On the applicability of MIL-Spec-based helium fine leak test to packages with sub-micro liter cavity volumes

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Abstract

The MIL-Spec-based helium fine leak test (test condition $A_1$ and test condition $A_2$) is reviewed for its applicability to packages with sub-micro liter cavity volumes. The existing gas conduction models are utilized to investigate the validity of the criteria defined in the test guidelines in terms of true leak rates. The application domains valid under the current guidelines are determined as a function of the internal cavity volume. The results show that the test is valid only for a finite domain of true leak rates when the volume is smaller than $10^{-2}$ cm$^3$ and the invalid domain increases as the cavity volume decreases.

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1. Introduction

Hermeticity of an electronic/MEMS package is a measure of its “leak-proof-ness” and the ability to maintain an acceptable level of stable and sometimes inert ambient for the packaged device. Poor hermeticity can lead to ingress of contaminants, ambient gases and moisture, thereby impacting device reliability. Hermetic sealing is a critical requirement for maintaining a controlled internal environment for the packaged device.

The guidelines specified in Method 1014.11 of the MIL-STD-883F document [1] have been used widely in the industry for hermeticity qualification, typically for packages with cavity volumes larger than those of typical MEMS packages ($<10^{-2}$ cm$^3$). The applicability of these guidelines has been discussed previously by Tao and Malshe [2]. Although the reference discussed the limited applicability of the Mil guidelines to smaller packages, it did not study the applicability of the Howl-Mann equation based test condition $A_2$ (the flexible method). It should be noted that the MIL-STD document specifies that “Flexible Method shall be used unless otherwise specified in the acquisition document, purchase order, or contract.” [1].

The theoretical and practical limits that can be measured by the helium mass spectrometer have been characterized previously [3]. This characterization is used in the present study to analyze the limitations of the MIL-STD guidelines for a helium mass spectrometer based hermeticity testing when they are applied to packages with small internal cavities ($<10^{-2}$ cm$^3$).

2. Background

The MIL-STD specified fine leak detection techniques that are commonly used are:

(a) The optical fine leak test (test condition $C_5$).
(b) The helium fine leak test (test conditions $A_1$ and $A_2$).

2.1. Optical fine leak test (test condition $C_5$)

In the optical fine leak test [3,4] the specimen is placed in a pressure vessel, where it is subjected to an invariant pressure. For a non-hermetic specimen, the pressure differential (i.e., the difference between the applied external pressure and the cavity internal pressure) changes over a period of time. Since the specimen deformation is proportional to the pressure differential, the leak rate can be determined using an analytical relationship between the deformation and the true leak rate. The concept is illustrated schematically in Fig. 1. It should be noted that the maximum value of the applied external pressure is less than or equal to the maximum pressure that the chamber and the specimen can withstand.

Section 3.6.1 of the MIL-STD-883F document [1] specifies the following formula for calculating the maximum allowable thickness of the cap/lid of the specimen.

$$\frac{R^4}{ET} \geq A$$

where $A$ is equal to $1 \times 10^{-4}$ in the limiting case, $R$ is the minimum width of free lid (inside braze or cavity dimension in inches), $E$ is the modulus of elasticity of the lid material in psi and $T$ is lid thickness in inches.
2.2. Helium fine leak test (test conditions A1 and A2)

2.2.1. Hermeticity measurement with a helium mass spectrometer

The definitions pertinent to this test are as follows [1]:

(a) Measured leak rate: The measured leak rate (\( R \)) is defined as the leak rate of a given package as measured under specified conditions and employing a specified test medium. The measured leak rate is also referred to as the apparent leak rate.

(b) Equivalent standard leak rate: The equivalent standard leak rate (\( L_a \)) of a package is defined as the leak rate at the high-pressure side is at 1 atm (760 mmHg absolute) and the low-pressure side is at a pressure of less than 1 mmHg absolute (i.e., \( \approx \) vacuum). The equivalent standard leak rate is also referred to as the true leak rate. It can be regarded as the leak rate normalized for a unit pressure differential.

The conceptual idea of the helium fine leak test is to "bomb" the specimen with helium, i.e., subject it to helium pressurized at a value called the bombing pressure, \( P_0 \), for a period of time, \( t_o \), and then transfer it to a helium mass spectrometer to measure the rate at which helium leaks out. It is to be noted that in this arrangement there is a dwell time, \( t_{dwell} \), between completion of bombing, i.e., when the specimen is taken out of the bombing chamber and start of the measurement of the leak rate. During this time some of the helium escapes from the specimen. In the spectrometer, the specimen is subjected to a vacuum. The helium leaks out and produces a signal proportional to the rate at which it comes out. The leak rate measured by the spectrometer is the measured or apparent leak rate, \( R \), as discussed above. The spectrometer is calibrated to indicate this apparent leak rate directly.

Mathematically, the process can be described by the Howl-Mann equation [6], which has the following form:

\[
R_i = \frac{L_i P_0}{P_t} \left( \frac{M_a}{M_{helium}} \right)^\frac{1}{2} \left( 1 - e^{-\frac{t_o}{t_{dwell}}} \right)^{\frac{1}{2}} e^{\frac{t_o}{t_{dwell}}} \left( \frac{M_a}{M_{helium}} \right)^\frac{1}{2}
\]

where \( M_a = 28.7 \) g and \( M_{helium} = 4 \) g are the molecular weight of air and helium, in grams, respectively; \( P_0 = 1 \) atm is the atmospheric pressure and \( R_i \) is the apparent leak rate at the instant the spectrometer is switched on.

The terms \( 1 - e^{-\frac{t_o}{t_{dwell}}} \left( \frac{M_a}{M_{helium}} \right)^\frac{1}{2} \) and \( e^{\frac{t_o}{t_{dwell}}} \left( \frac{M_a}{M_{helium}} \right)^\frac{1}{2} \) represent the exponential rise and decay in the cavity pressure during the bombing time and the dwell period, respectively [8]. As the specimen continues to leak inside the spectrometer, the apparent leak rate decreases exponentially and is given by the following relationship:

\[
R(t) = R_i \cdot e^{\frac{t_o}{t_{dwell}}} \left( \frac{M_a}{M_{helium}} \right)^\frac{1}{2}
\]

where \( t \) is the time elapsed since the spectrometer is turned on. It is obvious that the apparent leak rate depends on package parameters (\( L_i, V \)) and the test conditions (\( P_0, t_o, t_{dwell} \)). In addition, its value changes continuously during the test, i.e., it varies with the passage of time, \( t \).

2.2.2. Test conditions A1 and A2

The MIL-STD document prescribes two methods for the test; viz. fixed (A1) and flexible (A2) but advocates the use of the latter as the default choice. It should be noted that neither one of these two methods "quantifies" the package leak rate. Rather, they "qualify" it in that they establish that the leak rate is larger or smaller than a specified reject limit.

(a) Fixed method: In the fixed method, the specimen is tested using the appropriate conditions specified in Table 1. The time, \( t_o \), is the time under the bombing pressure and the time, \( t_{dwell} \), is the maximum time that is allowed after release of pressure before the device is tested in the spectrometer. The package is deemed "good" if the apparent leak rate is lower than the reject limit specified based on its internal cavity volume.

(b) Flexible method: In the flexible method, the reject limit is first established in terms of the true air leak rate. This value
Leak rates larger than the detection domain of the gross leak test to address the applicability of the method: fine leak test for smaller volumes. This limits the applicability of the helium to detectable apparent leak rate. However, there are two values of $R_i$ and $R_f$ to be considered:

<table>
<thead>
<tr>
<th>Volume of package ($V$) in cm$^3$</th>
<th>$R_i$ Reject limit (atm-cm$^3$/s He)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;0.05$</td>
<td>$5 \times 10^{-8}$</td>
</tr>
<tr>
<td>$&gt;0.05$–$&lt;0.5$</td>
<td>$1 \times 10^{-7}$</td>
</tr>
<tr>
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<td>$5 \times 10^{-8}$</td>
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<tr>
<td>$&gt;1.0$–$&lt;10.0$</td>
<td>$1 \times 10^{-7}$</td>
</tr>
<tr>
<td>$&gt;10.0$–$&lt;20.0$</td>
<td>$5 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

of “$L_m$” is substituted in the Howl-Mann equation. The user can choose any values for the test parameters $P_b$, $t_b$, and $t_{dwell}$ (the method is called flexible for this reason). The only guideline is that the chosen parameters should produce a measurable signal in the spectrometer. The package is deemed “good” if the apparent leak rate is lower than the value calculated from the Howl-Mann equation using the reject limit as $L_m$. The document specifies certain rejection limits and states that these limits should be used unless otherwise specified [1]. These limits are summarized in Table 2. It should be noted that the “unless otherwise specified” clause specified above provides the user with the option to set up different reject criteria depending on the application.

3. Mil-Spec-based helium fine leak test for smaller volumes

The leak behavior of packages when subjected to the helium fine leak test is investigated for different cavity volumes. The test parameters and the measurement sensitivity of the spectrometer in the analysis include $P_b = 5$ atm, $t_b = 6$ h, $t_{dwell} = 10$ min and $R_{limit} = 10^{-10}$ atm-cm$^3$/s. These values are chosen to be consistent with the requirements of both the test conditions ($A_1$ and $A_2$). Leak rates larger than the detection domain of the gross leak test ($10^{-4}$ atm-cm$^3$/s) are not considered since they are of no practical importance.

Eq. (2) can be used to obtain a plot of $R_i$ versus $L_m$ for a given volume. The plots of $R_i$ versus $L_m$ for three different volumes (0.001 cm$^3$, 0.1 cm$^3$, and 10 cm$^3$) are shown in Fig. 2. For the larger cavity volumes (0.1 cm$^3$ and 10 cm$^3$), there exists one-to-one correspondence between $R_i$ and $L_m$. As the cavity volume decreases, however, there are two values of $L_m$ which can produce the same $R_i$; i.e., the true leak rate cannot be defined uniquely from a measured apparent leak rate. This limits the applicability of the helium fine leak test for smaller volumes.

The following definitions will be used in the following sections to address the applicability of the method:

(a) True pass: good packages that meet the passing criterion.

(b) True fail: bad packages that do not meet the passing criterion.

(c) False pass: bad packages that meet the passing criterion.

(d) False fail: good packages that do not meet the passing criterion.

3.1. Measurable limit (inherent false signal)

The spectrometer measurement limit is defined as the lowest apparent leak rate that the instrument can detect. Superposition of the spectrometer measurement limit, i.e., $R_{limit}$, on the plot of $R_i$ versus $L_m$ yields the range of measurable leak rates [3]. This is schematically illustrated in Fig. 3 where a plot (obtained using
Eq. (2)) of $R_i$ as a function of $L_a$ for a package with volume, $V = 5 \times 10^{-5}$ cm$^3$. Similar plots can be found in the literature [3,4].

It is evident from Fig. 3 that the apparent leak rate, $R_a$, has to be higher than the measurement limit ($R_{\text{lim}}$) of the spectrometer to be able to detect a signal [3]. If the true leak rate is outside of the range established by these limiting values, the measured leak rate will be lower than the measurement limit and will not be detectable at the time of measurement. For the packages with true leak rates higher than the upper limit (region shaded in grey), nearly all the helium bombed into the packages leaks out during the dwell time, while the amount of helium bombed into the package is not sufficient to produce a detectable helium signal for those with true leak rates lower than the lower limit (region shaded in green).

In Ref. [3], the practical upper and lower limits were determined as a function of cavity volume using the spectrometer measurement limit, $R_{\text{lim}}$, as $10^{-10}$ atm-cm$^3$/s. The results are shown in Fig. 4. It is worth noting that the packages with true leak rates higher than the upper limit (region shaded in grey) can contain "False Pass" ones because the apparent leak rate produced by the packages ($\approx 0$) is always lower than the signal that the reject limit can produce regardless of the test conditions. This will be addressed for each test condition below.

### 3.2. Test condition A$_1$

Consider a package with $V = 10^{-3}$ cm$^3$. The reject limit of test condition A$_1$ is $5 \times 10^{-8}$ atm-cm$^3$/s (Table 1). The $R_i$ versus $L_a$ plot and the specified reject limit are shown in Fig. 5. For the specified reject limit, there are two corresponding true leak rates, $L_{a1}$ and $L_{a2}$. For the current example, substituting $R_i = 5 \times 10^{-8}$ atm-cm$^3$/s in Eq. (2) and solving for $L_a$ yields two values: $L_{a1} = 4.32 \times 10^{-9}$ atm-cm$^3$/s, $L_{a2} = 1.03 \times 10^{-7}$ atm-cm$^3$/s. The spectrum of true leak rates in the plot can be divided into the three regions, as shown in Fig. 5.

Packages with leak rates in Region I ($L_a < L_{a1}$) and Region II ($L_{a1} < L_a < L_{a2}$) fall into the categories of True Pass and True Fail, respectively. Region III ($L_a > L_{a2}$) represents False Pass. The apparent leak rate of Region III is lower than the specified reject limit but the true leak rate of Region III is actually higher than that of True Fail packages (Region II). As mentioned earlier, the helium bombed into the specimen leaks out significantly during the dwell time due to the high true leak rate, and hence the apparent leak rate becomes lower than the specified reject limit.

Region II can be detected without any ambiguity since a true leak in Region II produces an apparent leak rate higher than the specified reject limit. However, true leak rates in both Regions I and III produce apparent leak rates lower than the specified reject limit and are not distinguishable from each other. For larger volumes that exhibit the one to one correspondence between $R_i$ and $L_a$, only two regions (Regions I and II) exist, which can be easily distinguishable by comparing the apparent leak rate with the specified reject limit.

### 3.3. Test condition A$_2$

Test condition A$_2$ uses the true leak rate as the rejection criterion. The package is True Pass if the true leak rate of the package is lower than the specified reject limit ($L_{c}$). Since the true leak rate is not directly measured, the value of $R_i$ corresponding to the rejection criterion (will be referred to as $R_{i,c}$) is first determined using Eq. (2) and the condition for True Pass and Fail can be established if the measured apparent leak rate, $R_a$, is lower or higher than $R_c$.

The same problem seen in test condition A$_1$ exists due to the loss of the one-to-one correspondence. The value of $R_i$ corresponding to the rejection criterion uniquely exists but one more value of true leak rate will exist if the one-to-one correspondence is lost; this true leak rate will be referred to as$\tilde{L}_c$. Two false signals are possible depending upon whether or not the rejection criterion is higher or lower than the conjugate rate. They are illustrated in Figs. 6 and 7, where the arrows indicate the sequence of calculations.

Cuse 1 ($L_a < L_{c1}$): Consider a package with $V = 10^{-3}$ cm$^3$. The specified reject limit for the package is $L_{c1} = 5 \times 10^{-8}$ atm-cm$^3$/s (Table 2). The Howl-Mann equation (Eq. (2)) yields $R_i = 5.84 \times 10^{-9}$ atm-cm$^3$/s. Substituting $R_i = 5.84 \times 10^{-9}$ atm-cm$^3$/s in Eq. (2) and solving for $L_a$ yields the conjugate true leak rate $L_{c2} = 2.52 \times 10^{-6}$ atm-cm$^3$/s.

The entire $R_i$ versus $L_a$ plot for Case 1 is shown in Fig. 6, which is similar to Fig. 5. Like test condition A$_1$, packages with leak rates in Region I ($L_a < L_{c1}$) and Region II ($L_{c1} < L_a < L_{c2}$) fall into the category of True Pass and True Fail, respectively. Region III ($L_a > L_{c2}$) represents False Pass packages as the apparent leak rate of Region III is lower than $R_{i,c}$.
Fig. 6. $R_i$ as a function of $L_i$ for a cavity volume of $10^{-3}$ cm$^3$; the reject criterion of test condition $A_1$ ($L_i = 5 \times 10^{-8}$ cm$^3$) produces $R_i = 5.84 \times 10^{-5}$ atm-cm$^3$/s and $L_i = 2.52 \times 10^{-11}$ atm-cm$^3$/s.

Fig. 7. $R_i$ as a function of $L_i$ for a cavity volume of $10^{-3}$ cm$^3$; the reject criterion of test condition $A_2$ ($L_i = 5 \times 10^{-8}$ cm$^3$) produces $R_i = 2.16 \times 10^{-10}$ atm-cm$^3$/s and $L_i = 5.74 \times 10^{-11}$ atm-cm$^3$/s.

It should be noted that any further testing using a gross leak test, which can only measure leak rates of $10^{-4}$ atm-cm$^3$/s and higher [7], will not be able to detect these False Pass packages.

Case 2 ($L_r > L_c$): Let’s consider a package with $V = 10^{-2}$ cm$^3$. The specified reject limit for this volume is also $L_r = 5 \times 10^{-8}$ cm$^3$ (Table 2). The Howl-Mann equation (Eq. (2)) yields $R_i = 2.16 \times 10^{-10}$ atm-cm$^3$/s. Substituting $R_i = 2.16 \times 10^{-10}$ atm-cm$^3$/s in Eq. (2) and solving for $L_r$ yields the conjugate true leak rate $L_r = 5.74 \times 10^{-11}$ atm-cm$^3$/s.

The entire $R_i$ versus $L_i$ plot for Case 2 is shown in Fig. 7. As in Case 1, Region I ($L_r > L_c$) includes the True Pass packages and Region III ($L_r < L_c$) includes the False Pass ones. The packages with true leak rates within Region II ($L_c < L_r < L_c$) also produce $R_i$ larger than $R_i$. According to the test criterion, these parts should be rejected. However, these packages are “False Fail” because their true leak rates are lower than the reject limit.

4. Domain of applicability

The theory discussed above was used to generate the applicable domain of test conditions $A_1$ and $A_2$ prescribed in Method 1014.11 of the MIL-STD-883-F document. The results are shown in Figs. 8 and 9 for test conditions $A_1$ and $A_2$, respectively, where the domains of true leak rate, corresponding to the four definitions (True Pass, True Fail, False Pass and False Fail), are plotted as a function of the internal cavity volume.

Since the reject limit ($5 \times 10^{-8}$ atm-cm$^3$/s for the given range of volumes) for test condition $A_1$ is in terms of the measured leak rate (Table 1), this reject limit was converted into an equivalent true leak rate by using Eq. (2). It should be noted that solving Eq. (2) yields two roots, i.e., the two true leak rate values corresponding to the published reject limit.1 In Fig. 8, the lower one of these two values is plotted as the reject limit. The inflexion at $V = 10^{-2}$ cm$^3$ in Fig. 8 implies that the equivalent true leak rate based reject limit attains a minimum value at that point.

The practical upper limit of the helium fine leak test is also shown in Figs. 8 and 9. Physically, these plots depict how the range of true leak rates is divided into different domains by (1) the measurement sensitivity of the spectrometer that imposes an upper limit of true leak rate and (2) the reject limit imposed by the relevant MIL-Spec guideline. In these plots, the False Pass due to the spectrometer sensitivity domain implies that for a very leaky package the measured signal will be below the measurement sensitivity of the spectrometer and hence undetectable.

For both test conditions, the cavity volumes larger than $10^{-2}$ cm$^3$ do not produce any false signal. The domain for False Pass first takes place when the cavity volume becomes $10^{-2}$ cm$^3$ and increases as the cavity volume decreases.

It should be noted that test condition $A_1$ will not be valid for volumes less than $1.65 \times 10^{-3}$ cm$^3$ because the signal produced by the spectrometer will always be lower than the reject limit, $R = 5 \times 10^{-8}$ atm-cm$^3$/s, regardless of the true leak rate of the pack-

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1 Graphically, this is similar to plotting an $R_i$ versus $L_i$ plot for each of the considered volumes (similar to Fig. 3) and locating the points at which it intersects with the line $R = 5 \times 10^{-8}$ atm-cm$^3$/s.
The case of $1.65 \times 10^{-5}$ cm$^3$ is shown in Fig. 10. It is also worth noting that False Fail signal occurs only with test condition $A_2$ when the cavity volumes become smaller than $10^{-2}$ cm$^3$.

5. Discussion: constant reject limit of condition $A_2$

It is instructive to examine the validity of the constant reject limit of test condition $A_2$ for the internal cavity volume smaller than $10^{-2}$ cm$^3$. There is an inherent flaw in the constant reject limit in that as volumes get smaller, hermeticity requirement should become more stringent. The critical parameter in evaluating the effect of the ingress of a gas into the package is not the absolute amount of gas but the partial pressure (or concentration). The same amount of gas will produce a lower partial pressure in a larger package, and thus less detrimental.

If the package is initially at vacuum, the pressure inside the package at time $t$ when it is exposed to an ambient pressure of $P_b$ is:

$$p_t = P_b (1 - e^{-L_t/V_P})$$

It is evident from Eq. (4) that the pressure build-up over a fixed period of time$^2$ will be the same for different packages as long as the $L_t/V$ ratio is constant. As mentioned earlier, the MIL-STD document states that test condition $A_2$ is flexible in that it allows the user to set a different reject limit. For the cavity volumes smaller than $10^{-2}$ cm$^3$, a variable reject limit that takes the constant partial pressure into account is proposed as a more realistic reject limit.

Table 3

<table>
<thead>
<tr>
<th>Volume (cm$^3$)</th>
<th>Reject limit (atm-cm$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$</td>
<td>$5 \times 10^{-11}$</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>$5 \times 10^{-10}$</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>$5 \times 10^{-9}$</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>$5 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Fig. 9. Domain of leak qualification of test condition $A_2$ for the test parameters of $P_b = 5$ atm, $t_b = 6$ h, $t_{dwell} = 10$ min.

Fig. 10. Illustration of inherent invalidity of test condition $A_1$ for the volumes smaller than $1.65 \times 10^{-5}$ cm$^3$; the plot shows that the spectrometer signal of the package with $V = 1.65 \times 10^{-5}$ cm$^3$ is always lower than the reject limit regardless of the true leak rate.

Fig. 11. Domain of leak qualification of test condition $A_2$ using the variable reject limits.
The reject limit of the existing criterion for \( V = 0.01 \text{ cm}^3 \) is \( L_a = \frac{5}{C^2} \times 10^{\frac{8}{C_0}} \text{ atm-cm}^3/\text{s} \) (Table 2), which yields the \( L_a/V \) ratio of \( 5 \times 10^{-6} \). The reject limit \( (L_a) \) for each volume \( (V) \) can be adjusted to produce the constant value of \( L_a/V \) ratio. These values are summarized in Table 3.

These modified limits were used to recalculate the domain of leak qualification. The results are plotted in Fig. 11a. A significant enhancement of the domain of leak qualification is evident. Yet a small region of False Pass due to the reject limit exists.

This False Pass region can be eliminated if the suggested variable reject limit is further adjusted to make it equal to the lower limit of the measurable range for that particular volume. These modified limits are tabulated in Table 4 and the corresponding domain of leak qualification is depicted in Fig. 11b.

It should be noted that these are only examples of how the limits for test condition \( A_2 \) can be modified. No matter how the reject limits are set, the inherent False Pass due to the spectrometer measurement sensitivity cannot be eliminated. In practice, it would be imperative to develop limits in tune with the performance requirements of the packages under consideration while increasing the measurement sensitivity of the spectrometer in order to increase the range of the measurable true leak rates for a given cavity volume.

## Table 4

<table>
<thead>
<tr>
<th>Volume (cm(^3))</th>
<th>Reject limit (atm-cm(^3)/s)</th>
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</thead>
<tbody>
<tr>
<td>( 10^{-5} )</td>
<td>( 3.80 \times 10^{-11} )</td>
</tr>
<tr>
<td>( 10^{-4} )</td>
<td>( 1.15 \times 10^{-10} )</td>
</tr>
<tr>
<td>( 10^{-3} )</td>
<td>( 3.61 \times 10^{-10} )</td>
</tr>
<tr>
<td>( 10^{-2} )</td>
<td>( 1.13 \times 10^{-9} )</td>
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### 6. Conclusion

The guidelines specified in Method 1014.11 of MIL-STD-883-F for the optical interferometry and helium mass spectrometer based fine leak tests (test conditions \( C_5 \) and \( A_1 \) and \( A_2 \)) were reviewed. The existing gas conduction models were utilized to investigate the validity of the criteria defined in the test guidelines in term of true leak rates for their applicability to the packages with sub-micro liter cavity volumes. The results showed that only finite domain of true leak rates is valid when the volume is smaller than \( 10^{-2} \text{ cm}^3 \) and the invalid domain increases as the cavity volume decreases. The analytical framework was used to suggest the variable reject limits for test condition \( A_2 \) to extend its domain of applicability.

### References


