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The detrimental effects of water on electronic devices

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A B S T R A C T

Water in its various forms can affect the performance and reliability of today's electronics in unique ways. This paper discusses the forms of water and the degradation effect of water on electronics, identifies the types of failure mechanisms in electronics induced by liquid and vapor phase water, presents case studies of water-related failures, and provides recommendations for preventing water-imposed degradation in electronics. Test methods and standards based on different forms of water and specific applications of electronics are also presented.

1. Introduction

Current consumer products, computers, vehicles, medical devices, and almost all manufacturing, industrial, communications, space, and defense systems are highly dependent on electronics. For devices to be reliable and safe, they must withstand the environmental and operating conditions of their targeted application. Although companies under current practices test devices for thermal, vibration, impact, and stress conditions, a commonly underestimated cause of failure in electronics is their exposure to water in various forms [1].

A water molecule is composed of two hydrogen atoms and an oxygen atom. The atomic nuclei form an isosceles triangle with an H–O-H angle of approximately 104.5°. The resulting dipole moment of (μ=2.95D) makes water an extremely effective solvent for ionic compounds and polar molecules, such as sodium chloride (NaCl) and weak organic acids [2]. Hydrogen bonding occurs between hydrogen atoms and electron-rich donor atoms, (e.g., oxygen in hydroxyl, nitrogen in amine, and sulfur in thiol).

When substances dissolve in water or bond with water, they can drastically affect the properties of water . The conductivity of pure water is around 5 microSiemens per meter(μS/m), whereas water that contains a small amount of minerals (e.g., drinking water) exhibits a conductivity of between 5 and 50 mS/m. Seawater contains approximately 3.5% of salts has a conductivity of 5 S/m.This is10^6 times greater than pure water [3].

Moisture refers to either gas phase water dispersed in air as water vapor, or condensed water adsorbed on a surface or absorbed within a solid structure. Humidity is a measure of the amount of water vapor in a gaseous state, typically air. Absolute humidity is the total mass of water vapor present per unit volume of air. Relative humidity(RH) is the ratio of the partial pressure of water vapor to its saturated, or equilibrium, vapor pressure, which refers to the moisture capacity in the air. Therefore, relative humidity depends on temperature and pressure. For example, at a fixed absolute humidity, and decreased ambient temperature the saturated vapor pressure decreases and the relative humidity increases.

Water molecules can be absorbed or adsorbed by hygroscopic materials, which have moieties that can form hydrogen bonds with water or metal cations that can form a coordinate covalent bond with the oxygen atoms in water. Several polymers used in electronics, such as epoxy resins, polycarbonate, and poly (methyl methacrylate), are examples of hygroscopic materials. The saturated amount of absorbed moisture by such a material is proportional to the relative humidity.

C_{sat} of materials is linearly proportional to the relative humidity of the conditioning environment as described by Henry's Law at specific temperature [87]:

$$C_{sat} = p \times S \infty \%RH \tag{1}$$

where C_{sat} is saturated moisture concentration, S is solubility of the material in water and p is partial pressure of ambient water vapor. This

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is generally true except at high%RH where some materials may exhibit positive deviation from linearity.

Some materials having a strong affinity for water can exhibit deliquescent action. Deliquescence is a process in which a substance absorbs moisture from the surrounding air until it dissolves in the absorbed moisture to form a solution. Examples of deliquescent materials include many salts, such as sodium hydroxide (NaOH), magnesium chloride ($MgCl_2$), and potassium chloride (KCl) [4]. The minimum relative humidity level at which deliquescence occurs is specific for each salt and temperature. For instance, at 25 °C, the critical relative humidity level of NaOH is 8.2%, $MgCl_2$ is 32.8%, and KCl is 84.3%.

2. How water enters electronics

There are various ways that water can enter and damage electronics. Direct contact with liquid water occurs when electronics are splashed by water, rained on, or submerged. Water vapor can diffuse into an enclosure through openings or permeable materials. Humid environments also cause water to condense on surfaces or inside of electronics. Even water molecules trapped in electronics during the manufacturing process can condense when the external temperature changes. The following sections discuss how water can enter electronics.

2.1. Direct contact with liquid water

Opportunities for direct contact with liquid water are nearly ubiquitous. Home appliances can be exposed to beverages during general use. Cars, including electric vehicles, are exposed to rain and snow. Electronics on a ship may contact seawater dispersed as aerosols in the atmosphere.

Liquid water enters the interior of electronics through various openings. For example, when telecommunications equipment installed outside is exposed to rain, water can enter via louvers, vents, gaps at the edges of doors and casings, pinholes and other openings, and cracks or defects that form in gaskets during operation [5].

Liquid water can enter even through small openings. If the openings' inner wall has moieties capable of hydrogen bonding, water tends to adhere to the wall surface. The adhesive force between water and the inner wall can drive the water into the empty spaces in the wall; this is called capillary action [6–8]. The likelihood of water ingress by capillary action depends on the material properties, the size of the hole (opening of electronics), and the water pressure. Openings in electronic devices are in the order of mm (diameter size and wall thickness). Capillary action may more likely happen through cracks present in the casing/packaging. But this mechanism may be minimal towards the overall moisture ingress in the device.

The interface between the liquid and vapor phases is called the meniscus. The pressure difference across this interface (the exterior pressure minus the interior pressure) can be described by the Young-Laplace equation as [6]:

$$\Delta p = \frac{2\gamma}{\mathrm{R}} \tag{2}$$

where Δp is the Laplace pressure, which refers to the pressure difference across the meniscus; γ is the surface tension, which is 72 millinewtons per meter (mN/m) for the water-air surface at 25 °C; and R is the radius of curvature of the meniscus. For a given circular hole with radius a and contact angle with water θ, Eq. (2) is modified as [9]:

$$\Delta p = {}^{2\gamma cos\theta}/_{a} \tag{3}$$

The hydrostatic pressure is expressed as ρgh, where ρ is the water density, g is the gravitational acceleration, and h is the water height. Where there is an equilibrium between the hydrostatic pressure and the Laplace pressure Δp, the water height h is determined by the hole radius a and the contact angle θ which is the angle a liquid droplet forms in contact with a solid surface. Holes with inner wall made from hydrophobic material (e.g., materials with low affinity towards water and

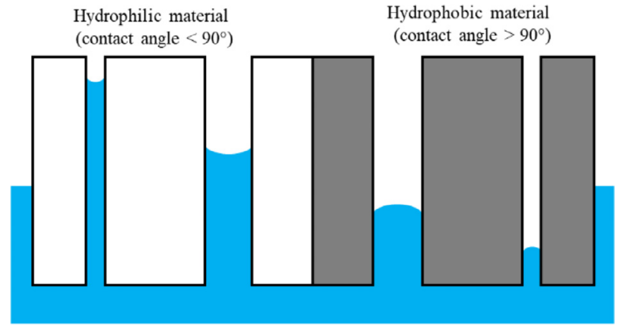

Fig. 1. Capillary action of water depending on the hole size and material properties [10].

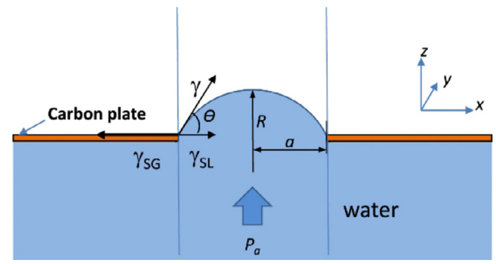

Fig. 2. The schematic of the model used to validate the effectiveness of Y-L equation at nanoscale. a is the pore radius, R is the radius of curvature of water surface, Pa is the reservoir pressure[9].

contact angle (θ) greater then 90°) will repel water. Additionally, the smaller the radius of the hole (a) will further limit the amount of water that can enter the enclosure. For example, for two different hole sizes, a_1 and a_2, present in an enclosure where a_2 is half of the size of a_1 the water height (h_2) of water entry in hole a_2 will also be half of the water height (h_1) in hole a_1 (as demonstrated in Fig. 1 on the right). The opposite is true for materials with high affinity towards water (i.e., contact angle (θ) smaller then 90°). These materials are called hydrophilic materials and in holes made from these material the water height will increase with decreasing hole radius (as demonstrated in Fig. 1 on the left) [10].

Various factors affect the capillary action-induced water ingress. In general, surface tension is inversely proportional to the temperature, since thermal expansion increases the distance between water molecules, reducing the cohesive force ,[11,12]. Effects of soluble substances on the surface tension depend on their affinity for water. Substances that have a higher affinity for water than that between water molecules (e.g., NaCl) tend to be barely present on the water surface due to the solute/water attraction, increasing the surface tension. Alternatively, substances showing a less affinity for water are pushed toward the water surface and reduce the surface tension. General detergents exhibit the latter behavior [88].

As mentioned in Ref [9] there is significant scatter in the experimental results of contact angle at nanoscale dimensions (e.g., nanopore radius range is 1.3–2.7 nm) and it is challenging to accurately measure the surface tension in this range to verify whether the Y-L equation is applicable or not. Nevertheless, Fig. 2 shows the schematic of an approach used to validate the applicability of the Y-L equation.

Liu and Cao [9] noted that molecular dynamics (MD) simulations, based on the behavior of pressurized water out of a nanopore (1.3–2.7 nm) in a flat plate, could be used to calculate the relationship between the water surface curvature and the pressure difference across the water surface. It was found that the water surface curvature is inversely proportional to the pressure difference across surface at nanoscale and this relationship holds for different pore sizes, temperatures and even for different electrolyte solutions. They also showed that the Young-Laplace

(Y-L) equation is valid in the nanoscale range.For electronics submerged in water, the hydrostatic pressure increases with the water depth. Electronics submerged in water have a greater likelihood of water ingress than those splashed by water.

2.2. Moisture ingress

Moisture in the air enters electronics through various mechanisms (depending on the driving force, such as a difference of temperature, pressure, or relative humidity). These mechanisms can be categorized as diffusion or advection. Moisture diffusion occurs when polymeric materials are exposed to humid environments. Fick's first law relates the diffusive flux to the gradient of the concentration. It postulates that the flux goes from regions of high concentration to regions of low concentration. Under non-steady-state conditions, Fick's second law for one-dimensional diffusion is [89]:

$$\frac{\partial C}{\partial t} = \frac{\partial^2 C}{\partial X^2} \tag{4}$$

where C is the concentration of the diffusing substance, t is the time and X is the axis along the concentration gradient.

Not all materials obey Fickian behavior. For example, for thin-film materials (0.2 mm and 0.5 mm thickness), a non-Fickian diffusion model may be required. A non-Fickian model for thin-film samples with concentration-dependent diffusivity D, has been expressed as [90]:

$$D = D_o \exp\left(-\frac{E_D}{kT} + aC\right) \tag{5}$$

where "a" is a constant, D is diffusion coefficient, k is thermal conductivity, T is temperature, D_o is pre-exponential diffusivity coefficient and E_D is activation energy for diffusivity. E_D and D_o can be determined through weight gain tests at different temperatures using bulk samples. The constant, "a", represents the degree of concentration dependency for the diffusivity.

In some cases, non-Fickian diffusion has also been associated with material damage or change in the material's internal stress state. Non-Fickian desorption is also observed in the high temperature desorption of some polymer materials subjected to prolonged moisture conditioning [90].

Diffusion-induced moisture ingress occurs mainly through openings in the housing of electronics, but also through permeable materials in the housing, which is known as permeation. The mass of water vapor that can permeate a thickness of material (L) in a given time is called the water vapor transmission rate and is described as [12]:

$$Transmission\ rate = P\left(p^{\circ} - p_i\right)/L \tag{6}$$

where p_o and p_i are the partial water vapor pressure of the exterior environment and the interior of the electronics, respectively, and P is the water vapor permeability coefficient, which varies by the material and temperature. Unlike materials such as glass and metal, a polymer has spaces between its flexible chains [12–14]. The size of these spaces depends on the composition and preparation methods of the polymer but is generally large enough (approximately 2.0 Å in diameter) for water molecules to pass through. At 25 °C and 1 atm, the water vapor permeability coefficient of natural rubber (polyisoprene), polyethylene terephthalate, and Teflon® is 5.25, 0.213, and 7.88×10^{-3} g•mm/m^2•day, respectively [15]. The hygroscopic materials inside electronics, such as solder masks, glass-reinforced epoxy laminate materials, flux residues, and epoxy molding compounds [16–18], can increase water vapor permeation. This is because hygroscopic materials absorb the water vapor to lower the internal partial pressure p_i and maintain the driving force of permeation.

Advection is the passive transport of substances by the bulk flow of a fluid, such as airflow. When there is an airflow through openings in the housing of electronics, moisture in the air can flow into the housing. The driving force for advection can be a cooling fan system or the pressure difference between the inside and outside of the electronic product. The pressure difference can be caused by the temperature disparity between the inside of electronics and the external environment. Consequently, this leads to an advection-induced moisture ingress, which is known as the "pumping" effect [19]. If multiple openings are present at different heights in a large electronic facility, such as wind turbines or data centers, moisture ingress may occur due to the chimney effect. In the chimney effect, hot air generated in the facility rises and escapes to the opening at a high height, while cold air from the outside enters through the other opening at a low height [7,20].

Conseil et al. [91] studied the ingress of moisture into typical electronic enclosures with openings in the enclosure (drain holes, intentional openings or leak), and sealing and casing materials, to investigate corrosion due to humidity build-up. Surface insulation resistance (SIR) test patterns were placed inside the enclosure to monitor the effect of the moisture ingress. They noted that, when exposed to cycling conditions, the ingress of water by a breathing effect was the dominant transport phenomenon, but, when exposed to constant conditions, with a high level of humidity in the surrounding air, the ingress of water by diffusion becomes the most important mechanism. Their study on enclosure materials and openings show that humidity build-up in polycarbonate (PC) enclosures is significantly affected by the diffusion through the PC material.

2.3. Condensation

Condensation refers to the change in the state of water vapor to liquid water, and occurs when the relative humidity reaches 100%. The relative humidity of 100% can be achieved as the moisture concentration in the air increases, or the temperature decreases to a saturation point. The saturation temperature of the water vapor is also called the dew point. The dew point has been used to determine the likelihood of condensation. For example, an environment of 25 °C/90% relative humidity corresponds to a dew point of 23.2 °C. When an electronic device whose temperature is less than 23.2 °C is placed in a 25 °C/90% relative humidity environment, condensation will occur on its surface.

There are various methods to determine the dew point from the relative humidity and temperature. Lawrence [21] established a simple equation applicable to a humid condition (when the relative humidity is higher than 50%), which is described as:

$$Dew\ point \approx T - (100 - Relative\ humidity)/5 \tag{7}$$

where T is the ambient temperature in degrees Celsius.

Condensation occurs on solid surfaces whose temperature is below the dew point. Those surfaces can include not only the housing of electronic products, but also the components inside the electronic products. The condensation mode appears in the form of a water droplet or water film, depending on the surface hydrophilicity [22].

Conseil et al. [19] reported that exposure to cycling temperatures can cause condensation inside the electronics. Due to the presence of the thermal mass in the device, the interior has a delayed thermal profile compared to the exterior. As a result, the internal temperature may cross below the dew point during cycling and lead to condensation, as shown in Fig. 3. They also mention that, the enclosures are not sealed, and P sensor measurements did not show relevant difference between the inside and outside (fast equilibrium rate). However, a slight local drop of P on the cold surface may be expected.

In all devices, under standard test conditions the temperature differs between the internal and the external environment. As a result, during thermal cycling the internal temperature is directed towards reaching a dew point to prevent overheating of the device. Reaching the dew point allows the internal air to cool down in order to be saturated with water vapor. The air pressure internally and externally is assumed and kept constant as well as the water content. These conditions will initiate condensation and water, in a liquid form, will form inside the device.

An additional condensation issue is related to rapid decompression, which can occur in aircraft experiencing a sudden loss in cabin pressure.

Table 1
Examples of failure mechanisms in specific electronic components when exposed to moisture.

Component	Failure Mechanisms	References
Capacitor		
Film Capacitor	Leakage current by water ingress	[27,101]
	Electrochemical corrosion, dielectric loss due to moisture absorption	[102]
Transistor	Corrosion – resulting in a reduction of the charge carrier mobility	[27]
Die metallization	Corrosion	[28]
Conductive adhesive	Corrosion	[29]
Anisotropic conductive film and nonconductive adhesive	Material degradation – resulting in reduced bonding strength	[30]
	Delamination/Crack	
Molding compound	Material degradation – resulting in reduced bonding strength	[31]
	Delamination/Crack	
Printed circuit boards	Fiber degradation	[18,31]
	Degradation of fiber/resin interface bonding	[18,30,32–34]
	Dendrite growth	[18,31,35]
	Corrosion on surface trace	[35]
	Creep corrosion	[36]
	Delamination	[37]
	Leakage Current	[38]

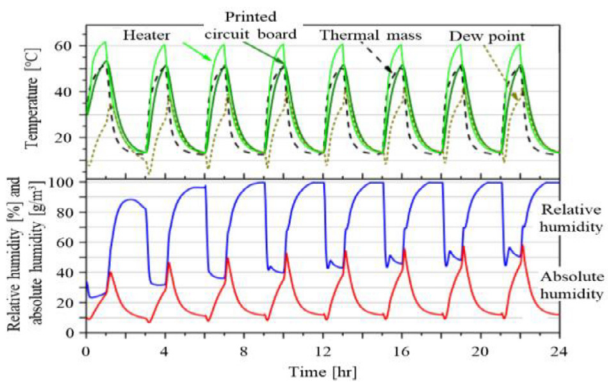

Fig. 3. Climate of a heater and a printed circuit board in polycarbonate enclosures under thermal-cycling conditions [19].

This can be recognized by a temperature decrease, and a cloud of fog or mist in the cabin due to change in temperature and humidity [94]. Colder air can hold less moisture; as a result, the air can fall below its dew point and so the excess moisture condenses into visible droplets.

Schimf et al. studied the physical effects of dew condensation and its influence on the reliability of microelectronics. They noted that dew condensation can cause a loss of performance or electrical shorts predominantly due to electrochemical migration [95].

3. Failures in electronics associated with water and moisture

Sandia National Laboratories reported that 20% of electronic failures are caused by water-induced corrosion [23]. An example of water-induced electronics failure is Samsung washing machine fires in 2016; these fires were due to moisture intrusion from the atmosphere during operation [24]. Moisture intrusion in the washing machines caused corrosion of the metal parts over time, resulting in the increased resistance of electrical conductors with an abnormal spike in temperature. Another example of moisture damage is the 2008 crash of the U.S. Air Force's B-2 Spirit bomber in Guam. It was determined that moisture on the sensors caused the jet to receive false data readings. The losses of the B-2 were estimated at $1.4 billion [25,26].

The effects of water on electronics and the resulting failures can be divided into two categories: (i) intermittent short-term failures resulting from water film formation, and (ii) long-term failures due to water-induced degradation of parts. Intermittent short-term failures are unpredictable, given that they depend on transient climatic conditions or unexpected exposure to water. For long-term failures, the progression of degradation may be predictable. However, such degradations are mostly irreversible and require replacement of parts. Table 1 summarizes failure mechanisms with respect to the type of component that absorbs moisture within the electronics.

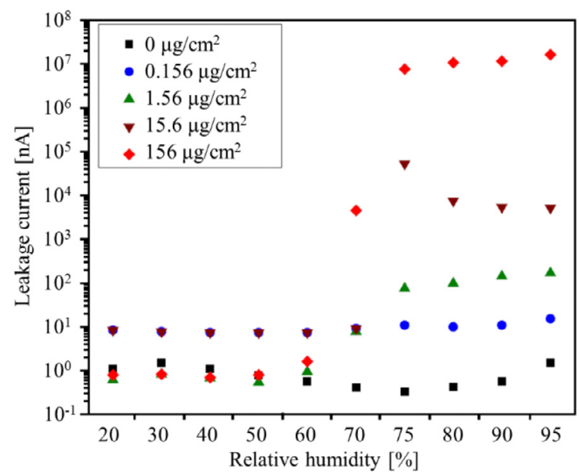

Fig. 4. Leakage current of PCB assemblies at varying relative humidity with different NaCl concentrations [38].

As an example, when a capacitor is charged, the dielectric is intended to prevent the flow of electrons through the dielectric layer. If the material does not provide proper insulation because of moisture absorption, then a leakage current path may develop [101].

Alternatively, Gupta et al. found that film capacitors were susceptible to electrochemical corrosion and dielectric loss due to moisture absorption, resulting in capacitance loss and an increase in the equivalent series resistance (ESR) [102].

3.1. Leakage current by water contact

Leakage current refers to an electric current that flows through an unwanted conductive path. Conductors can be connected via water, causing a stray current through the water layer. When moisture invades the electronic device one of the failure mechanism is produced as an electrical current leaking (i.e., flowing) through unwanted path. For example, making parts conductive when they are not supposed to be conductive. This in turn affects the functionality of printed circuit boards (PCBs) or components. Conseil et al. [38] observed that the leakage current of a PCB assembly increased as the relative humidity and salt concentration increased, which is shown in Fig. 4.

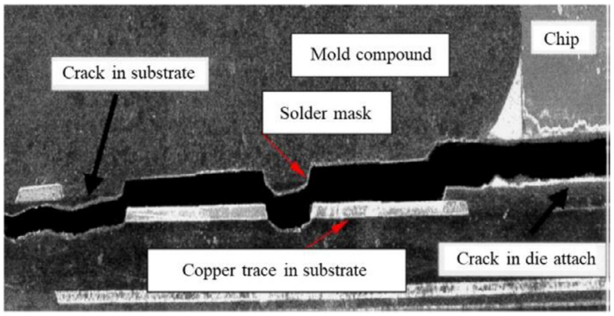

Fig. 5. Interfacial delamination between solder mask and copper trace in a plastic ball grid array [50].

Leakage current due to moisture is also found in transistor devices. A mechanism known as surface charge spreading can occur under a humid environment. Ionic charges spread laterally across the biased metals via moisture on the device surface [39], resulting in leakage current. Osenbach [40] observed an increase in leakage current by three orders of magnitude on an SiO_2 surface contaminated with aqueous sodium acetate solution. For organic thin-film transistors, water molecules can diffuse into voids in the organic film and increase the energetic disorder through charge/dipole interaction, leading to a decrease in the charge transport rate. Additionally, the mobility of hole charge carriers is reduced upon interaction with water molecules, resulting in a decrease of the saturation current and the on/off current ratio. The decrease of such electrical parameters lowers transistor performance or causes operational failure [41].

3.2. Degradation of polymeric material properties

Polymeric material that absorbs moisture can change its physical properties, including volume, fracture toughness, and elastic modulus, since water molecules interposed between the polymeric chains may disturb the intermolecular interactions [42,43]. Such moisture-induced material degradations can be observed in polymers that have hydrophilic moieties and spaces between polymer chains.

Adhesives applied to the interfaces of components are vulnerable to moisture. Under a humid environment, residual chemicals in adhesives (such as silane derivatives) can react with water molecules to form acids, which subsequently degrade interfacial adhesion [44]. In flexible electronics, the interface between silicon chips and flexible polyimide substrates is filled with epoxy materials, forming a silicon/epoxy/polyimide structure. Hydrogen and ester bonds in the interface lose their bonding strength due to the interaction with water molecules. Polyimide easily absorbs moisture, which can interact with the hydrogen bonding and ester bonding in the silicon/epoxy/polyimide interface, leading to adhesive debonding [45].

Moisture absorbed in adhesives can also induce cracks in devices during the solder reflow process [46–48]. When electronic assemblies are exposed to the reflow temperature, the moisture in adhesives evaporates. The resulting vapor pressure exerts stress on the interface, causing local delamination at the weakest adhesion site. Thus, a crack forms inside the assembly and propagates [49,50], as shown in Fig. 5. Such delamination-induced cracks occur at various places in electronics, including the bonding wires, substrates, and plated-through holes in PCBs.

Swelling due to moisture can be observed in hygroscopic materials, such as epoxy resin for the molding material of integrated circuits and the core material of PCBs. Water molecules absorbed in polymeric materials have two different states [31]. Water molecules present in voids between polymeric chains are in the “free” state, whereas ones that react with the chains via hydrogen bonding are in the “bound” state. The water molecules in both states contribute to the swelling of the polymer, as shown in Fig. 6 [51]. While the hygroscopic materials swell, the

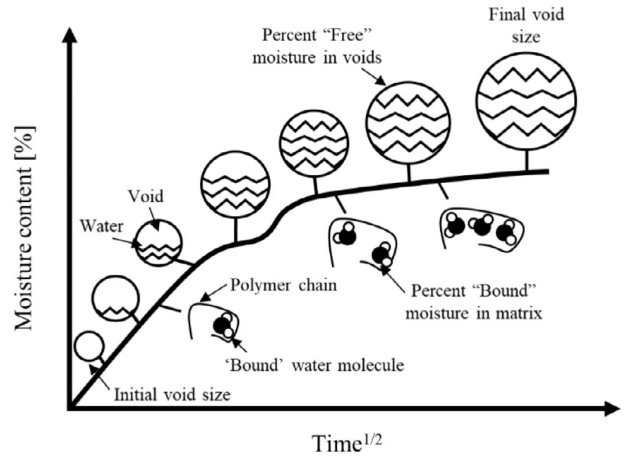

Fig. 6. Hygroscopic swelling due to water molecules [51].

moisture-impermeable materials (e.g., copper lead frame and silicone die) do not. The swelling mismatches between those materials cause warpage, leading to failure.

Epoxy resin in electronic packaging swells upon absorbing moisture and induces in-plane shear stress. In a study conducted by Wong et al. [52], samples of wire-bonded plastic ball grid array and flip-chip plastic ball grid array were subjected to a humidity stress test at JEDEC moisture sensitivity level (MSL) 2 (85 °C/60% relative humidity/168 hr). MSL is the moisture sensitivity performance of electronic packages which is introduced to identify the performance of SMD packages from MSL 1 to MSL 6 at a reflow temperature of 260 °C. Packages which achieve the most robust level MSL 1 can be interpreted as not sensitive to moisture, with unlimited floor life under typical room temperature and humidity, and for which dry packing is not required [97]. It was observed in the aforementioned study that the in-plane shear stress induced by hygroscopic swelling showed more than double that by thermal expansion at the reflow temperature.

Water absorbed in epoxy materials can increase segmental motions of polymer chains by disrupting the hydrogen bonds between hydroxyl groups, which lowers the glass-transition temperature (T_g) [53,54]. Ma et al. [55] observed that the T_g of an epoxy sample exposed to 85 °C/85% relative humidity for 192 h decreased from 148 °C to 122 °C. The lowered T_g can increase damage due to thermal stress and increases the dielectric constant. In turn, there is more electric power loss during operation. Then, circuit switching speeds decrease while propagation delay times increase [56,57]. Moisture can lead to the degradation of both mechanical material property degradation (e.g. adhesion strength, glass transition temperature) and electrical material property degradation (e.g. dielectric constant, insulation resistance).

3.3. Moisture induced mechanical failure

The presence of moisture inside polymers will induce volumetric expansion, known as hygroscopic swelling. As an example during electronic components assembly reflow process, the moisture will vaporize and generate significant amount of vapor pressure on pores or material interfaces at elevated temperature, resulting in cracking or delamination of the IC components, which is commonly known as “popcorn failure”.

The hygroscopic strain is defined as:

$$\varepsilon_h = \beta C \tag{8}$$

where, β is the coefficient of hygroscopic swelling (CHS) which is a measure of change in strain with moisture concentration(C). Similar to the thermal-mechanical stress, the hygro-mechanical stress will be induced when there is a mismatch of CHS among various materials in a package.

When the moisture is absorbed by the electronic assemblies, it will condense in free volumes or pores in the polymer-based packaging ma-

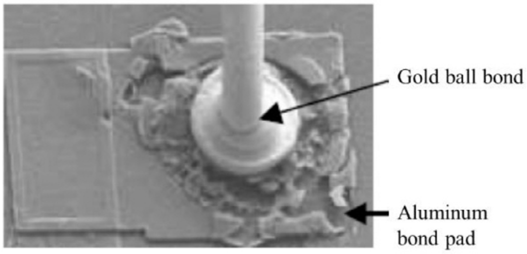

Fig. 7. Corrosion of Al bond pad in contact with Au ball bond [58].

terials. During the reflow process, the condensed moisture will vaporize and high amount of vapor pressure will be exerted on the package. Besides the CTE and CHS mismatch, the vapor pressure will induce additional mismatch to the package. The modulus of mold compound will show significant decrease at the reflow temperature, thus the vapor pressure induced strain may become as important as the thermal and hygroscopic strain.

Wang et al. reported that during the reflow process, the comprehensive effects of moisture, high temperature and vapor pressure may cause the delamination in the package, and under the combined effects of hygro-mechanical stress, thermal-mechanical stress and vapor pressure induced stress in the facture mechanics analysis, the strain energy release rate increases with temperature during reflow [92].

Chen and Li reported that the “popcorn effect” is resulted from the vaporization of absorbed moisture at high temperature together with mismatches in the coefficients of thermal expansion of the various package materials. It can lead to ball bonds lifted, wedge bonds broken, bond wires sheared and even die cracking. The problems induced by “popcorn effect” can be detected using nondestructive technique called c-mode scanning acoustic microscopy (C-SAM) and destructive technique called cross section analysis with mechanical polishing. To prevent damage from “popcorn effect”, plastic encapsulated microelectronic devices should be baked before assembly to drive out the moisture [93].

Alam et al. observed failures as a result of a sharp drop in the insulation resistance in the embedded capacitors that were biased at 5 V under 85 °C and 85% RH conditions. These failures seem to have been driven by defects in the dielectric, such as porosity and voids that can favor the formation of a conducting path under Temperature, Humidity, Bias (THB) conditions. The increase in capacitance and dissipation factor were found to be reversible. These parameters returned to their pre-THB values within 20 h after a high temperature bake at 125 °C. The insulation resistance failures also healed during baking at 125 °C. It was hypothesized that under THB conditions a conducting path was formed in the dielectric, which disappeared during baking [96].

3.4. Corrosion

Corrosion refers to any reaction of a material with its environment, regardless of the extent of the reaction or the rates of the initial and subsequent stages of the reaction [28]. In general, corrosion-related failure modes are irreversible. The underlying mechanism for moisture-induced corrosion is the electrochemical process, which can be either galvanic or electrolytic.

Galvanic corrosion occurs spontaneously once water film connects two dissimilar metals. Fig. 7 shows an example of galvanic corrosion due to the coupling between aluminum and gold with the presence of a water film [58]. The water film works as an electrolyte, and the electrochemically active aluminum becomes the anode and corrodes, whereas the resulting metal oxides are deposited on the gold. In 10% flux solution, electrochemical potentials for several metals are: Au (+186 mV), Ag (+ 147 mV), Cu (+50 mV), Ni (–110 mV), Sn (–438 mV), and Al (–532 mV) [58].

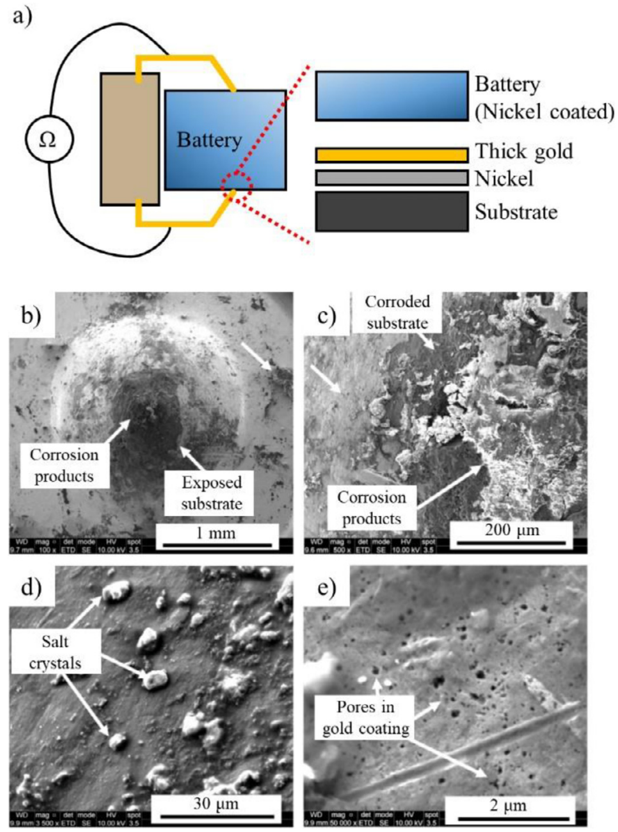

Fig. 8. Corrosion failures in hearing aid battery-spring contacts. (a) Illustration of a battery spring system and its contacts, (b) delamination of Au coating and corrosion, (c) corroded substrate and contamination, (d) salt crystals on the contact surface, and (e) pores in Au plating [59].

Another example of galvanic corrosion was observed in the battery contact springs of hearing aids during actual usage [59]. In the contact springs made of nickel electroplating with gold finish, pores were found on the gold surface, which appear to be formed by corrosion resulting from salt dissolved in water. Due to the pores, the galvanic corrosion occurred between the underlying nickel layer and the gold surface. The resulting metal oxides had high brittleness and caused cracking or delamination of the gold surface, which made the nickel layer more exposed, as shown in Fig. 8.

Galvanic corrosion also occurs at electrically conductive adhesives, which typically consist of metal particles and epoxy materials. Given the hygroscopic nature of epoxy, the electrically conductive adhesives tend to absorb moisture. The metal particles can cause galvanic corrosion of the electrodes or metal components under humid environments, leading to an increase in contact resistance. Lu and Wong [29] observed that the electrically conductive adhesives containing silver particles form galvanic corrosion with a tin/lead electrode. The electrically conductive adhesive having a higher water absorption property exhibited a faster contact resistance shift.

Creep corrosion, a type of galvanic corrosion, can form when a silver- or gold-finished board is exposed to a high level of sulfur gas with moisture [36,60]. At a silver/copper contact site, sulfur can dissolve into the moisture to form an acid electrolyte solution and promote corrosion. Copper, which is more reactive than silver, serves as the anode and produces copper sulfides, which are subsequently precipitated and grow around the silver/copper contact site, as shown in Fig. 9. When the copper sulfides reach adjacent conductors, electrical shorts occur. It was observed that flux residue, which is not completely cleaned after the soldering process, promotes creep corrosion further [36]. Flux usually contains carboxylic acids as activators to remove the oxides on the metal

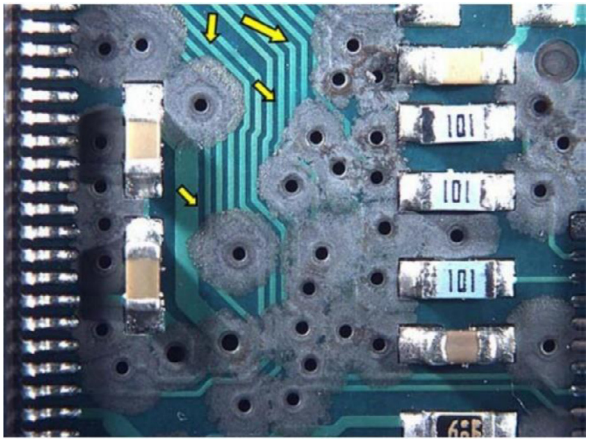

Fig. 9. Creep corrosion on silver-finished board [60].

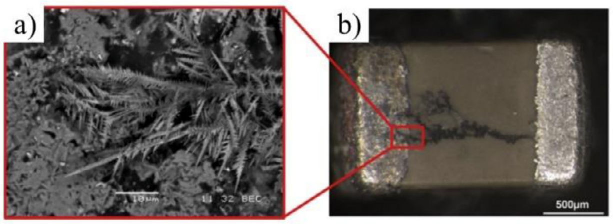

Fig. 10. Electrochemical migration and dendrite formation on a chip capacitor. (a) Scanning electron microscopic image and (b) overall view of the dendrite [61].

surface for better wettability. The carboxylic acids on the flux residue surface are known to provide active sites for creep corrosion [62].

Electrolytic corrosion is driven by electrical energy when water film connects two biased conductors. Electrochemical migration is an electrolytic corrosion-derived phenomenon and consists of a conductive dendrite formation that occurs on the insulating material surface between two adjacent conductors. As moisture provides a conductive pathway, electrical current flows due to the electric field between two biased metals. Metal ions form on the anode surface, move along with the moisture, and subsequently deposit on the cathode as a form of dendrite [16,35,64,65]. Fig. 10 shows an example of electrochemical migration on a component [61]. Another example for the electrochemical migration can be observed at silver particles embedded on the elastomer buttons of land grid array sockets. If there is a biased electric field between the adjacent elastomer buttons, electrochemical migration occurs and causes the silver ions to migrate. Yang et al. [66] observed a silver dendrite formation on the polyimide surface under a humid and biased environment. Such dendrite formation reduces the insulation between conductors and may cause short circuits.

The major difference between electrolytic corrosion and galvanic corrosion is: while galvanic corrosion is driven by the difference in corrosion potential between two metals (when two metals enter an electrolyte solution, the electrolytes connect to each metal, as they form a current flow from the anode-type metal to the cathode-type metal), the electrolytic corrosion is driven by the external sources of electromotive force (EMF), i.e., an electric current has been introduced into the conducive electrolyte solution. In the case of large motor bearings and generator bearings, induced EMF of the shaft can result in current flow in the bearing, resulting in bearing corrosion in the shape of pinhole-type pits formed on the bearing surface. Similarly, in the case of electrolytic corrosion of pipes, high-voltage direct current equipment and marine equipment, external leakage current can be a driving force for corrosion. Electrolytic corrosion is the reason why the metal near electrical and mechanical systems on a ship is more rusted and damaged, in which case the electrical source can be as simple as faulty wiring discharging its electric current into the water [98].

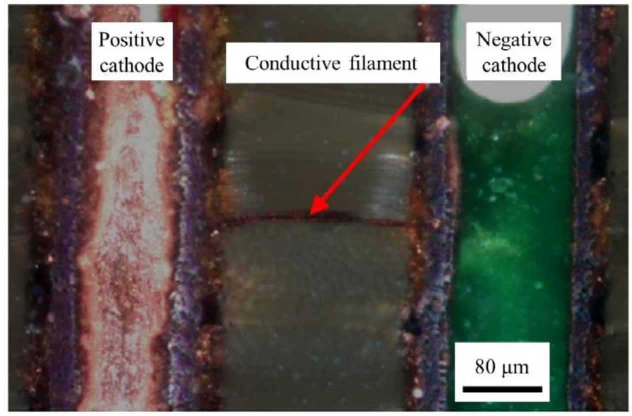

Fig. 11. Formation of a conductive anodic filament between plated-through holes in a PCB [63].

Conductive anodic filament formation is one of the electrochemical migration-derived failure modes that can be observed at the conductor spacings between plated-through holes of a PCB [34,67]. A transportation path for metal ions can form at the fiber/resin interface due to manufacturing quality, material properties, thermal cycling, and other factors. With water molecules, copper ions are produced at the anode and move to the cathode along the moisturized transport path, forming a copper filament, as shown in Fig. 11 [63].

Microorganisms, such as fungus, can grow on the surface of insulants in a humid environment and cause loss of insulation resistance by forming a conductive mycelial bridge [68]. Furthermore, various weak acids produced during metabolism, for example amino acids and other organics, may corrode metals and change the physical properties of electronic materials. It is difficult to predict the degree of effect by the microorganisms because of their complex enzymic actions [69].

Singh and Tan. [104] studied the relative humidity effect associated with dust contamination and showed that moisture was attracted between adjacent electrodes through physical and chemical processes, through the deliquescent process, capillary condensation in the porous mineral particles, in dust particle surface cracks, or between the glass fibers in the PCBs. The deliquescence process took place when the RH reaches a critical relative humidity (CRH); that is, a deliquescent relative humidity of the mixed salts in the dust samples [103]. At or above the CRH, water soluble salts absorb relatively large amounts of water from the atmosphere, forming a liquid solution. As the RH exceeded the CRH of the mixed salts in the dust samples, the deliquescence process continues to proceed by absorbing more vapor from the atmosphere and the solid particles transform into saline droplets and form a continuous path, causing impedance degradation which can cause early field failures of electronics in outdoor applications.

4. Water protection methods in electronics

There are various approaches to protect electronics from water, depending on several factors. For example, the expected type of water concerns for an indoor unit of an air conditioning system is mainly condensation, while protection methods for its outdoor condensing unit should focus on rain and snow. Micrometer-level methods may be enough to protect PCBs and components, whereas thicker protection methods are required to cover the electronic product. Protection methods that last for the product lifetime are preferred for portable electronic devices and home appliances, but large electronics facilities (such as data centers or wind turbines) may use protection methods that can be replenished during regular maintenance.

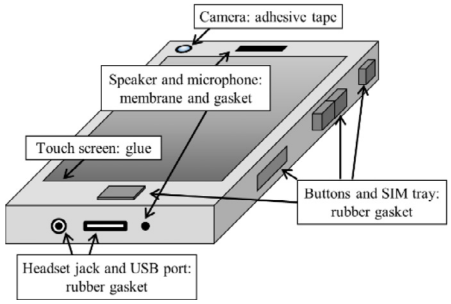

Fig. 12. Protection methods for potential water ingress points in a smartphone [70].

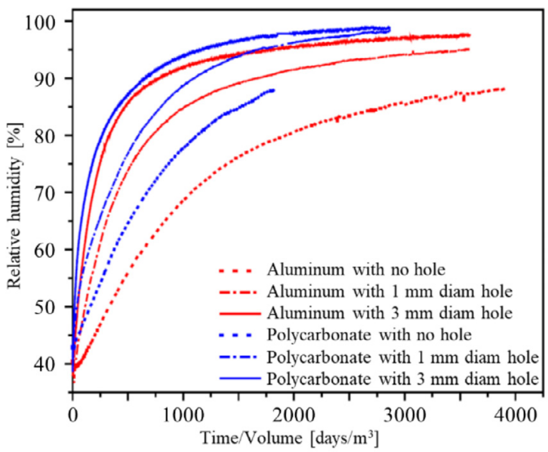

Fig. 13. Comparison of moisture ingress into polycarbonate and Al enclosures [73].

Physical volume and manufacturing cost of the products also need to be considered. Some application fields, such as military or medical devices, can afford to use high-performance and expensive water protection methods, which do not have to be applied to general electronic products. All protection methods have trade-offs. This section discusses various protection methods that correspond to different levels of water protection and their advantages and disadvantages.

4.1. Enclosures

The surface of an electronic product is covered with casing materials, and its openings can be enclosed by adhesives, rubber or silicone gaskets, and mesh or membrane, as shown in Fig. 12 [70,71]. Casing materials for electronic products can be selected from materials having various levels of permeability. In general, materials whose atoms are densely packed (such as metal, glass, and ceramics) exhibit lower permeability than polymeric materials but are heavy [72] (e.g., the density of glass, aluminum, and titanium is 2.6 g/cm^3, 2.7 g/cm^3, and 4.5 g/cm^3, respectively, while that of polycarbonate and poly[methyl methacrylate] is 1.21 g/cm^3 and 1.18 g/cm^3, respectively). Some metals, including aluminum and iron, are vulnerable to corrosion, whereas noble metals are costly to be used as casing materials. Ceramics are fragile because of their covalent and ionic bonding. For such limitations, impermeable materials tend to be used only when they are necessary, such as in cardiac pacemakers.

Various polymers are used as casing materials. As noted in Section II-B, polymers allow water to permeate. Conseil-Gudla et al. [73] observed that the humidity buildup in polycarbonate enclosures occurs faster than in aluminum enclosures because of moisture permeation through the polycarbonate material, as shown in Fig. 13. When the enclosures are made with polymer, the moisture transport properties of the materials (such as permeability, diffusivity, and solubility) need to be considered depending on the climatic condition at which the product is used.

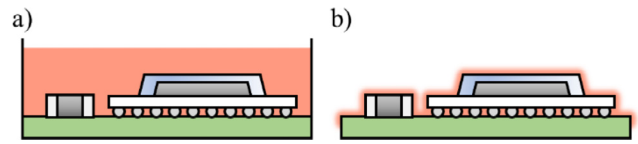

Fig. 14. Illustration of (a) potting and (b) conformal coating.

Electronics may need some openings that should not be sealed, such as vents for cooling, input/output ports for electrical connections, holes for direct connection to micro-electromechanical system-based microphones and speakers, and screw locations. Water ingress by such openings may be deterred by orienting the openings downwards (for equipment installed outside), minimizing the size of the openings, and utilizing hydrophobic materials. As the product ages, the openings can become enlarged due to wear and physical shocks [70]. Openings covered with hydrophobic membranes (e.g., polytetrafluoroethylene) can be used to regulate pressure in nonhermetically sealed packages without allowing liquid water to enter. Those measures are effective up to a specific water entry pressure (WEP), above which liquid water can penetrate the membrane. Although a membrane's WEP will vary based on its properties such as thickness, porosity, and morphology, these measures are useful for preventing water ingress due to splatter, rain or snow, and shallow immersion [70].

Rubber gaskets and adhesives are used to seal the openings on product housings. Those can be degraded by environmental loads, such as salty moisture, temperature fluctuations, and solar radiation. Moreover, during usage, cracks and other defects may form and will contribute to moisture ingress [70].

4.2. Coatings

To protect electronics at the level of PCBs or components, coating methods are used. Coating methods can be divided into potting and conformal coatings [74].

Potting is a protection method in which electronic assemblies are completely immersed in gel or solid compounds. As shown in Fig. 13(a), an electronic device is placed inside a pot and subsequently filled with the potting material. Materials for potting include epoxy resins, urethane, and silicone gels. Epoxy potting provides better adhesion to metals compared to urethane and silicone potting, because epoxy resin mostly consists of various functional groups; these groups include ether, ester, amide, and amine, which can chelate metal atoms on the surface. However, epoxy materials have a hygroscopic nature and sometimes cause various failure modes with moisture, as noted in Section III-B. Urethane potting exhibits a similar adhesive force with epoxy since it also contains several functional groups which can chelate metal atoms [75]. Urethane can be used in applications that require flexibility. The main disadvantage of using urethane is its low resistance against heat. Urethanes are usually softer than epoxies with lower glass transition temperature, modulus, and strength, but with higher elongation [99]. Urethane loses its mechanical properties when the temperature reaches 90 °C [75]. Urethane has hydroscopic tendencies, i.e. water absorption characteristics and upon water absorbtion can cause short life in electronic devices because it can no longer serve as an effective protection method. Silicone potting provides chemical inertness and can withstand temperature ranges of –50 °C to 200 °C, while it has a poor adhesive force compared to the epoxy and urethane materials [76]. Conformal coating methods are also widely used to protect the electronic device surface (Fig. 14(b)). Conformal coatings can be achieved via brushing, spraying, or dipping, and usually have a thickness of 25 to 125 μm [76,77]. Materials for conformal coating are similar to potting and include acrylic, epoxy, silicone, urethane, and parylene. Since the amount of material used is less than that of potting, conformal coating has advantages in weight

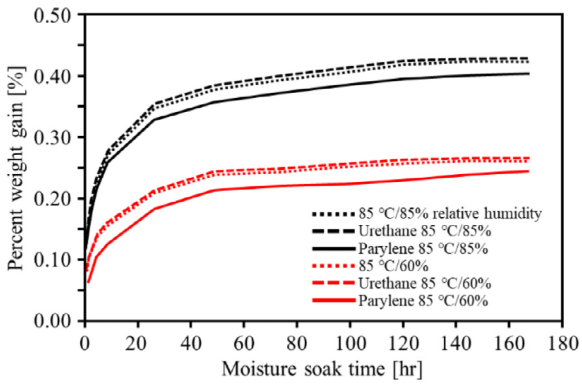

Fig. 15. Moisture absorption of printed ball grid arrays (noncoated, urethane-coated, and parylene-coated) [79].

and cost. Despite that, conformal coating is known to only delay the moisture ingress to a limited extent [78]. Zhang and Pecht [79] examined the effectiveness of conformal coatings with urethane and parylene for protecting a plastic ball grid array package from moisture-induced failures. It was observed that only parylene could slightly slow down the moisture ingress into the package. No evidence was shown that conformal coatings could prevent moisture-induced failures, as shown in Fig. 14. Nevertheless, although conformal coating is not completely water protecting, it is still used for its insulation benefit by allowing reduction in conductor spacing, protection against chemical and corrosive attack, and by providing mechanical support and vibration resistance.

More recent studies have shown that degradation of silicone used in high power white LEDs as a molding material has significant impact on the LED's lifetime and efficacy as silicon is prone to cracking under moisture [100,104]. P.Singha and C.M. Tan reported that, silicone molding material degradation is the dominant cause for lumen degradation of LEDs under high temperature and humidity condition which is caused by the hydrolysis of the Silicone, then condensation, followed by thermal oxidation and lastly thermal aging. Discoloration is found to be mainly due to hydrolysis and cracks propagation is found to be mainly due to thermal oxidation. The hydrolysis reaction resulted in the formation of SiOH bonds and these bonds then undergo condensation reaction under the high temperatures present inside the high power white LEDs. As the condensation reaction starts to drive away the incoming moisture and gain dominance over hydrolysis reaction after 45 h, temperature increases and this led to the initiation of oxidation reaction. The oxidation reaction leads to deeper cracks on silicone surface and invoked Si oligomers diffusion and lead to the crack depth recovery [100].

4.3. Desiccants and dehumidifiers

Desiccants can be used to suppress humidity inside of electronics. There are various types of desiccants, including silica gel, molecular sieves, calcium oxide, montmorillonite clays, and calcium sulfate. Each type has its own adsorption characteristics. Desiccants are available in many forms, such as packets, sheets, tapes, and compressed forms; desiccants can even be integrated into a polymer. Compressed-form desiccants are the most common desiccants in electronic products because they can be designed with a specific shape to fit a specific space.

Several factors to consider when using a desiccant are i) the amount of moisture that must be removed from the headspace air in the product, ii) the expected amount of water ingress during the product usage, iii) space constraints, and iv) compatibility with the product. Desiccants should be replaced regularly; otherwise, the saturated desiccants may desorb water inside the electronics [80].

Dehumidification can be installed in large electronic systems, such as wind turbines or data centers. The electronic equipment to be protected should be placed in a space which is separated from the outside to prevent airflow. A dehumidifier is then placed in the space and used to extract moisture [81]. The cost of the dehumidification equipment, along with the upkeep and maintenance required, should be considered.

4.4. Baking

All plastic integrated-circuit packages have a tendency to absorb moisture. During surface-mount assembly, this moisture can vaporize when subjected to the heat associated with solder reflow operations. Vaporization creates internal stresses that can cause the plastic molding compound to crack. This cracking process is commonly referred to as the "popcorn effect." Cracks in the plastic molding may cause broken bond wires or may allow contamination to penetrate to the die, which can reduce the reliability of the semiconductor device. Since plastic packages absorb moisture, care must be taken to prevent exposure to humid conditions greater than 10% RH for extended periods of time prior to surface mount reflow processing. If exposed to excessive moisture, the devices should be baked to remove moisture prior to solder reflow operations.A baking process widely used in integrated circuit (IC) manufacturing prior to printed circuit board assembly reduces the moisture level in the permeable surface mount device (SMD). Baking prevents moisture-induced delamination and popcorn failures. However, baking can degrade component solderability, e.g., the intermetallic compound (IMC) Au/sub 0.5/Ni/sub 0.5/Sn/sub 4/ can grow and cause the solder ball falling off issues at ball grid array (BGA) board assembly. From a risk tradeoff perspective, a longer baking time at relatively high temperature is beneficial to drive out moisture but has the disadvantage of being sensitive to the formation of IMC (Au/sub 0.5/Ni/sub 0.5/Sn/sub 4/). It is difficult to simultaneously achieve an acceptable yield of print circuit board assembly (PCBA) due to the tradeoff between the critical moisture level and formation of IMC unless the baking process is optimally controlled. Moreover, as the "green" electronics are introduced into SMD with characteristically higher moisture resistance, the baking time must be increased [37,44,46–49].

5. Water-related test methods

Several test methods evaluate how water in many forms affects the reliability and safety of electronics as environmental loading conditions. Such standard test methods have been applied in various fields, including aircraft, automobiles, submarines, cell phones, electronic or mechanical modules, PCB assemblies, bare boards, components, connectors, and cables. The selection of specific test methods depends on the application field. A list of standard test methods and submethods is included in the appendix of this paper.

5.1. Test methods to assess protection of electronics against water ingress

Ultrasonic testing is one of the examination methods used to inspect the sealed enclosures. Schwerz et al. [82] reported a method of inspection by coupling piezoelectric transducers onto the sealed enclosure where the transducers can send ultrasonic waves into the welding points. The difference between the ultrasonic waves can be used to determine the level of damage in the welded joints or sealing enclosures. Another method to test the tightness of the enclosures is an air pressure test, where over- or under-pressure is applied inside the enclosure. The decay or buildup of the internal pressure will be a comparative indication of the tightness. Manufacturers also use a similar test with a helium leak rate.

Among many water protection standards to indicate the robustness of product enclosure, the ingress protection (IP) classification by the IEC 60,529 standard has been widely used for general electronics with a rated voltage not exceeding 72.5 kV, although several ambiguities and limitations hamper IEC 60,529. An example of a rating is IP54, in which the first numeral describes the protection against solid objects, and the

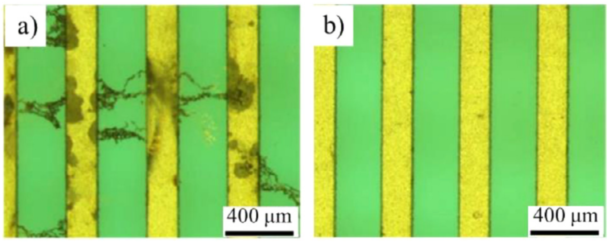

Fig. 17. Test boards used for a) surface insulation resistance measurements and b) electrochemical impedance spectroscopy [86].

second numeral describes the protection against liquid water. The degrees of protection are defined as protection of the equipment inside the enclosure against harmful effects due to the ingress of water without stating clearly what the "harmful effects" refer to. Also, the distinction between each grade is ambiguous. For instance, IPX7 is defined as the protection ability against temporary immersion, whereas IPX8 refers to the protection ability against continuous and more severe immersion. There is a lack of explanation for how long it means to be continuous and what is meant by a "more severe" water depth. IEC 60,529 does not consider the effects of product aging on its water protection ability [83,84].

5.2. Test methods to evaluate how water affects electronics

Surface insulation resistance measurement is often used to evaluate how moisture has affected the reliability of electronics. Surface insulation resistance refers to the resistance across the insulated surface between adjacent conductors. A direct current (DC) voltage is applied to a test sample, and the surface insulation resistance is recorded. A drop in the resistance indicates leakage current in the test sample, which is probably caused by corrosion processes.

Electrochemical impedance spectroscopy also can be used as an alternative to the surface insulation resistance measurement. In electrochemical impedance spectroscopy, an alternating current with a small amplitude of around 10 mV is applied to the test sample at a frequency range over several orders of magnitude. The magnitude and phase angle of the complex impedance are obtained from the output response. By establishing an electrical equivalent circuit that represents the test sample, the complex impedance can be used to recognize various moisture-induced electrochemical processes. If condensation occurs on the substrate surface between two conductors, the water which acts as a conductive medium will decrease the impedance and change the phase angle from capacitive characteristics to a resistive behavior [85]. Since the electrical load on the sample is small, the electrochemical impedance spectroscopy method has the advantage of being nondestructive compared to surface insulation resistance methods. Lauser et al. observed the water layer formation in test circuit boards using both the surface insulation resistance method and electrochemical impedance spectroscopy. In the test board to which a DC of 5 V was applied for the surface insulation resistance method, a dendrite formation across conductors was observed. Conversely, the other sample monitored through electrochemical impedance spectroscopy remained unharmed, as shown in Fig. 17 [86].

The resistance of electronics against corrosion is assessed through optical observation following exposure to humid conditions. After the test specimen is exposed to specified humid conditions, it is observed whether there is any evidence of corrosion, such as discrete white or colored spots, pitting of metal panel or excrescence, exposure of base metals. Resistance against metallic dendrite growth can be examined by similar test methods. Typically, a test sample is subject to humid conditions with DC bias and is stored for hundreds of hours [86]. Evaluation is subsequently conducted by measuring insulation resistance and observing dendrite growth with a microscope. Test methods for conductive anodic filaments also follow a similar test procedure, except that visual inspection includes microsectioning PCBs [86].

6. Conclusions

Water in its many forms (e.g., liquid water, condensation, water vapor, and adsorbed moisture) can cause product failures at any stage of product manufacturing, assembly, transportation, storage, and use. This paper describes the water-related performance and reliability issues that are often neglected but which can occur in electronic products.

This review identifies the failure modes and mechanisms related to the forms of water in electronics. Water film may connect conductors and result in leakage current. Material degradation by absorbing water may cause failures; these include adhesive debonding, cracks due to vapor pressure exerted from moisture in adhesives, warpage caused by swelling of hygroscopic polymers, and degradation of electrical parameters due to the lowered glass-transition temperature of epoxy resins. Galvanic and creep corrosion occur in the bimetallic surface, such as electrically conductive adhesives with electrodes, battery contact springs, and noble metal-finished PCBs. Moisture between biased metals causes metal ions to migrate and form metal dendrites on the capacitor electrodes or filament at the spacings between the plated-through holes in PCBs.

This study reviews water protection methods. Each method has its advantages and drawbacks. Electronics can be covered with casing materials which have various permeability levels and can be sealed with gaskets and adhesives. Some openings necessary for electronics are minimized in size or made of hydrophobic materials to deter water ingress by capillary action. Conformal coating and potting methodologies for electronic devices can delay water ingress but cannot prevent it. Desiccants and dehumidifiers can be applied to remove moisture but require large spaces with regular maintenance.

This study also discusses testing methods to evaluate a product's water protection ability and to assess the effects of water on electronics based on its application field. The IEC 60,529 standard and its ingress protection classification are used to indicate the degrees of protection against ingress of water, although the standard lacks consideration of product aging. Surface insulation resistance measurement in DC is mainly used to evaluate corrosion in electronics. On the other hand, the alternating-current electrochemical impedance spectroscopy method is also starting to emerge. This is because of its usefulness in analyzing the underlying moisture-induced chemical process in electronics (which is done by measuring complex impedance of the test structure).

Based on this study, electronics manufacturers should not underestimate the various detrimental effects of water on their products. There are various water ingress mechanisms that are hard to predict, and some failure modes occur intermittently, which is difficult to be found. Manufacturers should predict which type of water the product will be exposed to and which failure modes might occur under the use environment. Based on those factors, water protection methods should be considered from the design stage and should be selected along with the product's target reliability, size, and production cost. For each component or the entire system, the appropriate testing methods and standards should be used to evaluate the component's or system's water protection ability.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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APPENDIX. Water-moisture-related test methods

A. Military test methods

MIL-STD-810H Environmental engineering considerations and laboratory tests is a U.S. Department of Defense standard that includes several test methods for rain, humidity, salt fog, fungus, and icing/freezing. Military standards mainly focus on military applications, but their test methods can be used in other application environments depending on the customer specifications. The relevant water-related test methods are as follows:

Test Method 506.6 – Rain test, for evaluation of performance requirements of a test item under rain: This test evaluates material likely to be exposed to rain, water spray, or dripping water during storage, transit, or operation.

Test Method 507.6 – Humidity test: The purpose of this method is to determine the resistance of the material to the effects of a warm, humid atmosphere. This method does not address condensation and synergistic effects.

Test Method 508.8 – Fungus: The purpose of this test is to assess the extent to which material will support fungal growth and how any fungal growth may affect performance or use of the material. Since microbial deterioration is a function of temperature and humidity, and is an inseparable condition of the hot, humid tropics and the mid-latitudes, it should be considered in the design of all standard, general-purpose material.

Test Method 509.7 – Salt fog test: This test method is for evaluation of test items under aqueous salt atmosphere because salt is found in oceans, atmosphere, ground surfaces, lakes, and rivers. It is possible to avoid exposure to salt. The salt fog test is performed to determine the effectiveness of protective coatings and finishes on materials. It may also be applied to determine the effects of salt deposits on the physical and electrical aspects of the material.

Test Method 512.6 –Immersion test: This test determines if the material can withstand immersion or partial immersion in water (e.g., fording), and operate as required during or following immersion.

Test Method 520.5 – Combined environment (combinations of temperature, humidity, vibration, and altitude test): The purpose of this test is to help determine the synergistic effects of combinations of temperature, altitude, humidity, input electrical power, and vibration on airborne electronic and electro-mechanical material with regard to safety, integrity, and performance during ground and flight operations.

Test Method 521.4 – Icing/freezing rain test: The icing test is conducted to evaluate the effect of icing on the operational capability of the material. This test method is for evaluation of the effects of icing produced by freezing rain, mist, or sea spray on the material. This method also provides tests for evaluating the effectiveness of de-icing equipment and techniques, including prescribed means to be used in the field.

Test Method 524.1 – Freeze/thaw test: The purpose of this test is to determine the ability of the material to withstand the effects of moisture phase changes between liquid and solid, in or on the material, as the ambient temperature cycles through the freeze point as well as the effects of moisture induced by transfer from a cold-to-warm or warm-to-cold environment.

MIL-STD-883 G – *Microcircuits:* This standard establishes uniform methods, controls, and procedures for testing microelectronic devices suitable for use within military and aerospace electronic systems. This test method can be used to assess printed wiring board laminate materials, printed wiring board design and application parameters, printed wiring board manufacturing process changes, and press-fit connector applications.

Test Method 1014.12 – Seal test: This test method is to determine the effectiveness (hermeticity) of the seal of microelectronic and semiconductor devices with designed internal cavities.

Test Method 1018.5 – Internal gas analysis: This test method is to measure the water-vapor content of the atmosphere inside a metal or ceramic hermetically-sealed devices, and provides destructive or non-destructive analysis method.

MIL-STD-202 G – *Electronic and electrical component parts* establishes uniform methods for testing electronic and electrical component parts (e.g., capacitors, resistors, switches, transformers, and inductors), including basic environmental tests to determine resistance to deleterious effects of natural elements and conditions surrounding military operations, and physical and electrical tests.

Test Method 103B – Humidity (steady state): This test is performed to evaluate the properties of materials used in components as they are influenced by the absorption and diffusion of moisture and moisture vapor.

Test Method 104A – Immersion: This test is performed to determine the effectiveness of seal of component parts against immersion.

Test Method 106 G – *Moisture resistance*: This test is to evaluate the resistance of component parts and constituent materials to the deteriorative effects of the high-humidity and heat conditions typical of tropical environments. This test differs from the steady-state humidity test and derives its added effectiveness in its employment of temperature cycling, which provides alternate periods of condensation and drying essential to the development of the corrosion processes and produces a "breathing" action of moisture into partially sealed containers.

MIL-D-3464E Desiccants, Activated, Bagged, Packaging Use and Static Dehumidification covers bagged, chemically inert, dehydrating agents that prevent corrosion and mildew by adsorbing the moisture from the air of an enclosed space. This standard provides test methods to evaluate water vapor adsorption capacity of the agents.

B. IPC TEST METHODS

IPC, formerly Institute for Interconnecting and Packaging Electronic Circuits, is the association serving the printed board and electronics assembly industries, their customers, and suppliers. It has several water-related environmental test methods. IPC is located in Bannockburn, Illinois, USA.

IPC-TM-650 has several test methods under the sections of reporting and measurement, visual tests, dimensional tests, chemical tests, mechanical tests, electrical tests, and environmental test methods. Water-related test methods take place under environmental test methods, and these test methods refer to many sources of equipment and materials necessary to perform the tests.

*IPC-TM-650 2.6.*1 G – *Fungus resistance of printed board materials:* The fungus resistance test is used to determine the resistance of materials to fungi and to determine if such a material is adversely affected by fungi under conditions favorable for their development, namely, high humidity, warm atmosphere, and the presence of inorganic salts. Corrosion should be noted separately from the fungus test results.

IPC-TM-650 2.6.3F – Moisture and insulation resistance, printed boards: This test method determines the degradation of insulating materials by examination of the visual and electrical insulation resistance properties of printed board specimens after exposure to high humidity and heat conditions.

IPC-TM-650 2.6.3.1 – Moisture and insulation resistance, solder mask is to determine the moisture and insulation resistance of applied polymer solder mask.

IPC-TM-650 2.6.3.5 – Bare board cleanliness by surface insulation resistance is to characterize the cleanliness of PCBs by determining the degradation of insulation resistance under high temperature and humidity.

IPC-TM-650 2.6.3.7 – Surface insulation resistance: This test is performed to quantify the deleterious effects of fabrication, process or handling residues on surface insulation resistance in the presence of moisture. This test is focused on leakage current due to adsorbed moisture and ionic contamination and electrochemical degradation of test vehicles, including corrosion and dendritic growth. Test sample is subject to humid condition and then evaluated in terms of surface insulation resistance, percent reduction of spacing by dendrites, discoloration, water spots, and subsurface metal migration.

IPC-TM-650 2.6.14.1 – Electrochemical migration resistance test: This test method provides a means to assess the propensity for surface electrochemical migration. This test method can be used to assess soldering materials and processes.

IPC-TM-650 3.5A – Humidity, connectors: Two test conditions are provided as follows: The steady-state test is used to evaluate the hygroscopic nature of insulating materials as evidenced by deteriorated physical properties (e.g., dimensions, mechanical strength, etc.) or degraded electrical properties (e.g., insulation resistance). The humidity-temperature cycling test is used to evaluate the effectiveness of seals and gaskets in the presence of a pressure differential induced by varying temperatures; the corrosion resistance of metals and finishes exposed to alternate periods of condensation and drying; and the hygroscopic nature of insulating materials, with any degradation accelerated by the "breathing" action imposed by varying temperatures.

IPC-TM 2.6.25B – Conductive anodic filament resistance test: X-Y axis: This test method provides a means to assess the propensity for conductive anodic filament growth, a form of electrochemical migration, and similar conductive filament formation laminate material failure modes within a printed wiring board. This test method can be used to assess laminate materials, design and application parameters, manufacturing process changes, and press-fit connector applications.

C. JEDEC TEST METHODS

The Joint Electron Device Engineering Council (JEDEC) is developing open standards for the microelectronics industry. The center is located in Arlington, Virginia, USA.

JESD-020E – Joint IPC/JEDEC Standard for Moisture/Reflow Sensitivity Classification for Nonhermetic Surface Mount Devices: This document identifies the classification level of non-hermetic solid-state surface mount devices that are sensitive to moisture-induced stress. It is used to determine what classification level should be used for initial reliability qualification. The classicifcation level is identified as moisture sensitivity level (MSL) which is an electronic standard for the time period in which a moisture sensitive device can be exposed to ambient room conditions (30 °C/85%RH at Level 1; 30 °C/60%RH at all other levels)Once identified, the surface mound devices can be properly packaged, stored, and handled to avoid subsequent thermal and mechanical damage during the assembly solder reflow attachment and/or repair operation.

JESD22-A100D – Cycled temperature-humidity-bias life test: This test is performed for evaluating the reliability of non-hermetic packaged solid-state devices in humid environments. It employs conditions of temperature cycling, humidity, and bias that accelerate the penetration of moisture through the external protective material (encapsulant or seal) or along the interface between the external protective material and the metallic conductors that pass through it.

This test is performed for the purpose of evaluating the reliability of non-hermetic, packaged solid-state devices in humidity environments when surface condensation is likely. It employs conditions of bias, temperature cycling, and high humidity that will cause condensation to occur on the device surface. It is useful to determine device surface susceptibility to corrosion and/or dendritic growth.

JESD22-A101D – Steady-state temperature-humidity-bias life test: This standard establishes a defined method and conditions for performing a temperature-humidity life test with bias applied. The test is used to evaluate the reliability of non-hermetic packaged solid-state devices in humid environments. It employs high-temperature and -humidity conditions to accelerate the penetration of moisture through the external protective material or along interfaces between the external protective coating and conductors or other features that pass through it.

JESD22-A102E – Accelerated moisture resistance-unbiased autoclave: This test allows the user to evaluate the moisture resistance of non-hermetic packaged solid-state devices. The unbiased autoclave test is performed to evaluate the moisture resistance integrity of non-hermetic packaged solid-state devices using moisture condensing or moisture-saturated steam environments. It is a highly accelerated test that employs conditions of pressure, humidity, and temperature under condensing conditions to accelerate moisture penetration through the external protective material (encapsulant or seal) or along the interface between the external protective material and the metallic conductors passing through it.

This test is used to evaluate new packages or packages that have undergone changes in materials (e.g., mold compound, die passivation) or design (e.g., die/paddle sizes). However, this test should not be applied to laminate or tape-based packages, i.e., FR4 material, polyimide tape, or equivalent.

A device under accelerated moisture resistance shall be defined a failure if its parametric limits are exceeded, or its functionality cannot be demonstrated under nominal and worst-case conditions as specified in the applicable procurement document or datasheet.

JESD22-A107 – Salt atmosphere: This standard defines a method for determining the resistance of solid-state devices against corrosion as a result of exposure to a saline atmosphere.

This salt atmosphere test is conducted to determine the resistance of solid-state devices to corrosion. It is an accelerated test that simulates the effects of severe seacoast atmosphere on all exposed surfaces. The salt atmosphere test is considered destructive. It is intended for lot acceptance, process monitoring, and qualification testing.

A device shall be considered as having failed if: a) Specified markings are illegible when viewed under normal room lighting with a magnification of 1X to 3X. b) There is evidence of corrosion over more than 5% of the area of the finish or base metal of any package element (e.g., lid, lead, or cap), missing or broken leads, excessive lead-to-lead leakage (above that specified in the appropriate specification), or any corrosion that completely crosses the element when viewed with a magnification of 10X to 20X.

JESD22-A110-B – Highly accelerated temperature and humidity stress test: This test evaluates the reliability of non-hermetically packaged solid-state devices in humid environments. This document defines a standard method for performing a highly accelerated temperature and humidity stress test, which evaluates the reliability of non-hermetically packaged solid-state devices exposed to humid environments, particularly their resistance to internal corrosion. It employs severe conditions of temperature, humidity, and bias that accelerate the penetration of moisture into the package and die.

JESD22-A118B – Accelerated moisture resistance unbiased HAST: The unbiased highly accelerated temperature and humidity stress test is performed for the purpose of evaluating the reliability of non-hermetically packaged solid-state devices in humid environments. It is a highly accelerated test that employs temperature and humidity under noncondensing conditions to accelerate the penetration of moisture through the external protective material (encapsulant or seal) or along with the interface between the external protective material and the metallic conductors that pass through it. Bias is not applied in this test to ensure the failure mechanisms potentially overshadowed by bias can be uncovered (e.g., galvanic corrosion). This test is used to identify failure mechanisms internal to the package and is destructive.

A device will be considered to have failed if parametric limits are exceeded, or if functionality cannot be demonstrated under nominal and worst-case conditions as specified in the applicable procurement document or datasheet.

JESD22-A120B – Test method for the measurement of moisture diffusivity and water solubility in organic materials used in integrated circuits: This specification details the procedures for the measurement of characteristic bulk material properties of moisture diffusivity and water solubility in organic materials used in the packaging of integrated circuit components.

This test method provides a means for determining the moisture sorption properties of organic materials used in the packaging of electronic devices. This specification details the procedures for the measurement of characteristic bulk material properties of moisture diffusivity and water solubility in organic materials used in the packaging of electronic devices. These two material properties are important parameters for the effective reliability performance of plastic-packaged surface mount devices after exposure to moisture and subjected to high-temperature solder reflow.

IPC/JEDEC J-STD-033C-1 – Handling packing, shipping and use of moisture/reflow sensitive surface mount devices: The purpose of this specification is to provide surface mount device manufacturers and users with standardized methods for handling, packing, shipping, and use of moisture/reflow sensitive surface mount devices. These methods are provided to avoid damage from moisture absorption and exposure to solder reflow temperatures that can result in yield and reliability degradation.

D. IEEE MOISTURE-RELATED TEST METHODS

IEEE (Institute of Electrical and Electronics Engineers) is the world's largest technical professional organization publishing standards and papers, organizing conferences, and giving training for advancing technology for the benefit of humanity. The IEEE corporate headquarters is located in New York, NY, and IEEE_USA is located in Washington, DC.

IEEE 266–1969 – IEEE Test Procedure for Evaluation of Insulation Systems for Electronics Power Transformers: This test procedure establishes a uniform method by which the life of electronics transformer insulation systems can be compared. Thermal degradation is generally one of the major factors affecting the life of most insulating materials. It was chosen to be the major environmental factor in this test procedure. Other environmental factors, such as vibration, thermal shock, and moisture, have been included to simulate operating conditions.

IEEE 1142–2009 – IEEE Guide for the Selection, Testing, Application, and Installation of Cables having Radial-Moisture Barriers and/or Longitudinal Water Blocking: This guide provides cable manufacturers and users with extensive information on the design, testing, application, and installation of low-, medium-, and high-voltage power cables, as well as communication, control, and instrument cables that make use of metal-plastic laminates as radial-moisture barriers.

IEEE P62582 CD2 proposal, May 2017 – IEEE/IEC Draft – Nuclear power plants – Instrumentation and control important to safety – Electrical equipment condition monitoring methods. Part 6: Insulation resistance: Insulation resistance measurement is the most commonly applied method for indicating the condition of insulating components, primarily cable insulators, during a design basis event. A minimum value of the insulation resistance of cables is generally prescribed to be exceeded throughout the design basis event simulation, in order to assure a margin to the dielectric conditions at which malfunction of equipment connected to the cable may occur.

IEEE PC37.122.5/D8, May 2013 – IEEE Approved Draft Guide for Moisture Measurement and Control in SF6 Gas-Insulated Equipment: Guidelines for moisture level measurement, moisture data interpretation, and moisture control in gas-insulated switchgear are provided.

IEEE PC57.161/D3.1, January 2018 – IEEE Draft Guide for Dielectric Frequency Response Test: This guide is relevant to the dielectric frequency response test methods of liquid-immersed transformers. The guide includes recommendations for instrumentation, procedures for performing the tests, and techniques for analyzing the data. The dielectric frequency response measurement is a non-intrusive, non-destructive off-line testing technique developed as an advanced diagnostic tool.

IEEE Std 775 – 1993 Guide for Designing Multi-stress Aging Tests of Electrical Insulation in a Radiation Environment: Guidelines for evaluating electrical insulation materials that are subjected to more than one significant aging stress are provided. The focus is on materials or equipment intended for use in nuclear facilities, such as power stations, where thermal, moisture, and radiation stresses frequently are of importance.

IEEE 1783–2009 - IEEE Guide for Test Methods and Procedures to Evaluate the Electrical Performance of Insulators in Freezing Conditions: Since 1999, test methods for freezing conditions, including ice and snow, have been refined by the IEEE Dielectrics and Electrical Insulation Society and IEEE Power and Energy Society Task Forces on insulator icing.

E. ISO TEST METHODS

The International Organization for Standardization (ISO) is an independent, non-governmental international standardization organization, which has a membership of 161 national standards bodies. ISO depends on voluntary work through its members to share knowledge and develop consensus-based, market-relevant international standards that support innovation and provide solutions to global challenges. The Central Secretariat is in Geneva, Switzerland.

ISO 9022–2:2015 Optics and photonics – Environmental test methods – Part 2: Cold, heat and humidity: This standard specifies the methods relating to the environmental tests of optical instruments including additional assemblies from other fields (e.g., mechanical, chemical, and electronic devices), under equivalent conditions, for their ability to resist the influence of temperature and/or humidity. The purpose of the testing is to investigate to what extent optical, climatic, mechanical, chemical, and electrical (including electrostatic) performance characteristics of the specimen are affected by temperature and/or humidity.

ISO 9022–4:2014 Optics and photonics – Environmental test methods – Part 4: Salt mist: This standard specifies the methods relating to the environmental tests of optical instruments including additional assemblies from other fields (e.g., mechanical, chemical, and electronic devices), under equivalent conditions, for their ability to resist the influence of salt mist.

ISO 9022–7:2015 Optics and photonics – Environmental test methods – Part 7: Resistance to drip or rain: This standard specifies the methods relating to the environmental tests of optical instruments including additional assemblies from other fields (e.g., mechanical, chemical, and electronic devices), under equivalent conditions, for their ability to resist the influence of drip or rain.

ISO 9022–14:2015 Optics and photonics – Environmental test methods – Part 14: Dew, hoarfrost, ice: This standard specifies the methods relating to the environmental tests of optical instruments including additional assemblies from other fields (e.g., mechanical, chemical, and electronic devices), under equivalent conditions, for their ability to resist the influence of dew, hoarfrost, or ice. The purpose of testing is to investigate to what extent the optical, climatic, mechanical, chemical, and electrical (including electrostatic) performance characteristics of the specimen are affected by dew, hoarfrost, or ice.

ISO 9022–20:2015 Optics and photonics – Environmental test methods – Part 20: Humid atmosphere containing sulfur dioxide or hydrogen sulfide: This standard specifies the methods relating to the environmental tests of optical instruments including additional assemblies from other fields (e.g., mechanical, chemical, and electronic devices), under equivalent conditions, for their ability to resist the influence of sulfur dioxide (SO_2) or hydrogen sulfide (H_2S) in a humid atmosphere.

ISO 9455–17:2002 – Soft soldering fluxes – Test methods – Part 17: Surface insulation resistance comb test and electrochemical migration test of flux residues: This standard is to test deleterious effects that may arise from flux residues after soldering or tinning test coupons. This test method is applicable to fluxes in solid or liquid form, or in the form of flux-cored solder wire, solder preforms or solder paste constituted with eutectic or near-eutectic tin/lead solders.

ISO 16,750–4:2010 – Road vehicles – Environmental conditions and testing for electrical and electronic equipment – Part 4: Climatic loads: This standard applies to electrical and electronic systems/components for road vehicles and includes test methods for resistance against splash water, submersion, and humid envirionments.

ISO 20,653:2013 - Road vehicles – Degrees of protection (IP code) – Protection of electrical equipment against foreign objects, water and access: This standard applies to degrees of protection (IP code) provided by enclosures of the electrical equipment of road vehicles.

F. IEC/DIN/BS/DS/ TEST METHODS

The International Electrotechnical Commission (IEC) is the world's leading organization that prepares and publishes international standards for all electrical, electronic, and related technologies. These are known collectively as "electrotechnology." When appropriate, IEC cooperates with ISO (International Organization for Standardization) or ITU

(International Telecommunication Union) to ensure that international standards fit together seamlessly and complement each other. IEC provides a platform to companies, industries, and governments for meeting, discussing, and developing the international standards they require. All IEC international standards are fully consensus-based and represent the needs of key stakeholders of every nation participating in IEC work. The German Institute for Standardization (DIN), is the independent platform for standardization in Germany and worldwide.

DIN standards are the result of work at the national, European, and/or international level. Anyone can submit a proposal for a new standard. Once accepted, the standards project is carried out according to set rules of procedure by the relevant DIN Standards Committee, the relevant Technical Committee of the European standards organization (CEN), or the relevant committee at the international standards organization ISO (IEC for electrotechnical projects). DIN standards are reviewed at least every five years.

The British Standardization Institute (BSI) has played a leading role in developing a new generation of standards to help organizations become better governed and more responsible. These include anti-bribery, organizational governance, and asset management standards.

Danish Standards (DS) is the official Danish national standardization organization according to the EU Regulation on European Standardization, 1025/2012. As such, Danish Standards coordinates Danish involvement in European standardization within CEN, CENELEC, and ETSI, and Danish Standards adopts European standards as national standards.

IEC/DIN/BS/DS 60,068–2–10:2005- Environmental testing –Part 2–10: Tests - Test J and guidance: Mold growth: This standard provides a test method for determining the extent to which electrotechnical products support mold growth and how any mold growth may affect the performance and other relevant properties of the product.

IEC/DIN/BS/DS 60,068–2–18:2017 Environmental testing – Parts 2–18: Tests - Test R and guidance: Water: This test method provides methods of test applicable to products which, during transportation, storage, or in service, can be subjected to falling water drops, impacting water, immersion, or high-pressure water impact. The primary purpose of water tests is to verify the ability of enclosures, covers, and seals to maintain components and equipment in good working order after and, when necessary, under a standardized drop field or immersion in water. These tests are not corrosion tests and cannot be considered and used as such.

IEC/DIN/BS/DS 60,068–2–30:2005- Environmental testing – Part 2–30: Tests - Test Db: Damp heat, cyclic (12 h + 12 h cycle): This standard determines the suitability of components, equipment, or other articles for use, transportation, and storage under conditions of high humidity, combined with cyclic temperature changes and, in general, producing condensation on the surface of the specimen.

IEC/DIN/BS/DS 60,068–2–38:2009-Environmental testing – Part 2–38: Composite temperature/humidity cyclic: This standard provides a composite test procedure, primarily intended for component type specimens, to determine, in an accelerated manner, the resistance of specimens to the deteriorative effects of high temperature/humidity and cold conditions.

IEC/DIN/BS/DS 60,068–2–39:2015-Tests – Tests and guidance: Combined temperature or temperature and humidity with low air pressure tests: This standard provides a description of test methods and guidance for testing of equipment or components under combined temperature or temperature and humidity with low air pressure tests. The object of combined testing is to investigate to what extent the equipment or components are affected by combined temperature or temperature and humidity with low air pressure tests.

IEC/DIN/BS/DS 60,068–2–53:2010 - Environmental testing –Part 2–53: Tests and guidance - Combined climatic (temperature/humidity) and dynamic (vibration/shock) tests

IEC/DIN/BS/DS 60,068–2–78:2012 Environmental testing – Part 2–78: Tests - Test Cab: Damp heat, steady state: This standard establishes a test method for determining the ability of components or equipment to withstand transportation, storage, and use under conditions of high humidity. This part of IEC 60,068 provides a test method of high humidity at a constant temperature without condensation on the specimen over a prescribed period. This test is performed to evaluate the specimen as it is influenced by the absorption and diffusion of moisture and moisture vapor.

IEC/DIN/BS/DS 60,212:2010 - Standard conditions for use prior to and during the testing of solid electrical insulating materials: This standard gives the accepted conditions of exposure time, temperature, atmospheric humidity, and liquid immersion for use in testing solid electrical insulating materials.

IEC/DIN/BS/DS 60,512–11–12:2002 - Connectors for electronic equipment - Tests and measurements – Part 11–12: Climatic tests - Test 11 m: Damp heat, cyclic: This standard defines a standard test method to assess the ability of components (essentially connectors) to be stored and/or to function under conditions of high relative humidity and to observe the effects of such high humidity when combined with important temperature changes.

IEC 60,529:2013 Degrees of protection provided by enclosures (IP Code): The object of this standard is to give definitions for degrees of protection provided by enclosures of electrical equipment.

IEC/DIN/BS/DS IEC 60,721–2–1:2013 Classification of environmental conditions – Part 2–1: Environmental conditions appearing in nature - Temperature and humidity: This standard presents classifications of open-air climates in terms of temperature and humidity. It is intended to be used as part of the background material when selecting appropriate temperature and humidity severities for product testing and application.

IEC/DIN/BS/DS 60,749–4:2017 Semiconductor devices - Mechanical and climatic test methods – Part 4: Damp heat, steady state, highly accelerated stress test: This standard provides a highly accelerated temperature and humidity stress test for the purpose of evaluating the reliability of non-hermetically packaged semiconductor devices in humid environments.

IEC 60,749–5:2017(E) Semiconductor devices - Mechanical and climatic test methods – Part 5: Steady-state temperature humidity bias life test: This standard provides a steady-state temperature and humidity bias life test for the purpose of evaluating the reliability of non-hermetically packaged solid-state devices in humid environments.

IEC 60,749–7:2011 Semiconductor devices - Mechanical and climatic test methods – Part 7: Internal moisture content measurement and the analysis of other residual gasses: This standard specifies the testing and measurement of water vapor and other gas content of the atmosphere inside a metal or ceramic hermetically sealed device. The test is used as a measure of the quality of the sealing process and to provide information about the long-term chemical stability of the atmosphere inside the package. It is applicable to semiconductor devices sealed in such a manner but generally only used for high-reliability applications such as military or aerospace. This test is destructive.

IEC 60,749–13:2018 Semiconductor devices - Mechanical and climatic test methods – Part 13: Salt atmosphere: This standard describes a salt atmosphere test that determines the resistance of semiconductor devices to corrosion. It is an accelerated test that simulates the effects of severe sea-coast atmosphere on all exposed surfaces. It is only applicable to those devices specified for a marine environment. The salt atmosphere test is considered destructive.

IEC 60,749–20:2008 Semiconductor devices - Mechanical and climatic test methods – Part 20: Resistance of plastic encapsulated SMDs to the combined effect of moisture and soldering heat provides a means of assessing the resistance to soldering heat of semiconductors packaged as plastic encapsulated surface mount devices. This test is destructive.

IEC 60,749–24 Ed. 1.0 b:2004 Semiconductor devices - Mechanical and climatic test methods Part 24: Accelerated moisture resistance – Unbiased HAST: The unbiased highly accelerated stress test is performed for the purpose of evaluating the reliability of non-hermetically packaged solid-state devices in humid environments. It employs temperature and humidity under non-condensing conditions to accelerate the penetration of moisture through the external protective material or along with the interface between the external protective material and the metallic conductors which pass through it.

IEC 60,749–30 Ed. 1.1 b:2011 Semiconductor devices - Mechanical and climatic test methods – Part 30: Preconditioning of non-hermetic surface mount devices prior to reliability testing: IEC 60,749–30:2005+A1:2011 establishes a standard procedure for determining the preconditioning of non-hermetic surface mount devices prior to reliability testing. The test method defines the preconditioning flow for non-hermetic solid-state surface mount devices representative of a typical industry multiple solder reflow operation.

IEC 60,749–33 Ed. 1.0 b:2004 Semiconductor devices - Mechanical and climatic test methods - Part 33: Accelerated moisture resistance - Unbiased autoclave: The unbiased autoclave test is performed to evaluate the moisture resistance integrity of non-hermetically packaged solid-state devices using moisture condensing or moisture saturated steam environments. It is a highly accelerated test that employs conditions of pressure, humidity, and temperature under condensing conditions to accelerate moisture penetration through the external protective material or along the interface between the external protective material and the metallic conductors passing through it.

IEC 60,749–39 Ed. 1.0 b:2006 Semiconductor devices - Mechanical and climatic test methods - Part 39: Measurement of moisture diffusivity and water solubility in organic materials used for semiconductor components: This standard details the procedures for the measurement of the characteristic properties of moisture diffusivity and water solubility in organic materials used in the packaging of semiconductor components.

IEC/DIN/BS/DS 60,749–5:2017 Semiconductor devices - Mechanical and climatic test methods – Part 5: Steady-state temperature humidity bias life test: This standard provides a steady-state temperature and humidity bias life test for the purpose of evaluating the reliability of non-hermetic packaged solid-state devices in humid environments. This test method is considered destructive.

IEC/DIN/BS/DS 60,749–13:2018 Semiconductor devices: This standard describes a salt atmosphere test that determines the resistance of semiconductor devices to corrosion. It is an accelerated test that simulates the effects of the severe sea-coast atmosphere on all exposed surfaces. It is only applicable to those devices specified for a marine environment.

IEC/DIN/BS/DS 60,749–20 Ed. 2.0 b:2008 Semiconductor devices - Mechanical and climatic test methods - Part 20: Resistance of plastic encapsulated SMDs to the combined effect of moisture and soldering heat: This standard provides a means of assessing the resistance to soldering heat of semiconductors packaged as plastic-encapsulated surface mount devices. This test is destructive.

IEC/DIN/BS/DS 60,749–24 Ed. 1.0 b:2004 Semiconductor devices - Mechanical and climatic test methods - Part 24: Accelerated moisture resistance - Unbiased HAST: The unbiased highly accelerated stress test is performed for the purpose of evaluating the reliability of non-hermetically packaged solid-state devices in humid environments. It employs temperature and humidity under non-condensing conditions to accelerate the penetration of moisture through the external protective material or along the interface between the external protective material and the metallic conductors that pass through it.

IEC/DIN/BS/DS 60,749–33:2004 Semiconductor devices – Mechanical and climatic test methods - Part 33: Accelerated moisture resistance – Unbiased autoclave: The unbiased autoclave test is performed to evaluate the moisture resistance integrity of non-hermetically packaged solid-state devices using moisture condensing or moisture-saturated steam environments.

IEC 60,749–39:2006 / DIN EN 60,749–39 (German) / BS EN 60,749–39 (UK)/DSF/PREN (Proposed European) 60,749–12 (DASK) Semiconductor devices - Mechanical and climatic test methods - Part 39: Measurement of moisture diffusivity and water solubility in organic materials used for semiconductor components: This standard details the procedures for the measurement of the characteristic properties of moisture diffusivity and water solubility in organic materials used in the packaging of semiconductor components.

IEC/DIN/BS/DS 60,749–42:2014 Semiconductor devices - Mechanical and climatic test methods - Part 42: Temperature and humidity storage: This standard provides a test method to evaluate the endurance of semiconductor devices used in high-temperature and high-humidity environments. This test method is used to evaluate the endurance against corrosion of the metallic interconnection of chips of semiconductor devices contained in plastic molded and other types of packages.

IEC/DIN/BS/DS 61,189–5–503:2017 Test methods for electrical materials, printed board and other interconnection structures and assemblies - Part 5–503: General test method for materials and assemblies - Conductive anodic filament (CAF) testing of circuit boards: This standard specifies conductive anodic filaments and specifies not only the steady-state temperature and humidity test, but also a temperature-humidity cyclic test and an unsaturated pressurized vapor test.

IEC/DIN/BS/DS 61,196–1–206:2017 Coaxial communication cables - Part 1–206: Environmental test methods - Climatic sequence: This standard specifies the method of test to determine the stability of transmission performance of a finished RF coaxial cable when subjected to a set of temperatures, temperature changes, and humidity stresses that would accelerate exposures observed in storage and transportation.

IEC/DIN/BS/DS 61,300–2–19:2012 Fiber optic interconnecting devices and passive components - Basic test and measurement procedures - Part 2–19: Tests - Damp heat (steady state): This standard details a procedure for determining the suitability of a fiber optic device to withstand the environmental condition of high humidity and high temperature which may occur in actual use, storage, and/or transport. The test is primarily intended to permit the observation of the effects of high humidity at a constant temperature over a given period.

IEC 61,300–2–21:2009-fibre optic interconnecting devices and passive components - Basic test and measurement procedures - Part 2–21: Tests - Composite temperature/humidity cyclic test: EC 61,300–2–21:2009 determines the resistance of a fiber optic device to the deteriorative effects of high temperature, humidity, and cold conditions. It is intended to reveal defects in a device under test caused by breathing as opposed to absorption of moisture. The test covers the effect of the freezing of trapped water in cracks and fissures as well as condensation.

IEC 61,300–2–46:2006 Fiber optic interconnecting devices and passive components - Basic test and measurement procedures - Part 2–46: Tests - Damp heat, cyclic: The test is primarily intended to determine the suitability of fiber optic components under conditions of high humidity - combined with cyclic temperature changes and, in general, producing condensation on the surface of the specimen. Absorption of moisture may result in swelling that would destroy functional utility, cause loss of physical strength, and cause changes in other important mechanical properties.

IEC/DIN/BS/DS 61,300–2–48:2009 Fiber optic interconnecting devices and passive components - Basic test and measurement procedures - Part 2–48: Tests - Temperature-humidity cycling: This part of the standard details a procedure for determining the suitability of a fiber optic device or closure to withstand variations in humidity and temperature that may occur during operation, storage, and/or transport. The test is intended to indicate the performance of such devices when exposed to heat and humidity followed by short-term freezing. In general terms, this test provides a high temperature to induce potential failures due to softening and expansion, a high humidity to encourage moisture absorption and swelling, and a low temperature to facilitate ice formation, embrittlement, and contraction.

IEC/DIN/BS/DS 61,701:2011 Salt mist corrosion testing of photovoltaic (PV) modules: This test method describes test sequences useful to determine the resistance of different photovoltaic modules to corrosion from salt mist containing Cl- (NaCl, MgCl2, etc.). It includes a cycling testing sequence that combines in each cycle a salt fog exposure followed by humidity storage under controlled temperature and relative humidity conditions. This testing sequence is more suitable to reflect the corrosion processes that happen.

IEC/DIN/BS/DS 61,988–4–1:2015 Plasma display panels - Part 4–1: Environmental testing methods - Climatic and mechanical: This standard defines the temperature and humidity tests, air pressure tests, and mechanical test methods for evaluating the climatic and mechanical endurance characteristics of plasma display modules.

IEC/DIN/BS/DS 62,498–1:2010 Railway applications - Environmental conditions for equipment - Part 1: Equipment on board rolling stock: This standard covers the use of on-board electrical, electromechanical, and electronic equipment for rolling stock, for the parameters of altitude, temperature, humidity, air movement, rain, snow and hail, ice, solar, radiation, lightning, pollution, vibrations and shocks, electromagnetic interference environment, acoustic noise environment, and supply system characteristics.

IEC/DIN/BS/DS 62,498–2:2010 Railway applications - Environmental conditions for equipment - Part 2: Fixed electrical installations: This standard deals with the environmental influences on fixed electrical installations for traction power supply and equipment essential to operate a railway in the open air; in covered areas; in tunnels; and within enclosures placed in the above-mentioned areas. Such influences include altitude, temperature and humidity, air movement, rain, snow, hail, ice, sand, solar radiation, lightning, pollution, vibration, shocks, electromagnetic interference, and earthquakes.

G. SAE TEST METHODS

The Society of Automotive Engineers (SAE) International is a global body of scientists, engineers, and practitioners that advances self-propelled vehicle and system knowledge in a neutral forum for the benefit of society. SAE International is a global association of more than 128,000 engineers and related technical experts in the aerospace, automotive and commercial vehicle industries. Their core competencies are life-long learning and voluntary consensus standards development. SAE headquarters is in Warrendale, PA, USA.

ARP987B- The control of excess humidity in avionics cooling: This aerospace-recommended practice (ARP) outlines the causes and impacts of moisture and/or condensation in avionics equipment and provides recommendations for corrective and preventative action.

SSB-1, Rev. C- Guidelines for using plastic encapsulated microcircuits and semiconductors in military, aerospace and other rugged applications: This document provides reference information concerning the environmental stresses associated with tests specifically designed to apply to (or have unique implications for) plastic-encapsulated microcircuits and semiconductors, and the specific failures induced by these environmental stresses.

SSB1–001 Qualification and reliability monitors: This document is an annex to EIA Engineering Bulletin, SSB-1, Guidelines for Using Plastic Encapsulated Microcircuits and Semiconductors in Military, Aerospace and Other Rugged Applications (the latest revision). The scope of this document is to establish the recommended minimum qualification and monitoring testing of plastic-encapsulated microcircuits and discrete semiconductors suitable for potential use in many rugged, military, severe, or other environments.

AIR1167 Environmental criteria and tests for aerospace ground equipment in support of space systems: This specification is intended to define design requirements and test procedures (1) to be followed in subjecting aerospace ground equipment (AGE) for space systems to simulated and accelerated environmental conditions that will ensure satisfactory operating and (2) to be followed in reducing deterioration when AGE is operated and/or stored at manufacturing facilities, test facilities, and launch ranges. This specification establishes environmental criteria for designing AGE in support of space systems.

J1455 Recommended environmental practices for electronic equipment design in heavy-duty vehicle applications: The scope of this recommended practice encompasses the range of environments which influence the performance and reliability of the electronic equipment designed for heavy-duty on- and off-road vehicles, as well as any appropriate stationary applications which also use these vehicle-derived components. The climatic, dynamic, and electrical environments from natural and vehicle-induced sources that influence the performance and reliability of vehicle and tractor/trailer electronic components are included in this SAE recommended practice.

J2721- Recommended corrosion test methods for commercial vehicle components: This document establishes recommended practices to validate acceptable corrosion performance of metallic components and assemblies used in medium truck, heavy truck, and bus and trailer applications. The focus of the document is methods of accelerated testing and evaluation of results. A variety of test procedures are provided that are appropriate for testing components at various locations on the vehicle. The procedures incorporate cyclic conditions, including corrosive chemicals, drying, humidity, and abrasive exposure. These procedures are intended to be effective in evaluating a variety of corrosion mechanisms

H. ASTM TEST METHODS

The American Society for Testing and Materials (ASTM) International is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services. Some 12,575 ASTM voluntary consensus standards operate globally. The organization's headquarters is in West Conshohocken, Philadelphia, PA, USA. Founded in 1898 as the American Section of the International Association for Testing Materials, ASTM International predates other standards organizations such as the BSI (1901), IEC (1906), DIN (1917), ANSI (1918), AFNOR (1926), and ISO (1947).

ASTM F1996–14 Standard test method for silver migration for membrane switch circuitry active standard (latest version): This test method is used to determine the susceptibility of a membrane switch to the migration of the silver between circuit traces under dc voltage potential. Silver migration occurs when special conditions of moisture and electrical energy are present.

ASTM F1596–15 Standard test method for exposure of a membrane switch or printed electronic device to temperature and relative humidity: This test method covers a procedure for temperature and humidity cycling of a membrane switch or printed electronic device. This test method is performed to evaluate the properties of materials used in the construction of membrane switches or printed electronic assemblies as they are influenced by the absorption and diffusion of moisture and moisture vapor. Absorption of moisture by many materials results in swelling, which destroys their functional utility and causes loss of physical strength and changes in other mechanical properties. Insulating materials that absorb moisture may suffer degradation of their electrical properties.

ASTM D4730–13 Standard specification for flooding compounds for telecommunications wire and cable: This specification covers a variety of compounds used for flooding the shields and armors of telecommunications wires and cables (both electrical and fiber optic) for the purpose of preventing water and other undesirable fluids from entering or migrating along or through the cable sheath.

Hail testing is an important part of an overall environmental testing program for quality assurance and regulatory purposes. While any product that is exposed to the elements should be hail tested to some extent, the process is especially important for maintaining compliance with the following regulatory standards:

ASTM F320, which details acceptable hail impact testing standards for windshields used in aerospace applications.

ASTM E822, which outlines hail testing guidelines for solar collector covers and other ground-based commercial equipment.

ASTM E1038, which covers hail testing requirements for photovoltaic cells.

I. JEITA TEST METHODS

The objective of the Japan Electronics and Information Technology Industries Association (JEITA) is to promote the healthy manufacturing, international trade, and consumption of electronics products and components in order to contribute to the overall development of the electronics and information technology industries, and thereby further Japan's economic development and cultural prosperity.

EIAJ ED-4701–100 Environmental and endurance test methods for semiconductor devices: These standards provide environmental test methods and endurance test methods (especially life tests) aimed at evaluating the resistance and endurance of discrete semiconductor devices and integrated circuits used in electronic equipment mainly for general industrial applications and consumer applications, under the various environmental conditions that occur during their use, storage, and transportation.

J. ECSS TEST METHODS

The European Cooperation for Space Standardization (ECSS) is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities.

ECSS-E-ST-10–03C-Testing: 5.5.1.2 Humidity test: If the space segment equipment can be exposed to humidity levels above 65% during its lifetime then a humidity qualification test shall be performed.

Test Method 5.5.1.4. Humidity photovoltaic assemblies: The purpose of the humidity test is to demonstrate the endurance of assembled PVA components in a real-life environment against standard environmental conditions using accelerated tests.

Test Method 6.4.3.8. Humidity and temperature (HT): This test is an accelerated shelf-life test to monitor the cover glass conductive coating in a humid atmosphere.

Test Method 7.5.7.1. Humidity and temperature-Part 1 for qualification testing: This test is an accelerated shelf-life test to monitor the stability of contacts, anti-reflection coatings, and integrated diode in a humid atmosphere.

Test Method 7.5.7.2. Humidity and temperature-Part 2 for qualification and acceptance testing: This test is to verify the adherence of the contacts to the solar cell and diode, if available.

Test Method 8.7.11.1. Humidity and temperature for qualification testing: This test is an accelerated shelf-life test to monitor the stability of the cover glass coatings stability in a humid atmosphere.

Test Method 8.7.11.2. Humidity and temperature for acceptance testing: This test is to verify the adherence of coatings to the cover glass.

Test Method 9.6.6.1. Humidity and temperature (HT): This test is an accelerated shelf-life test to monitor the stability of functioning, contacts, and coatings of solar cell protection diodes in a humid atmosphere.

K. NEMA TEST METHODS

The National Electrical Manufacturers Association (NEMA) represents nearly 350 electrical equipment and medical imaging manufacturers that make safe, reliable, and efficient products and systems.

ANSI/NEMA C29.11–2012 Composite insulators— Test methods for composite electrical power insulators, includes water penetration test and water diffusion test.

L. UL STANDARDS

The Underwriters Laboratories (UL) Standards are used to assess products; test components, materials, systems, and performance; and evaluate environmentally sustainable products, renewable energies, food and water products, recycling systems, and other innovative technologies.

M. END PRODUCT STANDARDS

Most states require whole products to be evaluated to an end product standard, which evaluates safety, reliability, and efficiency, among other considerations. These standards are often written by the IEC and then amended by national bodies such as UL (United States), CSA (Canada), or CENELEC-EN (Europe).

IEC/UL/CSA/EN 60,335–1, Safety of Household and Similar Appliances, Part 1: General requirements: This standard is used to evaluate common appliances such as those used in cooking, cleaning, and cosmetics. It requires products to be exposed to 20–30 °C and 93% RH for 48 h. After 48-h exposure, leakage current and dielectric testing is conducted.

IEC/AAMI/CSA/EN 60,601–1, Medical electrical equipment, Part 1: General requirements: This standard is used to evaluate a wide range of medical devices from hearing aids to surgical equipment. It requires products to be exposed to 20–30 °C and 93% relative humidity for 48 h. After 48-h exposure, leakage current and dielectric testing is conducted.

IEC/AAMI/CSA/EN 60,601–1–11, Collateral Standard: Requirements for medical electrical equipment and medical electrical systems used in the home healthcare environment: This standard is used to evaluate medical equipment for use in the home, without medical supervision. It requires transit-operable products to be exposed to the lowest-rated temperature followed by exposure to the highest-rated temperature/humidity.

IEC/UL/CSA/EN 61,010–1, Safety requirements for electrical equipment for measurement, control, and laboratory use – General requirements: This standard is used to evaluate a wide range of laboratory equipment from environmental chambers to battery-powered multimeters. It requires products to be exposed to 40 °C and 93% relative humidity for 48 h. After 48-h exposure, leakage current and dielectric testing is conducted.

N. RTCA AND EUROCAE STANDARDS

The Radio Technical Commission for Aeronautics (RTCA) works with the Federal Aviation Administration (FAA) to develop comprehensive, industry-vetted, and endorsed standards that can be used as a means of compliance with FAA regulations.

The European Organization for Civil Aviation Equipment (EUROCAE) is the European leader in the development of worldwide recognized industry standards for aviation. About 50% of the EUROCAE Working Groups (WG) work jointly with RTCA, and another 10% with SAE.

EUROCAE RTCA DO-160 G provides standard procedures and environmental test criteria for testing airborne equipment for the entire spectrum of aircraft from light general aviation aircraft and helicopters through the “jumbo jets” and supersonic transport (SST) categories of aircraft. Coordinated with EUROCAE, RTCA/DO-160 G and EUROCAE/ED-14 G are identically worded. DO-160 G is recognized by ISO as the de facto international standard ISO-7137. The following sections of the standard are related to water: *Section 6.0 – Humidity, Category A – Standard Humidity Environment, Category B – Severe Humidity Environment and Category C – External Humidity Environment, Section 10.0 – Waterproofness, Section 13.0 – Fungus Resistance, Section 14.0 – Salt Fog, and Section 24.0 – Icing.*

O. OTHERS

There are some other test method providers for electronics, such as the Automotive Electronics Council (AEC) and Telcordia. Telcordia documents and special reports on telecommunications equipment, systems, and services are developed with industry participation. Ericsson acquired Telcordia Technologies, Inc., in January 2012.

Telcordia GR-78-CORE – Generic requirements for the physical design and manufacture of telecommunications products and equipment: This standard focuses on telecommunication products and contains test methods for surface insulation resistance and electromigration resistance of soldering fluxes, polymeric coatings/adhesive materials, and metal contact finishes.

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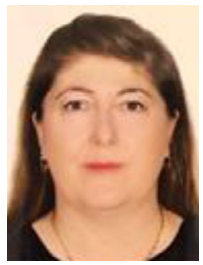

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