Statistical and Visual Analysis of Solder Joint Reliability in extreme Environments

By

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Abstract

Over the last several decades, surface mount technology has advanced and become the most profitable industry worldwide. Cell phones or some type of hand held technology have become prominent throughout multiple age groups. Due to the thermal cycling these products are subjected to during their day-to-day operation, the reliability of these handheld electronic devices has become a major concern for the manufacturers.

Recent testing at Auburn University, as well as other research institutions and industry, have shown significant concern with leadfree solder when exposed to long term isothermal aging. To address these, testing was performed to establish the top leadfree solder materials. In the first installment of the solder doping project, sixteen solder-paste materials were examined through thermal shock and mechanical (vibration and drop) testing. In thermal shock testing, boards were subjected to thermal shock test with temperatures between 40°C and +125°C in CSZ TSB Chamber, with 50 boards being tested at a time. The thermal shock cycle consisted of 3000 cycles with 5 minutes at each temperature extreme and transition time of 2.5 minutes. The setup test assemblies were mounted on an LDS LV217 electro-dynamic shaker table. The 4.6 Grms vibration profile was chosen to complete the test in 20 hours. In Drop testing, a Lasmont M23 Drop tower was used with the process as per JESD-B111 specifications. Boards were subjected to 300 drops or to failure with 1500G with 0.5 millisec half-sine shock pulse. Survival data for each test was analyzed with all variables taken into effect, and the top 5 performing materials were chosen for thermal cycle testing in TC2.

In the second phase of the study, the reliability performance of various electronic assemblies during thermal cycling testing are investigated. The top performing doped lead free solder alloys designed for high-temperature reliability from phase I testing are used. The test boards were 0.200" thick power computing printed circuit boards with MEGTRON6 substrate material and OSP coating. Single-sided assemblies are built separately for the Top-side and Bottom-side of the boards. JEDEC JESD22-A104-B test standard was followed; the test boards were subjected for thermal cycling between the temperatures -400C and +1250C, 120-minute cycle profile with 45-minute transitions and 15-minute dwells at peak temperatures is maintained. The test assemblies include surface mount resistors, 5mm, 6mm, 13mm, 15mm, 17mm, 31mm, 35mm and 45mm ball grid array packages respectively. The failure data of the test assemblies were used in this study to understand the effect of solder paste composition on the solder joint reliability during thermal cycling testing.

Results of these experiments have provided valuable data for materials that may be more reliable than SAC305 solder materials for high temperature storage and thermal cycling applications.

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Table of Contents

List of Figures

Chapter 1
Introduction to Electronic Packaging

1.1 History of Electronic Industry

The electronics industry has a significant impact on the world. The Oxford dictionary defines electronics as, "The branch of physics and technology concerned with the design of circuits using transistors and microchips, and with the behavior and movement of electrons in a semiconductor, conductor, vacuum, or gas." [1] The electronics industry emerged in the early 20th century with the development of the telephone and the radio. Electronics advanced rapidly in the 20th century based largely on necessity. World Wars I and II ushered a great need for advancements in location, communication, munitions, and weapons technologies. The electronics industry began with the development of the point-contact resistor developed in 1947 when Bell Labs realized the necessity for an improvement in the vacuum tubes used for signal amplification in telephones. The director of Bell Labs realized semiconductor technology was the answer. With the invention of the transistor, the semiconductor industry experienced rapid growth. [2]

Revenue surpassed $1 billion the first-year semiconductor technology was mass produced for market sales (1987). [29] Since then, the technology has continued to improve exponentially and is still expected to see continued improvements for the foreseeable future. Semiconductor technology has influenced multiple industries. [3]

The electronics industry consists of five major sectors including telecommunications, equipment, electronic packaging, industrial electronics, and consumer electronics, and several minor sectors. Electronic packaging is the largest of the electronic industry's sectors and has experienced tremendous amounts of growth and innovation. Growth in requirements and regulations in the market place, as well as innovations in materials and technologies, have spurred rapid improvement of electronic packaging technology. Figure 1.1 below shows the progression of electronic packaging from the beginning through 2020. The evolution from through-hole mount to surface mount and 3D technologies are shown with each component progression. [4]

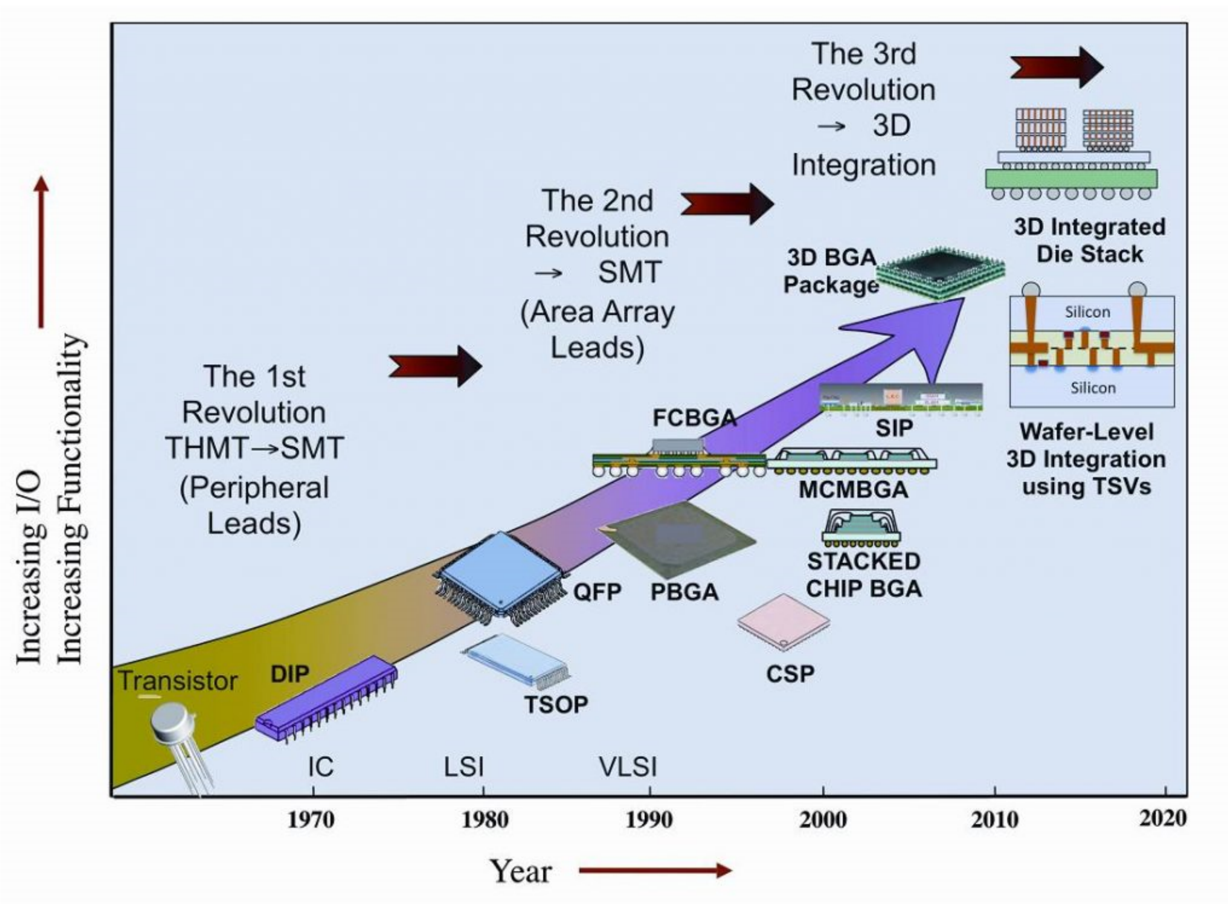


Figure 1-1: Progression of Electronic Packaging from 1960-2020 [5]

1.2 Electronic Components

An electronic component is any device in an electronic system used to create an electrical circuit with a specific function on a printed circuit board. Each component is mounted to the PCB based on the technology, through-hole mount technology (THMT) or surface mount technology (SMT). Surface mount technology has become the industry standard and will be the only component technology discussed in this research. Components are divided into three classes, passive, active, and electromechanical. Passive components, such as resistors and capacitors, can store and maintain an electrical charge but cannot emit one. Active components, such as diodes, transistors, and integrated circuits, use a source of electricity and control the flow of current through each component. Electromechanical components, such as batteries, switches, and fuses, are devices with integrated moving parts that carry out electrical operations to make some change to the system. [6]

1.3 Through-Hole Mount Technology

Through-hole mount technology (THMT) is the process of mounting leaded electronic components by inserting the leads through holes drilled into the PCB. The holes are then filled with solder to ensure strong electrical interconnect. Two types of through-hole components are used commonly in industry, axial and radial. Axial through-hole component leads protrude out of two opposite sides of the component. Radial through-hole component have leads protrude from only a single side of the component. [7]

Through-hole mount components present many advantages in reliability as opposed to other mounted components. THMT components can withstand mechanical stresses much more than SMT components because the bond to the board is extremely strong. The disadvantage of these components is the time and cost of drilling the holes into the boards, as well as the space each hole occupies. THMT can only be placed on one side of the PCB with limited space. Various through-hole mount components are available on the market including transistors, resistors, and capacitors, etc. [7]

Figure 1.2 shows the common assembly of a through-hole mount component to a PCB. The component shown is a common resistor, but assembly is similar for most all THMT components. As is shown, the leads of the component are placed through the PCB and solder is added via hand soldering, wave soldering, or paste in hole.

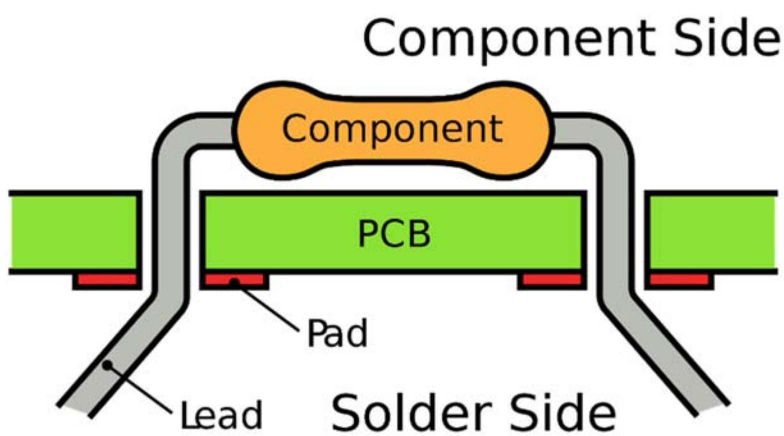


Figure 1-2: Through-Hole Mount Component Assembly [8]

1.3.1 Transistors

Transistors are miniature mechanical switches triggered by electronic signals, enabling or disabling an electric current through the circuit. The main purpose in the development of this technology was to increase signal amplification for telephones. The components in use were found to be unreliable and unpredictable in their electronic characteristics over long periods of use. To solve these problems, the bipolar junction transistor was developed. The transistor, based on whether they are enabling or disabling an electric current, will have conductive or insulating properties. Transistors are created using a doping process, where a material will gain either a positive or negative electric charge. Two types of bipolar junction transistors are most commonly used throughout industry and are named based on the electric charge of the material, which include NPN and PNP transistors. [9]

NPN transistors use the electric current passing through it to amplify and collect current. When the current collected is positive, the transistor becomes active. Figure 1.3 below shows the symbols of common bipolar junction transistors. The leads in the image are labeled as B (Base), C (Collector), and E (Emitter). The labels only describe how the transistor functions internally. Each lead must be properly connected based on the label or the transistor will be damaged upon first use.

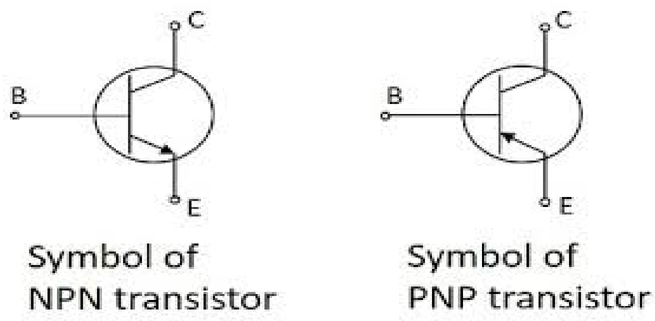


Figure 1-3: Bipolar Junction Transistors [9]

1.3.2 Resistors

Resistors are electronic packages used to limit the flow of electricity to a circuit based on an unwavering level a resistance. Resistors are known as passive components, meaning the package cannot generate an electric current but can absorb it. The main function of a resistor is to create a precise quantity of electrical resistance to be passed through a circuit. The resistance is measured in ohms and is manufactured to a particular level. Some resistors are manufactured to have varying resistances. Resistors are also measured by the amount of heat energy dispersed in watts. To measure the resistance, Ohm's Law is used, which states that the current through a conductor between two points is directly proportional to the voltage across the two points. The formula for Ohm's Law is:

$$I = V/R$$

Where V is the voltage drop of the resistor, measured in Volts (V), R is the resistance of the resistor, measured in Ohms (Ω), and I is the electrical current flowing through the resistor, measured in Amperes (A). [10, 11] Figure 1.4, below, shows how a common resistor looks. The components and wires are coded are with colors to correspond with the amount of resistance measured in kiloohms and the tolerance of the component.

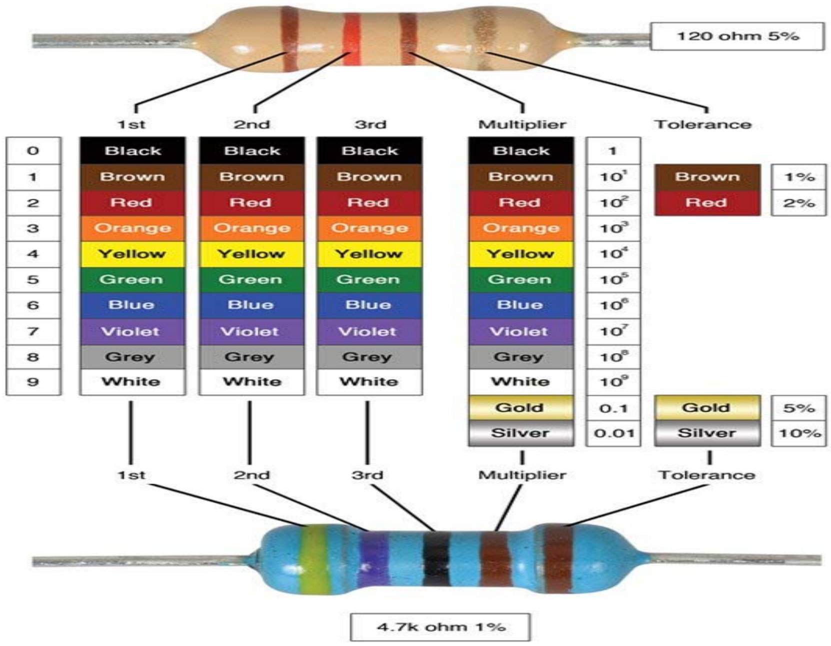


Figure 1-4: Color Coded Resistors [11]

1.3.3 Capacitors

Capacitors are devices used to store an electric charge, consisting of one or more pairs of conductors separated by an insulator and designed to add current to a circuit. These components are commonly used in electronic assemblies to block a direct current of electricity while allowing an alternating current to pass through it. The common capacitor is manufactured with a set of conductive materials with an insulator material between them. The function of the capacitor closely follows Coulomb's Law, which states, "the interaction between charged objects is a non-contact force that acts over some distance of separation." The capacitor's conductors thus hold equal and opposite charges, and the dielectric develops an electric field. The amount of electrical charge the capacitor can hold is defined as the capacitance and is measured in units of farads. The capacitance is found using the equation:

$$C = Q/V$$

where Q is the charge and V is the voltage. [12, 13] Figure 1.5 shows an image of a commonly used capacitor. The voltage and temperature dispersed is also identified, as shown in the capacitor on the right.

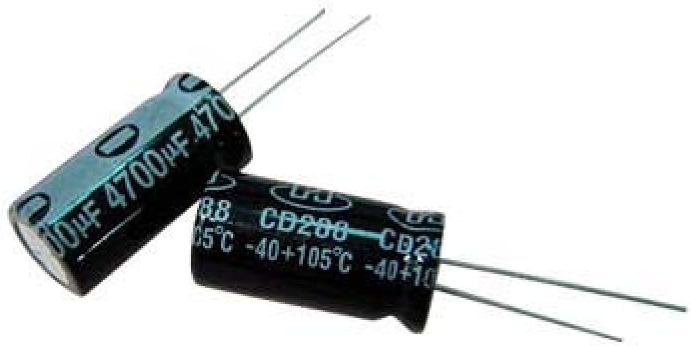


Figure 1-5: Capacitor [13]

1.4 Surface Mount Technology

A significant amount of electronics used today are comprised of surface mount components. Surface mount technology (SMT) was developed in the 1960s but did not become widely used throughout the industry till the 1980s, where it quickly gained dominance in the market. [14] Components using SMT are soldered to the surface of the PCB using solder balls placed directly to the bottom of the component or solder printed onto the board. Leaded THMT components do have some advantages including ease of inspection and repair as well as mechanical strength, but the SMT components offered advantages that THMT components could not and helped to improve innovation in the market place. A major benefit of this technology is that components may be placed on both the top and bottom sides of the PCB. SMT allowed for much smaller component and circuit boards with higher component density. The cost of manufacturing a PCB is greatly reduced with the use of SMT components due in large part to less drilling through the board. For all these reasons, surface mount components have become the industry standard throughout the electronics industry. All components discussed further will be leadless SMT packages.

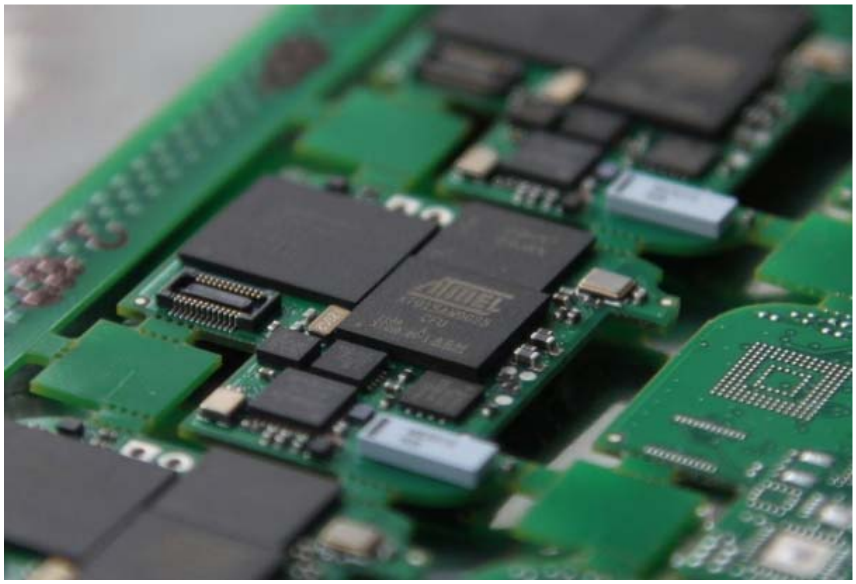


Figure 1-6: Surface Mount Technology [15]

Figure 1.6 above presents an array of different SMT components, as well as the how the components are mounted to the board. Compared to THMT, SMT components can be placed much closer together on the board improving density.

1.4.1 Quad Flat Packages

Quad flat packages (QFP) are surface mount components with leads extending from all four sides of the package. The leads of the package are called "gull-wing" leads based on the shape and how they bend downward toward the PCB. QFPs can commonly have a variance of 32 to 304 leads with a pitch ranging from 0.4 to 1 mil. Quad flat packages present many advantages over other components. A major advantage of the quad flat packages is the high number of interconnections that can be used in the electronic circuit, but this can also be a disadvantage. As more connections are added and the lead pitch size is reduced, solder deficiencies may occur. Some leads may receive an insufficient amount of solder resulting in a poor circuit connection, or too much solder may be added, which would cause bridging and lead to a short. To solve the problem of more leads with smaller pitch size, the ball grid array package was developed. Figure 1.7 presents a general view of a common quad flat package. The constraints of a high number of leads on the quad flat package can clearly be seen due to the area available for each lead. As the lead count rises and the pitch reduces, more chance for error in soldering may occur similar to the errors mentioned above. [16, 17]

Figure 1-7: Quad Flat Package [17]

1.4.2 Chip Carriers

Chip carriers are another surface mount technology component that is square with connections one all four sides. Chip carriers can be either leaded with a J shape lead or leadless made of either plastic or ceramic. The J-shaped lead offers special benefits over the gull-shaped leads used by other THMT components. The J-shaped, shown below in figure 1.8, leads also offer improved mechanical strength, with the ability to expand and contract during temperature cycling. These components are commonly used in medium to high density devices. For the leaded chip carriers, lead count can range from 20 to 84 based on connection needs. Chip carriers offer many advantages in electrical and thermal performance with high heat dispersion applications. Figure 1.9 shows a J-shaped leaded chip carrier. As is shown, the chip has leads around all four sides of the component with the ability to add a chip to the center. [16, 18, 19]

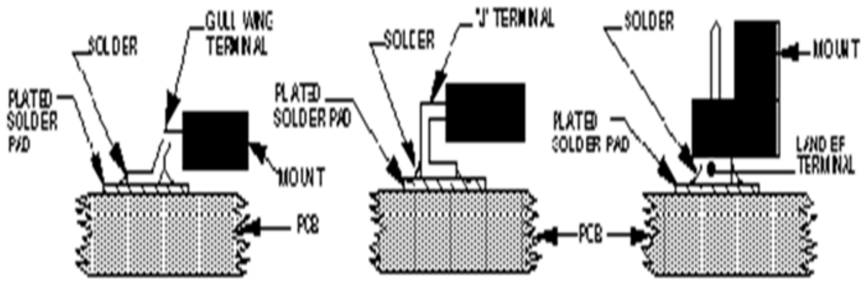


Figure 1-8: Examples of Gull Wing and J Wing Leads [19]

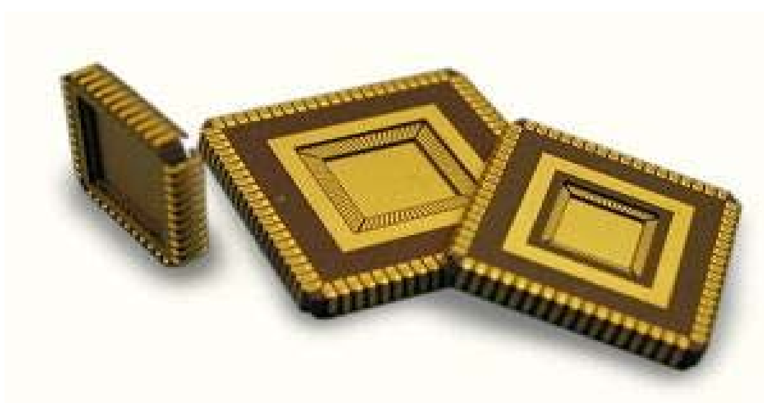


Figure 1-9: Chip Carriers with J Wing Leads [18]

1.4.3 Ball Grid Array

Ball grid array packages were designed to overcome the disadvantages of the packages presented earlier. The main function is to remove the leads of the components but have the same level of connectivity. The advantages of the ball grid array package include:

- Efficient use of space on the PCB, allowing components to be printed onto both sides of the PCB,
- A shorter path between the die and the PCB offers improvements in both thermal and electrical performance,
- Improvements in manufacturing yields with better levels of solderability,
- Reduced package size with improved power, which is extremely important with the development of smaller technologies. [20]

These advantages have made ball grid array components very popular throughout the industry and has become the industry standard. Disadvantages do exist for these components when compared with the THMT components. Comparatively, the mechanical strength is much less for ball grid array components than the THMT because the solder joints are subjected to the stresses without the support of leads. Ball grid array components are subjected to greater amounts of mechanical stresses during temperature cycling due to thermal expansion. [16, 20] Another main disadvantage of ball grid array components is the ability to inspect the solder balls and connections optically. X-ray machines are required to inspect the solder joints and ensure no manufacturing defects. Another disadvantage of ball grid array packages is the ability to rework the package if a fault is found. Specialized equipment is required to remove the faulty package from the PCB without damaging any of the other packages. To remove a ball grid array package from a PCB, the component must be heated to the temperature designated to melt the solder. Once the component has been heated to the correct temperature, the package is then lifted from the PCB using a vacuum device. This process can cause damage to the package as well as the surrounding packages if not performed correctly, so precision and accuracy are very important.

Many types of ball grid array packages exist in industry today, including Super Ball Grid Array (SBGA), Plastic Ball Grid Array (PBGA), Ceramic Ball Grid Array (CBGA), etc. The first ball grid array developed for mass production was the PBGA. PBGA components can range between 7 to 50 mm in size and can contain between 196 to 615 solder balls. [16]

Figure 1.10, below, presents a side view of a commonly constructed ball grid array package. As is shown, the solder balls are attached to the bottom of the component around the outer perimeter. From the side view, the issues encountered with inspection can be seen, as the only joint visible is the joint on the perimeter of the package. The solder joints on the interior are not visible.

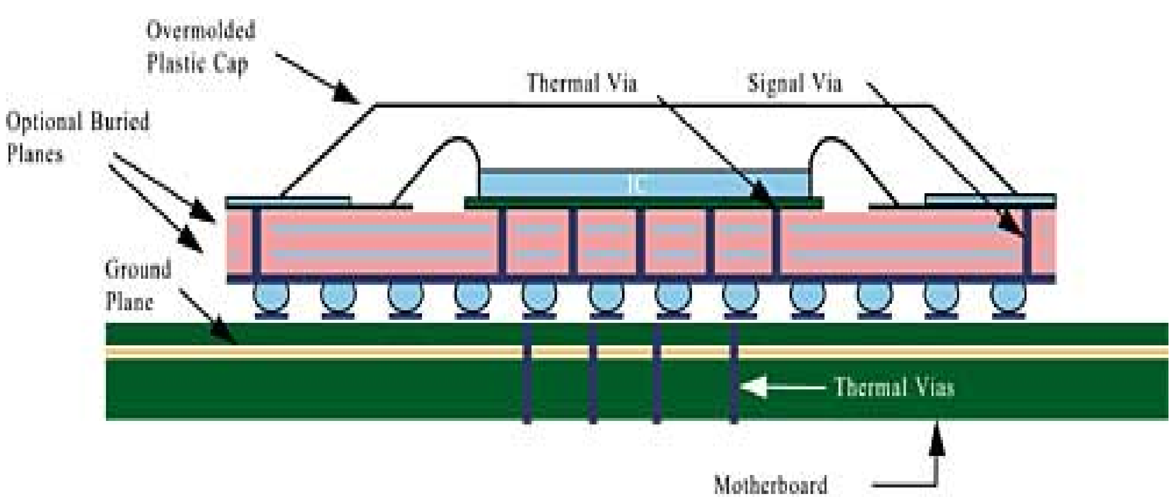


Figure 1-10: Typical Construction of BGA Component [21]

1.5 Printed Circuit Boards: PCB Assembly

Printed Circuit Boards (PCB) allow electrical interconnects of various packages using conductive traces or pads etched into the board. The mechanical characteristics of the PCB are determined by the thickness of the board, the thickness of each layer, as well as the makeup of each layer. Many characteristics must be considered when choosing a substrate material, including: Thermal, Electrical, Chemical, and Mechanical properties. Each property has multiple factors which will affect the overall efficiency of the PCB.

Thermal properties, generally measured in Celsius, deal with the temperature changes the PCB are subjected to throughout the manufacturing process and product life. During the manufacturing process, the glass transition and decomposition temperature are of upmost importance. The glass transition temperature is defined as the temperature range in which the PCB substrate transition from a stiff, glass epoxy to a softened state as the PCB is heated and vice versa as it is cooled. The decomposition temperature range is important to know for each PCB to ensure decomposition of the material does not occur. Another main factor of thermal properties when choosing a substrate material is the Coefficient of Thermal Expansion (CTE). Thermal expansion is defined as, “An increase in linear dimensions of a solid or in volume of a fluid because of rise in temperature.” Each material will have a separate CTE measurement. When the CTE of two materials are not closely matched, internal stresses are placed on the board and package causing solder cracks and component failure. The measurement of CTE occurs over a temperature range, so the part per million must be combined with a unit for temperature, commonly ppm/C. The measurement will differ greatly when the temperature is above and below the glass transition temperature (Tg). [22, 23]

Electrical properties deal with the interconnections throughout the PCB. To ensure optimal electrical performance, the dielectric constant must be considered. The dielectric constant is defined as, “A quantity measuring the ability of a substance to store electrical energy in an electric field.” The frequency of usage will lower the dielectric constant. For high frequency usage, a material must be chosen that does not exhibit a high change in the dielectric constant. The electrical strength is also important when choosing the substrate material. Electrical strength is determined by subjecting the PCB material to short high voltage pulses at standard AC power frequencies. The PCB must be able to withstand and resist electrical breakdown throughout the life of the product.

The chemical properties of the PCB deal with the material’s resistance to flammability, moisture and other chemical absorption. Moisture and chemical absorption affects the thermal and electrical properties of the material. Absorption is measured in percentages, with most materials having absorption values in the range of 0.01% to 0.20%. A Standard for Safety of Flammability of Plastic Materials for Parts in Devices and Appliances testing, UL94, has been developed to ensure materials adhere to a list of requirements including:

- The specimens may not burn with flaming combustion for more than 10 seconds after either application of the test flame

- The total flaming combustion time may not exceed 50 seconds for the 10 flame applications for each set of 5 specimens.
- The specimens may not burn with flaming or glowing combustion up to the holding clamp.
- The specimens may not drip flaming particles that ignite the dry absorbent surgical cotton located 300 mm below the test specimen.
- The specimens may not have glowing combustion that persists for more than 30 seconds after the second removal of the test flame. [24]

The mechanical properties of the PCB deal with the peel and flex strength as well as the density of the substrate. The peel strength defines the strength between the copper trace and the dielectric material. The stress/strain properties are very important because the PCB must be able to withstand mechanical stresses without fracturing. [23] All factors presented above must be considered when choosing a PCB material.

1.6 Solder Mask

Once the PCB material has been chosen and the substrate has been manufactured, solder mask is applied. Solder mask is a thin layer of polymer applied to the copper traces of the PCB to protect from oxidization and prevent faults in the soldering process. The solder mask also allows a higher level of electrical insulation, which allows higher voltage traces to be located closer together on the PCB without shorting. When the solder mask is applied to the PCB, the copper traces can be defined by leaving the area exposed. For non-solder mask defined (NSMD) printing, a space is left between the copper traces and the solder mask, which provides lower stress to the solder pad, leading to improved mechanical performance. [25] Figure 1.11 below presents both a solder mask and non-solder mask defined components.

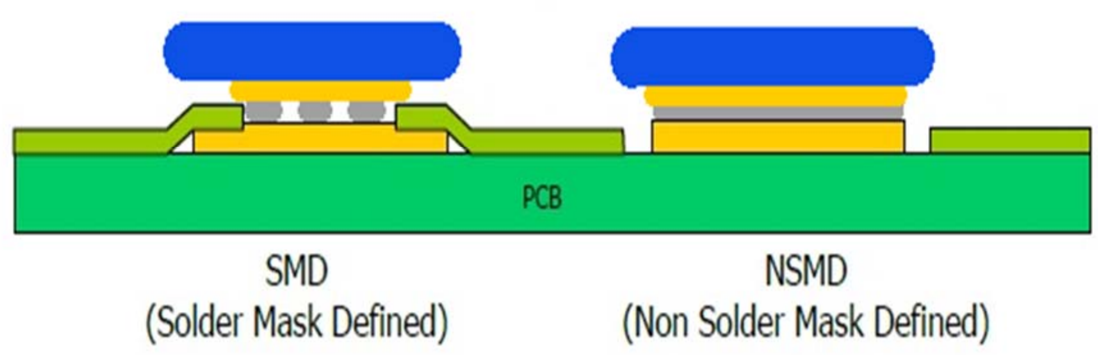


Figure 1-11: SMD and NSMD Components [25]

1.7 PCB Surface Finishes

Surface finishing is used to protect the exposed copper circuitry of the PCB and provide a surface suitable for soldering components. Multiple factors must be considered when attempting to choose the correct surface finish for a specific manufacturing process, such as cost, lead/lead-free, shelf life, thermal resistance, component packaging, volume and throughput, and many more. Six main types of surface finishes are used in industry including:

- Hot air leveling (HASL),
- Organic Solderability Preservative (OSP),
- Immersion silver (ImAg),
- Immersion Tin (ImSn),
- Immersion Gold (ENIG),
- Nickel palladium (ENEPIG) [26]

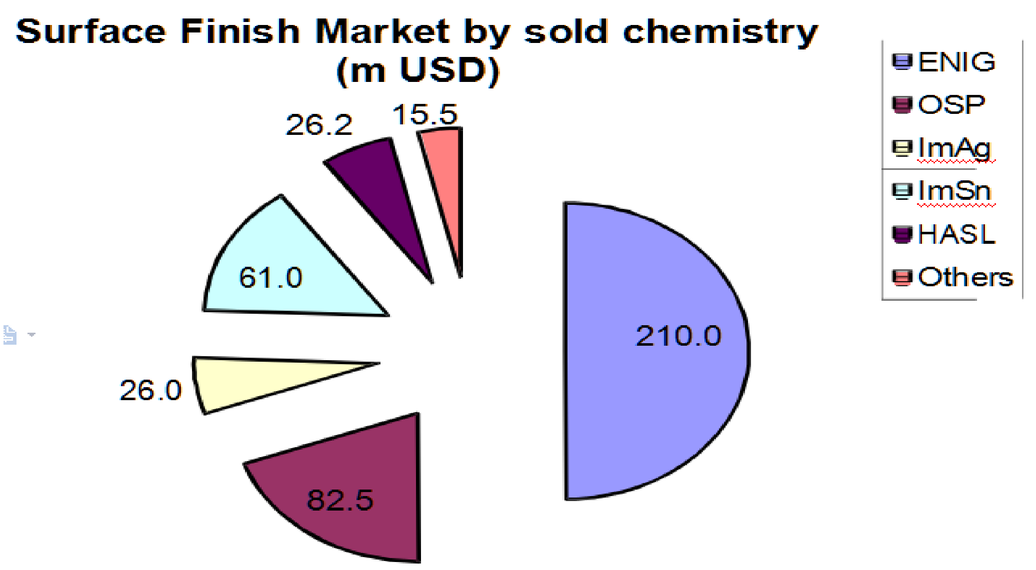


Figure 1-12: Surface Finish Market Sold by Chemistry (USD) [27]

Table 1: Surface Finishes

Surface Finish	RoHS Compliant	Flat Surface	Solderability	Shelf Life	Cost	Popularity
HASL SnPb	No	No	Best	>1 Year	Low	High
HASL Lead-Free	Yes	No	Good	>1 Year	Low	Medium
OSP	Yes	Yes	Good	6-11 months	Low	Low
Immersion Silver	Yes	Yes	Better	6-11 months	Medium	Medium
Immersion Tin	Yes	Yes	Good	6 months	Medium	Medium
ENIG	Yes	Yes	Good	>1 Year	High	High
ENIPIG	Yes	Yes	Good	>1 Year	Medium	High

1.7.1 Hot Air Leveling (HASL)

Hot air leveling is a commonly used surface finish where the PCB is submerged in leaded or lead-free, molten solder to cover exposed copper surfaces. The board is then removed from the solder, and any remaining solder is blown from the board using hot air knifes. HASL possesses many advantages over other surface finishes including low cost, high solder wettability, and long storage life. A main disadvantage is that the surface of the PCB can be very rigid after the HASL process making it difficult to solder SMT components to the PCB. Also, the PCB must be able to withstand high levels of heat, limiting the use of some types of PCBs. [26, 27]

1.7.2 Organic Solderability Preservative (OSP)

Organic Solderability Preservative (OSP) is an organic, water-based surface finish. OSP is also known as the anti-tarnish finish. Boards are first pre-cleaned and rinsed, then anti-tarnish is applied, then the board is rinsed again and dried. The main advantage of an OSP finish is the cost compared to all other counterparts. OSP boards also have a flat, planar surface more suitable for SMT components. Some issues do occur with OSP finishes, such as inspection can be very difficult since the finish is transparent and colorless. Other disadvantages of OSP are that the boards are very fragile to the touch, and the shelf life is limited, and an excessive amount of flux is needed during component placement. [26, 27]

1.7.3 Immersion Silver

As lead-free manufacturing continues to gain prominence, immersion silver (ImAg) has become a popular alternative with more PCBs using immersion silver than any other. Immersion

Silver offers many benefits as opposed to other lead-free surface finish options. Compared to other lead-free surface finishes, immersion silver is more available and cost efficient. With the use of a metallic surface finish and a flat, planar surface, immersion silver offers good solderability with strong electrical interconnects. Although, immersion silver is susceptible to high temperatures and fragile to the touch, and must be stored carefully to ensure sulfur does not react with the board and create silver sulfide, which can damage the PCB. Immersion silver is also known to cause “Champagne” voids. “Champagne” voids are small voids or bubbles that form along the intermetallic layer of the finish caused by outgassing during the plating process. To reduce and avoid the “champagne” voids, a specific, low reflow profile is required to prevent tarnishing of the silver. [26, 27]

1.7.4 Immersion Tin

Tin has become one of the most widely used material in the search for a lead-free alternative, Immersion Tin (ImSn) has become very popular. The process in manufacturing an immersion tin PCB is to first clean the board then it is micro etched, similar to the OSP process, and pre-dipped into a tin chemical solution to prepare the copper and ensure full adhesion when the tin is applied. The boards are then soaked in molten tin, and only the exposed copper pads are coated with tin. The board is then dried to ensure high metal quality and all moisture has been cleared from the board. A major disadvantage of using purely tin for manufacturing is the possible occurrence of tin whiskers. Tin whiskers are electrically conductive, tin structures that grow away from the surface of the board. Numerous electronic system failures have been attributed to shorting caused by tin whiskers that bridge closely-spaced packages. Immersion tin can also dissolve the solder mask which may result in oxidization in the board. [26, 27]

1.7.5 Immersion Gold (ENIG)

Gold is considered an excellent choice as a surface finish since it dissolves readily into the solder and does not easily tarnish or oxidize. The process for manufacturing a board with ENIG finish is to first apply a layer of nickel and then add a layer of gold. The reason for the first layer of nickel is copper diffuses into gold causing the copper to rise to the surface, which would leave the copper pads exposed. The gold protects the nickel from oxidization. ENIG offers many benefits over the surface finish counterparts. Some of these advantages include low contact resistance, higher than average shelf life, and excellent wetting. A major disadvantage of the use of higher gold content in the surface finish is reliability may be reduced due to the formation of gold-tin intermetallics, and the high cost of using gold. [26, 27]

1.7.6 Electroless Nickel, Immersion Palladium, Immersion Gold (ENIPIG)

Nickel Palladium (ENIPIG) has been available since the 1990's, but due to the high cost of palladium, did not gain in popularity. The cost of palladium has reduced greatly, which has increased the popularity of ENIPIG. A disadvantage ENIPIG presents is reliability may be reduced with a higher level of gold thickness. [26, 27]

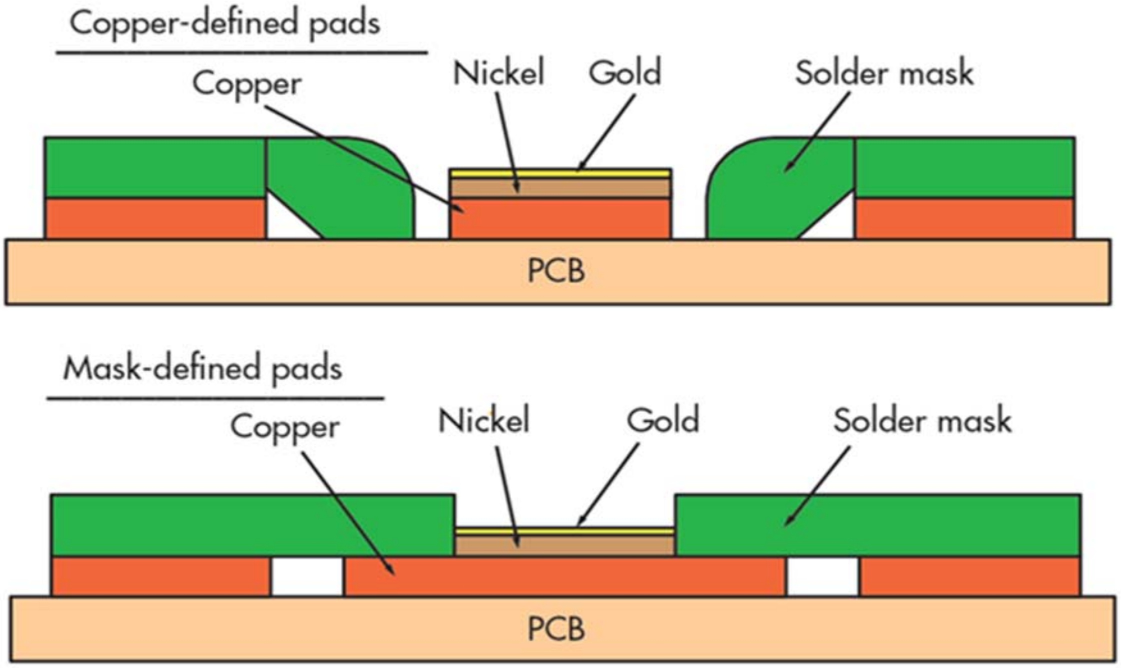


Figure 1-13: PCB Surface Finishes [28]

1.8 Electronics Industry Market Size

The electronics industry is expected to see continued growth. Many changes can and will be made in the field of electronics, including: automobiles, medical equipment, robotics, and common household electronic equipment. A major sector of electronics that is expected to see exponential growth over the next decade is consumer electronics. Consumer electronics include the electronic equipment purchased for common, everyday use, such as smart phones or televisions. According to Nasdaq, the global consumer electronic market is predicted to surpass $1,500 billion by 2024. Expectations for the future of consumer electronics include more interactive, connected, and energy efficient products. [29]

The top three countries, based on market size and revenue in the electronic industry include China, United States, and Japan respectively. Over the past decade, the revenue generated from consumer electronics in the United States has risen from $169.79 billion in 2009 to $228 billion in 2017, which is a 34 percent increase [30]. The global market has seen electronics start to follow four trends: environmentally friendly, smaller technologies, more internet connection, and further technological opportunity. [29]

1.9 Soldering

Packages must be soldered to the PCB to have electrical interconnects. Soldering is a process in which two or more items are joined together by melting and putting a filler metal, solder, into the joint. There are many types of solder available today that are both lead-based and lead-free. Solder can be used in a variety of ways to attach the components to the PCB. The solder can be printed directly to the board using a stencil, or the component can have solder balls attach to its underside.

When inspecting the solder, it is very important to inspect the shape of the solder joint after reflowing. As figure 1.14 shows, the joint can take many shapes after reflowing. It is important for the joint to be connected directly to the board with the joint concaving in to the board and pin. Many errors can occur during reflow, including:

- The joint can concave but lifted from the PCB
- The Joint could not reach liquidus temperature or overheat during reflow
- Or the joint may have received too much solder which can cause multiple errors.

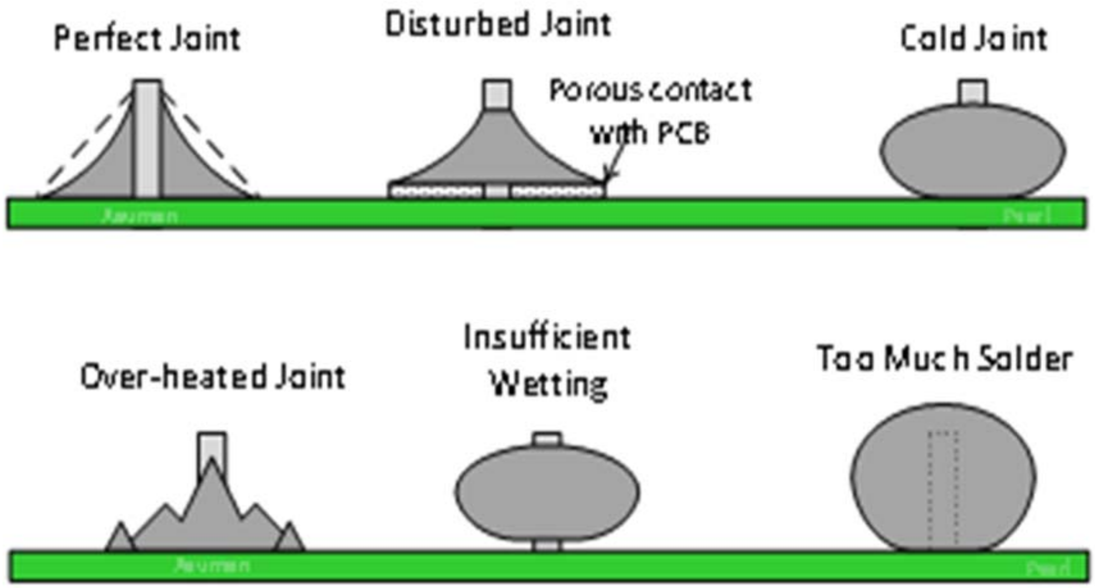


Figure 1-14: Wetting of Solder Joints After Reflow

Solder can be applied to PCBs in a variety of ways. Wave soldering and reflow soldering are two of the most popular methods. Reflow soldering is the most used method in the electronics industry for use in surface mount technology, and wave soldering is more common with through hole mount technology. Wave soldering is used to solder a high number of components in a short amount of time. Components are placed onto the boards. Then the boards are run through a machine where molten solder is pumped like a wave like motion to submerge the board and ultimately solder the components to the board. Boards are then cooled to ensure the components stay in place. In reflow, the solder is made into a paste and placed on the board via pads through use of a stencil. The board then enters a pick and place machine, where components are placed with precision. Once all components have been added, the boards are run through a reflow oven. In the oven, the boards are subjected to temperature to melt the solder and then harden once the connection has been made. The reflow cycle depends on the solder paste used, and each will vary in temperature and time needed. [30]

Many faults may occur after the soldering process that can result in a failure in the entire system. The faults include solder bridging, tombstoning, over excessive solder, solder skips, and pin holes. Solder bridging commonly occurs with fine pitched packages and is a function of solder unintentionally connecting two separate solder joints. This can cause the entire components to short. Tombstoning occur when the solder only reaches liquidus on one side of the component causing the component to lift off the board. Over excessive solder can cause inaccurate orientation of the components. Resulting in difficulties with components possessing fine pitch leads not making the correct connections. Solder skips is the exact opposite of the over excessive solder fault. Solder skips occur when no solder attaches to the pad causing the component to have no connectivity. Pin holes are holes in the solder joint. They occur when moisture is on the PCB during reflow. Other faults are possible, but the faults presented here are the most common. Companies are attempting to develop solders that will help reduce the number of faults occurring. The choice of solder is very important to achieve the desired outcome. [31, 32]

1.10 Tin-Lead (SnPb) Eutectic Solder

From the beginning of the electronics industry, tin-lead (SnPb) eutectic solder had been the industry standard. SnPb eutectic solder is comprised of 63% tin and 37% lead with a liquidus temperature equivalent to 183 degrees Celsius. The characteristics of the SnPb solder has many benefits over its counterparts such as the cost, availability, ease of use, and its thermal and mechanical properties. [33] Figure 1.15, below, shows the phase diagram of the SnPb eutectic solder. The first region is when the solder enters the liquidus phase. A phase transition then occurs in the solder while the solder is cooled, and it enters the solidus temperature. The solder joint enters a pasty range during this phase while the heat dissipates and ultimately solidifies as it enters the final cooling and cleaning stage.

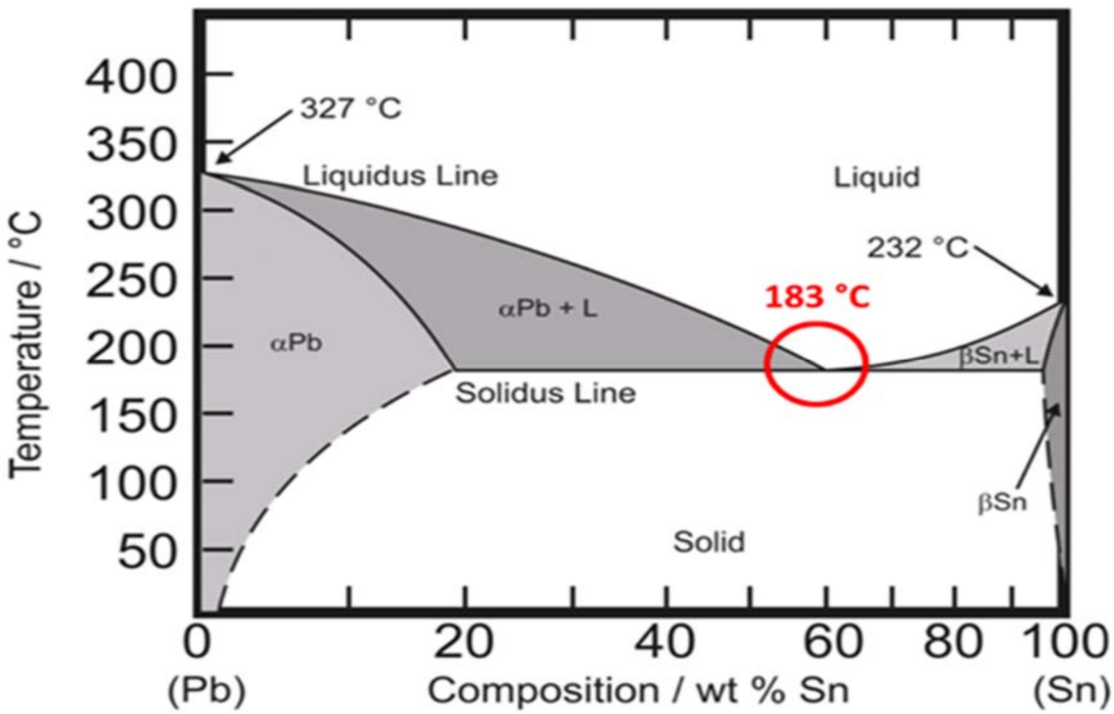


Figure 1-15: Phase Diagram of SnPb Eutectic Solder [34]

Carol Handwerker, Chief of the Metallurgy Division at the National Institute of Standards and Technology, states, "The whole electronics infrastructure was designed around the melting point and physical properties of lead." [35] The usage of lead in the solder became a worldwide concern based on the know harmful effects of lead to humans. Legislation to ban lead, as well as a few other materials, was implemented throughout the European Union (EU) by

Restriction of Hazardous Substances (RoHS) directives in Electrical and Electronic Equipment (EEE). China developed the "Management Methods for Prevention and Control of Pollution from Production of Electronic and Information Products" and in the United States, California legislated electronic waste recycling but not a total ban on lead in electronics. With all these standards and regulations being passed throughout the world, the electronics and other industries began the search for a Pb-free alloy that can compare to, or even surpass, the benefits of the SnPb solder. [36]

Many types of materials, such as tin, bismuth, zinc, silver, nickel, and gold, have been used to try and replace SnPb and help improve the reliability of the solder joints. Each material has its own advantages based on the specific requirements of the system. Many of the materials have been combined into solder alloys to help further the advantage and overcome the disadvantage of the materials. Some of the main factors to consider when choosing a material include:

- Corrosion Resistance
- Electric Conductivity
- Thermal Conductivity
- Solderability
- Wear Resistance
- Shelf Life
- Cost. [37]

The solder alloys may be doped with multiple materials to overcome the disadvantages of the materials alone. Possible dopant materials are presented in the table below. Table 2 shows how the materials rank for each factor from poor to excellent.

Table 2: Solder Dopant Materials

	Corrosion Resistance	Electric Conductivity	Thermal Conductivity	Solderability	Wear Resistance	Shelf Life
Tin	VG	VG	VG	E	P	G
Bismuth	G	VG	VG	G	G	G
Zinc	G	G	G	G	G	G
Silver	F	E	E	G	G	F
Nickel	G	F	F	F	G	G
Gold	E	E	E	VG	G	E

P = Poor, F = Fair, G = Good, VG = Very Good, E = Excellent

1.11 Near Eutectic SAC Solder

The most popular leadfree solder used throughout industry is a mixture of tin, silver, and copper, known as SAC solder, which possesses eutectic properties similar to SnPb. SAC solders have shown improved thermal fatigue with stronger solder joints as compared to the leaded solder. Many variations of SAC solders are available today with different material compositions. The most popular of these variations are the SAC105 and SAC305 solders. SAC105 is comprised of 98.5% tin, 1.0% silver, and 0.5% copper, and SAC305 is comprised of 96.5% tin, 3.0% silver, and 0.5% copper. Each has its own special properties and uses. SAC105 is popular due to its reduced cost compared to other SAC options. Although SAC305 does possess stronger reliability in most applications, SAC105 possesses higher reliability in drop testing. SAC305 solder is used most commonly in products with a thermal cycle requirement. [38]

SAC solders do have some disadvantages, most prominently during the manufacturing process. SAC solders have a melting temperature between 217°-220° Celsius, which is around 40° more than SnPb, shown in figure 1.16. The PCB and components are subjected to higher temperatures. With more materials in the alloy, the undesirable possibility of intermetallics forming increase. The effects of doping the alloy with additional materials is still being studied, with positive results. [38]

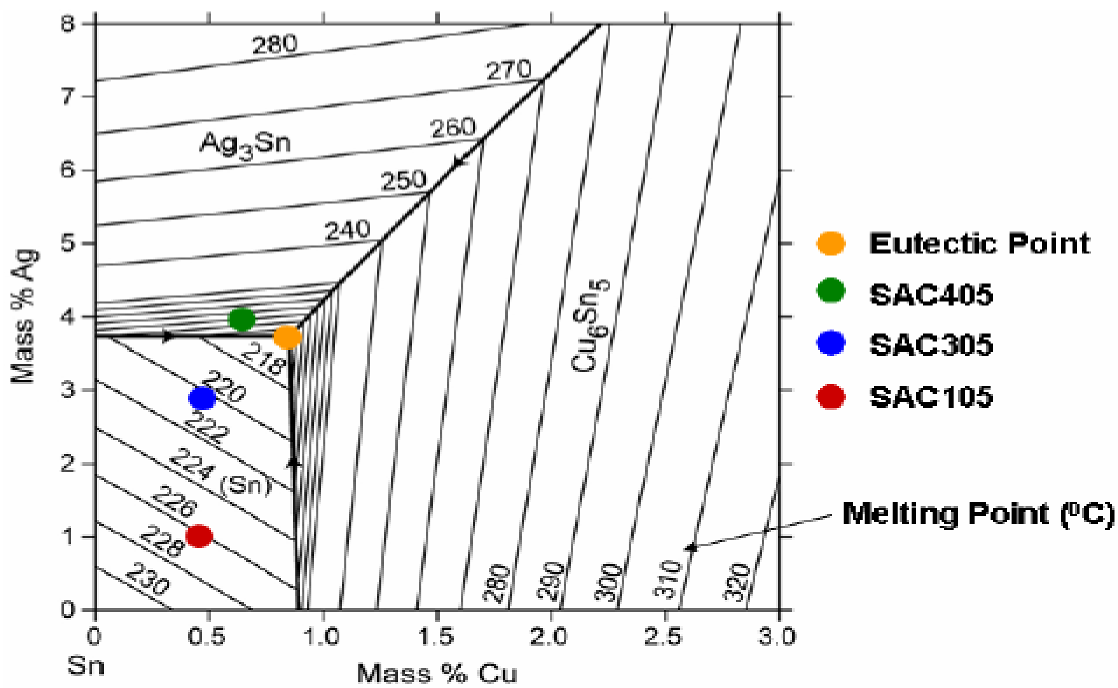


Figure 1-16: SAC Solders Phase Diagram [39]

Chapter 2
Data Analysis Techniques

2.1 Data Analytics

The Business Dictionary defines data analysis as, "The process of evaluating data using analytical and logical reasoning to examine each component of the data provided." [40] Data can be placed into two categories, either qualitative or quantitative. Qualitative data is data of quality and cannot be measured, (i.e. the color of the board). Quantitative data is data with a certain quantity that can be measured, (i.e. failure point of a component), and is the data to be analyzed throughout this research. With the tremendous amount of new data, the difficulty has been in learning how to organize, analyze and interpret these vast sources of information. To combat these difficulties, many data analytic techniques exist, which can help with complex data sets. The main data analysis technique used throughout the electronics industry is reliability analysis. The demand for high reliability in electronic products and the manufacturing process continues to grow.

With the large amounts of complex data and high number of factors obtained through reliability testing, it is difficult to understand how each factor effects the systems. It is important to understand the types of data effecting the system. This data can be divided into two groups, life and performance. Life data, or survival data, involves the product lifetime of a system while used in differing applications. Performance data involves how the system performs during use.

The analysis of these two types of data will differ depending on the type of data gained. [41] In this study, Survival Data is used.

2.2 Survival Analysis

Survival analysis is a set of statistical methods for analyzing the occurrence of events over time based on the effect of certain input variables. Two properties exist in the survival data, which invalidates most data analytic techniques. The properties are skewness and censoring. Survival data is not normally distributed and can be skewed upward. The data is also censored because upon completion of a test, some components will have not failed. Regression analysis was chosen to analyze the survival data.

- Time to death in biological systems.
- Failure time in mechanical systems.
- Time to recovery for an injury at the workplace.

Two important functions exist in survival analysis, the survival and hazard function. The survival function gives the probability an object will survive a certain event. The probability of the survival function in denoted:

$$S(t) = Pr(T > t)$$

The probability of an object surviving an event is difficult to observe. Therefore, an estimation of the probabilities is used. The Kaplan-Meier estimator is used to estimate the obtained survival data. The function is denoted:

$$S^\wedge(t) = \prod ti \leq \frac{tni - di}{ni}$$

2.3 Reliability Analysis

Reliability analysis is commonly used during accelerated life testing to obtain the life distribution and time-to-failure of an electronic package. Reliability is referred to as the ability to produce consistent results when measurements are repeated a defined number of times. The analysis is performed by determining the association between the scores obtained from the different measurements taken. The analysis can be performed on a singular component or on the entire system. [42] Four common types of approaches used in reliability analysis include:

- Test-Retest
- Internal Consistency Reliability
- Split Half Reliability
- Inter Rater Reliability

Test-retest analysis is the approach to reliability analysis where identical tests are run at separate intervals with equivalent test conditions to test the degree of reliability. To determine the degree of reliability, a correlation coefficient must be defined. As the correlation coefficient rises, the level of reliability rises and vice versa. Test-retest does have some limitations when performing the tests. The major limitation the interval of time between the running of the two tests. To ensure the correlation coefficient is accurately measured, the test must be performed concurrently with one another with equivalent variables. The second approach to reliability analysis, Internal Consistency reliability, is used when the data being measured is summed to form a total score. The major focus in performing this approach is to ensure the summed score are consistent across all sets of data. The third approach, Split Half Reliability, is a form of Internal consistency reliability. The way split half reliability differs is the summed scored are divided in half. When the halved scores are highly correlated, the reliability will have a high internal consistency. The limitation in this analysis is the reliability will differ based on the number of variable and how they are split. The final type of reliability analysis is inter-rater reliability. This analysis is used to establish a consensus when reliability cannot be found by other means.

2.4 Finite Element Analysis

Finite Element Analysis (FEA) is another commonly used technique throughout industry to predict how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects. Finite Element Method (FEM) is the numerical method in analyzing FEA by using partial differential equations. FEA can assist developers by allowing experiments and components to be optimized without the need of an excess number of runs or components. Finite element analysis is performed using partial differential equations. Differential equations can be used to describe the phenomena that occurs when running a test or using a component, but it can only supply an approximation. The partial differential equations can be defined as either elliptic, hyperbolic, or parabolic, and conditions of the test must be defined. SimScale is a commonly used component in industry and allows the user to predict the behavior of an experiment or component through virtual testing. [43]

2.5 Correlation Analysis

Correlation is one of the most widely used statistical methods. Data correlation is a statistical technique used to compare two or more quantitative factors to determine how the factors relate. With the tremendous number of factors present in test throughout industry, multiple correlation coefficient analysis, R, must be performed. This will define how strongly each separate variable correlates with one another. Data correlation can assist in multiple ways including, [44, 45] predicting one quantity from another, indicating the presence of a causal relationship, and can be used as a basic quantity and foundation for many other modeling techniques. Correlation can have a value:

- 1 is a perfect positive correlation
- 0 is no correlation (the values don't fit together at all)
- -1 is a perfect negative correlation

Figure 2.1, below, gives a graphical representation of the values a correlation may take between -1 and 1. The data with the correlation $r = 0$ is extremely scattered with no clear trend. As the value approaches the extremes, the data begins to gather till a clear trend can be seen.

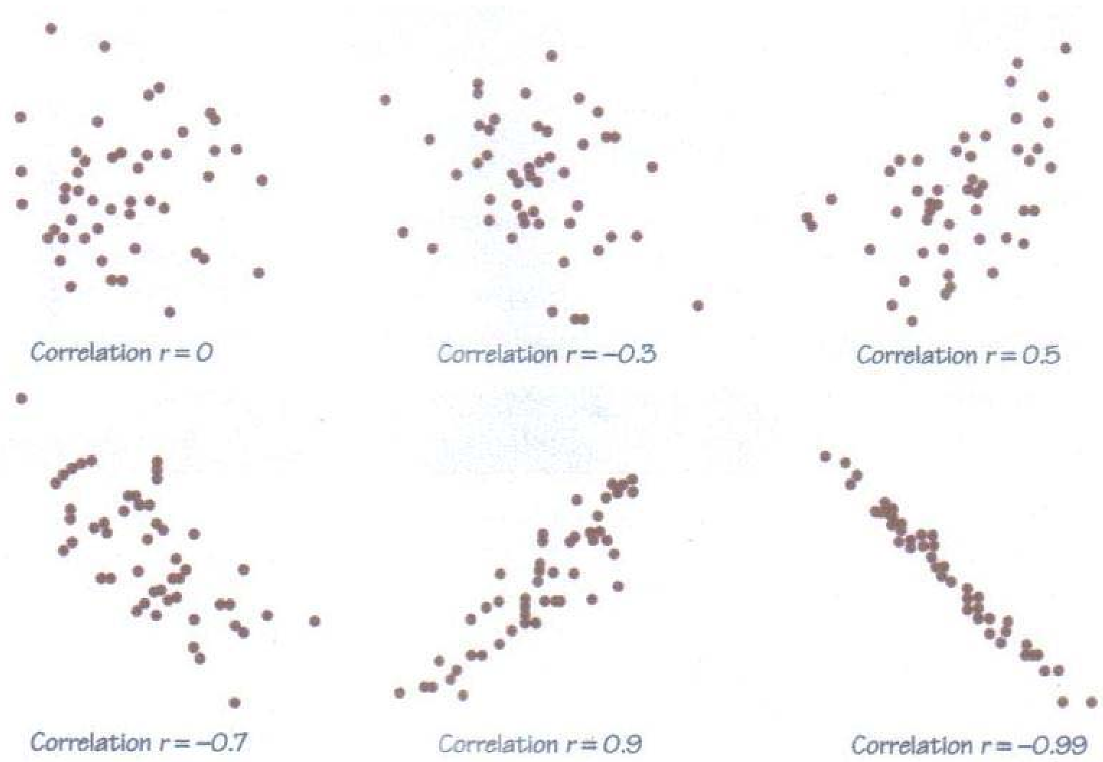


Figure 2-1: Correlation r Values

The data can be distributed in multiple ways, making it difficult to choose a singular distribution for the time-to-failure data. The figure above shows how the correlation in the data presents a regression line of the data. The image on the left shows data that is random with no seen trend. The image in the middle and right present data that is distributed negatively and positively, respectively. Weibull distribution is used most based on the trends obtained but does not fit the data distribution perfectly. Many distributions have seen a wave-like pattern, which is a combination of multiple distributions.

2.6 Regression Analysis

A powerful tool in understanding the relationship between all variables in a test is the statistical modeling process known as regression analysis. Regression analysis is a method of predicting a trend in a data set by fitting the set points to a graph. The analysis can determine which variable effect the system and to what level. Multiple regression analysis is used when attempting to determine the relationship of multiple sets of data. Regression analysis can be used with a mix of dependent or independent data to help understand how changes in certain variables will affect all other variables in the system.

Data sets are not commonly normally distributed with many differences between them, such as skewness or censoring. Multiple regression analysis tools were developed to handle the differences between the data sets. five most common types of regression are used in regression analysis, including:

- Linear Regression
- Logistic Regression
- Polynomial Regression
- Stepwise Regression
- Ridge Regression[47]

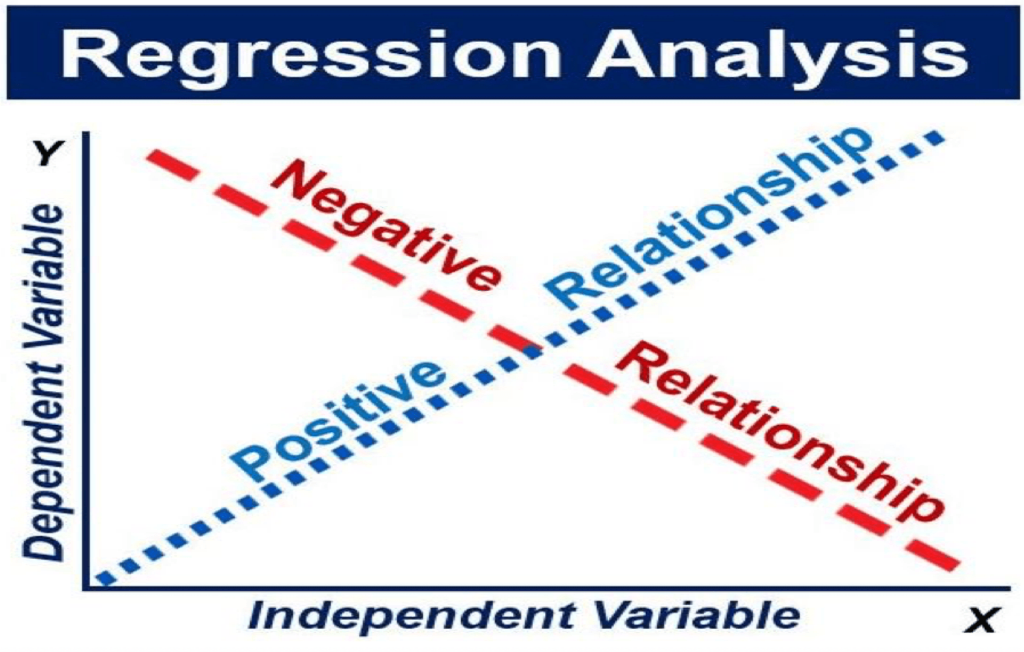


Figure 2-2: Relationships in Regression Analysis

Linear and the advanced forms of linear regression are commonly used throughout industry to analyze data. Linear regression is a type of predictive analysis used to examine which predictor variable predicts a dependent variable, as well as, which of those variables have the strongest impact. The goal of linear regression is to model the relationship between variables. A valuable numerical measure of association between two variables in regression analysis is the correlation coefficient, which is a value between -1 and 1 indicating the strength in correlation of the observed data for the two variables. Linear regression is defined by the function:

$$Y = a + bX$$

When developing a linear regression model, assumptions are drawn, which include:

- The relationship between the dependent variable Y and the independent variable X is linear in the slope and intercept parameters a and b.
- The independent variable X is not random.
- The expected value of the error term "ε" is 0.
- The variance of the error term is constant for all observations.
- The error term ε is uncorrelated across observations
- The distribution of the error terms is normal

When dealing with multiple independent variables, the function used to show the correlation between them is defined by the function:

$$Y = a + b1 * X1 + b2 * X2 + \ldots + bp * Xp$$

Although, with large data sets, the data can be unpredictable and does not fully fit the regression line. The points which deviate from the regression line are termed as residual values. Data of this magnitude does not fit one clear distribution. Outliers, or a point which lies far from the line, may also exist in the data, which would indicate a poor fitting regression. Due to the unpredictability of failure data, simple linear regression cannot be used. The industry standard for the distribution and visualization of failure data has been the Weibull distribution. Using the techniques discussed earlier, Weibull can show trends in the data and helps to predict how a product will perform. [47] Logistic regression can also be used in the prediction of how a product will perform over a set duration of time under the constraint of certain variables.

2.7 Logistic Regression Analysis

Failure data does not fit linear analysis techniques because it is unpredictable. Therefore, logistic regression was chosen for analysis. Logistic regression is a classification algorithm used to assign observations to a discrete set of classes, such as determining whether a component has survived or failed, (1) or (0). Logistic regression transforms its output using the logistic sigmoid function to return a probability value which can then be mapped to two or more discrete classes. The logistic transformation, used to transform the result interval to be between 0 and 1, is given by the function:

$$Y = \ln\left(\frac{Yi}{1 - Yi}\right) = logit\ (Yi) = \beta 0 + \beta 1xi$$

Where the probability of the outcome is defined as:

$$Yi = \frac{exp(\beta 0 + \beta 1xi)}{1 + \exp(\beta 0 + \beta 1xi)}$$

Logistic regression is the statistical technique used to predict the relationship between predictor and predicted variables where the dependent variable is binary. The predictors can be either continuous or categorical. Assumptions for a logistic regression include:

- Binary logistic regression requires the dependent variable to be binary.
- For a binary regression, the factor level 1 of the dependent variable should represent the desired outcome.
- Only the meaningful variables should be included.

- The independent variables should be independent of each other. That is, the model should have little or no multicollinearity.
- The independent variables are linearly related to the log odds.
- Logistic regression requires quite large sample sizes.

Three types of logistic regression exist, including binary, multinomial, and ordinal. Each type offers a varying number of categories with the option of ordering. Binary logistic regression is used when the response variable only consists of two possible outcomes, for example (Survival or Failure). Multinomial logistic regression is used when the response consists of three or more categories without ordering, for example, predicting which major is preferred (Industrial, Electrical, or Mechanical Engineering). Ordinal logistic regression is used when the response consists of three or more categories with ordering, for example, rating of a class (1 to 5).

The sigmoid function is a special case of a logistic function and is used mostly used in classification type problems based on the need to scale the data in some a given specific range with a certain threshold. Sigmoid function allows for the mapping of the predicted values' probabilities by mapping any real value into a value between (0) and (1). Mathematically, the sigmoid function is defined as:

$$f(x) = \frac{1}{1 + e^{-z}}$$

- $f(x)$ = Output between 0 and 1 (probability estimate)
- $z =$ Input to the function (algorithm's prediction e.g. mx + b)

In order to map the discrete values, a threshold value is chosen to classify the data into either class. The threshold value is known as the decision boundary and helps to determine which class the prediction is placed. Once the decision boundary has been established, the prediction function can be constructed. The prediction function is the probability of the observation obtaining a positive value. As the value approaches 1, confidence in the observation is increased. Figure   shows a graphical view of the sigmoid function and the decision bound.

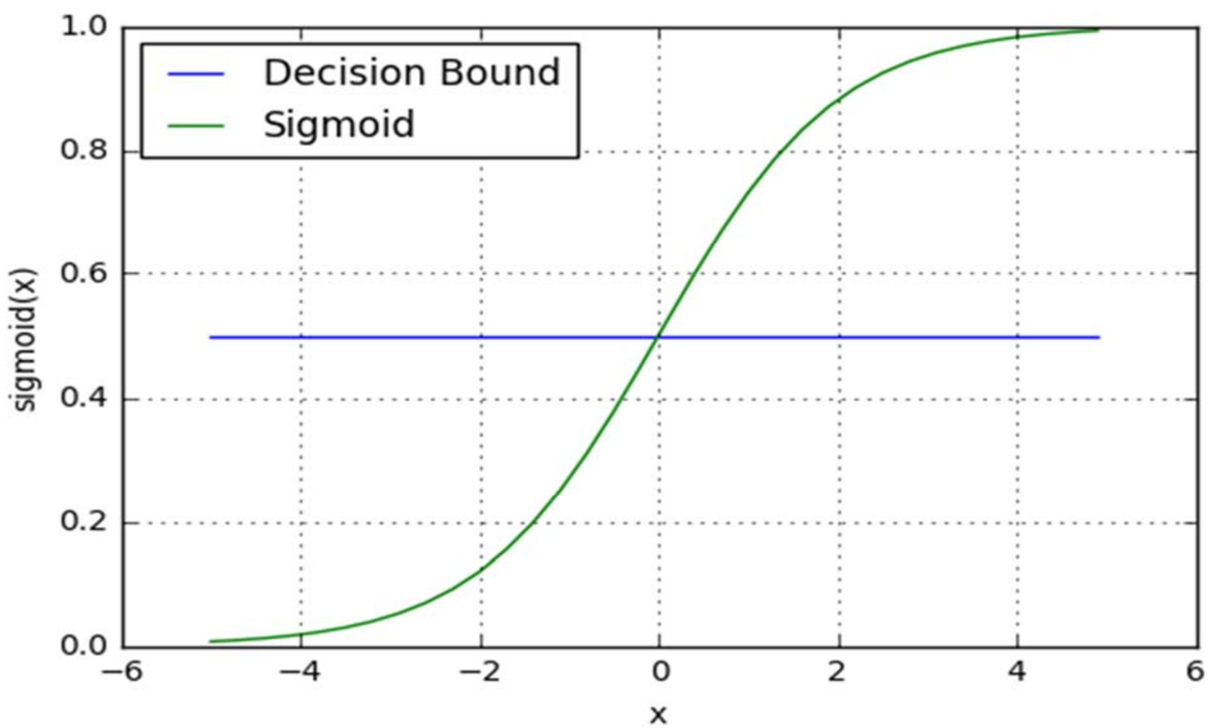


Figure 2-3: Plot of Logistic Regression

2.8 Cox Regression

Cox regression has many similarities to Logistic regression. Proportional Hazards regression analysis, also called Cox regression, builds a predictive model for time-to-event data. Cox regression will give the probability of a component experiencing a failure over an elapsed period of time and can be used for both discrete and continuous analysis. The model produces a survival function that predicts the probability that the event of interest has occurred at a given time for given values of the predictor variables. The result of this analysis will yield an interval of time a component will fail with certain factors affecting it. Cox regression can account for the skewness and censoring of survival data. The probability is given by the function:

$$h_i(t) = \exp(\beta x_i)\, h_0(t)$$

- $h_i(t)$ is the hazard function at time t for the ith individual in the study,
- β is the log of the hazard ratio,
- x_i is the value of the dummy variable X for the ith individual.
- $h_0(t)$ is the baseline hazard function at time t.

The Kaplan-Meier Estimator helps to show how input variables predict the result of an event by plotting the probabilities over an interval of time. Once the estimation is obtained, a logrank or proportional hazard test is used to analyze the statistical difference between the curves. The estimator is denoted:

$$L(\beta) = \frac{\left(\Pi \exp\left(\beta xj\right)\right)}{R_j \exp(\beta xi)}$$

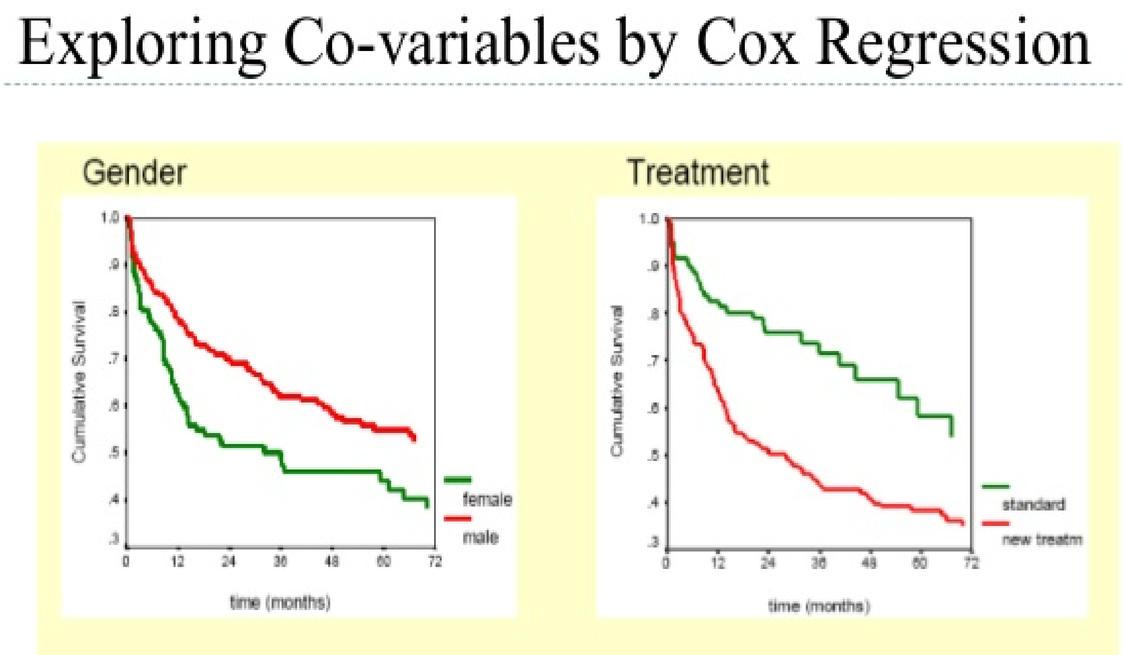


Figure 2-4: Cox Regression Plot Examples

Cox regression differs from logistic regression by how the event is interpreted. Cox regression will tell the time an event will occur, and logistic regression attempts to determine he factors contributing to the event. Cox and logistic regression can both have a predictor variable which is categorical or continuous and an outcome variable which is binary, but Cox regression adds the factor of time. Unlike Cox regression, logistic regression does not permit censoring of the data.

2.9 Data Visualization

Data visualization refers to the placing of data into visual context to further the understanding and determine significance. Patterns, trends, and correlations can be uncovered much easier with data visualization software. The goal of a visualization is to catch the attention of the audience and draw their attention to key insights.

The main platform used in analyzing and visualizing life data has been the Weibull ++ software. Weibull ++ software, a Reliasoft software, is an analysis tool used to obtain the life data of a product and defines a lifetime distribution, commonly measured in terms of cycles or hours. Although the data does not perfectly fit the distribution, the Weibull software is the most widely used software throughout the industry when characterizing a product's expected life. The factors used in the Weibull distribution include:

- β is the shape parameter, also known as the Weibull slope
- η is the scale parameter
- γ is the location parameter [48]

The most commonly used factors of the three are the shape parameter, β, and the scale parameter, η. The shape parameter defines how the distribution is shaped and the location it takes. The scale parameter defines where the bulk of the data lies on the distribution. When the location parameter is not used, we assume the value to be zero. When only the shape parameter and the scale parameter are used, this is known as two-parameter Weibull (used most commonly in industry).

An important factor of the Weibull distribution is the shape parameter, β. The shape parameter defines the slope of the probability line. From this, the life of the system being tested can be determined. A lower value of β will mean a higher variance in the failure times. To have a true understanding of how a solder reacts to a certain test, whether by count or time, researchers aspire to have a distribution with a higher valued β. When this occurs, the distribution of data is more clearly defined, and a true measurement can be taken.

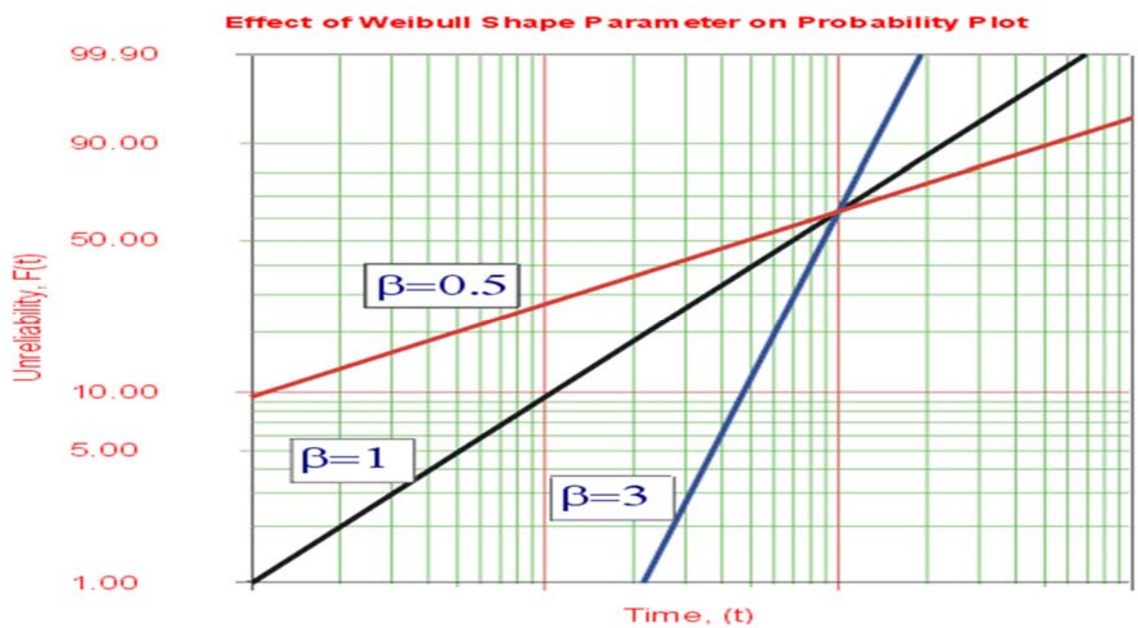


Figure 2-5 Weibull with Varying Shape Parameters **[48]**

The Weibull scale parameter defines how large the distribution is based on the defined data. Assuming the shape parameter is held constant, the distribution will be proportionate to the size of the scale parameter. The scale parameter can be distributed in three separate ways, including:

- If η is increased, while β and γ are kept the same, the distribution gets stretched out to the right and its height decreases, while maintaining its shape and location.
- If η is decreased, while β and γ are kept the same, the distribution gets pushed in towards the left (i.e., towards its beginning or towards 0 or γ), and its height increases.
- η has the same unit as *T*, such as hours, miles, cycles, actuations, etc. [48]

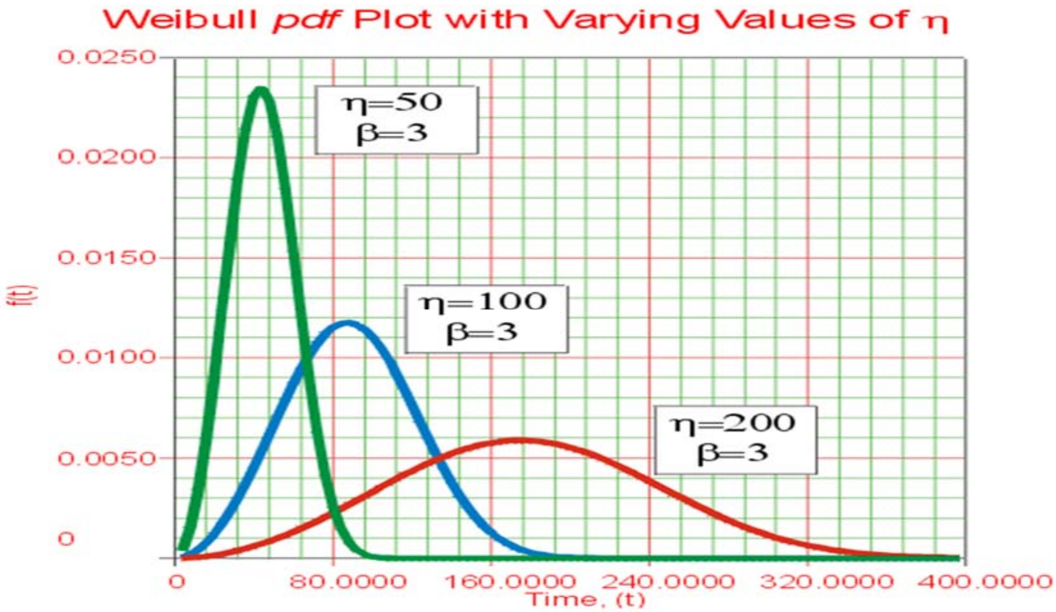


Figure 2-6 Weibull with Varying Scale Parameters **[48]**

The Weibull reliability function is given by:

$$R(T) = e^{\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$$

The Weibull failure rate function is given by:

$$\lambda(T) = \frac{f(T)}{R(T)} = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1}$$

The equation for the median life, or B_{50} life, for the Weibull distribution is given by:

$$\breve{T} = \gamma + \eta\,(\ln 2)^{\frac{1}{\beta}}$$ [48]

2.10 Visualizing Large Data Sets

Visualizations are a key component in understanding large datasets. The goal is to visualize the data focusing on extracting the most prominent information. Many applications are available in the visualization of large data sets, or big data. Datasets are continuing to grow and become more dynamic with a wide variety of dependent and independent factors. Many studies have found, "Data visualization has become a major research challenge involving several issues related to data storage, querying, indexing, visual presentation, interaction, personalization." Visualizations should be built based on certain aspects, including:

- Real-time Interaction
- On-the-fly Processing.
- Visual Scalability
- User Assistance and Personalization [49]

Datasets are commonly domain specific in the choice of visualization. Visualizations are chosen based on the type of dataset being analyzed. The visualization should take full advantage of perceptual cues such as size. positions. color, and depth. It is possible to display immense datasets in a single visualization for ease of navigation using compact glyphs. The visualizations can also be interactive to assist with display clutter in larger datasets by helping to reduce the information shown in the visualization. The choice of technology is also important when developing a visualization. The technology must be able to process multiple data types, allow for the use of various filters, enable real-time interactions, and connect with other software. The correct technology will allow for the dataset to be communicated with precision and accuracy.

When deciding on a visualization, determine the visualization goal and then choose the best chart to achieve that goal. Five communication types are commonly used when deciding which visualization will best fit the data. Visualizations are developed to communicate a story about the data. When a visualization is communicated appropriately, it can help to increase the understanding of complex concepts, strengthen claims, and bring light to certain insights. The Inform goal is to display and single point without requiring an exceptional amount of context. Compare visualizations convey similarities and differences between datasets. The change visualizations show trends in data over an elapsed period of time. Organize visualizations attempt to groups, patterns, or rank in the data. Relationship attempts to show correlations between the separate variables. Each type of communication has a visualization associated with it. With each communication technique,

Visualizing a tremendous amount of data points is extremely challenging. To handle large data sets, approximation techniques are available. These techniques allow the exploration of the data set on multiple levels of detail. Approximation techniques are also known as hierarchical approaches based on the levels of data explored. Most datasets in research throughout the electronics industry have a defined range, but these systems will allow for the continual processing of data throughout the entire test. The system used will be based on the data presented. Each system allows researchers to explore and analyze data in a multitude of scenarios, which may have not been recently explored.

2.11 Data Analysis Environment

The first step in performing data science is to insert the data into an analysis environment. The most commonly utilized environments on the market include Python, R, and Strata. Python is a real, general-purpose programming language which has become the most popular environment based on the ease of use and a reduction in time needed to write a code. Anaconda distribution was used to obtain python as well as the needed add-on libraries.

Python is an interpreted, object-oriented, high-level programming language with a simple, text-based interactive interface. The number of features in Python is small compared to other programming languages and requires much less time invested to learn. The main uses of Python include scripting and automation language. InfoWorld states, “The vast majority of the libraries used for data science or machine learning have Python interfaces, making the language the most popular high-level command interface to for machine learning libraries and other numerical algorithms.”

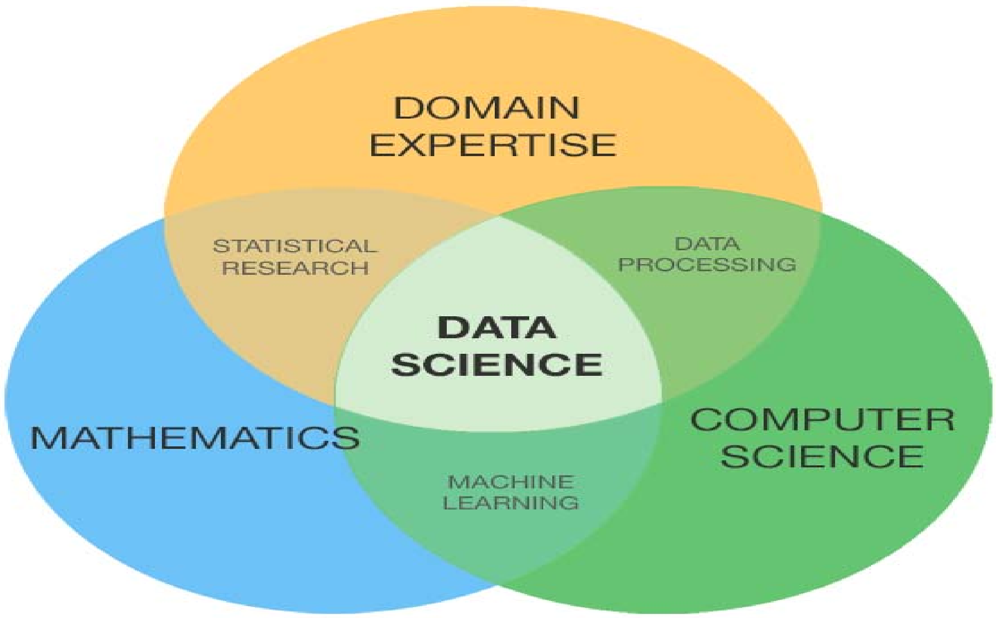


Figure 2-7: Fields of Data Science

Python itself does not include vectors, matrices, or DataFrames as fundamental data types. Many packages have been developed to assist in complex analysis, including:

- NumPy
- Pandas
- Matplotlib

NumPy is a scientific computing package for Python used as an efficient multi-dimensional container of n-dimension, homogenous data types. Pandas was developed to improve NumPy by introducing series and DataFrames for data analysis. DataFrames allow Python to read data formulated into column and rows and create a common data structure and can be created manually or imported from data files. Once analysis has completed, Matplotlib is used to for graphical visualizations of the data. All Packages mentioned will be utilized in the Survival analysis of this experiment.

2.12 Data Analysis of Large Data Sets

To examine large, complex data sets, multiple factors must be considered to ensure precision in the analysis. Summary metrics, such as mean or standard deviation, are commonly used to represent a distribution. An important factor to consider is the existence of outliers. Outliers can cause the data to become skewed. If the cause of the outlier is known, it can be removed from the data set. For the larger data sets, it may be helpful to split the data into smaller subgroups. The variables must be understood when deciding how to divide the groups.

Many techniques have been used in the analyzation of large data sets. The fields of data science can be divided into three main groups as presented below, figure 3.5. Many factors are involved in Big Data analytics. This paper will focus toward the method and algorithm factor. Software tools will be used to analyze the data.

Data analysis tools available on the market today empower users to obtain, group, interact with, explore, and visualize data from any combination of sources. These tools provide users with greater insight into their business processes, their industries, and their products. Some of the top technologies used in the analyses of large data sets include:

- Tableau Public
- OpenRefine
- Knime

- RapidMiner
- Python
- NodeXL

These tools are widely used based on the availability, ease of use, powerful capabilities, and well-documented resources.

2.13 Statistical Analysis

Statisticians have developed multiple methods of analyzing time to failure data. The array of failure modes for the varying types of solder makes it difficult to understand the proper data to analyze. The factors that affect the system most must be defined with the high number of factors possible.

Probabilistic simulation is a commonly used statistical analysis. The process is used when the main factors to affect the system are not known. Probability distribution are used on a specified number of units and attempts to predict any random event that can occur. This method has been used to simulate the probability of waveforms. The probabilistic simulation run as used in a program called CREST and written in C. The inputs provided allowed for alteration to be made to the test to help the system run more efficiently. [78]

Another statistical solution related to solder joint reliability is Finite Element Method (FEM). The FEM works by creating a model of some object of interest by cutting it into a number of small regions. An advantage of the Finite Element approach over other statistical solutions is that the FEM model can account for non-linear changes in material properties as a function of temperature. FEM problems generally require the solution to boundary value problems for partial differential equations. Finite Element models must also consider changes in material properties as a function of time. [76, 77]

- Reliability Given Time
- Probability of Failure Given Time
- Mean Life
- Failure Rate
- Reliable Life

Many advantages are present when using FEM analysis. A large advantage is the ability to accurately represent complex geometry, which is difficult with other tools. The material properties are able to be more thoroughly analyzed by splitting the elements into subdivisions to obtain a domain. These values are then combined to give a full representation of the material.

2.14 Logistic Regression

Logistic regression is used throughout a multitude of industries to analyze data with categorical results. The analysis provides a method for modelling a binary response variable, which takes values 1 and 0. The maximum likelihood estimation is used to determine the probability of an event occurring.

The choice of variables in regression analysis, especially in larger data sets, is important to achieve the best possible model. The number of variables is also important in logistic regression. If too many variables exist, the results may be biased. Multiple methods are available to assist in choosing the variables, including univariate association filtering, recursive feature elimination, etc. The advantage of using one of the selection methods is to ensure the data is not merely just a prediction. When multiple categorical variable exist, dummy variables are used to contrast the different categories. For each variable, a baseline category is chosen and then contrast all remaining categories with the baseline. If (n) number of categorical variables exist, n – 1 dummy variables are needed to inspect all the differences in the categories with respect to the dependent variable.

2.15 Cox Regression

Cox regression is used throughout a majority of industries to determine the probability an object will survive an event. The most common industry to employ this regression is medical. The models are used to predict the percentage of survival given a medical anomaly. An example of Cox regression in the medical industry includes:

> "Survival data from an inception cohort of five hundred patients diagnosed with heart failure functional class III and IV between 2002 and 2004 and followed-up to 2006 were analyzed by using the proportional hazards Cox model and variations of the Cox's model and also of the Aalen's additive model."

Cox regression has become a useful tool in the packaging technology industry. The analysis can be used to determine if a component or system will survive an event given certain input variables. When performing cox regression, three analytic techniques are commonly used, including:

- Testing the proportional hazards assumption.
- Examining influential observations (or outliers).
- Detecting nonlinearity in relationship between the log hazard and the covariates.

The Cox Model is different from ordinary regression in that the covariates are used to predict the hazard function. The implementation of covariates with time-varying effects failure prognostication models may reduce bias and increase the specificity of such models. The model is fit by maximizing the penalized partial likelihood, with smoothing parameters estimated by a likelihood-based criterion. The model may be extended to allow for multiple functional predictors, time varying coefficients, and missing or unequally spaced data. An example of Kaplan-Meier curve is below in figure 3.7.

2.16 Data Visualization Techniques for Large Data Sets

Visualization is one of the most powerful tools used in data analysis to fully understand what the data is saying. Interactive data tools have become an industry standard in data visualization. Similar to the problems seen before, large data sets lead to the problem of what data to visualize. In interactive data, the visualizations became slow and skewed with large amounts of data. The focus of study has been to fix these problems.

Weibull is the most prominently used programs of visualizing survival data. The Weibull program allows researchers to view the trends of a single system or compare the trends of many. Vasudevan of intel used Weibull to show the correlation of the material properties of different

BGA components. From these correlations, Vasudevan [69] could establish a suitable temperature range for typical use conditions. Networks have become popular to model the data of a complex system.

Interactive Visualizations have begun to gain dominance throughout the industry. Multiple visualization programs and algorithms are available today. Most systems have visual scalability functions allowing the system to effectively display large sets of data. Data Reduction is one of the main problems in visualizing data. Establishing the type of data being analyzed will help with the choice of which system to use. [75]

Chapter 3 Chapter 3
Literature Review

Solder is the crucial material of the electronics industry, and reliability is upmost importance. Over the past century, the most commonly used solder material was tin-lead (SnPb). In the early 2000's, legislation was enacted to prohibit the use of lead, as well as multiple other harmful materials, in in electronics. The necessity to find a solder alloy to replace the eutectic tin63/lead37 solder has led to multiple research program examining the performance of alternative solder resulting in immense amounts of data. Multiple factors play a role in selecting the best solder solution. With each solder having separate properties, it is important to know which solder is best for the application needed. A wide array of analysis methods have been used throughout industry, each with its advantages or disadvantages.

3.1 PCB Manufacturing

The PCB manufacturing process is complex with multiple factors involved throughout. The goal of the process is to achieve a high quality, low cost printed circuit board. Boards can be manufactured individually or in volume with a wide array of materials used. Multiple factors are involved in the manufacturing process, including: [51]

- Cost
- Board Area Size and Mass
- Melting Temperature Range
- Solderability
- Compatibility with common Flux Systems

- Solder Ball Compatibility
- External Visual Appearance for Inspection
- Health and Environmental Concerns

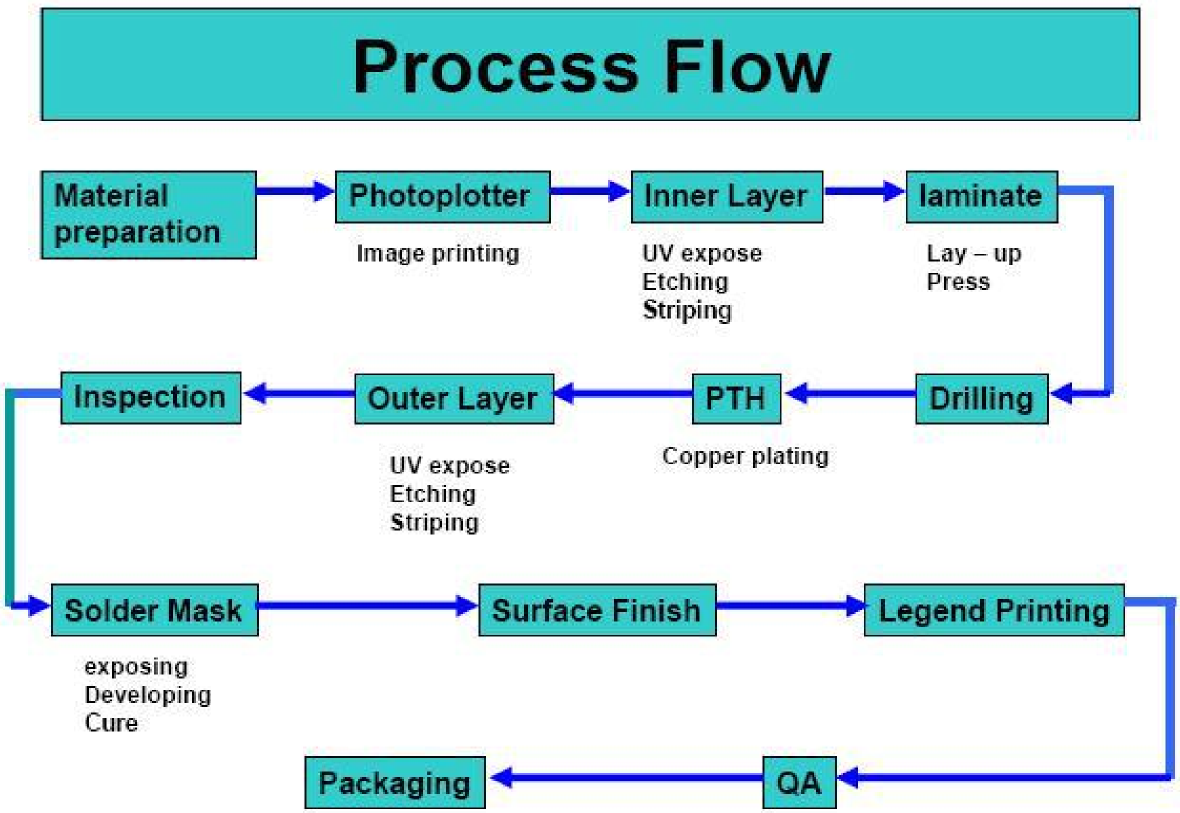


Figure 3-1: PCB Process Flow Chart [52]

3.2 Properties of Solder Alloys

The environment, application, and long term needs greatly impact the solder selection of particular concern in the need for long term reliability for election in high temperature conditions. The choice of solder alloy for the manufacturing of a PCB is based on the properties of the alloy. Some properties, such as cost and quality, have similar property requirements throughout all industry functions. During the manufacturing process, the thermal properties are important to understand the time needed to reach the liquidus level and the time needed to cool and harden the joint. [37,38]

Many properties are important to review when deciding on a solder alloy. Properties can be divided into two major sectors, which include the properties required for good reliability and the properties involved in the manufacturing process. The factors for both types include: [37, 38]

- Coefficient of thermal Expansion (CTE)
- Resistance to Voiding
- Effects of Aging
- Grain Growth and Microstructure
- Intermetallic Formation
- Mechanical Properties
- Failure Modes
- Performance under Thermal Cycling
- Resistance to Corrosion and Oxidation

Recent publications have illustrated the transition to leadfree solder has created concerns for applications needing long term reliability at high temperatures. The effect of adding small percentages of various materials has also been researched to understand if they can influence the properties of the solder alloy. The addition of certain materials, such as bismuth or zinc, can add several beneficial effects to the solder alloys. Dopants can help to improve the mechanical properties of the alloy while also reducing the amount of intermetallic growth. As the percentage of the dopant material increases, the properties of the alloy will continue to change. The over excessive use of a dopant material may cause a negative effect to the alloy. Bismuth has been seen to increase the tensile and sheer strength if a correct percentage is doped into the alloy. Too high of a percentage of bismuth doped into the solder alloy may cause the tensile strength to reduce. Bismuth has also been seen to improve the thermal properties of the alloy by lowering the liquidus temperature, extending the time the alloy is in the pasty range, and lowering the time the alloy takes to cool and harden. [55] Zinc has become a common dopant material throughout industry based on cost and availability. The thermal properties of the alloy have seen improvements with the addition of zinc, but intermetallic growth has seen to increase. [53]

The mechanical properties are very important for the manufacturing process. Researchers are attempting to find a solder with comparable tensile strength to the eutectic SnPb solders. To obtain the tensile strength of the solder, stress-strain curves are compared to see the range of stress the joint can withstand. Ultimate tensile strength and yield strength are important properties for reliability testing. Mechanical strength can be strongly affected by increased temperatures. Studies have found SAC305 to have the closest tensile strength to the eutectic SnPb solder. [23, 54]

3.3 Reliability Test Methods of Solder Alloys

Reliability throughout the electronics industry is determined based on the environment and application the electronics system uses. The level of reliability can be tested using a multitude of methods, which will differ based on the application of the system. With the evolutions of new technologies, new concerns have emerged with the reliability of the solder alloys. A variety of reliability tests can be used when assessing electronic assemblies: [37, 56]

- Thermal (temperature) Cycling (TC)
- Thermal Shock (TS)
- Mechanical Testing (Drop and Vibration)
- Power Cycling
- Functional Cycling
- Moisture Sensitivity (e.g. IPC/JEDEC-020C)
- Temperature + Humidity (e.g. 85/85 testing)
- High-Voltage extended-life
- Mechanical bending, twisting, and shear (e.g. IPC/JEDEC-9702)
- Electromigration

Mechanical testing is a main concern of researchers throughout industry. Many studies on drop testing have been performed to study the reliability of the alloys after being subjected a certain number of drops. In drop testing, JESD22-B111 specifications to maximum peak acceleration of 1500 G and half-sine shock pulse duration of 0.5 milliseconds standards are used. [56] The drops will cause the boards to excessively flex based on varying heights, which are predetermined. The yield stress obtained from the high number of drops does not allow the bulk solder to absorb the impact, which cause cracks to propagate through the intermetallic layer due to the transferring stresses. Strain rates of separate solders were study to see how compliant the material be under drop conditions. Many studies have found SAC105 to perform most optimally for drop testing. [56, 57] Vibration is another mechanical test commonly performed to study the effect of vibrations at certain levels on the joint. Reliability in the area is vitally important in many applications throughout the electronics industry.

Thermal shock is another common test used throughout industry through use of high temperature accelerated life tests. Boards are subjected to alternating, extreme temperatures set by the standards for thermal shock testing, equivalent to between -40°C to 125°C, with short dwell times and even shorter transition times. Boards are tested to failure up to a certain amount of cycles. Reliability will vary with differing materials based on the alloy and amount used. As the boards are cycled, the joints will experience thermo-mechanical fatigue and cracks can begin to propagate.

3.4 Types of Failures in Solder Joints

Solder joints experience a wide array of failure mechanisms, which can occur from manufacturing to product use. During the product lifetime, the joints will experience fatigue and multiple mechanical stresses. The joints can be affected during the reflow process through intermetallic growth or voiding causing the failure to occur earlier in the product life. [5]

The composition of the solder is altered greatly during the reflow process. Intermetallic compounds form between the solder ball and the PCB, changing the composition of the joint by a certain percentage. The reliability can be impacted critically with this change either positively or negatively. The largest impact to the joint has been seen in the elastic modulus. This can help reduce the stiffness of the joint, which would reduce the amount of strain accumulated, or the joint can see earlier failures with too much flex being allowed. Reportedly, a 20%-30% increase in the level of fatigue seen with the growth of intermetallics has been observed [53]. The reduction of intermetallic growth is currently a main field of study.

Voids are another mechanism that can cause failure in the solder joint and occurs during the reflow process. Voids are caused by the outgassing of flux or other moisture during the hardening process. Depending on how much area proportionate to the joint is taken, the voids can cause failure immediately or cause the joint to be brittle and fail early due to mechanical stresses. The effect of the void is strongly influenced by the position it takes in the joint and its size. It is difficult to study and predict when voids will occur based on their high level of unpredictability.

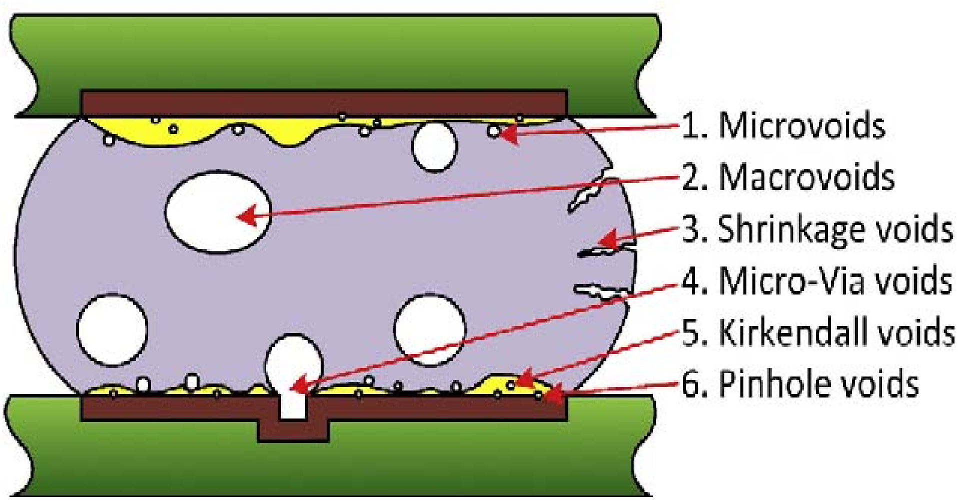


Figure 3-2: Types of Voiding

Solder fatigue is a main cause of failure in solder joints during the products lifetime use. As the joint is cycled, either in test or application, the joint accumulates fatigue due to thermal and mechanical stresses. From this fatigue, crack propagations commonly occur along either the board or package side. Differing coefficients of thermal expansion cause the solder to be compresses and elongated from the board causing the cracks. Figure 3.3 below show solder joints with crack propagations through the joint and is a representation of a differing CTE. This figure shows a crack occurring on the package side completely though the bulk solder of the joint causing complete failure. The figure also shows a crack propagating to a void on the package side. Complete failure may not occur instantaneously but has a higher probability over time. It is common for crack to occur on the package side in most studies, but boards side cracks also occur. [90]

Figure 3-3: Crack Through Solder [90]

3.5 Effects of Thermal Cycling

Electronics systems are not always in continuous service. Most systems will be switched on and off multiple times a day, which will cause the system to continually heat and cool. Thermal cycling is the heating and cooling to certain temperature extremes of a material.

Additionally, the environment can expand the temperature extremes experienced by the electronics. With consistent usage of an electronic system, the electronic packages and the solder joints associated will see continual changes in thermal activity. Thermal fatigue cracks are observed to see where in the joint the cracks occur.

During thermal cycling, the joint will experience degradation due to the coefficient of thermal expansion (CTE) mismatch between the component and PCB. The joints will also experience CTE mismatches internally in the grain structures as well. These mismatches throughout the system cause cyclical stresses to occur on the joint causing it to thermos-mechanically fatigue.

Most studies have found the majority of cracks propagate through the bulk solder, although cracks were also observed through the intermetallic layer. This is due to an unequal strain/stress load placed upon the bulk solder during thermal cycling. SAC305 performed much greater than SAC105 similar to applications in thermal shock. Vasudevan found SAC components outperformed the SnPb counterpart at thermal cycling between -25°C to 100°C, even with increased dwell times. [69]

The thermal profile associated with the thermal cycling plays a major role in the fatigue life. Research has found a quick fluctuation in temperature during profiling either on the extreme heat dwell can help to reduce the stress/strain accumulation of the joint. The standard profile used throughout industry is presented in the image below [Figure 3.4]. Profiles will vary based on the needs of the tests, but profiles will range equivalently to -40°C to 125°C. Research has also been performed on how the surface finish and how the PCB is fabricated affects the failure of the joints under thermal cycling. [59]

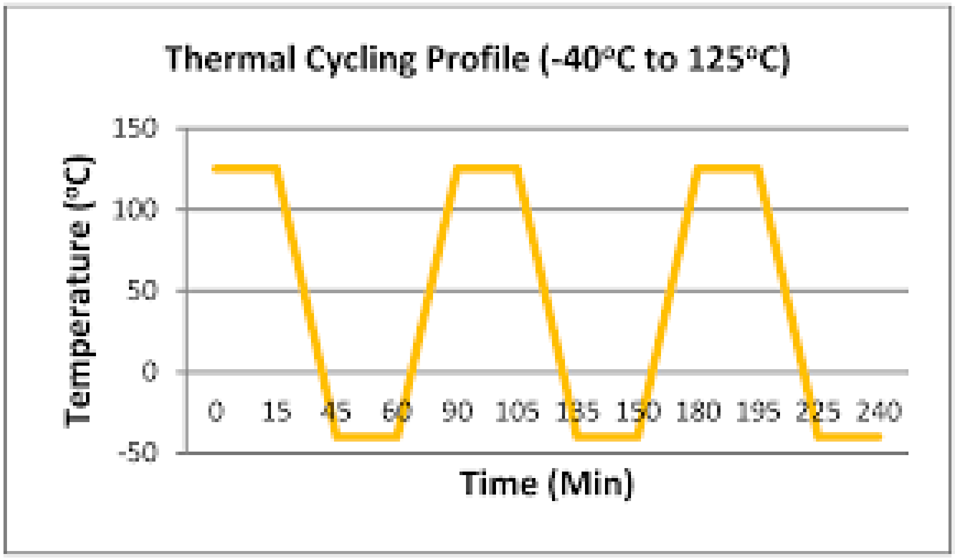


Figure 3-4: Thermal Cycling Profile Example [37]

3.6 Effects of Aging

Solder joints are subjected to a variety of aging methods from the assembly process to system use. Solder is subjected to temperature extremes multiple times throughout the assembly process causing thermal aging in the joint. [65] Research has been performed on the effect of aging at extreme temperature, equivalent to 150°C. Many joints have seen a major drop in reliability with the growth of the intermetallic layer. Zhao [60] found the solder joint experiences intermetallic growth along the grain boundary of the bulk solder with aging. The Intermetallic layer becomes brittle as aging continues. Li [41] found the growth of the intermetallic layer caused fatigue failure and an extreme loss in shear strength. SAC solders exhibit a reduction in their flow strength with increasing test temperatures after aged at 125°C for 24 hours, and their degree of strength is highly dependent on their composition. [42]

The microstructure of the solder joint after aging at various temperatures has become a major concern throughout the industry. Changes in the solder joint microstructure include interphase coarsening, intermetallic growth, and evolution of the intermetallic/solder interface. The changes will occur concurrently with the change of aging temperature. As the aging temperature rides, the changes in the solder joint microstructure will increase as well. The shear strength and ductility of the joint is also an area of study. The levels of deterioration in the joint strength is important for the overall reliability. The reliability has seen varying results with changes in the microstructure with varying aging times. Research is ongoing to understand the anomalies shown here. Figure 3.5, below, shows the IMC layer before and after aging. The IMC increases more with aging.

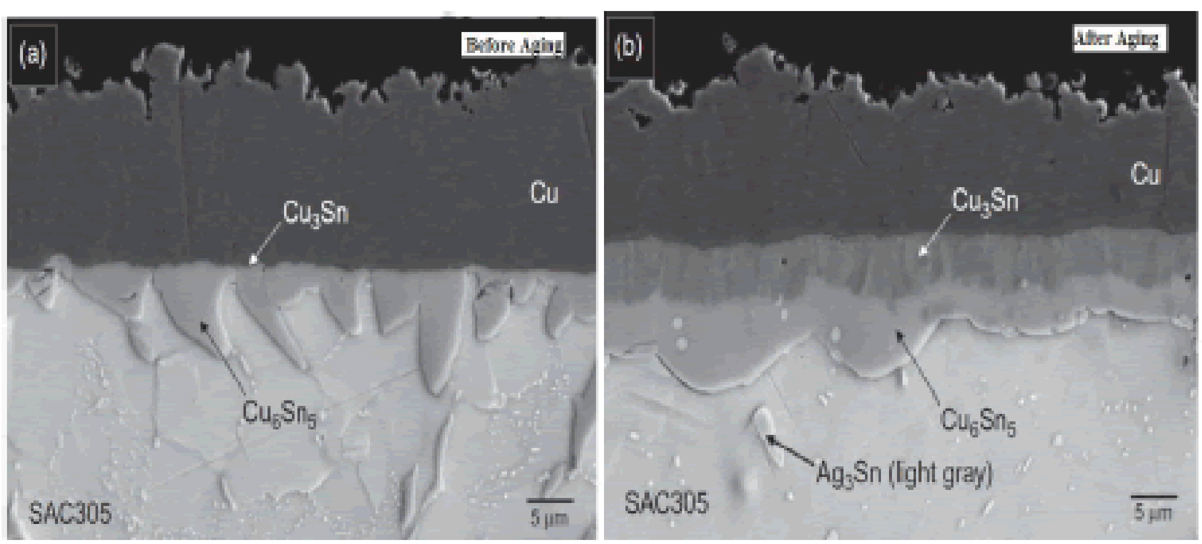


Figure 3-5: IMC Layer Before and After Aging

3.7 Failure and Reliability Analysis Techniques

The knowledge of when and how a system or component has failed is very important with the amount of research being performed on Pb-free solder. Many methods of failure analysis have been presented to completely analyze the failure and even predict when it will occur. Three main types of Reliability analysis are used including [74]

- Point Estimate Reliability Analysis Problem
- Rational Reliability Analysis Problem
- Functional Reliability Analysis Problem

Each method has its own inputs and outputs affecting the system. The use of algorithms in solving these methods is similar, but the computational methods are much more complex. [74]

3.8 Aging Effects: TV-7 Test

Through the early 2000's, limited research was performed to analyze the acceleration factors on aging effecting the reliability of different package designs. To break through these limitations, the TV-7 research project was developed. TV-7 was developed to analyze the effects of isothermal aging on SnPb and leadfree solder materials with different surface finishes. In this project, test vehicles were aged at 125°C for 0, 6, and 12 months. Upon completion, thermal cycling was performed, and the test vehicles were subjected to temperature extremes between -40°C to 125°C per JEDEC JESD22-A104B-Condition G. The profile was set for a 15 min dwell time and 30 min ramp time. The characteristic life for each material and each aging group for the 15mm BGA package is shown below in figures 3.6 and 3.7. [91]

High levels of degradation can be seen for all test vehicles. We can see the SAC305 alloy has degradation rates exceeding 55% as compared to a degradation rate of 33% for SnPb from no aging to 24-month aging, shown below in figure 3.6. These high levels of degradation caused much concerned and drew many questions which required further examination.

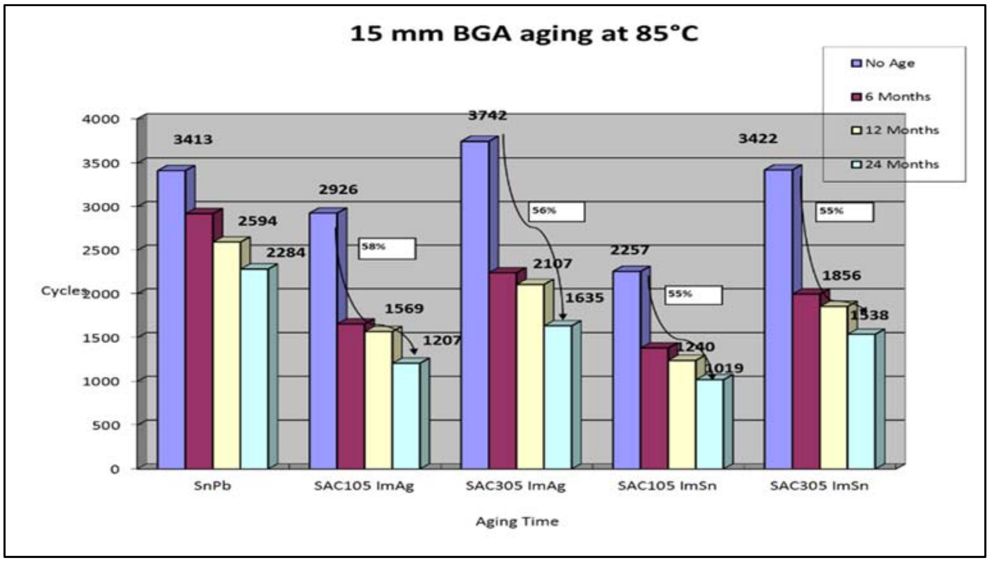


Figure 3-6: TV-7 15mm BGA Aging at 85°C [91]

The greatest concern is the degradation in reliability due to aging for vibration. Figure 3.7 shows the degradation in reliability for SAC105 and SAC305 when aged at 55°C for up to 24 months. The degradation in reliability is catastrophic for these materials.

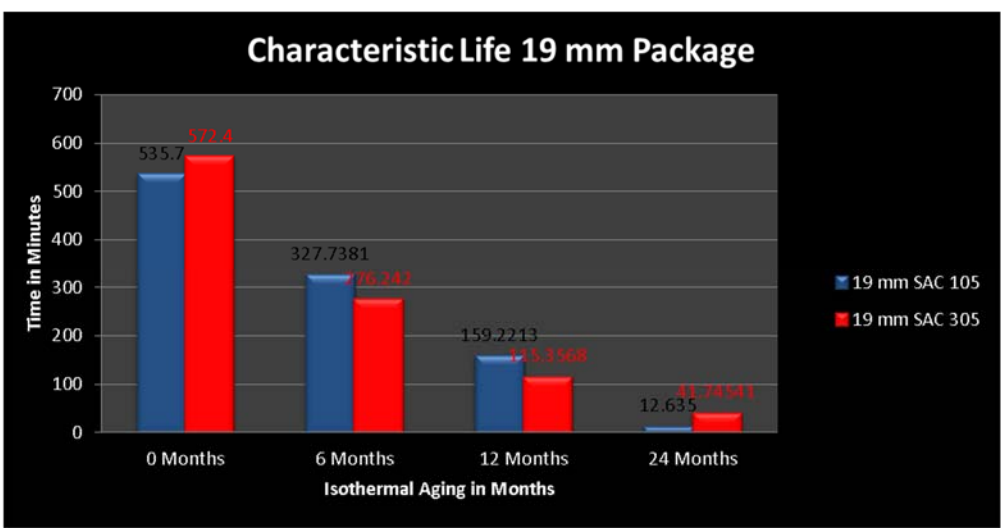


Figure 3-7: TV-7 Characteristic Life 19mm Package [91]

3.9 Aging Effects: TC1-SRJ

The TC1-SRJ test vehicle was designed by Peter Narbus and manufactured by TTM Technologies (Time-To-Market Interconnect Solutions), Chippewa Falls Division. The printed circuit board (PCB) used in the TC1-SRJ test vehicle is a commercial-grade laminate board consisting of two different printed circuit board materials: FR4-06 and Megtron6. The test vehicle incorporates land patterns for 5 mm, 6mm, 13mm, 15mm, 17mm, 31mm, 35mm and 45 mm Ball Grid Array packages with surface mount resistors ranging from 2512 to 01005s. A total of 910 printed circuit boards were built with 30 boards being used for setup during assembly while the remaining 880 boards were used in active testing. When considering the effects of Isothermal Aging on the relative reliability of various packages, the data indicate that even components that show similar initial reliability trends may display differences following aging. The level degradation of the lead-free solders relative to tin-lead solder appears to be package-dependent.

The characteristic life values as a function of time for the CVBGA 432, CABGA256, and CABGA 280 components using SAC305 and SnPb solder on the FR4-06 and Megtron6 substrate materials is shown in figure 3.8 below. High levels of degradation are experienced for each separate subset from no aging to 24-month aging. Similar trends in degradation are shown for the SAC and SnPb solder paste materials. The SAC305 solder material showed lesser levels of degradation over the SnPb material when attached to the FR4-06 substrates, but this trend reverses when the Megtron6 substrate is used. It should be noted that this trend is different than all other SAC305 testing only on FR406 performed at Auburn. Although, the Megtron6 substrate material does experience increased levels of degradation over the FR4-06 material. [37]

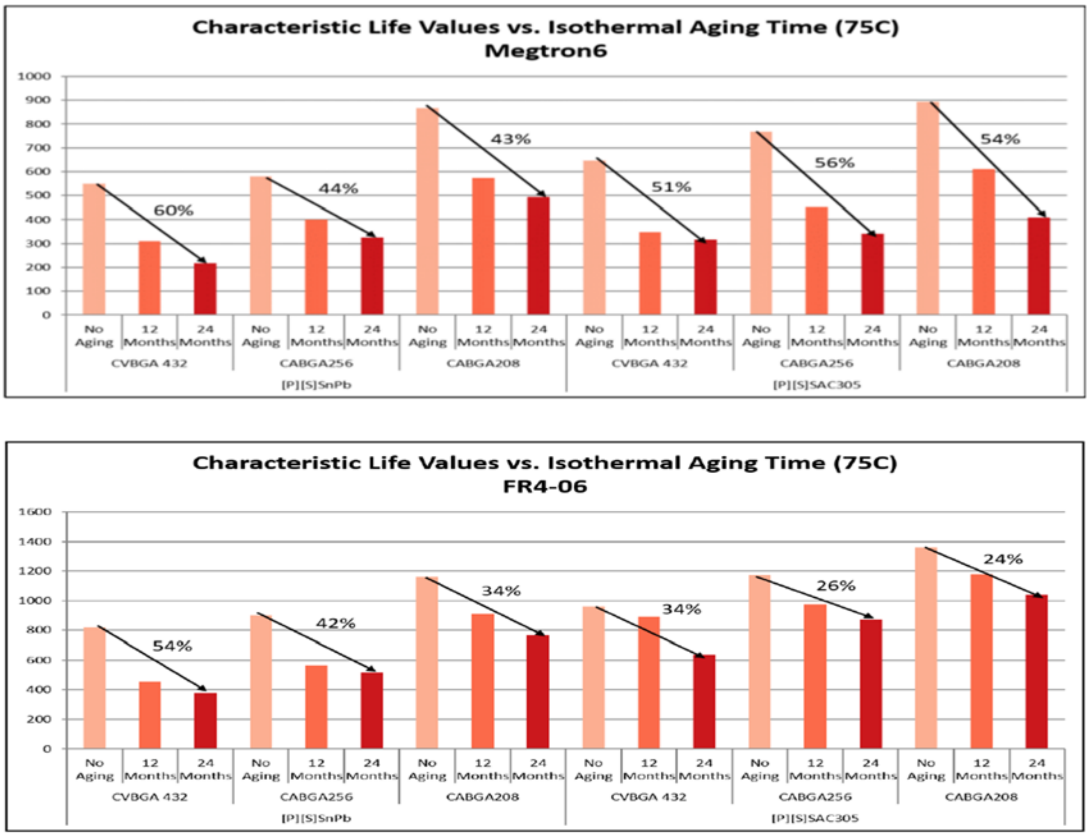


Figure 3-8: TC1 Characteristic Life Values: Megtron6 and FR4-06 [37]

3.10 Phase I Down Select

The major contribution to the degradation seen in lead-free solder joint material is the accumulation of the low cyclic stress induced on the bulk solder near the intermetallic formation over a long period. It is essential to understand the effect of doping various elements and impact of aging for these solder materials. The Phase I Down Select test was performed to address these issues. The test consisted of three components: Liquid Shock, Vibration, and Drop testing. The test vehicle was designed by Peter Narbus and manufactured by TTM Technologies. Two sets of boards were manufactured, the first set was tested with no aging, and the second set of boards were placed in an isothermal chamber, and a steady temperature of 125°C was maintained for 6 months to simulate aging before they were tested. The mechanical tests' test vehicles differed from the test vehicle used for the liquid shock test. The liquid shock test vehicles consisted of 35 mm, 31mm, 15 mm and 6mm ball grid array packages, shown in figure 3.9 below. Mechanical test vehicles were developed to focus on the difference in zone location for the components, shown in figure 3.10 below. Therefore, the 15mm package was the only package built onto the test vehicle.

Figure 3-9: Liquid Shock PCB

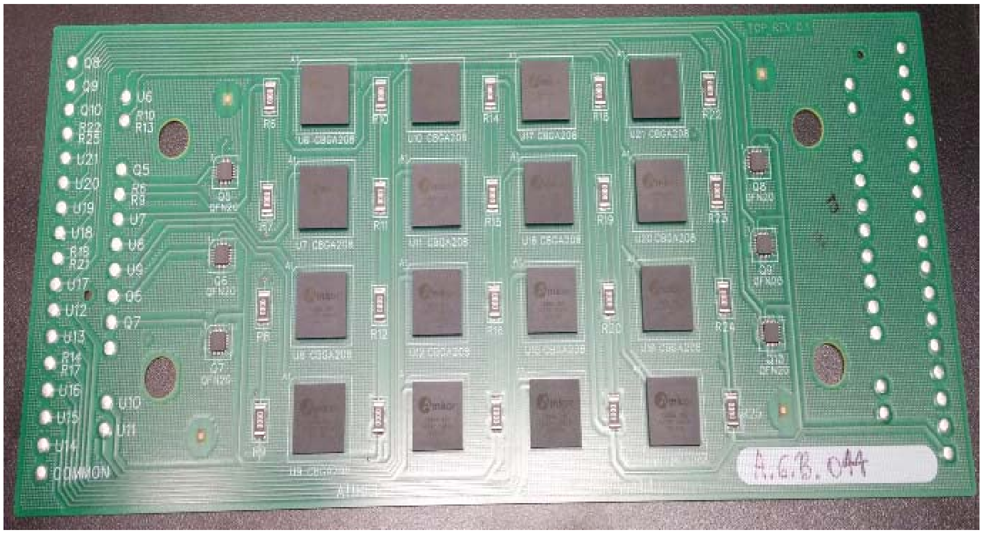


Figure 3-10: Mechanical Test PCB

The liquid shock test consisted of 3000 cycles with 5 minutes at each temperature extreme and a transition time of 2.5 minutes. All assembled test boards were subjected to thermal shock testing with peak temperatures of -40°C and +125°C in a CSZ TSB Chamber. Figure 3.11 below shows the survival rate vs percentage through testing for the Alpha SAC305 solder material. High levels of degradation are shown from no aging to 6-month aging.

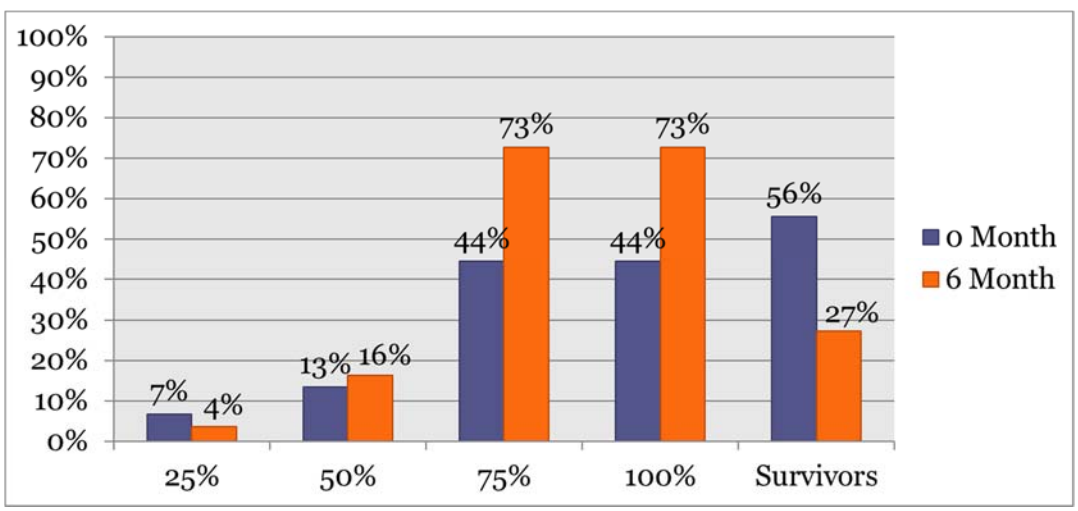


Figure 3-11: Liquid Shock Alpha SAC305 (Baseline) Failure Percentage vs. Percentage through Test

The setup test assemblies were mounted on an LDS LV217 electro-dynamic shaker table and subject to a 4.6 Grms stress vibration profile, shown in figure 3.12 below.

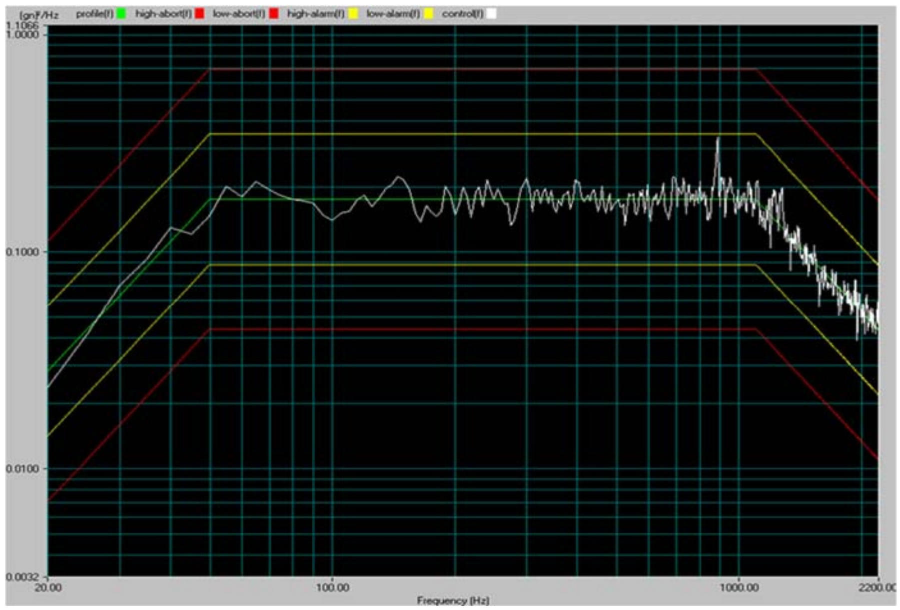


Figure 3-12: Vibration Test Profile

Boards were subjected up to 30 hours of vibration or to failure. Figure 3.13 below shows the survival rate vs percentage through testing for the Alpha SAC305 solder material. High levels of degradation are shown from no aging to 6-month aging after 30 hours of testing.

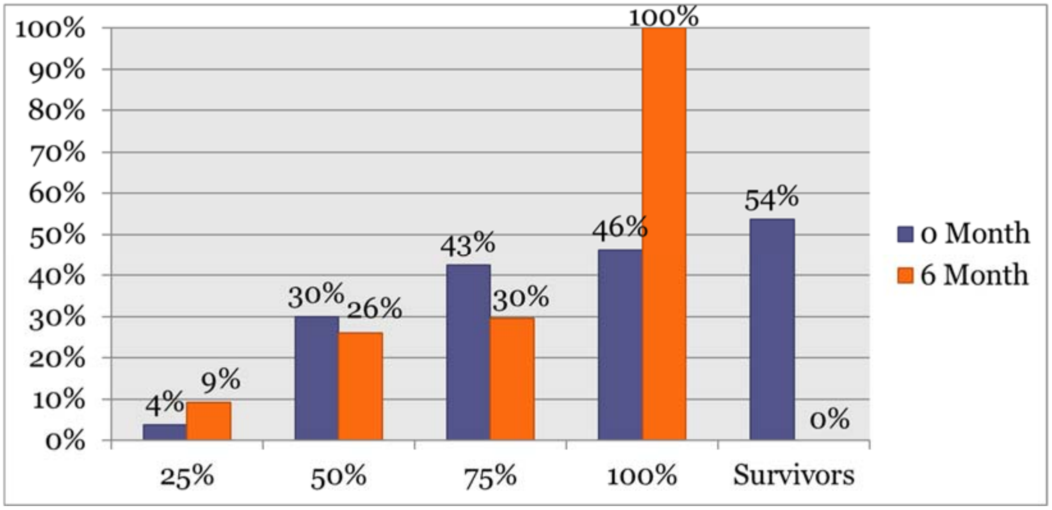


Figure 3-13: Vibration Alpha SAC305 (Baseline) Failure Percentage vs. Percentage through Test

Each board is mounted on vertical aluminum fixtures and are fastened onto the drop base plate for mechanical load testing on a Lansmont M23 drop tower. Boards were subjected up to 300 drops or to failure. Figure 3.14 below shows the survival rate vs percentage through testing for the Alpha SAC305 solder material. High levels of degradation are shown from no aging to 6-month aging throughout all periods of testing.

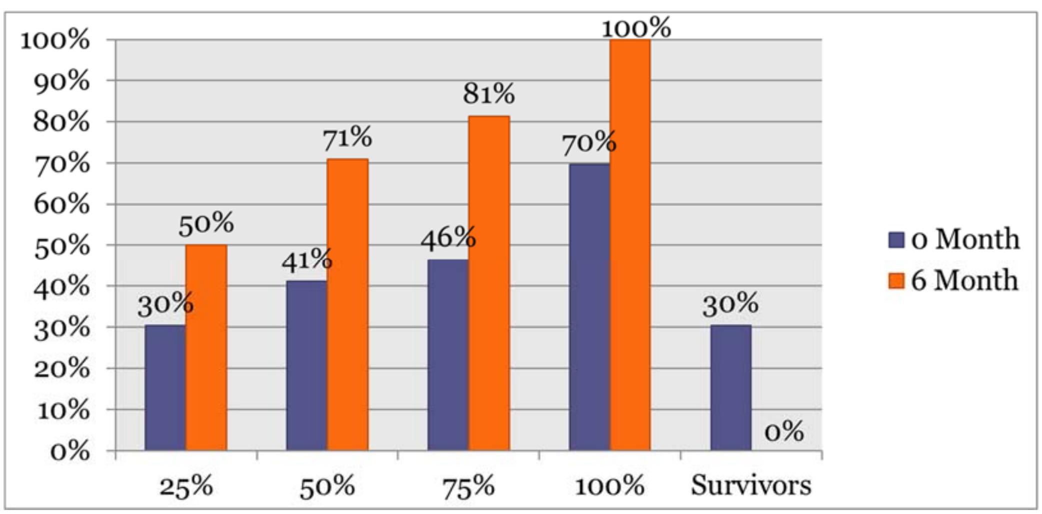


Figure 3-14: Drop Alpha SAC305 (Baseline) Failure Percentage vs. Percentage through Test

The Alpha Innolot performs better under most conditions except for the SBGAs. There are also some differences between FR-406 and Megtron6. From the thermal cycle test, Alpha Innolot appeared to increase the overall reliability by nearly 30% over SAC 305. For Thermo-Mechanical applications the Henkel 90SCLF318AGS88.5 and Indium Material 2 are observed to be better pastes after aging in both Liquid Shock and Vibration Tests. The other recommended materials for the test are AIM and Inventec solder pastes which performed very well under thermal shock. Based on differences, it would be best to use Megtron6 for the next thermal cycle build. The match material provides little value on any of the tests and materials with the exception of some improvement was Alpha Innolot. Auburn does not recommend building with matched on the next test. Auburn recommends the following materials to be built in the next phase of testing:

- Alpha Innolot
- Henkel 90SCLF318AGS88.5
- Indium Material 2
- AIM NC258 91-2 88.5, T3
- Inventec Ecorel Free 405Y-16

These materials were used for further testing in TC1-SJR Phase II (Thermal Cycling – Solder Joint Reliability) test using Megtron6 substrate. The Phase II will continue to evaluate the effects of long term aging using the best solder materials chosen from Solder Doping Downselect test.

Chapter 4

Purpose of Study

Previous studies and tests provide correlation analysis and data visualizations to tell the entire story of the test. Fine pitch lead-free packages have started to enter critical everyday instruments, but the knowledge of the combined effect on the reliability effect is limited. Especially for doped solder joint, the failure mechanism as well as failure modes have been seldom investigated. Reliability analysis is of major importance throughout the entire industry. The mechanical properties of SAC alloys have shown to change at elevated temperature, but a time conscious approach is needed to study the effect and to obtain a better understanding. The purpose of this project is to find a manufacturable solder paste with dopants that can mitigate the effect of aging and find a solder material to replace the SAC spheres and enhance the package reliability. The test conducted to evaluate the performance of various solder alloys include thermal cycling test at both no aged and aged conditions. Various form of reliability and data analysis are to be performed to capture what variables are truly affecting the survivability of the solder joint.

4.1 Test Vehicle

TC1-SRJ is the first installment of the isothermal solder doping project. The solder doping II project (TC2-SRJ) is the second installment of the solder doping I and TC1-SRJ projects. In the first installment of the solder doping project, sixteen solder-paste materials were examined through thermal shock and mechanical (vibration and drop) testing. In thermal shock testing, boards were subjected to thermal shock test with temperatures being 40°C to +125°C in

CSZ TSB Chamber. The thermal shock cycle consists of 3000 cycles with 5 minutes at each temperature extreme and transition time of 2.5 minutes. The setup test assemblies were mounted on an LDS LV217 electro-dynamic shaker table. The 4.6 Grms vibration profile is chosen in order to complete the test after 20 hours. In Drop testing, a Lasmont M23 Drop tower was used with drop as per JESD-B111 specifications. Boards were subjected to 300 drops or to failure with 1500G with 0.5 millisec half-sine shock pulse. Survival data for each test was analyzed with all variables taken into effect, and the top 5 performing materials were chosen for thermal cycle testing in TC2.

The test vehicle used for both TC1 and TC2 was a board designed by Peter Narbus and manufactured by TTM Technologies (Time-To-Market Interconnect Solutions), Chippewa Falls Division, figures 4.1 and 4.2 below. Overall board dimensions are 173 mm (10 inches) by 254 mm (6.81 inches) with a board thickness of 5 mm (0.2", or 200 mils). When the components are assembled onto the printed circuit board (PCB), each printed circuit assembly (PCA) will weigh close to one pound (Lb.).

The TC2-SRJ test vehicle PCBs were assembled by STI Electronics Inc. (Madison, Alabama). Test boards were assembled October 20 to October 23, 2015. A total of 260 test boards were built, along with an additional 20 boards used solely for setup purposes during assembly. All test boards are Megtron6 substrate material with FR4-06 boards being used for setup.

Five solder paste materials are selected for incorporation in this test based on their performance in Phase I. Four (4) Isothermal Aging times are included in the test plan: No Aging (0-month), 6-Month Aging, 12-Month Aging, and 24-Month Aging. Board are divided equally into these four aging groups.

Images of the top and bottom-side boards are presented in figures 4.1 and 4.2. The figure on the left is a real-life image, and the image on the left displays the complexities in the wiring of the components.

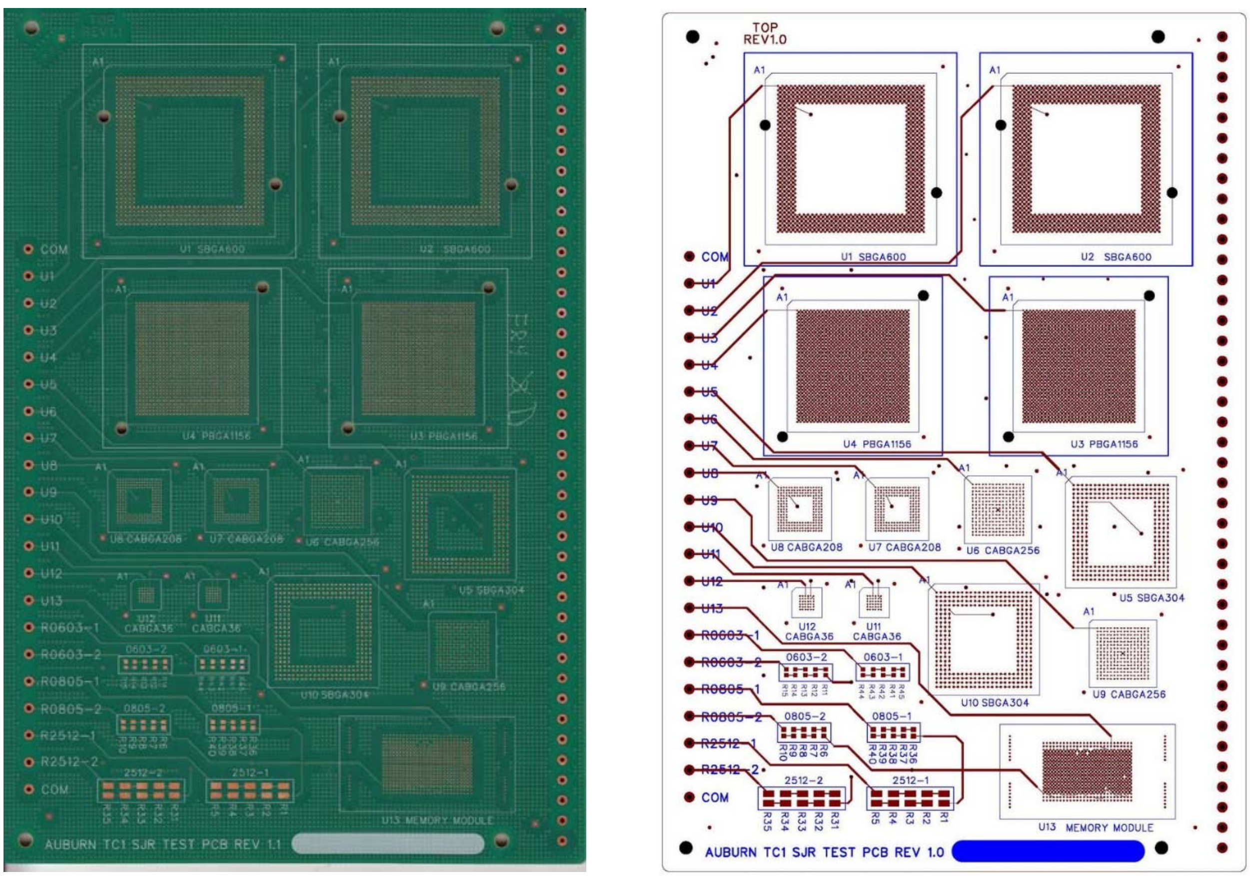


Figure 4-1: Top-Side PCB Image [37]

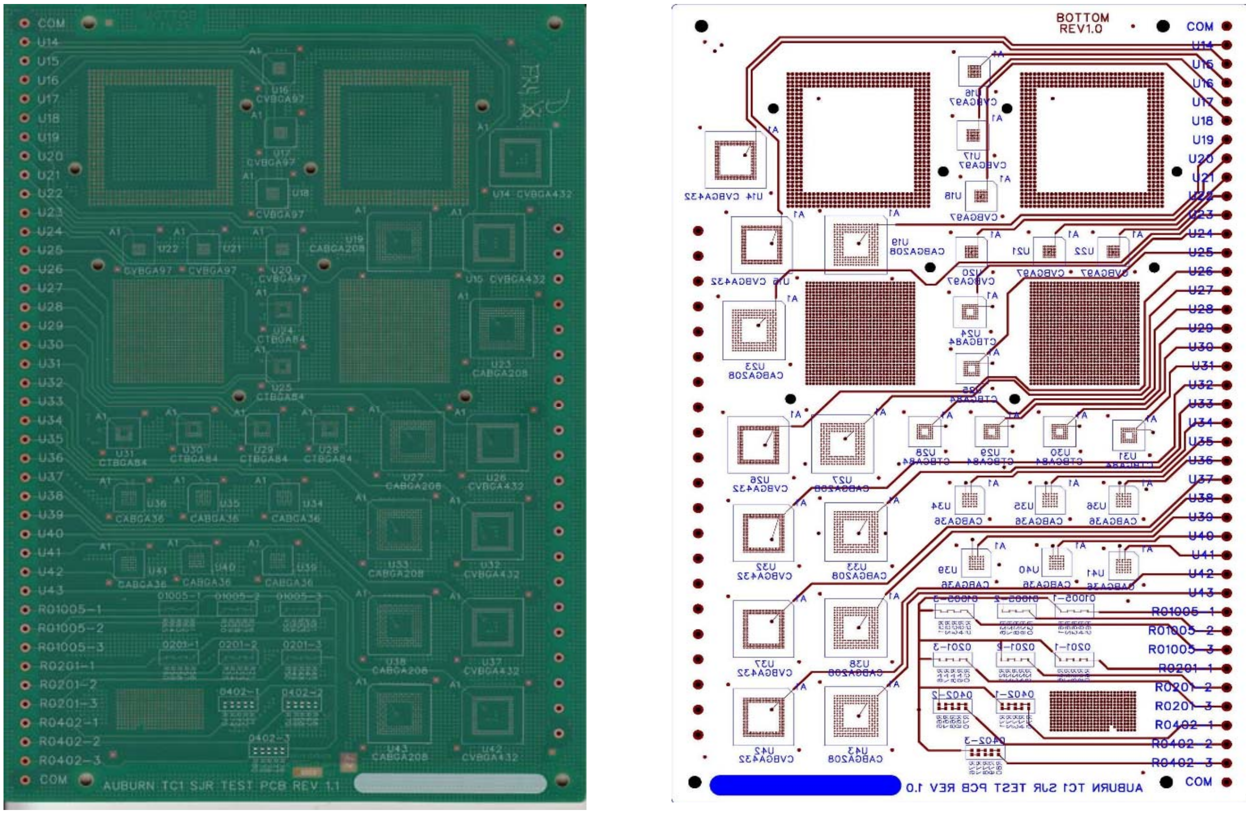


Figure 4-2: Bottom-Side PCB Image [37]

4.2 Test Vehicle Design and Specifications

Boards are assembled single-sided, with components on only one side of the board. Two groups are assembled: in one group, components are placed on the 'Top' side of the board; in the second group, components are placed on the 'Bottom' side of the board. The top and bottom-side assembled boards are shown above.

The TC2-SRJ board has 6 copper layers and over 14,600 pins. Up to 19 components can be assembled on the Top-Side, while up to 39 components can be assembled on the Bottom-Side (counting each set of 5 daisy-chained resistors as one component).

4.3 Test Plan

A total of 260 test boards are built, along with an additional 20 boards used solely for setup purposes during assembly. Based on data differences shown in TC1, all test boards are Megtron6 substrate material. The boards are being built/assembled in two groups: 'Top-side' boards have only the top-side components added, while 'Bottom-side' boards have only the bottom-side components added.

Aging	Material	Top Side	Bottom Side	Total
No Aging	A	9	4	13
	B	9	4	13
	C	9	4	13
	D	9	4	13
	E	9	4	13
6 months	A	9	4	13
	B	9	4	13
	C	9	4	13
	D	9	4	13
	E	9	4	13
12 months	A	9	4	13
	B	9	4	13
	C	9	4	13
	D	9	4	13
	E	9	4	13
24 months	A	9	4	13
	B	9	4	13
	C	9	4	13
	D	9	4	13
	E	9	4	13

	Total = 180	**Total = 80**	**Total Boards = 260**

Four (4) Isothermal Aging times are included in the test plan: No Aging (0-month), 6-Month Aging, 12-Month Aging, and 24-Month Aging. Board are divided equally into these four aging groups. For each material, there are 9 ‘Top-Side’ boards and 4 ‘Bottom-Side’ boards for every aging group. This yields a total of 52 boards per material (36 Top and 16 Bottom), with 13 boards in each aging group.

4.4 Solder Paste and Screen Printing

5 different solder paste materials (AIM, Alpha Innolot, Henkel, Indium, and Inventec) are used for testing in TC2, each from different suppliers. Those 5 materials were compared statistically with the 3 solder-paste materials (SAC305, SnPb, and Innolot) used in TC1 testing. The screen printing machine used is a Speedline Technologies MPM Momentum (right). The stencil thicknesses used are

- Bottom-Side Assemblies = 3 mil stencil
- Top-Side Assemblies = 5 mil stencil

Top-side assemblies were also solder bumped. Overall the top-side assemblies had approximately double the solder value over same bottom-side pads.

4.5 Component Placement

The SMT placement equipment used in construction of the boards were 2 pick-and-place machines for both the TC1 and TC2 assemblies: the Juki KE-2080L and Juki FX3, figure 4.3 below.

Figure 4-3: Pick and Place Machines

4.6 TC2-SRJ Reflow Profiles

Solder reflow was performed using a Heller 1913 MKIII reflow oven. Two different reflow profiles are used: one for the Top-Side boards and one for the Bottom-Side Boards, shown in figures 4.4 and 4.5. The reflow profiles were designed to match as closely as possible the original TC1-SRJ profile, which in turn was selected based on attempting to meet (solder paste) manufacturer recommendations while adjusting based on the realities of balancing time-above-liquidus, peak reflow temperature, etc. for a board of such high thermal mass.

To get accurate thermal readings, a test board was fitted with three thermocouples and passed through the reflow oven while attached to a thermal readout and recording device [EDC M.O.L.E. Thermal Profiler]. The oven temperature zones and pass-through speed were adjusted iteratively until a feasible reflow profile was obtained. The reflow profiles shown in the figures were used for top and bottom board assembly respectively, figures 4.4 and 4.5.

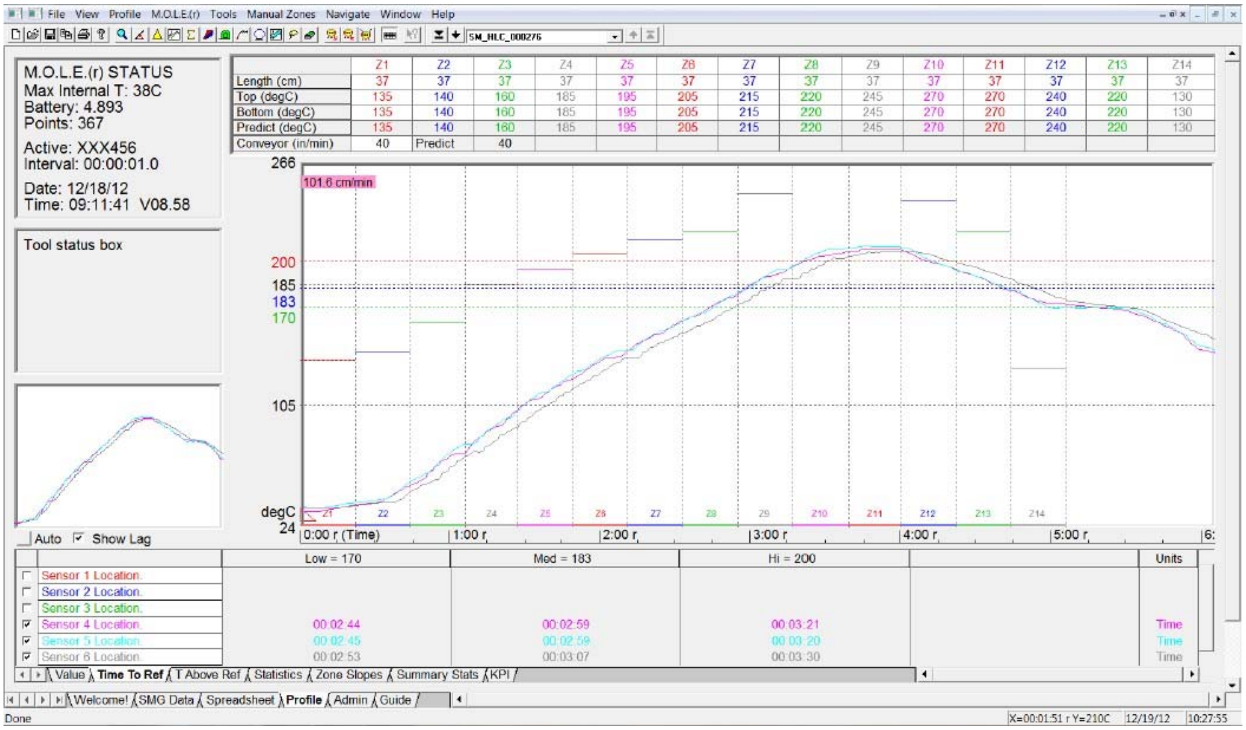


Figure 4-4:Top-Side Reflow Profile [37]

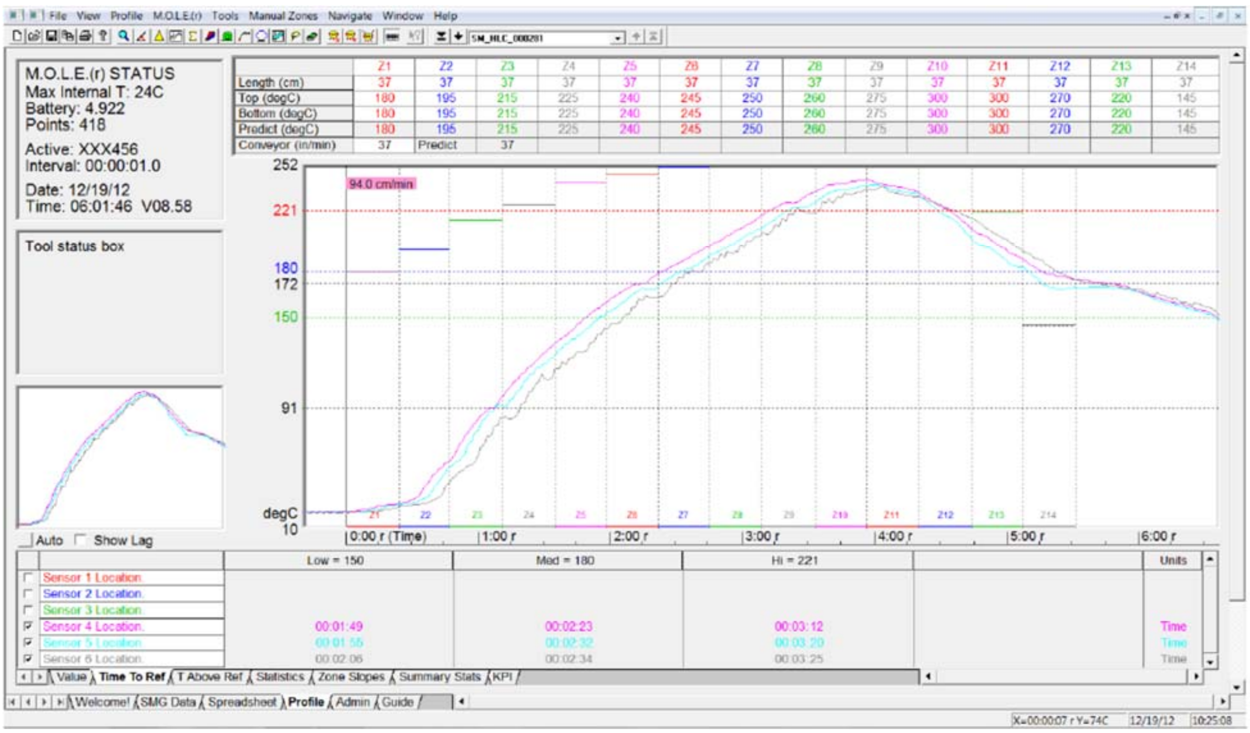


Figure 4-5: Bottom-Side Reflow Profile [37]

4.7 Quality Assurance

Several quality assurance steps were taken. The resistance of each daisy-chained circuit component was checked by hand following reflow to eliminate them from inclusion in further testing (if needed). Boards were also optically inspected, and x-ray analysis was used to determine typical solder-joint quality following reflow. In one instance, several components on one of the boards were sacrificed in a 'pry test' to assure the mechanical strength of the solder joints as reflowed.

Overall build quality was found to be very good. There were some solder-paste specific manufacturability issues. Some problems were found with the SBGA 600 components, of which a few components had missing or misaligned solder spheres/balls. In combination with a failure of the AOI algorithm for this component on the Juki KE-2080L, this led to the failure of several assembled SBGA 600 components. [93]

4.8 Thermal Cycling Test Parameters and Equipment

As per the test plan the assemblies are subjected to thermal cycling testing. A modified JEDEC JESD22-A104-B standard high and low temperature test in a single zone environment chamber is used to assess the solder joint performance. The cycles have dwell temperatures of -40°C to 125°C. This results to a thermal profile with 45-minute ramps with 15-minute dwells and totals to 120 minutes for an overall cycle. Each test group are subjected to 3000 thermal cycles.

Figure 4-6: Thermal Cycling Chambers [93]

4.9 Data Acquisition System

The electrical components used for this experiment are 'daisy-chained' for electrical continuity testing. The electrical resistance for each component was independently monitored. For the thermal cycling testing the test boards are mounted vertically on a heat-resistant plastic divider before placing them inside the chamber. Temperature resistance wires are hand soldered to each active data channel and ground channel for all the test boards. A LabVIEW based data acquisition system developed by Dr. Thomas Sanders of Auburn University is used. A switch scanning system is coupled with a digital multimeter, to continuously monitor the resistance change of the components. This system is couple with LabVIEW software to control and record the test results, figure 4.7 below. IPC-9701 standard is used to define the solder joint failure. resistance increased (from baseline) by over 100 ohms for 5 sequential resistance measurements.

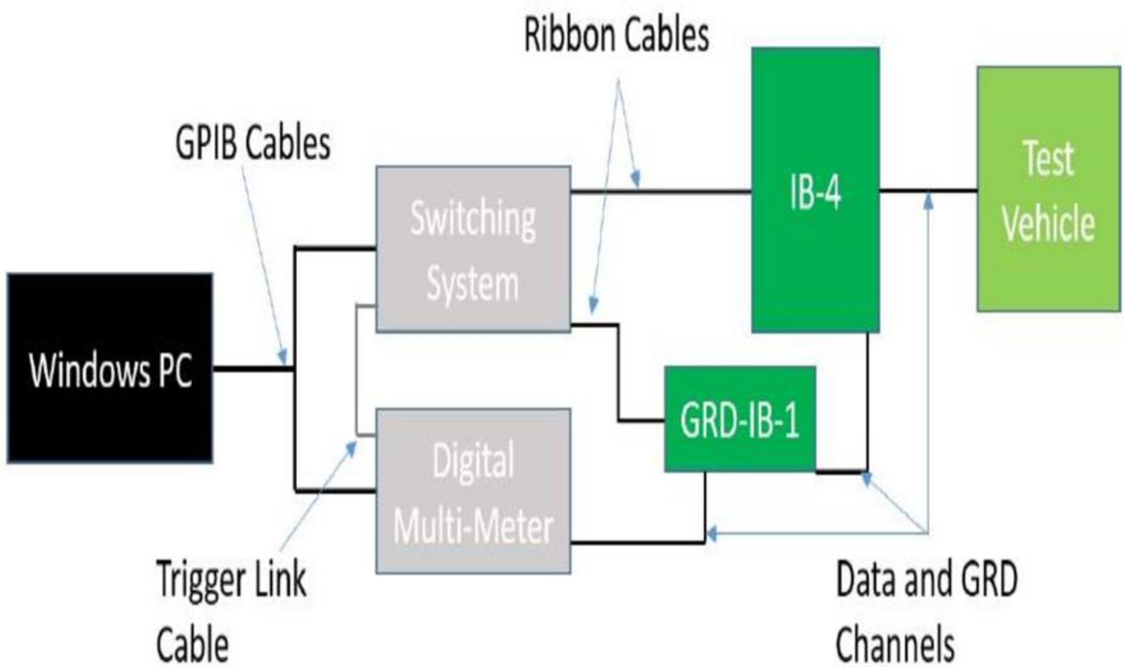


Figure 4-7:Data Acquisition System [37]

Failed test samples taken out and cross-sectioned for further microscopic investigation. The cross-section and sample preparation procedure include cutting of the sample with diamond sectioning blade. This is followed by cold mounting using two-part epoxy system (resin+hardner). Cured samples are polished using semi-automated Pace Technologies FEMTO – 1000 (with NANO-1000T polishing head) machine. PSA backed silicon carbide (SiC) grinding grit papers are applied in sequence.

Final polishing involves use of cloth pad and abrasive particles applied in form of slurry, paste or spray. Proper polishing is critical because the polishing steps must completely remove surface damage from all preceding sample preparation steps. ATLANTIS Polishing Pad is used for both intermediate and final polishing, although this is always subject to refinement. The intermediate polishing step was done using 1-micron alumina particles and the final polishing with 0.05-micron alumina.

Following polishing the samples are carbon coated and examined using scanning electron microscope (SEM). As the samples are metallic backscatter electron (BSE) mode of detection is used. Additionally, energy dispersive spectrometry (EDX) is done to record the material composition information.

4.10 Research Steps

Step 1: Perform Accelerated Life Testing of FR406 and Megtron6 PCB with OSP surface finish with various components and solder paste materials. The boards are isothermally aged at 75°C for the 6m, 12m, and 24m. Boards are to be subjected to thermal cycle testing up to 3000 cycles or to failure. Examples in industry include:

- Investigating the deterioration of an insulation used for electric motors,
- Extrapolating the behavior of the polymer at room temperature
- Discover the operating limits of the product

Step 2: From test, obtain life data. Break down data set from each aging group into each separate factor subgroup.

Step 3: Identify the variables presented from test.

- Response Variables:
  - Survival/Failure (1/0)
- Predictor Variables
  - Solder Paste
    - TC2
      - AIM
      - Alpha Innolot
      - Henkel
      - Indium
      - Inventec
    - TC1
      - SAC305
      - SnPb
      - Innolot
  - Solder Spheres
    - SAC105
    - SAC305
    - SnPb
  - Sphere Size
    - .3
    - .46
  - Stencil Thickness
    - 3mil
    - 5mil
  - Pitch
    - .4
    - .5
    - .8
    - 1
    - 1.27
  - Board Side
    - Top
    - Bottom
  - Aging Month
    - 0 Months
    - 6 Months
    - 12 Months
    - 24 Months
  - Component Type and Package Size
    - BGA
      - CABGA208
        - 15mm

        - CABGA256
            - 17mm
        - CABGA36
            - 6mm
        - CTBGA84
            - 5mm
        - CVBGA432
            - 13mm
        - CVBGA97
            - 5mm
        - PBGA1156
            - 35mm
        - SBGA304
            - 31mm
        - SBGA600
            - 45mm
    - SMR
        - 2512 SMR
- Heatsink
    - Yes
    - No

Step 4: Perform Weibull Regression and Survival Analysis to find a predictive value for the life values. When dealing with multiple independent variables, the formula used to explain the relationship between them is:

$$Y = a + b1 * X1 + b2 * X2 + \dots + bp * Xp$$

The Y (Fixed Variable) and each X (Explanatory Variable) will be clearly defined based on variables obtained in test defined above.

Step 5: From the variables presented, develop a degradation visualization to compare the varying solder paste materials. The response variable (outcome) for the test is survive/fail. Using degradation analysis, the effects of the predictor variables on the response variable will be shown. Changes in the predictor variables will result in a change of the probability of survival or failure. Response and predictor variables will differ with each model. The predicted probabilities of each factor will also be found by examining all possible values of a factor while averaging across the sample values of other factors. The variables used in the formula can differ from the variables presented in this test.

Previous testing has illustrated some potential reliability of the tested materials important with solder doping. The various selection of solder discussed herein are expected to reduce solder joint degradation and improve solder joint reliability.

Chapter 5
Weibull Analysis of Experiments

The TC1 and TC2 experiments consider the thermal cycle reliability of an assortment of different electronic components and evaluates them on FR406 (Present only in TC1) and Megtron6 printed circuit boards. Organic Solderability Preservative (OSP) surface finish is used with all test vehicles in both experiments. Three solder materials were used for testing in the TC1 experiment. For the TC2 experiment, the five best performing solder materials were selected from thermal shock, vibration, and drop down select testing. The design of the board and components used are similar for both the TC1 and TC2 experiment. Data from the TC1 and TC2 experiments were compared with the hopes of finding a leadfree solder material from the TC2 experiment with improved reliability over the materials tested in TC1. Comparison data was performed for only the Megtron6 substrate.

Isothermal storage at high temperature was used to accelerate the aging of the assemblies. Separate temperatures were used for aging in the TC1 experiment, and only one aging temperature was used for TC2. Aging durations are 0-Months (No Aging, baseline), 6-Months, 12-Months, and 24-Months. The no aged group was stored at 25°C shortly before testing, and the 6, 12, and 24-month aged group all had aging temperatures of 75°C. The test vehicles were then subjected to thermal cycling with temperature extremes of -40°C to +125°C on a 120-minute thermal profile (45-minute ramp and 15-minute dwell for each extreme) in a single-zone environmental chamber to assess the solder joint performance. The temperature cycling test results below show a comparison of the reliability data and survival percentages from the 0-

Month (No Aging), the 6-month, and 12-Month aging groups. (24-month aging data still being obtained)

Weibull and survival analysis were used to determine the trends in reliability and show when failures are occurring. Weibull ++ software was used as an analysis tool to obtain the life data of the solder materials and define a lifetime distribution, measured in terms of cycles. For all Weibull graphs exhibited in this chapter, the scale, shapes, and coloring are consistent throughout. Histograms are also used below to further display the trends in reliability. The scaling of the histograms is not consistent and will be defined. Coloring is not consistent with the Weibull plots. Comparison data is performed on the TC1 and TC2 experiments, but the focus of this study is to show the improvements of the TC2 experiment over TC1. Survival data for TC2 will be presented more predominately.

5.1 CABGA36

Chip Array ball grid array components are cutting edge technology, which offers high performance and reliability while requiring minimal space and cost. 3 types of CABGA components were built onto the test vehicles for both experiments. The smallest of these CABGA components and smallest BGA component is the CABGA 36 (6mm). The component is found on both the top and bottom-side with 2 components built on to top-side boards and 6 built on to bottom-side boards for all aging groups.

The CABGA 36 was one of the slowest failing components present in both experiments. Weibull analysis was not able to be performed on the survival data based on the number and distribution of failure points. The survival percentage of each solder material for the TC1 and TC2 experiments for the 12-month aging group, figure 5.1 below. No failures occurred for the no aged group, and a similar trend as is shown in the figure is also seen in the 6-month aging data. For the materials shown in the TC2 category, all failures occurred between 800-1000 cycles. Failures for the TC1 experiment were much more dispersed throughout the 3000 measured cycles.

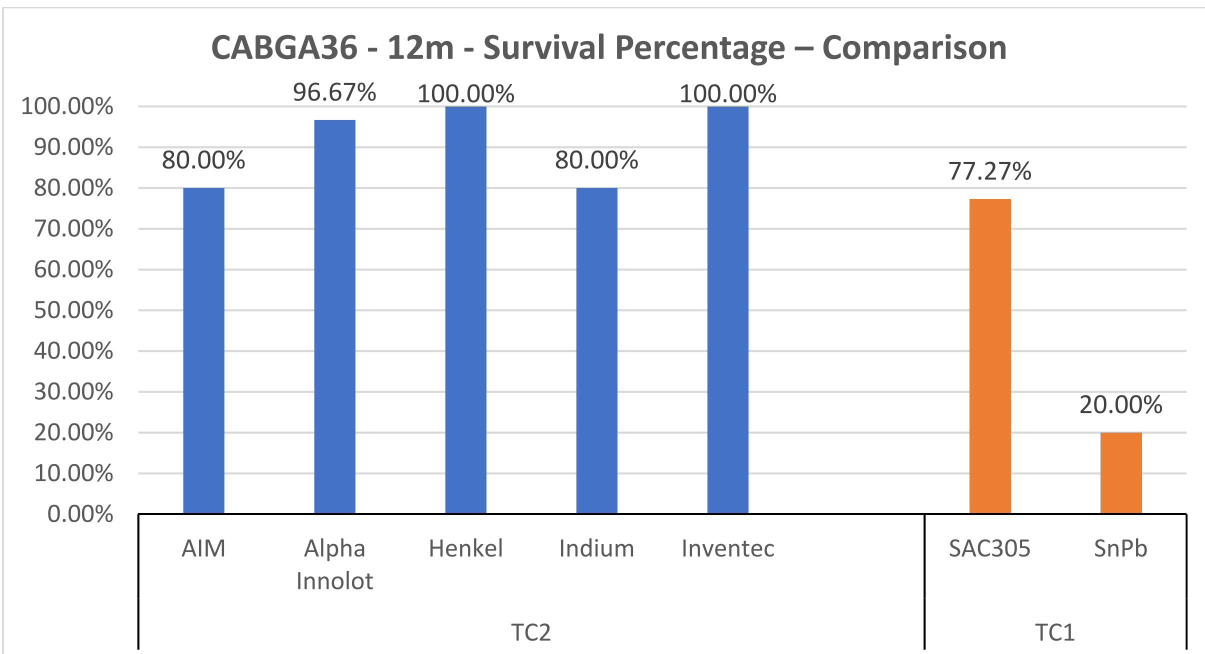


Figure 5-1: CABGA36 - 12m - Survival Percentage – Comparison

The survival percentage of the solder mater for the TC1 and TC2 experiments was analyzed in figure 5.1 above. The materials in the TC2 experiment outperformed the materials in the TC1 experiment in the amount of failures occurring throughout the test. For all test vehicles in the TC2 experiment, 30 samples were measured for the survival percentage. Although many failures occurred for the materials in TC1, high level of reliability were seen with both materials experiencing high Eta values. The TC1 experiment had a different number of samples for each of the solder materials used. The SAC305 solder material had 22 samples tested with an Eta value of 3357.78. The SnPb solder material had 50 samples. Although SnPb experienced a high number of failures, the material had an Eta value of 2944.86 meaning failures occurred toward the end of cycling. The trends shown for the materials is consistent with the other CABGA components analyzed below.

5.2 CABGA208

The second type of CABGA components built onto the test vehicles is the CABGA208. The CABGA208 is comparatively much larger (15mm) than the CABGA36 (6mm) component presented earlier. The component is also located on both the top and bottom side of the board. No significant difference was found in the plots between component placement on top or bottom boards. Survival data was obtained and analyzed on this component with the separate solder paste materials under the 0, 6, and 12-month aging.

Figure 5.2 below, displays the Weibull plot of comparison data for the CABGA208 component in the 12-month aging group of the TC1 and TC2 experiments. The test vehicles in TC2 performed poorly compared to TC1 with only one material from the TC2 experiment (Inventec) showing increased reliability over the materials in TC1, with the other four material showing much lesser reliability. Inventec surpassed all alternative materials in the TC2 experiment with an increase in the reliability between 32-40% over the second most reliable material for all aging groups. The CABGA208 component was also the only component to show a higher level of reliability of the SnPb over the SAC305 material.

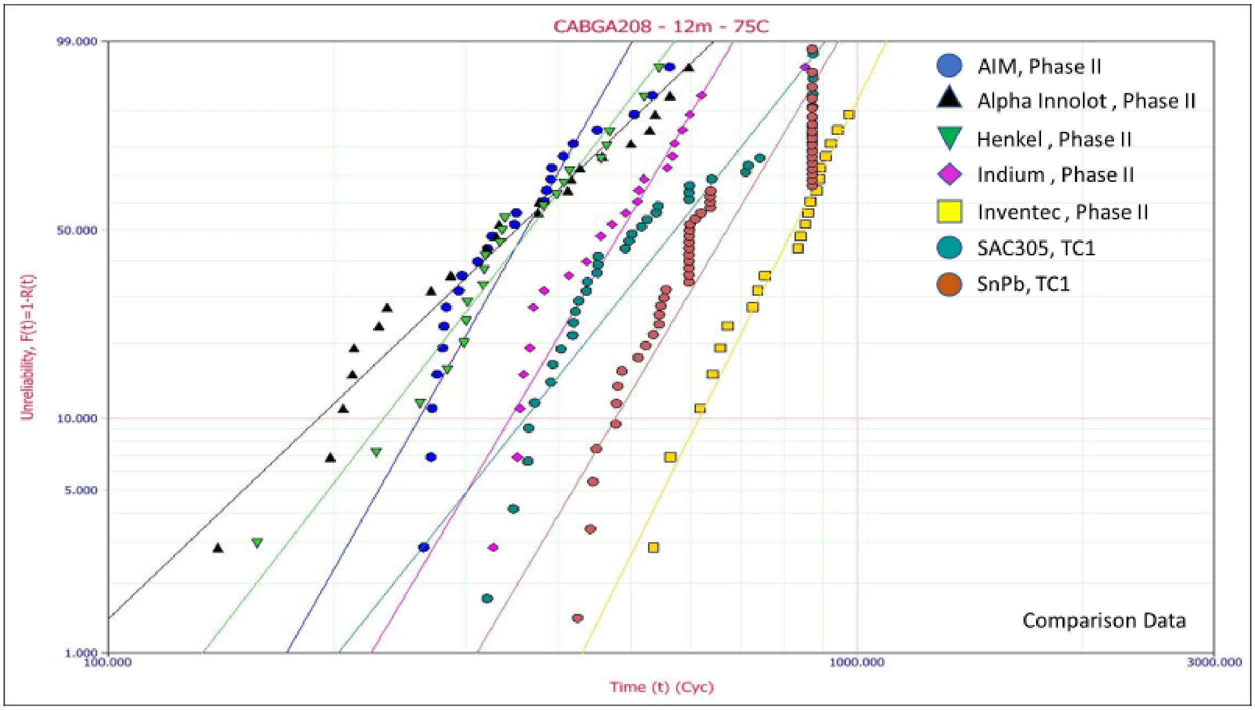


Figure 5-2: CABGA208 - 12m - 75C - Comparison

With the major decrease between Inventec and the other four materials in TC2, further analysis was performed. The trend throughout the aging groups is shown in the histogram below, figure 5.3. The graph displays the Eta values of the five materials for all aging groups. Inventec shows impressive reliability compared to the other material and degrades only 11.5% from no aged to 12-month aging. The other four materials experienced degradations rates between 22-38%. Alpha Innolot performed the poorest in reliability of all the materials in the test, but it had the second lowest degradation rate. The scale of the graph was reduced to 1000 cycles to more clearly show the trends. Overall, the CABGA208 was an earlier failing component compared to others in the test. From the figure below, the Inventec material clearly outperformed the other materials.

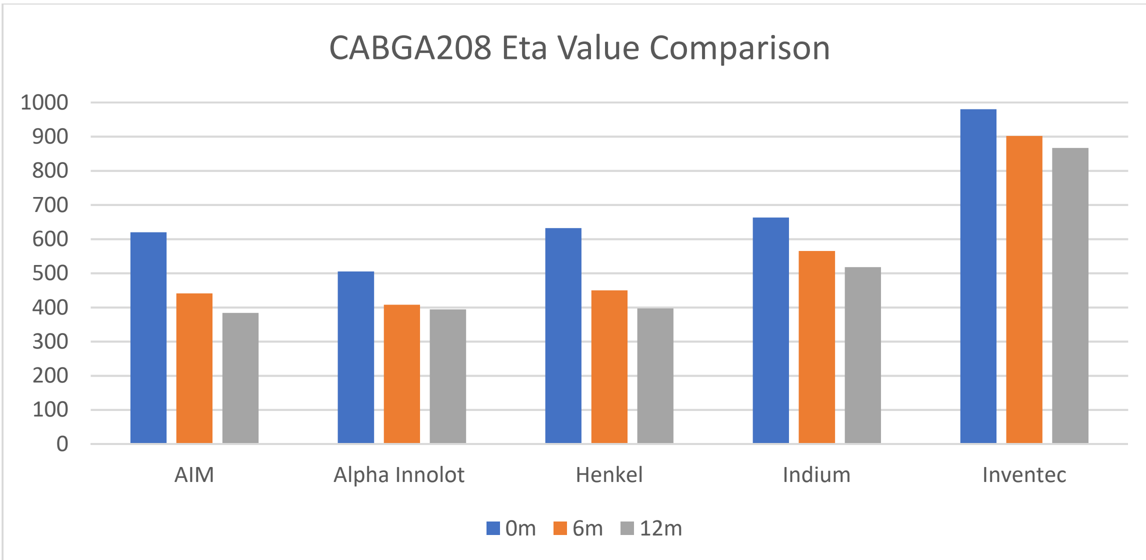
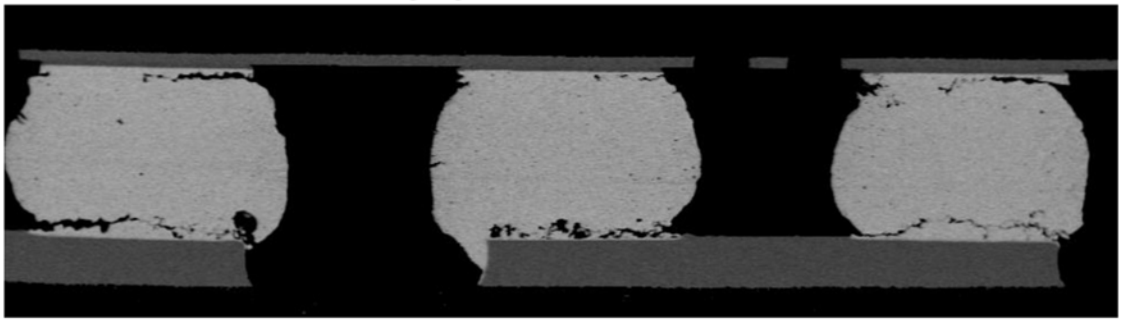


Figure 5-3: CABGA208 – TC2 – Eta Value Comparison

Figure 5.4 below shows the cross-section images for the SAC305 solder material from TC1 and the Inventec material from TC2. The SAC305 material experiences cracks propagating through the component and board side after 12-month aging. The Inventec material only experiences cracks propagating through the component side. This trend is believed to be the cause of the higher levels of degradation for the SAC materials. Further material analysis is ongoing.

TC1 SAC305 – 12m – Cross Section



TC2 Inventec – 12m – Cross Section

Figure 5-4: TC1 SAC305 and TC2 Inventec CABGA208 Cross Sections 12m [37]

5.3 CABGA256

The largest of the CABGA components used for testing is the CABGA256 (17mm). Comparatively, the CABGA256 showed decreased levels of reliability for the SAC305 and SnPb materials in TC1 and Inventec in TC2, but the trends for the other four materials in TC2 are consistent throughout. Figure 5.5, below, shows the comparison of the 12-month aging data for the CABGA256 component. This component failed early into the test with no material's Eta value exceeding 626.

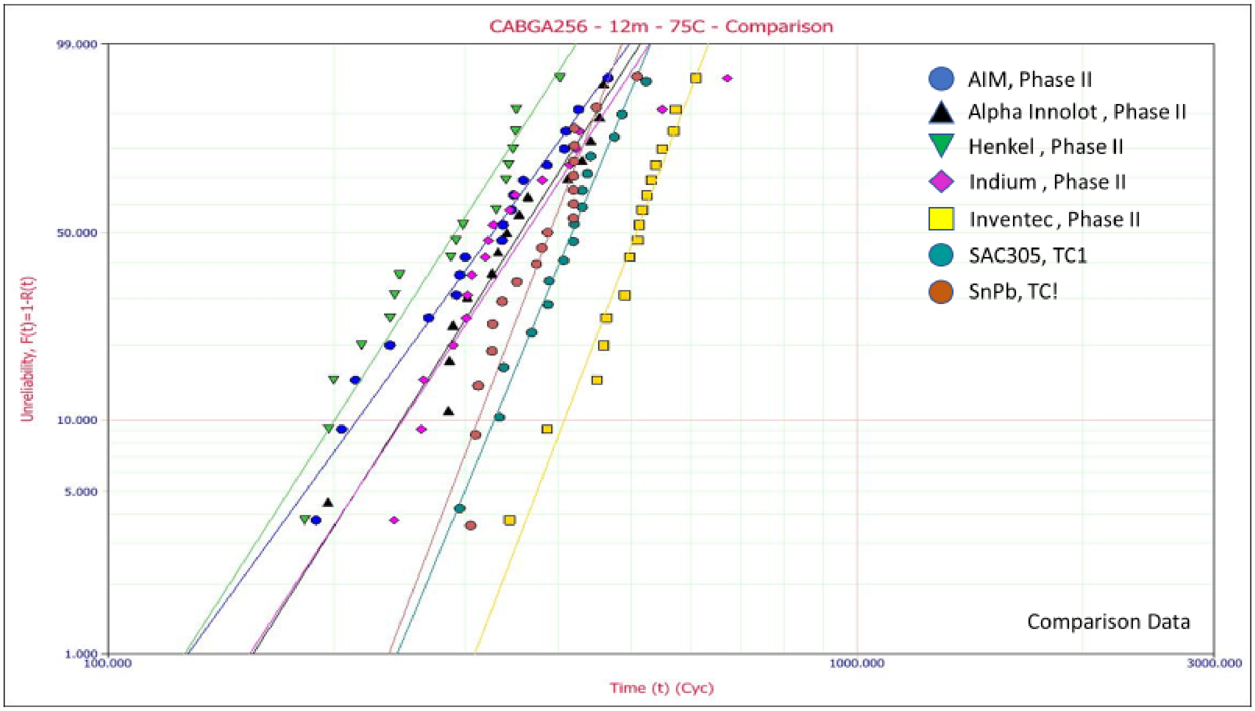


Figure 5-5: CABGA256 – 12m – 75C – Comparison

Similar to the CABGA208 component, the trends shown in the 12-month aging group are consistent with the no aged and 6-month aging group. Inventec has shown to be the best material for all CABGA components over all materials used in the TC1 and TC2 experiments. When comparing the reliability of various solder paste throughout the various gaining groups, a clear trend was revealed. The ranking of the materials differed from the CABGA components, with the rankings being:

- Inventec
- Indium
- Alpha Innolot
- AIM
- Henkel.

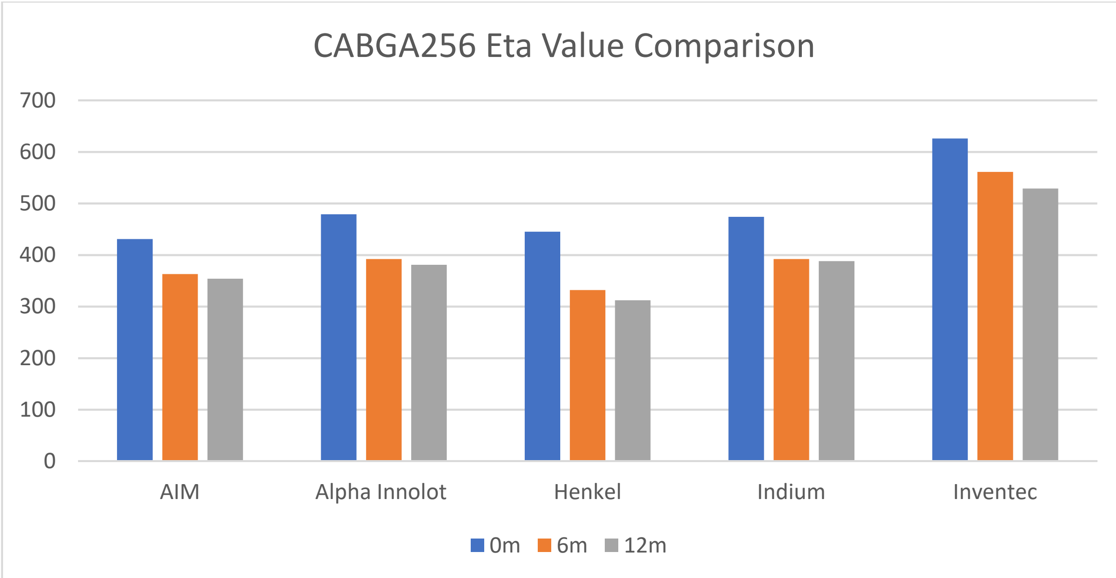


Figure 5-6: CABGA256 – TC2 – Eta Value Comparison

The cross-section images in figure 5.7 below show a similar trend seen above for the CABGA208 component. The crack propagates through the component and board side for the SAC305 material, and the crack propagates only on the component side for the Inventec material. This trend is believed to be the cause of the higher levels of degradation for the SAC materials. Further material analysis is ongoing.

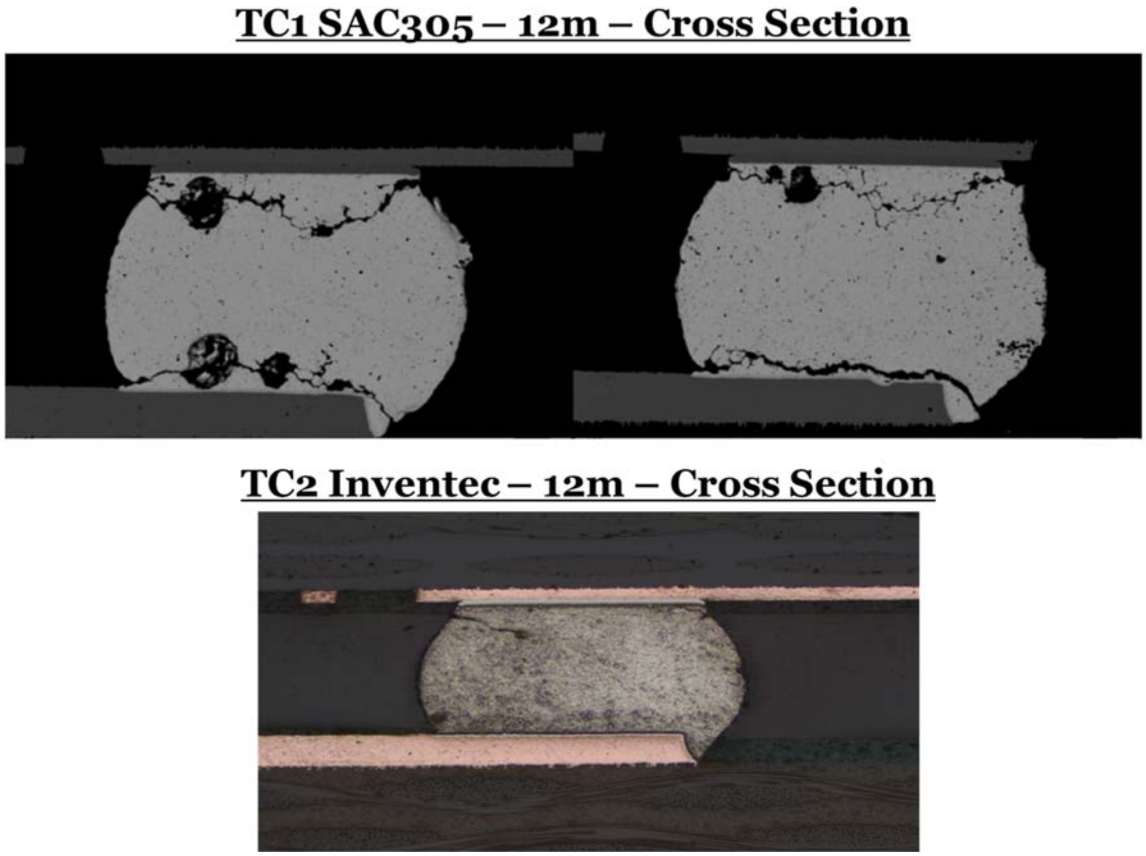


Figure 5-7: TC1 SAC305 and TC2 Inventec CABGA256 Cross Sections 12m [37]

5.4 CTBGA84

The ChipArray Thin Ball Grid Array (CTBGA) is the second component type to be analyzed. The CTBGA 84 is one of the smallest component appearing in both tests (6mm). This component is found only on the bottom-side of the test vehicle for both experiments.

The CTBGA 84 component was one of the slower failing components tested. Consequently, too few failures occurred in most test subgroups to form Weibull distributions. Figure 5.8, below, shows the available failure data from the 12-month aging group and give the survival percentage of all the materials. Similar to the CABGA36, the component failed very late into the test, with some materials experiencing failures after the 2500^{th} cycle. Overall, the

TC2 materials performed comparatively with the TC1 materials for the CTBGA84 under 12-month aging.

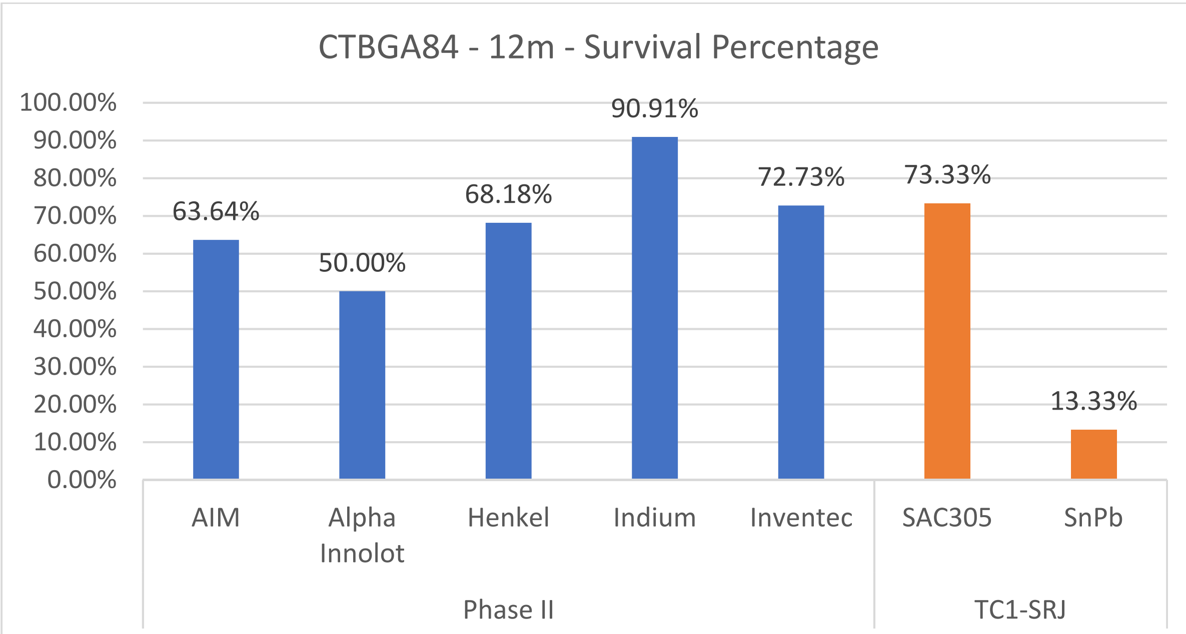


Figure 5-8: CTBGA84 - 12m - Survival Percentage - Comparison

Weibull analysis was not able to be performed based on the amount of failures for some of the solder materials. A comparison of the survival percentages of the 12-month aged groups from the phase II and TC1-SRJ are displayed in the histogram above. 22 samples for the Phase II materials were measured. For the TC1-SRJ materials, SAC305 had 15 samples, and SnPb had 30 samples. An average majority of failures occurring in the Phase II materials occurred between 1000-1200 cycles. The best performing material was Indium with failures occurring around the 2500th cycle.

5.5 CVBGA97

The ChipArray Very Thin Ball Grid Array (CVBGA) is the final iteration of the CABGA component appearing in the experiments. The CVBGA 97 is the smallest BGA package in the experiments at 5mm and has the finest pitch of any BGA component (Along with the CVBGA432 component mentioned later). This component is found only on the bottom-side of the test vehicles.

The CVBGA 97 component was one of the slower failing components tested. Consequently, too few failures occurred in most test subgroups to form Weibull distributions. Figure 5.9, below, shows the Substrate Comparison from the No Aging Group with matched SnPb solder. As with the other plastic ball grid array (BGA) components tested, the FR4-06 substrate outperforms the Megtron6 substrate. This substrate effect appears to be consistent for all standard (cavity-up) plastic ball grid array (BGA) packages tested, irrespective of any other factor.

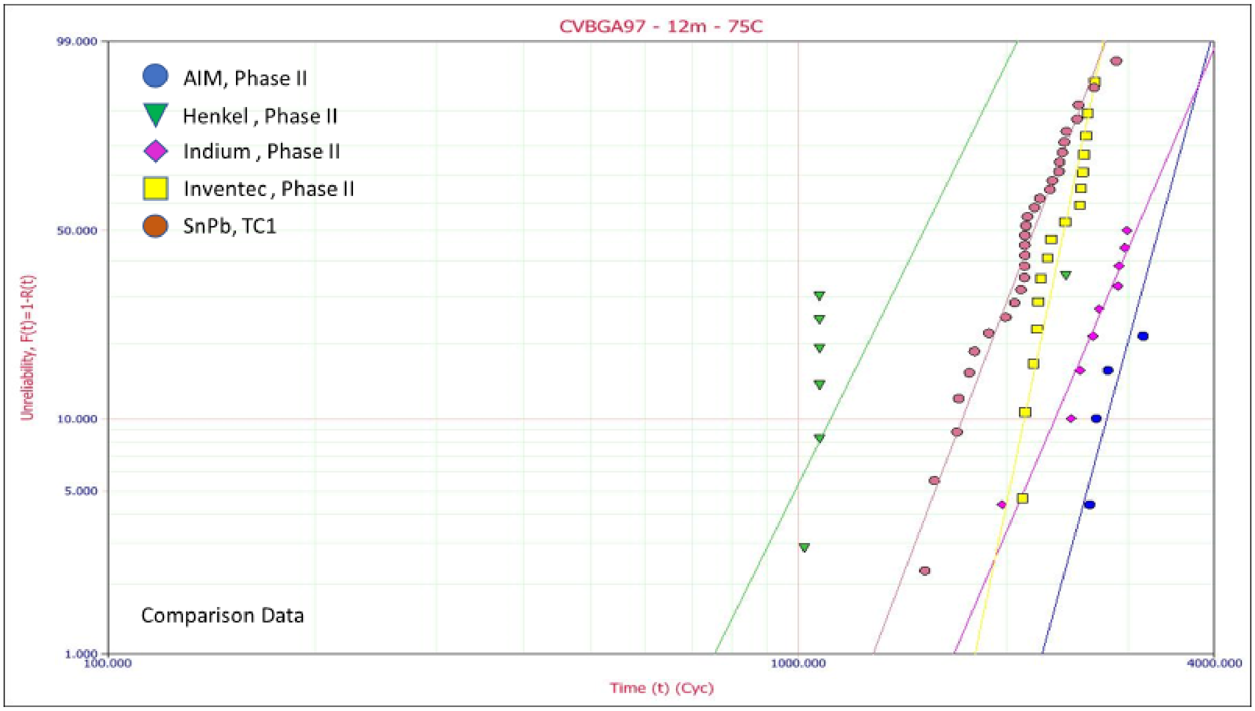


Figure 5-9: CVBGA97 - 12m - 75C - Comparison

The CVBGA97 component did not experience much failure throughout the test. For the 0-month aged group, the only materials to experience failures were the Inventec and Indium materials with less than 50% of components in the groups failing. Based on the amount of failures, two materials are not shown in the plot above, SAC305 and Alpha Innolot.The SAC305 material in the TC1 experienced only two failures occurring on the 2900th cycle. The Alpha Innolot

5.6 CVBGA432

CVBGA432 is abundantly larger (13mm) than the alternative CVBGA component, but has the smallest pitch of any BGA appearing in these experiments. The component is found only on the bottom-side boards.

The trends in reliability for all five materials are more closely correlated with each other, figure 5.10 below. Although Indium performed best for all aging groups, the statistical difference between the other materials is very small.

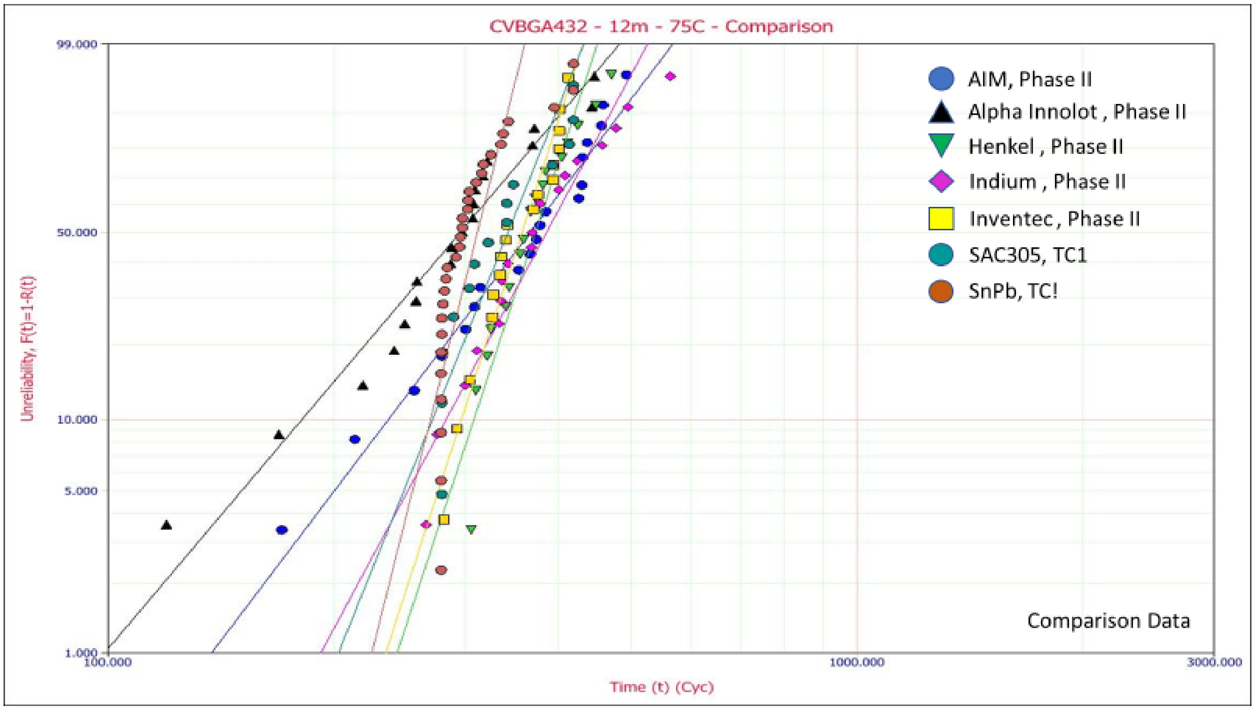


Figure 5-10: CVBGA432 – 12m – 75C – Comparison

A comparison of the Eta values for the CVBGA432 component under 0, 6, and 12-month aging in the TC2 experiment, figure 5.11 below, was analyzed to show how the materials compared with the CABGA component. When comparing the reliability of various solder paste throughout the various gaining groups, a clear trend was revealed. The ranking of the materials differed from the CABGA components, with the rankings being:

1. Indium
2. Aim
3. Henkel
4. Inventec

5. Alpha Innolot

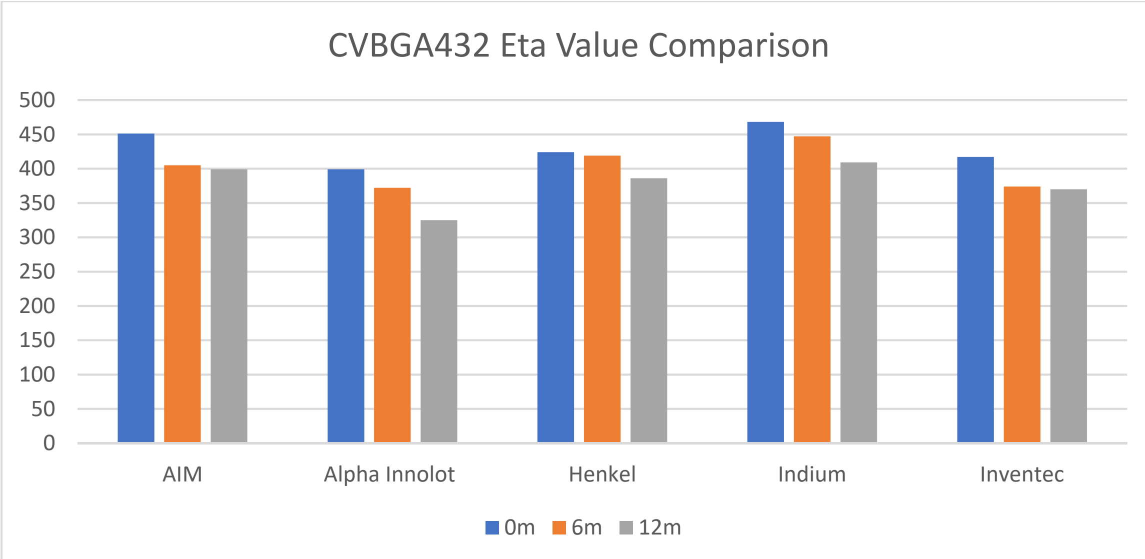


Figure 5-11: CVBGA432 - TC2 - Eta Value Comparison

All solder paste materials are contiguous in value with minor differences in reliability no greater 75 cycles. The Scale in this graph was reduced to 500 to more clearly show how closely related the Eta values are for the five materials. Although this component failed earlier in the test, not much degradation was seen as the component was aged.

5.7 PBGA1156

Plastic Ball Grid Array (PBGA) components provide a cost-effective advanced packaging solution, offering higher density over traditional leadframe packages. The PBGA1156 is the only plastic capped BGA component present in the test. Two PBGA1156 components were built on the top-side of the board with one of the components having a heatsink attached. Figure 5.12 and 5.13 below shows the reliability data for the PBGA1156 with a heatsink attached under 12-month aging.

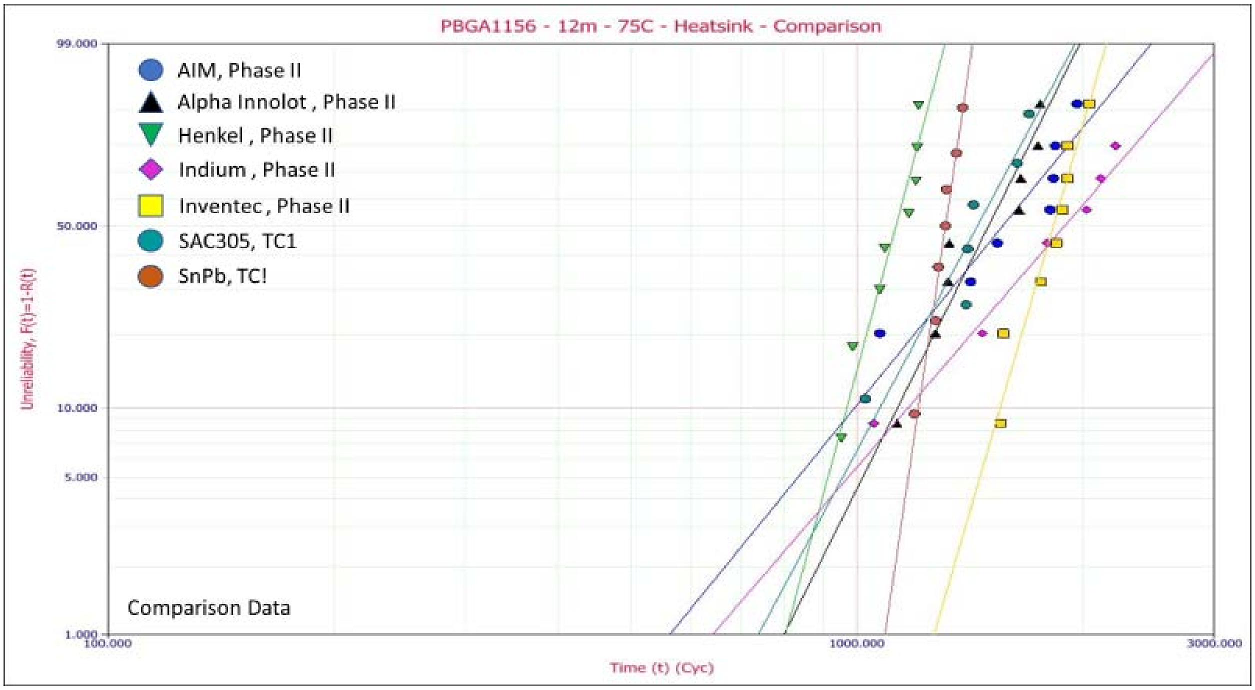


Figure 5-12: PBGA1156 - 12m - 75C - Heatsink - Comparison

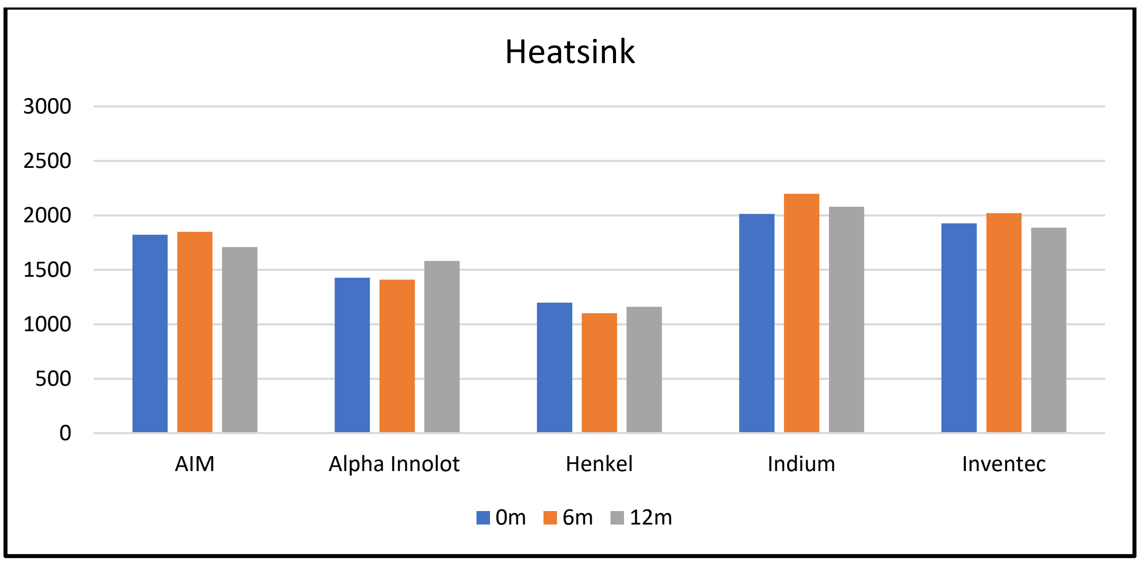


Figure 5-13: PBGA1156 - Heatsink - TC2 - Eta Value Comparison

figure 5.14 and 5.15 below shows the reliability data for the same component with no heatsink attached. The largest change seen when comparing the two plots is the increase in reliability for the SAC305 material in the TC1 experiment. Further analysis of the effect of heatsink will be discussed in the following chapter. Heatsinks have shown to reduce the level of reliability for materials.

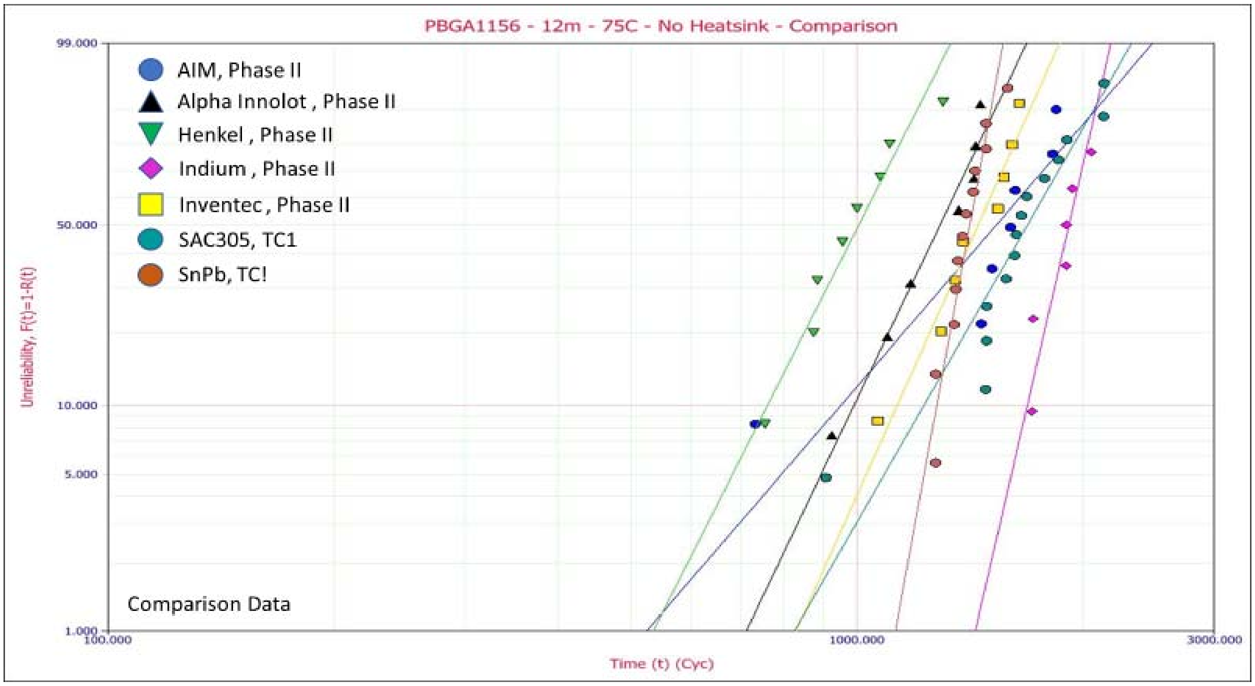


Figure 5-14: PBGA1156 - 12m - 75C - No Heatsink – Comparison

The PBGA1156 component overall showed an intermediate level of reliability compared to the other analyzed components. The heatsink seemed to have an effect on certain materials by lessening the level of reliability.

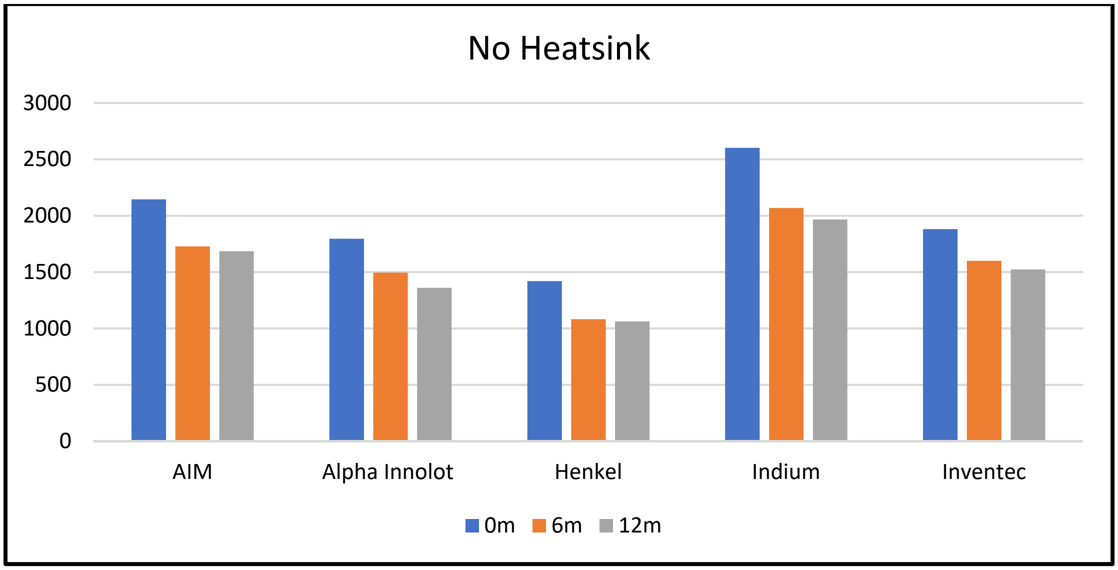


Figure 5-15: PBGA1156 - No Heatsink - TC2 - Eta Value Comparison

5.8 SBGA304

Super Ball Grid Array (SBGA) components very low profile, high-power BGAs with enhanced thermal properties. SBGA components are metal-capped, cavity-down designs and are therefore structurally distinct from the other ball grid array packages considered. The SBGA component are the two of the largest components present in both experiments, with the SBGA304 being 31mm. The SBGA304 component was a top performer extremely well even with the larger size.

The trends of reliability shown for the SBGA304 performed remarkably for all aging groups of TC1 and TC2. Of all the materials analyzed in testing, only three saw failures. The materials that saw failures were included:

- AIM
- Henkel
- Indium

Each of the three materials experienced approximately 2-4 failures from the available samples. Based on the failure rate, Weibull analysis was not able to be performed.

5.9 SBGA600

The SBGA600 is the largest component (45mm) present in this test. Similar to the PBGA1156 component, two SBGA600 components were built on to the top side of the board with a heatsink attached to one of them. For the large size of the components, failures were not seen until close to the end of testing.

Figure 5.16 below shows a comparison of the survival data of the 12-month aging group SBGA600 component with a heatsink attached. The scaling of the plot was stretched to 5000 cycles to mores clearly represent the distribution. All materials analyzed showed extremely high levels of reliability. In the TC2 experiment, Alpha Innolot only experienced one failure and therefore is not present in the plot. The Indium and Inventec materials outperformed the materials in the TC1 experiment.

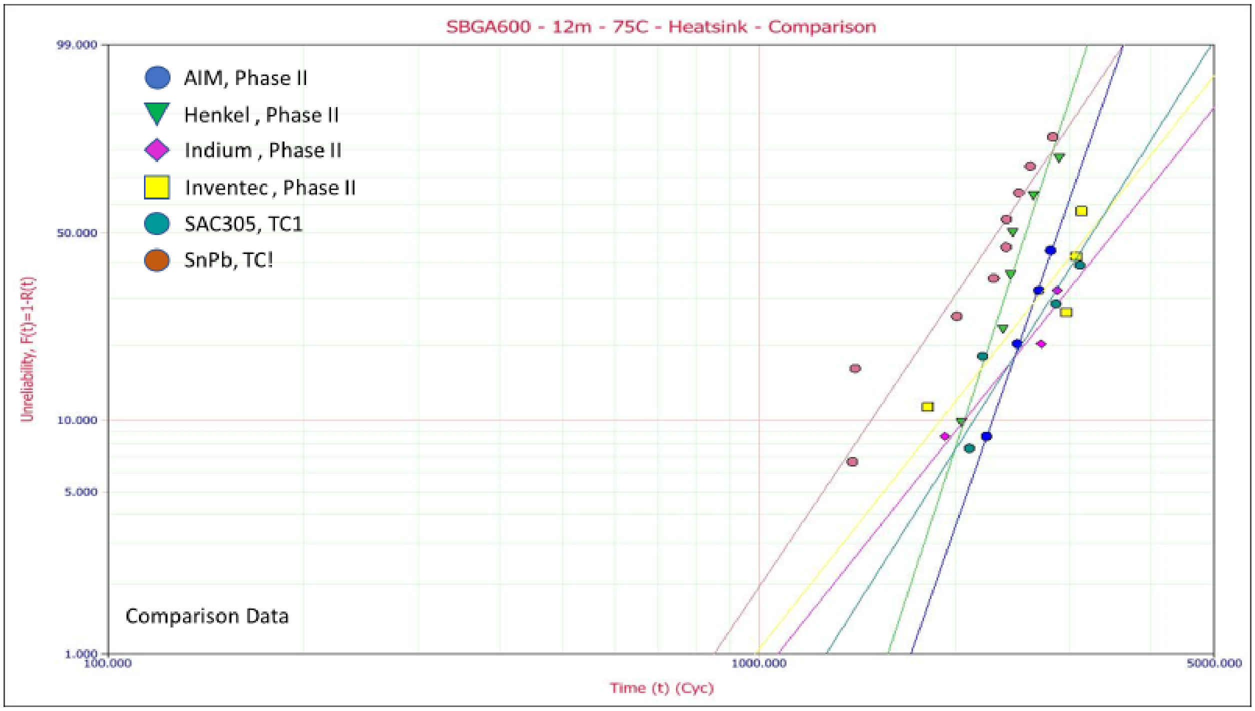


Figure 5-16: SBGA600 - 12m - 75C - Heatsink - Comparison

The reliability trends of the SBGA component are not consistent with the trends shown from other BGA components. The failures in the SBGA metal-capped packages reverse the substrate failure trends seen for the plastic packages of which failures first take place on the FR406 substrate followed by the Megtron6 substrate. Further analysis to understand the cause of these trends was performed and the analysis results were published.

5.10 SMR 2512

A wide variety of Surface mount resistors (SMR) were built onto the experiments' test vehicles, each with variations in measurement and power ratings. The SMR 2512 is the SMR chosen for analyzation and was built only on the TC2 test vehicles. The SMR 2512 is the largest resistor appearing in either experiment and typically have the least reliability. Figure 5.17 below shows the Weibull plot for the Survival data from the 12-month aging group. The trends shown here are consistent throughout the no aged and 6-month aging groups.

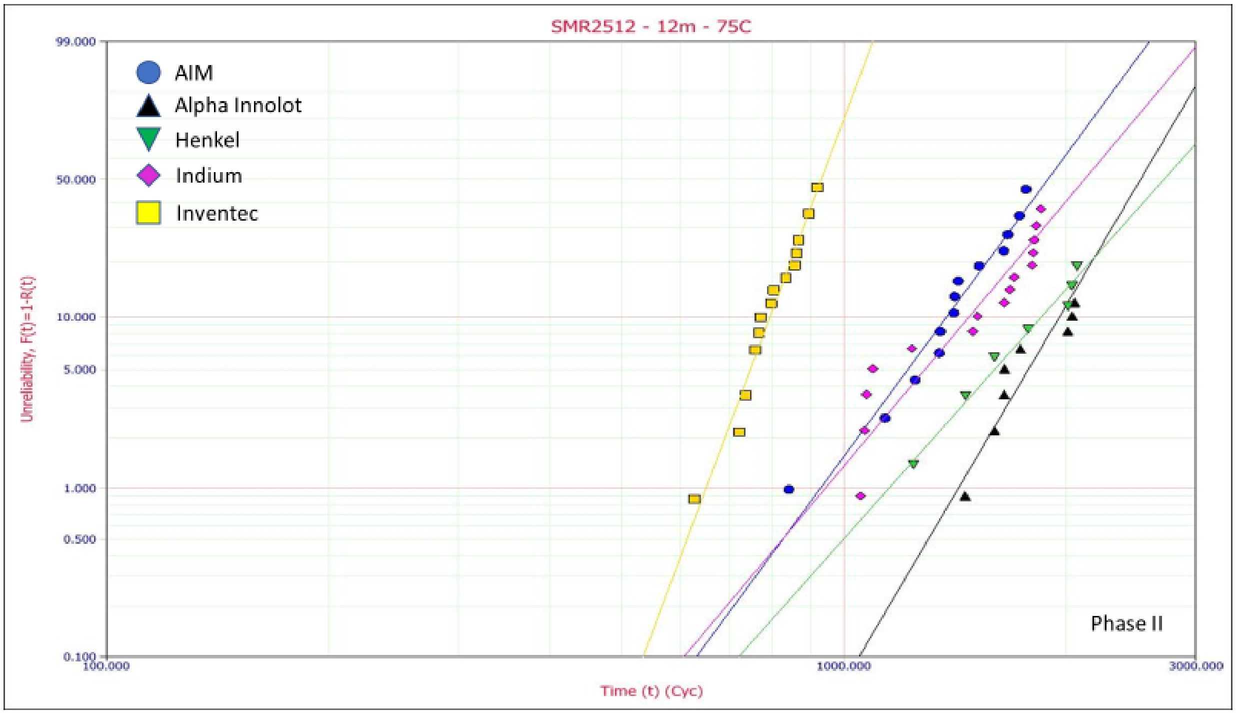


Figure 5-17: SMR2512 - TC2 - 12m - 75C

Overall, the SMR 2512 performed very well for all aging groups over the TC2 experiment. The interesting trend in this data is the reliability of the Inventec material. The Eta value for Inventec is approximately 1600 cycles lower than then four alternative materials. Inventec performed well for all other components beside the SMR. Material analysis is ongoing to understand these phenomena.

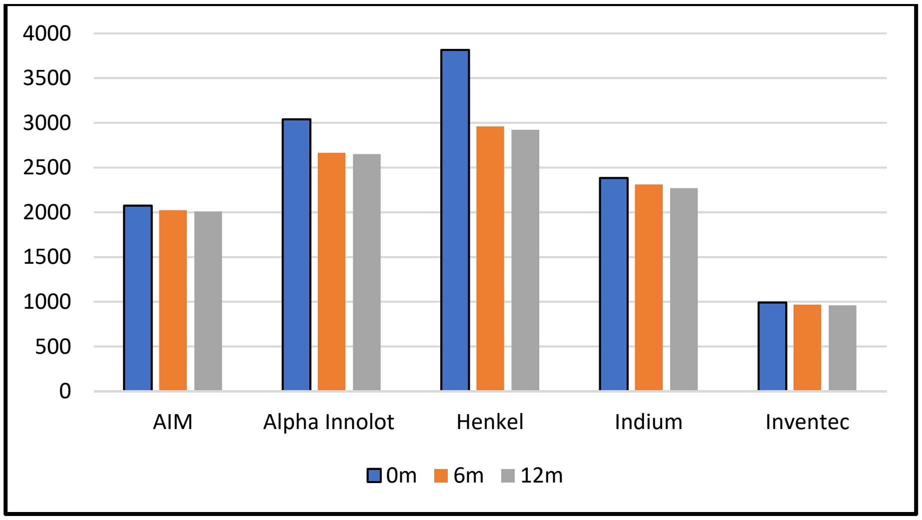


Figure 5-18: SMR2512 – TC2 – Eta Value Comparisons

A similar trend is shown in the cross-section analysis performed on the SMR2512 component, figure 5.19 below. The 2512 was not attached to the TC1 test vehicles. Therefore, an image was taken from the previously performed TV7 test. The crack can be seen propagating through the bulk solder for both images.

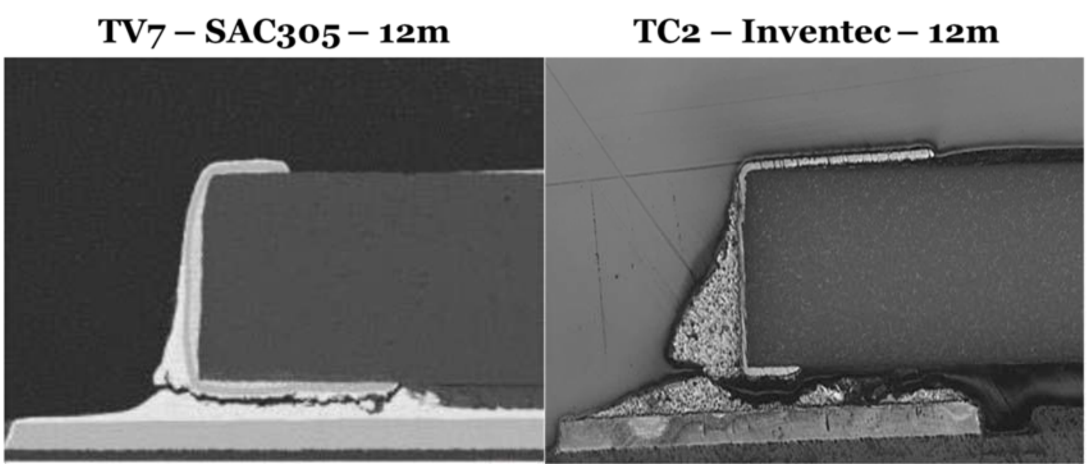


Figure 5-19: TV-7 SAC305 and TC2 Inventec Cross Sections 12m

5.11 Comparison Results

The performance of the solder materials differed greatly among the separate components of the TC1 and TC2 experiments. Components performed comparatively amongst both experiments. Some materials proved to show increased trends in reliability, including Inventec and Alpha Innolot. Henkel showed to be the worst material for all components beside the SMR, where Inventec showed the worst. Further analysis was performed in the following chapter to understand the effect of certain variables on the level of reliability and how they effect the survival probability.

Chapter 6
Survival Analysis and Visualizations

Weibull data provided the trends in reliability for all components in all aging groups, but further analysis of how the materials degrade with aging is required to understand their true performance. Degradation analysis is used to determine the effect of the input variables on the probability of survival. The predictor variable of this test is defined as, if a component survived the test? (Survival = 1 and Failure = 0)

6.1 Predict Variable

- Survived – Did the material survive the test? (Binary: "1" means "Survived", "0" means "Failed")

6.2 Input Variables

- Cycle Failed (Numeric)
- Solder Paste (Categorical: "AIM", "Alpha Innolot", "Henkel", "Indium", Inventec", "SAC305", "SnPb", "Innolot")
- Solder Sphere (Categorical: "SAC105", "SAC305", "Innolot", "SAC-Y", "SnPb", "N/A")
- Substrate (Categorical: "Megtron6", "FR406")
- Stencil Thickness (Numeric)
- Board Side (Categorical: "Top", "Bottom")
- Aging (Numeric)
- Aging Temp (Numeric)

- Component (Categorical: “CABGA36”, “CABGA208”, “CABGA256”, “CTBGA84”, “CVBGA97”, “CVBGA432”, “PBGA1156”, “SBGA304”, “SBGA600”, “2512SMR”)
- Package Size (Numeric)
- Pitch (Numeric)
- Heatsink (Categorical: “Yes”, “No”, “N/A”)

6.3 Data Investigation

The plot of survivability vs. time is utilized to compare the degradation rates of each individual TC2 material compared with SAC305 material from TC1. The horizontal lines represent the survival duration over the interval of cycles tested, and the vertical lines represent the cycle tested. Each of the intervals is constructed to be such that one observed failure is contained in the interval, and the time of the failure occurs at the start of the interval. As the cycle count increases, the probability for survival lowers. The scaling of the plots differs for each of the components being analyzed based on the differing failure rates. Analysis was performed on the 0-month and 12-month aging group for the various components on the Megtron6 substrate to understand the degradation rates for each material. Input variables were chosen based on the number of failures present. Smaller components did not experience sufficient failure data to perform analysis. B(10%) and B(63%) life comparisons were then performed to further analyze the data. Each material coincides with a distinct color.

- TC1 SAC305 – Orange
- TC2 AIM – Purple
- TC2 Alpha Innolot – Gray

- TC2 Henkel – Yellow
- TC2 Indium – Green
- TC2 Inventec – Blue

6.4 CABGA208

According to the Weibull analysis performed in the previous chapter, the only material in TC2 to outperform the materials in TC1 for the 12-month aged group was the Inventec material. In figure 6.1, the comparison of degradation from 0-month to 12-month aging of Inventec and SAC305 is shown. A high level of degradation can be seen for the SAC305 material throughout the test ($\Delta B(10\%) = 492.77$, $\Delta B(50\%) = 332.50$, $\Delta B(63\%) = 289.86$). Inventec exhibits a much lesser degradation rate and shows improved reliability for both aging groups ($\Delta B(10\%) = 164.34$, $\Delta B(50\%) = 120.72$, $\Delta B(63\%) = 121.34$).

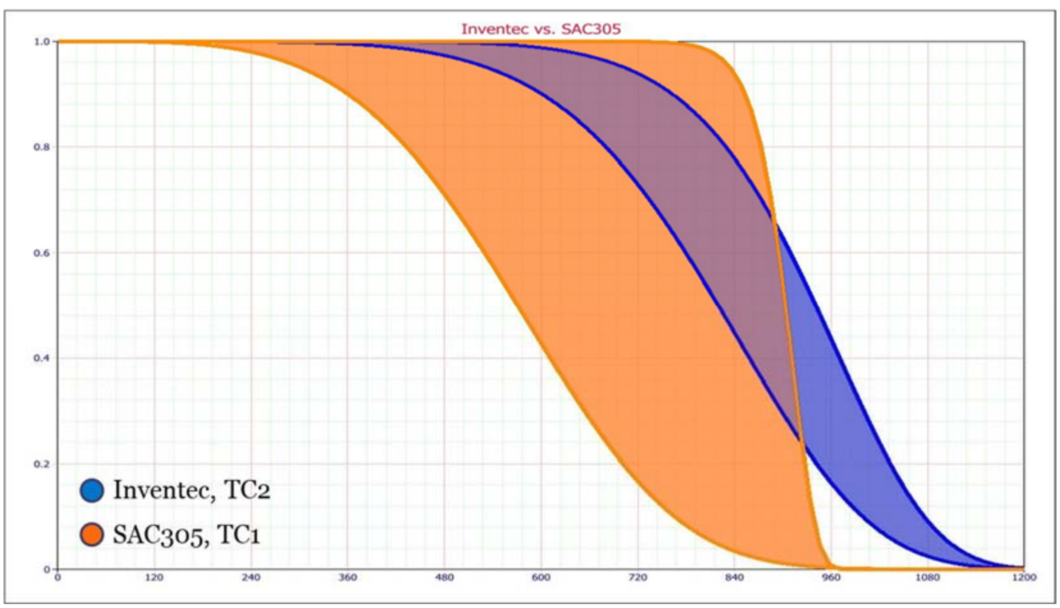


Figure 6-1: CABGA208 – TC2 Inventec/TC1 SAC305 Comparison - 12m - 75°C

The remaining TC2 materials are presented in figure 6.2 below. The degradation rates are much larger for much of the materials. Although, each material has a lesser degradation rate than the SAC305 material.

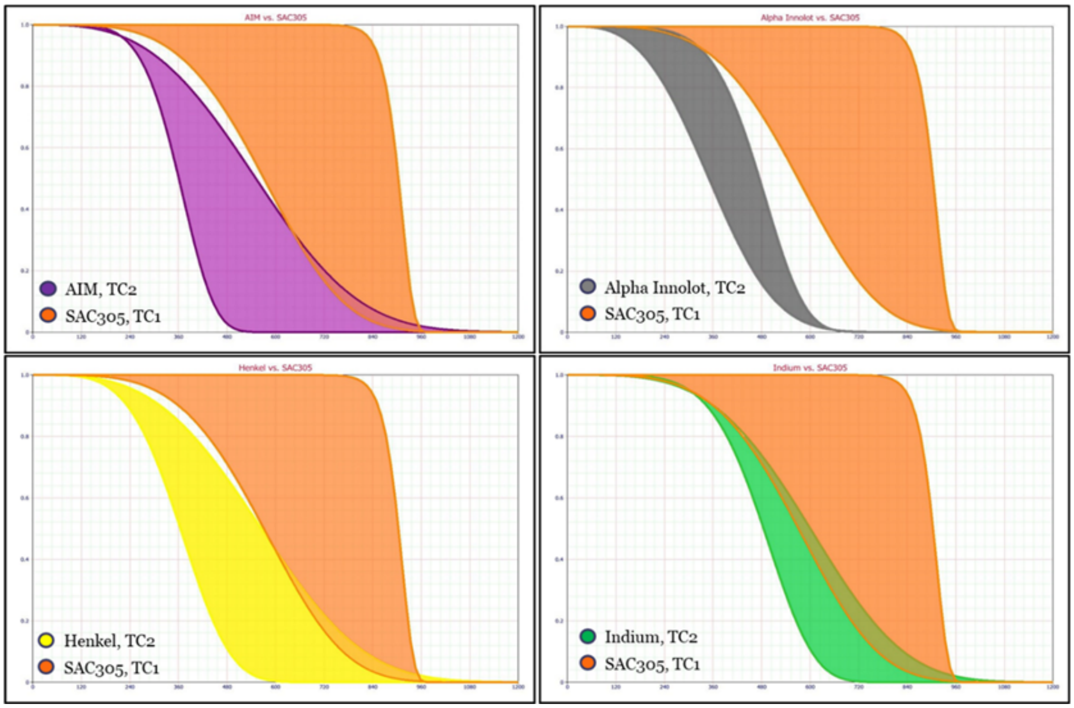


Figure 6-2: CABGA208 - Other TC2 Materials/TC1 SAC305 Comparison - 12m - 75°C

Further visualizations of the comparison of degradation through B(10%) and B(63%) of the CABGA208 are shown in figures 6.3, 6.4, and 6.5. Figure 6.3 and 6.4 present the B(10%) and B(63%) life comparisons for the 0, 6, and 12-month aging groups. The power formula is given for each degradation line. High levels of degradation can be seen for the SAC305 component in the early stages of testing and continue throughout. Figure 6.5 shows the interaction and main effect plots for each TC2 material. These plots present a simple way to rank the materials throughout each stage of testing. Inventec is clearly shown as the superior material for the CABGA 208 component.

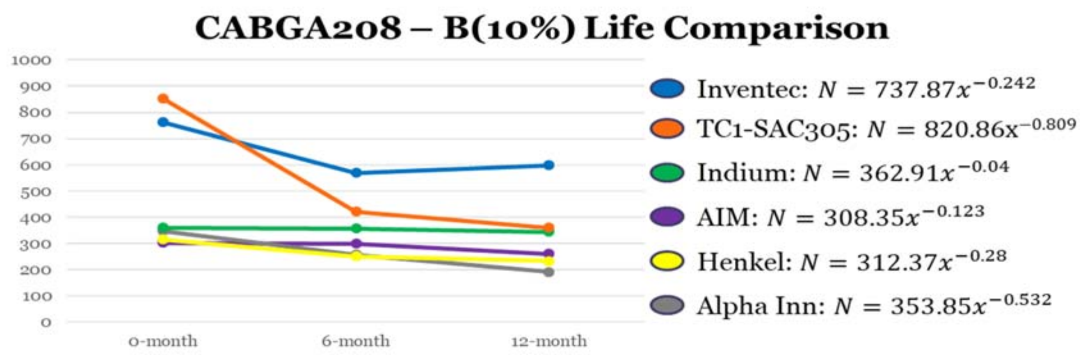


Figure 6-3: CABGA208 - B(10%) Life Comparison

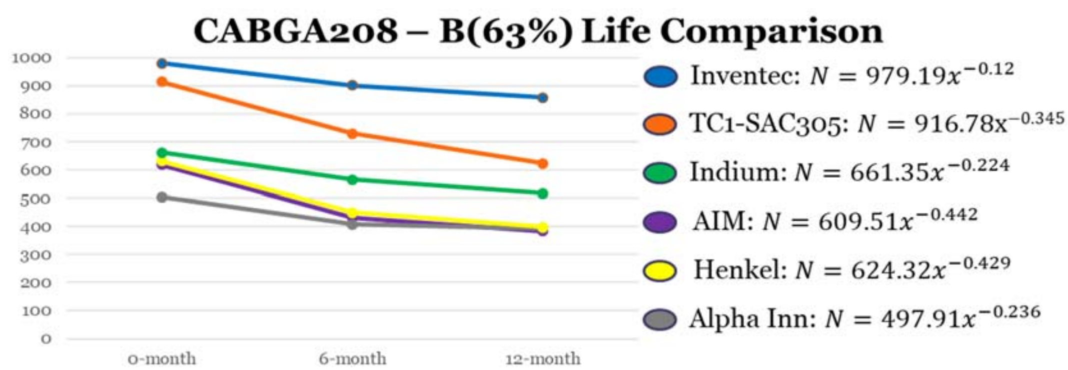


Figure 6-4: CABGA208 - B(63%) Life Comparison

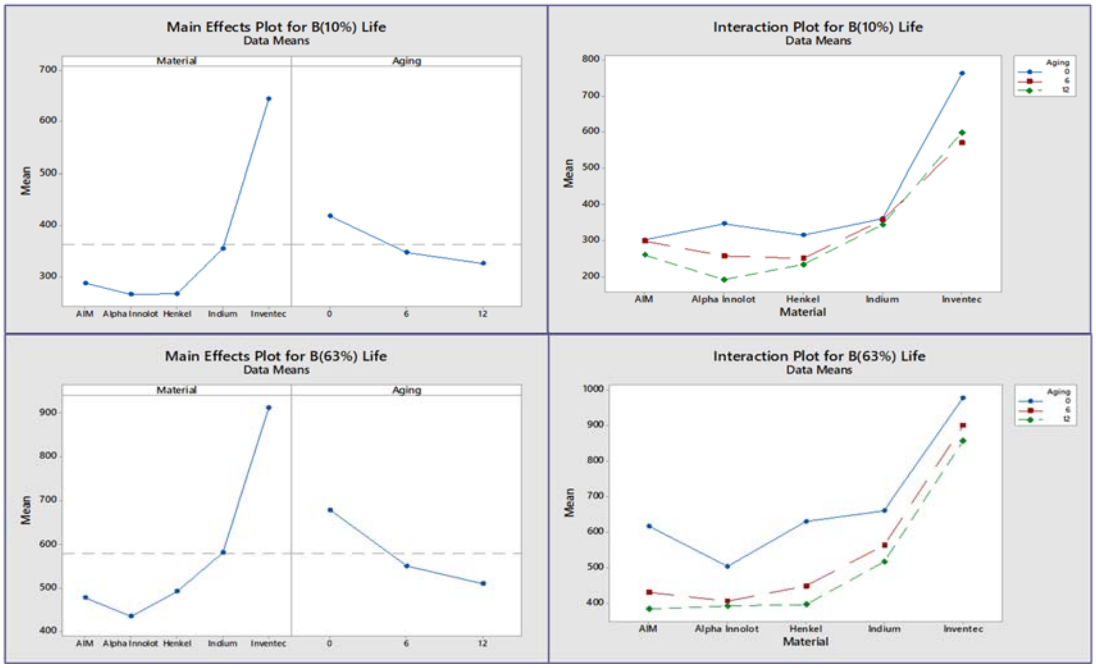


Figure 6-5: CABGA208 - B(10%) and B(63%) Life Main Effect and Interaction Plots

6.5 CABGA256

The trends of reliability shown for the CABGA256 compare similarly with the trends shown for the CABGA208 component for the TC2 materials. The TC1 SAC305 material showed a much higher level of degradation when compared to with the CABGA208, figure 6.6. Although the SAC305 material experiences much higher reliability in the 0-month aged group, the reliability drastically decreases when aged for 12 months ($\Delta B(10\%) = 502.62$, $\Delta B(50\%) = 447.67$, and $\Delta B(63\%) = 434.75$). Inventec exhibits a similar level of degradation to the level shown for the CABGA208 component ($\Delta B(10\%) = 63.66$, $\Delta B(50\%) = 79.55$, and $\Delta B(63\%) = 83.02$).

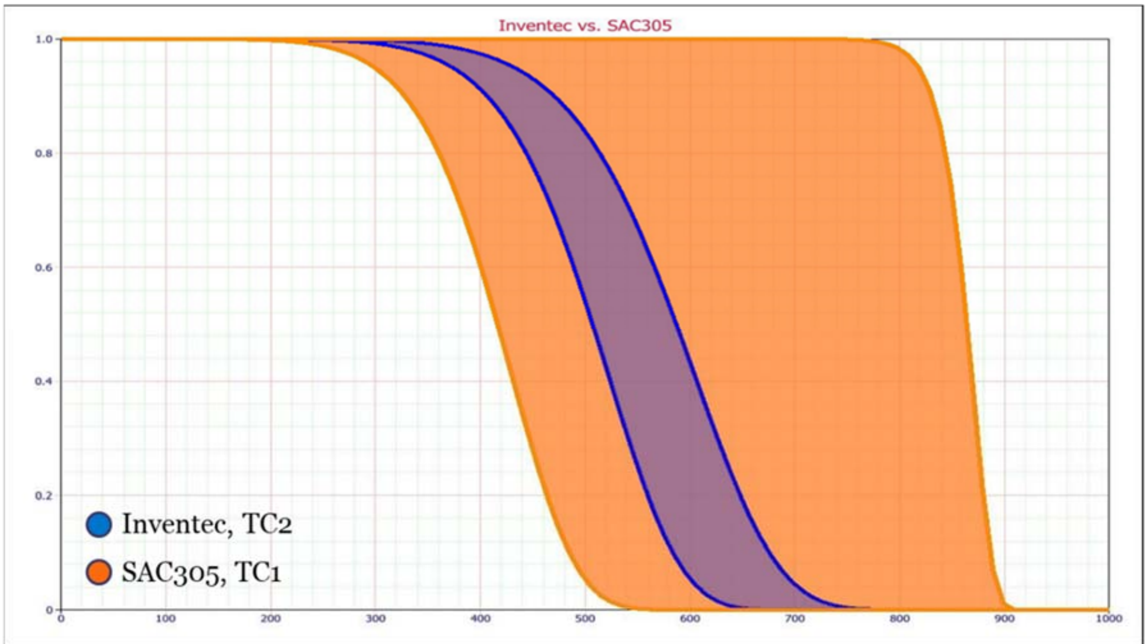


Figure 6-6: CABGA256 – TC2 Inventec/TC1 SAC305 Comparison - 12m - 75°C

The remaining TC2 materials are presented in figure 6.7 below. The degradation rates for the remaining TC2 materials exhibits a lesser degradation rate when compared to the CABGA208 component. Although, the ranking for the materials is consistent for all materials. The TC1 SAC305 material does show higher levels of reliability, but the degradation rate is much larger.

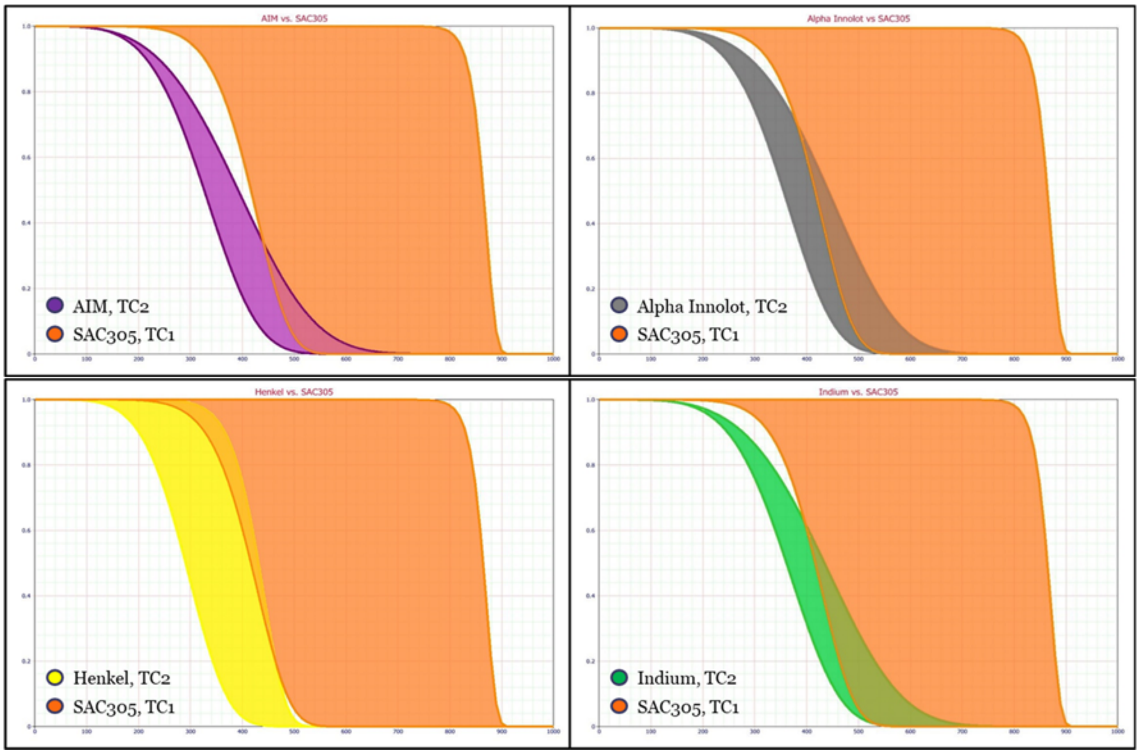


Figure 6-7: CABGA256 - Other TC2 Materials/TC1 SAC305 Comparison - 12m - 75°C

Further visualizations of the comparison of degradation through B(10%) and B(63%) of the CABGA256 are shown in figures 6.8, 6.9, and 6.10. Figure 6.8 and 6.9 present the B(10%) and B(63%) life comparisons for the 0, 6, and 12-month aging groups with the coinciding power formula. Extremely high levels of degradation can be seen for the SAC305 component in the early stages of testing and continue throughout. Figure 6.10 presents the interaction and main effect plots for each TC2 material. Inventec continues to be the superior material, as shown by the visualizations.

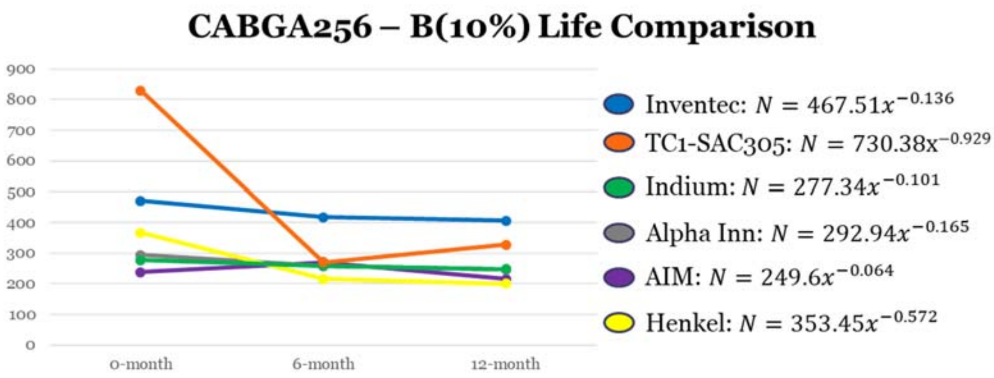


Figure 6-8: CABGA256 - B(10%) Life Comparison

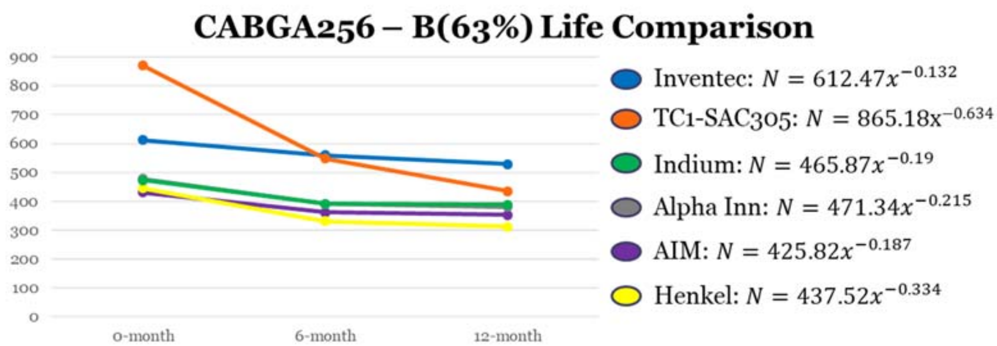


Figure 6-9: CABGA256 - B(63%) Life Comparison

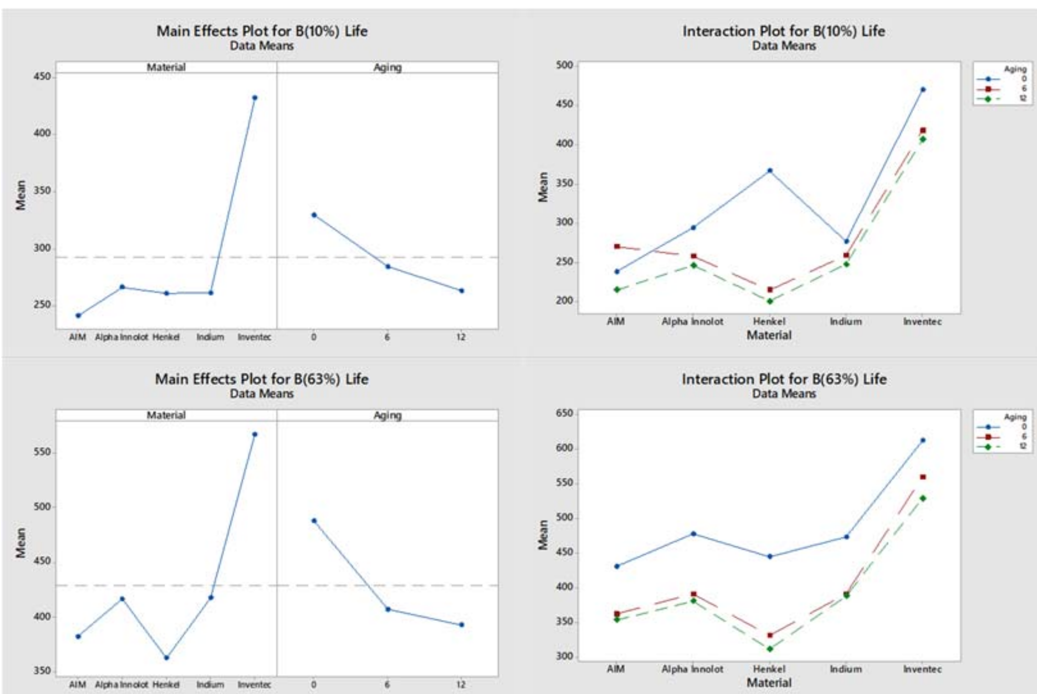


Figure 6-10: CABGA256 - B(10%) and B(63%) Life Main Effect and Interaction Plots

A common trend is exhibited in the analysis of all CABGA components for the TC2 materials. The TC2 materials, excluding Inventec, showed lesser levels of reliability in the Weibull analysis, but the degradation rates of the material when aged must be considered. For all TC2 materials, the level of degradation was much lesser than the TC1 materials. Both analysis techniques are beneficial in understanding the true trends in reliability for each material.

6.5 CVBGA432

The trends the CVBGA432 component shift with all materials experiencing much more closely correlated reliability and degradation rates. Figure 6.11 below shows the comparison of degradation rates for the TC2 Indium and TC1 SAC305 materials. Indium exhibited the highest level of reliability for all TC2 materials, as shown in the Weibull analysis. The TC1 SAC305 material exhibits a much lesser level of degradation when compared the components analyzed above but is still larger than the TC2 materials ($\Delta B(10\%) = 128.84$, $\Delta B(50\%) = 96.36$, and $\Delta B(63\%) = 89.09$). The TC2 Indium material experiences higher levels of reliability and a lesser degradation rate when compared to SAC305 ($\Delta B(10\%) = 58.72$, $\Delta B(50\%) = 59.83$, and $\Delta B(63\%) = 59.49$).

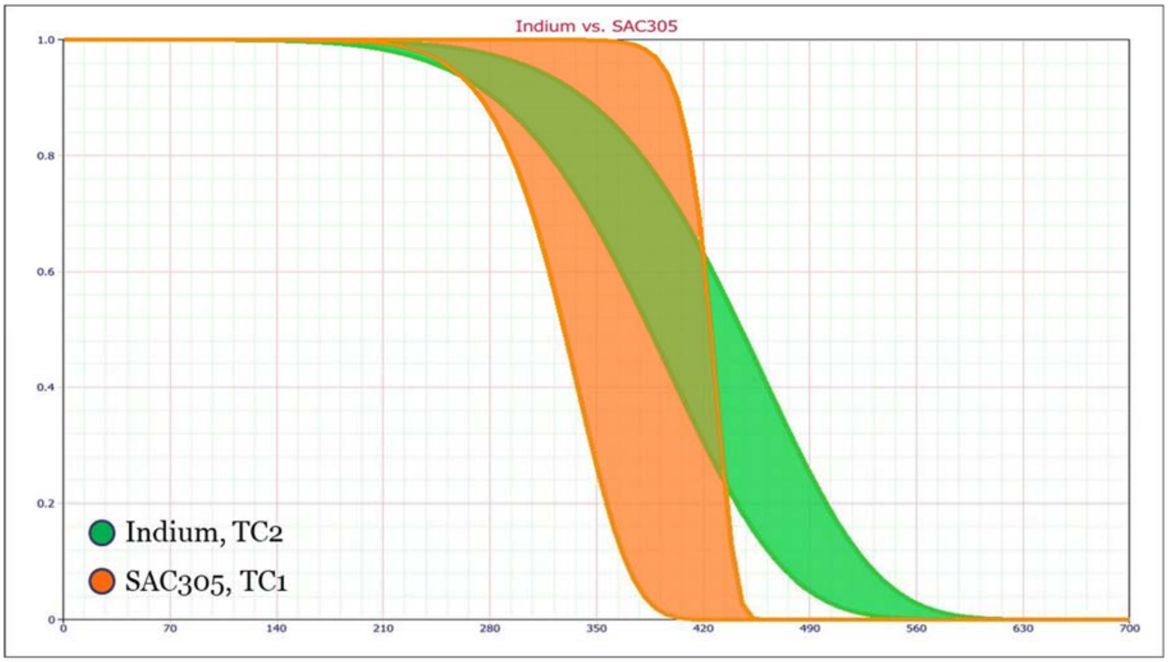


Figure 6-11: CVBGA432 - TC2 Indium/TC1 SAC305 Comparison - 12m - 75°C

The remaining TC2 materials are presented in figure 6.12 below. Each material exhibits higher levels of reliability with lesser degradation rates. When compared with the CABGA components, the TC2 materials all prove to be superior materials over the materials used in TC1. The rankings for the materials differs as well.

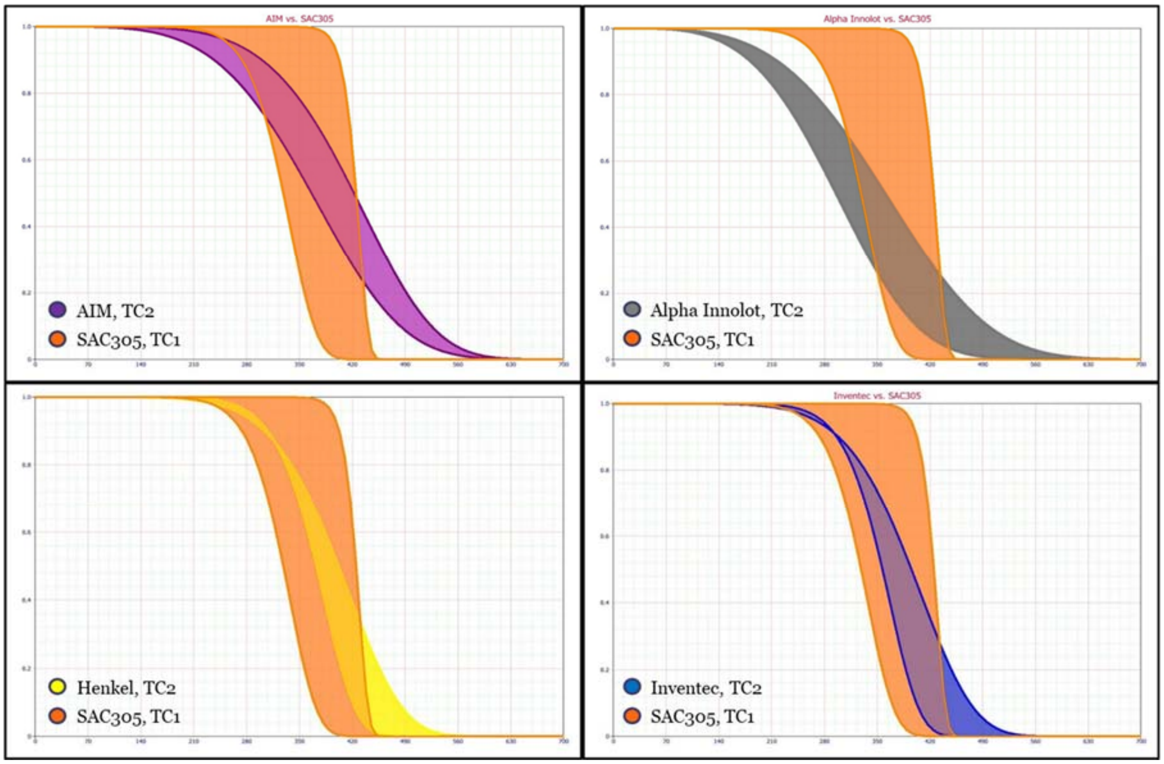


Figure 6-12: CVBGA432 - Other TC2 Materials/TC1 SAC305 Comparison - 12m - 75°C

Further visualizations of the comparison of degradation through B(10%) and B(63%) of the CVBGA432 are shown in figures 6.13, 6.14, and 6.15. Figure 6.13 and 6.14 present the B(10%) and B(63%) life comparisons for the 0, 6, and 12-month aging groups with the coinciding power formula. The levels of degradation presented are very closely correlated for all materials analyzed. Figure 6.15 shows the interaction and main effect plots for each TC2 material. The ranking of the materials is clearly shown to differ from the CABGA component analyzed above.

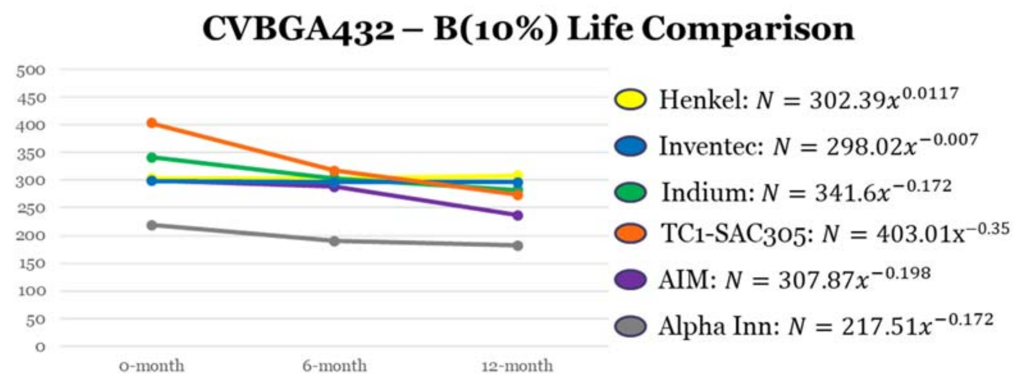


Figure 6-13: CVBGA432 - B(10%) Life Comparison

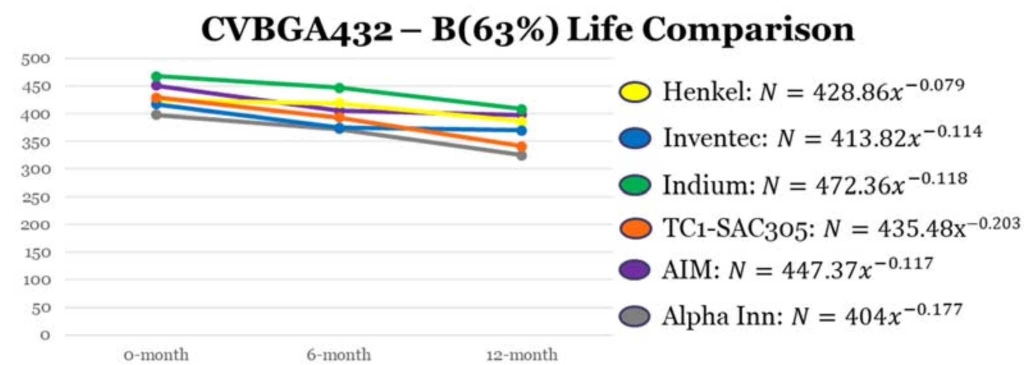


Figure 6-14: CVBGA432 - B(63%) Life Comparison

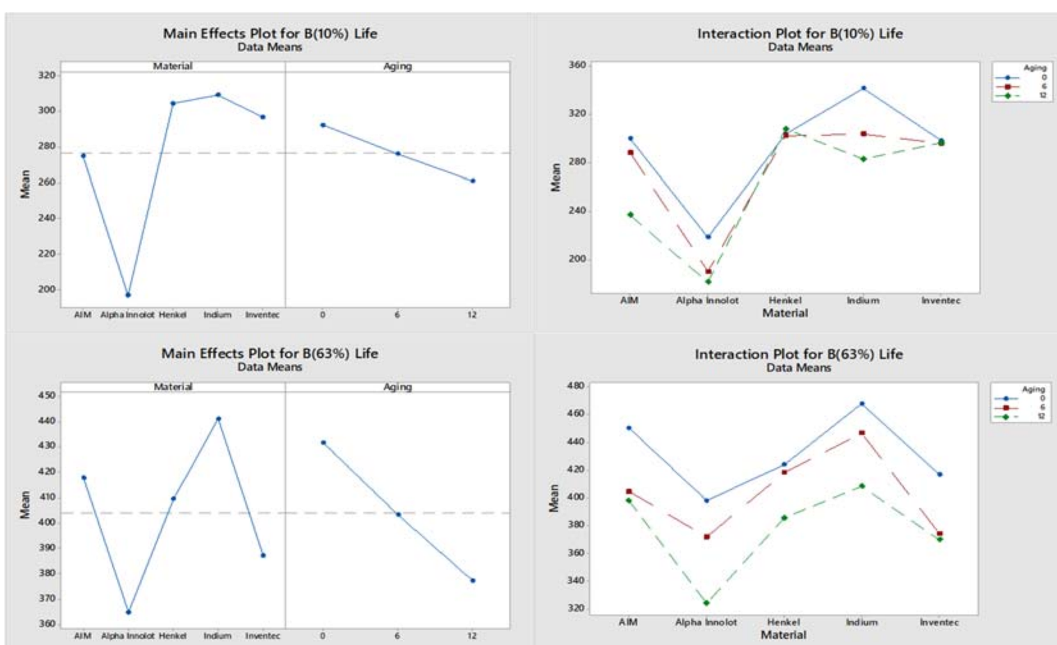


Figure 6-15: CVBGA432 - B(10%) and B(63%) Life Main Effect and Interaction Plots

6.6 PBGA1156

An analysis of the effects of heatsinks was performed on the PBGA1156 component to understand if a compelling statistical difference existed. Figures 6.16, 6.17, and 6.18 below shows the comparisons for the TC2 materials with a Heatsink attached. Figure 6.16 and 6.17 present the B(10%) and B(63%) life comparisons for the 0, 6, and 12-month aging groups with the coinciding power formula. The levels of degradation presented differ greatly for all materials. Figure 6.18 shows the interaction and main effect plots for each TC2 material.

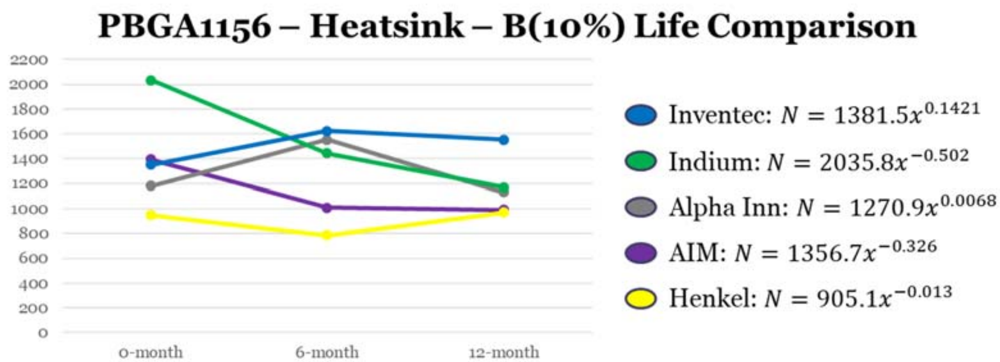


Figure 6-16: PBGA1156 - Heatsink - B(10%) Life Comparison

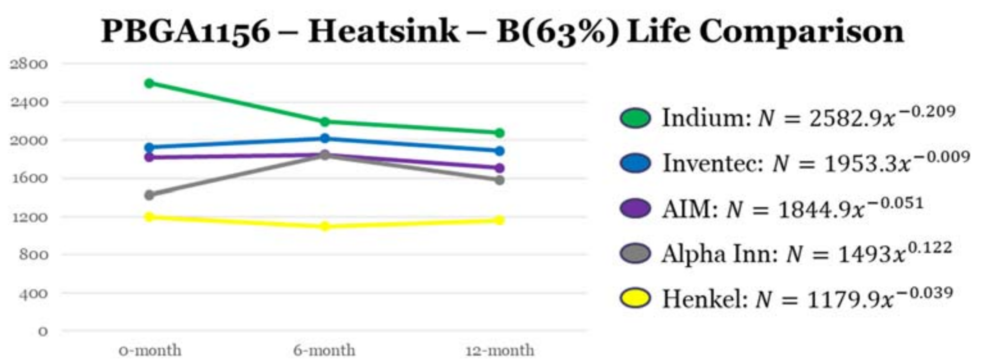


Figure 6-17: PBGA1156 - Heatsink - B(63%) Life Comparison

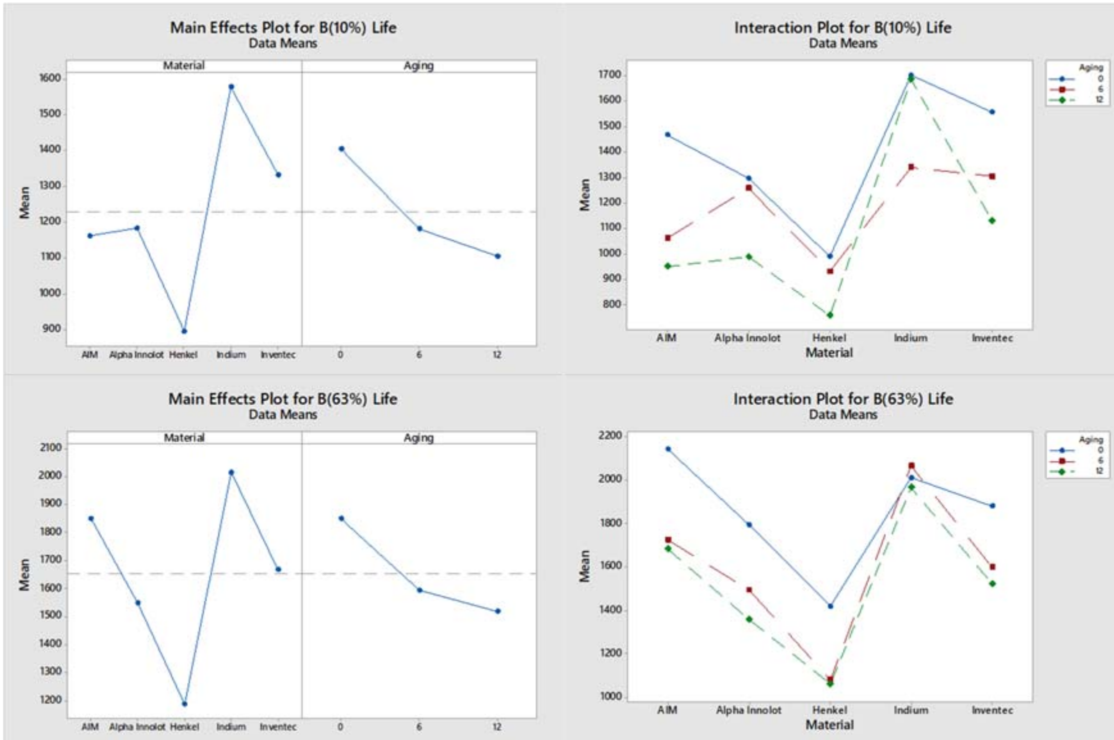


Figure 6-18: PBGA1156 – Heatsink - B(10%) and B(63%) Life Main Effect and Interaction Plots

Figures 6.19, 6.20, and 6.21 below shows the comparisons for the TC2 materials with no Heatsink attached. Figure 6.19 and 6.20 present the B(10%) and B(63%) life comparisons for the 0, 6, and 12-month aging groups with the coinciding power formula. The levels of degradation presented are very closely correlated to the analysis performed on the materials with a Heatsink attached. Figure 6.21 shows the interaction and main effect plots for each TC2 material. The ranking of the materials is compares similarly with the Heatsink data.

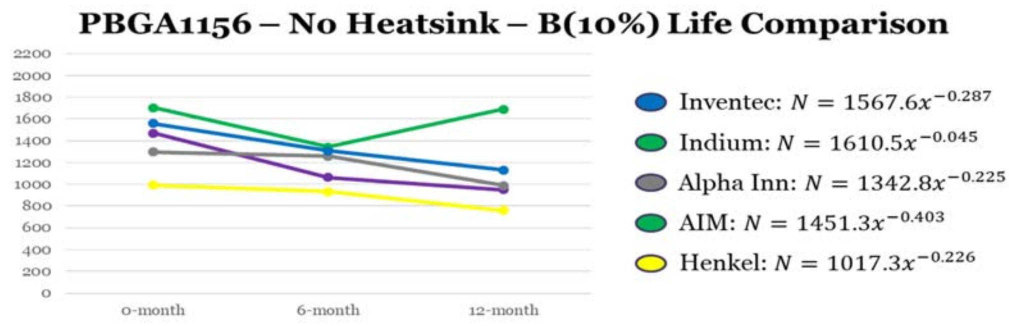


Figure 6-19: PBGA1156 - No Heatsink - B(10%) Life Comparison

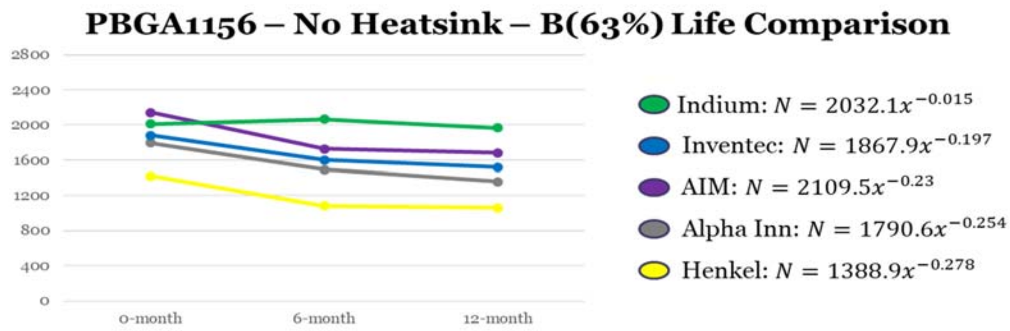


Figure 6-20: PBGA1156 - No Heatsink - B(63%) Life Comparison

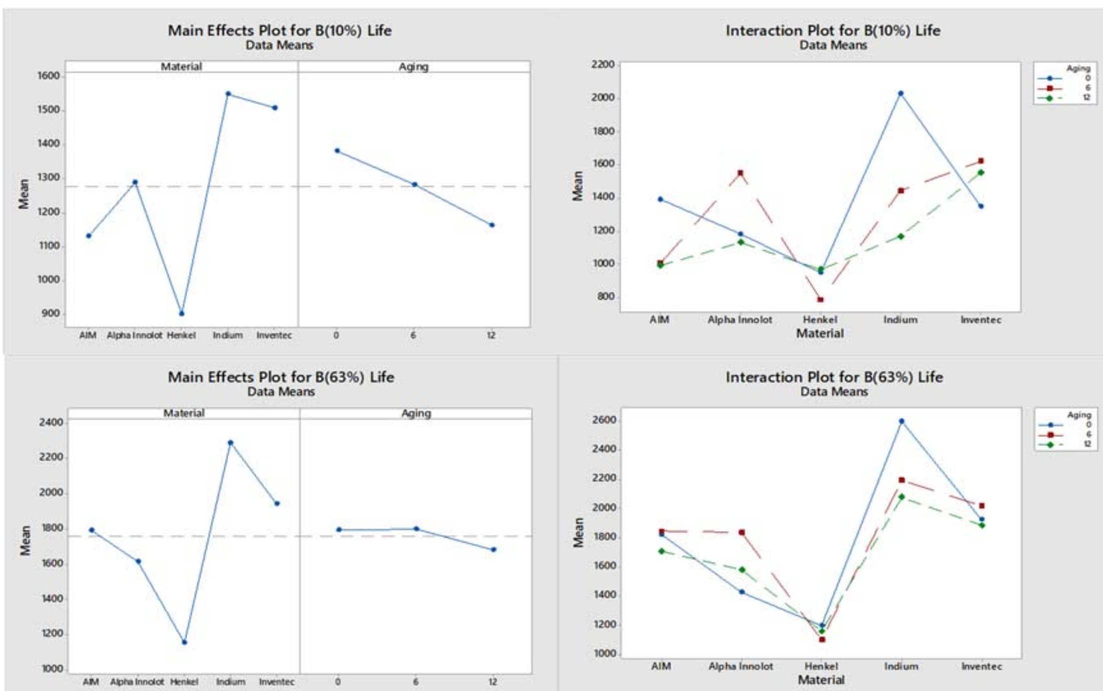


Figure 6-21: PBGA1156 – No Heatsink - B(10%) and B(63%) Life Main Effect and Interaction Plots

The effect of the heatsink on the PBAG1156 showed no statistical difference. The component with a heatsink attached did show minimally higher levels of reliability when compared to components with no Heatsink. This is believed to be caused by the stability added when attaching the Heatsink.

Further analysis is needed to determine if these trends will stay consistent. The other component present in this test with a heatsink attached did not experience sufficient failures to perform analysis. Survival data from the 24-month aging group will be analyzed to understand the trends shown.

6.7 SMR2512

As shown in the previous chapter, the materials performed much differently when used with the SMR2512 component. The levels of degradation are shown for all materials in figure 6.22 below. Alpha Innolot and Henkel were the top performing materials for the SMR and performed poorly for all other components. Inventec proved to be the worst material for this component. The main difference between the surface mount resistors and all other components is the absence of solder balls. All other components had the SAC305 solder ball attached to the component, which added a dopant material. Further testing must be performed to understand how the reliability of the materials is affected by doping the materials with various levels of SAC305.

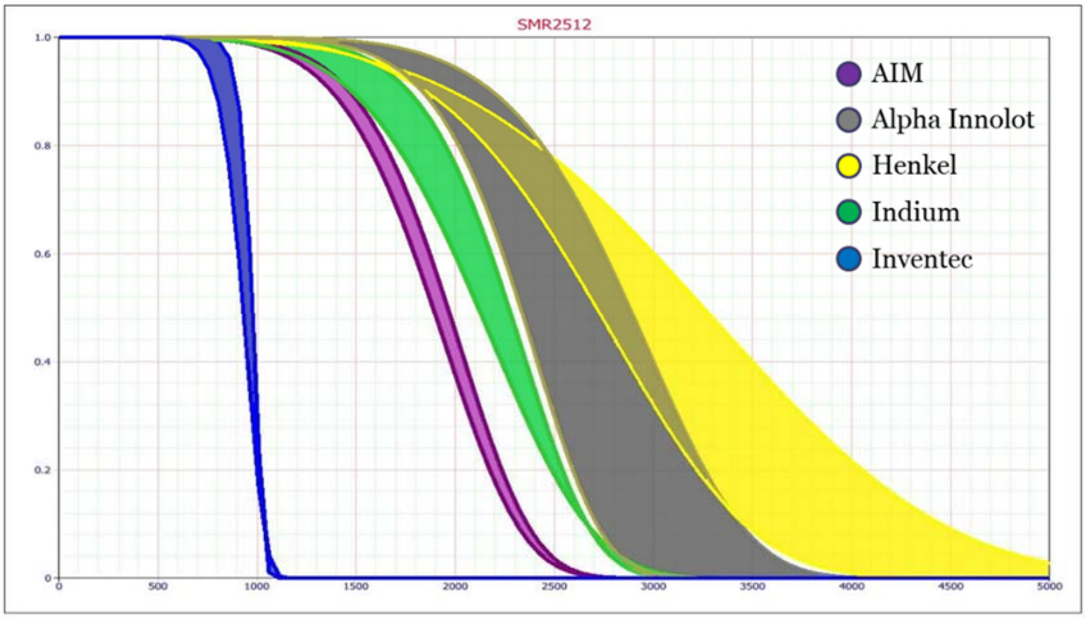


Figure 6-22: SMR2512 - TC2 Materials Comparison - 12m - 75°C

The SMR2512 was built only on the TC2 test vehicles, and therefore no comparison data is available between tests. The life comparisons, main effect, and interaction plots for B(10%) and B(63%) of the SMR2512 are shown in figures 6.23, 6.24, and 6.25. Figure 6.23 and 6.24 present life comparisons for 0, 6, and 12-month aging groups with the coinciding power formulas for each material. Alpha Innolot and Henkel exhibit the highest levels of degradation with the other three materials experiencing much lesser. Figure 6.25 shows the interaction and main effect plots for each TC2 material compared to the SAC305 material in TC1. The rankings of the materials for each aging group are clearly shown.

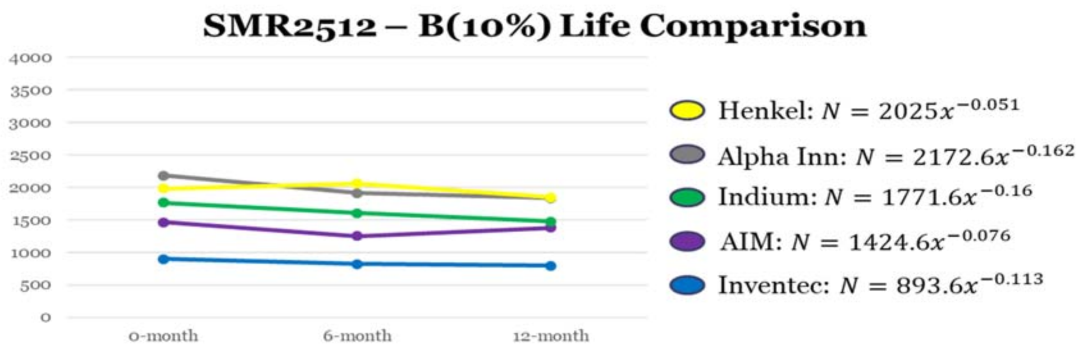


Figure 6-23: SMR2512 - B(10%) Life Comparison

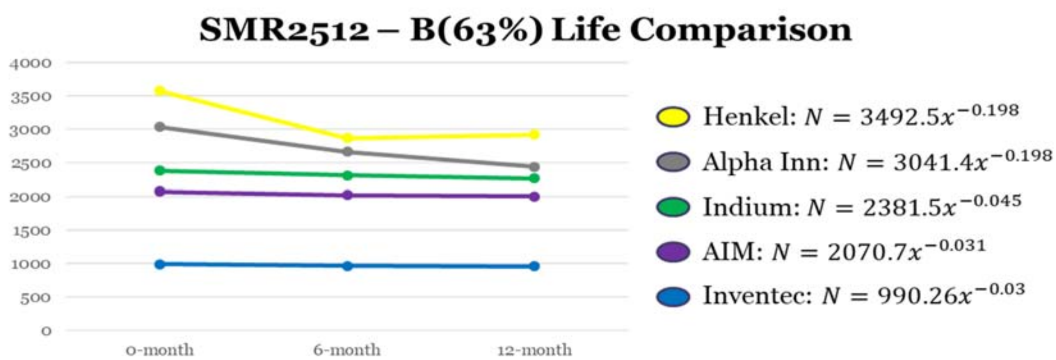


Figure 6-24: SMR2512 - B(63%) Life Comparison

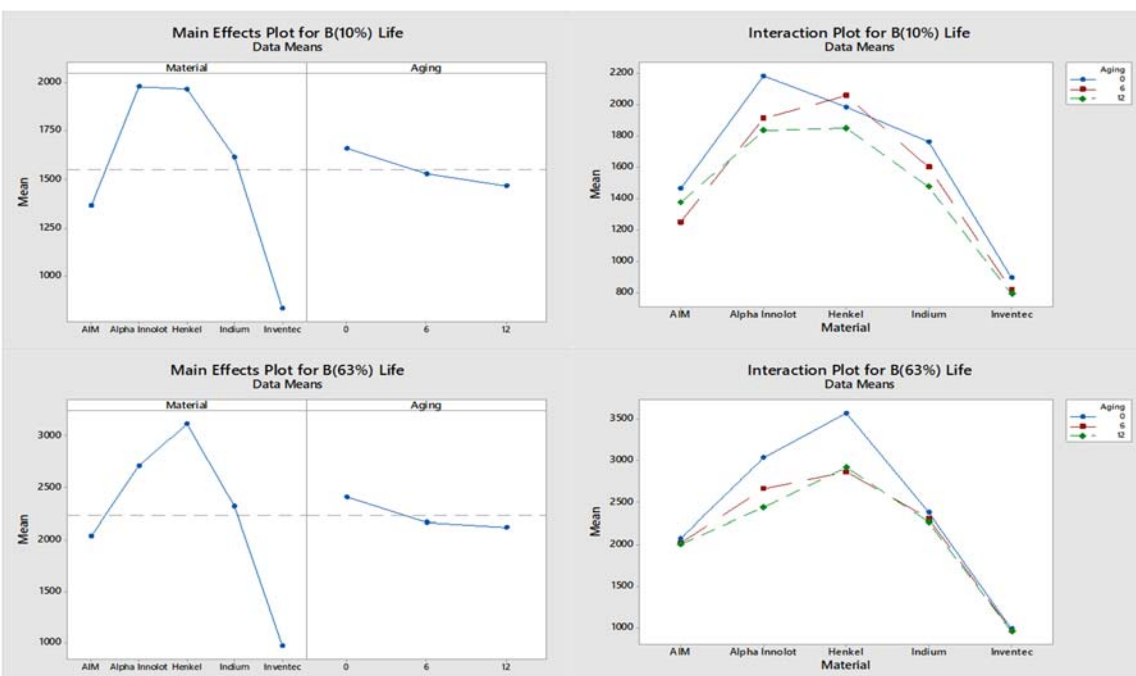
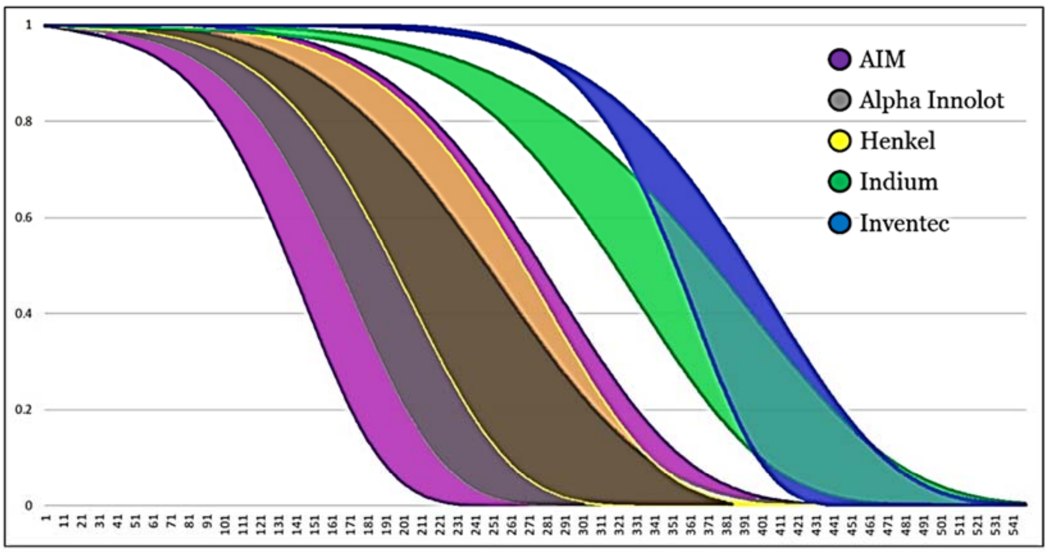


Figure 6-25: SMR2512 - B(10%) and B(63%) Life Main Effect and Interaction Plots

6.8 System Level Reliability

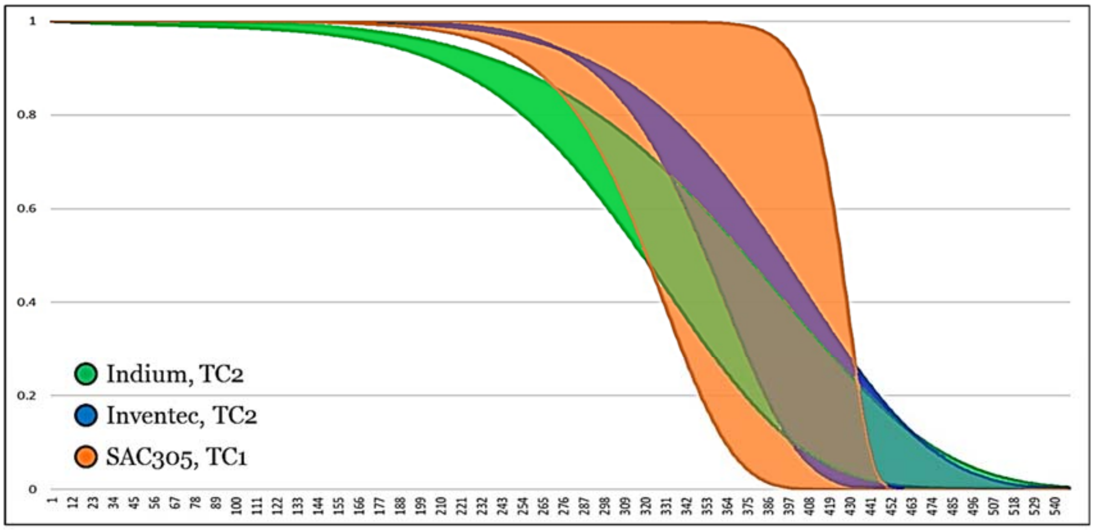
The reliability of the CABGA36, CABGA208, CABGA256, CVBGA97, CVBGA432, CTBGA84, and PBGA1156 components were combined to obtain the system reliability. The SBGA and SMR components were not added to the system reliability based on the trends shown for these components. Figure 6.26 shows the system level degradation rates for the TC2 materials with the delta values for each at B(10%), B(50%), and B(63%) Life.



AIM	Alpha Innolot	Henkel	Indium	Inventec
$\Delta B(10\%) = 112$	$\Delta B(10\%) = 55$	$\Delta B(10\%) = 58$	$\Delta B(10\%) = 26$	$\Delta B(10\%) = 8$
$\Delta B(50\%) = 140$	$\Delta B(50\%) = 80$	$\Delta B(50\%) = 68$	$\Delta B(50\%) = 53$	$\Delta B(50\%) = 19$
$\Delta B(63\%) = 147$	$\Delta B(63\%) = 95$	$\Delta B(63\%) = 75$	$\Delta B(63\%) = 58$	$\Delta B(63\%) = 32$

Figure 6-26: TC2 Materials BGA System Reliability Comparison

Figure 6.27 below shows the system level degradation rates of top two performing materials from TC2, Inventec and Indium, compared to the system level reliability for the TC1 SAC305 material. The materials in TC2 exhibit higher levels of reliability with much lesser degradation rates. From this analysis, it can be stated that the TC2 Inventec material is clearly a superior material over the TC1 SAC305 material.



Inventec	Indium	SAC305
$\Delta B(10\%) = 8$	$\Delta B(10\%) = 26$	$\Delta B(10\%) = 142$
$\Delta B(50\%) = 19$	$\Delta B(50\%) = 53$	$\Delta B(50\%) = 104$
$\Delta B(63\%) = 32$	$\Delta B(63\%) = 58$	$\Delta B(63\%) = 93$

Figure 6-27: TC2 Materials/TC1 SAC305 BGA System Reliability Comparison

6.7 Comparison Results

The analysis of degradation values provided excellent results, giving further knowledge of the materials. The trends of reliability shown in the regression analysis were consistent throughout the Weibull analysis, while offering new insights. These trends can be seen throughout all aging groups.

The major trend found from the degradation analysis is the TC2 materials degrade at a much lesser rate when compared to the materials test in TC1. Further analysis is being performed to understand these trends further. Testing for the 24-month aging group is still ongoing at Auburn University and concluded in December 2018. Comparison analysis will also be performed on this data. Materials analysis has been ongoing throughout the entirety of the test and will conclude early 2019 to understand the effects of addition of a certain percentage of material on the survival probability.

Chapter 7
Results and Conclusion

In these experiments, we have considered the thermal cycle reliability of an assortment of different electronic components and evaluated them on Megtron6 printed circuit board. Organic Solderability Preservative (OSP) surface finish was used with all test vehicles. Solder Materials in TC1 consisted of SAC305 and SnPb, and the materials in TC2 consisted of AIM, Alpha Innolot, Henkel, Indium, Inventec.

General trends can be seen in the reliability data based on the solder paste being used. For the smaller plastic BGA packages, Inventec has shown to be an effective strategy for improving characteristic life. However, as component size and pitch increase or decreases, this improvement seems to diminish. Inventec appears to be the worst material when using the 2512 SMR. The reliability trend from the materials analyzed appear to be largely stable over long periods of isothermal aging.

Significant differences in the reliability trends were seen between equivalent packages when using each individual solder material. Of the 5 materials in TC2, one of them was a top performer for each component. Although the TC1 materials performed comparatively well to TC2, a material from TC2 had a higher trend of reliability for all components in all aging groups. TC2 materials also saw failures at a much lesser rate.

Degradations in reliability are seen in all components and subgroups. The comparison in the degradation rates of the TC1 and TC2 experiments was performed to determine a leadfree material better than the materials in TC1. Degradation rates change drastically with the uses of the separate components.

Finite Element Analysis (FEA) may be beneficial in understanding why the Megtron6 substrate seems to affect the lead-free materials so aversely. When considering the effects of Isothermal Aging on the relative reliability of various packages, the data indicate that even components that show similar initial reliability trends may display differences following aging. Failure Analysis performed thus far demonstrates that a variety of crack propagation and failure modes are present even when considering only a limited set of components.

7.1 Ongoing and Future Work

The project status for the TC1 and TC2 experiments is as follows: The no aging, 6-month aging, and 12-month, and 24-month aging test groups have passed 3000 thermal cycles and are now finished with TC testing for TC1; The no aging, 6-month aging, and 12-month aging test groups have passed 3000 thermal cycles and are now finished with TC testing for TC2. 24-month aging boards have started thermal cycle testing and is projected to complete cycling December 2018. Data will then be obtained, and a final report will be tabulated to present all accumulated data. Failure analysis will continue upon completion with the hope of gaining further knowledge on the cause of failure.

7.2 Proposed Test #1

- Proposed Testing: Complete 24-month testing group and analyze the data to examine if the trends shown will continue.
- SAC305 continues to show a high degradation rate when aged for 24 months.

- Examine if TC2 materials continue to show similar degradation trends.

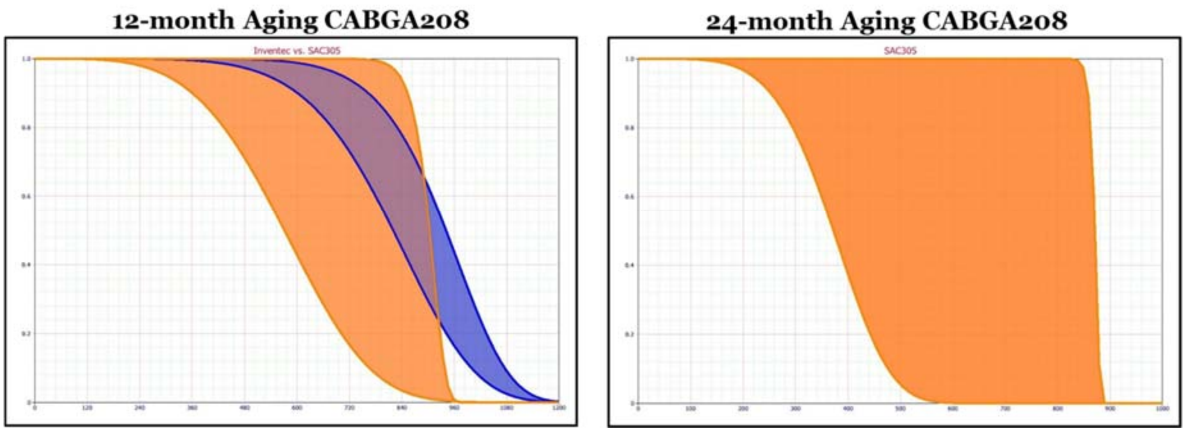


Figure 7-1: CABGA208 12m to 24m Degradation with Aging

Proposed Test #2

- Proposed Testing: Explain the difference in degradation rates between the FR4 and Megtron6 substrate materials.
- The focus of this study was on the Megtron6 component reliability.
- Leadfree Materials and 2512SMR should be tested on FR4-06 substrate to compare with Megtron6 data.

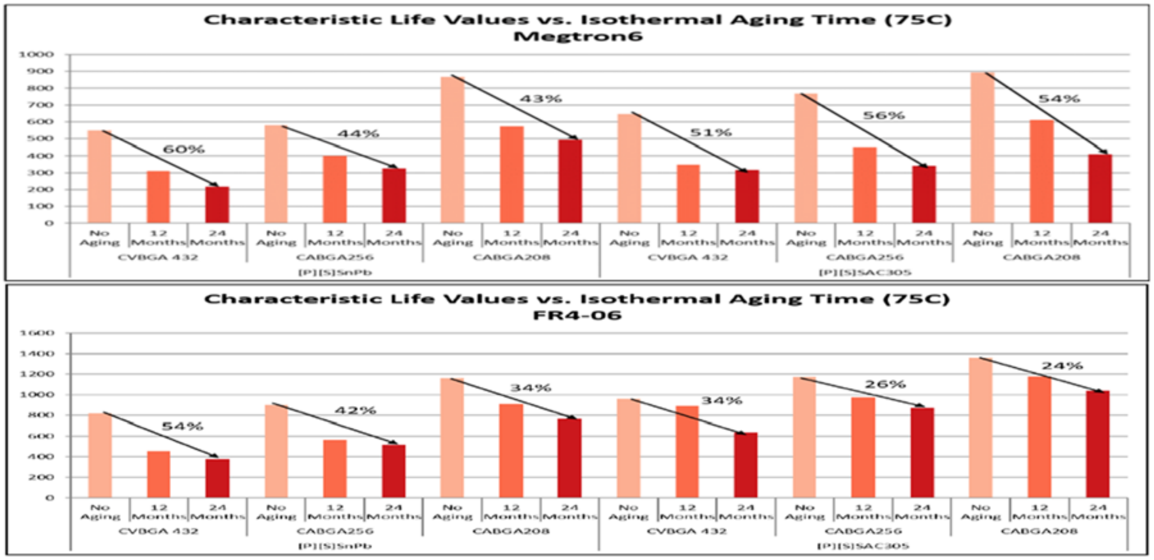


Figure 7-2: Comparison of Characteristic Life Values for Megtron6 and FR4-06 Substrates [37]

Proposed Test #3

- Proposed Testing: Show correlation between Thermal Cycling and Thermal Shock results.
- Materials tested in TC2 were selected from the Phase I downselect test with a main emphasis on Thermal Shock.
- The order of reliability for the materials in both test methods do not correlate directly.

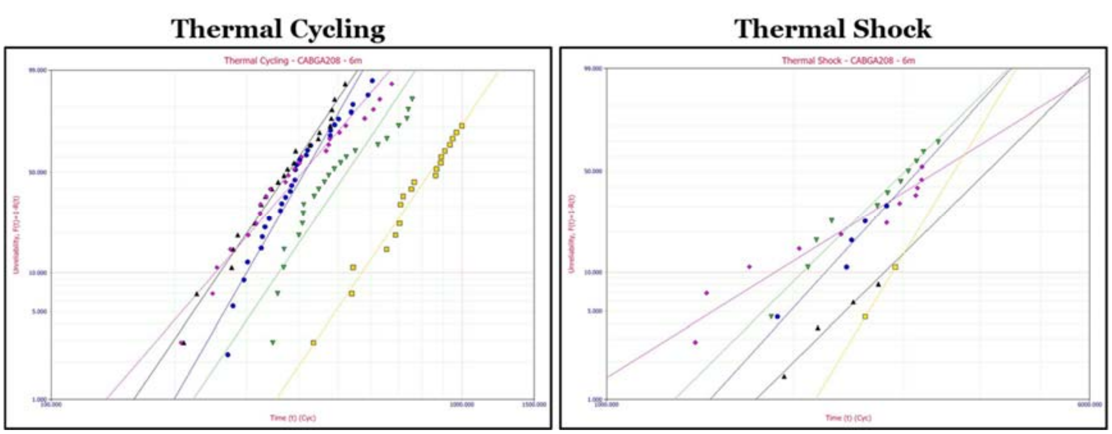


Figure 7-3: Thermal Cycling vs. Thermal Shock TC2 Material Reliability

Proposed Test #4

- Proposed testing: Introduce various levels of SAC305 dopant to the Inventec material to attempt to improve reliability.
- Inventec material has shown high levels of reliability when combined with SAC305 solder balls.
- SAC305 dopant can be added to other materials to examine the varying levels of reliability.

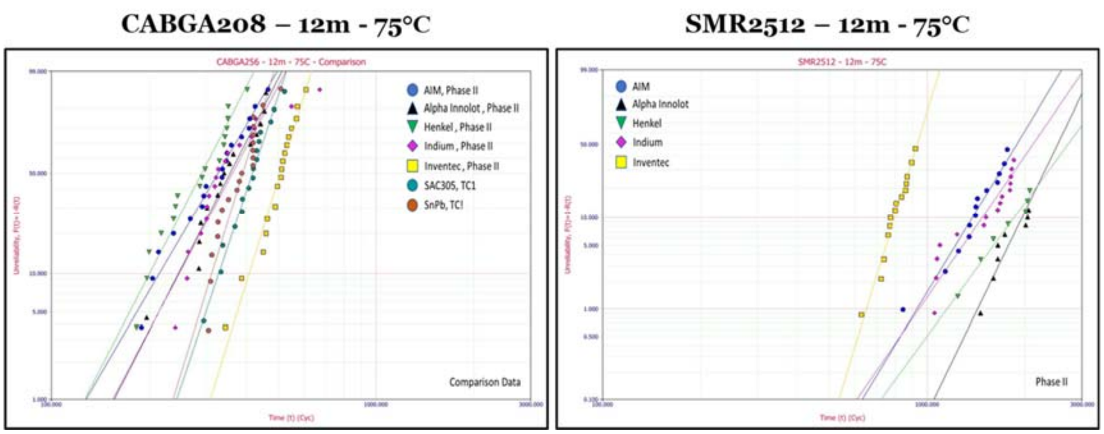


Figure 7-4: BGA vs. SMR Component for TC2 Inventec Material

Chapter 8
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