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U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Semiconductor Measurement Technology:

Graphical Solution for the Helium Leak Detector and Radioisotope Methods of Hermetic Test

Master Graphs and Instructions

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Master Graphs and Instructions

Stanley Ruthberg

Center for Electronics and Electrical Engineering
National Engineering Laboratory
National Bureau of Standards
Washington, DC 20234

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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Master Graphs and Instructions

Stanley Ruthberg
Semiconductor Materials and Processes Division
National Bureau of Standards
Washington, DC 20234

A graphical procedure for solution of the molecular flow approximation for the back pressurization method of hermetic test makes use of a set of characteristic curves and a test line. The characteristic curves are appropriate for both the helium leak detector and the radioisotope methods of test, although the form of the test line differs between the two methods. Master graphs of the characteristic curves and test lines are now provided in a scale and format appropriate for producing suitable worksheets with a copier. Step-by-step instructions are given for their use in obtaining solutions for various examples relative to the test specifications in acceptance standards such as MIL-STD 883B, etc. One set of characteristics is provided specifically for the helium leak detector mode as expressed directly in terms of air leak rate; a second set is provided specifically for the krypton-85 radioisotope mode also in terms of air leak rate; and a third set is retained in the original form for use with any tracer gas.

Key words: back pressurization; electronic packages; hermetic test; leak testing.

I. INTRODUCTION

Both the helium and the radioisotope leak test methods for hermetically sealed electronic packages are examples of the back pressurization procedure. This procedure involves forcing a tracer gas (or liquid) into the package interior and then measuring the quantity of gas that has penetrated through an existing leak. With helium as the tracer gas, measurement is made by extracting the gas back through the leak into a helium mass spectrometer leak detector; with radioisotope krypton-85 as the tracer, an external gamma counter determines the activity of the gas remaining in the interior. Neither technique gives the true leak size directly; rather, both require a knowledge of the gas flow mechanism and the use of appropriate mathematical models. Since the gas transport mechanism for leaks over the range of practical interest is complex and is not amenable to direct analytical solution, a number of simplifying flow models have to be used.

Traditionally, the helium leak test method has been quantified by a molecular flow model [1], and the test parameters set forth in such acceptance standards as MIL-STD 883, MIL-STD 750, NASA Certification Requirements, ASTM Standards, and others have been so derived [2-6]. Nevertheless, the relationship between the measured leak rate and the leak size is transcendental so that a numerical solution is necessary. On the other hand, the radioisotope method has usually been modeled by a laminar viscous flow approximation, which in principle is relevant to the larger leak sizes [2-8]. While such modeling leads to a simple relationship between count rate and leak size, the correlation of the results between the two methods is obscured. Furthermore, the test parametric values set forth in MIL-STDs 883 and 750 for the radioisotope method were not derived from flow models, but were established empirically through comparison of test results to those obtained using the helium leak detector method [9].

In a previous publication [10], a general solution to the molecular flow equation for the back pressurization method of hermetic testing was formulated into a normalized set of characteristic curves. Using these curves, a simple graphical procedure is followed to obtain quick and adequately precise solutions of the molecular flow fomulation for any particular set of test conditions and to provide a basis for comparing the results from both test methods. For this graphical procedure only a single set of characteristic curves is required along with the use of a test line. The curves and procedure are appropriate for both methods, although the form of the test line is different for the two methods. All test parameters are readily obtained for any package volume and leak test range, and the effect on test results due to a change in parameters is easily found.

The purposes of this publication are: (1) to provide master graphs of the characteristic curves and test lines from which worksheets can be made by photocopying, (2) to put the solutions directly in terms of air leak rate, and (3) to provide a manual of step-by-step instructions for obtaining leak test solutions. The detailed derivations and explanations of the graphical procedure are found in reference [10] (Appendix A).

II. Helium Leak Detector Method

A. Test Factors

Solutions for the helium leak detector method are found as intersections between appropriate test lines and the characteristic curves describing the interior gas pressure, as shown in figure 1 (also master graph 1). The internal fractional helium pressure, E, is a measure of the interior helium pressure per atmosphere of external pressurization at any elapsed time, t, after pressurization of the sealed packages in helium for a period of time, T, and is given by:

$$E = \frac{1}{P_0} \left[1 - \exp\left(-R_r T\right)\right] \exp\left(-R_r t\right) \tag{1}$$

in which R_r, the relaxation rate for helium, is related to that for air as

$$R_r = 2.69\ R_r^a \ . \tag{2}$$

The relaxation rate for air, R_r^a, defines the ratio of leak size and package interior free volume as

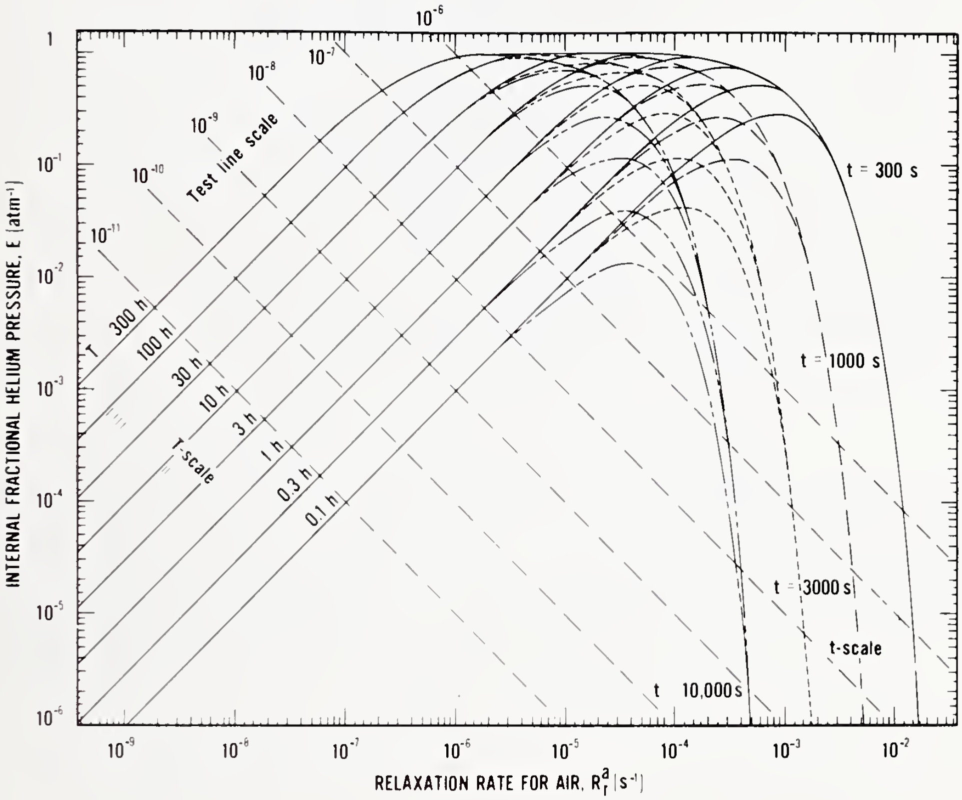


Figure 1. Characteristics and test lines for the helium leak detector method. E, the relative partial pressure of helium within the package per atmosphere of external helium pressurization, as a function of the relaxation rate for air R_r^a with pressurization time T and dwell time t as parameters. Test lines are at -45 deg and correspond to $E \cdot R_r^a$ = const. Intermediate values for test lines, for T, and for t are indicated by the scale for each. Tick marks include those at 1.25, 1.5, 1.75, and 2.5 with the remainder at integral values for each decade on the axes for $E \cdot R_r^a$, for T, and for t. Use master graph 1 for photocopying.

$$R_r^a = \frac{L_a}{P_0 V} . \qquad (3)$$

The test lines drawn in with a slope of minus one (-45 deg) on the log E-log R_r^a plane represent constant values of the product $E \cdot R_r^a$. The equation for these lines, and the formalized solution of the molecular flow model, is

$$E \cdot R_r^a = \frac{R}{2.69\ P_0 V P_E} . \qquad (4)$$

The requisite quantities are as follows:

L_a is the standard leak rate for air, or the leak size*
V is the package interior free volume
P_0 is one standard atmosphere (1.01325×10^5 Pa, ~ 14.7 psi)
P_E is the absolute pressurization value of helium
R is the leak detector response
T is the time interval of pressurization
t is the dwell time or that elapsed from the end of pressurization to detection.

In figure 1 test lines are included at values for $E \cdot R_r^a$ corresponding to each decade from 10^{-6} to 10^{-11} $s^{-1} \cdot atm^{-1}$. Lines at intermediate values can be obtained with the aid of the test line scale. Characteristic curves for E in the positive slope region at the left in figure 1 are indicated for pressurization times T in multiples of 1 and 3; intermediate values can be obtained with the T-scale. The characteristic curves are merged to a fewer number in the negative slope region with t as the significant parameter. The t-scale can be used for intermediate values.

B. Graphical Procedure

1. Unknown Leak Size

Conditions

Given:	pressurization value	P_E (in atm abs, helium)
	pressurization time	T (h)
	dwell time	t (s)
	leak detector response†	R ($atm \cdot cm^3/s$, helium)
	package free volume	V (cm^3)
Find:	leak size	L_a ($atm \cdot cm^3/s$)

* By definition the standard leak rate L for a given gas is that flow rate obtained with 1 atm of gas pressure upstream to the leak channel and zero pressure downstream.

† R is an above background value; use values large compared to background or correct for background.

Procedure

a. Compute $R/[2.69\ P_0VP_E]$. This is the value of the test line. Construct this line on the worksheet parallel to those given using the test line scale.
b. Find the two intersections of the test line with the characteristic curve of E for the given value of T and t.
If that E is not included in figure 1, construct a line parallel to those given passing through the required value of T on the T-scale (similarly for t).
c. Drop vertical lines through the points of intersection to the R_r^a axis.
Read values of R_r^a at the axis.
d. Compute L_a as $R_r^a\ P_0V$. These are the two possible leak values.

Example - See figure 2.

Let P_E = 5 atm helium, T = 0.3 h, t = 3000 s, R = 5×10^{-9} atm•cm^3/s for helium, V = 0.01 cm^3. Find two possible values of L_a.

a. $R/2.69\ P_0VP_E = 3.7 \times 10^{-8}$. See test line a.
b. The intersections are within the circled domains.
c. See lines b and c. $R_r^a = 3.8 \times 10^{-6}\ s^{-1}$ and $1.3 \times 10^{-3}\ s^{-1}$.
d. $L_a = 3.8 \times 10^{-8}$ atm•cm^3/s or 1.3×10^{-5} atm•cm^3/s.

2. Selection of test parameters: Pressurization time and maximum detectable leak.

Conditions

Given:	package free volume	V
	reject level (all leaks ≥)	L_a
	dwell time	t
	response	R
	pressurization value	P_E
Find:	pressurization time	T
	maximum detectable leak	L_a(max)

Procedure

a. Compute R_r^a by (3)
Draw a vertical line at that value.
b. Compute $R/[2.69\ P_0VP_E]$.
Construct this test line parallel to those given using the included scale if necessary.
c. Locate the intersection of the test line and the R_r^a line.
Find the value of T for the E-characteristic curve passing through this point. This is the pressurization value. If the E-curve is not included in figure 1 (or master graph 1), pass a line through the intersection parallel to those represented and extend it to the T-scale.

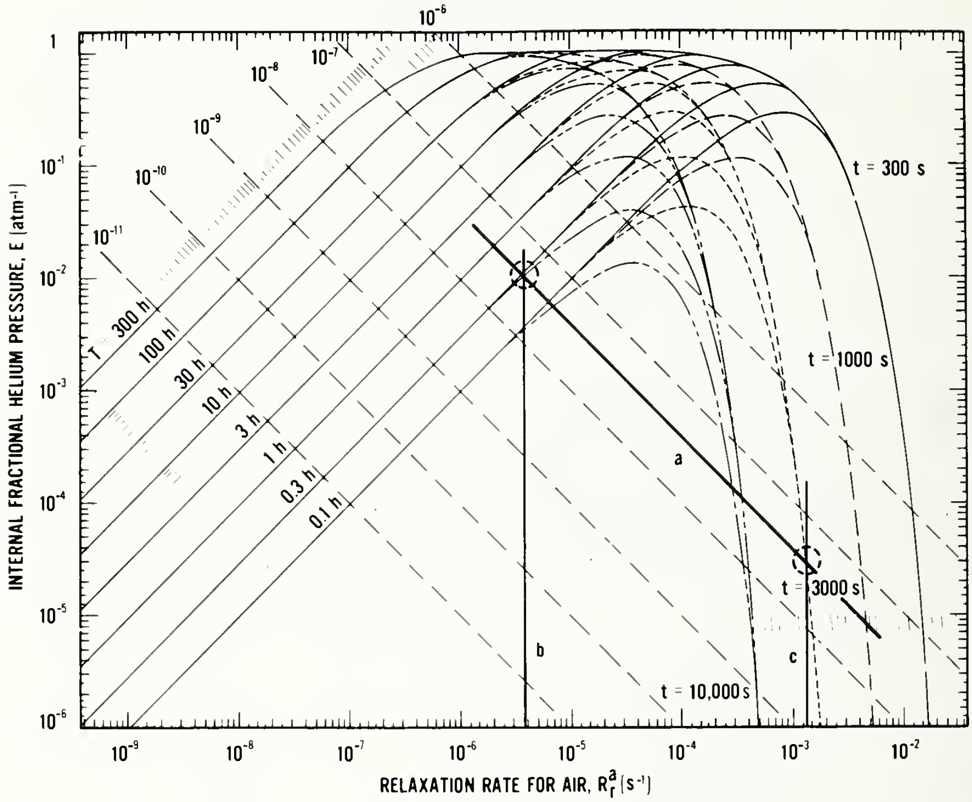


Figure 2. The graphical procedure for determining leak size with the helium test method from the leak detector indicated response for given conditions of P_E, T, t, and V. See example 1 of Section II. a - test line. b - first solution for R_r^a and hence the smaller possible value for L_a. c - second solution for R_r^a and hence the larger possible value for L_a.

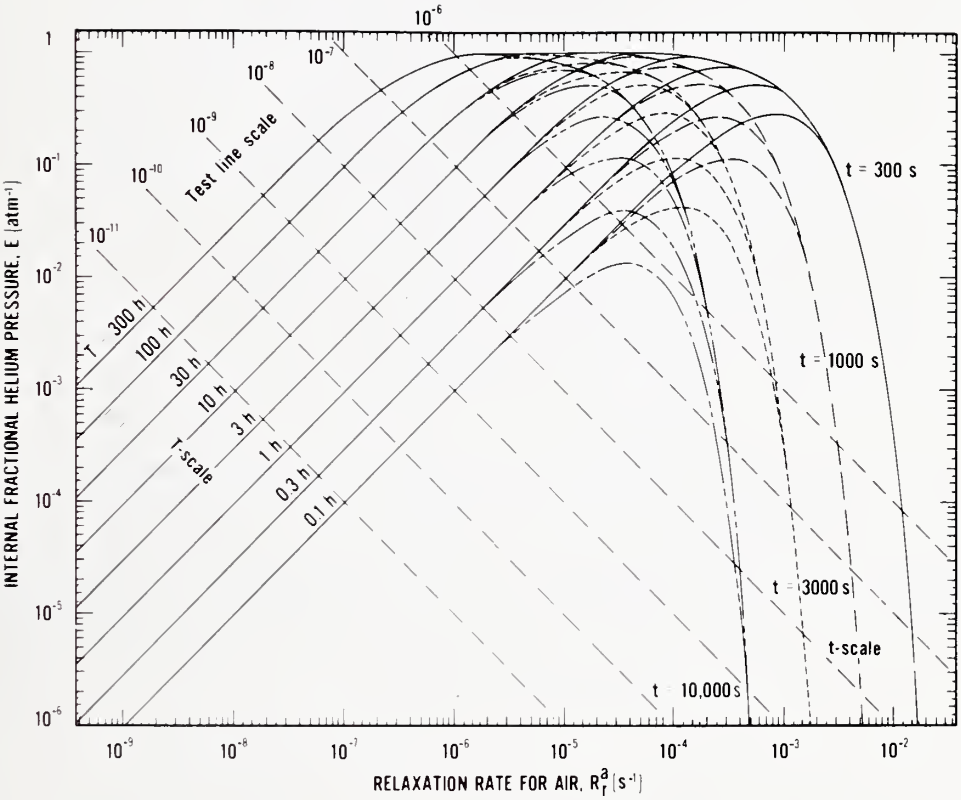
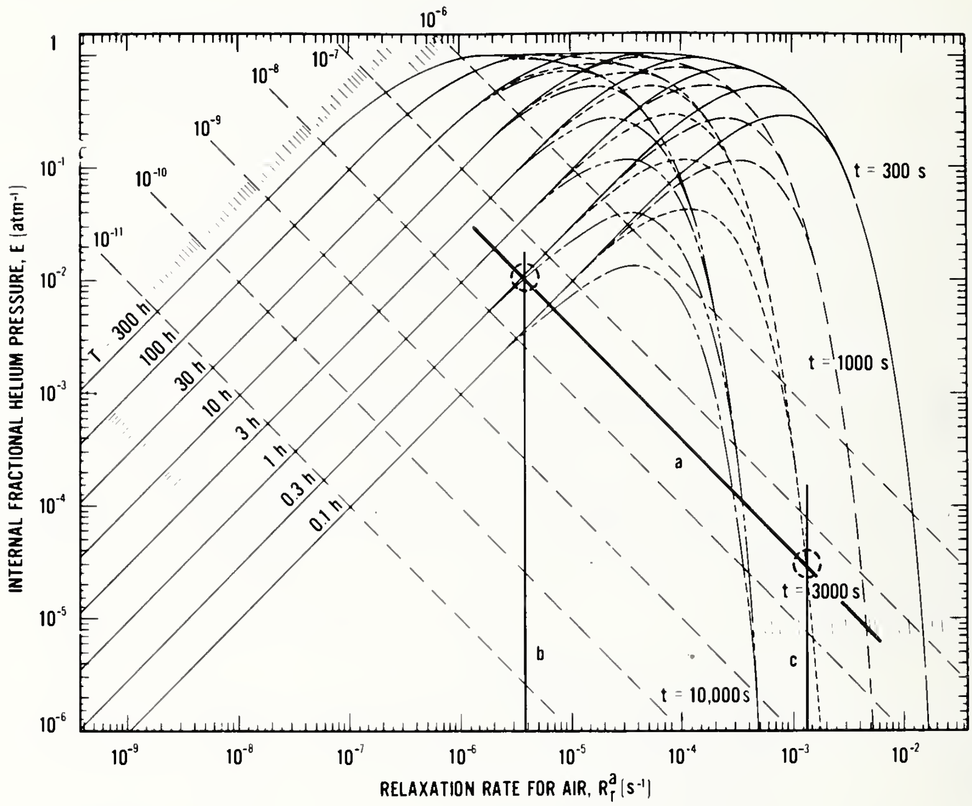


Figure 1. Characteristics and test lines for the helium leak detector method. E, the relative partial pressure of helium within the package per atmosphere of external helium pressurization, as a function of the relaxation rate for air R_r^a with pressurization time T and dwell time t as parameters. Test lines are at -45 deg and correspond to $E \cdot R_r^a$ = const. Intermediate values for test lines, for T, and for t are indicated by the scale for each. Tick marks include those at 1.25, 1.5, 1.75, and 2.5 with the remainder at integral values for each decade on the axes for $E \cdot R_r^a$, for T, and for t. Use master graph 1 for photocopying.



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d. Locate the intersection of the test line and the negative slope portion of the E-characteristic curve for the given value of t.
   Drop a vertical line to the R_r^a axis.
   Compute $L_a(max)$ from (3).

3. Selection of test parameters: Maximum allowable dwell time and pressurization value.

Conditions

Given:	upper leak limit required	$L_a(max)$
	package free volume	V
	leak detector response	R
Find:	maximum allowable dwell time	t
	pressurization value	P_E

Procedure

a. Compute $R_r^a(max)$ as $L_a(max)/P_0V$.
   Draw a vertical line through this value.
b. The $R_r^a(max)$-line intersects characteristics corresponding to a range of values of t. The information given is not definitive; therefore, some choice is allowed.
   Select a point on the $R_r^a(max)$-line which corresponds to a practical value for t.
c. Erect a test line through this point at -45 deg.
   Determine the test line value from the scale. Let this be α.
d. Compute $P_E = R/2.69\ P_0V\alpha$ from (4).
e. If the values for P_E and t are practical, then P_E becomes the pressurization value and t is the maximum dwell time allowed in order for the test range to include $L_a(max)$ for all parts tested.
   If P_E is not usable, adjust the value for t and/or the test line until satisfactory values are obtained.

4. Selection of test parameters: Minimum and maximum leak size limits as a function of pressurization time.

Conditions

This is a general case that applies to all packages independent of specific conditions.

Procedure

a. Choose any test line and mark the intersection with an E-characteristic curve for some value of T, e.g., test line (a) in figure 2.
   Drop a vertical line to the R_r^a axis, e.g., line (b) in figure 2.
b. Proceed up the test line to a second value of T, which is two decades greater than T_1.

Drop a vertical to the R_r^a axis.
Note that R_r^a has decreased by one decade; i.e., R_r^a changes as $-T^{1/2}$.

c. Follow the test line to the negative slope portion of the E-characteristic curve.
Note that the E-characteristic curves converge in this region, and the dependence on the pressurization time T vanishes. The dwell time t is the major factor for the determination of maximum leak size.

5. Leak Detector Response

Conditions

Given:	leak size reject value	L_a (atm•cm^3/s)
	pressurization time	T (h)
	pressurization value	P_E (atm)
	package free volume	V (cm^3)
Find:	leak detector response	R (atm•cm^3/s)

Procedure

a. Compute R_r^a by (3). Draw a vertical line at this value.
b. Locate the intersection of the R_r^a-line with the E-curve corresponding to the given T value. If that curve is not included in the representation, construct one parallel to those given and passing through the given value on the T-scale.
Read off the value of E corresponding to the intersection.
c. Compute $R = R_r^a \cdot E/P_0 V P_E$.

III. Radioisotope Hermetic Test Method

A. Test Factors

Although the molecular flow model is not normally employed for the radioisotope procedure, it is the appropriate model for fine leaks and for correlation of this test method with the helium leak detector method. Since detection in the radioisotope method is accomplished using the gas which still resides within the package, without resorting to extraction back through the leak channel, the graphical solution procedure is simplified.

Solutions for the radioisotope method require only the set of characteristics shown in figure 3 (and master graph 2). The internal fractional krypton-85 pressure, E*, represents the interior gas concentration at any time, t, after pressurization of the parts in krypton-85/nitrogen for a period of time, T. Test lines for this method are now horizontal straight lines with numerical values of E*. However, practical operational conditions tend to raise the test line into the nonlinear region of the E*-characteristic curves. The formalized solution is given by

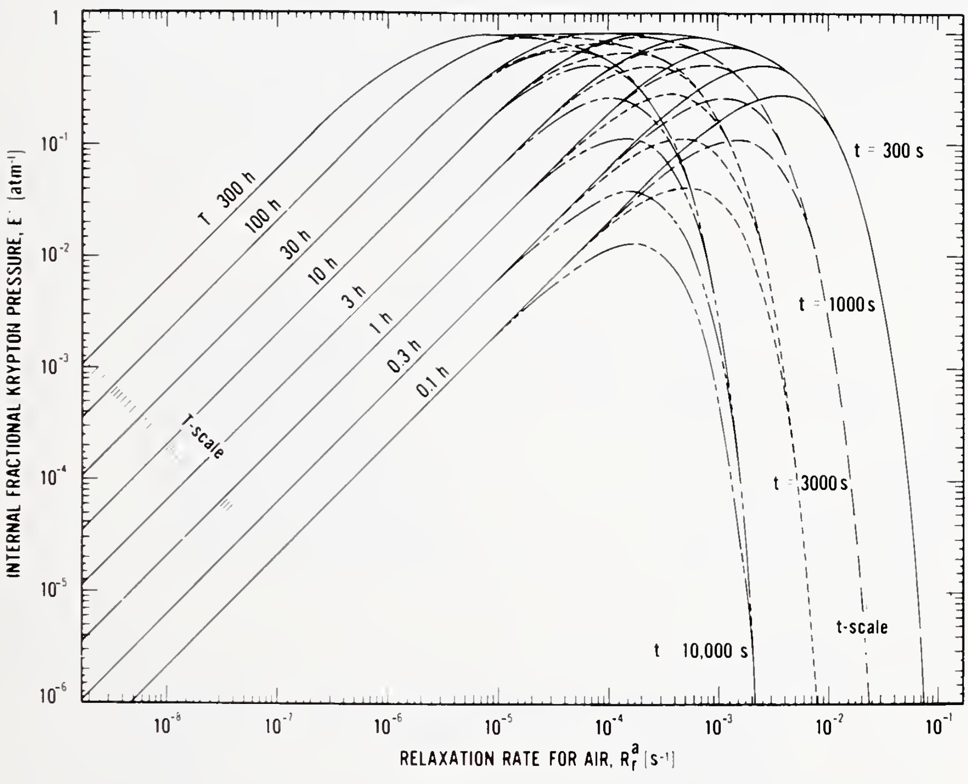

Figure 3. Characteristics for the krypton-85 radioisotope method. E^*, the relative partial pressure of krypton within the package per atmosphere of external krypton pressurization, as a function of the relaxation rate for air R_r^a with pressurization time T and dwell time t as parameters. Tick marks include those at 1.25, 1.5, 1.75, and 2.5 with the remainder at integral values for each decade on the axes, for T, and for t. Test lines are not included since these are easily constructed as horizontal lines at values for E^* = const. Use master graph 2 for photocopying.

$$E^* = \frac{R^*}{P_0 VSKP_E^*} \quad (5)$$

where

V is the package free volume
P_0 is one standard atmosphere
P_E^* is the absolute pressurization value for the Kr^{85}-N_2 gas mixture
R^* is the gamma count rate above background
S is the specific activity of the gas mixture
K is the overall counting efficiency

and the relaxation rate R_r^* for krypton-85 is

$$R_r^* = R_r^a/1.71 \quad (6)$$

for

$$L_a = 1.71\ L_{krypton} \quad (7)$$

where R_r^a is the relaxation rate for air, eq (3), and L_a is the leak size for air.

B. Graphical Procedure

1. Unknown Leak Size

Conditions

Given:	pressurization value	P_E^* (atm abs)
	pressurization time	T (h)
	dwell time	t (s)
	count rate	R^* (min^{-1})
	package free volume	V (cm^3)
	specific activity	S ($\mu Ci/atm \cdot cm^3$)
	counting efficiency	K ($min^{-1} \cdot \mu Ci^{-1}$)
Find:	leak size	L_a ($atm \cdot cm^3/s$)

Procedure

a. Calculate $E^* = R^*/[P_0 VP_E^* SK]$.
Draw a horizontal line at that value of E^*.
b. Locate the point of intersection with the E^* characteristic corresponding to the given value of T.
Drop a vertical line to the R_r^a axis. Read off R_r^a.
Calculate $L_a = P_0 VR_r^a$. This is one possible value.
c. Repeat b for the given value of t. This is the second possible value.

Example - See figure 4.

Let $P_E^* = 5$ atm, $T = 0.3$ h, $t = 3000$ s, $R^* = 1000\ \mathrm{min}^{-1}$, $V = 0.01\ \mathrm{cm}^3$, $S = 200\ \mu\mathrm{Ci/atm{\cdot}cm}^3$, and $K = 10^4\ \mathrm{min}^{-1}{\cdot}\mu\mathrm{Ci}^{-1}$. Find possible values for L_a.

a. $E^* = R^*/P_0VP_E^*SK = 10^{-2}\ \mathrm{atm}^{-1}$. See test line a.
b. See the circled domain at T = 0.3 h characteristic. See line b.
$R_r^a = 1.6 \times 10^{-5}\ \mathrm{s}^{-1}$.
$L_a = 1.6 \times 10^{-7}\ \mathrm{atm{\cdot}cm^3/s}$.
c. See line c.
$R_r^a = 2.5 \times 10^{-3}\ \mathrm{s}^{-1}$.
$L_a = 2.5 \times 10^{-5}\ \mathrm{atm{\cdot}cm^3/s}$.

2. Selection of test parameters: Pressurization time and maximum detectable leak.

Conditions

Given:	pressurization value	P_E^*
	dwell time	t
	count rate	R^*
	package volume	V
	reject level	L_a
	specific activity	S
	counting efficiency	K
Find:	pressurization time	T
	maximum detectable leak	L_a(max)

Procedure

a. Calculate $E^* = R^*/[P_0VP_E^*SK]$. Draw the horizontal test line at that value.
b. Calculate $R_r^a = L_a/P_0V$. Draw a vertical line at that value.
c. Locate the intersection of the two lines, E^* and R_r^a.
Find the value of T corresponding to the E-characteristic curve passing through this point. This is the pressurization value. If the E-characteristic curve is not included in figure 2, pass a line through the point of intersection parallel to the E-characteristic curve and extend to the T-scale.
d. Extend the horizontal test line to the negative slope region of the characteristic curves until it intersects with that curve corresponding to the given value of t.
Drop a vertical line to the R_r^a axis.
Compute L_a from (3). This is L_a(max).

3. Selection of test parameters: Maximum allowable dwell time and pressurization value.

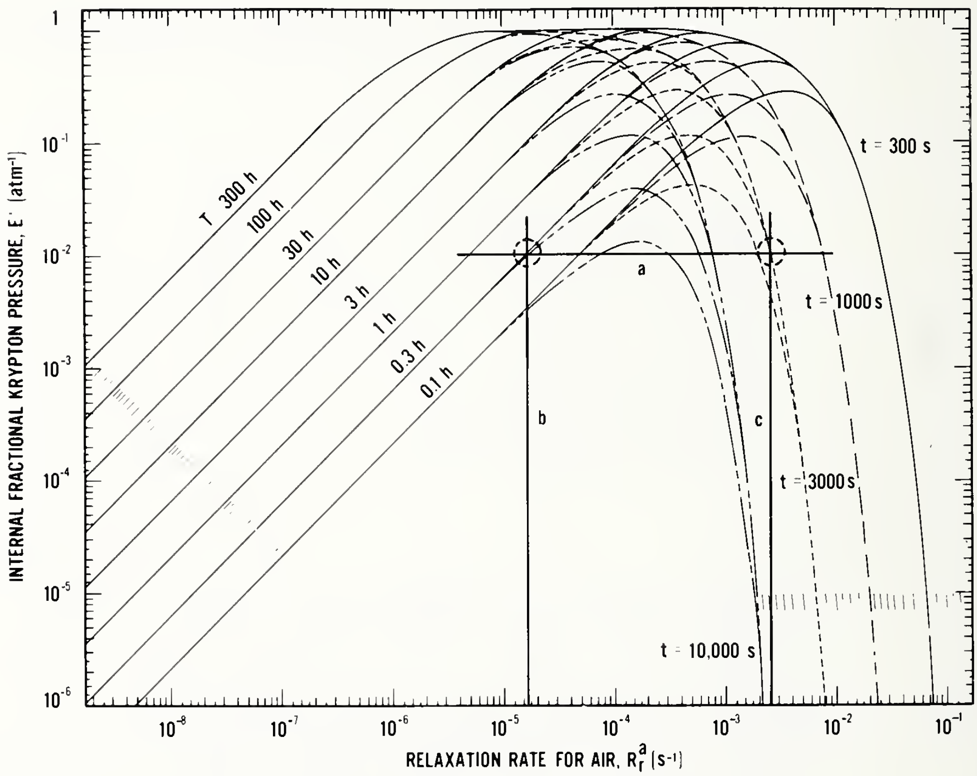

Figure 4. The graphical procedure for determining leak size with the radioisotope test method from the gamma count rate for given conditions of P_E^*, T, t, and V. See example 1 of Section III. a - test line. b and c - two solutions for R_r^a and hence L_a.

Conditions

Given:	package free volume	V
	count rate	R^*
	maximum leak limit required	$L_a(\max)$
	specific activity	S
	counting efficiency	K
Find:	maximum dwell time	$t(\max)$
	pressurization value	$P_E{}^*$

Procedure

a. Calculate $R_r{}^a(\max)$ from (3).
Erect a vertical line at this value.

b. Note that the information given is not sufficient to derive a specific value for either $t(\max)$ or $P_E{}^*$. Some choice is allowed.
Select a point on the $R_r{}^a(\max)$-line which corresponds to a usable value for t.

c. Draw a horizontal test line through this point.
Determine the test line value from the E* axis.

d. Compute $P_E{}^*$ from (5) or R^*/P_0VSKE^*.

e. If $P_E{}^*$ is a suitable value, then t is taken as the maximum dwell time allowed in order for the test range to include $L_a(\max)$, and $P_E{}^*$ is the pressurization value of test.
If $P_E{}^*$ is not a suitable value, adjust t and E*.

4. Selection of test parameters: Leak size as a function of pressurization time.

Conditions

This is a general case that applies to all packages independent of specific conditions.

Procedure

a. Choose a horizontal test line of some value E*, e.g., test line (a) in figure 4.
Locate the intersection with this and an E-characteristic curve at some value of T.
Drop a vertical line to the $R_r{}^a$ axis, e.g., line (b) in figure 4.

b. Proceed along the test line to a larger value of T by one decade.
Drop a vertical line.
Note $R_r{}^a$ has decreased by one decade; i.e., $R_r{}^a$ decreases proportionately to the increase in T.

c. Proceed to the other end of the test line.
Note that the E-characteristic curves may retain a significant dependence on the pressurization time T for typical values of the test line and dwell time t, e.g., at the intersection

of lines (a) and (c) in figure 4. This is different from the usual helium leak detector test situations.

5. Selection of Test Parameters: Count Rate

<u>Conditions</u>

Given:	leak size reject value	L_a(reject) (atm·cm^3/s)
	pressurization time	T (h)
	pressurization value	P_E*(atm)
	package free volume	V (cm^3)
	specific activity	S (μCi/atm·cm^3)
	counting efficiency	K (min^{-1}·μCi^{-1})
Find:	count rate	R (min^{-1})

<u>Procedure</u>

a. Compute $R_r{}^a$(reject) using (3). Draw a vertical line at this value.
b. Locate the intersection of the $R_r{}^a$-line with the E*-characteristic curve corresponding to the given T value. If that curve is not represented, construct one parallel to those drawn passing through the given value on the T-scale. Read off the value of E* corresponding to the intersection.
c. Compute $R^* = SK \cdot E^* \cdot P_0 V P_E{}^*$.

IV. General Characteristics

The internal fractional gas pressure per atmosphere of pressurization with <u>any tracer gas</u> is given by eq (1) when the relaxation rate R_r for the specific tracer gas is

$$R_r = \frac{L}{P_0 V} \tag{8}$$

and L is now the standard leak rate for the specific tracer gas. Characteristic curves for E as a function of the relaxation rate for any particular tracer gas are given in master graph 3.

If the tracer gas is drawn back through the leak for detection, as with a mass spectrometer, the solution is of the form of eq (4), i.e.,

$$E \cdot R_r = \frac{R}{P_0 V P_E} \tag{9}$$

with R_r given by eq (8). Test lines are at -45 deg on the log E-log R_r plane with values of $|E \cdot R_r|$. Figure 1 and the solutions for the helium leak detector are drawn from the general case by superposing the relaxation rate for air relative to that of helium from eq (4) on the log R_r axis and with test lines of value $|E \cdot R_r{}^a|$.

If the tracer gas is detected while in the package, the solution is of the form

$$\frac{R}{P_0 V P_E} = \beta \cdot E \tag{10}$$

where

$$R = \beta \cdot PV \tag{11}$$

and is a measurement of some property proportional to the quantity of gas (PV) at ambient temperature such as for another radioactive scheme, mass, etc. Test lines are horizontal on the log E-log R_r plane with values of E. Figure 3 and the solutions for the krypton-85 radioisotope method are drawn from this by superposing the relaxation rate for air relative to that of krypton-85 by eq (6).

References

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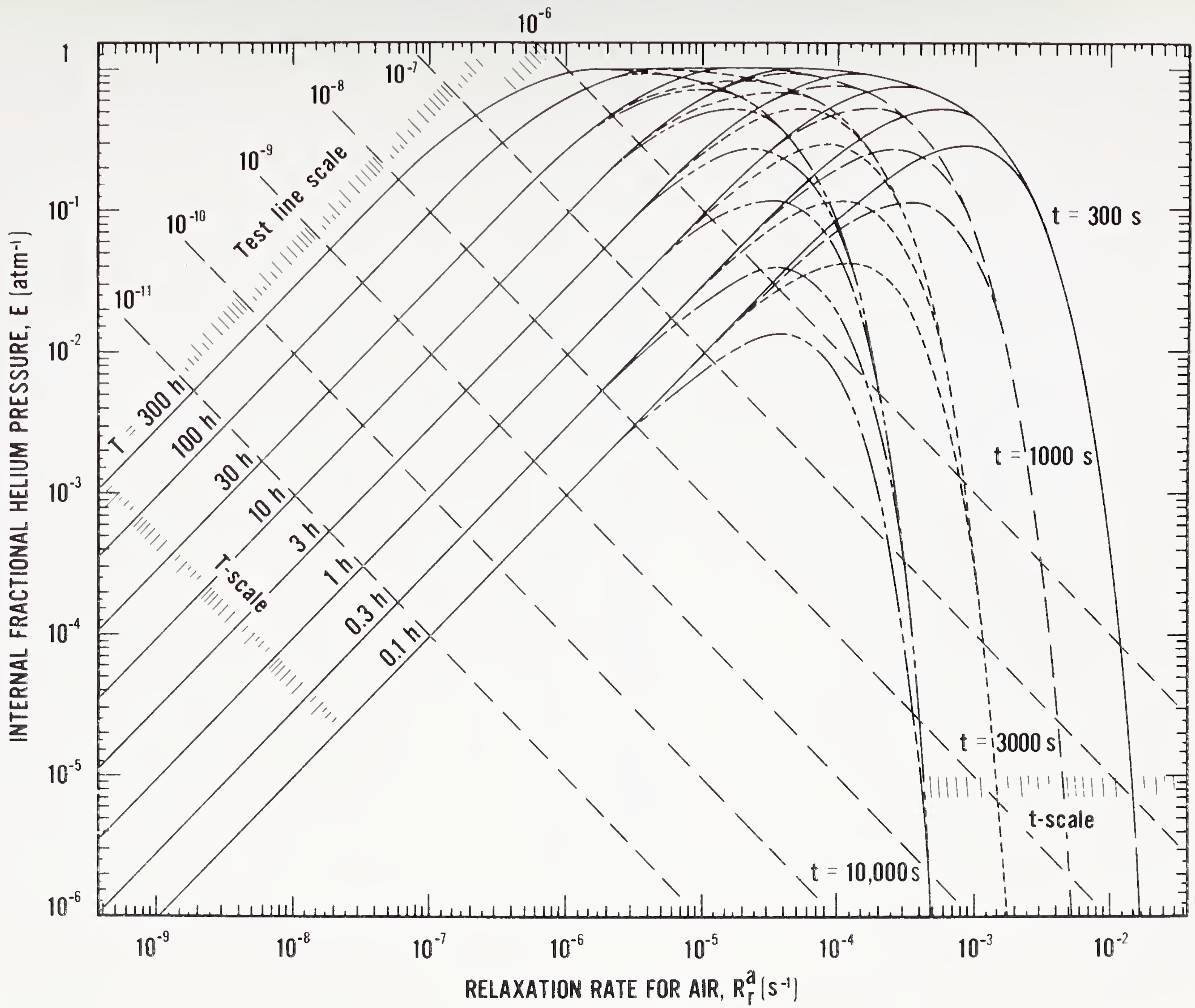
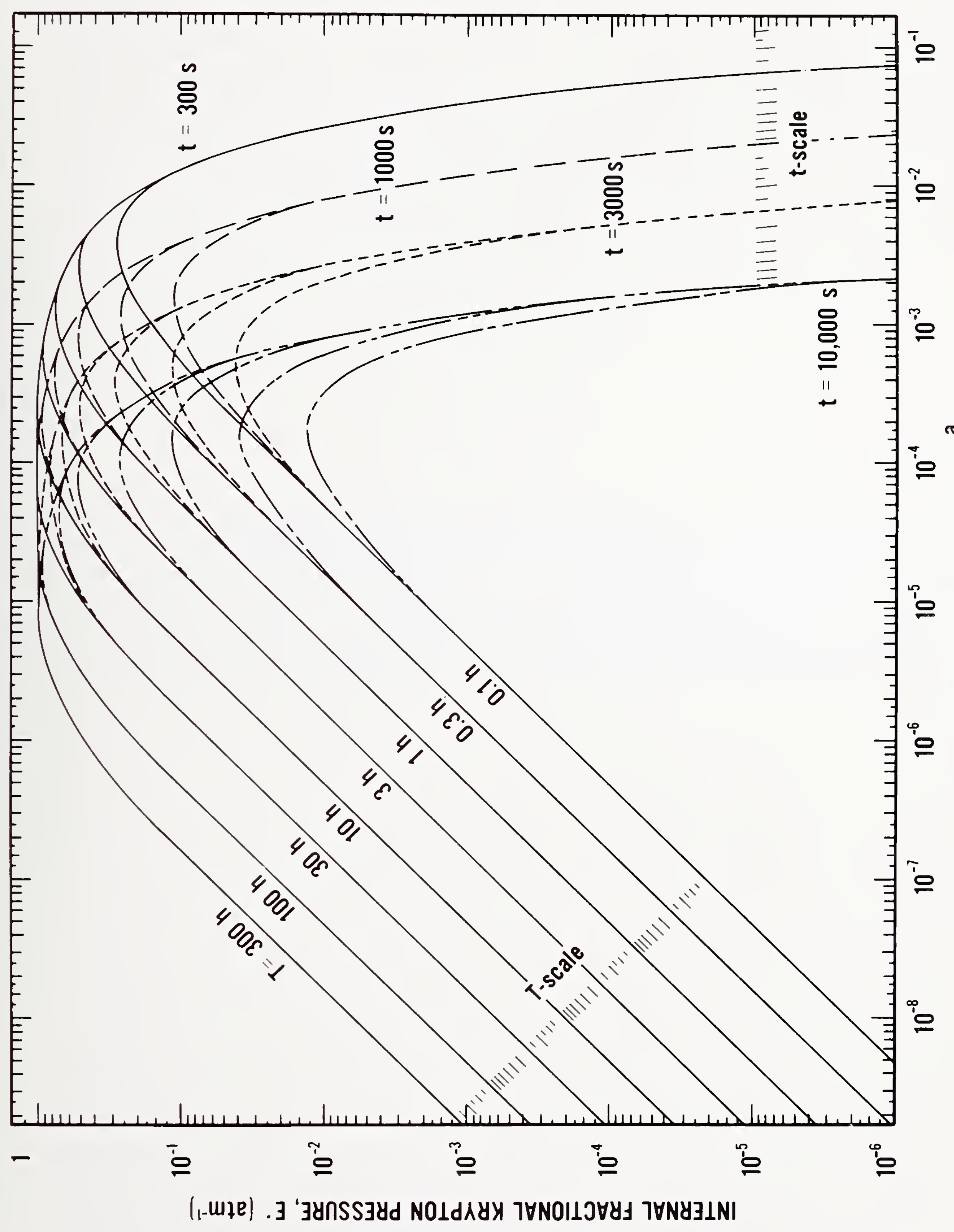
Master graph 1. <u>Characteristics and test lines for the helium leak detector method</u>. E, the relative partial pressure of helium within the package per atmosphere of external helium pressurization, as a function of the relaxation rate for air R_r^a with pressurization time T and dwell time t as parameters. Tick marks include those at 1.25, 1.5, 1.75, and 2.5 with the remainder at integral values for each decade on the axes, for $E \cdot R_r^a$, for T, and for t.

cut



INTERNAL FRACTIONAL HELIUM PRESSURE, E (atm⁻¹)
RELAXATION RATE FOR AIR, R_r^a (s⁻¹)
Test line scale
T-scale
t-scale
T = 300 h
100 h
30 h
10 h
3 h
1 h
0.3 h
0.1 h
t = 300 s
t = 1000 s
t = 3000 s
t = 10,000 s

Master graph 2. Characteristics for the krypton-85 radioisotope method. E^*, the relative partial pressure of krypton within the package per atmosphere of external krypton pressurization, as a function of the relaxation rate for air $R_r{}^a$ with pressurization time T and dwell time t as parameters. Tick marks include those at 1.25, 1.5, 1.75, and 2.5 with the remainder at integral values for each decade on the axes, for T, and for t.

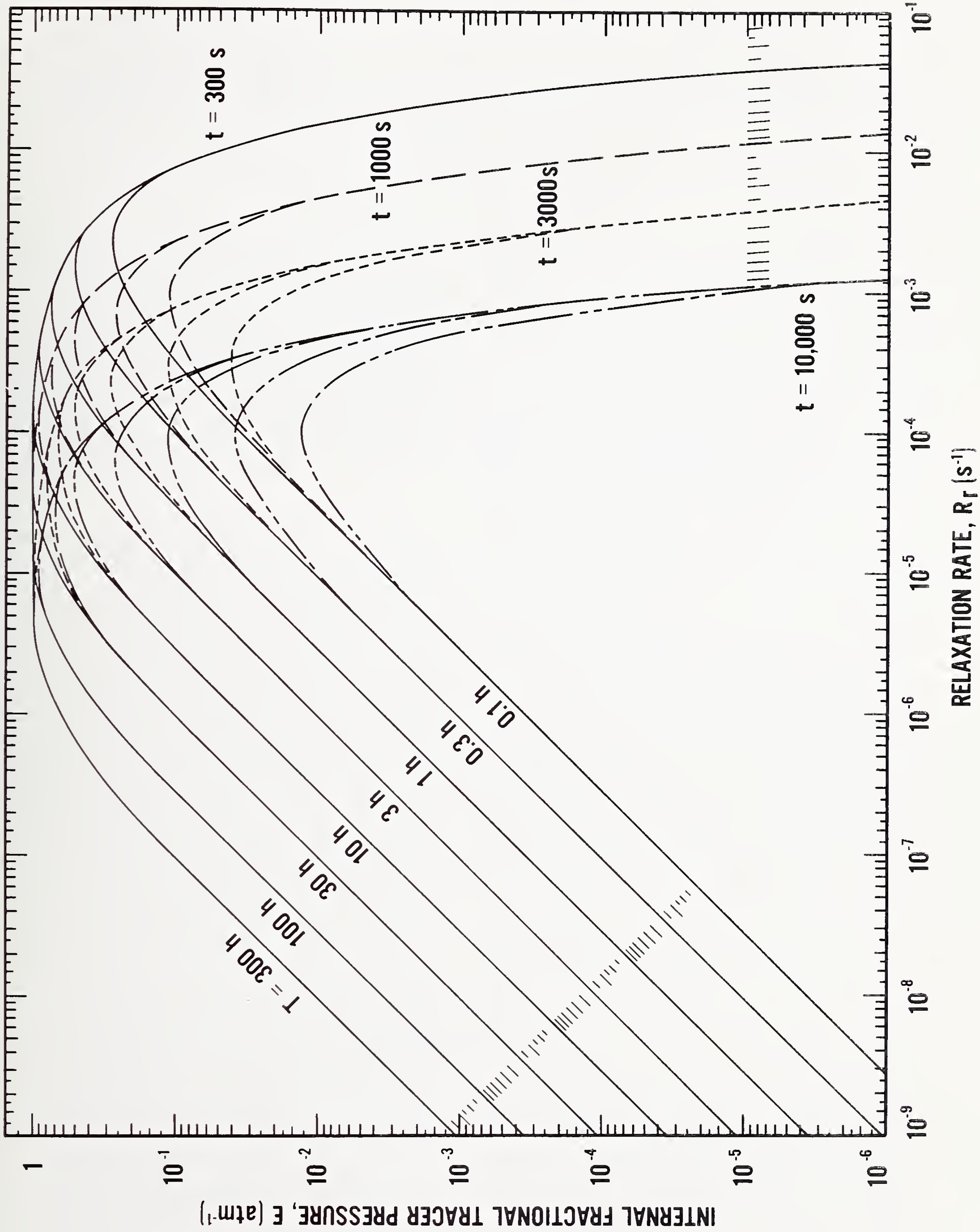


t = 300 s
t = 1000 s
t = 3000 s
t = 10,000 s
t-scale
T-scale
T = 300 h
100 h
30 h
10 h
3 h
1 h
0.3 h
0.1 h
RELAXATION RATE FOR AIR, R_r^a (s^{-1})
INTERNAL FRACTIONAL KRYPTON PRESSURE, E' (atm^{-1})
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

cut

Master graph 3. Characteristics for any tracer gas. E, the relative partial pressure of the specific tracer gas within the package per atmosphere of external pressurization in that gas, as a function of the relaxation rate for that specific tracer gas with T and t as parameters. Test lines are inclined at -45 deg with value $|R_r \cdot E|$ if the gas is extracted back though the leak for measurement or are horizontal with value $|E|$ if the quantity of gas is measured while within the package. Transport mechanism is molecular flow.

cut


INTERNAL FRACTIONAL TRACER PRESSURE, E (atm⁻¹)
RELAXATION RATE, R_r (s^{-1})
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
T = 300 h
100 h
30 h
10 h
3 h
1 h
0.3 h
0.1 h
t = 300 s
t = 1000 s
t = 3000s
t = 10,000 s

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Graphical Solution for the Back Pressurization Method of Hermetic Test

STANLEY RUTHBERG

Abstract—**The back pressurization method for leak-testing hermetically sealed electronic packages requires gas-flow modeling to relate indicated leakage rates to true leak size. The molecular flow relationship which is appropriate for fine leak sizes is nonlinear and requires a numerical solution, which in actual test application may involve either many trial calculations or the use of approximations that lead to limiting case values. A new graphical procedure is presented for complete solution of the molecular flow equation for any given test condition and package volume through the use of a single set of characteristic curves and a test line. The effects of repetitive testing and of prefill with tracer gas are also considered. The characteristic curves are appropriate for both the helium leak detector and the radioisotope methods of test, while the form of the test line distinguishes between the two methods.**

I. INTRODUCTION

THE BACK pressurization method for leak-testing hermetically sealed packages is accomplished by forcing a tracer gas into the package interior and then measuring the quantity of gas that has penetrated the leak channel. The two tracer gases most commonly used for semiconductor devices are helium and radioactive krypton. With helium as the tracer gas, measurement is made by extracting the gas back through the leak into the helium mass spectrometer leak detector; with radioisotope Kr^{85} as the tracer, an external gamma counter determines the activity of the internal gas. Neither technique gives the true leak rate value directly; rather, both require a knowledge of the gas transport mechanism and the use of appropriate mathematical models for the determination of test parameters. As the gas transport mechanism for leaks under pressurization is that of transition flow [1], which combines the elements of molecular and laminar viscous flow in a manner not amenable to direct analytical solution [2], a number of simplifying flow models have been used.

Traditionally the molecular flow approximation which is relevant for very fine leaks has been used to relate the helium leak detector indication to the leak size, but even here a transcendental relationship is obtained which is double-valued in leak size for each machine indication [3]. Thus numerical calculations are required to select pressurization parameters and to determine leak size. If precise values of leak size are required as in test evaluation or comparison, it is necessary either to use successive approximations or to construct a family of curves representing solutions for each parametric variation [4]. If an approximate correlation is sufficient, extensive tables of computer solutions for discrete values of parameters have been available [5]. Finally, if only approximate values for the minimum detectable leak size and/or the maximum detectable leak size are sufficient, as for screening purposes, graphs are available for a limited range of parametric values [6].

The radioisotope test method is usually modeled by the laminar viscous flow approximation [7] which is relevant in principle to the larger leak sizes. The assumption is made that the internal gas pressure remains small and increases linearly with time under pressurization. The loss of gas back through the leak is also neglected [8]. While such modeling leads to a simple relationship between gamma-ray count rate and leak size, correlation of the results between this method and the helium leak-detector method is obscured.

In this paper a graphical procedure is presented for complete solution of the molecular flow equation for any given test condition. Only a single set of characteristic curves is required along with the use of a test line. The selection of parametric values for pressurization, time of pressurization, and lapsed time to achieve a given leak-test range for any package volume is readily made, and the effect on test results due to variation in parameters is easily visualized. The procedure is applied to both the helium and the radioisotope methods, and a comparison of operational behavior is derived for the fine leak range for which molecular flow is appropriate. In addition the case of repetitive testing is considered. Either prior testing or a prefill of packages with tracer gas can affect test results considerably, yet this situation has not been approached previously on a formal basis. Correction of results is particularly appropriate for test evaluation and interlaboratory comparisons.

II. INTERNAL FRACTIONAL PARTIAL PRESSURE

A. Exact Solution

The gas transport into and out of a package due to a molecular flow leak is described by

$$V\frac{dP}{dt}=F(P_1-P_2) \tag{1}$$

where V is the internal free volume of the package available to gas collection, $V\,dP/dt$ is the flow rate into (or out of) the package at ambient temperature, F is the molecular-flow conductance of the leak channel [9], and P_1 and P_2 are the partial pressure of the tracer gas at each end of the leak channel. By definition the standard leak rate L for a given gas is that flow rate obtained with 1 atm of gas pressure up-

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The author is with the Electron Devices Division, National Bureau of Standards, Washington, DC 20234

stream to the leak channel and zero pressure downstream so that from (1)

$$L = FP_0 \tag{2}$$

for P_0 equal to 1 atm [10]. It then follows from (1) and (2) that when a previously unexposed package has been immersed in a tracer gas at a pressure P_E for a period T, the internal partial pressure P is

$$P = P_E\left[1 - \exp\left(-\frac{L}{P_0 V}\,T\right)\right].$$

When the pressurization ceases the tracer gas effuses back through the leak so that the interior tracer gas pressure decays exponentially. Then for any given lapsed or dwell time t

$$P = P_E\left[1 - \exp\left(-\frac{L}{P_0 V}\,T\right)\right] \exp\left(-\frac{L}{P_0 V}\,t\right). \tag{3}$$

If the interior partial pressure of the tracer gas is not zero but is initially P' due to a previous test or to a prefill of the package, the resultant pressure is

$$P = \left\{P' + [P_E - P']\left[1 - \exp\left(-\frac{L}{P_0 V}\,T\right)\right]\right\} \cdot \exp\left(-\frac{L}{P_0 V}\,t\right). \tag{4}$$

The pressure change within the package is thus determined by a time constant

$$\tau = \frac{P_0 V}{L} \tag{5}$$

or the relaxation rate R_r which is the reciprocal of the time constant

$$R_r = \frac{L}{P_0 V}. \tag{5a}$$

Now the bracketed expression in (3) is a measure of the relative increase in the internal gas concentration, and this value normalized by 1 atm pressure is defined here as the quantity

$$E = \frac{1}{P_0}\,[1 - \exp(-R_r T)]\,\exp(-R_r t) \tag{6}$$

which represents the internal fractional tracer gas pressure per atm of pressurization. This quantity E will be used below to characterize the back pressurization method of hermetic test for both the helium leak detector and the radioisotope procedures.

A family of projections for E as a function of the relaxation rate, with pressurization time and dwell time as parameters, is shown in Fig. 1 as derived from (6) for a range of parametric values sufficient for most semiconductor device packages; i.e., characteristics are included for a geometric series of values of pressurization time ranging from 0.1 to 300 h and values of dwell time ranging from 5 min to about 3 h. The initial and final segments for these curves can be obtained readily from limiting solutions for small leaks and for large leaks as follows.

B. Fine Leak Approximation

For relatively small values of R_r, from (6)

$$E \cong R_r T/P_0. \tag{7}$$

Therefore with T as a parameter the E, R_r characteristics are initially linear projections at a 45° slope on the log-log plane. A projection for any value of T can be erected quickly by taking a coordinate point and passing a line of 45° slope through the point, i.e., by calculating E for a given R_r or an R_r for a given E with T as a parameter in (7). The locations of lines of intermediate values of T are indicated in the figure by tick marks for $T = 1$-10.

C. Large Leak Approximation

For relatively large values of R_r

$$E \cong \frac{1}{P_0}\exp(-R_r t)$$

or

$$R_r \cong -\frac{1}{t}\ln(P_0 E). \tag{8}$$

Thus the relaxation rate increases directly as the dwell time diminishes, the pressurization time is not a significant factor, and the relaxation rate changes little with large variation in E for any given dwell time. This downslope segment for any $E(t)$ can be approximated readily by considering numerical values of E of the form

$$E = \frac{1}{P_0} \times 10^{-n}$$

whence

$$R_r \cong \frac{2.303n}{t} \tag{9}$$

and by joining with a straight line segment two points calculated from (9) for the selected value of t and two successive values of n in the R_r region of interest.

III. HELIUM LEAK DETECTOR METHOD

A. Test Equations

When the tracer gas is helium, the flow rate of helium from the package interior back through the leak conductance and

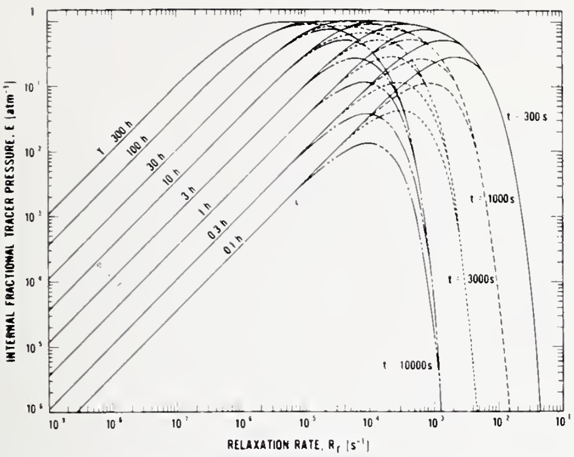

Fig. 1. E, the relative partial pressure of tracer gas within package interior free volume per atmosphere of external tracer gas pressurization, as function of relaxation rate R_r with pressurization time T and dwell time t as parameters. Transport mechanism is molecular flow.

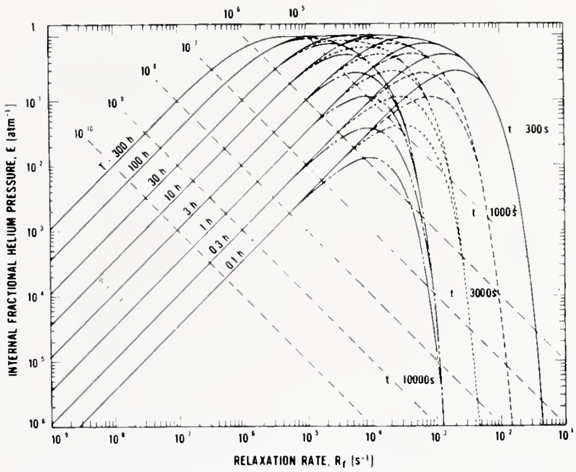

Fig. 2. Test lines for helium leak detector method. E and R_r are for helium gas. Test line values are for $R_r \cdot E$ = constant with indicated lines ranging from 10^{-5} to 10^{-10} $s^{-1} \cdot atm^{-1}$.

into the helium leak detector will by (1) give rise to an indicated leak rate R given by

$$R = F \cdot P \tag{10}$$

where the pressure within the leak detector is much less than P. Most tests for package leakage are done soon after assembly so that the initial interior helium concentration is zero. For such packages the leak detector indication is then from (2) and (3)

$$R = P_E \cdot L \cdot E$$

or from (5a)

$$\frac{R}{P_0 V P_E} = R_r \cdot E. \tag{11}$$

Thus the solution is characterized by the two factors E and R_r, and all solutions relating leak detector response to standard leak rate may be derived from the characteristic projections for E along with an appropriately placed test line.

B. Test Lines

It is apparent from (11) that the locus of all solutions for any test sequence will lie on a line of 45° negative slope on the log E-log R_r plane; for, with a given volume, indicated leak rate and pressurization the product $R_r \cdot E$ is a constant. Fig. 2 includes test lines ranging from 1×10^{-5} (atm · s)$^{-1}$ to 1×10^{-10} (atm · s)$^{-1}$.[1] A test line for any other value can be constructed similarly as a line of 45° *negative* slope through a coordinate point represented by $R_r \cdot E$ = constant.

[1] Although the SI system of metric units is now preferred, present engineering practice uses units of atm·cm^3/s for leak rate and lbf/in^2 for pressures near or greater than 1 atm. Converstion factors are 1 Pa = 1.451×10^{-4} lbf/in^2, 1 Pa·m^3/s = 9.869 atm·cm^3/s, and 1 atm = 1.01325×10^5 Pa.

Then specific solutions are defined by the intersection of the test line with that $E(T, t)$ characteristic corresponding to the particular test values of T and t. Solutions to all modes of test operation may be so obtained.

1) Unknown Leak Size: In one mode of operation it may be desired to determine the leak size of a specimen of internal volume V which has been subjected to an arbitrary set of back-pressurization parameters P_E, T, and t for which an indicated leak rate R was obtained. To solve this, the appropriate test line value is first computed from $R/(P_0 \cdot V \cdot P_E)$. The intersection of this test line with the upslope portion $E(T)$ of the curve corresponding to the given pressurization time and with the downslope portion $E(t)$ corresponding to the given dwell time determine the two possible solutions for R_r from which the standard leak rate for helium L is determined. The *leak size*, which is defined as the standard leak rate for air, is $L/2.69$.[2]

Example: Consider a volume of 0.1 cm^3 pressurized to 5 atm abs (~60 psig) in pure helium for 2 h and then put on the helium leak detector 50 min later to give a reading of 5×10^{-8} atm · cm^3/s. The true leak size is required. The appropriate parameters follow.

V = 0.1 cm^3.
P_E = 5 atm · abs
T = 2 h.
t = 3000 s.
R = 5×10^{-8} atm · cm^3/s.

The steps are as follows.

a) Compute $R_r \cdot E = R/(P_0 \cdot V P_E) = 1 \times 10^{-7}$ (atm · s)$^{-1}$.
b) In Fig. 2 find the intersection of the 1×10^{-7} (atm · s)$^{-1}$ test line with the T = 2 h characteristic. Since T = 2 h is not shown in Fig. 2, lay a scale parallel to

[2] Leak rate for helium/leak rate for air = (molecular weight air/molecular weight helium)$^{1/2}$ = 2.69, where M^{air} = 28.98 [11].

the R_r, E characteristics and through the 2-h tick mark. Determine the value of R_r at the intersection. $R_r \cong 3.6 \times 10^{-6} s^{-1}$. Therefore by (5a) L the standard leak rate for helium is 3.6×10^{-7} atm · cm^3/s from which the leak size is 1.3×10^{-7} atm · cm^3/s.

c) Follow the 1×10^{-7} test line to the $t = 3000$ s $E(t)$ characteristic. Determine the value of R_r at the intersect. $R_r = 2.8 \times 10^{-3} s^{-1}$. Therefore $L = 2.8 \times 10^{-4}$ atm · cm^3/s and $L_{air} = 1 \times 10^{-4}$ atm · cm^3/s.

d) The leak size is either 1.3×10^{-7} or 1×10^{-4} atm · cm^3/s. Discrimination is made with a followup reading on the leak detector at a later time. Any significant change indicates that the leak rate is the larger value.

2) Pressurization Parameters: By far most hermetic test activity is for screening purposes. This requires a selection of parametric values so that all specimens with leak sizes greater than some specified value be rejected. The upper limit of the test is determined, however, by the shortest dwell time that can be obtained, and it is hoped the test range can be made broad enough to overlap that of the gross leak test that would follow.

First the reject level relaxation rate is calculated from (5a) from the package-free volume and the specified standard leak rate for helium, and a vertical line is erected on the chart at that value. The test line is calculated from the left side of (11) with the selected value of leak detector signal R, the package volume V, and a convenient pressurization value P_E. The intersection of this test line with the R_r line sets the choice for T. If the first test line selected produces an inconvenient value for T one can move away from the first intersection to choose more satisfactory values for both T and a test line. The only constraint is that the leak detector reject signal has to be greater than the minimum detectable signal by a suitable amount [12]. Then the corresponding maximum value of R_r that can be detected is easily picked off by extending the test line to the $E(t)$ characteristic corresponding to the attainable dwell time. Alternatively the major factor in the test may be the maximum detectable leak size. Then the maximum value of R_r is calculated and a vertical line extended from this value. The intersection with a suitable $E(t)$ characteristic determines the lower end of the test line which is then extended at a $-45°$ slope to a suitable $E(T)$ characteristic.

Example: Consider an IC package of 0.01 cm^3 nominal free volume for which a reject leak size of 5×10^{-8} atm · cm^3/s of air is required [8]. Suppose the background signal is found to be 1×10^{-9} atm · cm^3/s of helium and a signal-to-background value of five is selected. Also the tests could be completed within 50 min after release from the pressurization chamber. Consider $P_E = 5$ atm · abs. The appropriate parameters follow:

V	$= 0.01$ cm^3,
$L_{\text{air reject}}$	$= 5 \times 10^{-8}$ atm · cm^3/s,
R_{reject}	$= 5 \times 10^{-9}$ atm · cm^3/s (helium),
t	$= 3000$ s,
P_E	$= 5$ atm · abs.

Then

L	$= 1.35 \times 10^{-7}$ atm · cm^3/s,
R_r	$= 1.35 \times 10^{-5}$ s^{-1},
$R_{\text{reject}}/P_0 V P_E$	$= 1 \times 10^{-7}$ atm^{-1} · s^{-1}.

The intersection of test line 1×10^{-7} and R_r of 1.35×10^{-5} is at $T = 0.15$ h (see Fig. 3). But $T = 9$ min is too short for convenience. Consider $T = 0.3$ h instead. Doubling the value of T at constant R_r doubles E, as seen in (7), and hence the value of the test line; thus the detector reject level is increased to 1×10^{-8} atm · cm^3/s. A $-45°$ test line established at $T = 0.3$ h and $R_r = 1.35 \times 10^{-5} s^{-1}$ ($R_r E = 2 \times 10^{-7}$) intersects the $t = 3000$ s characteristic at $R_r = 3.3 \times 10^{-3}$ so that the maximum standard leak rate for helium $L = 3.3 \times 10^{-5}$ atm · cm^3/s and then $L_{air} = 1.2 \times 10^{-5}$ atm · cm^3/s. However 1.2×10^{-5} is borderline for any gross leak test, and the only way to increase the present limit significantly is to decrease the dwell time. Decreasing dwell time to the 1000-s (~17-min) characteristic would lead to an R_r of 1.1×10^{-2} and hence an $L_{air} \sim 4.1 \times 10^{-5}$ atm · cm^3/s for some improvement in overlap between the fine and gross leak test. Note that an increase in dwell time beyond ~1 h would pull the intersection point off the straight line region of $E(T)$. It should also be noted that P_E could be dropped to 2.5 atm pressure and the original value of leak detector reject limit of 5×10^{-9} atm · cm^3/s be retained without changing the pressurization time test limits. Only the ratio of signal to background would be affected.

Since a leak size of 5×10^{-8} atm · cm^3/s in a 0.01-cm^3 volume produces a time constant of only 2 days, consider a decrease in the reject leak size by a factor of 5 to give 1×10^{-8} atm · cm^3/s. Then R_r becomes 2.7×10^{-6} s^{-1} and the intersection of this value with the 2×10^{-7} test line shows $T = 7.5$ h, a 25-fold increase in pressurization time; i.e., with (7) $R_r \cdot E \sim R_r^2 T/P_0$.

3) Repetitive Measurement: Often the package may include an initial partial pressure of helium because of prior testing or prefill, and this initial concentration will affect the test results. In practice specimens are conditioned in vacuum or allowed to stand for some time until an initial leak detector reading is relatively small, but when such a long wait time may not be suitable or where some accuracy is required a formal correction procedure is desirable.

The specimen is first placed in the inlet of the leak detector and an initial measurement is made of the effusion. The effusion rate R_1 is related to the interior partial pressure P_1 and to the standard leak rate through (2) and (10) as

$$R_1 = P_1 \frac{L}{P_0}.$$

After another delay period of t'', the specimen is subjected to hermetic test, and a final measurement is made. The initial partial pressure P' just prior to pressurization, after further possible effusion during the delay, is

$$P' = \frac{R_1 P_0}{L} \cdot \exp(-R_r t''). \tag{12}$$

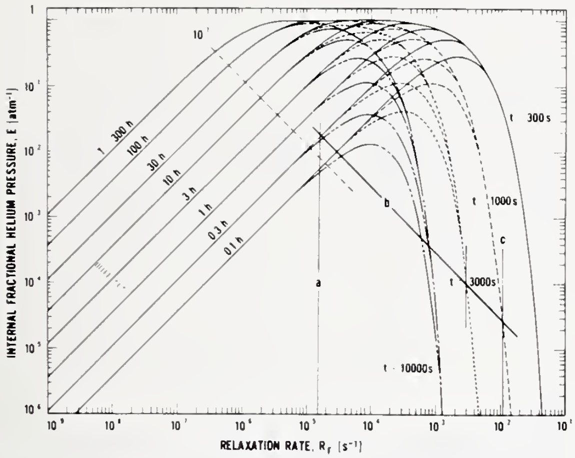

Fig. 3. Selection of pressurization parameters for helium leak detector method: an example. Reject leak size (air) of 5×10^{-8} atm·cm^3/s with $V = 0.01$ cm^3, $P_E = 5$ atm, $t = 3000$ s, and minimum detectable signal of 5×10^{-9} atm·cm^3/s for signal-to-noise of 5. Line (a) represents an R_r of 1.35×10^{-5} s^{-1} for helium. Then $R/(P_0 V P_E) = 1 \times 10^{-7}$ s^{-1}·atm^{-1}. First intersection of 10^{-7} test line and (a) at $T \sim 0.15$ h is not satisfactory, so $T = 0.3$ h is chosen. Line (b) becomes the test line. Intersection of (b) at $t = 3000$ s leads to leak size of 1.2×10^{-5} atm·cm^3/s of air. Line (c) for intersect at $t = 1000$ s leads to $L_{air} \approx 4.1 \times 10^{-5}$ atm·cm^3/s.

The measured leak rate R_2 obtained after pressurization is equal to LP/P_0 where P is now described by (4). With (4), (6), and (12), it follows that

$$R_2 = R_1 \exp(-R_r t'') \left[\exp(-R_r t_2) - P_0 E_2\right] + P_0 V P_E R_r E_2 \tag{13}$$

where the subscript 2 denotes the quantities related to the pressurization sequence. As a general approach, the solution is obtained by successive approximation as follows.

a) Compute an approximate test line value from

$$\frac{R_2}{P_0 V P_E} \cong R_r \cdot E_2.$$

b) With this test line find the approximate values for R_r and E_2 at $E(T_2, t_2)$, here designated as R_r' and E_2'.

c) Compute the value of $\exp(-R_r' t_2)$ from the value of t_2 used in the test.

d) Compute the value of $\exp(-R_r' t'')$ from the measured value of t''.

e) With these approximate values from b, c, d

$$\frac{R_2 - R_1 \exp(-R_r' t'') \left[\exp(-R_r' t_2) - P_0 E_2'\right]}{P_0 V P_E} \cong R_r \cdot E_2. \tag{14}$$

This then is a corrected test line from which the two possible solutions may be obtained at the intersects for $E(T_2)$ and $E(t_2)$. Further iteration can be made.

If however the first approximated test line crosses the $E(T)$ characteristics in the region of straight line projections, then

$$\exp(-R_r t'') \to 1$$

$$\exp(-R_r t_2) \to 1$$

$$E_2 \ll 1,$$

so that by (14)

$$\frac{R_2 - R_1}{P_0 \cdot V \cdot P_E} = R_r \cdot E_2 \tag{15}$$

as one might expect.

At the large leak end of the test line, the solution is somewhat insensitive to variation in test line value since R_r is primarily a function of t_2, i.e.,

$$\exp(-R_r t'') < 1$$

$$\exp(-R_r t_2) \to 0$$

$$E_2 \ll 1$$

so that

$$\frac{R_2}{P_0 V P_E} \cong R_r \cdot E_2, \tag{16}$$

and the prereading does not produce a significant correction.

Thus one only need see where the approximated test line falls to determine how much further iteration is required. If it falls in the fine leak area of straight line projections, simply take the difference between the final leak detector value and the prereading and calculate the test line value. The "true" value for R_r is either at $E(T_2)$ or $E(t_2)$. If only the large leak value is desired, simply calculate the test line from R_2. If the approximated test line falls in the intermediate R_r range, the iteration procedure is appropriate.

IV. RADIOISOTOPE METHOD

A. Test Equation

Since the ~0.5-MeV gamma radiation emitted by Kr^{85} easily penetrates most semiconductor package walls the amount of pure Kr^{85} that has passed through a leak channel and *remains within* the package cavity after pressurization in a Kr^{85}-N_2 gas mixture can be measured without resorting to extraction back through the leak channel as in the use of the helium leak detector. Thus the gamma count rate R^* becomes

$$R^* = (PV) \cdot A \cdot K \tag{17}$$

where P is the internal partial pressure of Kr^{85}, PV is the quantity of Kr^{85} at ambient temperature within the cavity,

A is the activity of pure Kr^{85} (μCi/atm · cm^3),[3] and K is the overall counting efficiency of the detector for the particular package type at a particular location within the crystal detector well (count rate/μCi). The interior partial pressure is given by (3), but the external partial pressure P_E is

$$P_E = \frac{S}{A} \cdot P_E^* \tag{18}$$

where S is the specific activity of the Kr^{85}-N_2 gas mixture (μCi/atm · cm^3) and P_E^* is the pressurization value for the gas mixture. Thus

$$\frac{R^*}{P_0 \cdot V \cdot P_E^*} = SK \cdot E^* \tag{19}$$

where the solution is characterized only by the internal fractional partial pressure for Kr^{85}, here designated as E^*.

1) Fine Leak Approximation: For relatively small values of relaxation rate with krypton R_r^* by (7) and (19),

$$\frac{R^*}{P_0 V \cdot P_E^* \cdot SK} \cong \frac{R_r^* T^*}{P_0},$$

with T^* denoting pressurization time with krypton. Thus

$$\frac{R^* P_0}{P_E^* SKT^*} = L^* \tag{20}$$

where L^* is the standard leak rate for Kr^{85}. Package volume is not a factor, and (20) differs from the traditional recipe [7], [8] in that P_E^* is now raised only to the first power rather than to the second power as in the laminar viscous flow model.

B. Test Lines

For a given volume, indicated count rate, and pressurization in a particular gas mixture the locus of all solutions is now on a horizontal line of value E^* rather than the 45° slope of the helium leak detector, and there is now no need to construct a set of such lines superimposed on the E, R_r plane. Specific solutions for the test sequence are as before at the intersection of the test line with the $E(T, t)$ characteristic specified by the parametric values of T and t.

1) Pressurization Parameters–Example: Consider again the 0.01-cm^3 package to be leak tested to 5×10^{-8} atm · cm^3/s of air with a dwell time of 1000 s. Background count rates are generally of the order of 500 counts/min, a typical value for S is 200 μCi/atm · cm^3, and a typical value of K is 10^4 min^{-1} · μCi^{-1}. Assume a signal-to-background ratio of 5 for the reject level count rate and a 5-atm pressurization. It is desired to establish the required value of T and the maximum detectable leak size L_{air}. The appropriate parameters follow.

[3] Although the SI system of metric units is now preferred, present engineering practice uses units of curie for disintegration rate; 1 Ci = 3.7×10^{10} Bq (events/s).

V = 0.01 cm^3,
L_a reject = 5×10^{-8} atm · cm^3/s
R_0^* = 500 min^{-1}
R^* reject = 2500 min^{-1}
S = 200 μCi/atm · cm^3,
K = 10^4 min^{-1} · μCi^{-2},
t^* = 1000 s.

Then with $(M^{air}/M^{Kr^{85}})^{1/2} = 1/1.71$, one obtains

$$L_{Kr^{85}} \text{ reject} = 5 \times 10^{-8} \left(\frac{M^a}{M^{Kr}}\right)^{1/2}$$
$$= 2.92 \times 10^{-8} \text{ atm} \cdot \text{cm}^3/\text{s}$$

whence

$$R_r^* = 2.92 \times 10^{-6} \text{ s}^{-1}$$

so

$$R^*/(P_0 V P_E^* SK) = E^* = 2.5 \times 10^{-2} \text{ atm}^{-1}.$$

As shown in Fig. 4 a line is erected at $R_r = 2.94 \times 10^{-6}$ s^{-1}, and a horizontal test line is placed at $E^* = 2.5 \times 10^{-2}$. At the intersection, T = 2.4 h. At the intersection with the t = 1000 s segment, R_r^* max = 3.7×10^{-3} s^{-1} such that $L_{air} = 6.3 \times 10^{-5}$ atm · cm^3/s. Note that leak rates are for Kr^{85} and hence R_r values are smaller than for helium for a given air leak.

Were the reject limit lowered to an L_{air} of 1×10^{-8} atm · cm^3/s, R_r^* would be 5.88×10^{-7} s^{-1} so that T is 11.8 h; that is, the pressurization time changes linearly with R_r, as evidenced in Fig. 4 and in (20) for the straight line projection region of $E(T)$.

2) Repetitive Measurement: An initial count rate made on the specimen relates to the quantity of Kr^{85} already within by (17). After a lapsed time t'' the specimen is pressurized. The interior pressure just before this is equivalent to that expressed in (12) or

$$P' = \frac{R_1^*}{V \cdot A \cdot K} \exp(-R_r^* t'').$$

The final pressure after processing is as in (4), and the final count rate is again determined by (17) as

$$\frac{R_2^* - R_1^* \exp(-R_r t'') \left[\exp(-R_r^* t_2) - P_0 E_2^*\right]}{P_0 V \cdot P_E^*}$$
$$= SK \cdot E_2^* \tag{21}$$

which is of the same form as (14). In the small leak range where $\exp(-R_r^* t'')$ and $\exp(-R_r^* t_2)$ are ~1, and as $E_2^* \ll 1$, the initial count rate is a direct correction or

$$\frac{R_2^* - R_1^*}{P_0 V \cdot P_E^*} = SK \cdot E_2^*. \tag{22}$$

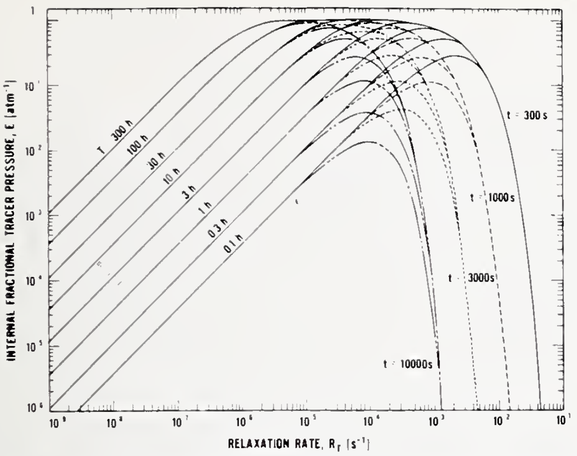

Fig. 1. E, the relative partial pressure of tracer gas within package interior free volume per atmosphere of external tracer gas pressurization, as function of relaxation rate R_r with pressurization time T and dwell time t as parameters. Transport mechanism is molecular flow.

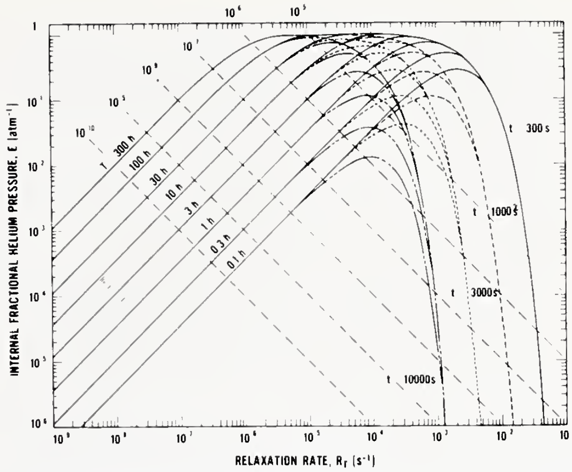

Fig. 2. Test lines for helium leak detector method. E and R_r are for helium gas. Test line values are for $R_r \cdot E$ = constant with indicated lines ranging from 10^{-5} to 10^{-10} $s^{-1} \cdot atm^{-1}$.

into the helium leak detector will by (1) give rise to an indicated leak rate R given by

$$R = F \cdot P \qquad (10)$$

where the pressure within the leak detector is much less than P. Most tests for package leakage are done soon after assembly so that the initial interior helium concentration is zero. For such packages the leak detector indication is then from (2) and (3)

$$R = P_E \cdot L \cdot E$$

or from (5a)

$$\frac{R}{P_0 V P_E} = R_r \cdot E. \qquad (11)$$

Thus the solution is characterized by the two factors E and R_r, and all solutions relating leak detector response to standard leak rate may be derived from the characteristic projections for E along with an appropriately placed test line.

B. Test Lines

It is apparent from (11) that the locus of all solutions for any test sequence will lie on a line of 45° negative slope on the log E-log R_r plane; for, with a given volume, indicated leak rate and pressurization the product $R_r \cdot E$ is a constant. Fig. 2 includes test lines ranging from 1×10^{-5} $(\text{atm} \cdot \text{s})^{-1}$ to 1×10^{-10} $(\text{atm} \cdot \text{s})^{-1}$.[1] A test line for any other value can be constructed similarly as a line of 45° *negative* slope through a coordinate point represented by $R_r \cdot E$ = constant.

[1] Although the SI system of metric units is now preferred, present engineering practice uses units of atm·cm³/s for leak rate and lbf/in² for pressures near or greater than 1 atm. Converstion factors are 1 Pa = 1.451×10^{-4} lbf/in², 1 Pa·m³/s = 9.869 atm·cm³/s, and 1 atm = 1.01325×10^5 Pa.

Then specific solutions are defined by the intersection of the test line with that $E(T, t)$ characteristic corresponding to the particular test values of T and t. Solutions to all modes of test operation may be so obtained.

1) Unknown Leak Size: In one mode of operation it may be desired to determine the leak size of a specimen of internal volume V which has been subjected to an arbitrary set of back-pressurization parameters P_E, T, and t for which an indicated leak rate R was obtained. To solve this, the appropriate test line value is first computed from $R/(P_0 \cdot V \cdot P_E)$. The intersection of this test line with the upslope portion $E(T)$ of the curve corresponding to the given pressurization time and with the downslope portion $E(t)$ corresponding to the given dwell time determine the two possible solutions for R_r from which the standard leak rate for helium L is determined. The *leak size*, which is defined as the standard leak rate for air, is $L/2.69$.[2]

Example: Consider a volume of 0.1 cm³ pressurized to 5 atm abs (~60 psig) in pure helium for 2 h and then put on the helium leak detector 50 min later to give a reading of 5×10^{-8} atm · cm³/s. The true leak size is required. The appropriate parameters follow.

V = 0.1 cm³.
P_E = 5 atm · abs
T = 2 h.
t = 3000 s.
R = 5×10^{-8} atm · cm³/s.

The steps are as follows.

a) Compute $R_r \cdot E = R/(P_0 \cdot V P_E) = 1 \times 10^{-7}$ $(\text{atm} \cdot \text{s})^{-1}$.
b) In Fig. 2 find the intersection of the 1×10^{-7} $(\text{atm} \cdot \text{s})^{-1}$ test line with the T = 2 h characteristic. Since T = 2 h is not shown in Fig. 2, lay a scale parallel to

[2] Leak rate for helium/leak rate for air = (molecular weight air/ molecular weight helium)$^{1/2}$ = 2.69, where M^{air} = 28.98 [11].

the R_r, E characteristics and through the 2-h tick mark. Determine the value of R_r at the intersection. $R_r \cong 3.6 \times 10^{-6} s^{-1}$. Therefore by (5a) L the standard leak rate for helium is 3.6×10^{-7} atm · cm^3/s from which the leak size is 1.3×10^{-7} atm · cm^3/s.

c) Follow the 1×10^{-7} test line to the $t = 3000$ s $E(t)$ characteristic. Determine the value of R_r at the intersect. $R_r = 2.8 \times 10^{-3} s^{-1}$. Therefore $L = 2.8 \times 10^{-4}$ atm · cm^3/s and $L_{air} = 1 \times 10^{-4}$ atm · cm^3/s.

d) The leak size is either 1.3×10^{-7} or 1×10^{-4} atm · cm^3/s. Discrimination is made with a followup reading on the leak detector at a later time. Any significant change indicates that the leak rate is the larger value.

2) Pressurization Parameters: By far most hermetic test activity is for screening purposes. This requires a selection of parametric values so that all specimens with leak sizes greater than some specified value be rejected. The upper limit of the test is determined, however, by the shortest dwell time that can be obtained, and it is hoped the test range can be made broad enough to overlap that of the gross leak test that would follow.

First the reject level relaxation rate is calculated from (5a) from the package-free volume and the specified standard leak rate for helium, and a vertical line is erected on the chart at that value. The test line is calculated from the left side of (11) with the selected value of leak detector signal R, the package volume V, and a convenient pressurization value P_E. The intersection of this test line with the R_r line sets the choice for T. If the first test line selected produces an inconvenient value for T one can move away from the first intersection to choose more satisfactory values for both T and a test line. The only constraint is that the leak detector reject signal has to be greater than the minimum detectable signal by a suitable amount [12]. Then the corresponding maximum value of R_r that can be detected is easily picked off by extending the test line to the $E(t)$ characteristic corresponding to the attainable dwell time. Alternatively the major factor in the test may be the maximum detectable leak size. Then the maximum value of R_r is calculated and a vertical line extended from this value. The intersection with a suitable $E(t)$ characteristic determines the lower end of the test line which is then extended at a $-45°$ slope to a suitable $E(T)$ characteristic.

Example: Consider an IC package of 0.01 cm^3 nominal free volume for which a reject leak size of 5×10^{-8} atm · cm^3/s of air is required [8]. Suppose the background signal is found to be 1×10^{-9} atm · cm^3/s of helium and a signal-to-background value of five is selected. Also the tests could be completed within 50 min after release from the pressurization chamber. Consider $P_E = 5$ atm · abs. The appropriate parameters follow:

$$\begin{aligned} V &= 0.01 \text{ cm}^3, \\ L_{\text{air reject}} &= 5 \times 10^{-8} \text{ atm} \cdot \text{cm}^3/\text{s}, \\ R_{\text{reject}} &= 5 \times 10^{-9} \text{ atm} \cdot \text{cm}^3/\text{s (helium)}, \\ t &= 3000 \text{ s}, \\ P_E &= 5 \text{ atm} \cdot \text{abs}. \end{aligned}$$

Then

$$\begin{aligned} L &= 1.35 \times 10^{-7} \text{ atm} \cdot \text{cm}^3/\text{s}, \\ R_r &= 1.35 \times 10^{-5} \text{ s}^{-1}, \\ R_{\text{reject}}/P_0 V P_E &= 1 \times 10^{-7} \text{ atm}^{-1} \cdot \text{s}^{-1}. \end{aligned}$$

The intersection of test line 1×10^{-7} and R_r of 1.35×10^{-5} is at $T = 0.15$ h (see Fig. 3). But $T = 9$ min is too short for convenience. Consider $T = 0.3$ h instead. Doubling the value of T at constant R_r doubles E, as seen in (7), and hence the value of the test line; thus the detector reject level is increased to 1×10^{-8} atm · cm^3/s. A $-45°$ test line established at $T = 0.3$ h and $R_r = 1.35 \times 10^{-5} s^{-1}$ ($R_r E = 2 \times 10^{-7}$) intersects the $t = 3000$ s characteristic at $R_r = 3.3 \times 10^{-3}$ so that the maximum standard leak rate for helium $L = 3.3 \times 10^{-5}$ atm · cm^3/s and then $L_{air} = 1.2 \times 10^{-5}$ atm · cm^3/s. However 1.2×10^{-5} is borderline for any gross leak test, and the only way to increase the present limit significantly is to decrease the dwell time. Decreasing dwell time to the 1000-s (~17-min) characteristic would lead to an R_r of 1.1×10^{-2} and hence an $L_{air} \sim 4.1 \times 10^{-5}$ atm · cm^3/s for some improvement in overlap between the fine and gross leak test. Note that an increase in dwell time beyond ~1 h would pull the intersection point off the straight line region of $E(T)$. It should also be noted that P_E could be dropped to 2.5 atm pressure and the original value of leak detector reject limit of 5×10^{-9} atm · cm^3/s be retained without changing the pressurization time test limits. Only the ratio of signal to background would be affected.

Since a leak size of 5×10^{-8} atm · cm^3/s in a 0.01-cm^3 volume produces a time constant of only 2 days, consider a decrease in the reject leak size by a factor of 5 to give 1×10^{-8} atm · cm^3/s. Then R_r becomes 2.7×10^{-6} s^{-1} and the intersection of this value with the 2×10^{-7} test line shows $T = 7.5$ h, a 25-fold increase in pressurization time; i.e., with (7) $R_r \cdot E \sim R_r^2 T/P_0$.

3) Repetitive Measurement: Often the package may include an initial partial pressure of helium because of prior testing or prefill, and this initial concentration will affect the test results. In practice specimens are conditioned in vacuum or allowed to stand for some time until an initial leak detector reading is relatively small, but when such a long wait time may not be suitable or where some accuracy is required a formal correction procedure is desirable.

The specimen is first placed in the inlet of the leak detector and an initial measurement is made of the effusion. The effusion rate R_1 is related to the interior partial pressure P_1 and to the standard leak rate through (2) and (10) as

$$R_1 = P_1 \frac{L}{P_0}.$$

After another delay period of t'', the specimen is subjected to hermetic test, and a final measurement is made. The initial partial pressure P' just prior to pressurization, after further possible effusion during the delay, is

$$P' = \frac{R_1 P_0}{L} \cdot \exp(-R_r t''). \tag{12}$$

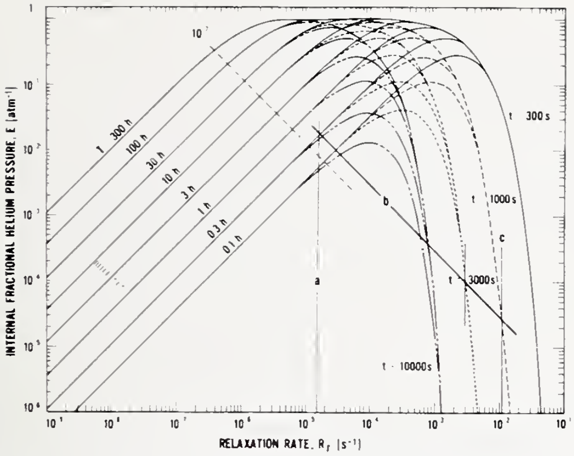

Fig. 3. Selection of pressurization parameters for helium leak detector method: an example. Reject leak size (air) of 5×10^{-8} atm·cm^3/s with $V = 0.01$ cm^3, $P_E = 5$ atm, $t = 3000$ s, and minimum detectable signal of 5×10^{-9} atm·cm^3/s for signal-to-noise of 5. Line (a) represents an R_r of 1.35×10^{-5} s^{-1} for helium. Then $R/(P_0VP_E) = 1 \times 10^{-7}$ s^{-1}·atm^{-1}. First intersection of 10^{-7} test line and (a) at $T \sim 0.15$ h is not satisfactory, so $T = 0.3$ h is chosen. Line (b) becomes the test line. Intersection of (b) at $t = 3000$ s leads to leak size of 1.2×10^{-5} atm·cm^3/s of air. Line (c) for intersect at $t = 1000$ s leads to $L_{air} \approx 4.1 \times 10^{-5}$ atm·cm^3/s.

The measured leak rate R_2 obtained after pressurization is equal to LP/P_0 where P is now described by (4). With (4), (6), and (12), it follows that

$$R_2 = R_1 \exp(-R_r t'')\,[\exp(-R_r t_2) - P_0 E_2] + P_0 V P_E R_r E_2 \tag{13}$$

where the subscript 2 denotes the quantities related to the pressurization sequence. As a general approach, the solution is obtained by successive approximation as follows.

a) Compute an approximate test line value from

$$\frac{R_2}{P_0 V P_E} \cong R_r \cdot E_2.$$

b) With this test line find the approximate values for R_r and E_2 at $E(T_2, t_2)$, here designated as R_r' and E_2'.

c) Compute the value of $\exp(-R_r' t_2)$ from the value of t_2 used in the test.

d) Compute the value of $\exp(-R_r' t'')$ from the measured value of t''.

e) With these approximate values from b, c, d

$$\frac{R_2 - R_1 \exp(-R_r' t'')\,[\exp(-R_r' t_2) - P_0 E_2']}{P_0 V P_E} \cong R_r \cdot E_2. \tag{14}$$

This then is a corrected test line from which the two possible solutions may be obtained at the intersects for $E(T_2)$ and $E(t_2)$. Further iteration can be made.

If however the first approximated test line crosses the $E(T)$ characteristics in the region of straight line projections, then

$$\exp(-R_r t'') \to 1$$

$$\exp(-R_r t_2) \to 1$$

$$E_2 \ll 1,$$

so that by (14)

$$\frac{R_2 - R_1}{P_0 \cdot V \cdot P_E} = R_r \cdot E_2 \tag{15}$$

as one might expect.

At the large leak end of the test line, the solution is somewhat insensitive to variation in test line value since R_r is primarily a function of t_2, i.e.,

$$\exp(-R_r t'') < 1$$

$$\exp(-R_r t_2) \to 0$$

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and the prereading does not produce a significant correction.

Thus one only need see where the approximated test line falls to determine how much further iteration is required. If it falls in the fine leak area of straight line projections, simply take the difference between the final leak detector value and the prereading and calculate the test line value. The "true" value for R_r is either at $E(T_2)$ or $E(t_2)$. If only the large leak value is desired, simply calculate the test line from R_2. If the approximated test line falls in the intermediate R_r range, the iteration procedure is appropriate.

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whence

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so

$$R^*/(P_0 V P_E^* SK) = E^* = 2.5 \times 10^{-2} \text{ atm}^{-1}.$$

As shown in Fig. 4 a line is erected at $R_r = 2.94 \times 10^{-6}$ s^{-1}, and a horizontal test line is placed at $E^* = 2.5 \times 10^{-2}$. At the intersection, $T = 2.4$ h. At the intersection with the $t = 1000$ s segment, R_r^* max $= 3.7 \times 10^{-3}$ s^{-1} such that $L_{air} = 6.3 \times 10^{-5}$ atm · cm^3/s. Note that leak rates are for Kr^{85} and hence R_r values are smaller than for helium for a given air leak.

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which is of the same form as (14). In the small leak range where $\exp(-R_r^* t'')$ and $\exp(-R_r^* t_2)$ are ~1, and as $E_2^* \ll 1$, the initial count rate is a direct correction or

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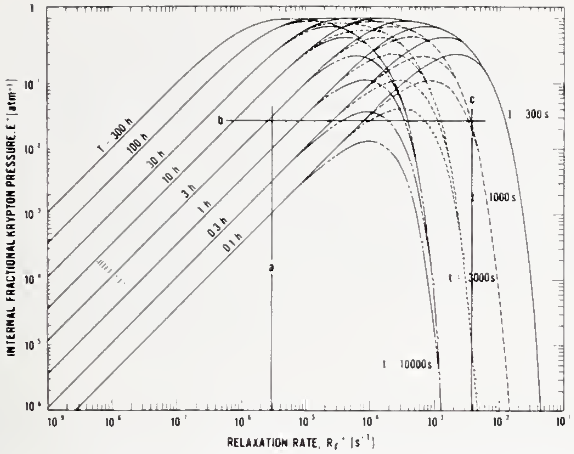

Fig. 4. Test line and example of test range for radioisotope method. Reject leak size of 5×10^{-8} atm·cm^3/s of air with $V = 0.01$ cm^3 $P_E^* = 5$ atm of Kr-N_2 mixture, $S = 200$ μCi/atm·cm^3, $K = 10^4$ min^{-1}·μCi^{-1}, and a minimum detectable count rate of 2500 min^{-1} for a signal-to-noise ratio of 5. Line (a) represents R_r^* of 2.94×10^{-6} s^{-1} for Kr^{85}. $R^*/(P_0 V P_E^* SK) = E^* = 2.5 \times 10^{-2}$ atm^{-1} is test line (b). The intersection of (a) and (b) sets $T = 2.4$ h. At the intersection of (b) and the $t = 1000$ s, line (c) represents $R_r^* = 3.7 \times 10^{-3}$ s^{-1} which leads to $L_{air} = 6.3 \times 10^{-5}$ atm·cm^3/s.

In the large leak range where $\exp(-R_r^* t'') < 1$, $\exp(-R_r^* t_2) \rightarrow 0$, and $E_2 \ll 1$, the prereading is not significant. In the intermediate range, (22) is solved by iteration just as for the helium leak detector with the exception of the horizontal test lines and R_r^* values for Kr^{85} rather than for helium.

V. COMPARISON OF HELIUM AND RADIOISOTOPE METHODS

Within the molecular flow regime test results obtained with the two methods can be compared with the use of characteristic leak-test curves. The capability of the helium leak detector method is oriented toward the larger leak sizes and smaller volumes, for the pressurization time increases rapidly along the helium test line as the relaxation rate diminishes. The radioisotope method requires a longer pressurization time with intermediate leak sizes because the leak rate for Kr^{85} is some 4.6 times smaller than that for He in the same leak channel; however the pressurization time increases but linearly as the relaxation rate diminishes. The radioisotope test line tends to lie in the nonlinear portion of the characteristics, particularly at the large leak end, but in this range the 45° slope of the helium leak detector method tends to both the smaller values for E and the larger values of R_r where straight line segments give reasonable approximation. However in the conversion to air leak rates, both methods produce the same approximate upper limit when the same dwell times are used. The radioisotope method does allow shorter dwell times in use and therefore can in principle extend to a larger upper limit of leak size. The short dwell time obtainable with the radioisotope method also allows two cycle testing for extension to gross leak sizes [13].

TABLE I
COMPARATIVE VALUES FOR HELIUM LEAK DETECTOR AND RADIOISOTOPE TESTING OF HERMETIC PACKAGES[1]

V (cm^3)	L_{air} (atm·cm^3/s)	R_r (s^{-1})	T^*	T/T^*	n^*/n
0.01	10^{-6}	2.7×10^{-4}	255 s	0.0016	
	10^{-7}	2.7×10^{-5}	0.71 h	0.016	
	10^{-8}	2.7×10^{-6}	7.1 h	0.16	0.16
10	10^{-6}	2.7×10^{-7}	255 s	1.6	
	10^{-7}	2.7×10^{-8}	0.71 h	16	
	10^{-8}	2.7×10^{-9}	7.1 h	161	161

[1] Derived from (23). Pressurization times T/T^* for equal signal-to-background ratios, and signal-to-background ratios n^*/n for equal pressurization times. $S = 200$ μCi/atm·cm^3, $K = 10^4$ min^{-1} μCi^{-1}, $R_0 = 5 \times 10^{-10}$ atm·cm^3/s helium, $R_0^* = 500$ min^{-1}.

A direct numerical comparison can also be obtained for the fine leaks by using (19) for the radioisotope method, (11) for the helium method, the approximation of (7), and the detector outputs in terms of signal-to-background, for the same pressurization value, as

$$\frac{n^* R_0^*}{n R_0} = \frac{SK}{4.61 R_r} \cdot \frac{T^*}{T} \tag{23}$$

where the ratio R_r^* to R_r is equal to the ratio of the standard leak rates for a given leak size which is $(M^{He}/M^{Kr})^{1/2}$ or 1/4.61, n is the signal-to-background ratio, and R_0 is the threshold signal. Some results are listed in Table I. Note that the radioisotope pressurization times are independent of volume per (20). A comparison of signal-to-background ratios is listed in the last column for equal pressurization times.

VI. SUMMARY

The molecular flow formulation for the back pressurization method of hermetic testing has been condensed into a normalized set of characteristic curves from which specific solutions can be obtained by means of a test line. The characteristics are appropriate for both the helium leak detector and and radioisotope methods of test, while the form of the test line distinguishes between two methods. Minimum detectable and maximum detectable leak sizes can be determined simultaneously from the one set, and the selection of suitable test conditions is facilitated. Procedures are also derived for applying corrections due to prior testing or prefill.

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A graphical procedure for solution of the molecular flow approximation for the back pressurization method of hermetic test makes use of a set of characteristic curves and a test line. The characteristic curves are appropriate for both the helium leak detector and the radioisotope methods of test, although the form of the test line differs between the two methods. Master graphs of the characteristic curves and test lines are now provided in a scale and format appropriate for producing suitable worksheets with a copier. Step-by-step instructions are given for their use in obtaining solutions for various examples relative to the test specifications in acceptance standards such as MIL-STD 883B, etc. One set of characteristics is provided specifically for the helium leak detector mode as expressed directly in terms of air leak rate; a second set is provided specifically for the krypton-85 radioisotope mode also in terms of air leak rate; and a third set is retained in the original form for use with any tracer gas.

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