

THB RELIABILITY MODELS AND LIFE PREDICTION FOR INTERMITTENTLY-POWERED NON-HERMETIC COMPONENTS

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Abstract

Results of temperature-humidity-bias (THB) acceleration experiments are often expressed in terms of a power-law function of relative humidity and an Arrhenius temperature dependence (Peck's model). For steady-state operation, we show how to calculate the effect of power dissipation on service life (or its reciprocal, acceleration). We derive an interesting inequality involving Peck model parameters which determines whether a moisture-related mechanism is accelerated or decelerated by increased power dissipation. For intermittently-powered components the steady-state acceleration is multiplied by a time-on factor (TOF). We introduce a new, broadly applicable, formula for the TOF. The formula involves thermodynamic properties of the molding compound encapsulating the die. The formula applies to most plastic encapsulated devices under typical "use" conditions.

1. Introduction

Life models for non-hermetic components depend on: (1) intensive moisture transport properties of molding compound, (2) extensive attributes of the package, such as dimensions, which influence diffusional transport of moisture and (3), the kinetics of degradation of the internal element of the package as a function of the *local* relative humidity (RH) and temperature at the element. The first two factors determine the rate at which moisture reaches, and leaves, a vulnerable internal element of the package, for example, the die¹.

For a steady state exposure to a humid ambient, such as in an environmental test, the molding compound comes to equilibrium with the ambient. Thermodynamics requires that the partial pressure of water vapor at the die be the same as the ambient irrespective of the properties of the molding compound. Thus the local environmental conditions at the die are easily calculated independently of properties of the molding compound or geometry of the package. In Section 2 we discuss the determination of accelerations of mechanisms for a steady-state stress.

Applications of non-hermetic devices often involve non-steady state ambients or intermittent powering-up and -down. Daily on-off cycling of equipment is a common example. In these cases the partial pressure of water vapor at the die is not the same as the ambient since the molding compound cannot come into instantaneous equilibrium with the ambient. In Section 3 we discuss solutions to the diffusion problem for non-steady-state stresses which frequently occur in service. We demonstrate that if, as is often the case, the average period of on-off cycling is short compared to the characteristic saturation time for a package, then an important simplification occurs. This simplification makes it possible to derive simple formulae for "time-on-factors" which multiply the steady-state accelerations derived in Section 2. Formulae for the time-on-factors are presented in Section 4.

We collect, in Section 5, the conclusions of the paper, and discuss the range of applicability of the formulae derived. We argue that the

range of applicability is considerably broader than the derivation would suggest.

2. Steady-State Stress

Water Vapor Pressure and Relative Humidity

If a non-hermetic component is held in a constant ambient, and is operated at a constant junction temperature, the system will come into thermodynamic equilibrium. In this case, thermodynamics requires that *the partial pressure of water vapor shall be the same everywhere* - in the ambient and at the die. That is,

$$P_{\text{H}_2\text{O}}(\text{die}) = P_{\text{H}_2\text{O}}(\text{ambient}). \quad (1)$$

The relative humidity, H , at a particular temperature is the actual partial pressure of water vapor expressed as a fraction of the saturated vapor pressure at that temperature. The saturated vapor pressure, $P_{\text{sat}}(T)$, is the pressure at which liquid water and water vapor can coexist at the temperature T . The saturated vapor pressure P_{sat} can be looked up in steam tables, or calculated from an analytical representation of the steam tables². From these definitions we may rewrite Eq. (1) as

$$H_j \times P_{\text{sat}}(T_j) = H_a \times P_{\text{sat}}(T_a) \quad (2)$$

or,

$$H_j = H_a \times \frac{P_{\text{sat}}(T_a)}{P_{\text{sat}}(T_j)} \quad (\text{steady - state}) \quad (2a)$$

where the subscript "a" designates the "ambient" temperature far from the power-dissipating die and the subscript "j" refers to the die. The relative humidity at the die can be calculated using Eq. (2a) for any steady state condition. In the special case of no power dissipation, then

$$T_j = T_a \quad \text{and} \quad H_j = H_a \quad (\text{no power dissipation}). \quad (3)$$

An Arrhenius plot of P_{sat} is nearly a straight line with a slope of corresponding to about 0.42 eV. This slope is related to the latent heat of vaporization of water. This can be seen by integration of the Clapeyron equation to give the approximate formula:

$$P_{\text{sat}}(T) = P_0 \exp\left(\frac{-Q_p}{kT}\right) \quad Q_p = \frac{k\lambda M}{R} = 0.42 \text{ eV} \quad (4)$$

where $\lambda = 2262.6$ joule/gm is the latent heat of vaporization of water, $M = 18.015$ gm/mole is the gram molecular weight of water, $R = 8.32$ joule/(mole °K) is the universal gas constant, and $k = 8.617 \times 10^{-5}$ eV/°K is Boltzman's constant.

Acceleration Models

Klinger³ has argued that relative humidity is the fundamental moisture-related environmental variable. Peck⁴ introduced a THB acceleration model which depends on relative humidity and temperature *at the die* according to:

$$AF = (a + b \times V) \times H_j^m \times \exp(-Q / kT_j). \quad (5)$$

Peck's formula has the convenient formal properties of vanishing as $H \rightarrow 0$, and of generating straight-line iso-acceleration contours on an Arrhenius plot of $\log H$ versus $1/T$. Parameters in Peck's formula are determined by steady-state experiments in which the effects of molding compound are irrelevant since there is ample time for the molding compound to reach equilibrium saturation. Values of Q, m reported in the literature range from $Q = 0.74$ eV, $m = 5$ for package tape leakage⁵ to $Q = 0.9$ eV, $m = 3$ for corrosion⁶ to $Q = 0.79$ eV, $m = 4.6$ for bit failure due to passivation crack⁷ to $Q = 1.15$ eV, $m = 1$ for moisture-related gold bond degradation⁸. In the present work we shall use the passivation defect mechanism (with $a = 0$, $m = 4.64$, and $Q = 0.79$ eV) in examples.

Determination of Steady-State Acceleration

Fig. 1 is an Arrhenius plot of $\log H$ versus $1/T$ in which we superimpose iso-acceleration contours for the passivation defect mechanism over water vapor pressure isobars. The iso-acceleration contours have a slope proportional to Q/m . This can be seen by taking the logarithm of Eq. (5). The isobars have a slope proportional to $k\lambda M/R = 0.42$ eV. This can be seen by taking the logarithm of Eq. (4). Isobars connect temperatures and humidities which are in thermodynamic equilibrium for mass transport.

Fig. 1 can be used to determine graphically the steady-state acceleration of a power-dissipating die. In Fig. 1, thermodynamics (Eq. (1)) requires that a steady-state power-dissipating device in city climate "X" will have temperature and relative humidity *at the die* given by "Y". "Y" is another point at a higher temperature *on the same isobar* as "X". For the mechanism illustrated, "Y" lies on a contour with lower acceleration relative to "X". In the example shown, "X" is an ambient with temperature/humidity given by $T/H = 17^\circ\text{C}/75\%$, while the conditions at the die, "Y", are $T/H = 30^\circ\text{C}/36\%$. The steady-state acceleration of the mechanism is less by a factor of 10 at "Y" than if it were not dissipating power (i.e. at "X").

The isobars in Fig. 1 also show the accelerations accessible with temperature-humidity test equipment. For example, a pressure vessel (HAST) is needed to access pressures greater than 1 atm.

It is apparent that if Q/m satisfies $Q/m = k\lambda M/R = 0.42$ eV then the iso acceleration contours and the isobars would be parallel in Fig. 1. In this case, increasing the power dissipation of the die (that is, going from "X" to "Y" in Fig. 1) would not change the acceleration of the mechanism. This idea can be generalized to:

The mechanism becomes less or more accelerated as $T_j - T_a$ increases, according to whether Q/m is less or more, respectively, than 0.42 eV.

Most published moisture-related mechanisms satisfy $Q/m < 0.42$ eV, and so become less accelerated as $T_j - T_a$ increases. For example, the passivation defect mechanism of Fig. 1 has $Q/m = 0.17$ eV. This is, however, not always true. The moisture-related gold ball bond degradation mechanism in Ref. 8 has $Q/m = 1.15$ eV, and so becomes more accelerated as $T_j - T_a$ increases.

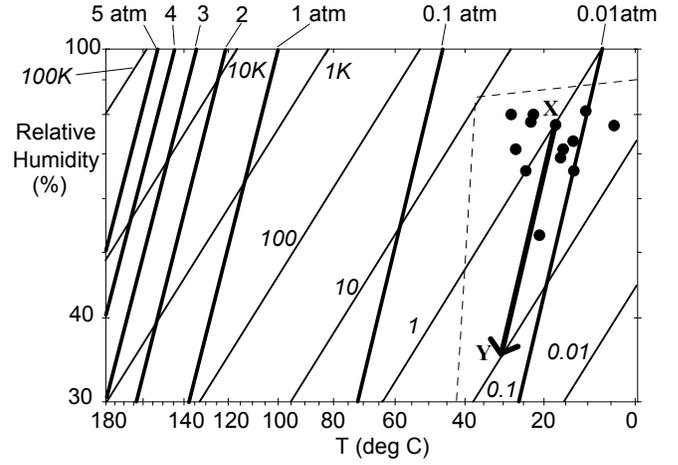


Fig. 1 Arrhenius plot of iso-acceleration contours for the passivation crack mechanism ($a = 0$, $m = 4.64$, $Q = 0.79$ eV) superimposed on water vapor pressure isobars. $T/H = 25/65$ is taken as a reference condition of unit acceleration. Zone of typical service ambients (dotted line) and average world city climates are also superimposed on the plot.

Instead of determining the steady-state acceleration of a power-dissipating die graphically as in Fig. 1, it is computationally more convenient, but less enlightening, to calculate the steady-state acceleration by substituting Eq. (2a) into Eq. (5).

$$AF(\text{steady-state}) = (a + bV) \times \left\{ H_a \frac{P_{sat}(T_a)}{P_{sat}(T_j)} \right\}^m \times \exp\left(-\frac{Q}{kT_j}\right) \quad (6)$$

When a non-hermetic device is cycled on and off quickly, or the ambient is changed quickly, there is not sufficient time for the moisture transport in the molding compound to come to equilibrium. In this case, Eq. (2a) *does not* apply, and the calculation of H_j requires explicit consideration of the moisture transport and thermodynamic properties of molding compound, and in some cases, the geometry of the package, as described in the following section.

3. Non-Steady-State Stress.

This section explains how to calculate the generally time-dependent value of H_j in the non-steady-state case of a power cycled device, or a device that is exposed to a variable ambient.

Thermodynamic Properties of Molding Compound

The thermodynamic parameters of the molding compound needed in the calculation are the diffusion coefficient, D , and the saturation coefficient, S , given by

$$D(T) = D_0 \exp\left(-\frac{Q_d}{kT}\right) \quad S(T) = S_0 \exp\left(\frac{Q_s}{kT}\right) \quad (7)$$

Kitano et al.⁹ have supplied the values in Table I of the parameters in the definitions of D and S . The diffusion coefficient appears in Fick's diffusion law, and the saturation coefficient is the constant of proportionality in Henry's law relating the equilibrium moisture concentration in molding compound to the partial pressure of water vapor over it:

$$M_{sat} = P_{H_2O} \times S = H_a \times P_{sat}(T_a) \times S(T_{mc}) \quad (8)$$

where the second equality uses the definition of relative humidity as a fraction ($0 \leq H \leq 1$) of the saturated vapor pressure at the temperature of the ambient. H_a and T_a are the relative humidity and temperature of the ambient in which the package is immersed. The molding compound temperature, T_{mc} , is greater than the ambient temperature if the chip dissipates appreciable power. Although there is actually a temperature gradient through the molding compound from die to package surface, only a small error is introduced by approximating the molding compound temperature as the average of the die temperature, T_j , and the case temperature, T_c :

$$T_{mc} = \frac{1}{2}(T_j + T_c) \quad (9)$$

This approximation is used in the examples discussed in this paper.

Table I Values of molding compound properties used in this paper. From Ref. 9.

Diffusion Coefficient	$Q_d = 0.50$ eV	$D_0 = 4.7 \times 10^{-5}$ m ² /sec
Saturation Coefficient	$Q_s = 0.40$ eV	$S_0 = 2.76 \times 10^{-8}$ mole/m ³ Pa

Calculation of Relative Humidity at the Die

The procedure has 3 steps:

Step 1. Calculate the moisture concentration at the surface of the package. Concentration change in the molding compound at the surface of the package (or "slab") occurs in response to change in partial pressure of water vapor in the ambient adjacent to the surface, and in response to change in the temperature of the molding compound. Although Henry's law was written in Eq. (8) for the case of equilibrium bulk moisture concentration, it holds *instantaneously* for the local moisture concentration *at the package surface*, C_c (the subscript "c" stands for "case". We therefore relate ambient temperature and relative humidity to the concentration of water vapor in the molding compound at the surface:

$$\begin{aligned} C_c &= P_{\text{H}_2\text{O}}(\text{ambient}) \times S(T_{mc}) \\ &= H_a \times P_{\text{sat}}(T_a) \times S(T_{mc}) \end{aligned} \quad (10)$$

Step 2. Solve the diffusion equation to find the moisture concentration in molding compound adjacent to the die, C_j . C_c is used as a boundary condition in the solution of Fick's equation for the diffusion profile in the package. Moisture diffusion into a plastic package is often idealized as a one-dimensional diffusion problem of diffusion into a slab as shown in Fig. 2. Analytical solutions to one-dimensional diffusion problems have been given by, for example, Crank¹⁰.

A solution of the diffusion equation gives the moisture concentration profile as a function of time and position, and in particular gives the concentration in molding compound adjacent to the die surface, C_j , as a function of time.

Step 3. Calculate the local relative humidity at the die, H_j , from C_j via Henry's law applied adjacent to the die:

$$\begin{aligned} C_j &= P_{\text{H}_2\text{O}}(\text{die surface}) \times S(T_{mc}) \\ &= H_j \times P_{\text{sat}}(T_j) \times S(T_{mc}) \end{aligned} \quad (11)$$

or

$$H_j = \frac{C_j}{P_{\text{sat}}(T_j) \times S(T_{mc})} \quad (11a)$$

Thus we know the instantaneous temperature and humidity, T_j and H_j at the die, which in turn governs the instantaneous kinetics of the moisture-related failure mechanisms of interest.

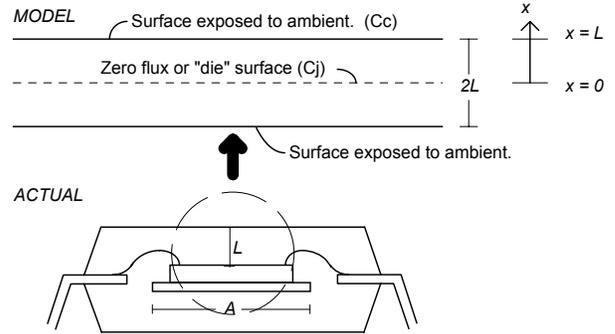


Fig. 2 Diffusion of moisture from package surface to die surface can be represented as a one-dimensional diffusion problem. The concentration in molding compound at $x = L$, C_c , is instantaneously influenced by the ambient, while changes in the concentration at the die surface, C_j , lag changes in the ambient.

Step-Function Stress

It will be important in the following discussion to understand the characteristic time constant for moisture saturation of plastic packages.

Consider a dry slab (of thickness $2L$) of molding compound suddenly immersed in a humid ambient. Solution of the one-dimensional diffusion equation (Crank) gives the time to 90% of saturation as:

$$t(\text{sat}) = 0.8481 \times \frac{L^2}{D_0} \times \exp\left(\frac{Q_d}{kT_{mc}}\right) \quad (12)$$

Values of $t(\text{sat})$ may be looked up in Fig. 3 for the diffusion parameters of Table I and typical package types.

Solution for Intermittent Stress

Plastic-encapsulated integrated circuits are often exposed to intermittent stress, depending on the application of the circuit. For example, a circuit may be "off" in a humid ambient, with the molding compound absorbing moisture, and subsequently turned "on" with consequent heating, and drying of the molding compound. Then, before the molding compound can be completely dried-out, the unit may turned "off" again and the molding compound will begin to absorb moisture again. Under these conditions, the time evolution of the moisture profile in the molding compound is non-trivial. Shirley and Hong⁷ derived an analytical expression by which these profiles may be computed analytically for ambients which cycle intermittently between two values. The solution for the special case of *periodic* switching between two ambients is reiterated in the Appendix of the present paper.

We use the solution in the Appendix to calculate the evolution of moisture profiles for the two examples shown in Figs. 4a and 4b. Both examples are for a DIP package with 50 mil molding compound thickness over the die. For both examples, the unit is powered "On" for 8 hours and "Off" for 16 hours, repeated indefinitely. In both examples, the die temperature exceeds the ambient temperature by 20°C. The difference between the examples

is that for Fig. 4a the ambient is 100°C and 85% relative humidity, while for Fig. 4b the ambient is 60°C and 85% relative humidity. In both examples the molding compound temperature T_{mc} was calculated assuming that $T_c - T_a = (2/3) \times (T_j - T_a)$, which is typical for this package type.

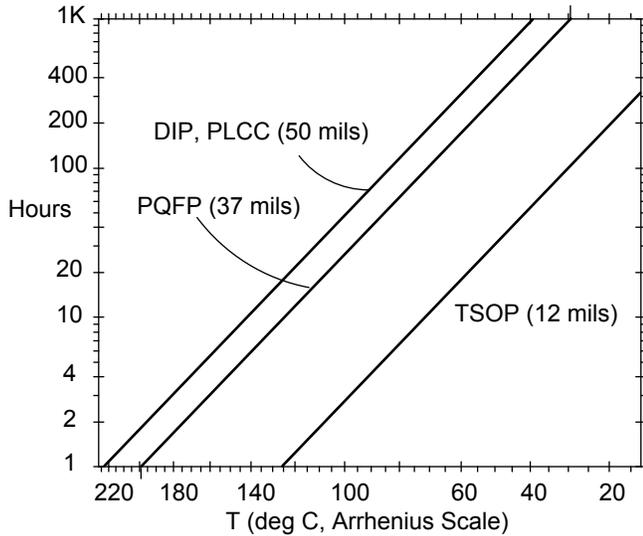


Fig. 3 Time to 90% of package saturation for several package types, using the diffusion coefficients of Table I. Dimensions in parentheses are L , the thickness of molding compound over the die.

In Fig. 4a, in a 100°C ambient, the time-varying moisture concentration at the package surface propagates into the package, causing a smoothed, damped, and delayed time variation of moisture in the molding compound at the die surface. This leads to a time-varying relative humidity at the die surface. Notice from Fig. 3 that at $T_{mc} = 117^\circ\text{C}$ the characteristic time constant for saturation of the package is 28 hours, and is comparable with the 24 hour on-off period. Calculation of the effective acceleration in this case involves using the time-varying value of C_j in Eq. (11a) and substituting time-varying H_j into the Eq (5) to calculate an instantaneous acceleration, and then averaging by integrating the instantaneous acceleration over time. This complicated procedure was discussed by Shirley and Hong⁷.

In Fig. 4b, which is for conditions 40°C cooler than Fig. 4a and more representative of conditions that occur in service, the same time-varying concentration profile is almost fully damped at the die and constant at a level intermediate between the concentrations at the package surface. Notice from Fig. 3 that at $T_{mc} = 77^\circ\text{C}$ the characteristic time constant for saturation of the package is 153 hours. This is considerably longer than the 24 hour on-off period. We show in the Appendix, that whenever the on-off cycle time is rapid compared with the characteristic saturation time constant for the package given by Eq. (12) or Fig. 3, then the moisture concentration at the die surface is a constant. The value of the constant is given in Eq. (A6).

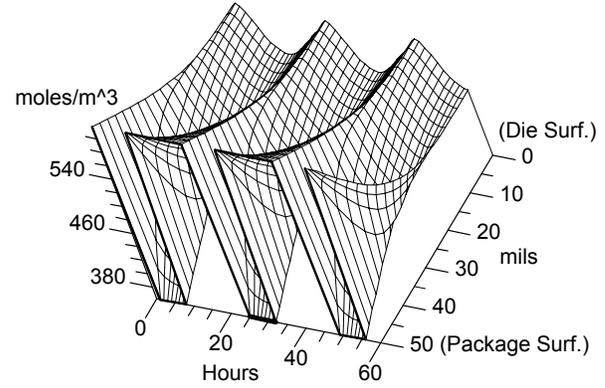


Fig. 4a Evolution of the moisture concentration profile in molding compound for an ambient temperature of $T_a = 100^\circ\text{C}$ for a device turned on (8 hours, with $\Delta T_{ja} = 20^\circ\text{C}$) and off (16 hours) repeatedly. The characteristic saturation time (28 hours, from Fig. 3) is nearly the same as the period so the concentration profile at the die varies with time.

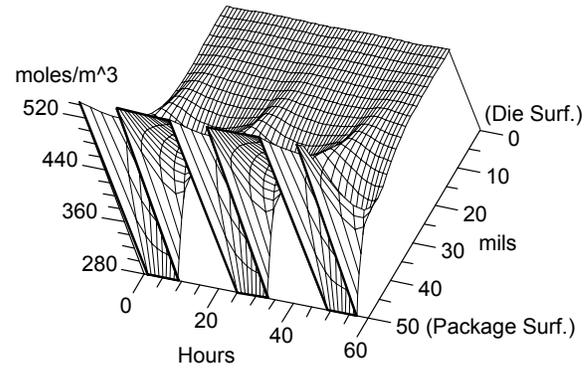


Fig. 4b Evolution of the moisture concentration profile in molding compound for an ambient temperature of $T_a = 60^\circ\text{C}$ for a device turned on (8 hours, with $\Delta T_{ja} = 20^\circ\text{C}$) and off (16 hours) repeatedly. The characteristic saturation time (153 hours, from Fig. 3) is longer than the period so the concentration profile at the die is nearly constant.

4. Time-On Factors

In the case when the on-off period is much shorter than the characteristic saturation time of the package, it is possible to derive an analytical formula for the average acceleration for a two-part stress cycle. Substitution of the expression for C_j in Eq. (A6) into Eq. (11a), and then substitution into Eq. (5) gives, after some manipulation, the following expression for the acceleration factor:

$$AF(\text{Average}) = TOF_A \times AF(\text{Steady - State A}) + TOF_B \times AF(\text{Steady - State B}) \quad (13)$$

where $AF(\text{Steady-State A})$ is the acceleration which would be calculated via Eq. (6) for the conditions of the stress condition A (replacing V by V_A , T_a by $T_{A,a}$, etc.). $AF(\text{Steady-State B})$ is similarly defined.

TOF_A is given by

$$TOF_A = r \times \left\{ \frac{r + WXY(1-r)}{r + W(1-r)} \right\}^m \quad (14a)$$

and TOF_B is given by the expression

$$TOF_B = (1-r) \times \left\{ \frac{W^{-1} X^{-1} Y^{-1} r + (1-r)}{W^{-1} r + (1-r)} \right\}^m \quad (14b)$$

where

$$W = \frac{D(T_{B,mc})}{D(T_{A,mc})} \quad X = \frac{S(T_{B,mc})}{S(T_{A,mc})} \quad Y = \frac{H_{B,a} P_{sat}(T_{B,a})}{H_{A,a} P_{sat}(T_{A,a})} \quad (14c)$$

Notice that if the *ambient* conditions are the same in both the A and B parts of the cycle (as in the example in Figs 4a and 4b, and Fig. 5 below), then $Y=1$. If, further, both parts of the cycle have negligible power dissipation, then $T_{A,mc} = T_{B,mc}$ and $W = X = 1$ so the average acceleration is the duty-cycle-weighted average of the steady-state accelerations as one would trivially expect.

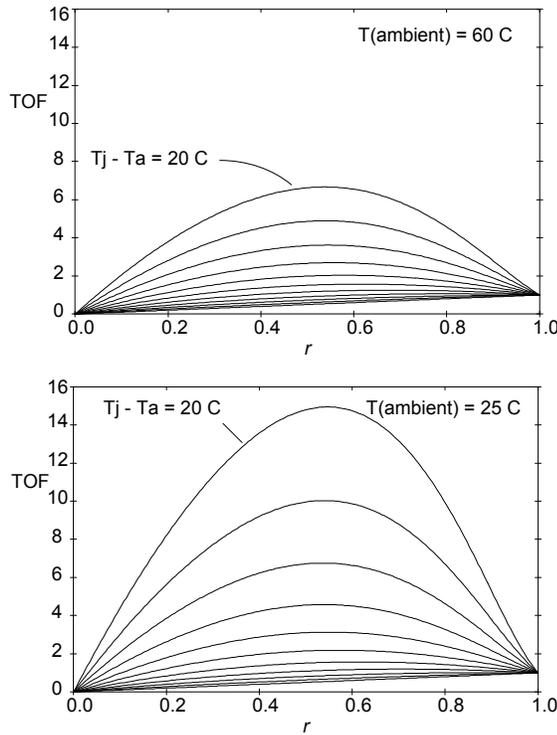


Fig. 5 Example Time-On Factors calculated using Eq. (14a) as a function of duty cycle, r , for various values of ΔT_{ja} at 2°C intervals from 0°C to 20°C for the passivation crack model, with $a = 0$, $m = 4.64$, $Q = 0.79$ eV in Eq. (5). Top: For an ambient temperature of 60°C . Bottom: For an ambient temperature of 25°C .

We show in Fig. 5 results of an example calculation of the TOF for the passivation crack mechanism discussed above, in which the bias is cycled on and off, and in which the molding compound parameters in Table I are used. If "A" is taken as the "on" part of the cycle, then AF (Steady-State B) = 0, and only TOF_A , Eq. (14a), is relevant to the discussion. The applicability of the calculated TOF may be determined by comparing the moisture saturation time constant of the package of interest with the on-off period of cycling of ambient and power. If the example TOF calculations in Fig. 5 are to be applied to a PDIP package with a 50 mil half-thickness, then the average period of the stress should be less than 125 hours for the 60°C ambient (Fig. 5, top), or less than 1300 hours for the 25°C ambient (Fig. 5, bottom). Since most applications are in room temperature ambients under stresses with median quasi-period of much less than 1300 hours (typically 24 hours), the example illustrates the broad applicability of the formula. The example also

illustrates that the TOF can assume large values, increasing with decreasing ambient temperature. Finally, the example verifies the result, first described by Ajiki, et al.¹¹ that, for devices which dissipate sufficient power, "on some of the time" is more accelerated than "on all of the time". In the case of Figs. 5, a device with $\Delta T_{ja} > 5^\circ\text{C}$ will be more accelerated if it is "on" only some of the time.

5. Conclusions

Most temperature-humidity-bias environmental testing of non-hermetic encapsulated devices is performed in a steady-state high-temperature humid ambient. The devices sometimes dissipate appreciable power. Under these conditions the transport properties of the molding compound are irrelevant to analysis of the data and extraction of acceleration models. We showed how to invoke the thermodynamic principle of constant partial pressure of water vapor to calculate the steady-state humidity at the die, or other vulnerable internal element of the package. We derived an interesting criterion that parameters in Peck's moisture acceleration formula must satisfy for a mechanism to become less accelerated with increasing power dissipation; viz. $Q/m < 0.42$ eV.

On the other hand, non-hermetic devices are actually *used* at low temperatures in varying ambients, or under quasi-periodic power cycling. Typical "use" cycling periods would be, for example, 24 hours for a components in desktop computer (on 8 hours, off 16 hours), or several minutes for components in a laptop computer with automatic power-down software. We noticed that these cycle times are almost always much shorter than the characteristic moisture diffusion time constants of plastic packages at "use" temperatures. This observation led to a simple formula for the TOF ("time-on-factor"), Eq. (14), depending only on thermodynamic properties of the encapsulant, die and ambient temperatures, and fraction of time which the device is "on". The formula is *independent* of the on-off period and package dimensions, as long as the median on-off period is shorter than the characteristic saturation time constant of the package. The formula for TOF therefore allows convenient and accurate calculation via Eq. (13) of effective accelerations under these "use" conditions without resorting to elaborate numerical analysis.

Although the derivation of Eq. (14) relied on taking the short cycle-time limit of a periodic one-dimensional solution, the formula has a wider validity than the solution from which the limit was taken. It is apparent that the formula given in Eq. (A5) for the moisture concentration in the molding compound adjacent to the die will be valid for *any* quasi-periodic stress where the average period is much less than the characteristic moisture diffusion time constant of the package. Moreover, although the limit was taken using a one-dimensional solution of the diffusion equation, the effects of geometry disappear in this limit, so that the results apply for *any* package geometry, as long as the average on-off period is much shorter than the characteristic moisture diffusion time constant of the package.

The simple TOF formula fails for thin packages operating at high temperature with long off-on cycles. One such instance occurs when the on-off cycle time is much longer than the characteristic time constant of the package. In this "very long period" case, it is appropriate merely to concatenate steady-state periods. Another case occurs when the on-off period is about the same as the characteristic time constant of the package (as in the example of Fig. 4a), then geometrical factors must be taken into account in a complicated solution which gives the time variation of the moisture concentration in the molding compound next to the die. Happily, the criteria for applicability of the TOF formula in Eq. (14) are satisfied for the "use" conditions of most plastic packaged devices.

Appendix

Shirley and Hong⁷ derived the analytical solution for the evolution of the moisture concentration profile in a slab (representing a package) subjected to a periodic stress (with period, p) in which the ambient alternates indefinitely between two conditions; stress A for fraction of the period, r , and stress B for fraction of the period $1-r$. The fraction r ($0 \leq r \leq 1$) is called the duty cycle. The symbols in the solution are summarized in Table A.

After a sufficient number of cycles, "memory" of any initial profile is lost and the analytical solution in the "A"-part of the cycle ($0 \leq t \leq t_A$) is:

$$\frac{C(x,t) - C_{A,c}}{C_{B,c} - C_{A,c}} = \sum_{n=0}^{\infty} \frac{4(-1)^n}{\pi(2n+1)} \times \left\{ \frac{E_n[\tau_A \times (t/t_A)] - E_n[\tau_B + \tau_A \times (t/t_A)]}{1 - E_n(\tau_A + \tau_B)} \right\} \times \cos\left[\frac{1}{2}(2n+1)\pi\varepsilon\right] \quad (A1)$$

where $E_n(\tau)$ is defined by

$$E_n(\tau) \equiv \exp\left[-\frac{1}{4}(2n+1)^2 \pi^2 \tau\right] \quad (A2)$$

and

$$\varepsilon = \frac{x}{L} \quad \tau_A = \frac{D(T_{A,mc}) \times t_A}{L^2} \quad \tau_B = \frac{D(T_{B,mc}) \times t_B}{L^2} \quad (A3)$$

In the "B" part of the cycle ($0 \leq t \leq t_B$), the expression for the concentration profile is given by Eq. (A1), with "A" replaced by "B" and *vice versa*.

If the durations of both the "A" and the "B" parts of the cycle (t_A and t_B , respectively) are short compared with the characteristic time to saturation of the package, Eq. (12), then

$$\tau_A \ll 1 \quad \text{and} \quad \tau_B \ll 1, \quad (A4)$$

and it is easy to show that in this limit the function in the braces in Eq. (A1) has the limit

$$\left\{ \frac{\dots}{\dots} \right\} \xrightarrow{\tau_A, \tau_B \rightarrow 0} \frac{\tau_B}{\tau_A + \tau_B}.$$

When Eq. (A1) is evaluated in this limit at the die ($x=0$, $\varepsilon=0$), then, using the fact that

$$\sum_{n=0}^{\infty} \frac{4(-1)^n}{\pi(2n+1)} = 1,$$

we find the central result of this paper:

$$C_{A,j} = C_{B,j} = C(0,t) = \frac{\tau_A C_{A,c} + \tau_B C_{B,c}}{\tau_A + \tau_B} \quad \text{for } \tau_A, \tau_B \ll 1. \quad (A5)$$

We have inserted " $C_{B,j}$ " into the equalities in Eq. (A5) since the equation could also have been derived for the "B" part of the cycle. In the limit described, the moisture concentration in molding compound is independent of time and has the same value in both the "A" and "B" parts of the cycle.

Table A. Device alternates indefinitely between stress A and stress B. Summary of symbols describing the two stress conditions.

Parameter	Stress A	Stress B
Ambient Temperature	$T_{A,a}$	$T_{B,a}$
Package Case Temperature	$T_{A,c}$	$T_{B,c}$
Die Temperature	$T_{A,j}$	$T_{B,j}$
Molding Compound Temp.	$T_{A,mc} = (T_{A,j} + T_{A,c})/2$	$T_{B,mc} = (T_{B,j} + T_{B,c})/2$
Ambient Relative Humidity	$H_{A,a}$	$H_{B,a}$
Relative Humidity at Die Surface	$H_{A,j}$	$H_{B,j}$
Duration	$t_A = r \times p$	$t_B = (1-r) \times p$
Package Surface Moisture Conc.	$C_{A,c}$	$C_{B,c}$
Die Surface Moisture Conc.	$C_{A,j}$	$C_{B,j}$
Bias	V_A	V_B

Equation (A5) expresses the fact that when the frequency of oscillation between two steady-state ambients is sufficiently rapid (with period much shorter than the characteristic time-to-saturation of the package), then the moisture concentration in molding compound adjacent to the die surface is a constant given by the "Fourier-duration"-weighted average of the moisture concentration in molding compound at the package surface. The "Fourier durations" are the dimensionless measures of the durations in the "A" and "B" parts of the cycle. In terms of the duty cycle and the diffusion coefficient of the molding compound,

$$C_j = C_{A,j} = C_{B,j} = \frac{r C_{A,c} + W(1-r) C_{B,c}}{r + W(1-r)} \quad \text{for } \tau_A, \tau_B \ll 1 \quad (A6)$$

where

$$W = \frac{D(T_{B,mc})}{D(T_{A,mc})} = \exp\left\{ \frac{Q_d}{k} \times \left(\frac{1}{T_{A,mc}} - \frac{1}{T_{B,mc}} \right) \right\} \quad (A6a)$$

where Q_d is the activation energy of the diffusion coefficient for moisture in the molding compound.

References

- [1] Throughout the paper we use the term "die" (and the subscript "j", for "junction") to refer to the vulnerable internal element of the package. However, it is understood that the model applies to all internal elements affected by exposure to moisture.
- [2] A useful representation of the steam tables is derived by a fit of $\ln(P_{sat})$ to a cubic polynomial in $1/T$:

$$P_{sat}(\text{kPa}) = \exp(a + bx + cx^2 + dx^3)$$

$$x = 1/[273 + T(^{\circ}\text{C})]$$

$$a = 16.0332248 \quad b = -3515.138060$$

$$c = -2.90850583 \times 10^5 \quad d = 5.09723605 \times 10^6$$

The error is less than 0.15% for $5^{\circ}\text{C} < T < 240^{\circ}\text{C}$. Fitted to table in "CRC Handbook of Chemistry and Physics", CRC Press 73rd Edition (1992) pp6-14 to 6-15. Derived in turn from Haar/Gallagher/Kell "NBS/NRC Steam Tables", Hemisphere Publishing, N.Y., (1984).

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