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# RELIABILITY OF ELECTRONICS: A PHYSICS-OF-FAILURE APPROACH

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AGENTSCHAP INNOVEREN & ONDERNEMEN

# CONTENT

The electronics reliability quantification challenge

The traditional approach

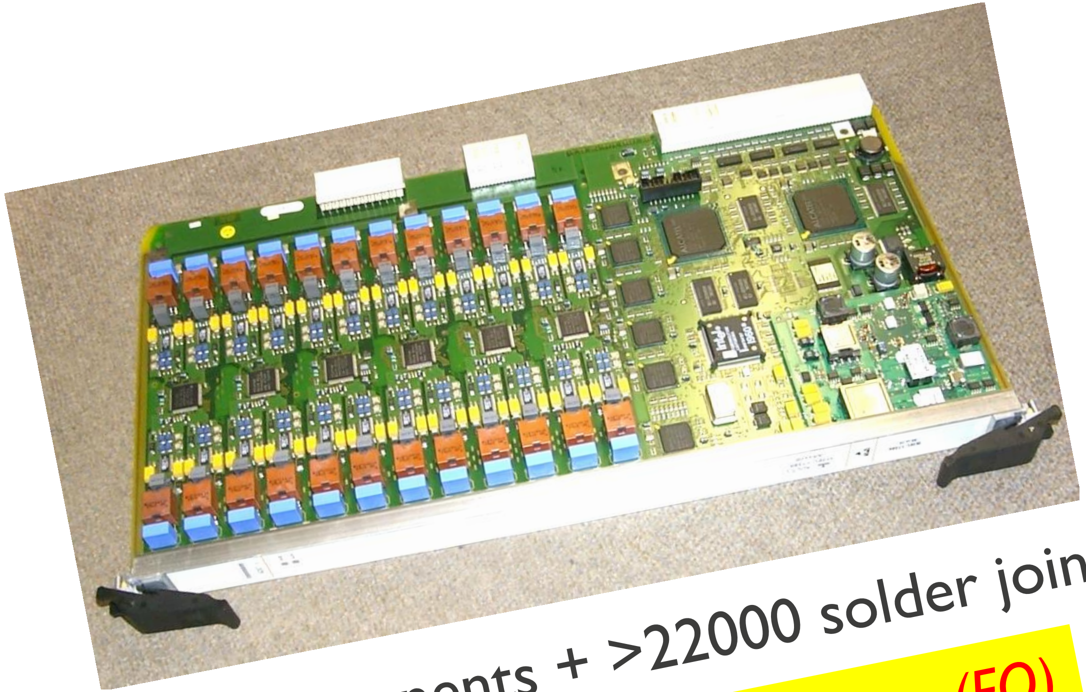
The Physics-of-Failure approach

Physics-of-Failure in practice today

Conclusions

# THE RELIABILITY QUANTIFICATION CHALLENGE

## SO MANY THINGS CAN FAIL ...



2500 components + >22000 solder joints

= >40000 failure opportunities (FO)

Components

Solder joints

PCB

PBA

1 PBA =(1K to 100K FO)
x *n* failure mechanisms/FO

# THE RELIABILITY QUANTIFICATION CHALLENGE

## RELIABILITY RELATED QUESTIONS

CONSUMER

Assure less than *X*% products fail within warranty period

PROFESSIONAL

Guarantee lifetime of *N* years

SAFETY CRITICAL

The failure rate must remain below *M* failures/year

(FIT, 1/MTTF)

# THE TRADITIONAL APPROACH

## RELIABILITY PREDICTION STANDARDS



MIL-HDBK-217 - *the oldest, best-known most outdated (1995)*

Telcordia SR-332 - *previously Bellcore, telecommunication, US.*

IEC-61709/SN 29500 - *Siemens, industrial, Germany.*

IEC-TR-62380/Fides 2009 - *French industry, industrial-avionics, France.*

217plus – *Quanterion, commercial MIL-HDBK-217 update, US.*

GJB/Z 299C – *China.*

Describe how to determine the reliability of a **system of** electronic **components** using **constant failure rate statistics** and field failure data.

Basic principle:

$$\lambda_{\mathrm{sys}} = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \ldots \cdot \lambda_n \cdot \lambda_{\mathrm{PCB}}$$

# THE TRADITIONAL APPROACH
## CONSTANT FAILURE RATE: WHAT DOES IT MEAN?

Buy NEW

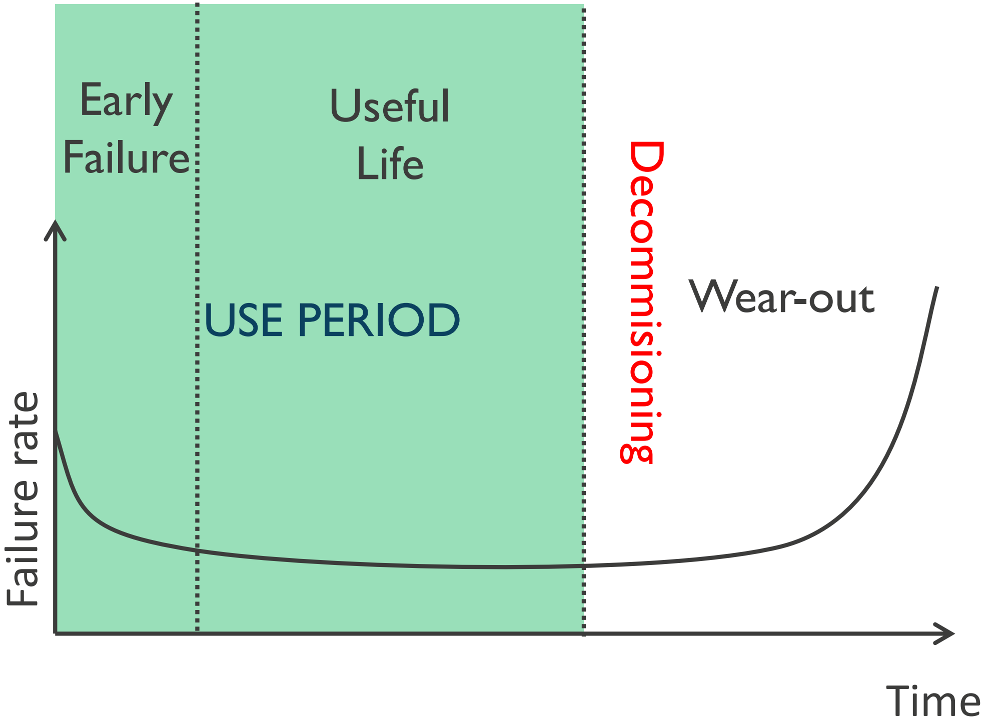
Buy USED


Do you expect the same failure rate for a used car as for a new one?

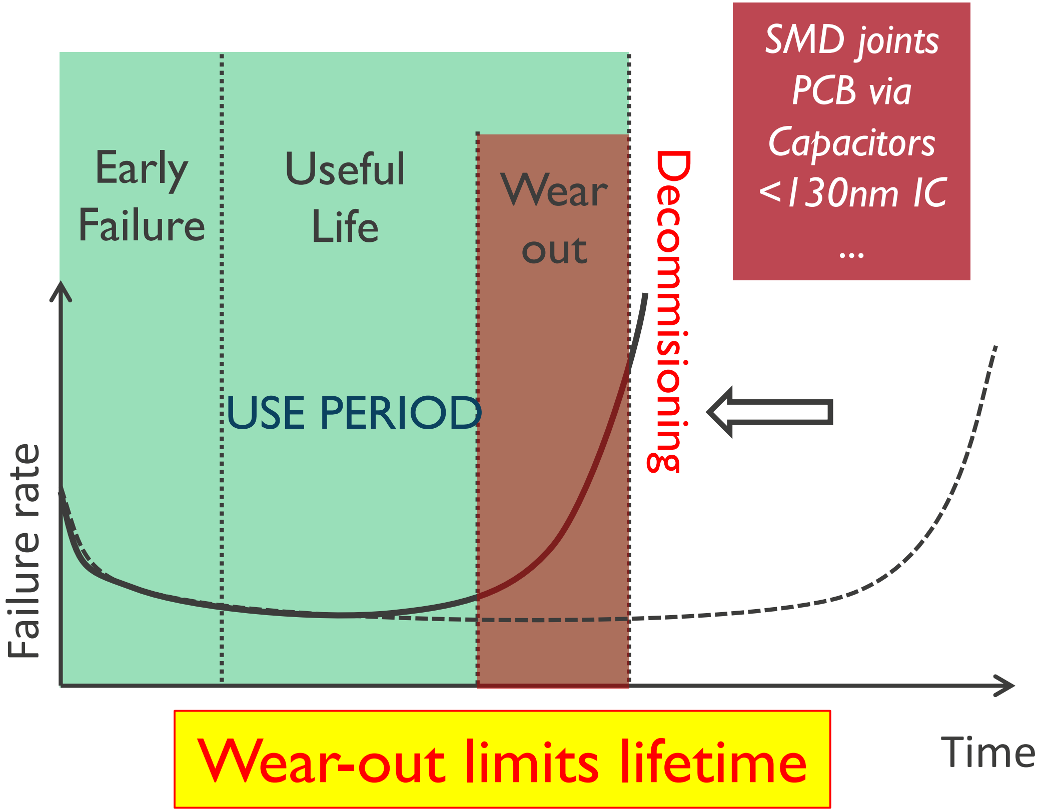
# THE TRADITIONAL APPROACH

## THE REAL WORLD


### What it was (before the '80s)




### What is now!



# THE TRADITIONAL APPROACH

## STRESS FACTORS AND FAILURE RATE

Semi-empirical/statistical treatment of stress and quality.

Failure rate
Semiconductor
Component

IEC TR-62380

**MATHEMATICAL MODEL :**

$$\lambda = \left\{ \underbrace{\left\{\lambda_1 \times N \times e^{-0.35\times a} + \lambda_2\right\} \times \left\{ \frac{\sum_{i=1}^{y} (\pi_t)_i \times \tau_i}{\tau_{on} + \tau_{off}} \right\}}_{\lambda_{die}} + \left\{ \underbrace{2.75\times 10^{-3} \times \pi_\alpha \times \left( \sum_{i=1}^{z} (\pi_n)_i \times (\Delta T_i)^{0.68} \right) \times \lambda_3}_{\lambda_{package}} \right\} + \left\{ \underbrace{\pi_I \times \lambda_{EOS}}_{\lambda_{overstress}} \right\} \right\} \times 10^{-9} / h$$

**NECESSARY INFORMATION:**

$(t_{ae})_i$ : average outside ambient temperature surrounding the equipment, during

$(t_{ac})_i$ ... oard (PCB) near the compon

$\lambda_1$ ... d circuit family. See Tab

$\lambda_2$ ... g of the integrated circuit

$N$ : number of transistors of the integrated circuit.

a : [(year of manufacturing) – 1998].

$(\pi_t)_i$ : i[th] temperature factor related to the i[th] junction temperature of the integrated circuit mission profile.

$\tau_i$ : i[th] working time ratio of the integrated circuit for the i[th] junction temperature of the mission profile.

**This is not physics!**

Quality factors allow failure rate range 1 to 8000 (FIDES)

# TRADITIONAL APPROACH

## WHY IS IT STILL USED?

- *"We have always done it that way."*
- The method is (still) accepted in industry.
- It is more or less comprehensive.
- It always gives a number.
- It is relatively simple to use (multiplying).
- Provides a lot of stretch... (1 – 8000)
- Lack of Physics-of-Failure know-how at user side.

# THE PHYSICS-OF-FAILURE APPROACH
## DEFINITION

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A science-based approach to reliability that uses modeling and simulation to design-in reliability.

It helps to understand system performance and reduce decision risk during design and after the equipment is fielded. This approach models the root causes of failure such as fatigue, fracture, wear, and corrosion.

An approach to the design and development of reliable product to prevent failure, based on the knowledge of root cause failure mechanisms. The Physics of Failure (PoF) concept is based on the understanding of the relationships between requirements and the physical characteristics of the product and their variation in the manufacturing processes, and the reaction of product elements and materials to loads (stressors) and interaction under loads and their influence on the fitness for use with respect to the use conditions and time.

# THE PHYSICS-OF-FAILURE APPROACH
## THE BASICS

1. Quantitative physical model of the failure mechanism.
   - Fatigue failure: solder joints, PCB via's & tracks.
   - Diffusion and evaporation of liquids: degradation of Al-capacitors.
   - Electro-migration (electric field driven) and corrosion.
   - …

2. Calculation of the stress level dependent "damage factor" determining the lifetime.

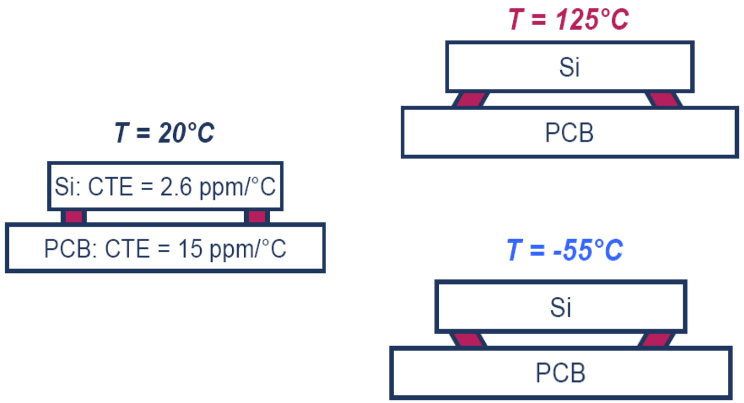
3. Apply (empirical) lifetime model: lifetime = F("damage factor")
   (e.g. Wöhler curve)

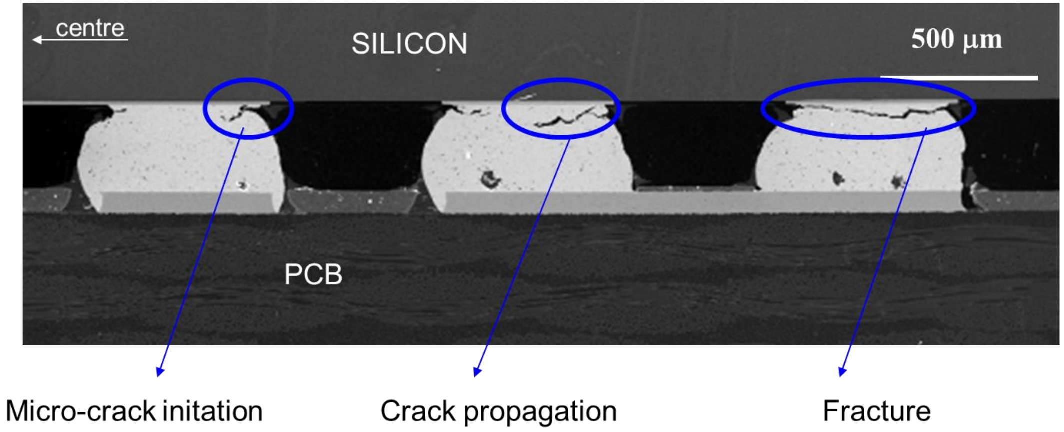
# THE PHYSICS-OF-FAILURE APPROACH

## AN EXAMPLE: SOLDER JOINT FATIGUE DUE TO THERMAL CYCLING



**Failure Mechanism**

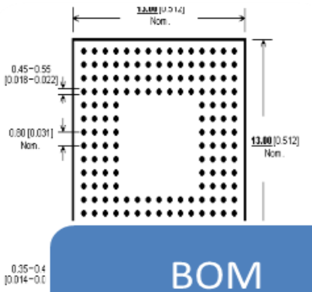


# THE PHYSICS-OF-FAILURE APPROACH

## AN EXAMPLE: SOLDER JOINT FATIGUE DUE TO THERMAL CYCLING

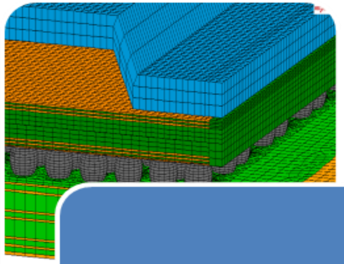
**Quantification**



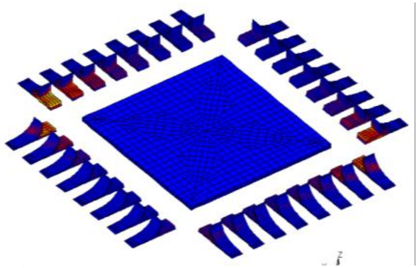
BOM

+

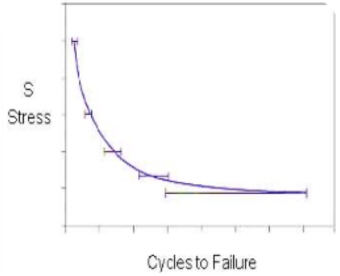
Mission profile



Modelling / Quantification / Simulation



Cyclic strain in solder joints



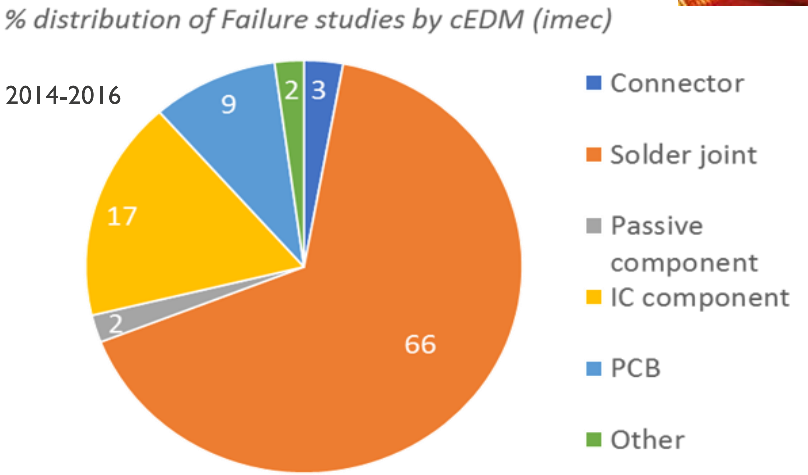

Life time model

# THE PHYSICS-OF-FAILURE APPROACH

## RELIABILITY OF A SYSTEM

$$\lambda_{sys} = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \ldots \cdot \lambda_n \cdot \lambda_{PCB}$$

is not valid.




How to handle?

- Identify all failure opportunities (EDM-D-100 – www.cedm.be)
- PoF based reliability function $R_i(t)$ *per FO*.

$R_i(t)$: Probability that no failure has occurred at time *t* at failure opportunity *i*.

- For a system without redundancy: $R_{sys}(t) = \prod_{\forall \text{ Fail.Opp.}} R_i(t)$

# THE PHYSICS-OF-FAILURE APPROACH

## OBTAINING *R(t)* FOR 1000 TO 100000 FAILURE OPPORTUNITIES?



### What do we need?

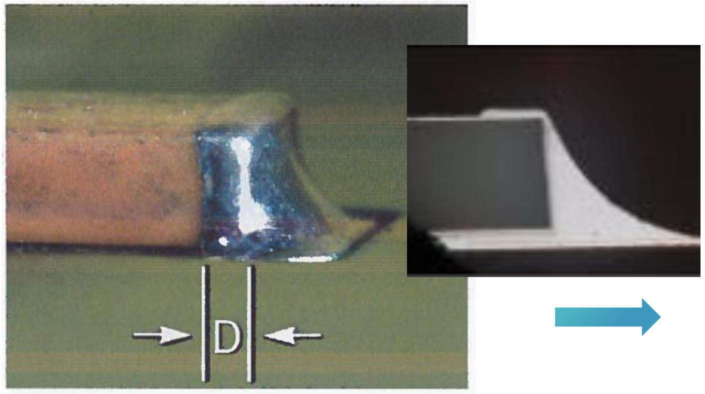
- Quantified understanding of the relationship between design and mission profile and the probability of failure.
- Fast (seconds) quantification of $R_i(t)$ for all (relevant) failure opportunities to evaluate a PBA in an acceptable time.

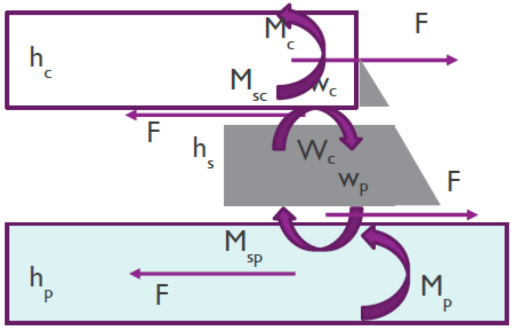
### The answer: Analytical modeling

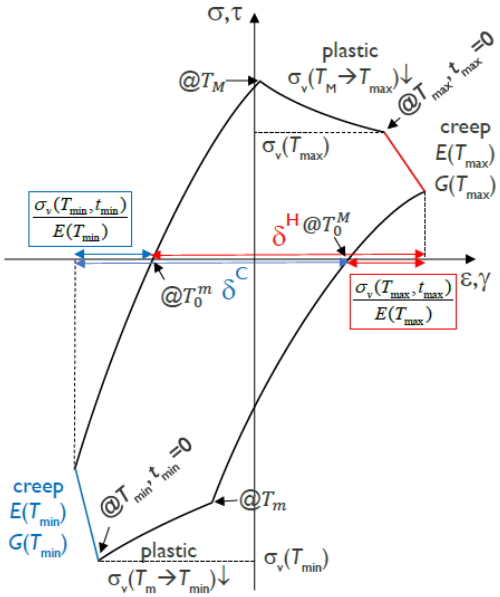
- Physics-based equations that directly relate the stress factors to the "damage factor".
- Complete physical understanding and insight.
- "immediate" calculation of required answer with basic tools, even Excel.

# THE PHYSICS-OF-FAILURE APPROACH

## AN EXAMPLE: SOLDER JOINTS OF A "CHIP" COMPONENT




$$\frac{L-w_c}{2}\left[(\alpha_p-\alpha_c)(T_{\max}-T_0^m)-F_{\max}(s_h,T_{\max},t_{\max})\left(\frac{1}{E_p h_p b_p}+\frac{1}{E_c h_c b_c}\right)\right]$$

$$-\frac{L-w_c}{2}\left[\left(1+\frac{\alpha_p+\alpha_c}{2}(T_{\max}-T_0^m)\right)\left(\frac{h_p+h_s}{2}\frac{M_p^{\max}(T_{\max})}{E_p I_p}+\frac{h_c+h_s}{2}\frac{M_c^{\max}(T_{\max})}{E_c I_c}\right)\right]=\delta^H$$

Elastic/plastic/creep, bending, 2D/3D, temperature, dimensions, fillet, materials, ....

# THE PHYSICS-OF-FAILURE APPROACH

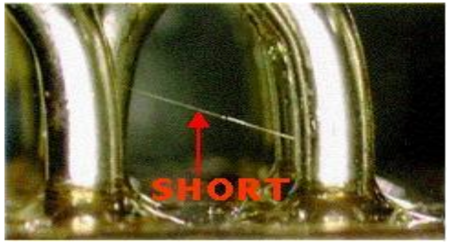
## ANALYTICAL ANALYSIS: CHALLENGES AND LIMITATIONS

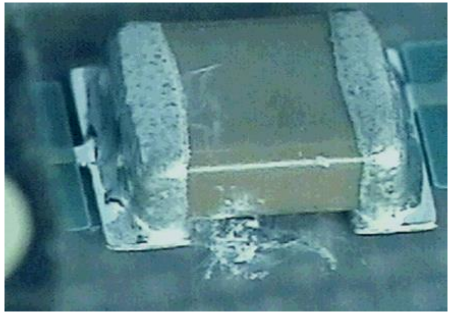
Not all failure mechanisms are understood quantitatively. E.g. whisker growth.

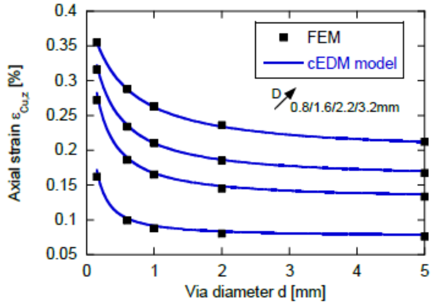
Model parameters cannot be obtained with the required accuracy. E.g. corrosion.

(Still) limited availability of sufficiently accurate analytical models. Effort to develop the analytical models.

Acceptance by industry of analytical modeling/evaluation.





# PHYSICS-OF-FAILURE IN PRACTICE TODAY

## ELIMINATING FAILURE OPPORTUNITIES: THE UNKNOWNS

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### Step 1: Know what you do not know!

Identify failure opportunities for which the wear-out failure mechanism is unknown.

Exotic cases? Applies to the major part of the components!

### Action:

- Document, register as unknown (and hope for the best[1])...
- ... or start some research and test.

(1): Some may find some peace of mind by using constant failure rate modeling. It has no added value w.r.t. to wear-out.

# PHYSICS-OF-FAILURE IN PRACTICE TODAY

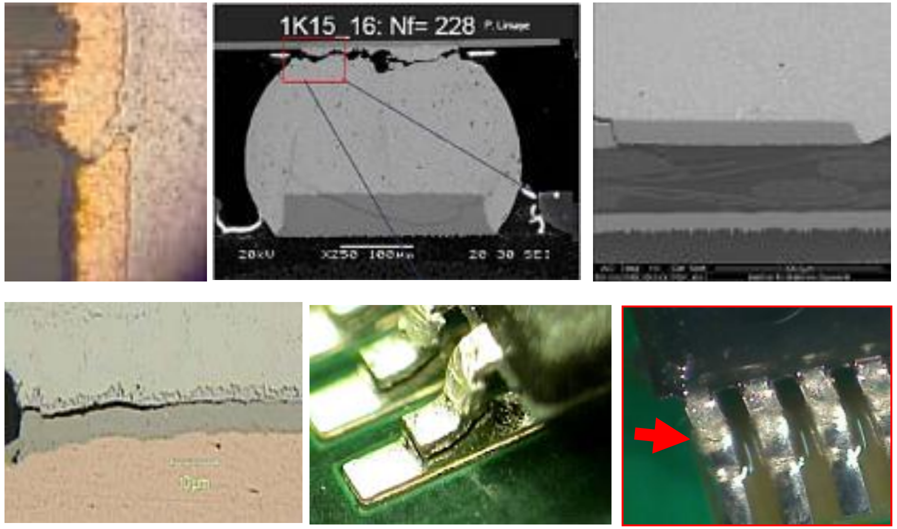
## ELIMINATING FAILURE OPPORTUNITIES: QUANTIFICATION VS. MITIGATION



Step 2

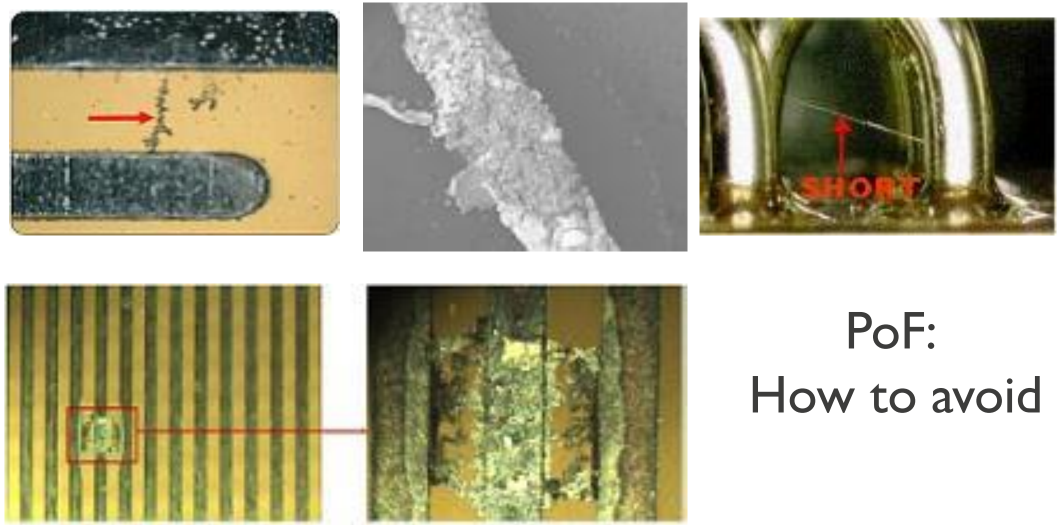
***Quantification*** versus ***Mitigation***

***Connection failure***




Quantifiable with PoF:
Thermo-mechanical stress

***Insulation failure***




PoF:
How to avoid

- Material specification e.g. fluxes
- Coating
- Environmental protection

$$R_i(t)=1$$

# PHYSICS-OF-FAILURE IN PRACTICE TODAY

## ELIMINATING FAILURE OPPORTUNITIES: NOT CRITICAL



### Step 3: Eliminate non-contributors using FMEA.

E.g. Solder joint fatigue (see EDM-D-002)

Not critical:

- Through-hole connections
- Components with flexible leads
- Components soldered to thin and/or flexible boards

Critical:

- Large SMD ceramic chip components ≥1810
- QFN > 4mm x 4mm

This requires some PoF expertise.

# PHYSICS-OF-FAILURE IN PRACTICE TODAY

## MODELS & TOOLS

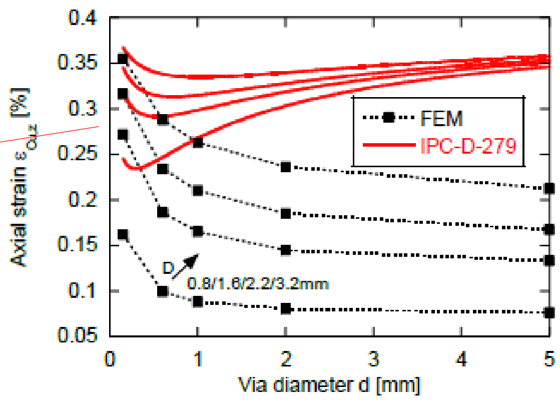
Scientific literature:

- Often too detailed (in-depth), complicated, hard to implement and use. For scientific use not for industrial implementation.
- Far from complete.

Standard: Physics of Failure Reliability Prediction ANSI/VITA 51.3 (2016)

Models:

- Large empirical part including "quality" factors
- Limited number effects taken into account.
- Not very accurate e.g. IPC-D-279 (solder joint and via fatigue model)



# PHYSICS-OF-FAILURE IN PRACTICE TODAY

## MODELS & TOOLS

Physics-of-Failure based tools combining DfR FMEA, numerical and analytical modeling

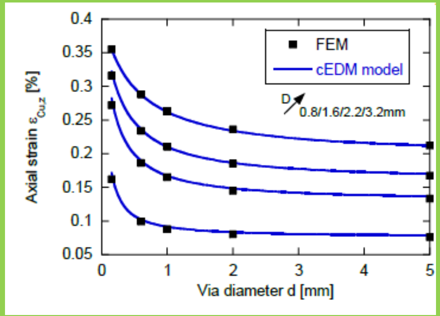
### CALCE's SARA

https://www.calce.umd.edu/software/


### DfR Solutions' Sherlock

http://www.dfrsolutions.com/what-is-sherlock


Guidelines, tools and assistance



# CONCLUSION

A Physics-of-Failure based reliability assessment is the only viable approach to lifetime assessment of modern electronics.

Analytical modeling is pivotal in providing physical insight, fast and sufficiently accurate analysis, increasing the coverage and ease of use.

More modeling and tool development effort is required.

More on this topic today

Craig Hillman (DfR Solutions):
*Best Practices in Implementing Physics of Failure into the Design Process*

# THANK YOU

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