Characteristic Times of Moisture Diffusion and Bake-out Conditions for Plastic Encapsulated Parts

Alexander Teverovsky
QSS Group, Inc./Goddard Operations
Alexander.A.Teverovsky.1@gsfc.nasa.gov

Abstract

Simple equations for calculation of the characteristic times of moisture diffusion in plastic packages of different shapes and sizes are suggested. It is shown that the moisture-prevention strategy can be developed and the adequate bake-out regimens for different situations can be calculated based on the temperature dependency of the moisture diffusion coefficient, D(T), of encapsulating polymer materials.

Moisture diffusion characteristics of molding compounds used in plastic encapsulated microcircuits (PEMs) available in the literature have been analyzed and typical D(T) characteristics are calculated. The bake-out times calculated using averaged diffusion characteristics of molding compounds are in agreement with the JEDEC recommendations. Examples of calculations of bake-out regimens for parts allowing only low temperature treatment and for parts temporarily exposed to high humidity conditions are considered.

Introduction

The capability of polymer materials to absorb moisture from the environment is one of the major reliability concerns for microelectronic devices encapsulated in plastic packages. Moisture condensation into microgaps (delaminations or cracks) between the die surface and molding compound (MC) can cause failures due to increased leakage currents, charge instabilities, or corrosion of aluminum metallization. Moisture sorption in the volume of molding compounds causes swelling of the packages, resulting in additional mechanical stresses in dice and in parametric shifts in precision linear devices.

The presence of moisture in plastic packages might cause failures during assembly of surface mount technology (SMT) devices on boards. Special measures, such as limited exposure of the SMT parts to moisture environments and bake-outs before reflow soldering, should be performed to keep the moisture content below the critical level and to prevent the popcorning effect.

Moisture in epoxy molding compounds, conformal coatings, or glob top encapsulants decreases glass transition temperature and plasticizes polymer materials, thus decreasing internal mechanical stresses in the parts. Desorption of moisture in vacuum for the parts intended for space applications will result in increasing stiffness and in shrinkage of polymers, which might cause cracking and delaminations in the encapsulating materials and failure of the parts. For this reason, it is important to perform testing of parts that are sensitive to mechanical stresses in conditions close to those in space where polymer materials contain no moisture.

Bake-out conditions (time and temperature) for SMT parts should be provided by the part manufacturer. However, in most cases manufacturers specify the industry standard bake: 125 °C for 24 hours [1]. Obviously this condition cannot be optimal for all cases. For example, if deterioration of solderability and lead finishing at high temperatures is a concern, the maximum allowable temperature must be decreased (sometimes temperatures as low as 40 °C are recommended). The bake-out times depend on the size and shape of the package; however, in most cases these factors are neglected. One may use the bake-out regimens recommended by IPC standard (IPC-TM-650): 125 °C for 6 hours for packages with less than 2 mm of body thickness, and 24 hours for thicker packages. A recent IPC/JEDEC J-STD-033 document, “Standard for Handling, Packing, Shipping and use of moisture/reflow Sensitive Surface Mount Devices” (July 2002), has more-refined bake-out regimens that are discussed below.

It should be noted that all IPC/JEDEC standards and manufacturer recommendations for bake-out conditions are focused on only moisture/reflow sensitive SMT parts and are intended to prevent the pop-corning effect and avoid damage caused by exposure of the parts to high temperatures during reflow soldering onto the boards. However, the major quality assurance strategy for all types of PEMs intended for space applications is to prevent moisture sorption in parts during the whole ground phase integration, testing, and storing period, which lasts typically from 2 to 5 years. This strategy can be realized by a computer simulation or engineering estimations of moisture content in the package during exposure to humid environments and by implementing adequate bake-out conditions for PEMs and PEM-containing assemblies.

The following study was performed to establish simple equations for the characteristic times of moisture diffusion in plastic packages of various shapes and sizes and to estimate bake-out conditions for different devices based on the experimental data of the temperature dependence of diffusion characteristics of molding compounds.

Theoretical modeling

Moisture sorption/desorption processes in a plastic package are described by the same equation and result in the same characteristic times of the diffusion process. For simplicity, a sorption process is considered in the following analysis.

Fick’s second law controls distribution of moisture concentration in plastic packages. In the case of a flat package it can be described by the following one-dimensional equation:

$$\frac{dC}{dt} = D\frac{d^2C}{dX^2} \tag{1}$$

where C is the moisture concentration (which depends on time t and coordinate X), and D is the diffusion coefficient of moisture in the plastic.

Assuming that the package initially contains no moisture, its thickness is 2h, and the die-plastic interface is in the middle of the package (X=0), the following initial and boundary conditions can be written:

$$\begin{aligned} &C(X,0) = 0 && \text{at } -h < X < h \\ &C(-h,t) = C(h,t) = C_o && \text{at } t > 0 \\ &\frac{dC(X,t)}{dt} = 0 && \text{at } X = 0,\ t > 0 \end{aligned} \tag{2}$$

where C_o is the equilibrium concentration of moisture at saturation.

The solution to the equations (1) and (2) gives the moisture concentration at the die surface C(t) as a function of time [2]:

$$\frac{C(t)}{C_o} = 1 - \frac{2}{\pi}\sum_{k=0}^{\infty}\frac{(-1)^k}{(k+0.5)}\exp(-S_k t) \tag{3}$$

where $S_k = \pi^2 D/h^2 \times (k+0.5)^2$, $k = 0, 1, 2, ...$

Ignoring all terms in this series except for the first one, the solution to the diffusion equation for a flat plastic package can be approximated by the following simple expression:

$$C(t) = C_o \times [1 - \frac{4}{\pi}\exp(-t/\theta_{FP})] \tag{4}$$

where $\theta_{FP} = 4h^2/(\pi^2 D)$ is the characteristic time for moisture diffusion in a flat package.

A sphere or cylinder is a convenient approximation for many discrete semiconductor devices (such as switching or emitting diodes, transistors, rectifiers, etc.). For a spherical package of radius R, the solution of the relevant Fick's equation can be written as:

$$\frac{C(r,t)}{C_o} = 1 - \frac{2R}{\pi}\sum_{k=1}^{\infty}\frac{(-1)^{k+1}}{k}\exp(-F_k t)\frac{\sin(k\pi r/R)}{r} \tag{5}$$

where $F_k = \pi^2 k^2 D/R^2$, and r is the die's effective radius.

The power series (5) at a relatively large time (t) will converge on zero. Ignoring all terms but the first, Eq. (5) can be approximated by the following expression:

$$C(t) = C_0 \times \left[1 - 2\frac{R}{\pi}\exp(-t/\theta_{SP})\frac{\sin(\frac{\pi r}{R})}{r} \right] \quad (6)$$

where $\theta_{SP} = R^2/(\pi^2 D)$ is the characteristic time for moisture diffusion in a spherical package.

If r<<R the above equation can be simplified further:

$$C(t) = C_0 \times [1 - 2\exp(-t/\theta_{SP})] \quad (7)$$

For a cylindrical package, the time dependence of the moisture concentration can be expressed using Bessel functions of the first (J_o) and second (J_1) type:

$$\frac{C(r,t)}{C_0} = 1 - 2\sum_{k=1}^{\infty}\exp(-M^2{}_k Dt/R^2)\frac{J_0(M_k r/R)}{M_k J_1(M_k)} \quad (8)$$

where M_k are positive roots of equation $J_o(M) = 0$.

The series (8) will also quickly converge on zero with time and at r<<R Eq. (8) becomes:

$$C(t) = C_0 \times [1 - 1.6\exp(-t/\theta_{CP})] \quad (9)$$

where $\theta_{CP} = 0.176R^2/D$ is the characteristic time for moisture diffusion in a cylindrical package.

Figure 1 displays variations of the rated moisture concentration at the die surface vs. rated times (t/θ_P) calculated by exact (3, 5, 8) and simplified (4, 7, 9) equations. Here ϑ_P is the characteristic time of diffusion in the package, which is equal to ϑ_{PF}, ϑ_{PC}, and ϑ_{PS} for flat, cylindrical, and spherical packages, respectively.

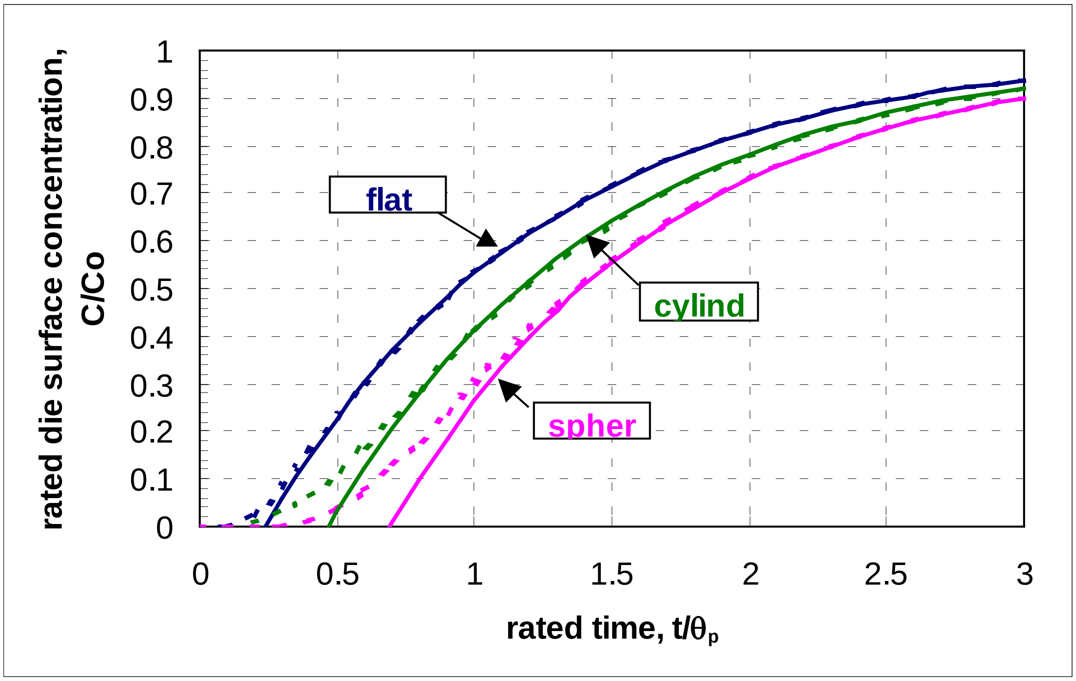

Figure 1. Variation of moisture concentration at the die surface vs time for plastic packaged devices of different shapes. The dashed lines were calculated using the exact equations (3, 5, 8) and the solid lines were calculated using approximations (4, 7, 9).

The exact and the approximate curves converge for C/C_o greater than 0.2, suggesting that the simplified equations give a fairly good approximation for the moisture concentration variance with time at $t/\theta_P > 0.3$ for a flat package and $t/\theta_P > 1$ for a spherical package. At $t = \vartheta_P$ the rated concentration is far from the saturation levels: $C/C_o \sim 0.55$ for flat packages and $C/C_o \sim 0.3$ for spherical packages. Thus, the characteristic times of moisture diffusion can be defined as times when the concentration of moisture at the surface of a die in initially dry package reaches 55%, 44%, and 29% respectively for flat, cylindrical, and spherical packages.

It is reasonable to assume that the bake-out time of moisture diffusion, τ_p, is the time when moisture concentration at the die surface for a device, which is presaturated in moisture to equilibrium uptake, decreases to 10% of the saturation level. In Figure 1 this condition corresponds to C/Co = 0.9. At this condition $\tau_p = 2.5\times\theta_{FP}$ for a flat package, $2.3\times\theta_{CP}$ for a cylindrical package, and $3\times\theta_{SP}$ for a spherical package. Table 1 shows formulae that allow calculation of the moisture bake-out times for packages of different shapes.

Table 1. Moisture diffusion characteristic times (θ) and bake-out times (τ_b) for packages of different shapes.

Package Shape	θ	τ_b

Flat, thickness 2h	$4h^2/\pi^2 D$	$1.01 \times h^2/D$
Sphere, radius R	$R^2/\pi^2 D$	$0.3 \times R^2/D$
Cylinder, radius R	$0.176 R^2/D$	$0.4 \times R^2/D$

Numerical computations of Eq. (1) and (2) allow for calculation of the distribution of moisture concentration, C(X,t), across the thickness of a package at different times of exposure to humid environments. Results of these calculations for a flat plastic package are shown in Figure 2.

Integrating these distributions allows for calculation of the mass of desorbed water, dM, at different moments of time during baking:

$$dM/M_0 = \int_0^h \frac{C(X,t)}{C_0} dX \qquad (10)$$

where M_o is the total mass of the desorbed water.

The results of these computations together with C/Co data from Figure 1 are shown in Figure 3. As expected at $t/\tau = 1.01$, which corresponds to the bake-out time as it is shown in Table 1, C/Co = 0.1 and dM/Mo = 0.06.

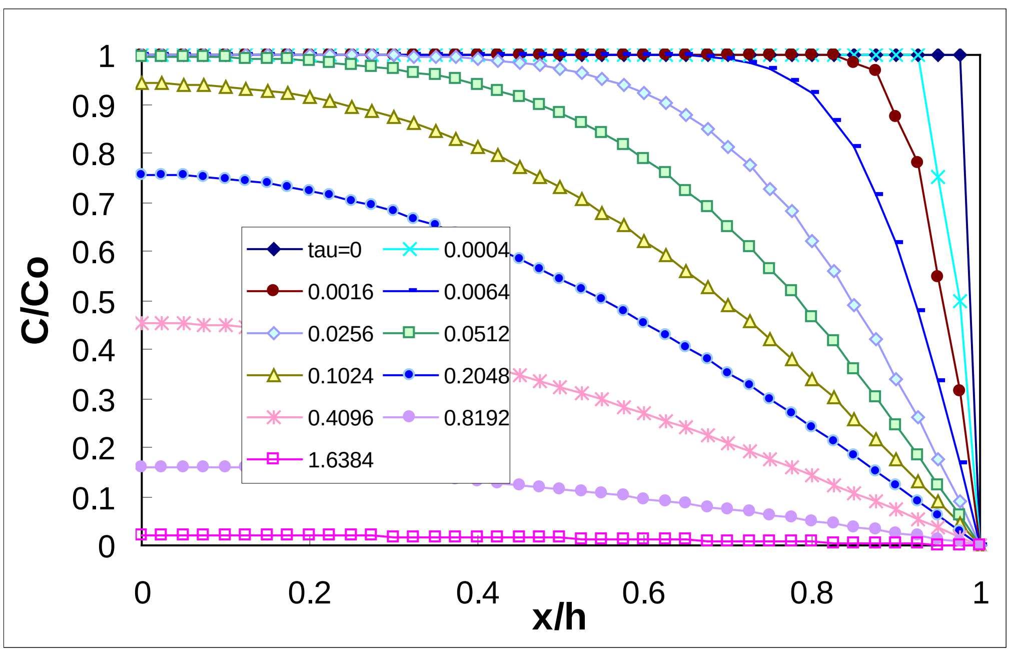

Figure 2. Normalized distributions of moisture concentration in a flat package at different times, (t/τ, where $\tau = h^2/D$), during moisture desorption.

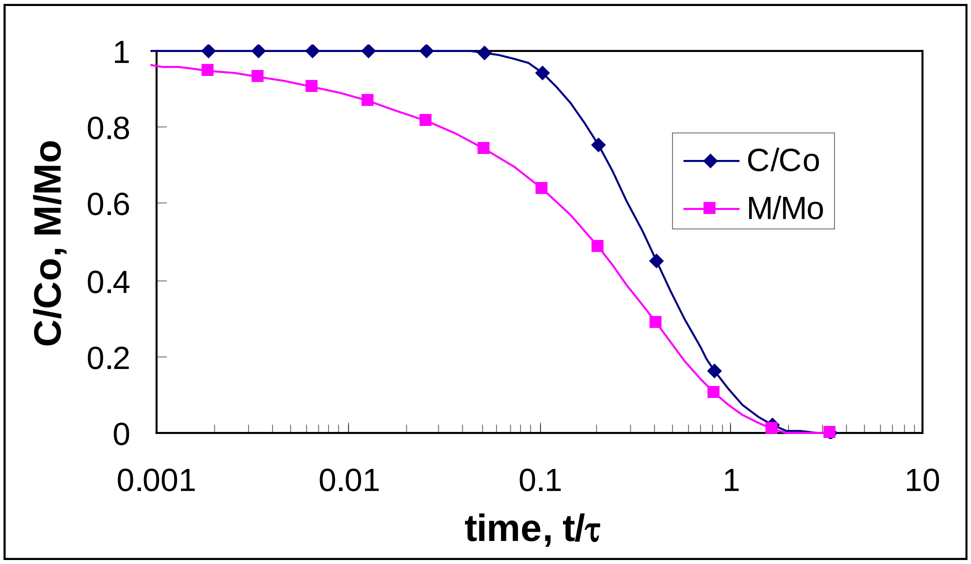

Figure 3. Moisture concentration at the die surface and mass losses of a flat package with time of baking. Here the $\tau = h^2/D$.

The moisture uptake or release for PEMs is usually expressed as a percent of the package mass, $\delta M/M_p$, where δM is the mass of absorbed/released water and M is the mass of a part. Typically, this value varies from 0.2% to 0.5% when devices are stored at 85% RH. This means that baking of the parts, which are fully saturated with moisture, during the time calculated per Table 1 will reduce the moisture content to less than 0.012% to 0.03%. This is a negligibly small amount, which in most cases will not cause any moisture-related degradation even in parts with a high level of sensitivity to moisture. It should be noted that in the cases when parts are exposed to humid environments with RH < 85% and/or for the time $t < \tau_b$, the baking would reduce moisture content to a level much less than 0.03%.

Diffusion characteristics of epoxy encapsulating materials

To estimate bake-out conditions for PEMs, the value of the diffusion constant D for the encapsulating material must be known. The data available on diffusivity of epoxy encapsulating molding compounds, which were found in the literature, together with our data obtained for several types of molding compounds manufactured by Poliset, Nitto Denko, and Sumitomo, are displayed in Figure 4. It is seen that at a given temperature different compounds have diffusion constants scattered over an order of magnitude. All temperature dependencies of D reported in the literature indicate that the D exponentially increases with temperature and the D(T) characteristics follows Arrhenius law:

$$D = D_o \exp(-U / kT) \tag{11}$$

where D_o is constant, U is the activation energy, T is the absolute temperature, and k is the Bolzman constant.

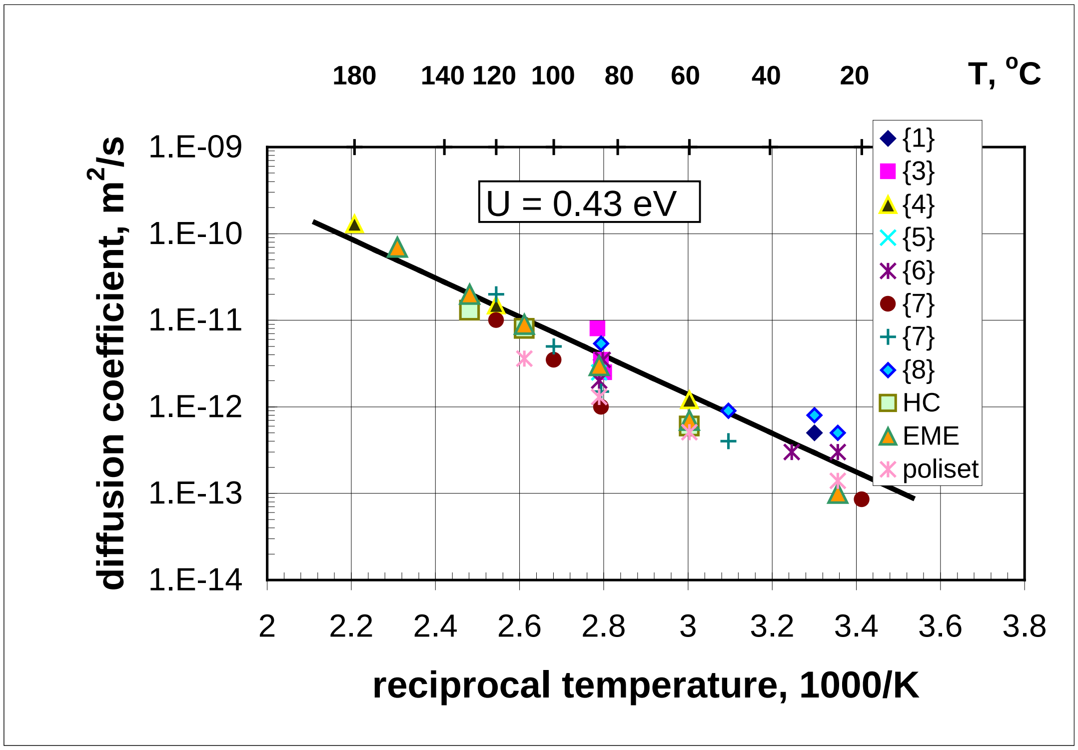

Figure 4. Experimental data on temperature dependence of moisture diffusion coefficient for different epoxy encapsulating materials. Figures in brackets are references.

The best-fit curve approximation to all data displayed in Figure 4 gives $D_o = 7.35\times10^{-6}$ m^2/sec and U = 0.43 eV. This value of activation energy is fairly close to those reported by the other authors [3, 4, 8, 9].

Rating bake-out times with temperature

Considering Eq. (11) a temperature dependence of the bake-out times can be written in the following form:

$$\tau_b = A \times L^2 \times \exp(U / kT) \tag{12}$$

where A is a shape-dependent parameter (see Table 2.), L = h for a flat package, and L = R for a cylindrical or spherical package.

Table 2. Shape parameters in Eq. (12) for different packages.

Package shape	A, hr/mm^2
Flat	3.83×10^{-5}
Sphere	1.15×10^{-5}
Cylinder	1.53×10^{-5}

Temperature dependencies of bake-out times for flat packages with thicknesses of 4 mm, 2 mm, and 1 mm, as well as for spherical and cylindrical packages with a radius of 2 mm, are shown in Figure 5. These times vary from approximately 1 year for thick (4 mm) flat packages at room temperature (in dry conditions or in vacuum) to several hours for thin (1 mm) packages at high (140 °C to 150 °C) temperatures. This means that plastic parts with a thickness of more than 2 mm can retain a high level of moisture concentration at the die surface for thousands of hours after being exposed to humid environments. For example, during the highly accelerated temperature and humidity stress test (HAST) performed per JEDEC Method A110 at temperature of 140 °C, an equilibrium of moisture distribution would occur in approximately 40 hours (for a thick flat plastic package of 4 mm). At room temperature this part would keep excessive moisture for several months. Storage at temperatures below 20 °C (for example, dormant period of an instrument during a deep space mission) can preserve high moisture concentration in the parts for years.

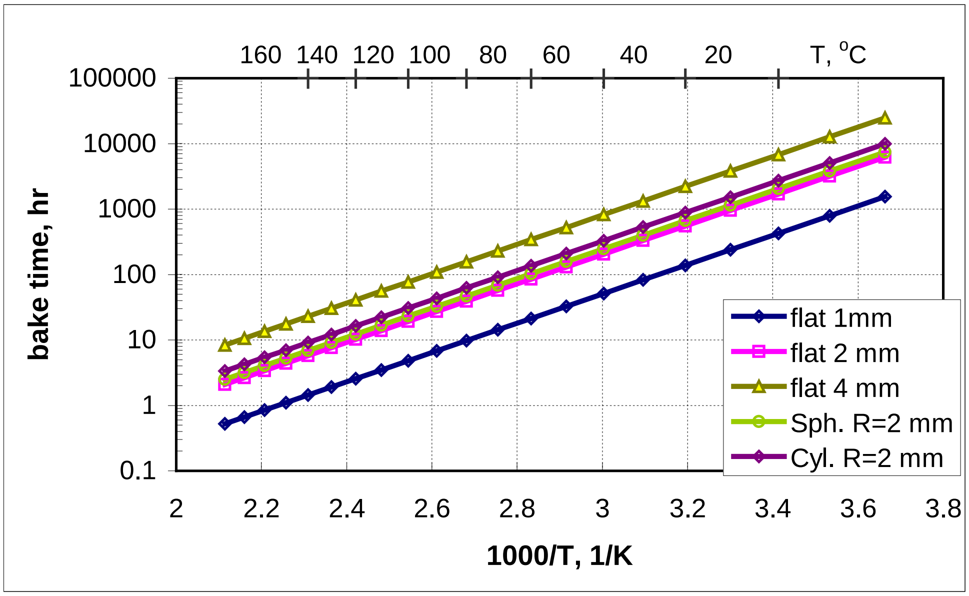

Figure 5. Calculated temperature dependencies of moisture bake-out times for packages of different size and shape.

Comparison of the calculated bake-out times with the JEDEC recommendations

The bake-out times for several types of PEMs at temperatures of 40 °C, 90 °C, and 125 °C were calculated using Eq. (12) and diffusion characteristics for a typical molding compound (D_o= 7.35×10^{-6} m^2/sec and U=0.43 eV). The results of these calculations are shown in Table 3. The bake-out conditions recommended by IPC/JEDEC J-STD-033 (July 2002), "Standard for Handling, Packing, Shipping and use of moisture/reflow Sensitive Surface Mount Devices", are shown in brackets. The minimum value in the brackets corresponds to a less moisture sensitive devices (level 2), and the maximum value corresponds to devices with a moisture sensitivity of level 5.

Table 3. Calculated bake-out times for different plastic packages and JEDEC recommendations for parts with moisture sensitivity levels from 2 to 5 (in brackets).

Package type	Thickness, mm	Temperature		
		40 °C	90 °C	125 °C
DIP-24	3.8	1996 (1608-1608)	206 (168-240)	59 (48-48)
DIP-8	3.2	1416 (1608-1608)	146 (168-240)	41 (48-48)
PQFP-44	2	553 (528-1608)	57 (48-144)	16 (16-40)
PLCC-32	3	1244 (1608-1608)	128 (168-240)	36 (48-48)
TSOP-32	1	138 (120-240)	14 (11-24)	4 (3-10)

Generally, the data presented in Table 3 are in agreement with the JEDEC recommendations, suggesting that the recommendations were made based on averaged moisture diffusion characteristics of molding compounds used in PEMs. However, in some cases these recommendations result in much greater times than necessary to properly dry out the part. For example for a part packaged in PLCC-32 the required time is 30% to 35% greater, however, for DIP-24 parts it is 25% to 30% less than necessary. This is most likely due to a relatively rough classification of the parts according to their thickness: all parts are divided only in three groups: ≤ 1.4 mm, ≤ 2 mm, and ≤ 4.5 mm.

It should be noted that the bake-out time is proportional to the square of the package thickness. This means that size variations within the same size group used in IPC/JEDEC J-STD-033 might more than five times change the value of τ_b. Considering possible variations in D, which might exceed an order of magnitude, the time recommended per IPC/JEDEC J-STD-033 can be either more than 10 times greater or less than the time necessary to remove moisture from the part.

Low temperature bake-out conditions

A temperature of 40 °C is recommended to bake out parts susceptible to lead finishing oxidation and/or intermetallic growth. Low-temperature bake conditions might be necessary also for assemblies containing PEMs.

Figure 6 shows variations of the relative humidity calculated inside the chamber, which is installed in a room with a temperature of 25 °C and humidity of 60% RH. It is seen that the relative humidity in this chamber at 40 °C would be 25%. Obviously, this level of humidity is not low enough and a 40 °C bake can be performed only in vacuum. The vacuum conditions do not speed up the moisture release process compared to conditions in a regular chamber at the same temperature, and it would take several weeks of pumping to dry out even a relatively thin 2 mm package. Besides, using a low-pressure oven with a mechanical pump might cause contamination of the leads with pumping oil, which would affect solderability of the parts.

Based on temperature dependence of the relative humidity in the chamber displayed in Figure 6, reasonably dry conditions (< 10% RH) in the chamber can be reached at temperatures above 58 °C. The bake-out time at this temperature for a 2 mm part would be approximately 1 week. This bake-out condition is much more practical and in many cases should not create any problems with lead finish oxidizing or intermetallic formations.

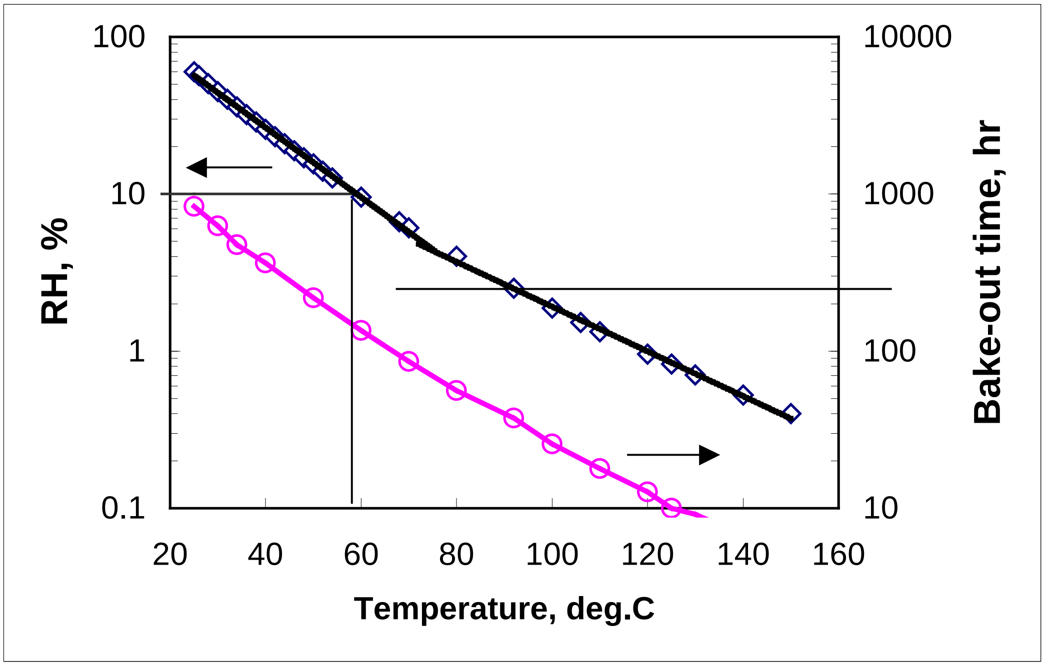

Figure 6. Temperature dependence of relative humidity in a non-hermetic temperature chamber (diamond marks) at room conditions: T = 25 °C, RH = 60%. The circle marks show the calculated bake-out times for a 2 mm flat package.

High temperature testing of PEMs stored in laboratory conditions

Let us consider a lot of 2 mm thick PEMs, which had no moisture in the package initially, but had been stored for 1 month before testing in laboratory conditions at 25 ^oC, 70% RH. Let us assume that these parts will be subjected to burn-in testing at 85 ^oC for 1 week. Results of the numeric calculations of the rated concentration at the die surface and moisture content in the package during storage at the lab conditions and during burn-in testing are displayed in Figure 7. The diffusion characteristics of the molding compound were assumed to be: $D_o = 7.3\times10\text{-}6\ m^2/s$ and U= 0.43 eV.

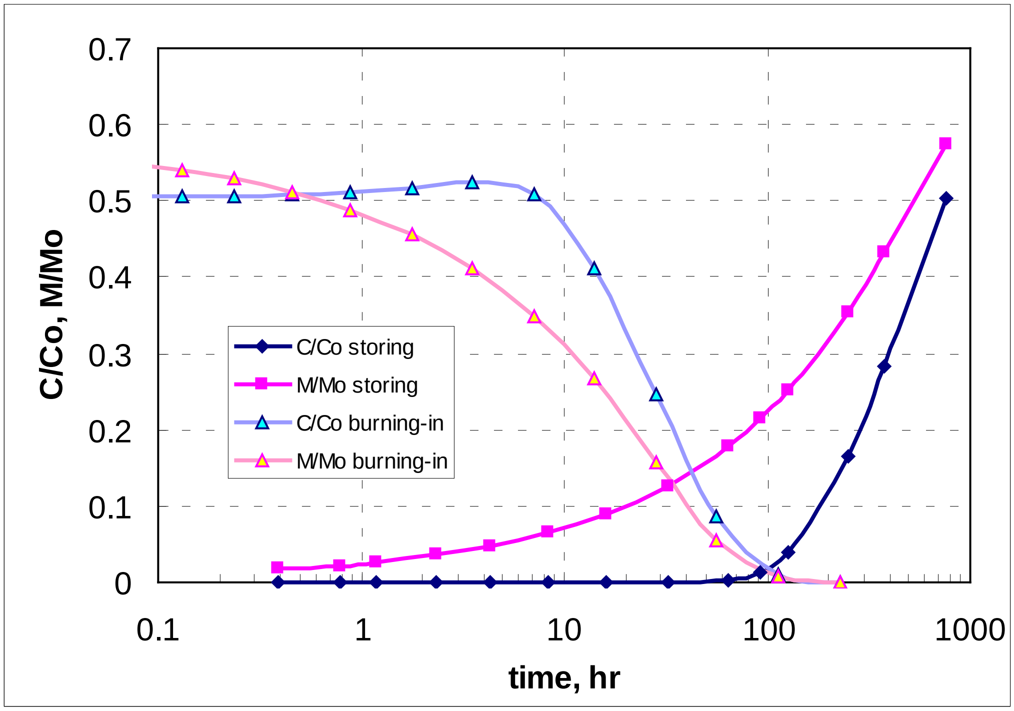

Figure 7. Variations of moisture concentration and mass in a 2 mm thick package with time during 1 month storing at 25 ^oC and 70% RH and then during burn-in testing at 85 ^oC. Note, that $C/C_o = 1$ corresponds to the equilibrium moisture saturation at 100% RH.

It is seen that the concentration of moisture at the die surface reaches ~50% of the level corresponding to 100% RH after one month of the storage; this level remains stable, and even slightly increases, during approximately 9 hours at 85 ^oC. This means that during the first 9 hrs of burning in, the moisture concentration remains relatively high and the conditions of this testing are close to the conditions of the moisture resistance test, which is performed at 85 ^oC and 85% RH. Note that in the latter case C/Co = 0.85 after ~ 70 hr required for moisture saturation at 85 ^oC. To avoid possible problems related to moisture during this testing, a bake-out at 85 ^oC could be performed. Figure 7 shows that during 96 hours at this temperature, both moisture concentration and moisture content drop below the 10% level.

Conclusion

- Simple equations have been suggested to calculate moisture diffusion characteristic times and bake out regimens for plastic encapsulated devices of different sizes and shapes.
- Analysis of moisture diffusion coefficients reported in the literature shows that different molding compounds have values of D varying approximately an order of magnitude. Considering variations in shape and size of different plastic encapsulated parts, the required bake-out times might vary more than 10 times even within the same size group of the parts. To develop an adequate moisture protection strategy for parts intended for space applications, D(T) characteristics of the molding compound should be measured for each lot of PEMs.
- Comparison of the bake-out times, which had been calculated using average moisture diffusion characteristics ($D_o = 7.35\times10^{-6}$ m^2/sec and U = 0.43 eV), and the regimens suggested by the existing JEDEC standards IPC/JEDEC J-STD-033, are in reasonable agreement. However, the suggested method allows for estimations of adequate bake-out conditions and provides much more flexibility, enabling calculation of the regimens for a specific lot of parts depending on their history of exposure to moisture environments and possible temperature conditions.
- Calculations of the bake-out conditions for parts that do not allow high temperature treatment are performed. Variations in moisture concentration and content in PEMs temporarily exposed to humid environments before burn-in testing have been analyzed.

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