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HERMETIC PACKAGE LEAK TESTING RE-VISITED

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INTRODUCTION

The two main reasons to seal devices hermetically, thereby preventing hermetic enclosure ambient compromise (HEAC), are: (1) operating characteristics that require protection from condensed, adsorbed, or gaseous water that can cause corrosion, electrical leakage, fogging, stiction, or related fail modes, and (2) to maintain reduced-pressure ambients during the product's expected storage and operating lifetime.

There are two primary means of preventing HEAC: (1) selecting package materials and executing seal processes (M&P) that neither incorporate moisture in the enclosure at time of seal nor outgas volatiles into the enclosure at any time post-seal, and (2) using M&P that insure airtight seals preventing moisture or external ambient gas ingress during product storage and operating lifetime. Item (1) is always necessary. For certain component types in certain enclosure types, Item (2) becomes necessary. Item (2) alone is never sufficient for any product to avoid HEAC.

Two test methods provide data for avoiding HEAC: (1) residual gas analysis (RGA, MIL-SPEC Test Method 1018), and (2) gross and fine leak testing (MIL-SPEC Test Method 1014). Per military specification, the maximum allowable water vapor content in sealed enclosures is 5000ppmv (0.5v%). Until recently, leak rate expectations have been expressed as[1]:

"Unless otherwise specified, devices with an internal cavity volume of 0.01 cc or less shall be rejected if the equivalent standard leak rate (L) exceeds 5 x 10-8 atm cc/s air. Devices with an internal cavity volume greater than 0.01 cc and equal to or less than 0.4 cc shall be rejected if the equivalent standard leak rate (L) exceeds 1 x 10^{-7} atm cc/s air. Devices with an internal cavity volume greater than 0.4 cc shall be rejected if the equivalent standard leak rate (L) exceeds 1 x 10^{-6} atm cc/s air."

However, technological progress has greatly broadened the applicable dynamic ranges of hermetic enclosure internal volumes, pressures, leak rates[2,3], and the device types and failure modes relevant to HEAC, per Table 1:

	When test methods were developed	**Today**
Leak rate, cc atm/sec	E-8 to E-2	E-12 to E-2
Orders of magnitude	6	10
Enclosure internal volume, cc	E-2 to E1	E-6 to E2
Orders of magnitude	3	8
Enclosure internal pressure, atm	nominally E0	E-6 to E0
Orders of magnitude	<1	6
Device types	LSI single chip IC's simple hybrids	nanoscale IC's complex hybrids optoelectronics MEM's, MOEM's medical devices etc., etc.
Fail modes	Corrosion by moisture condensate Electrical leakage via adsorbate	Corrosion by moisture condensate Electrical leakage via adsorbate Fogging Stiction Pressure changes

Table 1

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The dramatically broadened dynamic ranges change the landscape for leak testing. As such, hermeticity testing is not a "one size fits all" test. Gas phase flow physics of helium and krypton are different from that of air and water vapor. Leak rates measured with pressurized He or Kr do not model reality for enclosures whose internal pressures are nominally the same (1 atm) as typical storage and operating surroundings. The equations of Howl and Mann and the Davy Combined Flow Equation[4,5,6] quantify fine leak testing using large pressure differences between the cavity and the outside. But these leak physics and rates differ from that for a unit with a leak path but no pressure difference between inside and outside, a condition better modeled by Fickian diffusion[7].

A fine leak in the E-8 to E-12 leak rate range can present a genuine threat of HEAC to small volume (E-6 to E-2 cc) enclosures with MEMs or optical devices, especially if their internal pressure is <1 atm. But the same leak does not similarly threaten a microelectronic device in a larger enclosure at 1 atm whose principal vulnerability is to corrosion by moisture condensate. Not enough moisture can ingress at such low leak rates over expected operating lifetimes to cause simple corrosion. This is especially true if its operating ambient is ≤50%RH and 20ºC.

Applying pressures significantly greater or less than 1atm to test an enclosure create physical and mechanical stresses in units atypical of field service. These test conditions can create ephemeral or permanent leaks, causing unnecessary noncompliant results in leak testing. [8]

A vital consideration often neglected by over-emphasizing leak rate testing for avoiding HEAC, particularly as internal volumes get smaller, is M&P-sourced moisture and gas ambient compositions at time zero, plus degradation of these compositions due to materials outgassing post-seal over time. Leak testing contributes to preventing HEAC only when PRECEDED by robust M&P in manufacturing achieving very low (<≈0.05%) moisture in enclosures at time of seal, with negligible outgassing of volatiles over storage and operating lifetime.

As a case in point, it is not entirely unusual for residual gas analysis of enclosures that pass leak tests to show moisture approaching or exceeding 0.5v%. The analytical data often show that such enclosures, presumably sealed under inert gas, have elevated moisture accompanied by (1) carbon dioxide greatly exceeding its natural level (<≈0.04v%) in air, and/or (2) significant levels (>≈0.05v%) of volatile organic compounds, and (3) exhibiting negligible or non-detectable argon. In these cases most if not all the moisture came from M&P, not ambient ingress. HEAC in such units is entirely due to poor M&P, not poor hermeticity. This paper emphasizes that the first line of defense against HEAC is robust M&P in manufacturing, established by gas analysis. Leak testing supplements this assurance against HEAC for device types in very small enclosures (especially at reduced pressures) that are vulnerable to failure modes in addition to simple aqueous-based corrosion. Gas analysis and leak tests are very different in how they are conducted, but the data are complementary when applied to avoidance of HEAC.

LEAK RATES AND HERMETICITY

When determining the critical factors impacting HEAC it is critical to understand the conditions and mass flow sources/pathways in a system to be hermetically sealed.

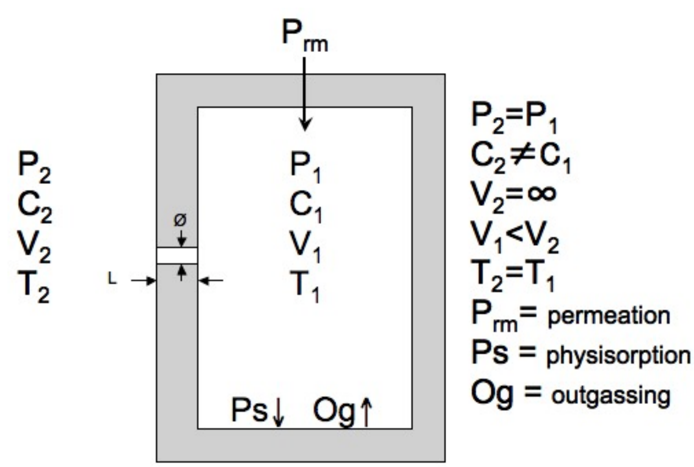

Fig. 1.
A visual representation of the system modeled in this paper. Inside the cavity C_1 is dynamic as it is diminished by physisorption on internal surfaces, added to by outgassing from those surfaces, and added to by influx from the external ambient.[9]

The classical model for addressing leaks in such a system is Davy's Combined Flow Equation:[10]

$$R = 1.249 \times 10^8 \left[\frac{Yd^4}{l + \left(\frac{Y}{Z} \right) d} \right] \overline{P} \Delta P + 4.961 \times 10^4 \frac{d^3}{\left[l + (4/3)d \right] \left(d/\lambda + 1.509 \right)} \Delta p$$

Eq. 1.

where:

R = the measured leak rate of one gas species (e.g., He) through the capillary leak in atm cm^3 sec^{-1}
Y and Z = viscous-flow dimensionless parameters that correct for end effects and molecular slip
l and d = length and diameter of capillary, in cm
$\overline{P}$ = average pressure, atm
ΔP = difference in total pressure, atm
Δp = difference in partial pressure of measured gas species, atm
λ = mean free path, cm

It must be kept in mind that at a nominal 1 atm within and without the cavity under consideration that there are no pressure differentials, so no flow physics apply. Consequently, this paper considers the reality of a non-hermetic condition (for enclosures nominally at 1 atm since seal) to be described by simple Fick's Law diffusion:

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

Eq. 2.

For water vapor, m = mass of diffusing species (18):
t = time
D = diffusion constant (for water, 2.4E-5 sq m/sec at 20ºC)
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. For cases where M&P is effectively executed, $C_1 \equiv 0$

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 truly apply to enclosures nominally at 1 atm after seal, stored or operating in an ambient air environment.

DELTA BETWEEN FICK AND DAVY IN THE P2=P1 CASE

An example system with a cavity with an internal volume of 1 cm^3 and leak length of 100 µm and operating conditions of 25C, 85%RH, P1=P2=1 atm was modeled to compare Fick and Davy. Internal concentration of water vapor at t=0 is assumed to be 0 ppmv and 5,000 ppmv at end of life. For a leak range of 1-10 µm the time delta to 5,000 ppmv between the two flow calculations averaged 2.5x with Fickian flow rates being the slower. At leak diameters significantly below 1 µm (e.g. 0.05 µm) the methods diverge significantly and are no longer comparable. Therefore using the Fickian method in leak analysis is adequate when a simpler method is desired.

MASS FLOWS OTHER THAN LEAKS WITHIN A DEVICE PACKAGE

Outgassing and permeation are underappreciated contributors to the total mass load over the lifetime of a small internal volume. While they can be minimized through proper selection of materials and processes, they can never be eliminated. A quick perusal of the literature will show that these mass flows are in the ranges currently being proposed for enhanced leak testing. An example is simple, well baked out aluminum foil:

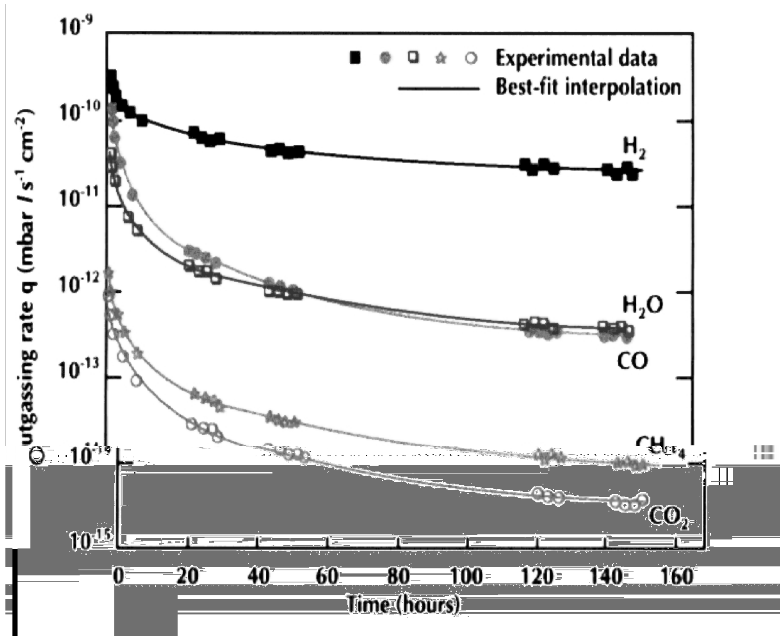

Fig. 2

Al foil outgassing rates over time at 300°C. 350°C Bakeout for 2 hours. [11]

Possible scenarios, occurring in a small volume vacuum device, are displayed in table 2, where the total gas load after 10 years is shown as a function of different initial outgassing rates. Assuming a package with a volume of 0.1 cc, an internal area of 2.4 cm^2 and an initial pressure of 10^{-5} mbar, it is possible to calculate the total gas load after 10 years and the pressure increase inside the device:[12]

Initial outgassing Rate (cc mbar/cm^2)	Gas load after 10 years (cc mbar)	Pressure increase (mbar)
10^{-6}	0.09	0.9
10^{-7}	0.009	0.09
10^{-8}	0.0009	0.009
10^{-9}	0.00009	0.0009

Table 2
Total gas load as a function of different initial outgassing rates.

However, simple leak checking, however sensitive, doesn't allow for diagnosing these mechanisms due to the many potential species and sources involved. It is critical that analytical techniques that can discern the actual species present be utilized, particularly in very small volumes (as has been recently developed by Oneida Research Services.)[13]

PRACTICAL CONSEQUENCES

It is difficult to generate global models to accommodate all of the various factors impacting device life time from a leak. Consider matters from a simple mass flow perspective. Taking guidance from Method 1014, a leak rate of $5x10^{-8}$ atm cc s^{-1} is the maximum acceptable for volumes of 0.01 cm^3 or less. Indeed it is the lowest leak rate mentioned for any volume device in the Method. Compare it with other leak rates for the time to reach 1 atm from a perfect vacuum:

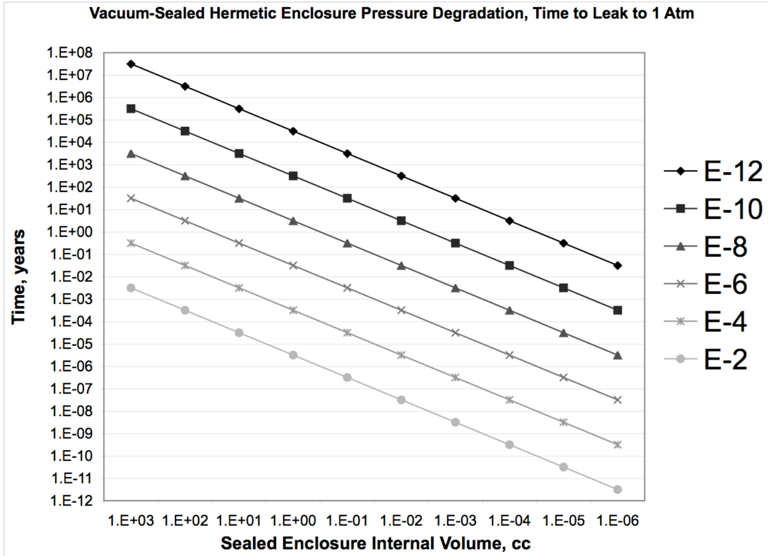

Fig. 3
Time to reach 1 atm from a vacuum for various leak rates and device volumes.

As can be seen, once volumes drop below 0.01 cm^3, simply following the guidance in Method 1014 does not result in practical lifetimes, particularly if operating pressures below 1 atm are to be maintained.

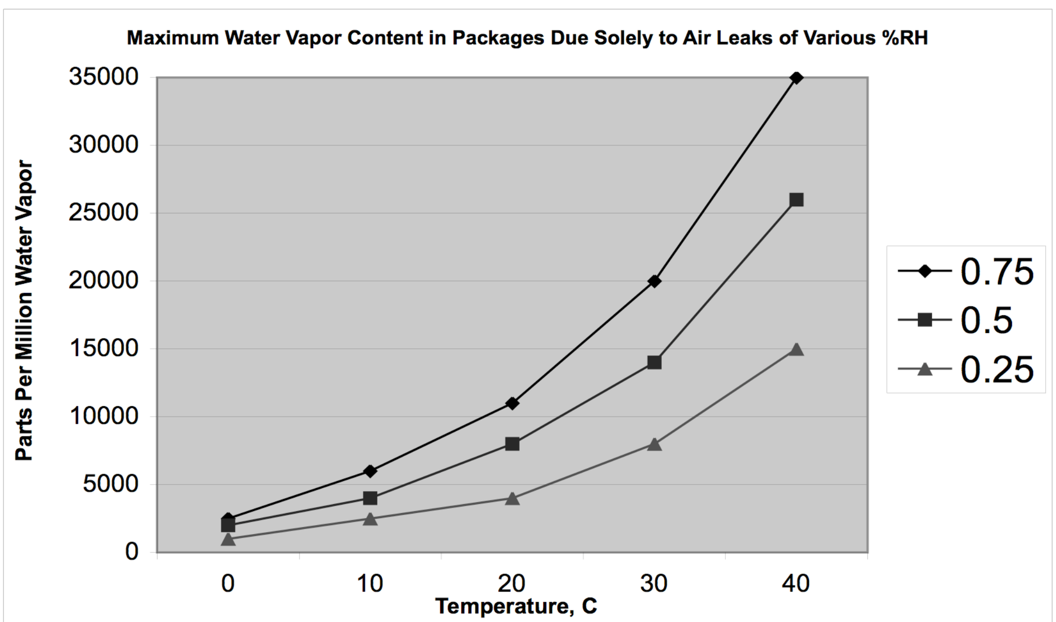

Fig. 4
Where 0.25 = 25% RH, 0.5 = 50% RH and 0.75 = 75% RH.

Figure 4 further emphasizes the importance of M&P for preventing HEAC. For example, at cool temperatures and "nominal" levels of RH, an enclosure will never reach levels of moisture that could cause a threat of corrosion simply by leaking. So controlling moisture sourced from M&P is the only means of preventing HEAC, Where components are sensitive to moisture in other ways, e.g. stiction for MEMs, controlling moisture from M&P to even lower levels becomes even more important.

Pre-existing levels of water vapor at time zero, or building levels of water vapor due to outgassing during lifetime, (either/both caused by poor materials selection and process control) get an enclosure to dangerous conditions sooner, so there is less margin of safety if non-hermeticity is present or develops. The key point is that it is quite possible to engineer and control materials and processes to achieve dry packages at time zero, so as to create the most protection for the package. It is much harder to engineer and control materials and processes to be as certain of leak prevention as of dry initial conditions.

CONCLUSION

Leak rates and leak rate testing are the secondary line of defense against moisture and other gas related problems. The principal line of defense is M&P selection and control. When dry and minimally outgassing enclosure materials are assured at time zero, hermeticity considerations do acquire importance especially for reduced-pressure, low internal volume enclosures with components particularly sensitive to low levels of moisture and HEAC. For relatively large-volume enclosures containing components sensitive primarily to quantities of moisture that cause chemical corrosion or electrical leakage, moisture control via M&P contributes far more to product reliability assurance than leak rate testing in the reduced leak-rate regime.

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