ACCELERATED LIFE TESTING (ALT) IN ELECTRONICS AND PHOTONICS
and Its Role in Probabilistic Design for Reliability (PDfR) and Qualification Testing

"You can see a lot by observing"
Yogi Berra, American Baseball Player

"It is easy to see, it is hard to foresee"
Benjamin Franklin, American Scientist and Statesman

E. Suhir

Bell Laboratories, Physical Sciences and Engineering Research Division, Murray Hill, NJ (ret),
University of California, Dept. of Electrical Engineering, Santa Cruz, CA,
University of Maryland, Department of Mechanical Engineering, College Park, MD, and
ERS Co. LLC, 727 Alvina Ct. Los Altos, CA, 94024
Tel. 650-969-1530, cell. 408-410-0886, e-mail: suhire@aol.com

Tutorial at PHM Conference,
Portland, OR, October 11, 2010

Contents

I. Accelerated Testing (AT) and the Roles of Advanced Measurement Techniques (AMT) and Predictive Modeling (PM)

II. Probabilistic Design for Reliability, Its Role and Significance: What Could One Gain by Using It?

III. Do Electronic and Photonic Industries Need New Approaches to Qualify Their Products?

I. Accelerated Testing (AT) and the Role of Predictive Modeling (PM)

Reliability is part of applied probability

➢Reliability Engineering **(RE)** deals with failure modes and mechanisms, root causes of failure occurrence, role of various defects, methods to estimate and prevent failures, and design for reliability **(DfR)** methodologies.

➢RE provides guidance on how to make, through the appropriate qualification testing **(QT),** a promising and viable device into a reliable and marketable product.

➢RE is part of Applied Probability **(AP)** and Probabilistic Risk Management **(PRM)** bodies of knowledge, and   includes the item's (system's) dependability, durability, maintainability, repairability, availability, and other properties that should be viewed and evaluated as probabilities of likely failures.

➢The use of the AP and PRM approaches and techniques puts the art and practices of RE on a "reliable" scientific foundation.

"If a man will begin with certainties, he will end with doubts; but if he will be content to begin with doubts, he shall end in certainties."
*Sir Francis Bacon, English Philosopher and Statesman*

"We see that the theory of probability is at heart only common sense reduced to calculations; it makes us appreciate with exactitude what reasonable minds feel by a sort of instincts, often without being able to account for it… The most important questions of life are, for the most part, really only problems of probability."
Pierre Simon, Marquise de Laplace

"Mathematical formulas have their own life, they are smarter than we, even smarter than their authors, and provide more than what has been put into them"
Heinrich Hertz, German Physicist

E. Suhir

"
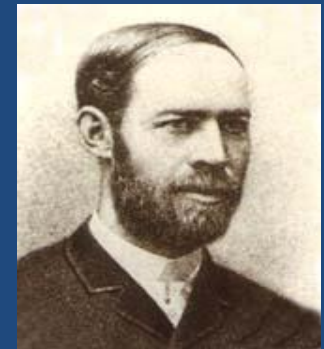
The reliability evaluation and assurance cannot be delayed until the device is made (although it is often the case in many actual industries). Reliability should be

➢ "conceived" at the early stages of its design (a reliability and optical engineers should start working together from the very beginning of the optical device engineering),

➢ implemented during manufacturing (quality control is certainly an important part of a manufacturing process),

➢ qualified and evaluated by electrical, optical, environmental and mechanical testing (both the customer requirements and the general qualification requirements are to be considered),

➢ checked (screened) during production, and, if necessary and appropriate,

➢ maintained in the field during the product's operation, especially at the early stages of the product's use.

Why accelerated tests?

➢It is impractical and uneconomical to wait for failures, when the mean-time-to-failure **(MTTF)** for a typical today's device (equipment) is on the order of hundreds of thousands of hours.

➢For this reason Accelerated Testing **(AT)** is a powerful means in understanding and improving reliability. This is true whether one runs non-destructive QT ("testing to pass") or destructive Accelerated Life Testing (**ALT**) -"testing to fail".

➢To accelerate the device's degradation and failure, one has to deliberately "distort" ("skew") one or more conditions (high temperature dwell; low temperature storage; temperature or power cycling; etc.) affecting the device's functional performance, mechanical (structural, "physical") reliability or environmental durability.

➢ALT uses elevated stress levels and/or higher stress-cycle frequency as stimuli to precipitate failures over a short time frame. Note that the "stress" in RE is not necessarily mechanical or thermo-mechanical: it can be any electrical, optical, thermal or mechanical factor responsible for the device reliability.

Accelerated test categories

Accelerated test type (category)	Product development (verification) tests (PDTs)	Qualification ("screening") tests (QTs)	Accelerated life tests (ALTs) and highly accelerated life tests (HALTs)
Objective	*Technical feedback to ensure that the taken design approach is viable (acceptable)*	*Proof of reliability; demonstration that the product is qualified to serve in the given capacity*	*Understand modes and mechanisms of failure and accumulate failure statistics*
End point	*Time, type, level, and/or number of failures*	*Predetermined time and/or the # of cycles, and/or the excessive (unexpected) number of failures*	*Predetermined number or percent of failures*
Follow-up activity	*Failure analysis, design decision*	*Pass/fail decision*	*Failure analysis and statistical analysis of the test data*
Perfect (ideal) test	*Specific definition(s)*	*No failure in a long time*	*Numerous failures in a short time*

Some most common accelerated test conditions

- High Temperature (Steady-State) Soaking/Storage/ Baking/Aging/ Dwell,
- Low Temperature Storage,
- Temperature (Thermal) Cycling,
- Power Cycling,
- Power Input and Output,
- Thermal Shock,
- Thermal Gradients,
- Fatigue (Crack Initiation and Propagation) Tests,
- Mechanical Shock,
- Drop Shock (Tests),
- Random Vibration Tests,
- Sinusoidal Vibration Tests (with the given or variable frequency),
- Creep/Stress-Relaxation Tests,
- Electrical Current Extremes,
- Voltage Extremes,
- High Humidity,
- Radiation (UV, cosmic, X-rays),
- Altitude,
- Space Vacuum

Qualification Tests (QTs)-1

➢ QT is the major means, through which the industries assure that their products will successfully satisfy the market needs.

➢ QT is time limited and, ideally, non-destructive.

➢ The QT objective is to prove that the reliability of the product is above a specified level, which is defined by zero or next-to-zero percentage of failures per lot and/or the number of failures per unit time (failure rate).

➢ QT enables one to "reduce to a common denominator" different products, as well as similar products, but produced by different manufacturers.

➢ QT reflects the state-of-the-art in a particular field of engineering, as well as typical requirements for the performance of the product.

➢Products that met the QT specifications are expected to be able to satisfactorily perform a required function, without failures or breakdowns, for a specific envisaged period of time and under the stated (anticipated) operation and maintenance conditions.

➢Although industry cannot do without QT and standards, the today's QT and specifications might only be good for what they are intended - to confirm that the given device is qualified to become a product.

➢If a device passed the existing QT, it is not always clear why it was good, and if it failed, it is often equally unclear what could be done to improve its reliability.

➢Since QT is not supposed to be destructive, i.e., does not lead to a failure, it is unable to provide the ultimate reliability information - the probability of failure in the field.

➢ALT, on the other hand is aimed at the detecting the possible failure modes and mechanisms, and thereby - at revealing and understanding the physics of failure (**PoF**).. Another objective of the ALT is to accumulate representative failure statistics.

➢Thus, ALT addresses the two major aspects of the RE – physics and statistics of failure.

➢ Adequately planned, carefully conducted, and properly interpreted ALT provides a consistent basis for the prediction of the probability of failure under the given (anticipated) loading (stress) conditions and after the given time in service.

➢This information enables one to effectively decide on what could be changed, if necessary, to design and manufacture a viable and reliable product.

➢Any functional, structural, materials or technological improvement can be "translated", using the ALT data and the appropriate sensitivity analyses, into a low probability of failure in the field.

Accelerated Life Tests (ALTs)-2

➢ Well-designed and thoroughly implemented ALT can dramatically facilitate the solutions to many engineering and business-related problems, associated with cost effectiveness and time-to-market.

➢ It is highly desirable that ALT should be conducted in addition to, and preferably before the QT. There might be also situations, when ALT can be used as an effective substitution for the QT, especially for new products, when suitable QT and standards do not yet exist.

➢While it is the QT that makes a device into a product, it is the ALT that enables one to understand the reliability physics behind the product and, ultimately, to create a product with a low and, if necessary, even controlled probability of failure.

➢ Technical diagnostics, prognostics and health monitoring and management (**PHM**) can play an important role in such an effort.

➢Advanced and reliable measurement techniques (**AMT**) are a must in the ALT effort.

Burn-ins – special type of ALTs

➢ Burn-in ("screening") tests are widely implemented to detect and eliminate infant mortality failures.

➢The rationale behind the burn-in tests is based on a concept that mass production of devices generates two categories of products that pass qualification specifications:

1)   robust ("strong") components that are not expected to fail in the field and

1)   relatively unreliable ("week") components ("freaks") that will most likely fail in the field in some future time, if shipped to the customer.

➢ ALT cannot do without simple and meaningful predictive modeling. It is on the basis of the PM that one decides which ALT parameter should be accelerated, how to process the experimental data and, most importantly, how to bridge the gap between what one "sees" as a result of the ALT and what he/she will most likely "get" in the field conditions.

➢By considering the fundamental physics that might constrain the final design, PM can result in significant savings of time and expense, and shed important light on the PoF.

➢The most widespread ALT models are aimed at the prediction of the MTTF.

➢ Examples:

•power law (used when the PoF is still unclear),

• Boltzmann-Arrhenius equation (used when there is a belief that the elevated temperature is the major cause of failure),

•Coffin-Manson equation (inverse power law; used particularly when there is a need to evaluate the low cycle fatigue life-time),

•crack growth equations (used to assess the fracture toughness of brittle materials),

- Bueche-Zhurkov and Eyring equations (used to assess the MTTF when both the high temperature and stress are viewed as the major causes of failure),
- Peck equation (used to consider the role of the combined action of the elevated temperature and relative humidity)
- Black equation (used to consider the roles of the elevated temperature and current density),
- Miner-Palmgren rule (used to consider the role of fatigue when the yield stress is not exceeded),
- creep rate equations,
- weakest link model (used to evaluate the MTTF in extremely brittle materials with defects),
- stress-strength interference model, which is, perhaps, the most flexible and well substantiated model.
- double exponential of the extreme value distribution (EVD) type

➤ Various PM, other than directly related to ALT, can be extremely helpful to understand the PoF and can be effectively used to optimize the performance, lifetime and cost effectiveness of the item of interest, provided, of course, that its PoF is well understood.

➢ If Boltzmann-Arrhenius equation is used, the mean time-to-failure, τ=tau, is proportional to an exponential function, in which the argument is a fraction, where the activation energy, Ua, eV, is in the numerator, and the product of the Boltzmann's constant, k=8.6174×10^{-5}eV/$^{\circ}$K, and the absolute temperature, T, is in the denominator:

$$\tau = \tau_0 \exp\left[\frac{U_a}{k\left(T - T^*\right)}\right]$$

The equation was first obtained by the German physicist L. Boltzmann in the statistical theory of gases, and then applied by the Swedish chemist S. Arrhenius to describe the inversion of sucrose. Boltzmann-Arrhenius equation is applicable, when the failure mechanisms are attributed to a combination of physical and chemical processes.

➢ Since the rates of many physical processes (such as, say, solid state diffusion, many semiconductor degradation mechanisms) and chemical reactions (such as, say, battery life) are temperature dependent, it is the temperature that is used as an acceleration parameter.

➢As to the failure rate, if, for instance, one assumes that the random time to failure is distributed in accordance with the exponential law, then the steady-state failure rate for a system whose mean-time-to-failure is given by the Boltzmann-Arrhenius equation can be found as

$$\lambda = \frac{1}{\tau_0} \exp\left[-\frac{U_a}{k\left(T - T^*\right)} \right]$$

➢The probability of failure at the moment *t* of time can be found as

$$P = 1 - e^{-\lambda t}$$

This formula is known as exponential formula of reliability.

Mechanical Behavior and Reliability of Solder Joint Interconnections in Thermally Matched Assemblies
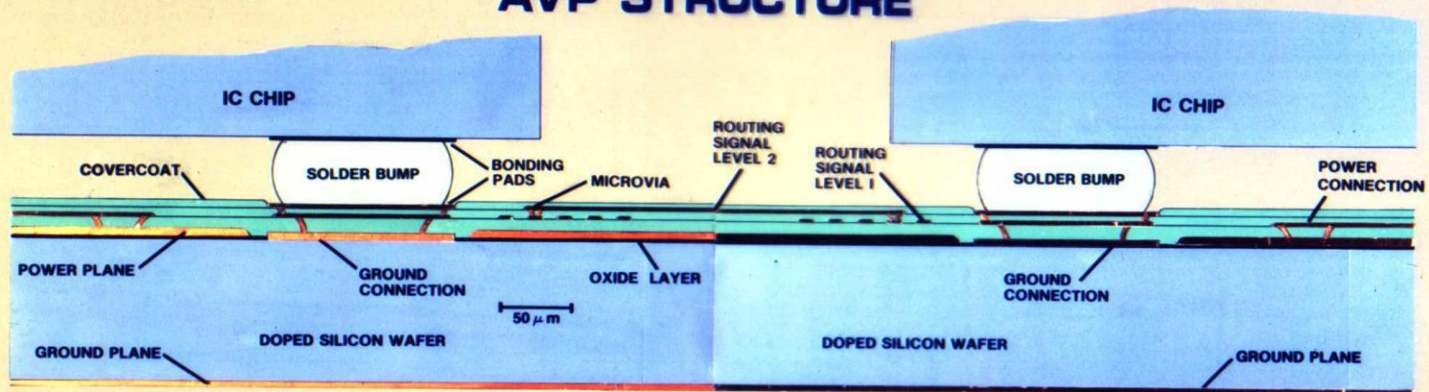
Example

E. Suhir
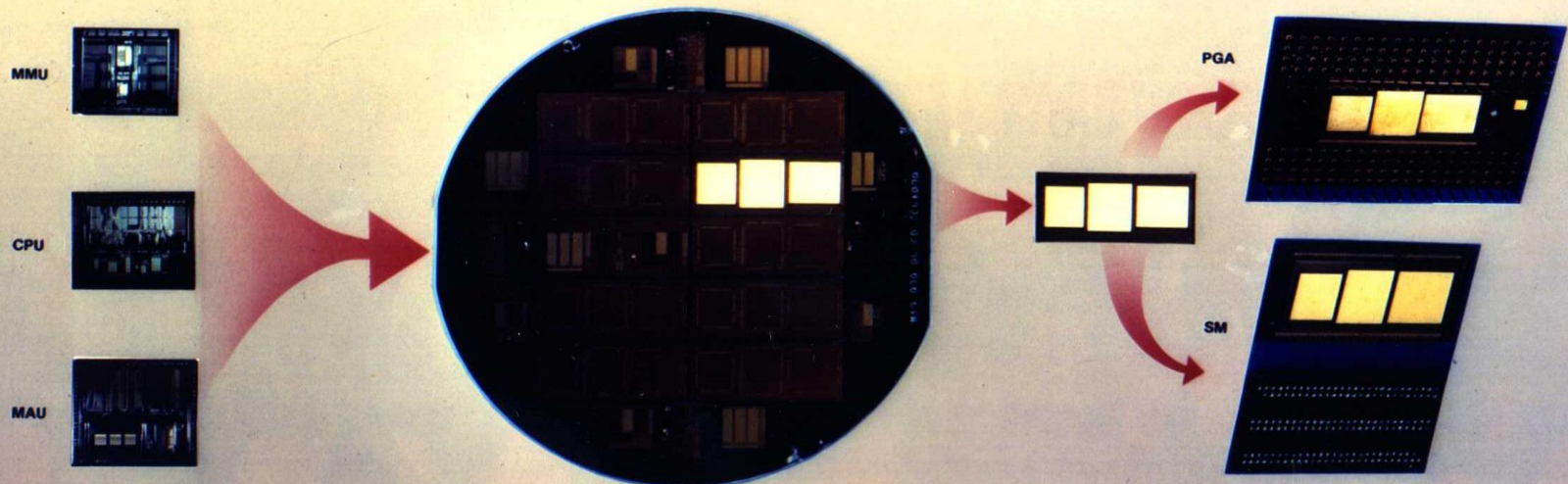AT&T Bell Laboratories
Murray Hill, New Jersey

ADVANCED VLSI PACKAGING (AVP) TECHNOLOGY

IC FLIP-CHIP SOLDER BUMP TECHNOLOGY
AND SILICON SUBSTRATE WITH MULTILAYER INTERCONNECTION
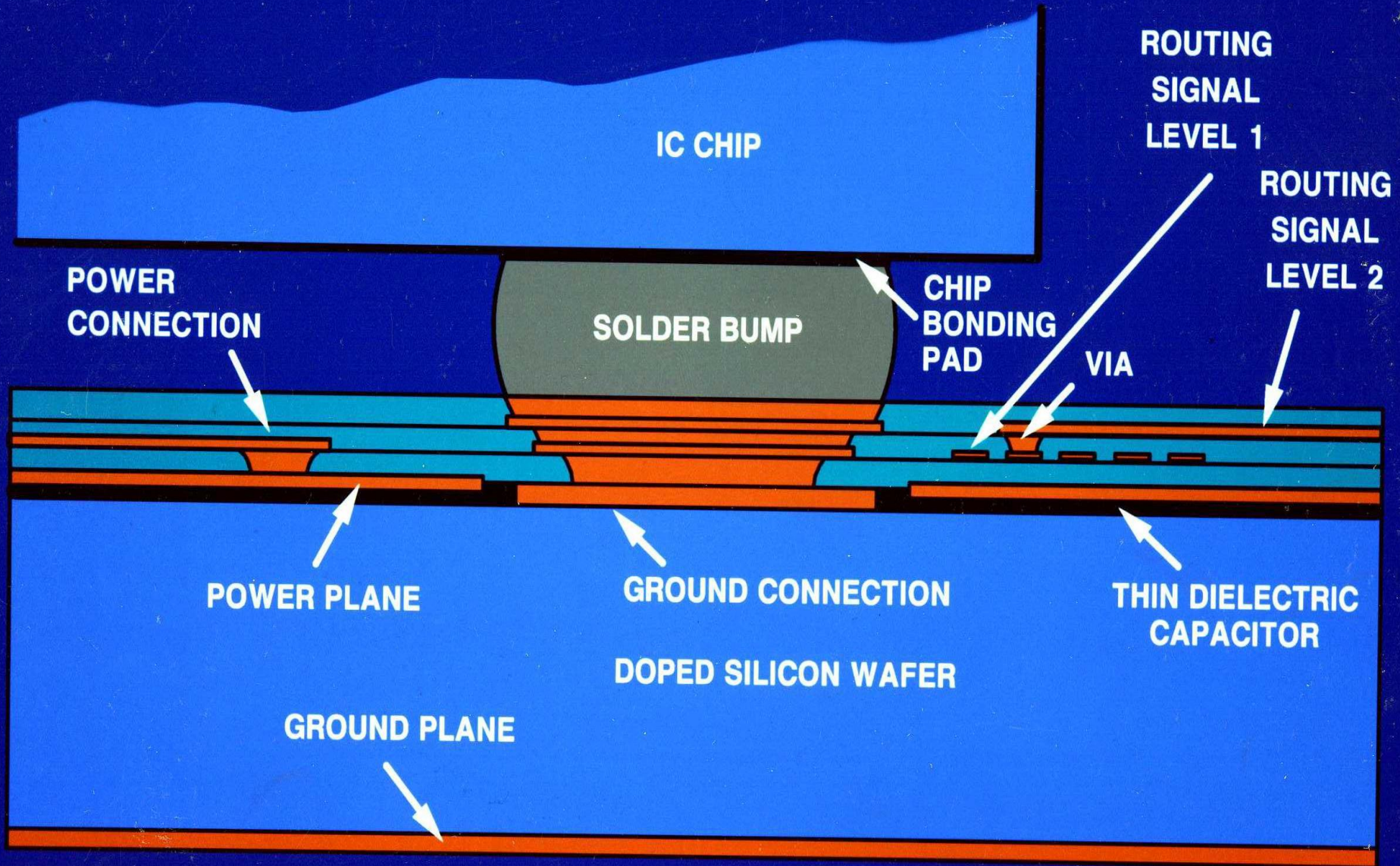
AVP STRUCTURE

IC CHIP

COVERCOAT

SOLDER BUMP

BONDING PADS

MICROVIA

ROUTING SIGNAL LEVEL 2

ROUTING SIGNAL LEVEL I

IC CHIP

POWER CONNECTION

POWER PLANE

GROUND CONNECTION

OXIDE LAYER

GROUND CONNECTION

50 μm

DOPED SILICON WAFER

DOPED SILICON WAFER

GROUND PLANE

GROUND PLANE

DEMONSTRATION PROJECT--32100 MICROPAC

MMU

CPU

MAU

PGA

SM

HIGH DENSITY INTERCONNECT TECHNOLOGY

ROUTING SIGNAL LEVEL 1

ROUTING SIGNAL LEVEL 2

IC CHIP

POWER CONNECTION

SOLDER BUMP

CHIP BONDING PAD

VIA

POWER PLANE

GROUND CONNECTION

THIN DIELECTRIC CAPACITOR

DOPED SILICON WAFER

GROUND PLANE

THERMAL FATIGUE IN SOLDER JOINTS

MANSON-COFFIN'S FORMULA:

$$\Delta\gamma = \Delta\alpha\Delta T \frac{\ell}{h}$$

$$N_F = \left(\frac{A}{\Delta\gamma}\right)^m f^2 \exp\left(-\frac{\beta}{kT_{max}}\right),$$

SMD(CHIP)

WHERE

A = MATERIAL CONSTANT

f = CYCLIC FREQUENCY

T_{max} = MAXIMUM TEMPERATURE IN THE CYCLE, °K

k = BOLZMANN'S CONSTANT

$\Delta\gamma$ = PLASTIC STRAIN

m,n, β = EMPIRICAL CONSTANTS
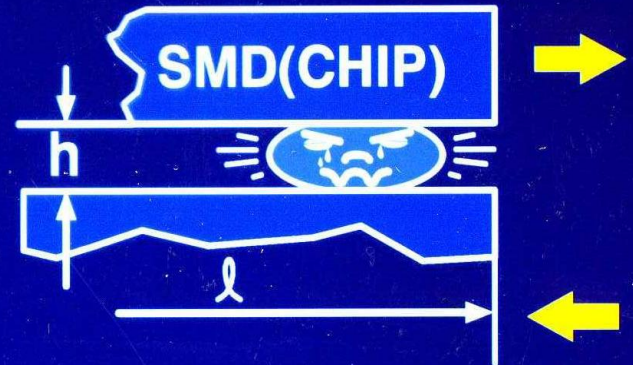
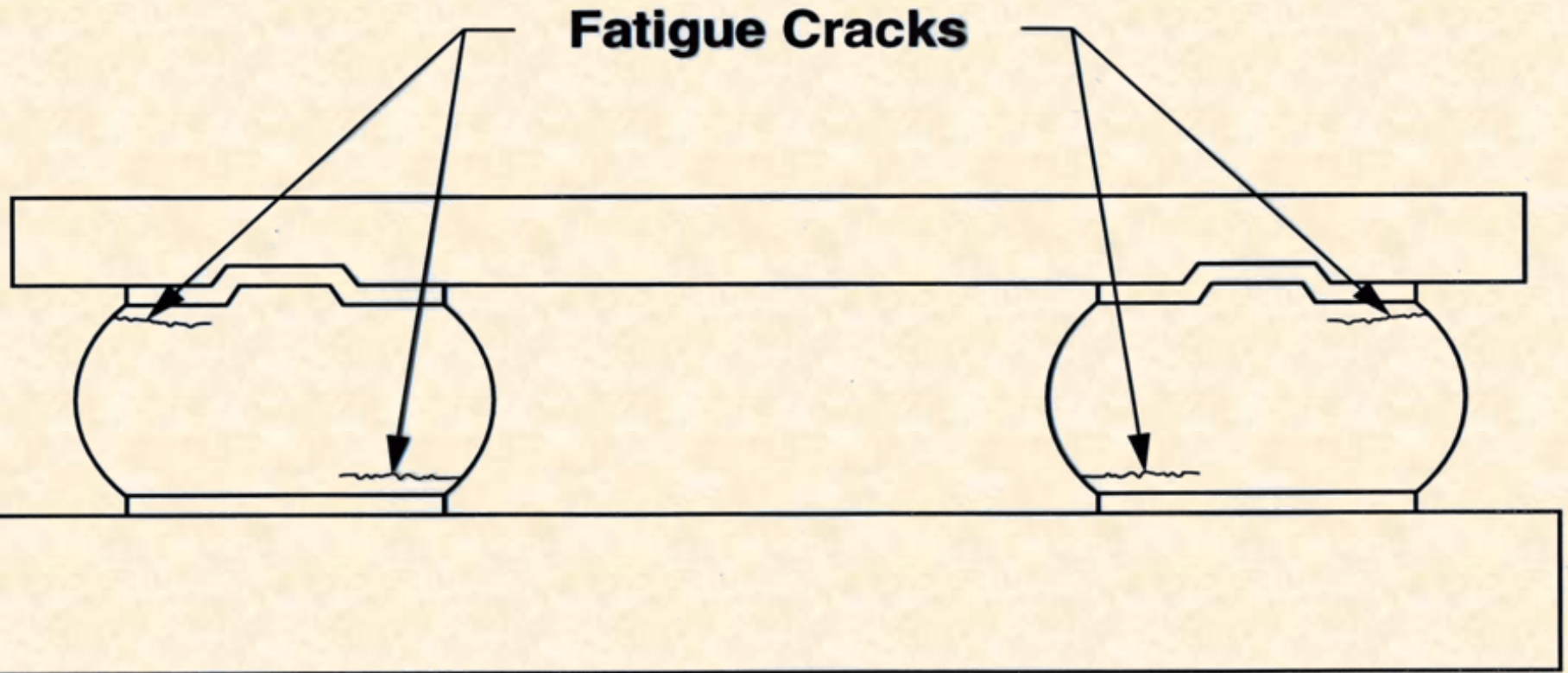$\Delta\alpha\Delta T$ = THERMAL EXPANSION (CONTRACTION) MISMATCH STRAIN
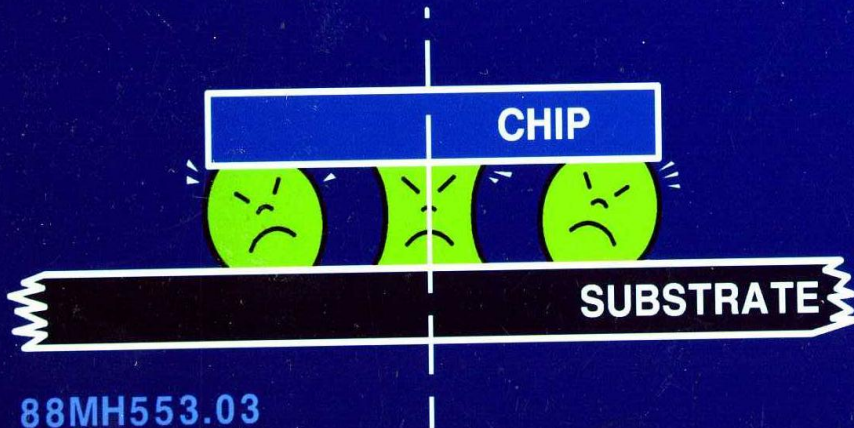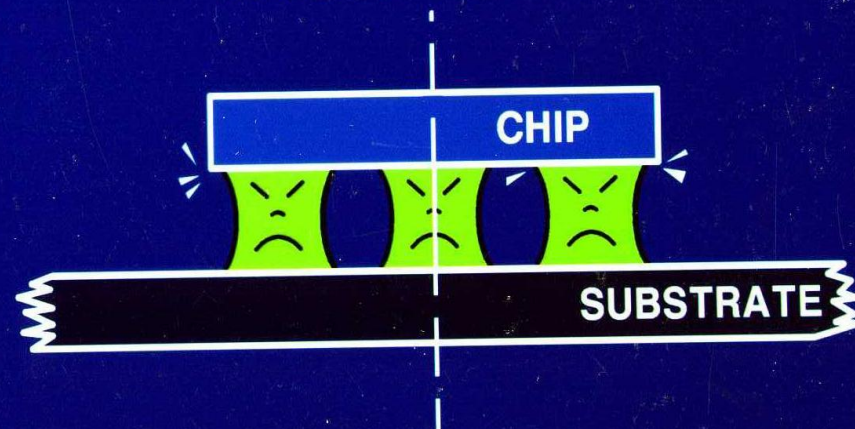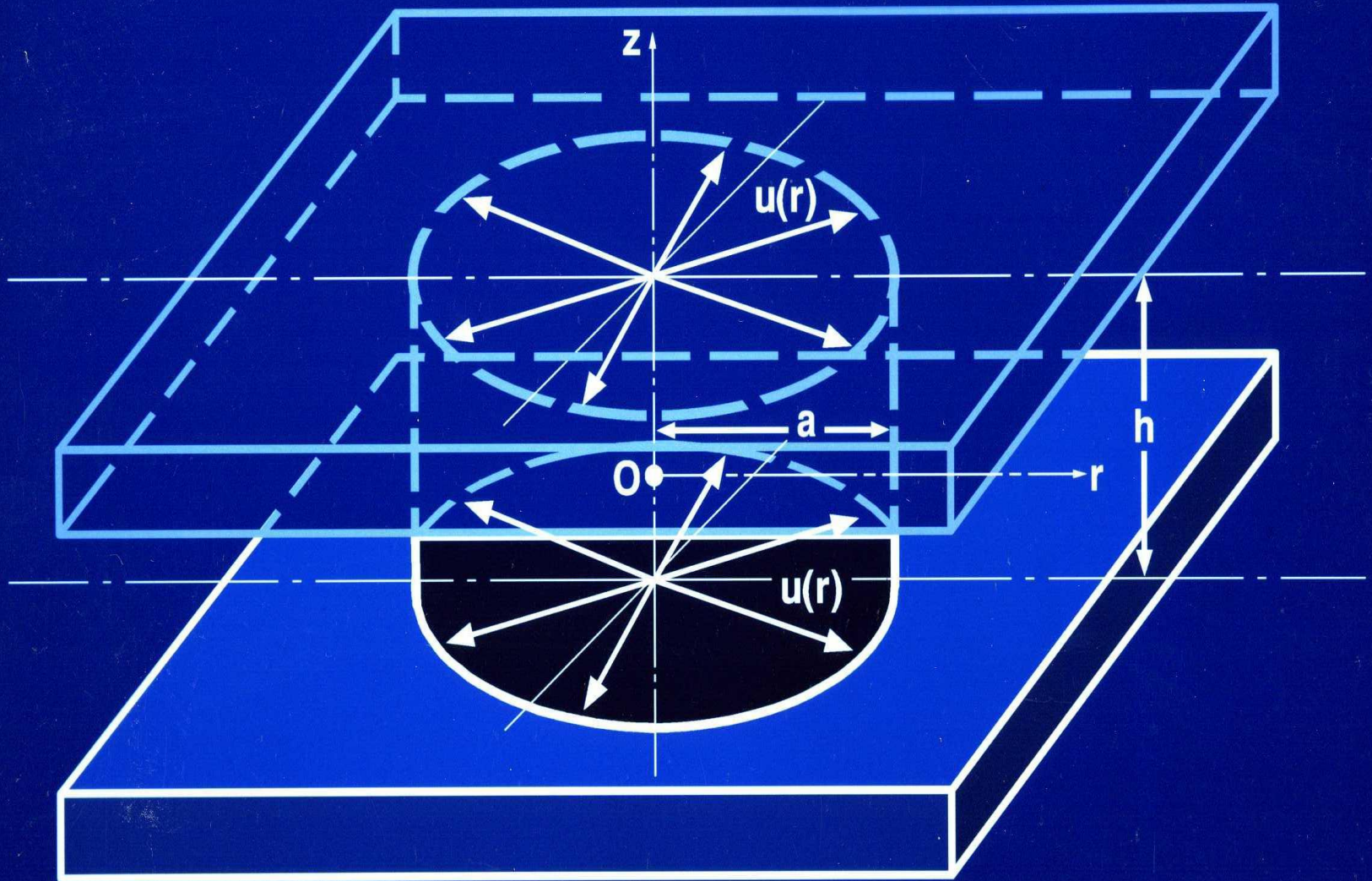
Schematics Showing Locations of Thermal Fatigue Cracks

Fatigue Cracks

CIRCULAR CYLINDER CLAMPED AT ITS END PLANES

DISTRIBUTION OF STRAINS AND STRESSES ALONG THE RADIUS OF THE CYLINDER

NOTE:

THE SHOWN LINEAR STRAINS AND NORMAL STRESSES ACT IN THE END PLANES. SHEAR STRAINS AND STRESSES ACT IN CROSS-SECTIONS LOCATED AT A QUARTER OF THE CYLINDER'S HEIGHT

$$\xi = 6\left(\frac{a}{h} = 0.955\right)$$

STRAINS:
ϵ_r = RADIAL
ϵ_t = TANGENTIAL
ϵ_z = AXIAL
γ_{rz} = SHEAR

STRESSES:
σ_r = RADIAL
σ_t = TANGENTIAL
σ_z = AXIAL
τ_{rz} = SHEAR

$$\frac{STRAIN}{\Delta\alpha\Delta t}$$

$$\frac{STRESS}{E\Delta\alpha\Delta t}$$

88MH553.12

ANSYS 4.3
JUL 18 1988
9:04:36
POST1 STRESS
STEP=1
ITER=1
SY (AVG)
STRESS GLOBAL

ZV=1
DIST=.0033
XF=.0015
YF=.005
MX=62935
MN=-17059
NCON=18
VMIN=-12856
VINC=4211
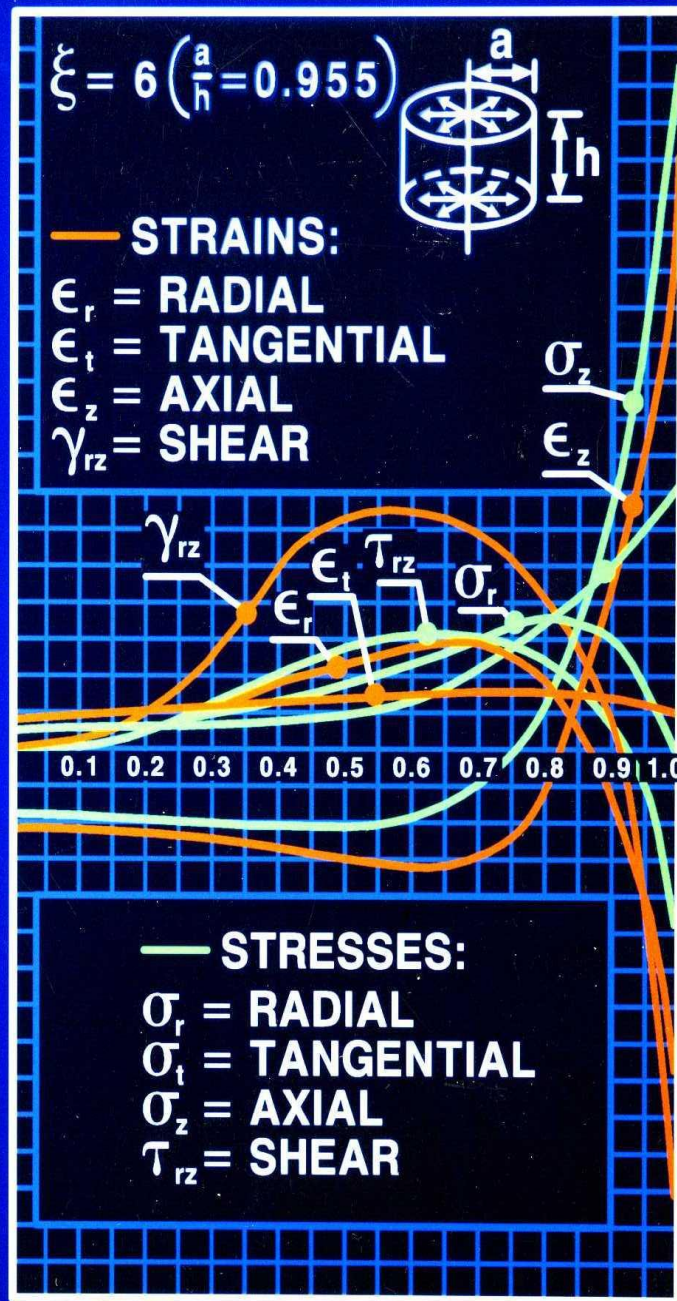
IEEE COMPONENTS, PACKAGING AND
MANUFACTURING TECHNOLOGY SOCIETY

Axial Stress
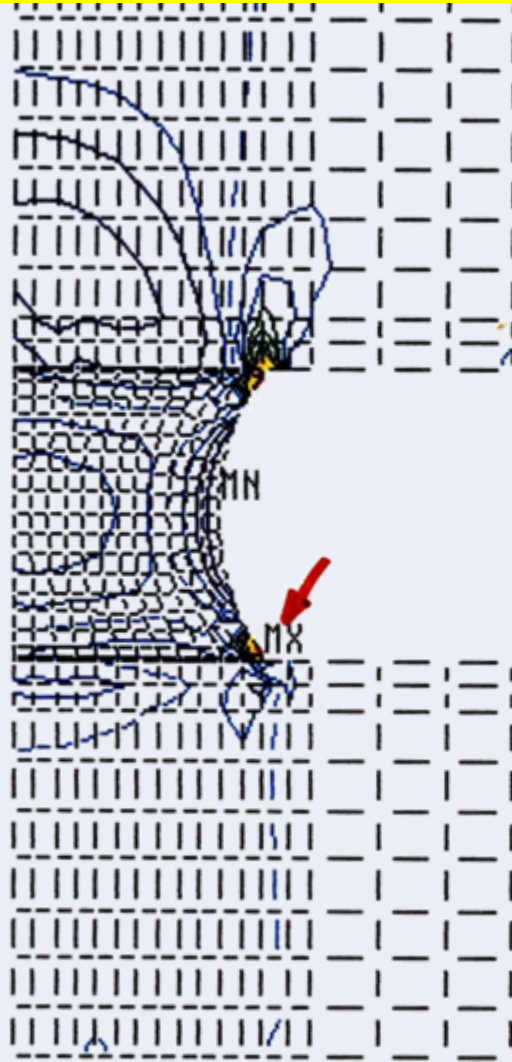
SOLDER BUMP, 3 MILS DIAMETER, 2 MILS HEIGHT

D/H = 1.5

Predicted Stresses and Strains in a Short Cylinder

Maximum Strains and Stresses vs Diameter-to-Height Ratio

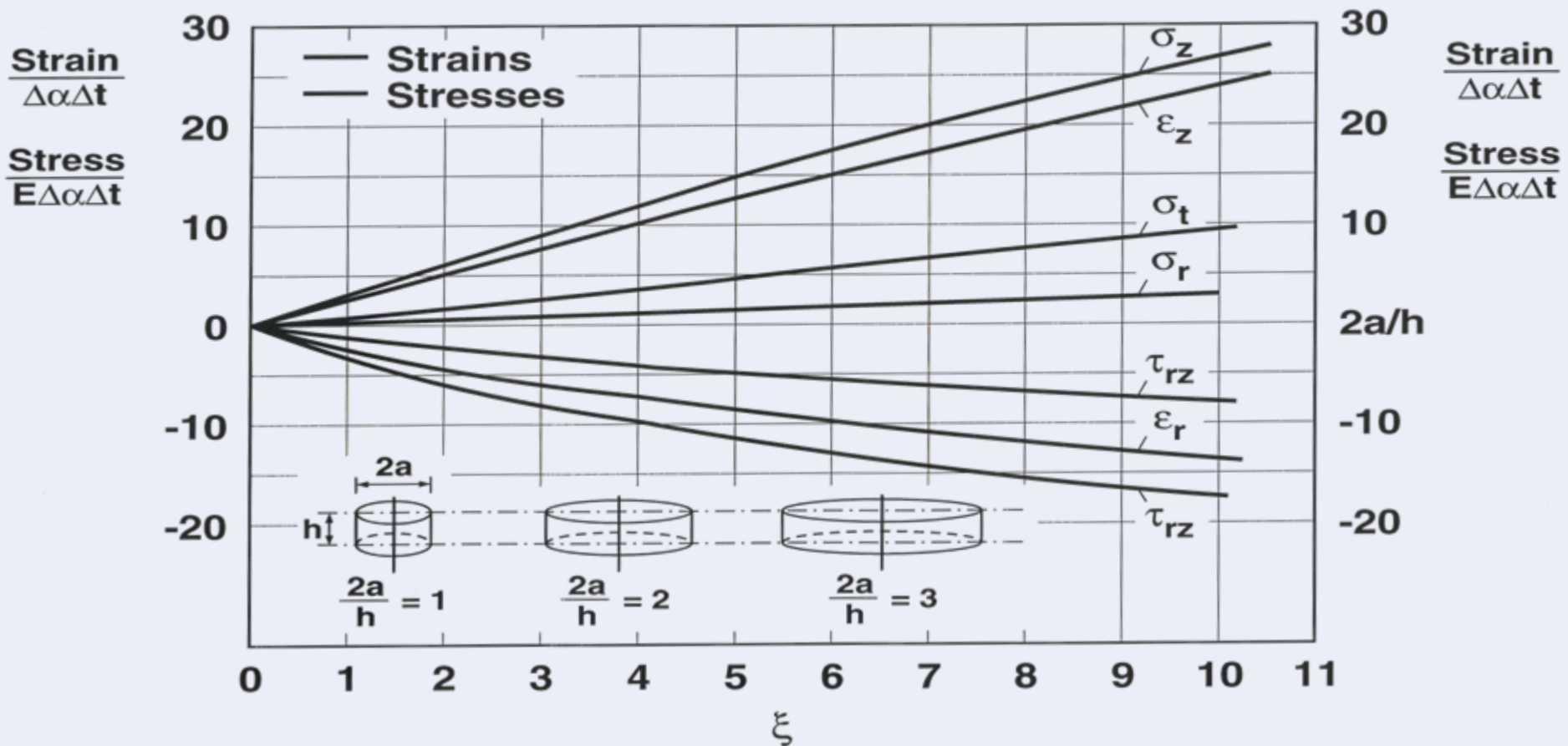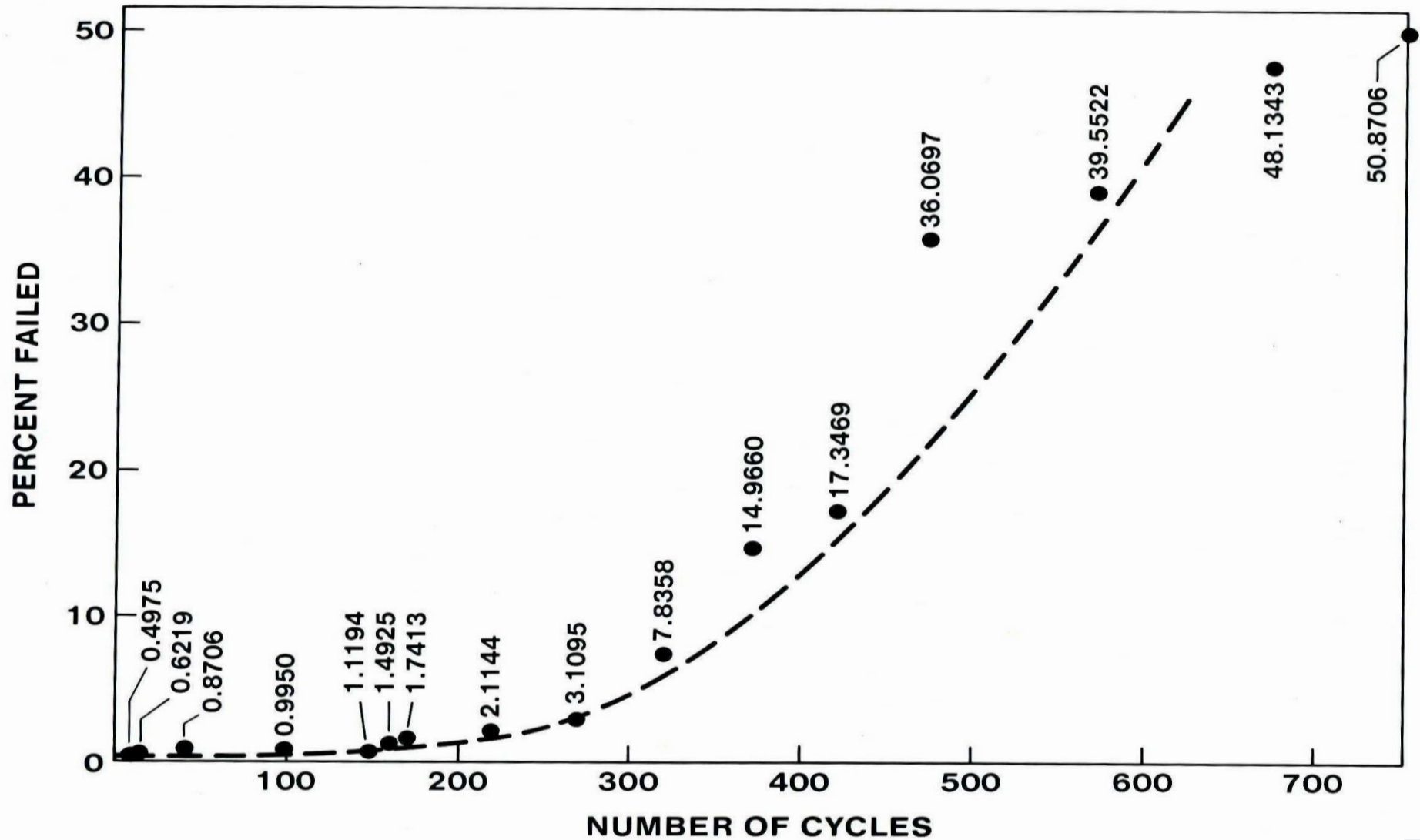# PERCENTAGE OF FAILED JOINTS
VS.
NUMBER OF CYCLES

FAILURE RATE, 1/CYCLE ("BATHTUB" CURVE)
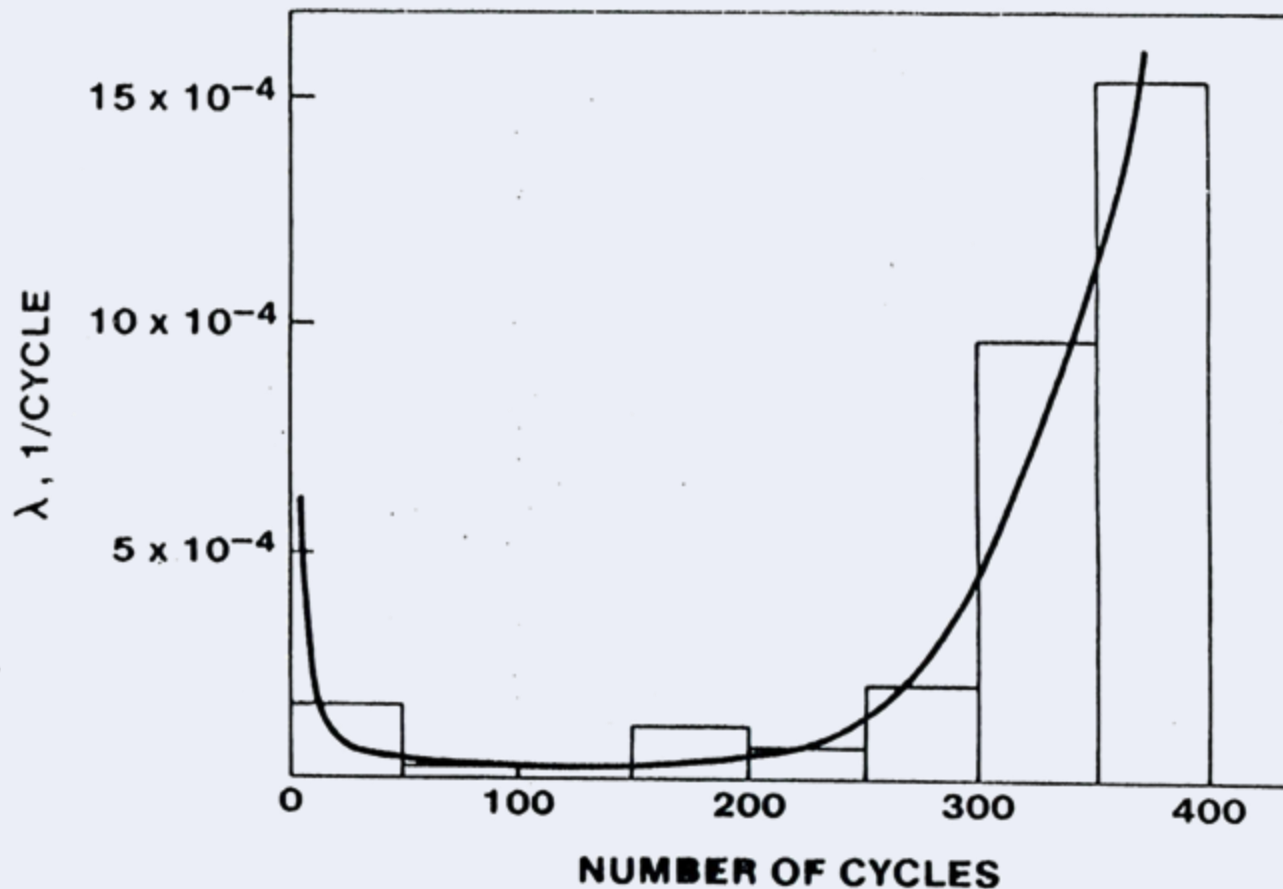
ASSESSED FATIGE LIFE FOR ACTUAL CONDITIONS

$$\frac{N}{N_a} = \left(\frac{\varepsilon_a}{\varepsilon}\right)^n , \quad n = 2.5 \rightarrow 3.0 \text{ (ENGELMAIER)}$$

N = ACTUAL NUMBER-OF-CYCLES-TILL-FAILURE (NCTF)

N_a = ACCELERATED NCTF

ε = ACTUAL MAX STRAIN

ε_a = ACCELERATED STRAIN

$$\text{ASSUMING} \quad \frac{\varepsilon_a}{\varepsilon} = \frac{(\Delta t)_a}{\Delta t} = \frac{150\,°C - (-65\,°C)}{80\,°C - 20\,°C} = 3.5833$$

AND $N_a \cong 150$, WITH $n = 2.5$,

WE HAVE:

$$N = N_a \left(\frac{(\Delta t)_a}{\Delta t}\right)^n = 150 \times (3.5833)^{2.5} = 3646 \text{ CYCLES}$$

FOR ONE CYCLE – PER-DAY THE EXPECTED FATIGUE LIFE IS

$$T = \frac{3646}{365} \cong 10 \text{ YEARS}$$

Importance of advanced measurement techniques: some examples

➢ **Electronics:** PDfR of a Cerdip/Cerquad seal-glass bonded ceramic package (AT&T)

➢ **Photonics:** Accuracy in the MEMS fabrication (Iolon)

➢ **Advanced Moire interferometry** in modeling of the mechanical behavior of electronic and photonic assemblies subjected to thermal and/or mechanical loading

➢ Role of **nondestructive evaluations**

II.Probabilistic Design for Reliability, Its Role and Significance

Design-for-Reliability

➢ DfR is a set of approaches, methods and best practices that are supposed to be used during the design phase of the product to minimize the risk that the product might not meet the reliability requirements and customer expectations.

➢ While 50% of the total actual cost of an electronic product is due to the cost of materials, 15% - to the cost of labor, 30% to the overhead costs and only 5% to the design effort, this effort influences about 70% of the total cost of the product ("Six Sigma", M. Harry and R. Schroeder).

➢ If reliability is taken care of during the design phase, the final cost of the product does not go up. If a reliability problem is detected during engineering the cost of the product goes up by a factor of 10. If the problem is caught in production phase, the cost of the product increases by a factor of 100 or more.

Deterministic approach

➤ The traditional, deterministic, DfR approach is based on the concept that reliability is assured by introducing a sufficiently high deterministic safety factor **(SF)** defined as the ratio of the capacity ("strength") C of the item to the demand ("load") D:

$$\delta = SF = \frac{C}{D}.$$

➤ The SF level is chosen depending on the consequences of failure; acceptable risks; the available and trustworthy information about the capacity and the demand; the accuracy, with which these characteristics are determined; possible costs and social benefits; variability of materials and structural parameters; construction (manufacturing, fabrication) procedures, etc.

➤ In a particular problem the capacity and demand could be different from the strength and load, and the role of these characteristics could be replaced by, say, acceptable and actual current, voltage, light intensity, electrical resistance; etc.

➤ The SF is being established from the previous experiences for the considered system in its anticipated environmental or operation conditions.

Probabilistic approach-1

➢ Probabilistic DfR **(PDfR)** approach is based on the AP and PRM concepts, and, if applied broadly and consistently, brings in the probability measure (dimension) to each of the design characteristics of interest.

➢ Using AT data and particularly ALT data, and the PM techniques, the PDfR enables one to establish the probability of the (anticipated) failure under the given operation conditions and for the given moment of time in operation.

➢ After the probabilistic PMs are developed, one should use **sensitivity analyses (SA)** to determine the most feasible materials and geometric characteristics of the design, so that the lowest probability of failure **(PoF)** is achieved.

Probabilistic approach-2

➢ In other cases, the PDfR approach enables one to find the most feasible compromise between the reliability and cost effectiveness of the product.

➢ When PDfR approach is used, the reliability criteria (specifications) are based on the acceptable (allowable) low PoF for the given product.

➢ A possible PDfR approach could be based, particularly, on the stress-strength ("interference") model

Reliability function

➢ **The simplest objects (items) in reliability engineering are those that do not let themselves to restoration (repair) and have to be replaced after the first failure. The reliability of such items is due entirely do their dependability, i.e., probability of non-failure, which is the probability that no failure could possibly occur during the given period of time. The dependence of this probability of time is known as the reliability function.**

➢ **As any other probability, the dependability of a sufficiently large population of non-repairable items can be substituted by the frequency, and therefore the reliability function can be sought as**

$$R(t) = \frac{N_s(t)}{N_0}$$

,

where N_0 is the total number of items being tested and $N_s(t)$ is the number of items that are still sound by the time *t* .

➢ **Differentiation the relationship**

$$R(t) = \frac{N_s(t)}{N_0}$$

with respect to time *t*, we have:

$$\frac{dR(t)}{dt} = \frac{1}{N_0}\frac{dN_s(t)}{dt} = -\frac{1}{N_0}\frac{dN_f(t)}{dt}$$

where $N_f(t) = N_0 - N_s(t)$ **is the number of the failed items.**

➢ **The failure rate is introduced as follows:**

$$\lambda(t) = \frac{1}{N_s(t)}\frac{dN_f(t)}{dt}$$

As evident from this formula, the failure rate is the ratio of the number of items that failed by the time *t* to the number of items that remained sound by this time. The failure rate characterizes the change in the dependability of an item in the course of its lifetime.

Bathtub curve

Failure of Prognostic Cell

Burn-in or infant mortality region

Useful Life Region

Wear out or end-of-life region
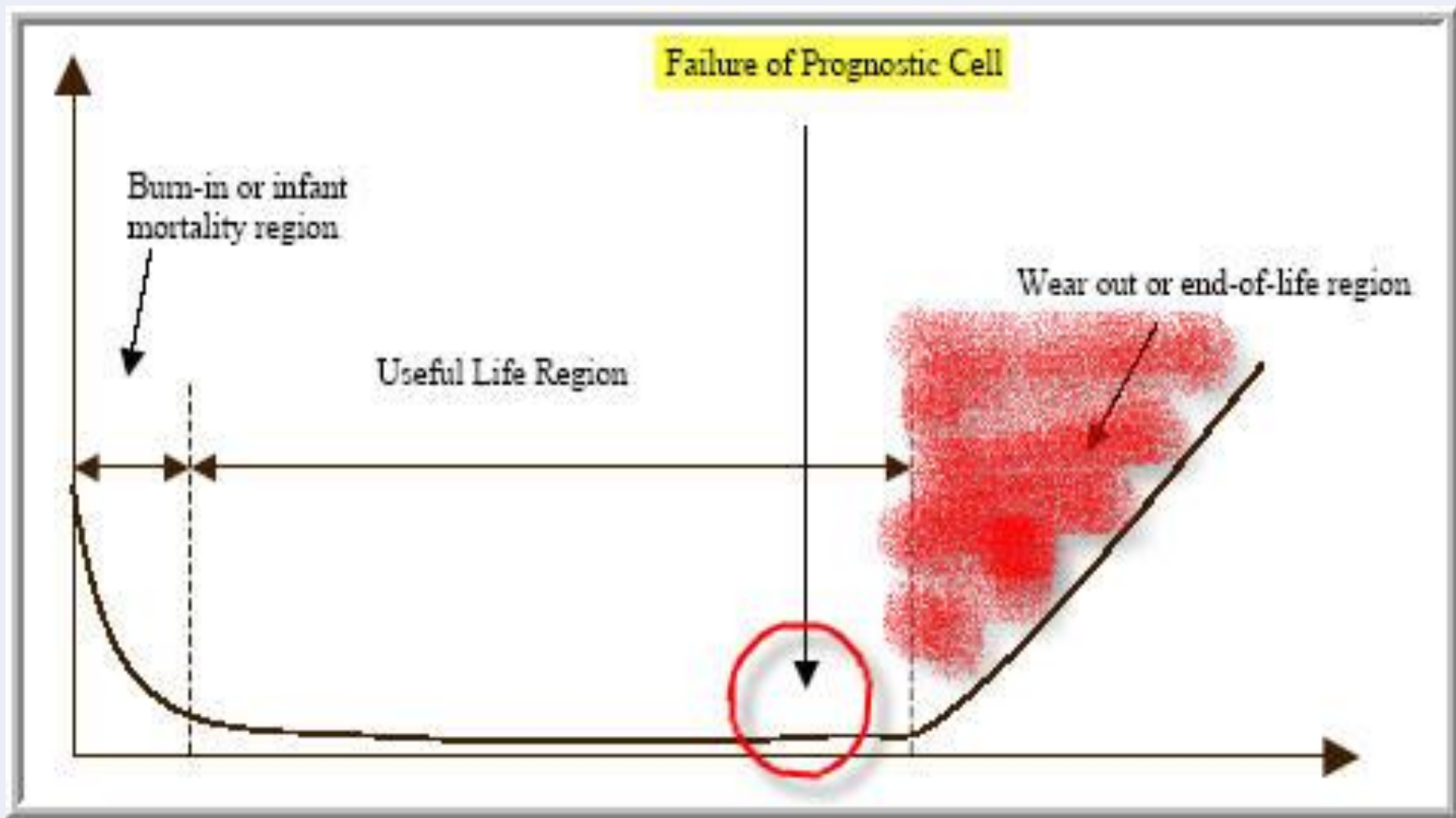
Bathtub curve with indication of the Prognostic Cell failure specification

Stress-strength ("interference") model

The curve on the right should be obtained experimentally, based on the accelerated life testing and on the accumulated experience. The bearing capacity of the structure should be such that the probability of failure, P(t), is sufficiently low, and the safety factor (SF) is not lower than the specifies value, say, SF=1.4.   In a simplified analysis the curve on the right could be substituted, particularly, by a constant value, which, if a conservative approach is taken, should be sufficiently low.

Probability density function for a particular mechanical or thermal characteristic (response) of the tile structure to the given environmental factor at the given moment of time ("Demand", D)

Capability of the tile structure with respect to the particular mechanical or thermal loading (may or may not be time-dependent). In the current analysis we assume that the bearing capacity for a particular reliability characteristic is either a constant value or a normally distributed random variable with a known (evaluated) mean and standard deviation ("Capacity", C)
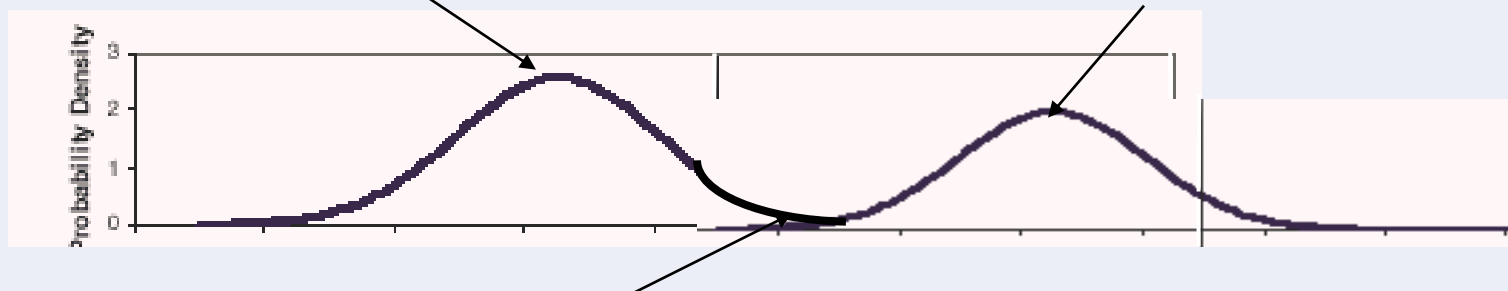
The larger is the overlap of these two curves, the higher is the probability of failure, and the lower is the safety factor. After these two curves are evaluated (established) for each reliability characteristic of interest and for each moment of time (separately, for the take off and landing processes) we evaluate the probability distributing function, f(ψ), for the safety margin, ψ=C-D, its mean, <ψ>, and standard deviation, $\hat{s}$, and the safety factor, SF= <ψ>/ $\hat{s}$. It should not be lower than the specified value, say, SF=1.4.

Safety factor

➢ Direct use of the probability of non-failure is often inconvenient, since, for highly reliable items, this probability is is very close to one, and thereforeeven significant change in the item's (system's) design, which have an appreciable impact on the item's reliability, may have a minor effect on the probability of non-failure.

➢ In those cases when both the mean value, $<\psi>$, and the standard deviation, $\hat{s}$, of the margin of safety (or any other suitable characteristic of the item's reliability, such as stress, temperature, displacement, affected area, etc.), are available, the <u>safety factor</u>

$$SF=\delta= <\psi>/\hat{s}$$

can be used as a suitable reliability criterion.

➢ In many cases the safety factor, SF, can be determined as the ratio of the <u>mean time-to-failure</u> (MTTF) to the standard deviation, STD, of the time-to-failure:

$$SF=MTTF/STD$$

Example

As a simple example, examine a device whose MTTF, τ, during steady-state operation is described by the Boltzmann-Arrhenius equation $\tau = \tau_0 \exp\left(\dfrac{U}{kT}\right)$. The failure rate is therefore

$\lambda = \dfrac{1}{\tau} = \dfrac{1}{\tau_0} \exp\left(-\dfrac{U}{kT}\right)$. If Weibull law is used to predict the probability of failure, then the probability of non-failure (dependability) can be evaluated on the basis of the following probability distribution function: $P = \exp\left[-(\lambda t)^{\beta}\right] = \exp\left[-\left(\dfrac{t}{\tau_0} \exp\left(-\dfrac{U}{kT}\right)\right)^{\beta}\right]$, where β is a shape parameter. Solving this equation for the absolute temperature T, we obtain: $T = -\dfrac{U}{k \ln\left[\dfrac{\tau_0}{t}\left(-\ln P\right)^{1/\beta}\right]}$.

Example (cont)

Let for the given type of failure (say, surface charge accumulation), the $\dfrac{U}{k}$ ratio is $\dfrac{U}{k} = 11600\,^0K$, the τ_0 value predicted on the basis of the ALT is $\tau_0 = 5x10^{-8}$ hours, and the shape parameter β turned out to be close to $\beta = 2$ (Rayleigh distribution). Let the allowable (specified) probability of failure at the end of the device's service time of, say, $t = 40,000$ hours be $Q = 10^{-5}$ (it is acceptable that one out of hundred thousand devices fails). Then the above formula indicates that the steady-state operation temperature should not exceed $T = 349.8^0 K = 76.8^0 C,$ and the thermal management tools should be designed accordingly. This rather elementary example gives a feeling of how the PDfR concept works and what kind of information one could expect using it.

General approach using probability density functions (pdf)

"Probable is what usually happens"
Aristotle
"Probability is the very guide of life"
Cicero

The most general PDfR approach could be based on the use of probability density distribution functions for

➢ the probabilistic reliability **characteristics** of importance (such as, e.g., electrical parameters (current, voltage, etc.), light output, heat transfer capability, mechanical ultimate and fatigue strength, fracture toughness, maximum and/or minimum temperatures, maximum accelerations/decelerations, etc.) and

➢ the **factors** affecting these characteristics (such as, e.g., high an/or low temperatures, high electrical current or voltage, electrical and/or optical properties of materials, mechanical and thermal stresses, displacements, maximum temperatures, etc.)

PDfR Characteristics

➢ The appropriate electrical, optical, mechanical, thermal, and other physical **characteristics** that determine the functional performance, mechanical (physical/structural) reliability and/or environmental durability of the design/device/apparatus of interest should be established.

➢ Examples of such characteristics are: appropriate electrical parameters (current, voltage, etc.), light output, heat transfer capability, mechanical ultimate and fatigue strength, fracture toughness, maximum and/or minimum temperatures, maximum accelerations/decelerations, etc.

PDfR factors affecting PDfR characteristics-1

➢ Establish the electrical, optical, mechanical, thermal, environmental and other possible (say, human) stress (loading) **factors** (conditions) that might affect the reliability characteristics, i.e., characteristics that determine (affect) the short- and long-term reliability of the object (structure) of interest.

➢ Examples of such factors are: high an/or low temperatures, high electrical current or voltage, electrical and/or optical properties of materials, mechanical and thermal stresses, displacements, maximum temperatures, size of the affected areas, etc.

➢ This should be one separately for each characteristic of interest and, if necessary, for each manufacturing process and for different phases of manufacturing, testing and/or operations

PDfR factors affecting PDfR characteristics-2

➢ Based on the physical nature of the particular environmental/loading factor (electrical, optical, mechanical, environmental) and on the available information of it, establish if this factor should be treated as a non-random (deterministic) value, or should/could be treated as a random variable with the given (assumed) probability distribution function.

➢ At this stage one could treat random characteristics of interest as nonrandom functions of random factors, and establish the probability distribution functions for the random factors using experimental data, and/or Monte-Carlo simulations, and/or finite-element analyses (FEA), and/or evaluations based on analytical ("mathematical") modeling, etc.

Example

➢ Let, for instance, the absolute temperature T be distributed in accordance with the Rayleigh law, so that the probability that a certain level T_* is exceeded is determined as

$$P(T \triangleright T_*) = \exp\left(-\frac{T_*^2}{T_0^2}\right)$$

where T_0 the most likely value of the absolute temperature T.

Then, using the Boltzmann-Arrhenius relationship

$$\tau = \tau_0 \exp\left(\frac{U_a}{kT}\right)$$

we conclude that the probability that the random mean-time-to-failure τ ("random", because of the uncertainty in the level of the most likely temperature) is below a certain level τ_*

Example (cont)

(probability of failure is defined in this case as the probability that the specified level is not achieved) can be found as

$$P(\tau \rhd \tau_*) = \exp\left(-\frac{T_*^2}{T_0^2}\right) = \exp\left[-\left(\frac{U_a}{kT_0 \ln\frac{\tau_*}{\tau_0}}\right)^2\right]$$

Solving this equation for the most likely (specified) T_0 value, we find:

$$T_0 = \frac{U_a}{k\ln\frac{\tau_*}{\tau_0}\sqrt{-\ln P}}$$

This formula indicates how the (most likely) level of the device temperature should be established, so that the probability that the specified level τ_* of the MTTF is not achieved is sufficiently low.

1) Develop a detailed list of possible electrical, mechanical (structural), thermal, and environmental failures that should be considered, in one way or another, in the particular design (package, invertor, module, structure, etc.)

2) Make, based on the existing experience and best practices, the preliminary decision on the materials and geometries in the physical design and packaging of the product and its units/subunits/assemblies

3) Conduct predictive modeling (using FEA or other simulation packages, as well as analytical/"mathematical" wherever possible) of the stresses and other failure criteria (say, elevated temperatures or electrical characteristics), considering steady state and transient thermal, stress/strain and electrical fields.

4)Consider possible loading in actual use conditions (electrical, thermal, mechanical, dynamic, as well as their combinations) and distinguish between short-term high-level loading (related to the ultimate strength of the structure) and long-term low-level loading (related to the fatigue strength of the structure

5) Review the existing qualification standards (JEDEC, MIL specs) for the similar structures, having in mind, however, that these standards were designed, although for similar, but for different (power, geometry, materials, use) conditions, than what we will be dealing with; come up with the preliminary level of acceptable stresses, accelerations, temperatures, voltages, currents, etc.

Twelve steps to be conducted to add value to the existing practice-3

6) Having in mind Accelerated Life Testing (ALTs) and Highly Accelerated Life Testing (HAST) procedures, decide on the constitutive relationships (formulas, FEA procedures, plots) that govern the failure mechanisms in question (Arrhenius type of equations for high temperature "baking", Minor type- for the materials that are expected to work within the elastic range, Erdogan-Paris type - for brittle materials, etc.)

7) Design, conduct and interpret the results of the accelerated life tests ALTs) and, based on these tests, predict the reliability characteristics of the assemblies, joints, subunits and units of interest

8) Based on the obtained information, the state-of-the-art in the area in question and the requirements of the existing specifications, decide on the allowable (acceptable) values of the characteristics of failure, with consideration of the economically and technically feasible lifetime of the module and its major subassemblies

Twelve steps to be conducted to add value to the existing practice-4

9) Write first draft of the qualification specs (in other words, revise, if necessary, the existing JEDEC specs) for the module and its unites/subunits of interest

10) Develop root cause analysis (RCA) methodologies

11) Decide on the burn-in conditions and establish adequate service for collecting field failures

12) Conduct, on the permanent basis, revisions of the designs and the reliability specifications

III. Do Electronic and Photonic Industries Need New Approaches to Qualify Their Products?

"I do not need an everlasting pen. I do not intend to live forever"
Ilf and E. Petrov, "The Golden Calf" (in Russian)

"A pinch of probability is worth a pound of perhaps"
James Thurber

Are the existing qualification specs adequate?

➢ The PDfR approach can be helpful in answering this question.

➢ The short-term down-to-earth and practical goal of a particular electronic or photonic device manufacturer is to conduct and pass the established QT, without questioning whether they are perfect or not.

➢ On the other hand, the ultimate long-term and broad goal of electronic, opto-electronic and photonic industries, regardless of a particular manufacturer or even a particular product, is to make the industry deliverables sufficiently reliable in the field, be consistently good in performance, and so to elicit trust of the customer.

➢ QT, such as, e.g., those prescribed by the JEDEC, Telcordia, AEC or MIL specs, is the major means that the electronic, opto-electronic and photonic industries use to make their viable-and-promising devices into reliable-and-marketable products.

Do industries need new approaches to qualify their products??

➤ It is well known, however, that devices that passed the existing qualification tests often fail in the field. Should it be this way? Is this a problem indeed? Are the existing qualification specifications adequate? Do electronic and photonic industries need new approaches to qualify their devices into products?

➤ If they do, could the today's qualification specifications and testing procedures be improved to an extent that if the device passed these tests, its performance in the field would be satisfactory and preferably could be predicted and assured?

➤ Would it be possible to "prescribe", predict and, if necessary, even control the low enough and specified probability of failure for a device that operates under the given stress (not necessarily mechanical, of course) for the given time?

Improvements in the existing qualification tests are possible

➢ We argue that such improvements in the QT, as well as in the existing best practices, are indeed possible, provided that the PDfR methodologies are employed.

➢ One effective way to improve the existing QT and specs is to

♦ conduct, on a much wider scale than today, ALT-1 and ALT-2 and, since ALT cannot do without PM,

♦ carry out, whenever and wherever possible, PM to understand the PoF and to accumulate failure statistics;

♦ revisit, review and revise the existing QT and specs considering the ALT data for the most vulnerable elements of the device of interest;

♦ develop and widely implement the PDfR methodologies having in mind that nobody and nothing is perfect, that probability of failure is never zero, but could be predicted and, if necessary, controlled and maintained at an acceptable low level.

QT could be viewed as "quasi-ALT"

➢ If the QT has a solid basis in ALT, PM and PDfR, then there is reason to believe that the product of interest will be sufficiently robust in the field.

➢ In such a situation, the QT could be viewed as "quasi-ALT," as a sort-of the "initial stage of ALT" that more or less adequately replicates the initial non-destructive, yet full-scale, stage of ALT.

➢ We believe that such an approach to qualify devices into products will enable industry to specify, and the manufacturers -to assure, a predicted and low enough probability of failure for a device that passed the QT and will be operated in the field under the given conditions for the given time.

➢ We expect that the suggested approach to the DfR and QT will be accepted by the engineering and manufacturing communities, implemented into the engineering practice and be adequately reflected in the future editions of the QT specifications and methodologies.

Qualification tests are still non-destructive

➢ Such QTs could be designed, therefore, as a sort of mini-ALTs that, unlike the actual ALT, is non-destructive and conducted on a limited scale.

➢ The duration and conditions of such mini-ALT QT should be established based on the observed and recorded results of the actual HALT and ALT, and should be limited to the stage when no failures in the actual full-scale HALT or ALT were observed.

➢ Prognostics and health management (PHM) technologies (such as "canaries") should be concurrently tested to make sure that the safe limit is not exceeded.

Conclusion

➤ We expect that eventually the suggested new approach becomes widely accepted by the engineering and manufacturing communities, be implemented in a timely fashion into the engineering practice and be adequately reflected in the future editions of the qualification specifications and methodologies.

➤ Particularly, we expect that not only testing, but predictive PDfR modeling should become part of qualification standards.

➤ We believe that our new approach to the qualification of the electronic devices will enable industry to specify and the manufacturers - to assure a predicted and low enough probability of failure for a device that passed the qualification specifications and will be operated under the given stress (not necessarily mechanical) conditions for the given time.

➤ We believe also that the wide implementation of our new PDfR approach that needs support of ALT, AMT and PM methods and algorithms, will create many new jobs.