-rays due to composition and size; particles smaller than 0.025 mm (0.001 in.) are not detectable and some small particles can be masked by silicon-gold die attached material.

A variation on radiographic testing combined with vibration is conducted by imaging the device and making a radiograph. The device is then subjected to a shock and vibration environment and a second radiograph is taken. The two exposures are compared to locate particles that have moved during vibration.

### **PIND TESTING HISTORY**

Particle impact noise detection, once known as acoustical loose particle detection (ALPD)) began to emerge in the early 1960's with the widespread use and acceptance of transistors in applications such as missiles and satellites.[4]. The problem of loose particles was identified when an analysis of telemetry data from a failed satellite mission showed the cause of failure to be a short in a transistor. The cause of the short was due to a small conducting particle encapsulated within the device cavity.

Texas Instruments began developmental work on equipment to detect loose particles inside semiconductors in the early 1960s. Their first PIND tester consisted of a sinusoidal vibration shaker, an accelerometer with a high output voltage, a passive low frequency filter, and an oscilloscope.[5]. In 1966, both Lockheed (Sunnyvale) and General Electric (Valley Forge) experienced problems with particulate contamination in relays. Lockheed attempted to duplicate GE's system for PIND testing which consisted of a large vibration shaker and a very low g force. During Lockheed's attempt problems in mounting devices were experienced. Lockheed borrowed an ultrasonic frequency translator and used a smaller shaker and the first PIND system for relays was born.[6].

Around 1976, PIND testing was also used in electromechanical relays during a Delta launch vehicle countdown.[7]. A critical part failure was traced to a loose wire and a million dollar retrofit ensued. McDonnell Douglas was contracted by NASA to update and improve the equipment system and technique. As a result of McDonnell Douglas's work and the SPWG, Military Standard 883, Method 2020 evolved.

A commercial mechanical PIND system was built in 1970 by Dunegan Corporation, today Spectral Dynamics, Inc. This system consisted of a vibration shaker, acoustic emission transducer, high frequency amplifier, active low noise filter, oscilloscope, and audio speaker. The system has evolved into a sophisticated microprocessor based unit with software tailored to military specification requirements.

The importance of PIND testing can be most dramatically illustrated with the US Space Shuttle Columbia. In November 1983, the Columbia's landing was delayed eight hours with speculation about indefinite suspension in space because of loose particles in integrated circuits (which had not been PIND tested) that were housed in the guidance and navigation computers.[1][2]. Another example of a high visibility PIND failure was seen during the early launches of the Trident Missile for the US Navy.

## **MILITARY STANDARDS GOVERNING PIND TESTING**

Particle impact noise detection of completely fabricated electronic components is most often employed because it is generally accepted as the most economic and technically the best test for a finished device.[8]. This is supported by the fact that PIND testing has been incorporated into the most widely used PIND Military Standard 883 Method 2020, Military Standard 750 Method 2052, Military Standard 202F Method 217, Military Standard 39016 Appendix B and is required for Class-S microcircuits and semiconductors.

Military Standard 883C Method 2020 falls under the auspices of the Air Force and defines testing of integrated circuits and hybrids. Devices are tested in one of two categories; condition-A or condition-B. Components tested in condition-A are usually high reliability flying hardware type components and are tested at 20 g peak vibration at frequency ranges of 40 to 130 Hz. Components tested in condition-B are usually ground based hardware and are tested at less stringent levels of 10 g at 60 Hz.

Military Standard 750C Method 2052 under the auspices of the Air Force and defines testing of discrete devices while Military Standard 202F Method 217 falls under the auspices of the US Army and defines testing of relays.

## **INSTRUMENTATION OVERVIEW**

The PIND tests are monitored with special ultrasonic sensors to "listen" to high frequency acoustic signals produced by particle impacts and convert that energy to electrical signals. The very small electrical signals produced by this transducer are amplified by a factor of 1,000 to increase their amplitude for processing. Three different methods are used for detection of impacts. They are (1) audio detection; (2) oscilloscope (visual); and (3) threshold detection (electronic).

## **INSTRUMENTATION SPECIFICATIONS**

Military Standard 883 Method 2020 defines the major specifications of the instrumentation (see Figure 1) used for PIND testing.

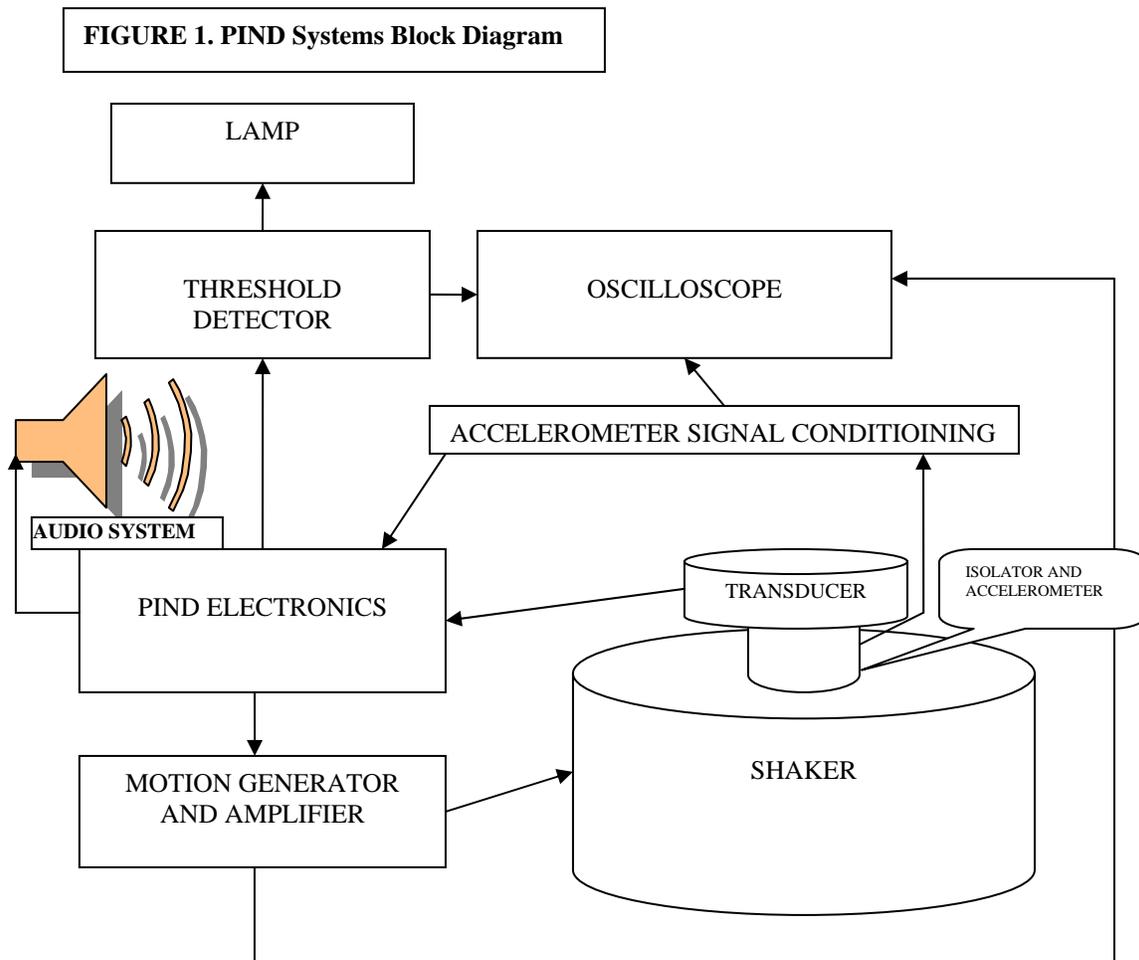
The detection *transducer* is specified as using a nominal peak sensitivity of 77.5 dB referred to one volt per microbar. Restated in other terms, a transducer with this sensitivity produces 133 microvolts of electrical signal from a pressure of one microbar. The sensor is used at a frequency that corresponds to one of the crystal resonances, and that resonance must lie between 150 and 160 KHz.

Typically the amplifier assembly consists of a low noise preamplifier, followed by a filter to limit the noise bandwidth and a second amplifier to bring the total amplification to 1,000. In one commercial system, the preamplifier is located on the sensor head itself. The amplifier must contribute no more internal noise than the equivalent of a ten microvolt transducer signal.

Audio detection uses electronic circuits to shift the ultrasonic acoustic signal down to the audible frequency range. It is amplified and applied to either a loudspeaker or headphones. The operator listens for the characteristic slightly musical click or click from particle impacts.

Oscilloscope detection applies the amplified ultrasonic signal to the vertical axis of an oscilloscope having a sensitivity of 20 millivolts per vertical division. Impacts appear as sinusoidal bursts having a fast rising edge and a longer (approximately exponentially decaying) trailing edge. The exact nature of the oscilloscope display depends on how the horizontal axis of the oscilloscope is driven. Military Standard 883C Method 2020 allows the horizontal beam position to be a function of the shaker excitation or semiconductor acceleration or a linear triggered sweep.

Threshold detection compares the amplified ultrasonic signal to a precision threshold that is set to 5 mV above peak system noise. When the amplifier output exceeds this threshold, it typically lights an indicator lamp that must be manually reset.



## NATURE OF PARTICLES

It is important to point out that particle mass, shape, size, composition and the type of device tested all have direct bearing on whether the particle is detectable, whether the PIND test results are repeatable and whether the particle is capable of compromising device integrity.

A variety of examples of contaminant loose particles have emerged from various PIND test studies. These include textile fibers, silicon splinters, gold wire, glass beads, aluminum wire, weld splatter, potting particles, acoustic ceiling fibers, hair, ceramic splinters and even a contact lens.

In the early years of PIND testing before the advent of more sophisticated sensor devices, the first PIND systems were capable of reliably detecting particles with masses of 30 micrograms or greater. Detection of particles with masses of 7 micrograms was sometimes possible. Today, the practical detection limit for a typical Mil-Std PIND test is particles as small as 0.16 micrograms (using a gold ball as a standard).

An excellent study was conducted where high speed movies were made to view the behavior of particles at frequency ranges of 60 to 2000 Hz at levels of 7 to 35 G and power spectral density levels of 0.0065 to 0.49 G<sup>2</sup> per hertz.[8]. Device types used were specially fabricated glass cans mounted on headers. Particle sizes and compositions included: 0.05 and 0.1 mm (0.002 and 0.004 in.) lead spheres, 0.05 and 0.1 mm (0.002 and 0.004 in.) gold flakes and 0.18 x 0.1 mm (0.007 x 0.004 in.) gold wire. The following observations were made.

1. At 2000 Hz, vibration of 35 G, only the 0.1 mill (0.004 in.) sphere and gold flakes exhibited activity. The sphere moves along the cavity floor but the flakes bounce height is significant enough to allow shorting in some devices.
2. At 1,000 Hz, vibration of 35 G, particles exhibit virtually the same behavior as 2,000 Hz. Both masses are capable of causing component failure under this condition.
3. At 300 Hz, vibration of 35 G, vigorous activity is displayed by all particles, allowing frequent contact of critical component elements both vertically and laterally.
4. At 60 Hz, vibration of 7 G, only the spheres are active, bouncing off cavity floor and ceiling but with little lateral movement.
5. At 150 Hz to 2,000 Hz random vibration at 0.49 G<sup>2</sup> per hertz, all particles are very active vertically and laterally. All particles make contact with critical component elements.
6. At 150 Hz to 2,000 Hz random vibration at 0.0065 to 0.49 G<sup>2</sup> per hertz, activity is very limited until a *break away* point is reached.

## **MEASURING PIND PARAMETERS AND RELATING TO PARTICLE SIZE**

The PIND test is somewhat unique in that the particles themselves are never measured directly. Only a very sensitive acoustic detector measures the effects of moving particles as they impact the inside of the cavity. There are three basic direct measurements, which result in the PIND TEST system measurement:

1. DETECTION
2. VIBRATION
3. SHOCK

### **Detection**

When the particles in motion contact the lid of the cavity part of their kinetic energy is transferred to acoustic energy in the form of a longitudinal particle wave, which propagates through the cavity lid to the ultrasonic detector below. The sensors of choice use a piezoelectric element of Lead Zirconate Titanate most often called PZT-5A. Acoustic energy, generated by the particle impact with the cavity lid, propagates through the cavity lid until it reaches the sensor wear plate. The acoustic pressure causes it to deflect ever so slightly pushing on the crystal, which then generates an electrical output. Please note that if the signal is forced to propagate further such as through the substrate, it will lose significant energy.

The sensor is defined in terms of its longitudinal sensitivity  $-77.5\text{dB} \pm 3\text{dB}$  ref 1V/microbar to the physical parameter of pressure. The measurement of the sensitivity of these electro acoustic sensors is described well in United States Naval Research Laboratory (NRL) texts and has been made into an ANSI standard which used a full-field three sensor underwater reciprocity calibration technique to accurately measure the sensitivity of the crystal response. Less accurate methods of sensitivity measurement used include capacitive pickup calibration or ultrasonic white noise calibration. Either of these methods can be used to measure the sensor output but are only relative measurement methods and can made accurate only by referring back to the absolute calibration method of ANSI S1.2-1988.

The PZT-5 sensors are simply the most sensitive sensors available. To get maximum sensitivity they are used at peak resonance. The exact sensitivity and resonant frequency can both vary at time of manufacture and over time with use. The frequency of resonance is allowed to vary from 150 to 160 KHz. The peak sensitivity can be dampened by a variety of factors including improper or weakened bonding to the wear plate. The most common reason for sensors to lose sensitivity over time is the bond that holds the crystal to the front surface wear plate will begin to micro crack with use and age.

After the sensor converts the acoustic energy to electrical energy, it is amplified and filtered to yield a signal of sufficient amplitude and then displayed on a monitor scope, converted to a low frequency audio signal for audio interpretation, and finally compared to a threshold to provide an impartial indicator of signal. The amplification is described by the Military Standards to be  $60\text{dB} \pm 2\text{dB}$ . Tight frequency filtering helps to eliminate unwanted noise from RFI or line voltage spikes.

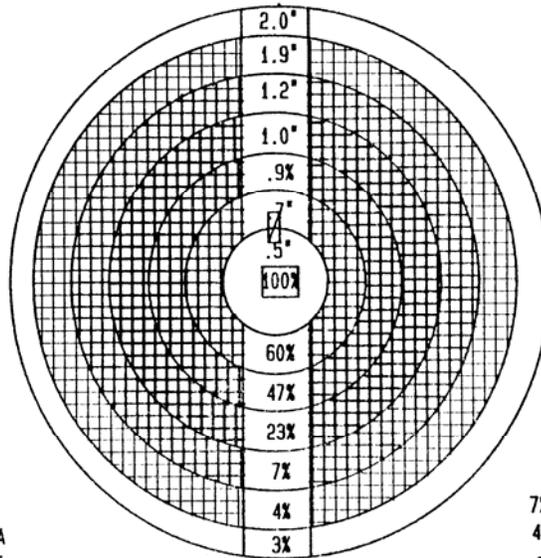
As the sensor and the source of the acoustic wave get farther apart the measured energy is reduced. The PIND test is applicable to a wide variety of package types. Signal loss is caused by three factors: attenuation, reflection, and geometric spreading.

1. Attenuation is the absorption of energy as the acoustic wave propagates through a material. Metals have low absorption while softer materials have higher absorption. Eutectic would attenuate signals greater than metals.
2. Reflection is caused by the boundary between two dissimilar materials. In the case of the PIND tests the path from the lid to the work surface is simple with low reflection loss. But the path through the substrate is more complex with the die, die bonding material, substrate, and finally substrate bonding material all comprising different materials leading to reflection losses.
3. Geometric spreading is the greatest source of signal loss. At the time of impact, all of the energy of the acoustic signal is contained in a single point. Later the wave has expanded into a circle (in three dimensions a sphere) but still contains the same energy. In this two dimensional model a circle of circumference  $2\pi \times \text{radius}$  contains the same energy as the original point source. In short the longer the signal path the greater the attenuation.

The diagram below is experimental data showing the actual sensitivity loss as the signal moves further away from the source.

## TRANSMISSIBILITY RESPONSE OF PIND TRANSDUCER TEST PLATFORM

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### TRANSMISSIBILITY RESPONSE

100% = 0 - 0.5 IN DIA AREA  
 60% = 0.5 - 0.7 IN DIA AREA  
 47% = 0.7 - 0.9 IN DIA AREA  
 23% = 0.9 - 1.0 IN DIA AREA

7% = 1.0 - 1.2 IN DIA AREA  
 4% = 1.2 - 1.9 IN DIA AREA  
 3% = 1.9 - 2.0 IN DIA AREA

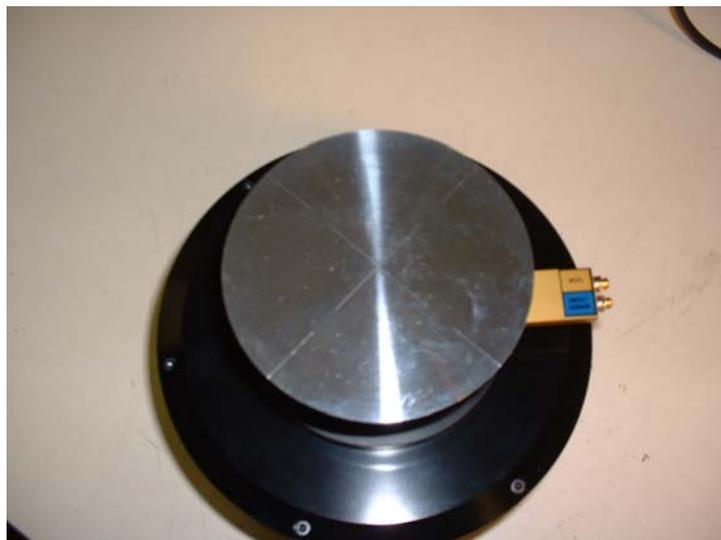
03 060 MFR/gj

The older discrete packages tended to be small with at least one flat surface. For years these were tested with a small, about one-inch sensor active area. When tested lid down, the particle impinges on the lid, and the energy is transferred through the lid to the work surface of the sensor and is converted to an electrical signal. If one places the part substrate down, the acoustic signal must propagate either through the substrate or around the substrate to the work surface of the sensor causing significant signal loss.

Today the parts are much larger often measuring several inches across. To PIND large parts one needs to test them multiple times with a single crystal sensor or employ multiple crystals within the sensor. Below is a picture of a modern four crystal sensor used for larger hybrid and Multi-Chip Module package types. Placing more crystals in the sensor allows for the testing of larger packages in a single pass.

### Vibration

Vibration is used to impart kinetic energy to particles that are contained within the cavity. The energy can be described by  $\frac{1}{2} (\text{Mass of particle}) * (\text{Velocity of particle})^2$ . If there are no particles or there is no movement then the particle energy is zero and hence the electrical output of the sensor is also zeroed. The effect of vibration on loose particles has been well studied. The graphs of Figures 2-6 describe the effects of varying the particle velocity and mass. Adjusting the vibration amplitude and/or the frequency of vibration can alter the velocity of the particle. The velocity is determined by



the rate of change of the displacement so the greater the displacement the greater the velocity. Figure 2 shows the effect of varying the frequency on amplified sensor output from a known particle. Note that over the normal range of frequencies used to PIND test, 45 to 130Hz, the voltage output is nearly constant. Testing at higher than normal frequencies will produce less throw and hence less voltage output.

FIGURE 2

COMPARISON OF OUTPUT AMPLITUDE  
PARTICLES AT DIFFERENT FREQUENCY

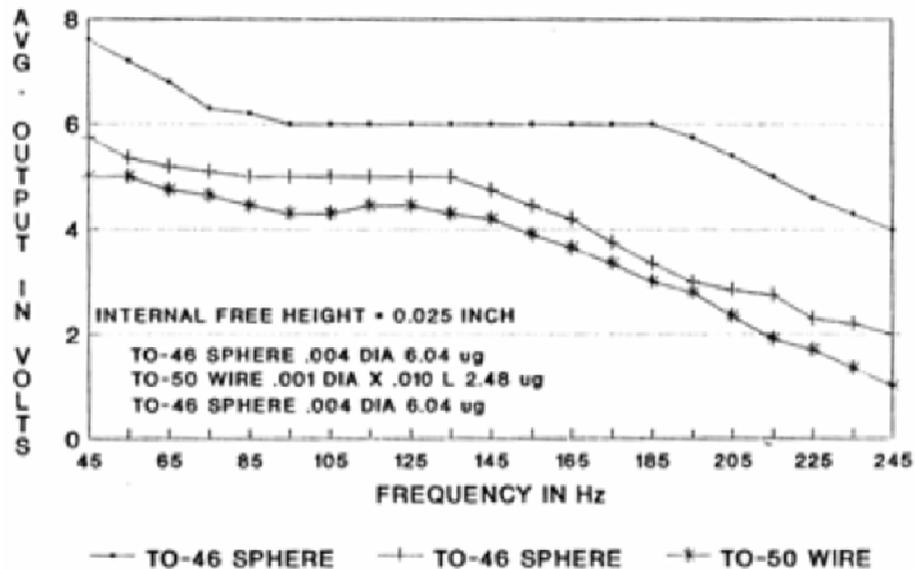


Figure 3 is a graph that shows the amplified output of the sensor in voltages as a function of "G" level. Of note is the increasing output as a function of acceleration. Doubling the acceleration from 10 to 20 "G" can increase the output by 30-50%. Overall the effect of varying velocity within the framework of the PIND test can have the result of increasing or decreasing the output by 50%.

COMPARISON OF OUTPUT AMPLITUDE  
OF PARTICLES USING DIFFERENT  
ACCELERATION LEVELS AT 65 Hz

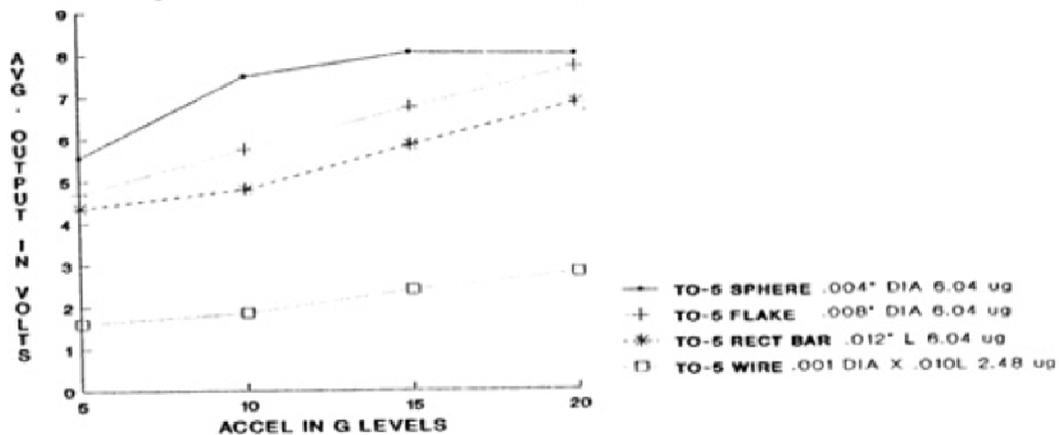


FIGURE 3

PARTICLE IMPACT NOISE DETECTION

COMPARISON OF OUTPUT AMPLITUDE OF PARTICLES USING DIFFERENT ACCELERATION LEVELS AT 65 Hz

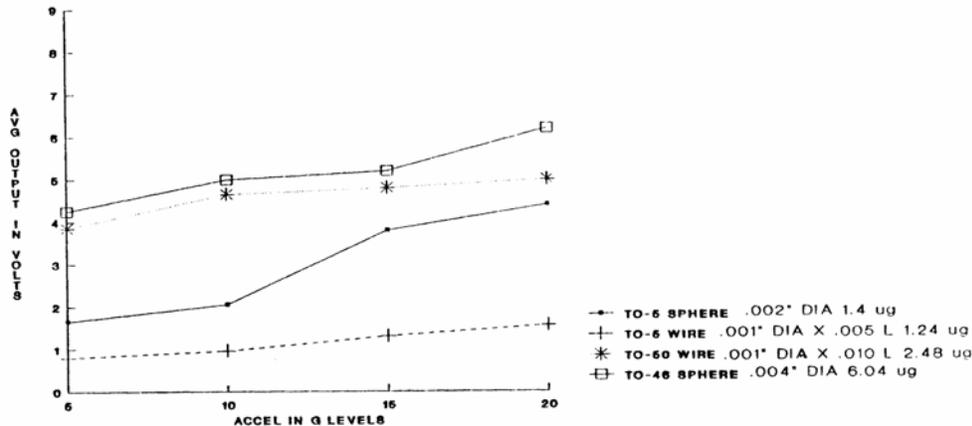


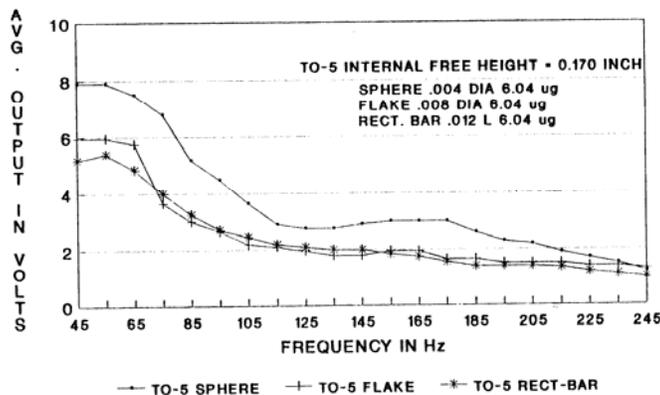
FIGURE 4

Figure 4 is a graph showing the amplified voltage output as a function of "G" level for particles of differing mass. Higher mass give higher voltage outputs. The 6-microgram particle gives an output that is about four times greater than the 1.24 microgram particle expected with the higher particle energy.

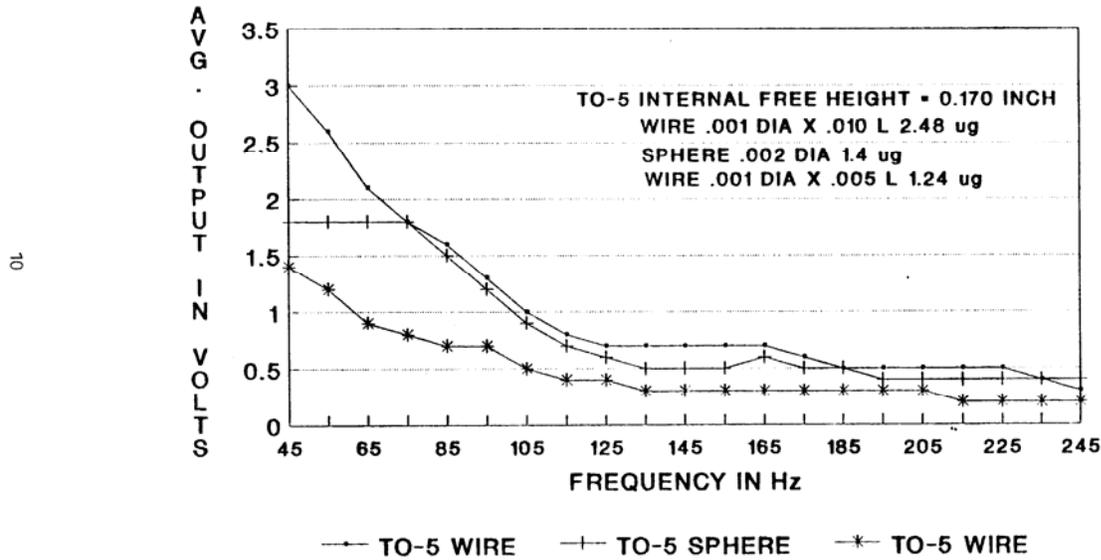
Figure 5 shows the amplified voltage output versus frequency for particles with the same mass but with different shapes. Within some error they behave about the same. The sphere gives greater signals because it is round and is less dependent on direction of impact than those of non-uniform shape.

Finally Figure 6 shows the amplified voltage output versus frequency for three different particles in the same TO-5 package. With the two wire type particles the voltage output is double for the wire with twice

COMPARISON OF OUTPUT AMPLITUDE PARTICLES AT DIFFERENT FREQUENCY MASS vs SHAPE



**COMPARISON OF OUTPUT AMPLITUDE  
PARTICLES AT DIFFERENT FREQUENCY  
MASS vs SHAPE**



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ATTACHMENT C

FIGURE 6

the mass.

Both velocity and mass can affect the signal output from the PIND test. Velocity is constrained by the dimensional limits of the PIND test and is generally limited to about 50% change. The particle mass on the other hand has a great affect on the output as one would effect from the initial kinetic energy equation for a particle in motion.

For ever larger packages care must be taken to insure that the particle velocity is created repeatedly by using the same acceleration level for all tests. This is best accomplished through the user of feedback control of the acceleration as measured by a sensor.

**Shock**

The shock is used in the PIND test to knock particles that adhere inside the cavity loose to allow the vibrating motion. Particles can be both mechanically trapped as well as electrical trapped. As particles impact the inside of the cavity the triboelectric effect causes them to acquire a static charge. Neither all particles nor elements within the cavity are perfect conductors many are "semiconductors" which increase the triboelectric problem. Both conductive and partially conductive particles acquire charge during vibration and then adhere to the inside of the cavity most notably somewhere on the substrate.

Without the particle sticking problem there would be no need for the shock. Figure 8 is a plot of amplified sensor output as a function of mass of several known loose particles. The dotted line is an extrapolation of the data to small particles. Note that for the threshold limit described by MILSTD-883E (20millivolts) the limit of detection is about 0.03 microgram. In practice the industry cannot detect particles that are this small with the normal PIND test. The problem is that the smallest particles exhibit the property of adhesion and stop moving during the vibration cycle.

## PIND SHOCK SENSITIVITY RESULTS

### *Amplified Sensor Output vs. Particle Mass*

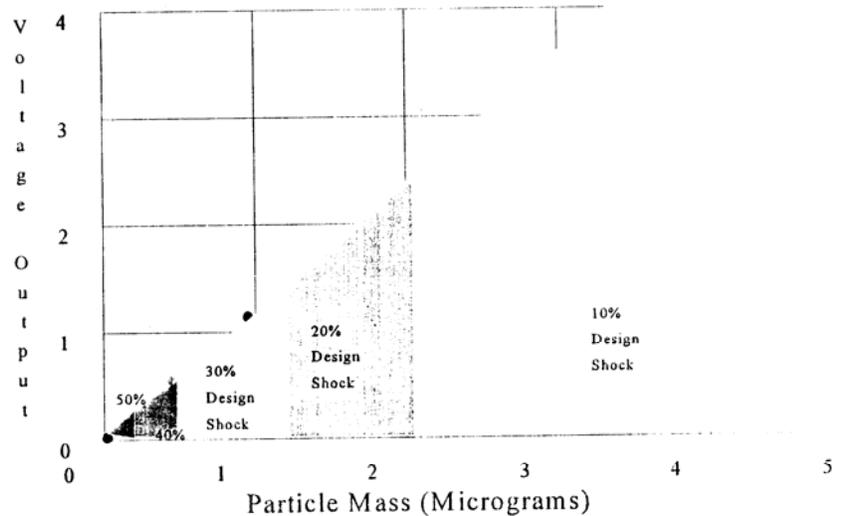


FIGURE 8

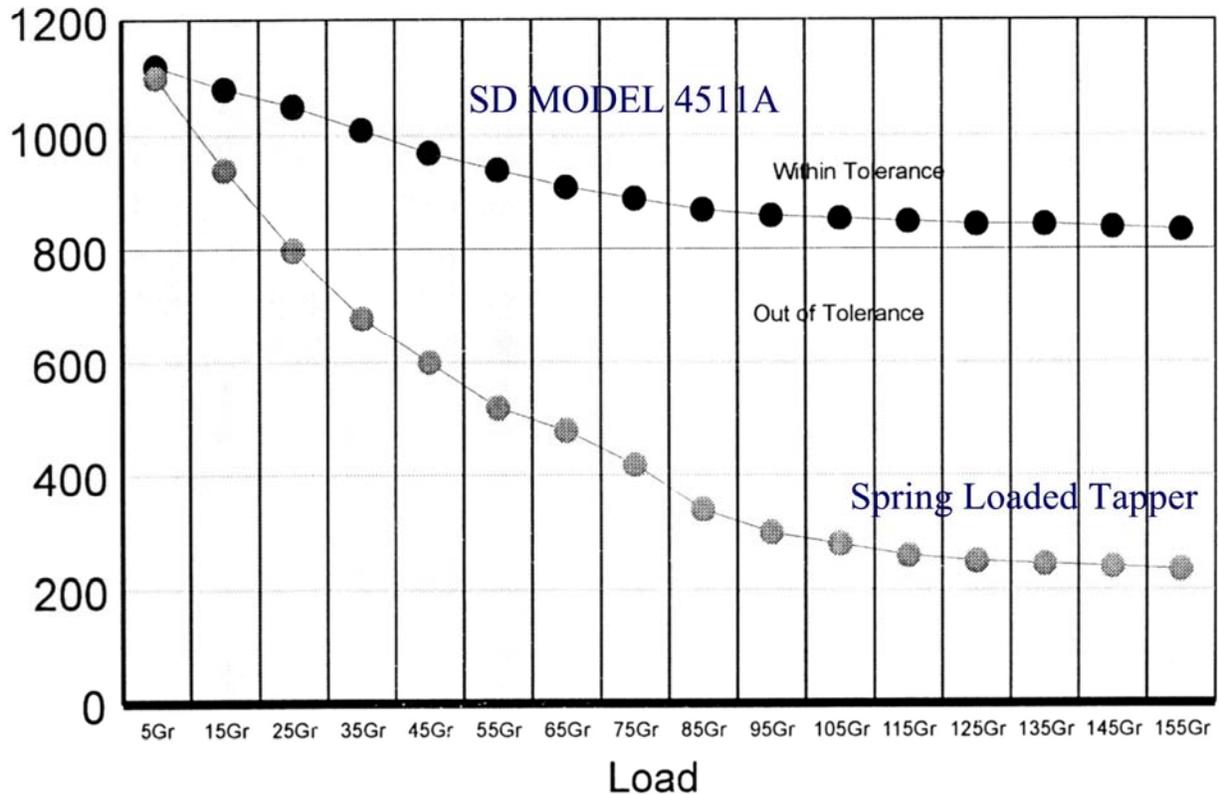
Larger particles, those with masses greater than about 6 micrograms, need no shock to be detected. But smaller particles require shock energy to knock them back into motion so they can be detected. Figure 8 is the summary of results of a work performed by Raytheon Electronics in Massachusetts to create an "enhanced PIND test" with an increase in the sensitivity of the PIND test. Because the shock energy is the product of both the amplitude and pulse width, it is best described as a percentage of the design qualification shock pulse. Nearly all electronic packages use the same design qualification shock pulse, with amplitude of 1500 "G" and full pulse width measured at the 10% amplitude of 500 microseconds. The shock energy for wider pulse widths requires a small amplitude or "G" value to give the same energy. The investigation at Raytheon has shown that shock pulses of up to 50% of qualification design are effective in knocking even the smallest particles loose, thus insuring adequate sensitivity of the PIND test. The results of this work clearly show that it is the shock pulse that determines the "SENSITIVITY" of the PIND test

In Mil-Std 883E, the PIND test shock pulse is described by measuring at the 50% of peak amplitude. Thus for a half sine shock the full pulse width would be 200microseconds. The amplitude is targeted for 1000G. Since the shock pulse energy is the area under the curve the target PIND shock pulse is 26% of the qualification design shock pulse. The newer PIND specification of MIL-STD-39016D, Appendix B, describes a PIND test shock pulse with full pulse width of 1000microseconds and amplitude of 200G, again 26% of qualification design. The language of the Military standards is very weak in that they use the old terminology of "not to exceed" assuming that everyone would understand that the pulse width is important. In fact one could decrease the shock pulse width to nearly zero and still comply with the military standard. There is an active effort started to correct this language in the military standards. Clearly a 200G, 50microsecond pulse width (4% of qualification design) does very little good to knock small particles loose, making the shock clearly ineffective.

Shock is the single most valuable tool for failure analysis applications. If the loose particles are large the particles can be vibrated out easily. BUT when the particle size decreases then the small particles adhere easily. Once tested then the particles latch up. It can take up to 24 hours for the static charges to dissipate. The only tool available to free these loose particles is shock. Increasing the shock energy will knock even the most stubborn particles loose again to be vibrated out for further analysis.

## SHOCK LEVEL VS LOAD

### SD MODEL 4511A vs Spring Loaded Tapper



As the parts get heavier more shock energy is required to achieve the same resultant shock level. The chart above shows the measured shock level as the load increases for a modern system that employs adaptive control of the shock level versus an old mechanical spring actuated system. As the load increase the open loop system soon goes out of tolerance while the closed loop controlled system continues within test tolerances.

### CONCLUSION

Loose particle detection in hermetic electronic packages has been a problem since the early 1960s. Since then, PIND systems have provided an economic and effective tool to screen out defective parts. The equipment used has evolved from custom mechanical systems to the more sophisticated microprocessor based systems available today. PIND system detection capability has dramatically increased from 30 micrograms to less than 0.10 micrograms.

In comparison to alternate test methods, and because the PIND test has been incorporated into Military Specifications 883, 750 202, 39016 and is required for Class-S microcircuits and semiconductors, it is widely accepted as the most economical and technically advanced test for finished electronic devices.

It is important to remember that particle mass, shape, size, composition and the type of device the particle is encapsulated in have direct bearing on whether the particle is detectable, whether the PIND test is repeatable and whether the particle is capable of compromising device integrity.

Larger packages often require multiple crystal sensors to insure the signals generated by the loose particles are not attenuated before they are detected. Larger parts often require larger shakers and better control of the vibration creation. Finally larger parts require a closer monitoring of the shock energy used to keep the loose particles within the cavity moving ideally with closed loop control.

- [1]. Golden, Frederic. "Those Balky Computers Again." *Time Magazine* (December 19, 1983).
- [2]. Dembart, Lee. "Computer Flaws on Shuttle Tied to Tiny Objects." *Los Angeles Times* (December 22, 1983).
- [3]. Adolphsen, John, William Kagdis, and Albert Timmins. *A survey of Particle Contamination in Electronic Devices*. Greenbelt, MD: Goddard Space Flight Center (December 1976).
- [4]. Clark, I.D., J.C. Burnes, and B.D. Clark "Evaluation of selected Methods for Detecting Contaminants within Semiconductors" *Proceedings of the Institute of Environmental Sciences Annual Technical Meetings* (1965).
- [5]. Reynolds, Willy. *PIND Test Training Report*. Report No. 03-060-WRR. Texas Instruments (May 1985).
- [6]. Hurd, Walter. Personal correspondence. Burbank CA Lockheed Corporation. (March 1984).
- [7]. McGuinness, N. *PIND Testing Workshop Report*. Report TOR 0082 (2902-04)-4 (March 1982): pp 14.
- [8]. Adolphsen, John W. *The Effectivity of PIND Testing*. Greenbelt, MD. NASA Goddard Space Flight Center (1979)
- [9]. McCullough, Ralph E. "Screening Techniques for Intermittent Shorts." *IEEE Reliability Physics Symposium*. New York, NY: Institute of Electrical and Electronics Engineers (1972): pp 19.
- [10]. McCullough, Ralph E. "Hermeticity and Particle Impact Noise Test Techniques." - *IEEE Reliability Physics Symposium*. New York, NY: Institute of Electrical and Electronics Engineers (1972): pp 256.
- [11]. McCullough, Ralph E., James C. Burrus and Willy R. Reynolds "PIND's Role as a Failure Analysis Tool." *Proceedings of the ATFA Conference* (1979j).
- [12]. Chesne, T. and B. Lemaire. "PIND Test—Summary of Studies Conducted at Crouzet." *Proceedings of the Third International Conference on Reliability and Maintainability*. Crouzet, France (October 1982).
- [13]. Harman, G.G. *IEEE Transactions on Parts, Hybrids and Packaging*. Vol. PHP-13, No. 2. New York. NY: Institute of Electrical and Electronics Engineers (September 1977): pp 116-12.
- [14]. Harman, C.G. and K.O. Leedy. *Proceedings of the Tenth Annual IEEE Reliability Physics Symposium*. New York, NY: Institute of Electrical and Electronics Engineers (April 1972): pp 49-56.