The Unsettled World of Leak Rate Physics: 1 Atm Large - Volume Considerations Do Not Apply to MEMS Packages, A Practitioner's Perspective

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ABSTRACT

The world of leak testing, and the applicable physics, is unsettled. While globally lower MIL-STD leak rate criteria are under consideration even for 1 atm-large volume packages, industry is conversely moving rapidly into very small volume MEMS and vacuum packaging for advanced devices. These changes point out serious conceptual disconnects between the reality of properly characterizing a leak and the conceptual tools used to ensure the desired lifetime. The physical understandings and associated tool sets used to test and model the leaks are described. We modeled two actual packages, a large, ≈200 cc volume multichip module for aerospace applications and a small ≈0.01cc volume MEMS package for sensor applications. Impacts of various physical models of leak flow into a package are compared to include Fickian Diffusion, The Davy Model, Howl-Mann, and an empirically derived model based on Kr-85 leak testing as called out in the most recent edition of MIL-STD-883. As shown in the comparisons, simple He leak testing and physical models based thereon fall apart in the small volume MEMS packaging space.

Key Words: MEMS Packaging Leaks Fick Davy Helium Howl-Mann Krypton

1. INTRODUCTION

The world of leak testing, and the applicable physics is unsettled. While globally lower MIL-STD leak rate criteria are under consideration, even for 1 atm-large volume packages, industry is moving rapidly into very small volume MEMS and vacuum packaging for advanced devices. These changes point out serious conceptual disconnects between the reality of properly characterizing a leak and the conceptual tools used to ensure the desired lifetime. In fact, practical experience has repeatedly shown that other contributors to moisture mass flows within and without a package to include outgassing of materials and the actual packaging process are the major contributors to moisture issues.

For example, review of a private hermetic package database of one of the authors revealed the extent and nature of hermetic package moisture noncompliance.[1] This database comprised both single chip microcircuit packages as well as some hybrid units. In the review, any unit exceeding 0.5v% internal water vapor was termed "noncompliant". There were 69 noncompliant units with no components of air, another 69 units with approximate air composition, 30 noncompliant units with more moisture than simple air ingress can explain, and 35 noncompliant units that were gross leakers indicated by presence of fluorocarbon.[2]

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Table 1. Reasons For Moisture Noncompliance of 1,889 “Hermetic” Units

Category	Number of Units	Percent of total units
Compliant	1686	89.3%
Noncompliant, no air present	69	3.7%
Noncompliant, evidence of air leak	69	3.7%
Noncompliant, fluorocarbon present	35	1.9%
Noncompliant, small amount of air present	30	1.6%
Total Units	1889	

Review of a larger database of over 10,000 units reported similar results, with a total of 14% of units noncompliant and a similar breakdown of non-compliants.[3] The reviewed data shows that the general extent of moisture noncompliance in hermetic packages is surprisingly high. Humidity ingress through leaks, and post-seal internal materials volatility, are roughly equally responsible for moisture noncompliance.

2. CLASSICAL LEAK PHYSICS: MOISTURE INGRESS INTO HERMETIC PACKAGES

Even without a leakage path, moisture can be present inside sealed enclosures due to either moisture impurity in the blanket seal gases or volatility from package materials.[4] Assuming that moisture from these sources both at time of seal and over unit storage and service life remains negligible (a perilous assumption), a failure of seal integrity then becomes a potentially significant source of moisture. Based on the assumption that a failure of seal integrity is the root cause for elevated concentrations of moisture and other species within a package, workers in the field have modeled leaks and leak physics in great detail.

3. LEAK MODELING

3.1 Primary Approaches to Leak Modeling

Context is critical to quantitatively assessing moisture flows through a capillary as the physics behind this topic has been massively confused by historical events and engineering rules of thumb developed in response to those events. This confusion is the root cause for leak testing, modeling, and regulatory efforts to be a current hot topic in the industry.

Commonly used approaches to understanding leaks into a package assume a positive flow of gas. Such flow is typically assumed to be pressure driven and is, in fact, actually so when traditional leak check methods are used. But is this truly applicable when it is considered that there are two pressure regimes to consider:

$$P_1=P_2 \tag{1}$$
$$P_1 \neq P_2 \tag{2}$$

In a typical microelectronic package, not purposely sealed under reduced pressure, and in storage or installed in a system on the surface of the earth, $P_1=P_2$ applies. This puts the physics into a pure Fickian Diffusion mode, which is more appropriate than flow based physics to understand moisture transport into a typical microelectronic package.

The significant differences between diffusion-based mass flow and physical-pressure-based mass flow physics have not stopped practitioners in the field from trying to apply data obtained by flow based methods, e.g. leak testing, to model what is in actuality often a diffusion-based regime.

The three main approaches to modeling leaks into packages are Fick, Davy and Howl-Mann. We will give a brief overview of each. As the applicable physics for most devices is $P_1=P_2$, the authors view Fickian diffusion as the most important method, with flow based methods like Davy and Howl-Mann are special case tools. We shall also briefly touch on current work by Rossiter & Neff to generate an empirically derived relationship between krypton leak rates and permissible leak rates.

3.2 Fick's Diffusion Physics

The authors' preference for understanding 'leaks' into packages using Fick's Law is based upon decades of analyzing real world hermetic systems, ranging in size from very small MEMS packages to huge cryogenic vessels. Analyzing failure modes across this broad range of systems does not agree with a leak or flow-based perspective of hermeticity.

Our analysis separates the data sets into two main families based on pressure regimes. Fundamentally, there is either a ΔP across the boundary between the inner cavity of the hermetic system and the outer ambient, or there is not. Where a true ΔP exists, typically when the internal cavity is under a vacuum, classic flow physics apply and the traditional approaches to calculating a mass flow through a leak are applicable. Focusing solely on leaks considers only air and water flows into the system. This ignores other potentially adverse mass flows due to mechanisms such as outgassing or permeation. While these flows are often the true root cause of a system's failure to reach its designed lifetime, further discussion of them is outside of the scope of the current paper.

For the purposes of the current discussion a leak can be viewed as a very tiny capillary connecting the internal cavity of a package with the outer world. As the package has been sealed at the same atmospheric pressure as the outer world, $P_1=P_2$ applies. Diffusion physics determines how long it will take for an equilibrium to form between the partial pressure or concentration of moisture within a sealed cavity and that in the external ambient.

$$\frac{m}{t} = \frac{DA(C_2 - C_1)}{L} \tag{3}$$

where:

m = molecular weight of the diffusing species (18 for water vapor)
t = time
D = diffusion coefficient (for water, 2.4E-5 m^2/sec at 20°C)
A = the smallest cross-sectional area of the leak path
L = the length of the leak path
$C_2 - C_1$ = the concentration difference between the cavity and the outside ambient. Where materials & processes are effectively executed, $C_1 = 0$.

Inside the cavity C_1 is dynamic, as it is diminished by physisorption on internal surfaces and augmented by outgassing from those surfaces or by influx from the external ambient.

Leaks described by Fick's Law thus are driven by temperature, concentration (partial pressure) differences, and leak geometry (primarily leak path diameter). These are the conditions that apply to enclosures nominally at 1 atm after seal, when stored or operating in an ambient air environment.

Care should be taken when comparing the outcomes of diffusion-based models with flow-based models. As Davy writes:[5]

"… the rate at which helium leaks out of a package when it is being tested (under vacuum by a helium mass spectrometer leak detector) sets an upper limit to the rate at which air may leak into the same package while it is in use in air at one atm, but that upper limit may be orders of magnitude greater than the true value."

3.3 Davy's Combined Flow Equation

Davy made an effort to combine all of the flow regimes, viscous, molecular and diffusional in his combined flow equation (CFE):[6]

$$R = 1.249x10^8 \left[\frac{Yd^4}{l + \left(\frac{Y}{Z}\right)d}\right] \overline{P}\Delta P + 4.961x10^4 \left[\frac{d^3}{\left(l + \frac{4}{3}d\right)\left(\frac{d}{\lambda} + 1.509\right)}\right]\Delta p \tag{4}$$

where:

R = the measured leak rate of one gas species through the capillary in atm-cc sec^{-1}
Y & Z = viscous flow dimensionless parameters correcting for end effect and molecular slip
l & d = length and diameter of the capillary in cm
$\overline{P}$ = the average pressure in atm
ΔP = the difference in total pressure in atm
Δp = the difference in partial pressure of measured gas species in atm
λ = mean free path in cm

Pressure-driven mass flow regimes account for the first half of the CFE equation. However, since the pressures are equal on both sides of the leak, $\Delta P = 0$, the results are determined by the diffusion-driven second half of the equation, where the dimensions of the leak are critical.

3.4 Howl-Mann Leak Rate Equation

In early work Howl and Mann derived an equation[7,8] that is the basis for many leak rate considerations and supports the physics of helium and krypton leak rate testing specified in Mil-Std test methods:[9]

$$R_1 = \frac{LP_e}{P_0}\left(\frac{M_A}{M}\right)^{\frac{1}{2}}\left\{1 - e^{\left[\frac{Lt_1}{VP_0}\left(\frac{M_A}{M}\right)^{\frac{1}{2}}\right]}\right\} e^{\left[\frac{Lt_2}{VP_0}\left(\frac{M_A}{M}\right)^{\frac{1}{2}}\right]} \tag{5}$$

where:

R_1 = the measured leak rate of tracer gas (He) through the leak in atm-cc sec^{-1} of He
L = the equivalent standard leak rate in atm-cc sec^{-1} of air
P_E = the pressure of exposure in atmospheres absolute of He
P_O = the atmospheric pressure in atmospheres absolute
M_A = the molecular weight of air in g (28.7 per Method 1014)
M = the molecular weight of the tracer gas in g
t_1 = the time of exposure to P_E in sec
t_2 = the dwell time between release of pressure and leak detection, in sec
V = the internal volume of the device package cavity in cc

Howl-Mann is solved by considering the three terms separately:

First: Converts true air leak rate to that of helium.
Second: Calculates the amount of helium entering the package during the bomb cycle T_1.
Third: Represents the amount of helium remaining in the package at test time T_2.

From a practical standpoint the important parameters are bomb time T_1, bomb pressure P_E, package volume V, and dwell time T_2. When Howl-Mann is looked at from this perspective it is clear that what it is actually measuring is the ability of an internal overpressure of He to leak out of a package. Given this reality and the lack of correlation to internal moisture build up within a package over its service life, the fact that Howl-Mann is honored more in the breach than in day-to-day practice becomes understandable.

3.5 Rossiter & Neff

In order to square the circle between diffusion and flow based understandings of leaks into packages, particularly small packages of the sort used in MEMS, T. Rossiter of Oneida Research (RGA service laboratory) and G. Neff of IsoVac Engineering (krypton leak testing) made an in depth study of leak rates of very small packages using the Kr^{85} method as commercialized under the Radiflo trademark. This study used oxygen concentration as the key marker. Measurements of the oxygen concentration were done by internal vapor analysis (a form of RGA.) This study resulted in an empirically derived equation giving the permissible air leak rates into these packages.[10] The relationship is simple:

$$L_{air} = \frac{0.5\,V}{t} \qquad (6)$$

where:

L_{air} = the permissible air leak rate
V = the volume of the internal cavity in cubic centimeters
T = the desired system life in seconds

While there is a reasonable correlation for permissible air leak rates in larger systems, this work was done on very small MEMs packages and has not been verified for larger volume systems

4. COMPARISONS

It mustn't be forgotten that moisture movement through capillaries into a sealed cavity is a subset of the larger volatile dynamics within and without a sealed cavity. These mass flows consist not only of air, water vapor and other species through a capillary, but also occur due to permeation, outgassing, and physisorption.[11] Understanding these mass flows is further complicated by the fact that moisture is not the only species involved, nor are there any lack of potential chemical reactions within or without a sealed cavity that can complicate understanding of the total mass flow system.

To give a sense of scale to where leaks fit within these mass flow mechanisms for MEMS packages, a simple boundary condition calculation can be performed using the equation:

$$t_{3ml} = \frac{3M_{ml}A_i}{Q} \qquad (7)$$

Where:

t_{3ml} = the time for adequate moisture to flow into a package to create 3 monolayers
M_{ml} = the mass of a monolayer of water (30 ng/cm^2)[12]
A_i = the internal surface area of the package
Q = the mass flow rate of moisture into the package

Assuming that:

- There are no mass flows (Q) in or out of the package other than an arbitrary leak of mass n/unit time.
- Moisture sorption on the surface is instantaneous for practical purposes.
- The number of monolayers at t=0 equal 0. I.E. the package is bone dry.
- The pressures within and without the package are equal.
- *Only the mass needed to form 3 monolayers of water is determined by this approach, not the total mass necessary to generate an internal concentration of 5,000 ppmv.*

Performing this calculation, which is a variant of the DerMardosian equation for moisture ingress time,[13] for a relatively small package with dimensions of 0.2x0.2x0.05 cm and a leak rate of 1e-8 sccm of water vapor, results in time to form three monolayers of 15,508 years! There is obviously a serious disconnect here that supports the conclusions in our prior work that materials and processes issues are greater contributors to adverse accumulations of water within packages than leaks are, so long as the package seal has passed a reasonable level of leak check (e.g. 1-0X sccm.) [14]

4.1 Comparisons with Fick, Davy, and Rossiter& Neff

Given the conceptual differences between these approaches to modeling leaks a true correlation is beyond the scope of the current work. However, norming inputs in two cases, a large package with 200 cc internal volume and a small package of 0.01 cc does give an indication of the differing results given by the various methods. In each instance a fine leak rate of 1e-8 sccm will be assumed. Both Fick and Davy are dependent on the geometry of the leak. In this comparison a leak length of 0.01 cm and a diameter of 3e-05 cm are used.

Time to 5000 ppmv Moisture

	200 cc internal volume	**0.01 cc internal volume**
Fick	160 years	0.008 years
Davy	89 years	0.004 years
Rossiter & Neff	850 years	4 years

5. CONCLUSIONS

- Very large packages, with volumes in the range of 10's of cm^3 and larger, can accommodate fine leaks below 1e-07 atm-cc sec^{-1} (nominal) without compromising reliability via moisture failure mechanisms.
- Boundary condition calculations indicate that very small packages with high surface area-to-volume ratios can withstand very large leak rates before 3 monolayers of water form, creating the conditions for corrosion.
- Calculated times to unacceptable moisture levels can differ significantly between gas-flow driven and simple gaseous diffusion models.
- Regardless of models used, none give exactly the same results.

Are leaks really the issue? Our analysis, using various accepted industry models as well as the actual physics involved, Fickian diffusion, points towards materials and processing issues as the major contributors of moisture within a package. A materials and process approach both helps the practitioner to understand and solve more problems than a simple leak rate perspective.

The need to solve day-to-day problems in the field force the empirical approach. That these problems continue to bedevil practitioners after decades of work, indicates a need to refine the underlying science of mass flow mechanisms within the package and its environment. Leaks continue as a hot topic because everything looks like a leak when all one has is a leak tester. The issue is further clouded by commercial agendas of leak equipment suppliers.

We see a wonderful opportunity for academia and the national laboratories to reset the science of mass flows in microelectronic packaging using a hard, analytical approach. The end result should be a 'unified field theory' of leaks. The questions to be answered are many, but the results are critical as packages become ever smaller in the era of MEMS.

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