Hermeticity and Reliability Issues in Microsystems Packaging

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Leading the Next

Hermeticity and Reliability Issues in Microsystems Packaging

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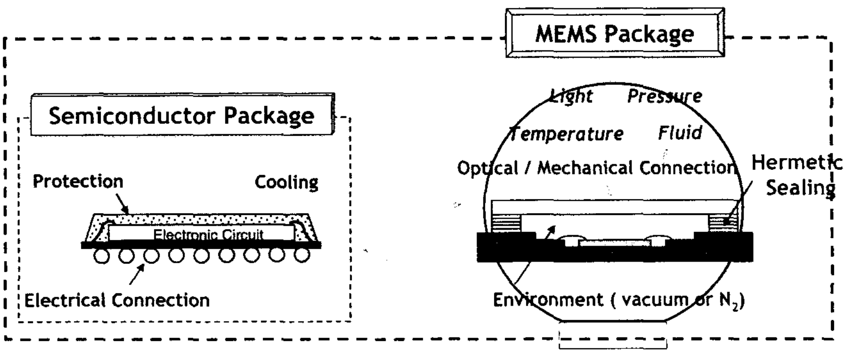
Traditional Semiconductor vs. MEMS Packaging

- Semiconductor Packaging :
  Electrical Connection, Heat dissipation, Mechanical Protection
- MEMS Package :
  Electrical, Optical and Mechanical Connection
  Hermetic or Vacuum Cavity for moving structure



Hermeticity Requirement

- Hermeticity is the ability of a seal to maintain an acceptable level of stable and sometimes inert ambience for the packaged device.
  - Units of measurement: atm-cc/s

Why is hermeticity required in MEMS?

Maintain a high-vacuum environment in order to obtain a high Q-factor	Prevent ingress of moisture and contaminants
- e.g. MEMS accelerometers and gyroscopes	- e.g. Thin-Film Bulk Acoustic Wave Resonators (FBARs) Oxidation of the metal electrode of the FBAR filter can result in a frequency shift

Classification of MEMS devices

- Class I : No moving parts
  - Accelerometers, Pressure Sensors, Ink Jet Print Heads, Strain gage
  - Particle contamination, Shocked-induced stiction
- Calss II : Moving parts (No rubbing or impacting surfaces)
  - Gyros, Comb Drives, Resonators, Filters
  - Particle contamination, Shocked-induced stiction, Mechanical fatigue
- Class III : Moving parts (Impacting surfaces)
  - TI DMD, Relays, Valves, Pumps
  - Particle contamination, Shocked-induced stiction, Stiction, Mechanical fatigue, Impact damage
- Class IV : Moving parts (Impacting and rubbing surfaces)
  - Optical switches, Shutters
  - Particle contamination, Shocked-induced stiction, Stiction, Mechanical fatigue, Mehcnical fatigue, Friction, Wear

MEMS Reliability Issues

- Mechanical Wear
  - Sliding contact
  - Solid against solid (some actuators), Liquid against solid (nozzles)
- Fracture
  - High strain
  - Flex joints (some actuators), Springs(resonators)
- Fatigue
  - Repetitive strain
  - Flex joints, Springs
- Optical Degradation
  - Due to high intensity light or environmental effects
  - Mirror surfaces

MEMS Reliability Problem Sources

- Charging
  - In dielectrics in MEMS
  - Comb drives
- Shocks
  - High g applications, Dropping devices, Shipping (especially released)
- Vibration
  - Mobile applications, Aerospace vehicles, Land vehicles (esp. military)
- Stiction
  - High humidity, During initial release, During high-humidity storage
  - Capillary, Electrostatic, van der Waals force
- Thermal Degradation
  - High temperature applications
  - Degradation of hydrophobic coatings, Change in stress

MEMS Reliability Issues

- ❑ Thermal Cycling
  - Non-temperature controlled applications
  - Difference in thermal expension coefficient
- ❑ Humidity
  - Possible stiction, wear
- ❑ Stress Corrosion Cracking
  - High stress with high humidity
- ❑ Creep
  - Repetitive high strain usage
  - Resonators, High flex optical redirectors
- ❑ Environmental Degradation
  - Corrosive or other adverse environments, Devices that interact directly
  - Pressure/chemical sensors etc.

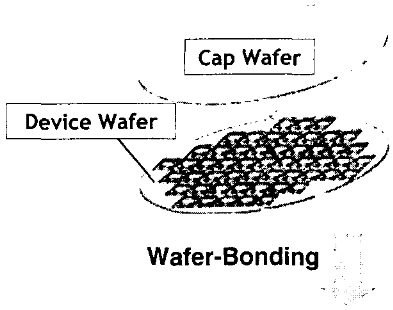
MEMS Reliability Issues

- ❑ Radiation
  - Space, Reactors
- ❑ Electrostatic Discharge
  - Handling MEMS, Packaging
- ❑ Residual stress
  - Thermal mismatch, Intrinsic stress
  - Microstructure
- ❑ Cavitation force
  - Erosion
  - Flow channel, Inkjet print head

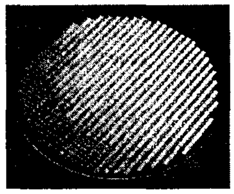
Wafer level Package (WLP)

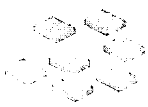
- The die and package are fabricated and tested on the wafer *prior* to singulation.

- Advantages
  - Batch processing.
    Lowest cost because the processing and testing is done at the wafer level in one set of parallel steps.
  - Enhanced electrical performance because of the short interconnections
  - Smaller package



Dicing





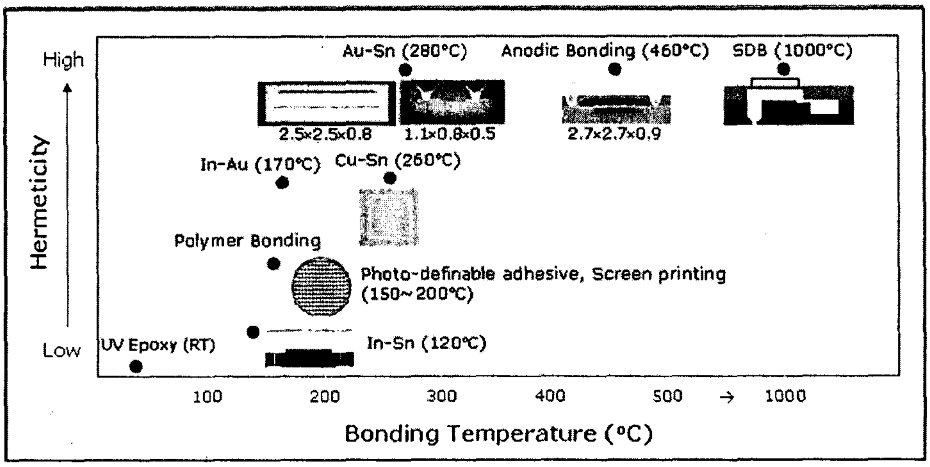
Array of wafer level packages formed by bonding a cap wafer to the substrate wafer. Each package houses a MEMS device and is eventually singulated by dicing

Bonding Technology

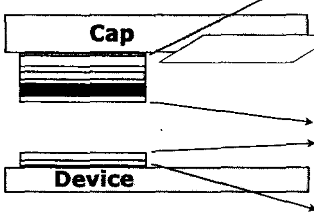
Bonding Techniques

Techniques without intermediate layer			Techniques with intermediate layer		
Seam/Laser Welding	**Silicon direct fusion bonding**	**Anodic bonding**	**Eutectic bonding**	**Adhesive bonding**	**Glass frit bonding**
Kovar @low temp	Fusion Bonding Si-Si @~1100°C Glass-glass @~650°C	Si-glass @300°C	Si-Au @~400°C PbSn @183°C InSn @118°C	polymer, PR, polyimide, epoxy @125°C~400°C	Glass @~400°C
-Partially low temp -Reliable,Hermetic -High cost	-Wafer level -High temp -Vacuum process	-Wafer level -High temp -Vacuum process	-Low cost -Hermetic -Oxidation	-Low cost -Non hermetic -Outgassing	-Wafer level -High temp -Outgassing

Wafer Bonding Solutions



SEM Image & EDAX Analysis of the bonding layers



Cr	0.05
Au	1.5
Ti	0.1
Ni	0.2
Au	0.07
Sn	2.9
Au	0.08

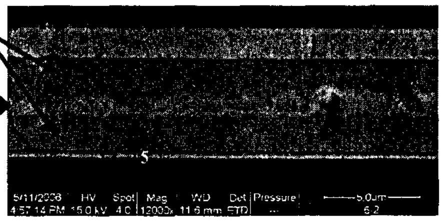
Au	2.0
Ni	0.2
Ti	0.1

TABLE 1
EDAX RESULT OF DIFFERENT INTERFACIAL LAYERS

Layer	Element	Weight %	Atomic %
L1	Au	100	100
L2	Au	52.48	36.37
	Sn	39.88	45.87
	Ni	7.64	17.77
L3	Au	91.54	86.70
	Sn	8.46	13.30
L4	Au	51.59	34.56
	Sn	38.16	42.42
	Ni	10.25	23.02

$AuSn_2$ (ε Phase) with ternary Au-Sn-Ni

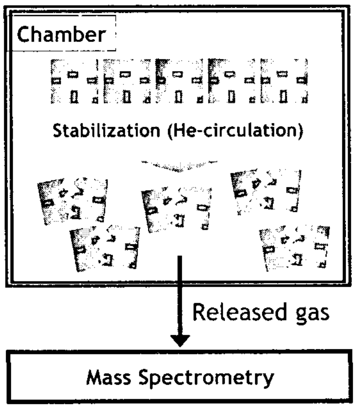
Au_5Sn (ζ Phase)



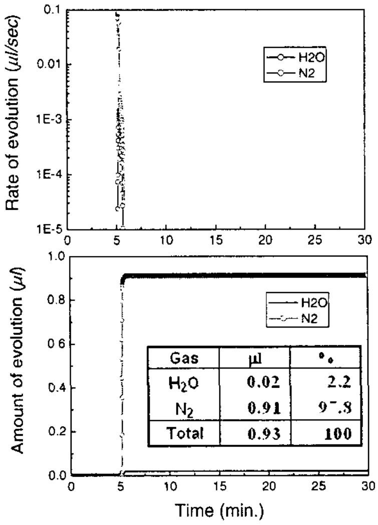
- The shear strength values measured for many samples are ranged from 50.79 Mpa to 86.76 MPa, and an average value of **71.5 MPa** was obtained.

Residual Gas Analysis

TPD-MS (Temperature-programmed desorption-mass spectrometry



- 5 x Cavity Volume (0.14 µl) = 0.7 µl
- Bonding at 1atm N_2 Environment

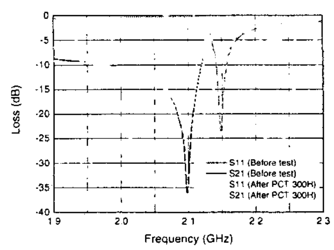


Gas	µl	%
H_2O	0.02	2.2
N_2	0.91	97.8
Total	0.93	100

Summary of Reliability Test

❑ RF performance of FBAR before and after reliability test

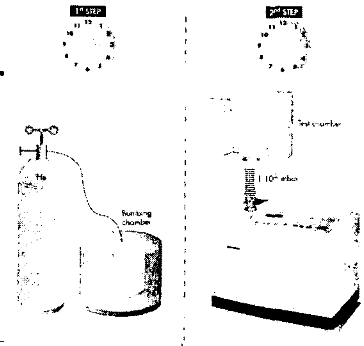
Item	Condition	Samples		Δf_s (MHz)	Δf_r (MHz)	ΔIL (dB)
Pressure cooker test	121°C, 100% RH, 2 atm 300 Hours	21	Mean	2	0	0.014
			STD	0.79	0	0.015
High humidity storage test	85°C, 85% RH 1000 Hours	21	Mean	2	0	0.016
			STD	0.67	0.43	0.004
High temp storage test	125°C, 100% RH 1000 Hours	21	Mean	2	0	0
			STD	0.57	0	0.006
Temperature cycle test	-55°C ↔ 125°C, 15 min. dwell 1000 cycles	21	Mean	2	0	0
			STD	0.81	0	0.005



❑ RGA before and after reliability test

Gas	Amount of gas					
	Before the tests		PCT 300 Hours		85/85 1000 Hours	
	µl	%	µl	%	µl	%
H_2O	0.02	2.2	0.02	2.0	0.02	2.5
N_2	0.91	97.8	1.12	98.0	0.90	97.5
Total	0.93	100	1.14	100	0.93	100

Helium fine leak test*



Specimen with cavity volume, V, is pressurized with high-pressure (P_b) helium in a bombing chamber for several hours (t_b)

↓

Specimen is transferred into a He mass spectrometer.

↓

Spectrometer is switched on. The *measured* (apparent) leakage rate, R is proportional to the spectrometer output current.

Dwell time (t_{dwell})

Time between the *end of bombing* and the *start of the measurement* in the spectrometer.

Note that some helium leaks out during this time.

- ❑ **Procedure has been described in Method 1014 of MIL-STD-883**

*Greenhouse, H., Hermeticity of electronic packages, Noyes publications, NJ, USA, , 2000, pp. 197.

True leak rate and Apparent leak rate

- ❑ **Apparent leakage rate, *R***
  - The leak rate measured by the spectrometer.
  - Dependent on test conditions
  - Depends on the pressure differential and is hence *time variant.*

- ❑ **True leakage rate, *L***
  - Defined as the amount of gas that would leak out per second for a pressure differential of 1 atm between the outside and the inside of the package.
  - Independent of test conditions
  - For a given gas it is a characteristic of the package and is hence *time invariant.*
  - Straightforward correlation between true leak rates of different gases.

True leakage rate facilitates meaningful comparisons.

Governing Equation for the He Fine Leak Test

Molecular conduction based equation

$$P_{specimen} = P_b(1 - e^{-Lt_b/VP_o})$$ Bombing

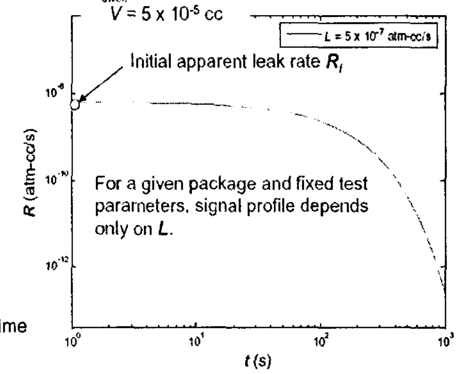
$$P_{specimen} = P_b(1 - e^{-Lt_b/VP_o})e^{-Lt_{dwell}/VP_o}$$ After leakage during dwell

$$P_{specimen} = P_b(1 - e^{-Lt_b/VP_o})e^{-Lt_{dwell}/VP_o}e^{-Lt_s/VP_o} \; *$$

$$R = \frac{LP_{specimen}}{P_o}$$ Apparent leakage rate

$$\Rightarrow R = \frac{LP_b}{P_o}(1 - e^{-Lt_b/VP_o})e^{-Lt_{dwell}/VP_o}e^{-Lt_s/VP_o}$$

P_b = 5 atm
t_b = 6 hours
t_{dwell} = 10 minutes
V = 5 x 10^{-5} cc



P_b : Bombing pressure, t_b = Bombing time, t_{dwell} = Dwell time
V = Package volume
L = True *helium* leak rate
t_s = time elapsed after switching on the spectrometer

* The second exponential term accounts for leakage once the spectrometer starts.

MIL-STD-883 Method 1014*

- Establishes the guidelines for the helium fine leak test
  - Fixed method
  - Flexible method

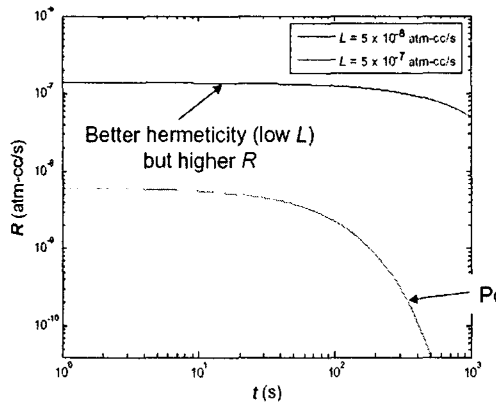
Fixed method

Volume of package (V) in cm³	Bomb condition			R_l Reject limit (atm cc/s He)
	P_b Psia ±2	Min. Exposure time hours (t_b)	Maximum dwell hours (t_{dwell})	
<0.05	75	2	1	5 x 10^{-8}
>0.05 - <0.5	75	4	1	5 x 10^{-8}
>0.5 - <1.0	45	2	1	1 x 10^{-7}
>1.0 - <10.0	45	5	1	5 x 10^{-8}
>10.0 - <20.0	45	10	1	5 x 10^{-8}

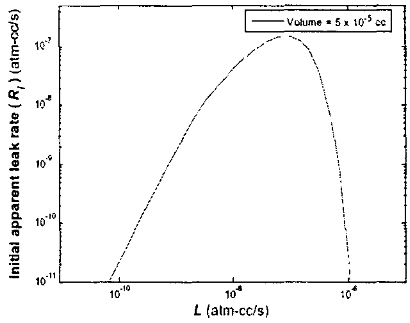
- Prescribed volume-dependant test conditions for the fixed method
- The package is rejected if the apparent leak rate is higher than R_l

Apparent Leak Rate (*R*) is Not a Hermeticity Metric!

Simulated Parameters
P_b = 5 atm
t_b = 6 hours
t_{dwell} = 10 minutes
$V = 5 \times 10^{-5}$ cc



R_i Depends on Test Parameters



Poorer hermeticity (high *L*) but lower *R*

MIL-STD-883 Method 1014 (contd.)

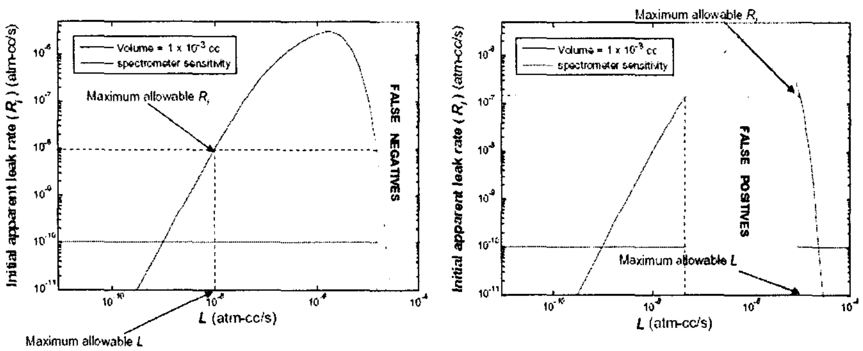
Flexible method

- Reject limit is established in terms of the true air leak rate (L_a).
  - Less than 5×10^{-8} atm cc/s air (V < 0.01cc)
  - Less than 1×10^{-7} atm cc/s air (0.01cc < V < 0.4cc)
  - Less than 1×10^{-6} atm cc/s air (V > 0.4cc)
- Reject limit in terms of the apparent leak rate (R_l) is calculated using this value.

$$R_l = \frac{L_a P_b}{P_0}\left(\frac{M_a}{M_{helium}}\right)^{\frac{1}{2}}\left\{1-e^{-\frac{L_a t_b}{VP_0}\left(\frac{M_a}{M_{helium}}\right)^{\frac{1}{2}}}\right\}e^{-\frac{L_a t_{dwell}}{VP_0}\left(\frac{M_a}{M_{helium}}\right)^{\frac{1}{2}}}$$

  - M_a and M_{helium} are the molecular weights of air and helium, respectively.
  - P_0 is a constant and is equal to 1 atm.
  - P_b, t_b and t_{dwell} are the bombing pressure, bombing time and the dwell time, respectively.
  - V is the package volume.
- Guideline: Any values can be chosen for the test parameters as long as they produce a signal in the spectrometer.
- Recent change to MIL TM 1014 dated June 2004 requires the "Flexible" method unless otherwise specified.

Applicability of MIL-STD Guidelines



Simulated Test Parameters:
P_b = 5 atm, t_b = 6 hours and t_{dwell} = 10 minutes.

- ❑ **Applicability of the MIL-STD guidelines to small volumes is limited.**

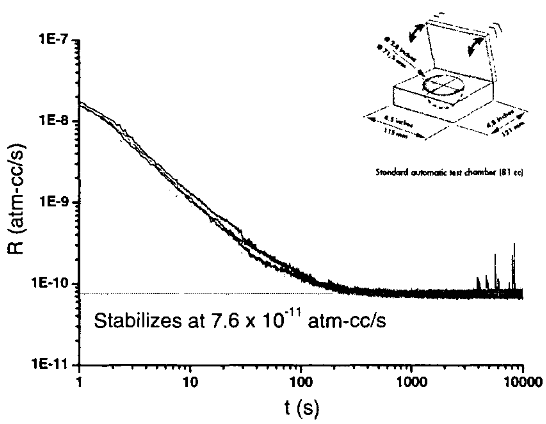
Quantifying Hermeticity

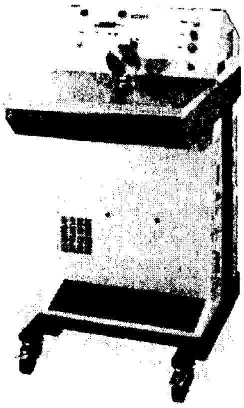
- ❑ **MIL-STD guidelines are inadequate for hermeticity testing of micro- and nano-liter packages.**
- ❑ **There is a need to generate a *characteristic metric (L)* of the package which can be used for reliability analysis.**
  - **'R' cannot be used as a metric for packages with small volumes.**
- ❑ **He fine leak test has been used only for qualitative comparisons.**
  - **Prediction of leakage under different ambient conditions/temperature is not possible.**

- ❑ **Procedure to extract *L* from the test.**
- ❑ **Standardization of the procedure.**

Zero Signal

- ❑ Noise due to He present in the test chamber of the spectrometer, which is measured by operating the spectrometer without a specimen.



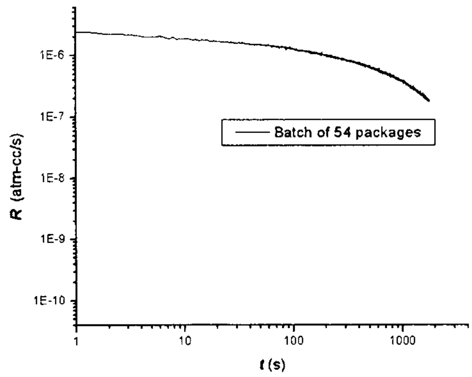


Batch Test Using Multiple Packages

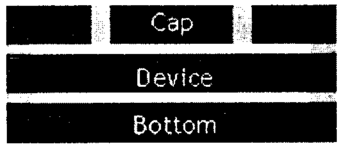
- ❑ Measurement of a leakage rate lower than the lower measurable limit seems possible by a batch test using multiple packages:
  - Several small packages are bombed simultaneously and then the entire batch is transferred into the spectrometer for testing.
  - Total leakage, i.e., the spectrometer signal is the *sum* of leakage from each of the packages in the batch and can be detected by the spectrometer.

Preliminary Experiment

- ❑ Tested a batch of 54 packages



Apparent leak rate profile from the test on a batch of 54 packages.



Schematic cross-section of the package

$V = 2.156 \times 10^{-4}$ cc

Test Parameters

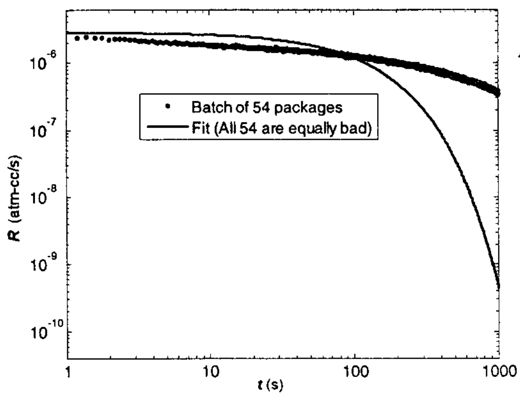
$P_b = 5$ atm

$t_b = 6$ hours

$t_{dwell} = 10$ minutes.

Assumption: All 54 are equally bad

- ❑ Using the governing equation (modified for the above assumption) as the fitting function, a very poor fit was obtained



$$R = \frac{54LP_b}{P_0}(1-e^{-Lt_b/VP_o})e^{-Lt_{dwell}/VP_o}e^{-L_1t_s/VP_o}$$

Test Parameters

$P_b = 5$ atm

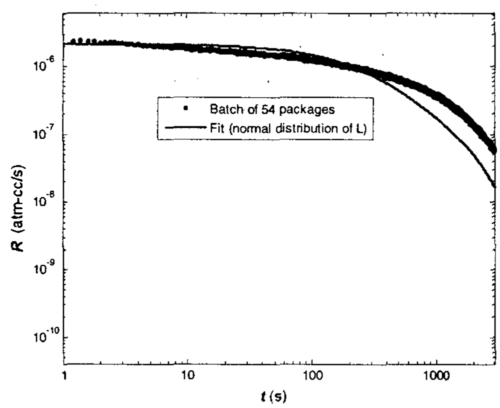
$t_b = 6$ hours

$t_{dwell} = 10$ minutes.

$V = 2.156 \times 10^{-4}$ cc

Assumption: Gaussian distribution of *L*

- This yields an improved fit but not a very good one.



$$R=\sum_{i=1}^{54}\frac{L_iP_b}{P_0}(1-e^{-L_it_b/VP_0})e^{-L_it_{dwell}/VP_0}e^{-L_it_s/VP_0}$$

where, L_i $(1 \le i \le 54)$ are normally distributed

Test Parameters

P_b = 5 atm
t_b = 6 hours
t_{dwell} = 10 minutes.
V = 2.156 x 10^{-4} cc

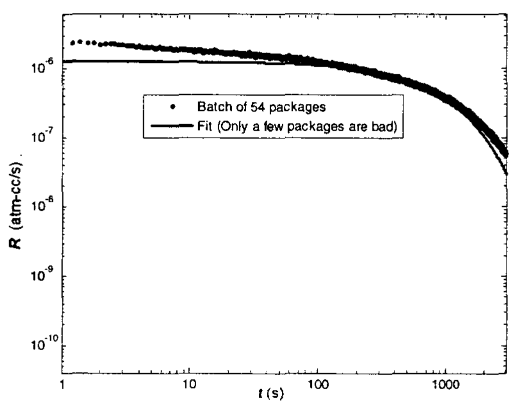
R^2 = 0.8299

L_μ = 4.9 x10^{-6} atm-cc/s

L_σ = 2.6 x10^{-6} atm-cc/s

Assumption: Only a few packages, with the same *L*, are bad

- This yields the best possible fit.



$$R=\frac{nLP_b}{P_0}(1-e^{-Lt_b/VP_0})e^{-Lt_{dwell}/VP_0}e^{-Lt_s/VP_0}$$

Test Parameters

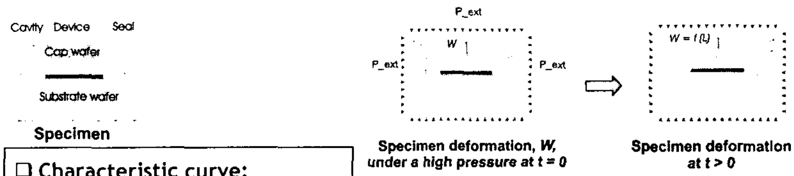
P_b = 5 atm
t_b = 6 hours
t_{dwell} = 10 minutes.
V = 2.156 x 10^{-4} cc

R^2 = 0.9484

Number of bad packages = 2

L = 2.7 x 10^{-7} atm-cc/s

Hermeticity Measurement by an Optical Technique



❑ Characteristic curve: Relationship between the deformation and the pressure differential
$W(t) = g(\Delta P(t))$

❑ Measure deformation under a constant applied pressure as a function of time W_{t_1}, W_{t_2}

❑ Governing equation for leakage rate
$L = \Gamma(\Delta P_{t_1}, \Delta P_{t_2}, t_1, t_2, V)$

$$L = \ln\left(\frac{(\Delta P)_{t_1}}{(\Delta P)_{t_2}}\right)\left(\frac{V}{t_2 - t_1}\right)$$

Summary

❑ A mathematical model has been developed and used to analyze the limits of He fine leak test.

❑ Uncertainties inherent in using the MIL-STD-883 guidelines for hermeticity evaluation of small packages have been demonstrated.

❑ A new methodology to quantitatively characterize hermeticity has been developed.

감사합니다