

# Corrosion and Accelerated Testing

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Sandia National Laboratories



Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

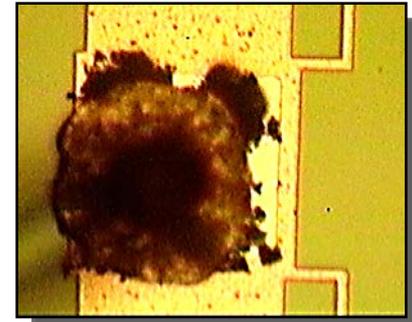
# What is corrosion?

## Environmental degradation of materials

### ➤ Aqueous (general & localized attack)

- electrochemical
- oxidation / reduction

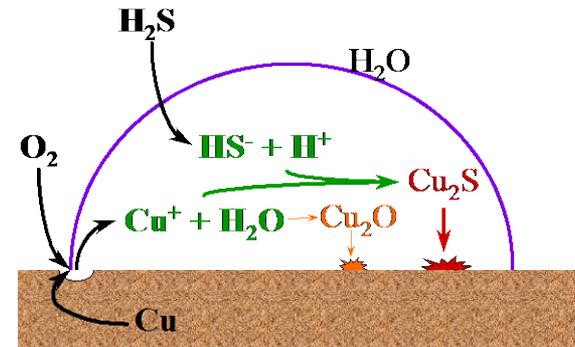
Processing



### ➤ Atmospheric

- gas-metal reaction (slow)
- condensed phase electrochemical
- pollutant gasses (ppt levels of  $\text{H}_2\text{S}$ ,  $\text{NO}_2$ ,  $\text{Cl}_2$  ...)

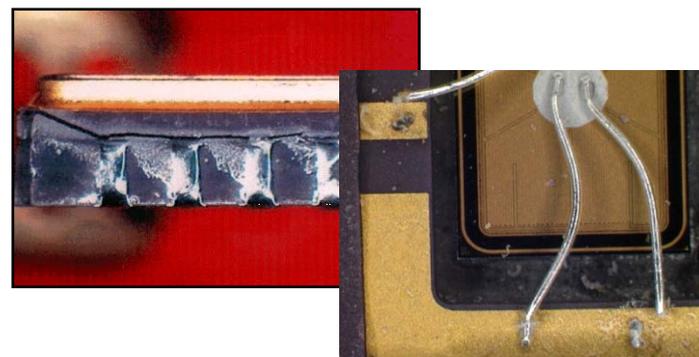
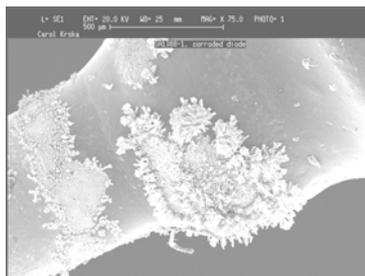
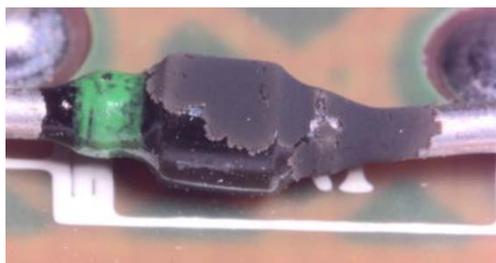
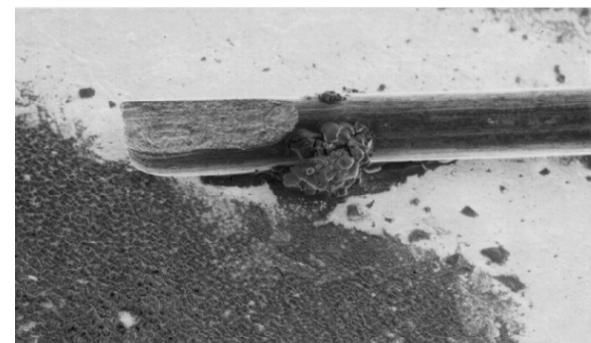
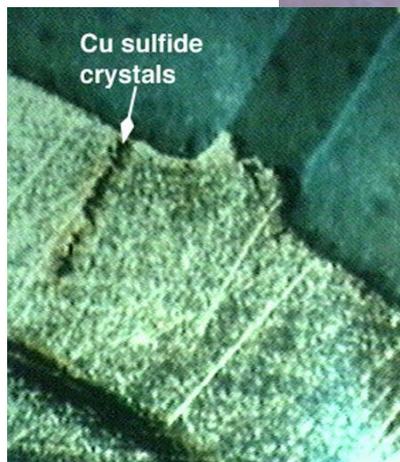
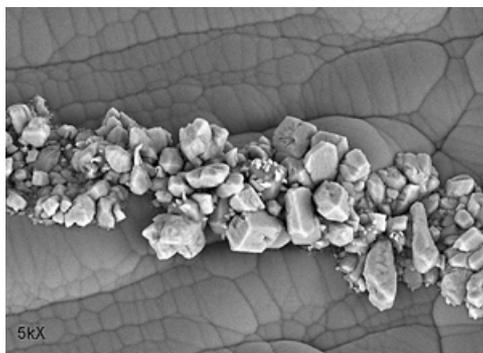
Use



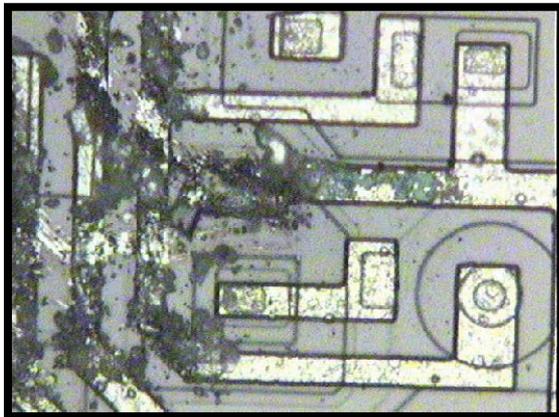
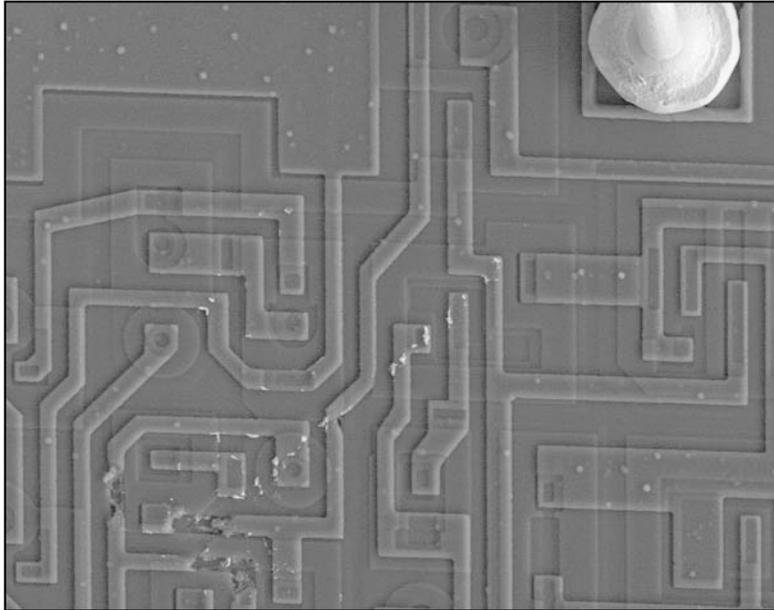
# Corrosion normally occurs due to defects or unexpected environments



Cruise missile fuel line

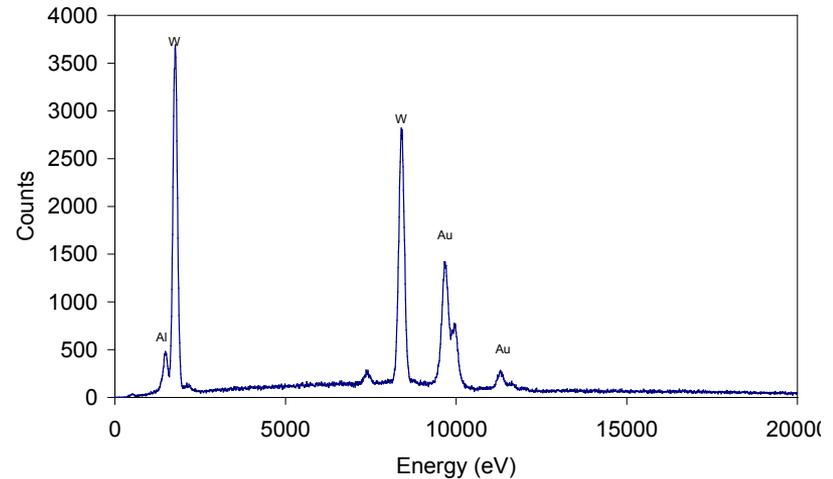


# A plastic encapsulated IC failed after 5 years in dormant storage.



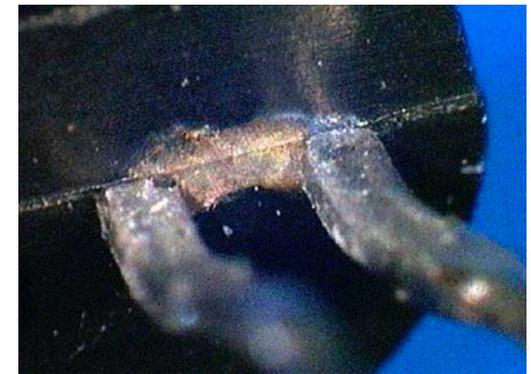
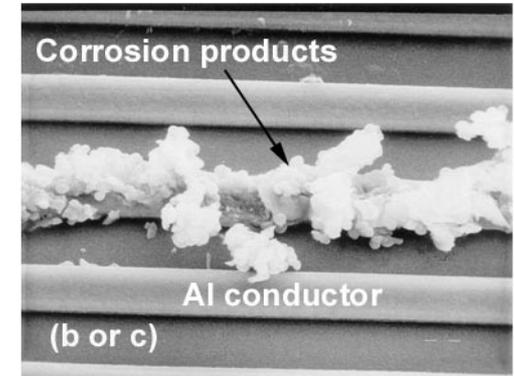
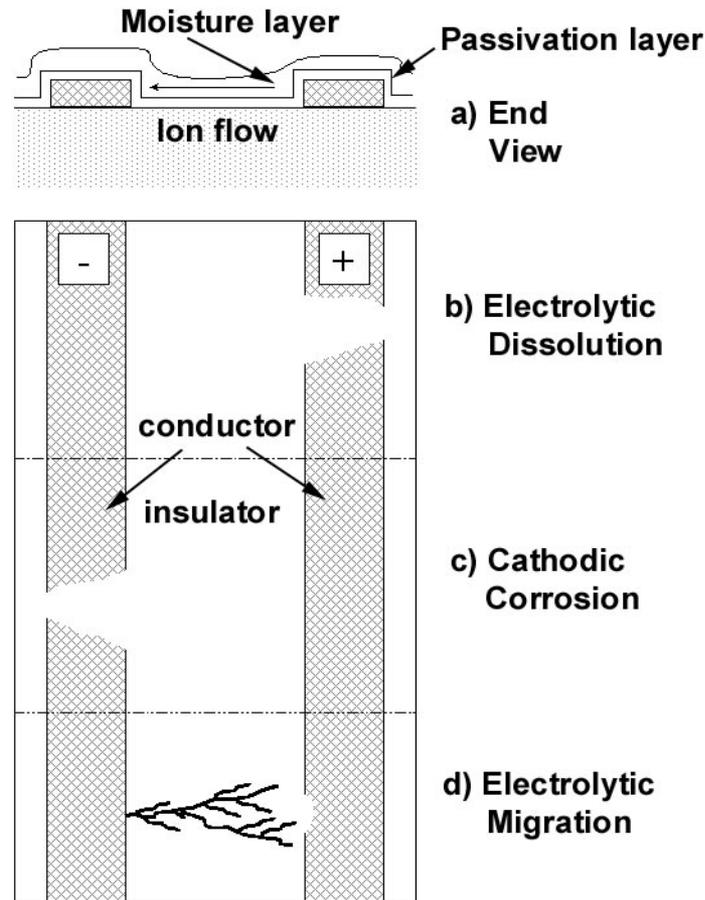
## Defects:

- Damaged passivation
- Au (galvanic couple)



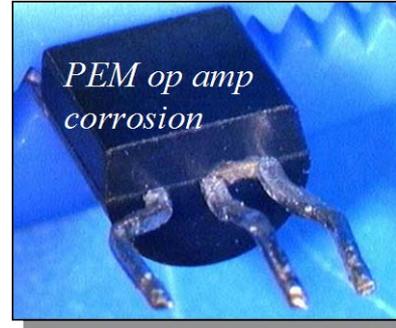
# Several non-traditional corrosion mechanisms exist in microelectronics that involve electrical bias

- **Electrolytic dissolution**
- **Cathodic corrosion (alkalization)**
- **Electrolytic migration**



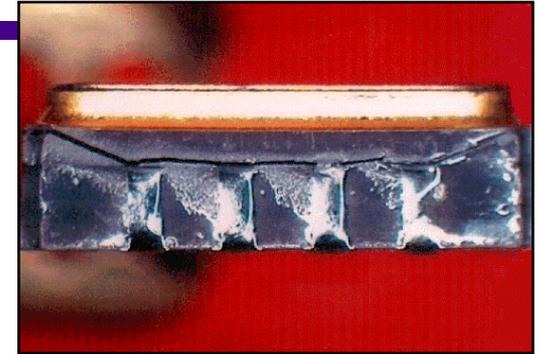
# Conditions required for electrolytic migration

- Applied voltage
  - powered system
- Susceptible alloy
  - Ag used in ground plane
  - Solder
  - Copper
- Conductive surface
  - flux residue (activator)
- Electrolyte
  - High humidity
    - Temperature cycling
  - Seacoast environment (NaCl)



# Corrosive environments can contact metallization features

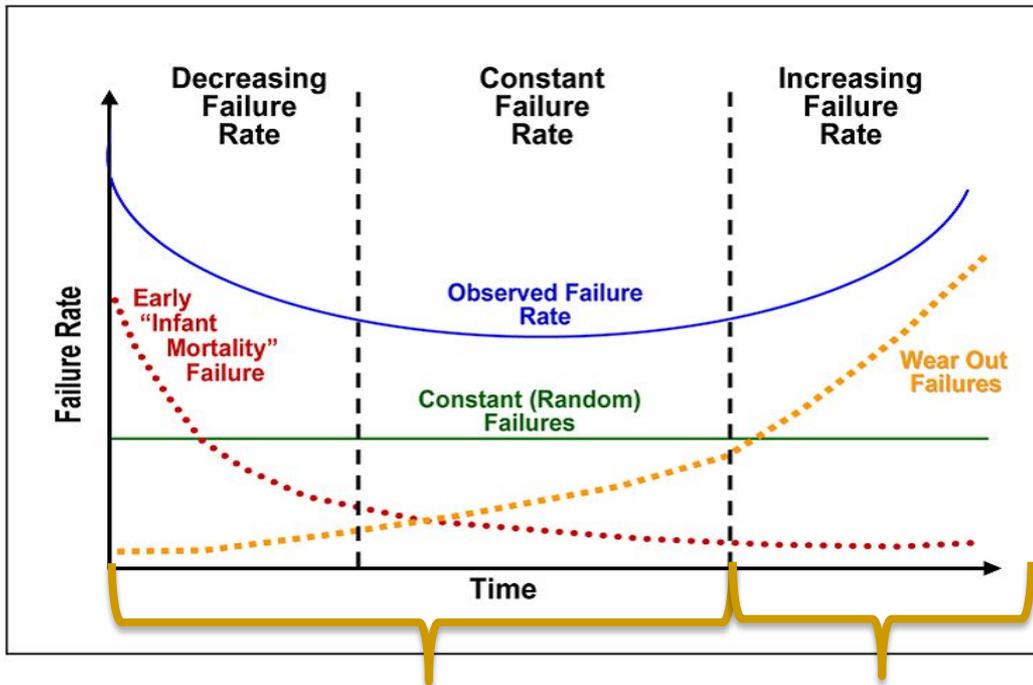
- **Breach in hermetic packaging in CHP**
- **Use of encapsulants in PEMs with high water permeability**
- **Specific unintended exposures (e.g., military)**
  - **high T, RH, [Cl<sup>-</sup>] possible**



# Materials Degradation Affects Reliability

Probability of failure-free performance, item's useful life, or a specified timeframe specified environmental duty-cycle conditions.

Reliability  Cost



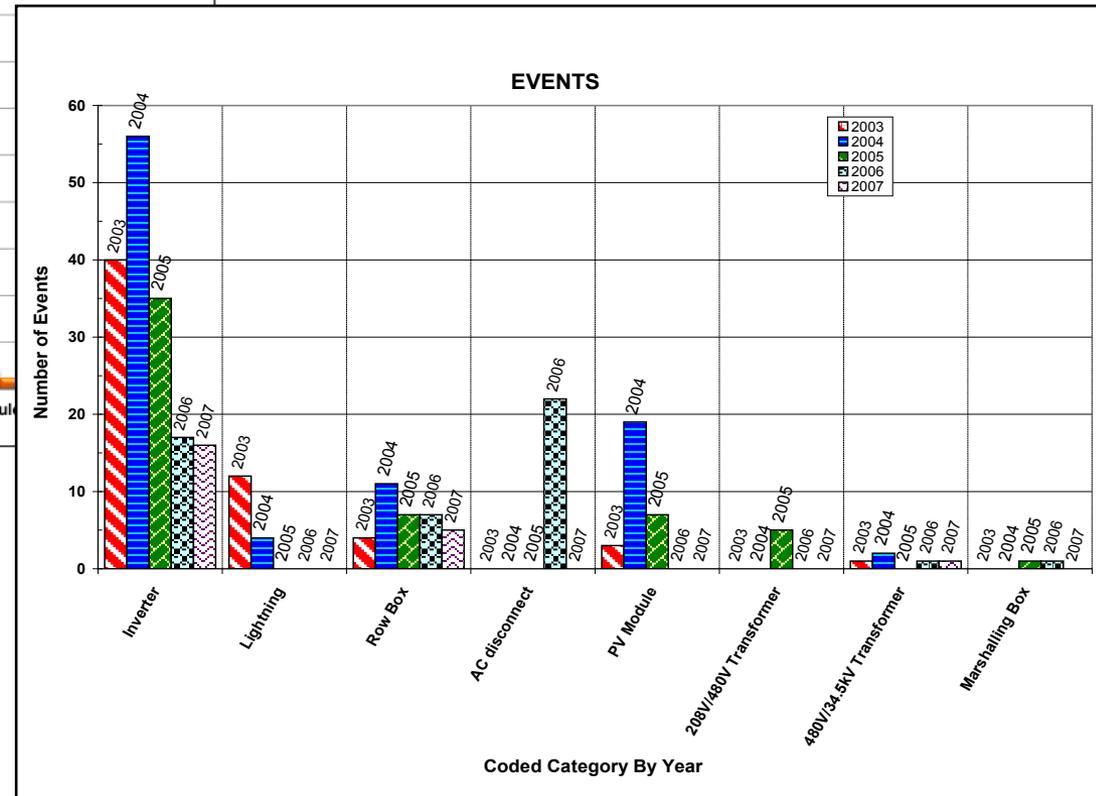
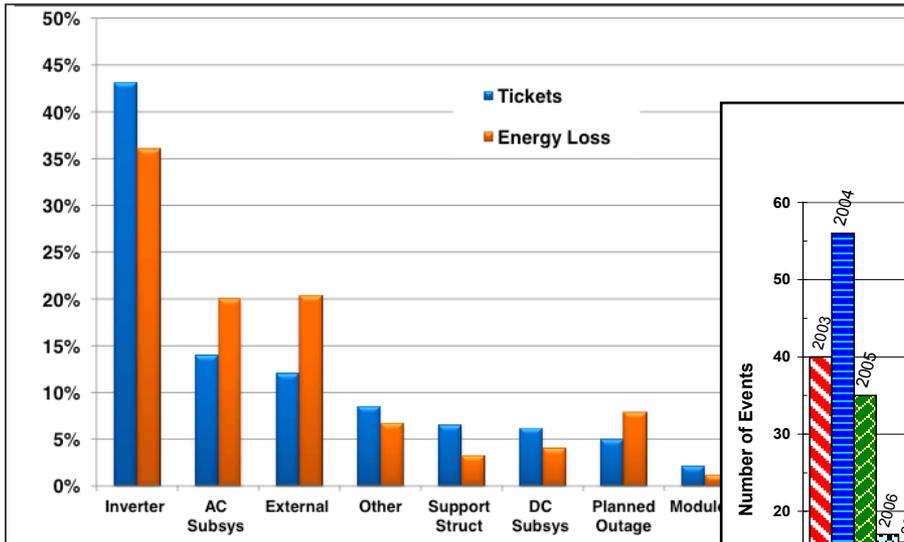
Lab and Field Data

Accelerated Tests

**Accelerated testing plays a key role in determining reliability**

- **Must be applicable to failure modes**
  - **Reproduce field failures**
- **Acceleration factor**
  - **Range of stresses**
  - **Long term tests**

# The inverter is a significant contributor to reliability issues



Sun Edison – Owner/Operator (A. Golnas, “PV System Reliability: An Operator’s Perspective,” in 38th Photovoltaic Specialists Conference, Austin, TX, Jun. 2012, pp. 1–32.)

Tucson Electric Springerville Plant.  
Sandia Study

# What is ALT & why?

## What?

- Component life tests
- High stresses
  - Single or combined
  - Activate “appropriate” failure modes
  - Measureable
- Time compression (cyclic stresses)
- Failure analysis

## Why?

- Time
- Full system is expensive and complicated

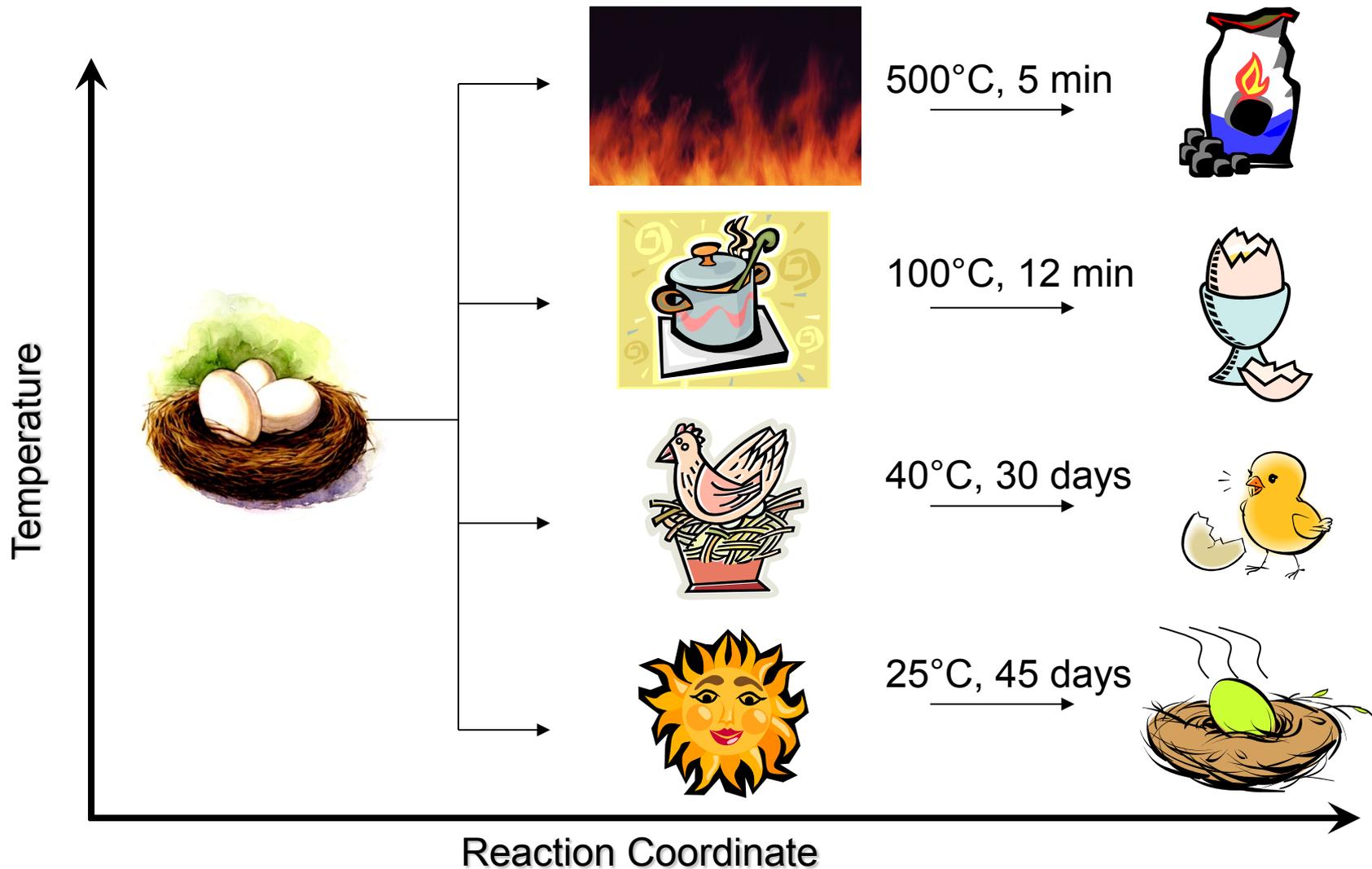
# Failure Modes for Crystalline Silicon

(John Wolgemuth – BP Solar)

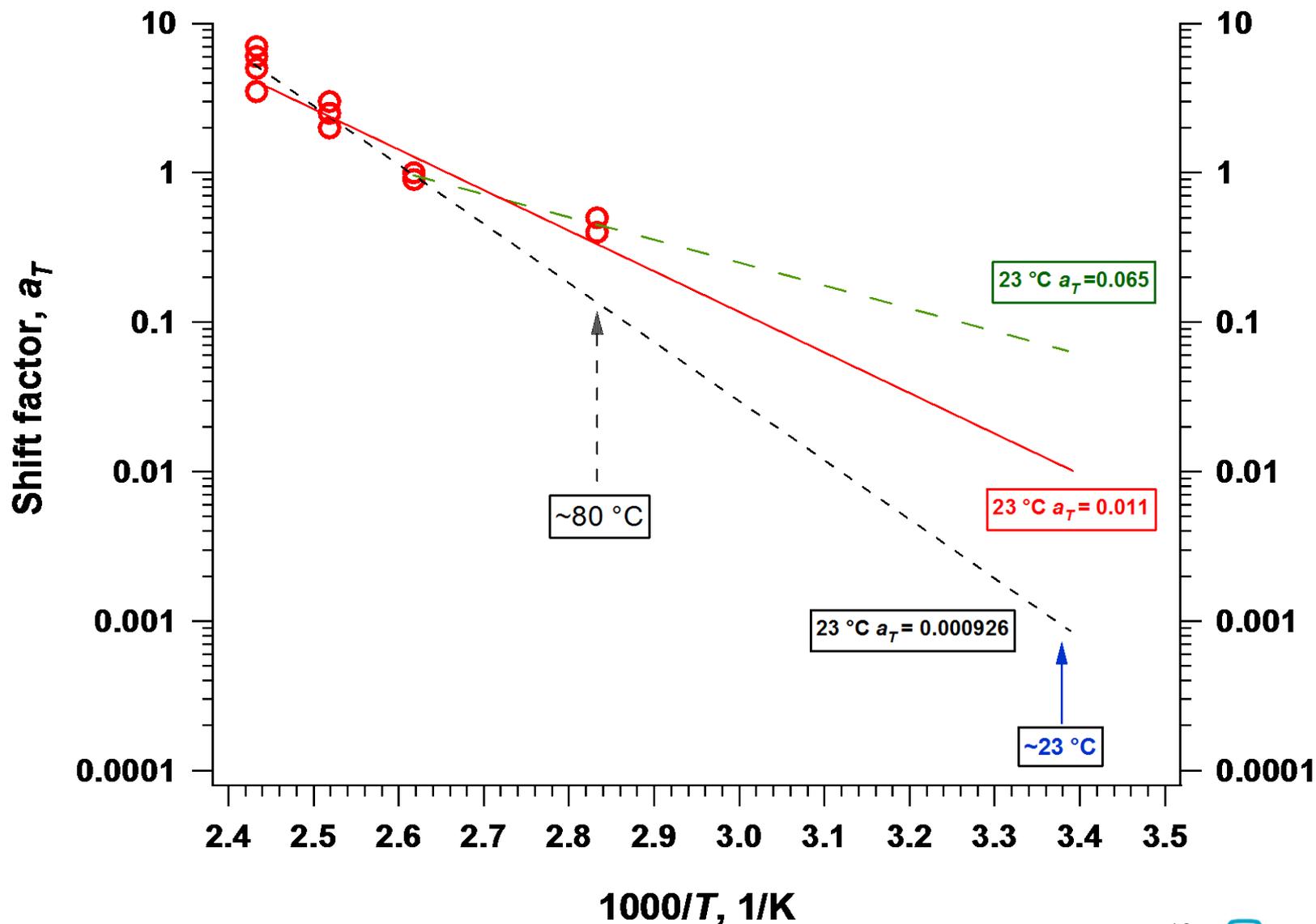
- Broken interconnects
- Broken Cells
- Corrosion
- Delamination and/or loss of elastic properties
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Hot Spots
- Ground faults
- Junction box and module connection failures
- Structural failures

Would you expect a single test to capture all of the expected failure modes?

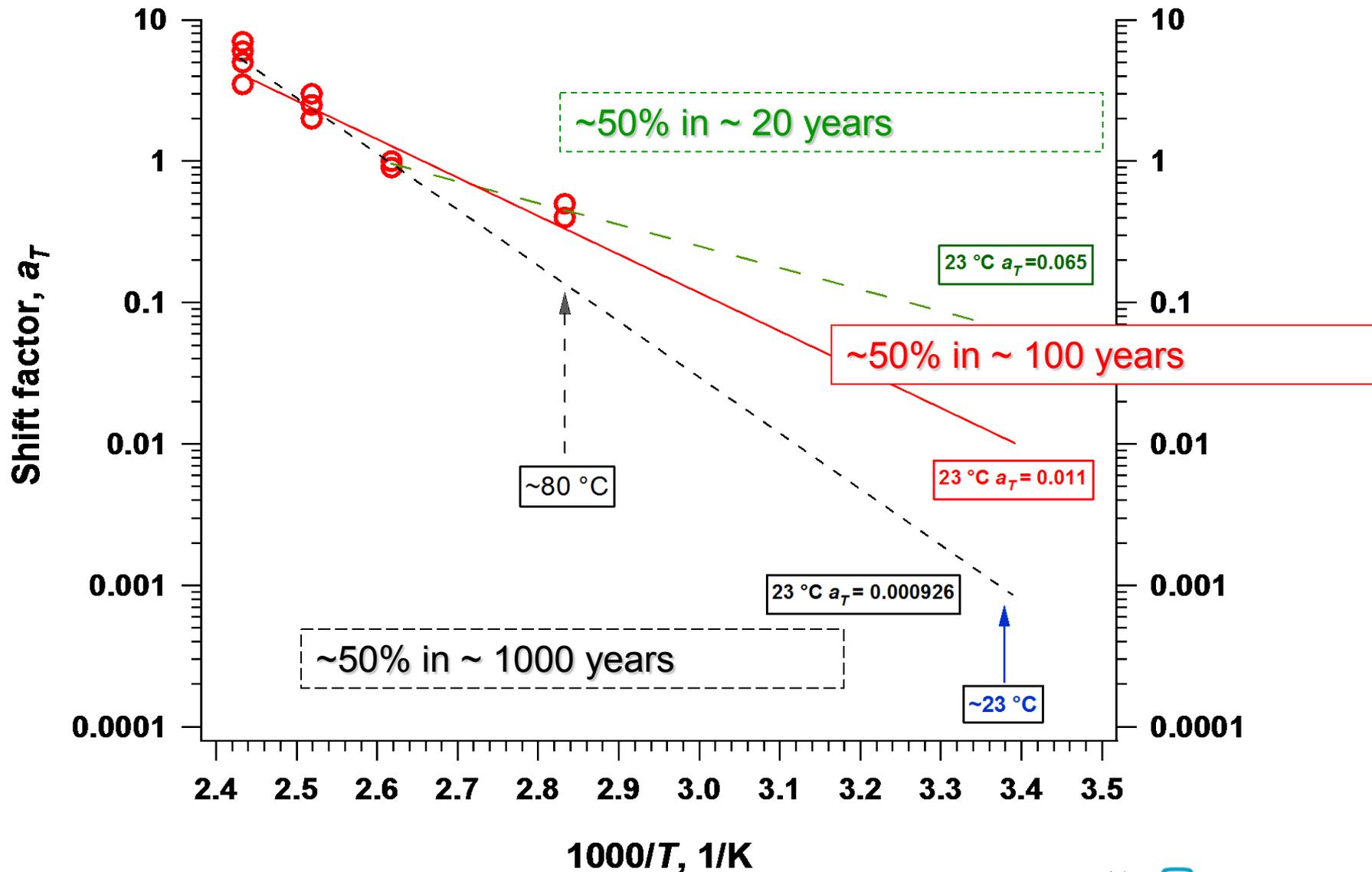
# It is important to understand the degradation mechanism and select appropriate stress level



High T data are extrapolated to “use” conditions  
(room temperature)



# How you extrapolate can influence lifetime predictions.



# Two approaches to accelerated testing are used throughout industry

## ➤ **Qualitative Accelerated Tests**

- HALT tests
  - HAST tests
  - HASS tests
- } Small sample size  
Severe level of stress

Increase reliability  
(product improvement)  
Qualify new designs  
Design quantitative ALT

Reliability under normal  
use conditions

## ➤ **Quantitative Accelerated Life Tests**

- Controlled application of accelerated stress
- Produces acceleration factors (AF)
  - Usage rate acceleration  
(Time compression)
  - Overstress acceleration

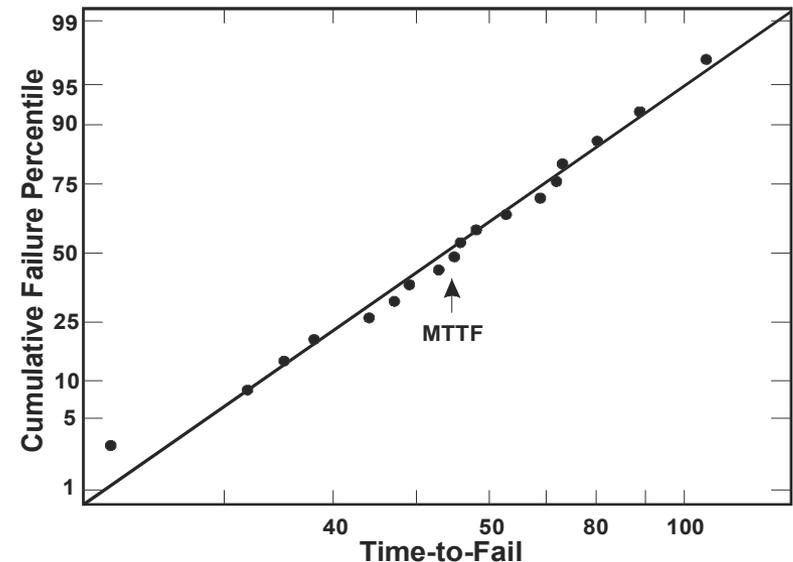
Used to determine TTF  
Determine reliability

Long Time  
Need degradation / failure  
mechanisms

The Goal of an ALT program is to produce acceleration factors

- Often empirical correlations
- Limited root-cause analyses

$$AF = \left( \frac{MTTF_{\text{field}}}{MTTF_{\text{test}}} \right)$$

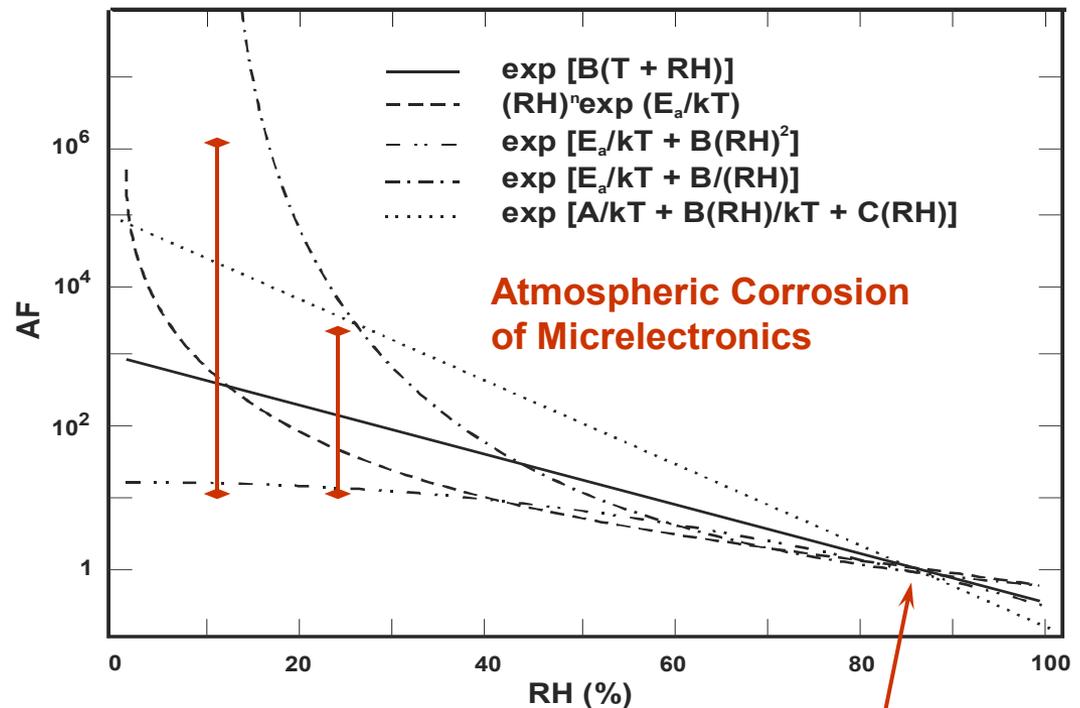


$$AF = \exp \left[ \frac{E_a}{k} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right] \left( \frac{RH}{RH_0} \right)^n \left( \frac{a + bV}{a + bV_0} \right)$$

# ALT must capture valid degradation / failure mechanisms

## Example:

- Five recognized models for corrosion in micro-electronics
- All agree at 85%RH
- Disagreement at 10%-30% prevent uniform application of either model



# Acceleration factors depend on the stress characteristics

## ➤ Thermal (Arrhenius)

- Activation energy
- Verify no mechanism change
- Bin damage by time at temperature

## ➤ $\Delta T$

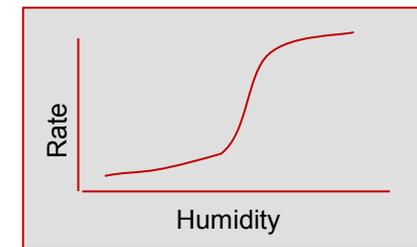
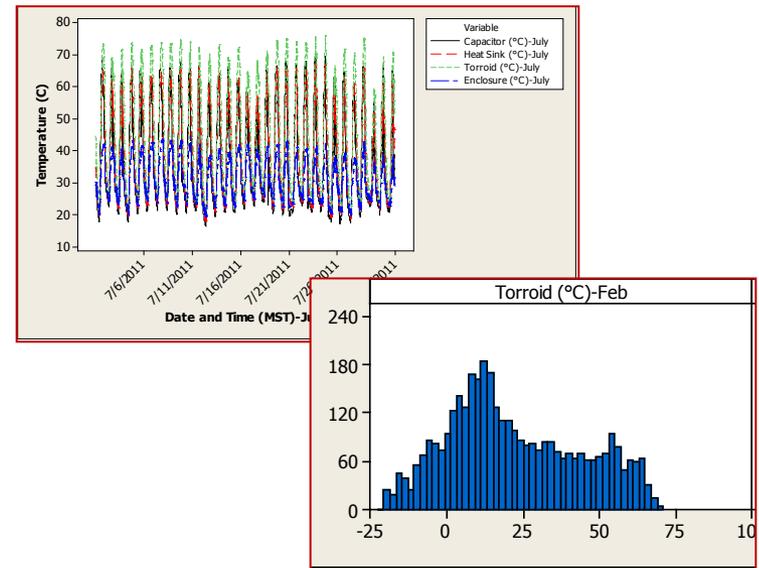
- Linear (time compressions),
- Increased temperature range
- Frequency analysis (rainflow counting)

## ➤ Voltage

- Linear (must understand relationship)

## ➤ Humidity

- Tends to be complex (adsorbed water)



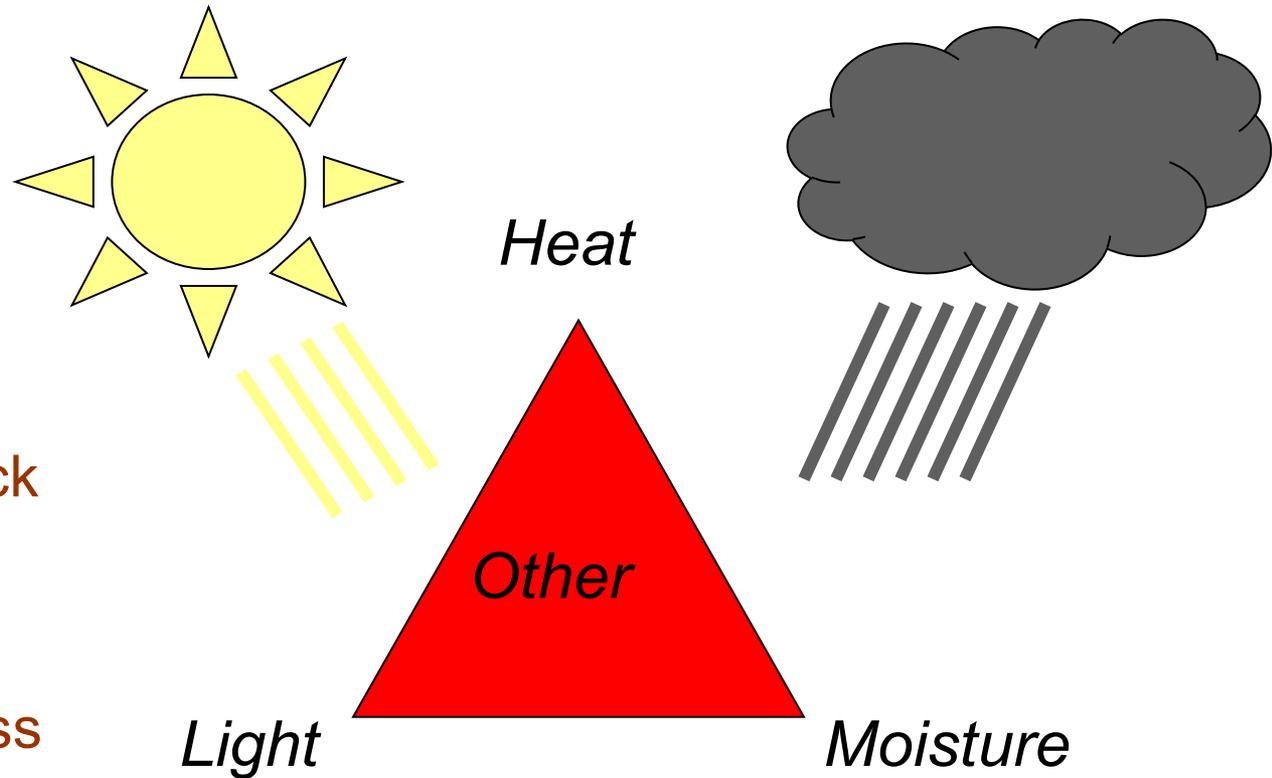
# Issues with ALT

- Unknown failure mechanisms
- Unknown / variable use environment
- Changing mechanisms as function of environmental stress
- Difficult to control and characterize defects
- Long duration experiments
- Evolving / improving technology

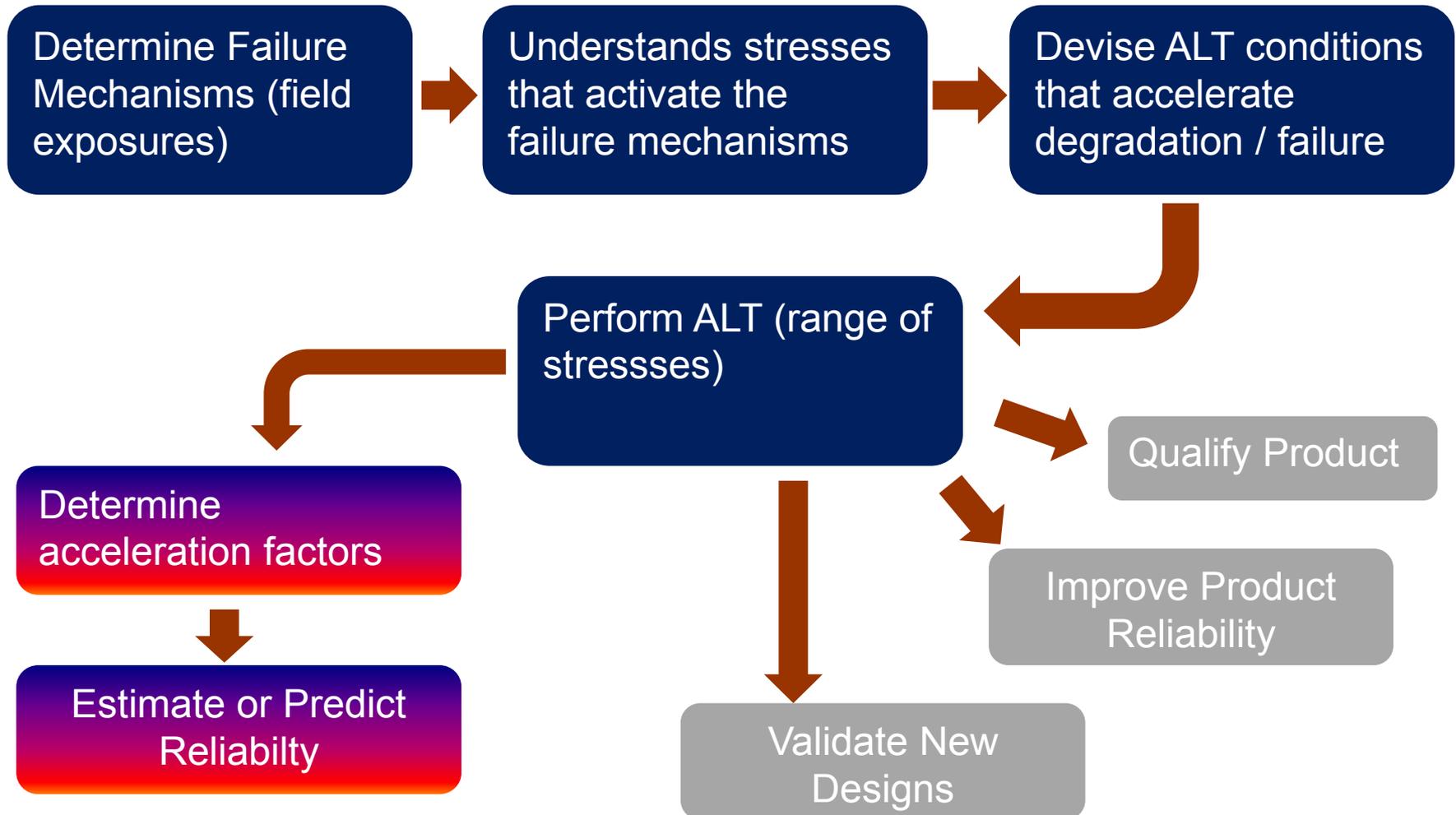


# What are the likely stresses that lead to Inverter Failure?

- Voltage
- Temperature
- Thermal cycling
- Thermal Shock
- Vibration
- Mechanical Shock
- Humidity
- Contamination
- Mechanical Stress
- ???
- ???

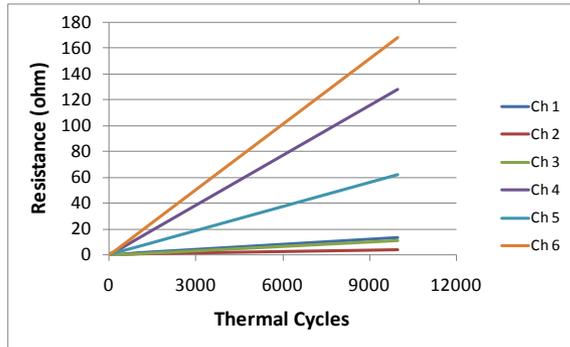
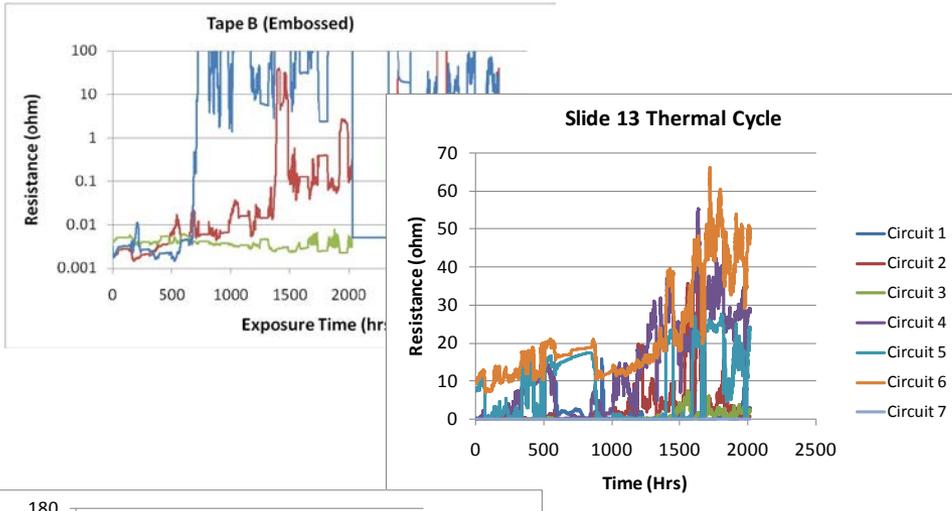


# How do we apply ALT to predicting end-of-life (wear out)?

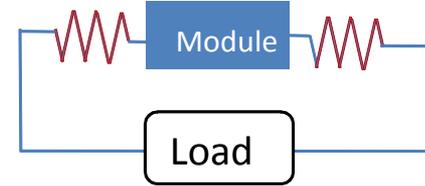


# Analysis of metal foil tape degradation

## Generate ALT data



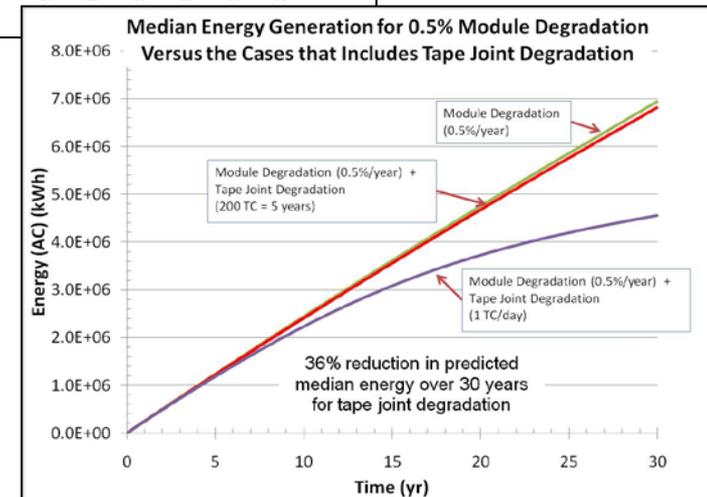
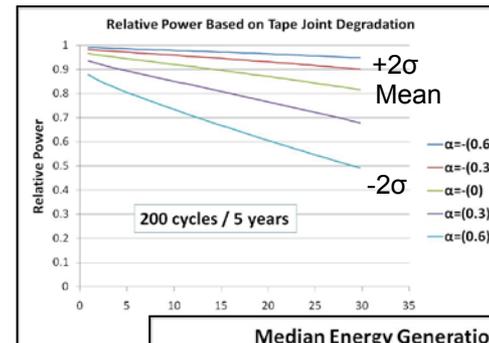
## Determine performance effect



$$E = I \times R$$

$$P = I \times V = I^2 \times R$$

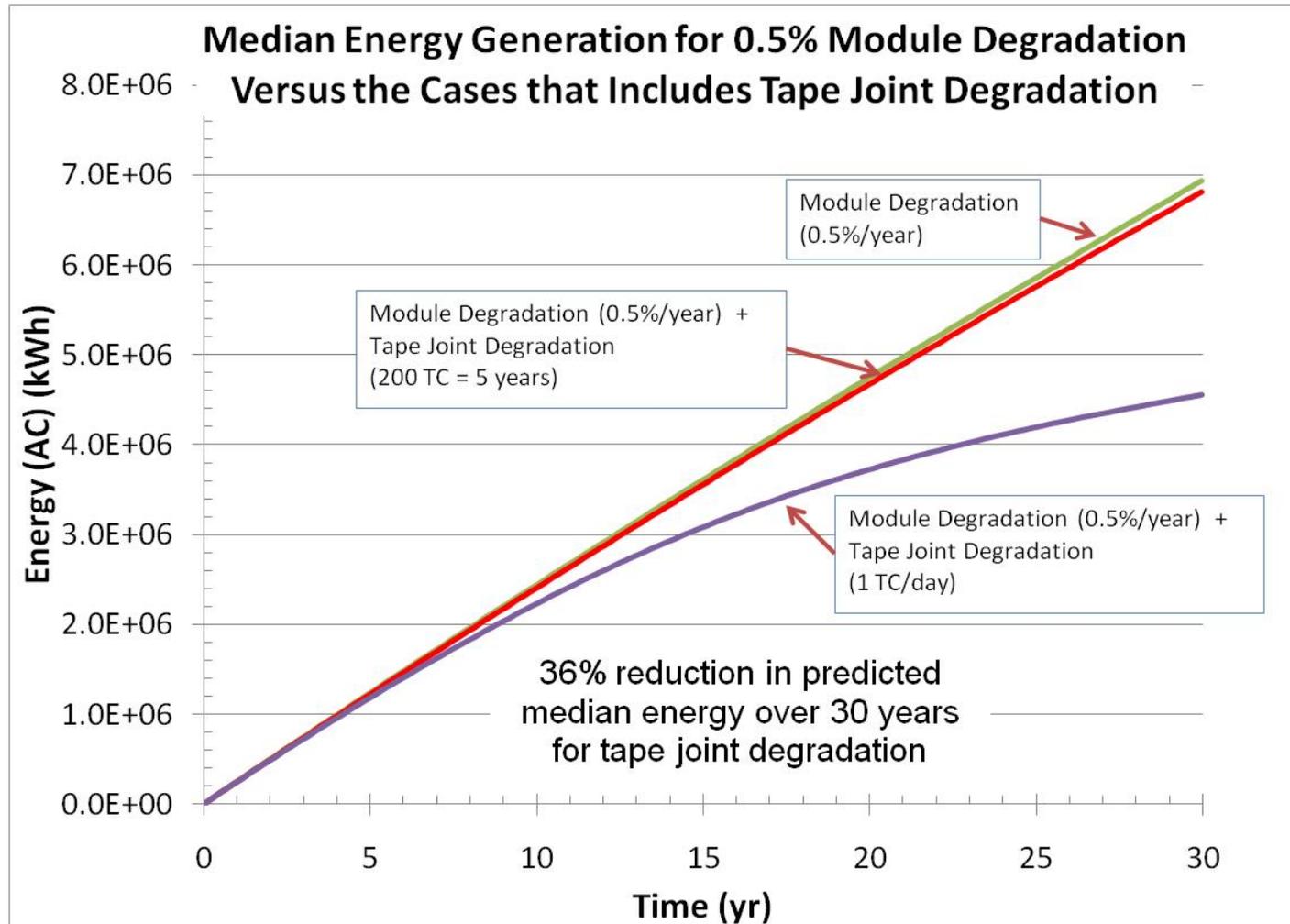
## Apply acceleration factors to field



## Develop "acceleration factors"

$$R = 10^{(0.028(\sqrt{t}) + \alpha)}$$

# Use the ALT data to predict long-term performance degradation (wear-out???)



# Summary

Accurate prediction of reliability is complex

- Requires understanding of degradation processes
- Data Driven
  - Field data
  - Accelerated testing
- Effect on performance (what is failure?)
- Includes uncertainty

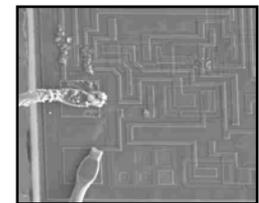
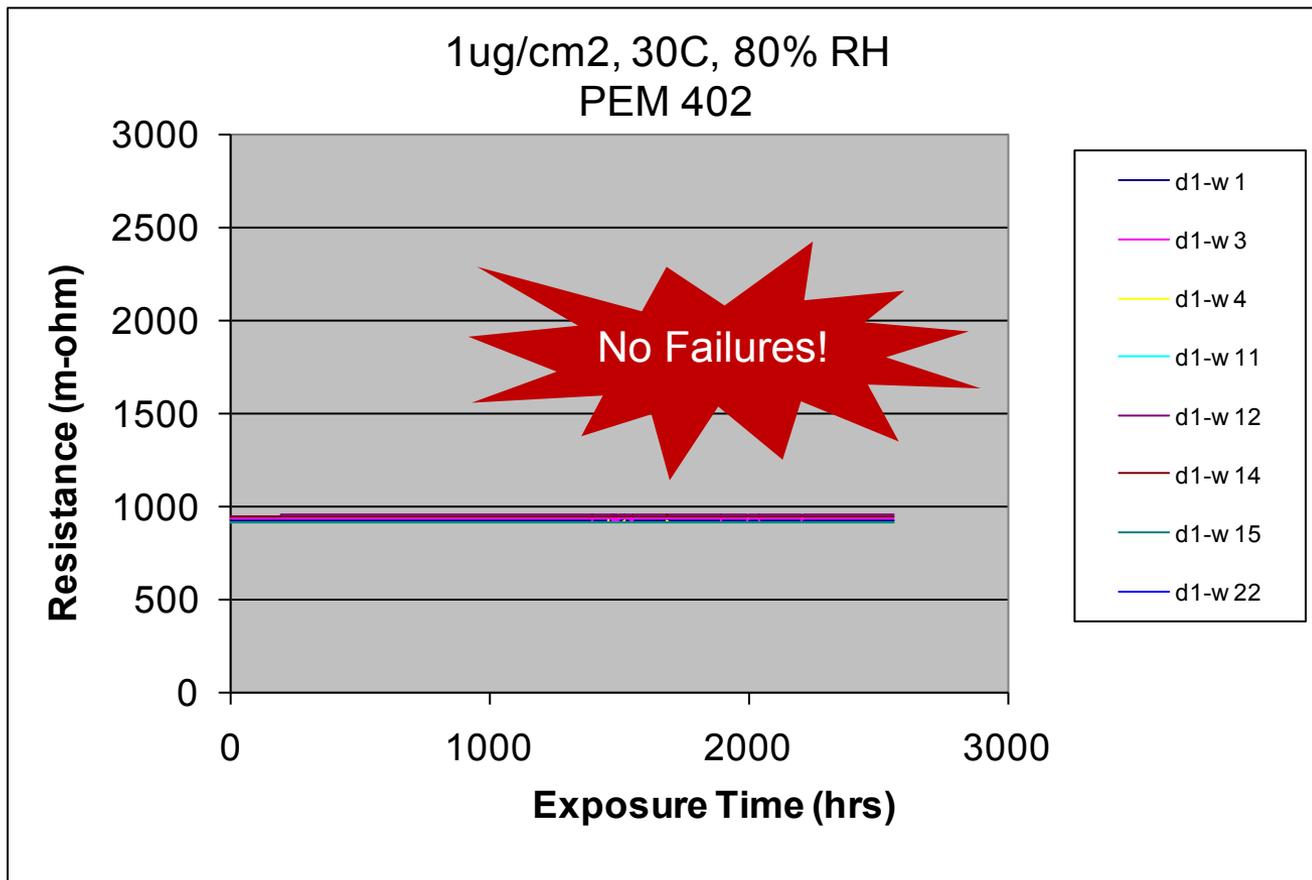
# Extra Slides

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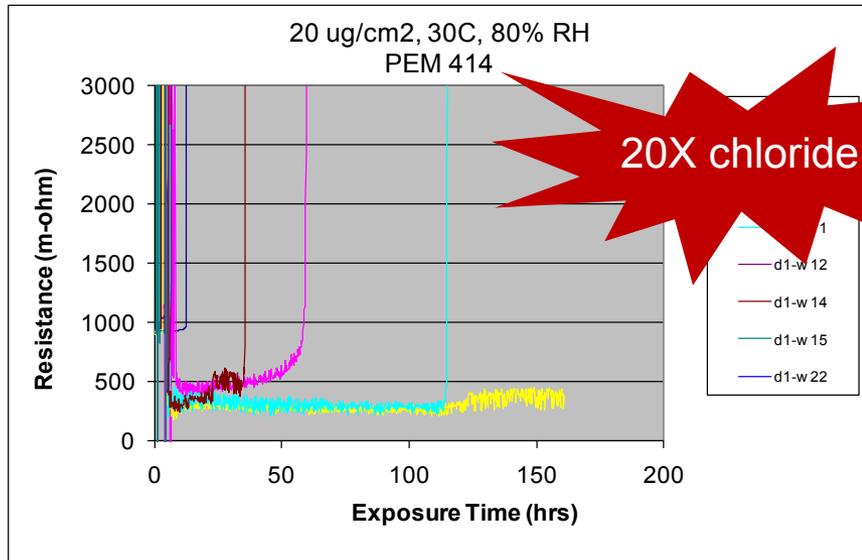


Example: Al bondpad corrosion: corrosion requires moisture and contamination & is accelerated by temperature.

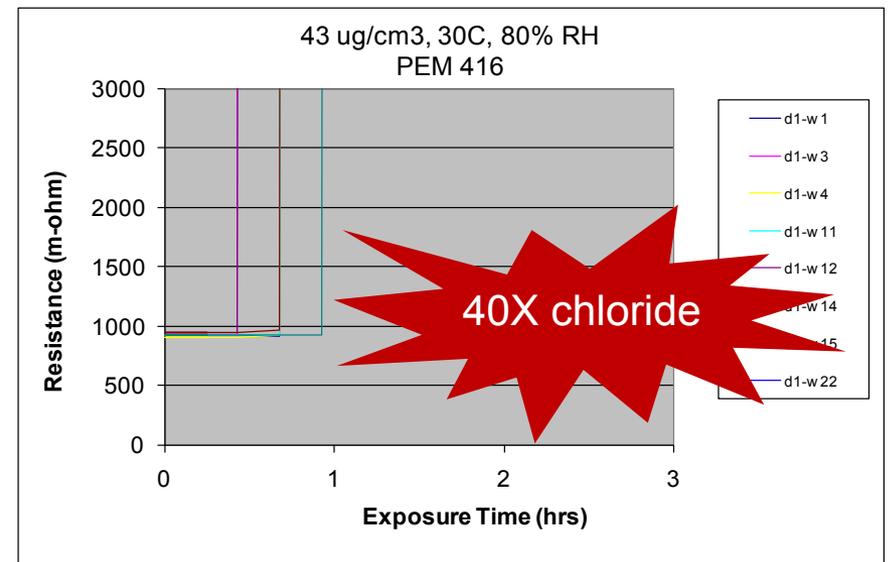
Three environmental variables (T, RH, [Cl])



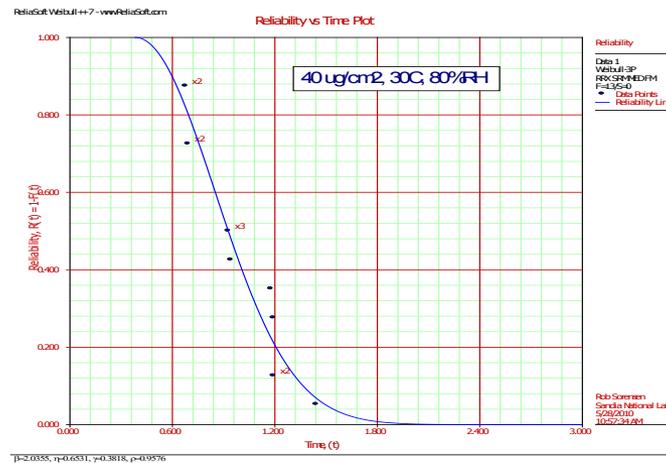
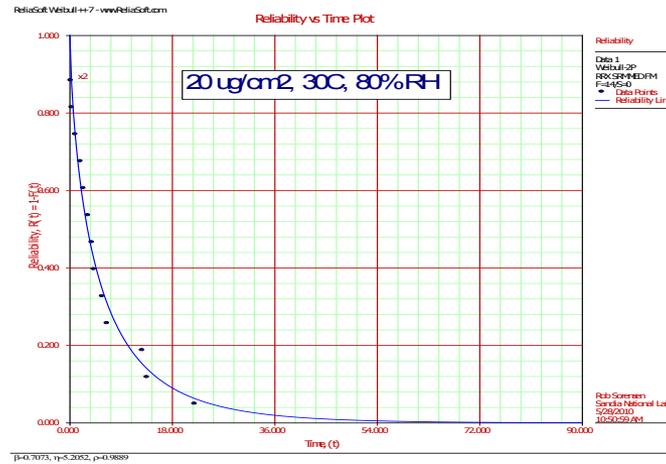
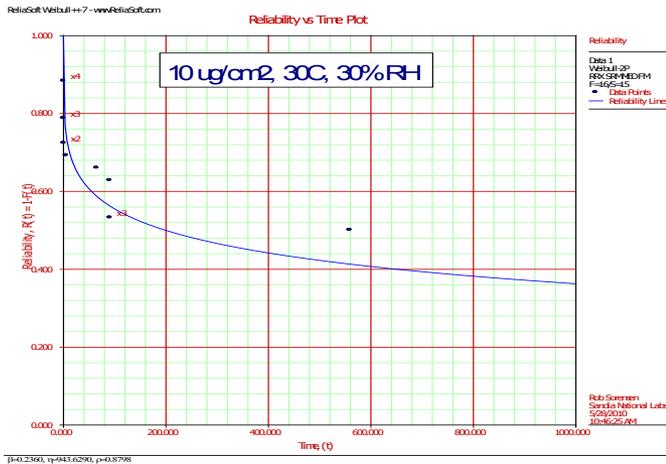
# Increasing contaminant level causes failure.



Distribution of failure times  
Not all failed  
Clear effect of [Cl]



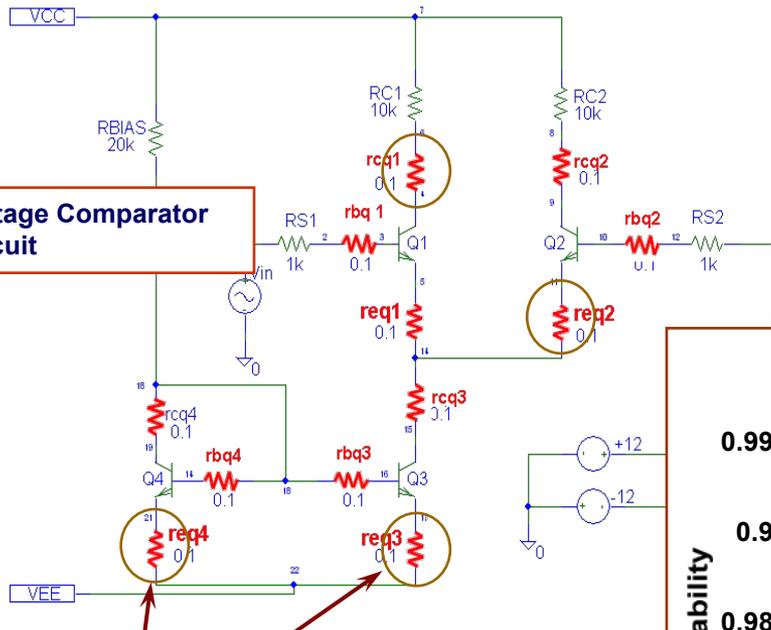
# Statistical treatment (life-data analysis) provides a means of analyzing the bondpad data



$$AF = \left( \frac{MTTF_{\text{field}}}{MTTF_{\text{test}}} \right)$$

- Provides distributions
- Includes suspension results
- Basis for models {Pfail = f(T, RH, [Cl])}

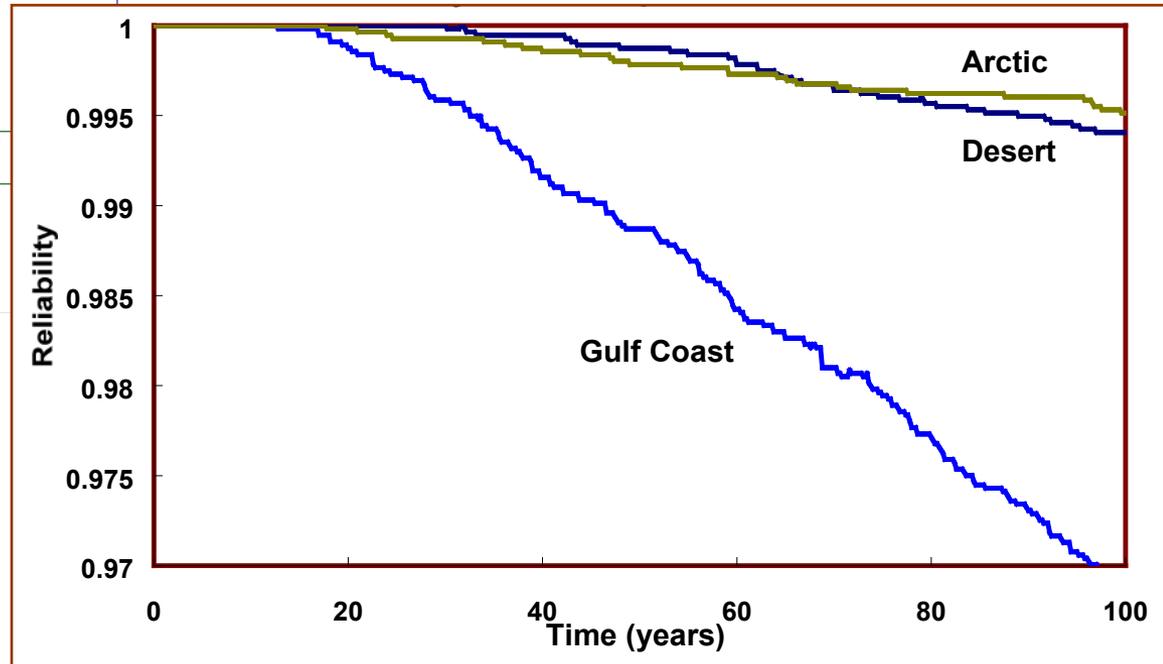
The distributed wirebond property (probability of failure) is input into an electrical system model & other component outcomes (reliability, performance threshold) can be determined



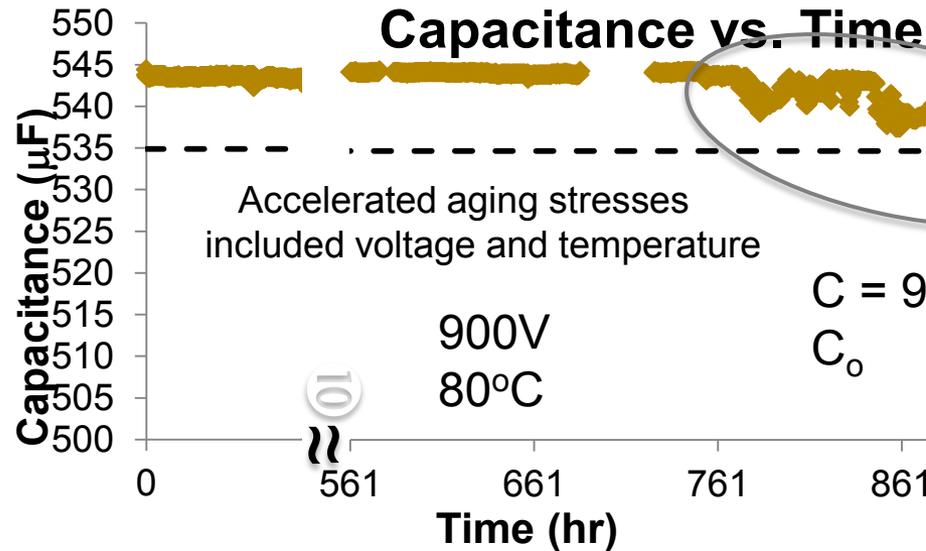
Voltage Comparator Circuit

Bondpad corrosion is modeled as an additional series resistor

Prediction of the effect of corrosion on reliability as f(storage location)



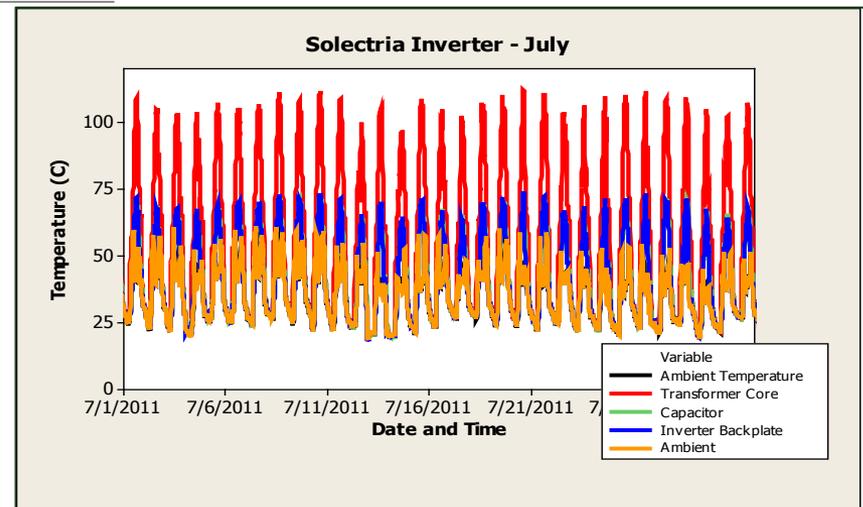
# Accelerated aging induced capacitor degradation.



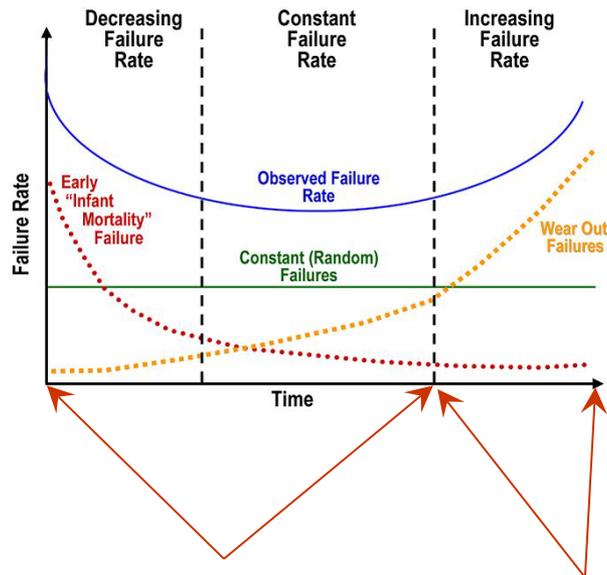
Capacitor failed in accelerated testing

Pre failure signature

Accelerated Aging  
Voltage & Temperature  
Capacitor failure  
Failure pre-cursor (decreased capacitance)



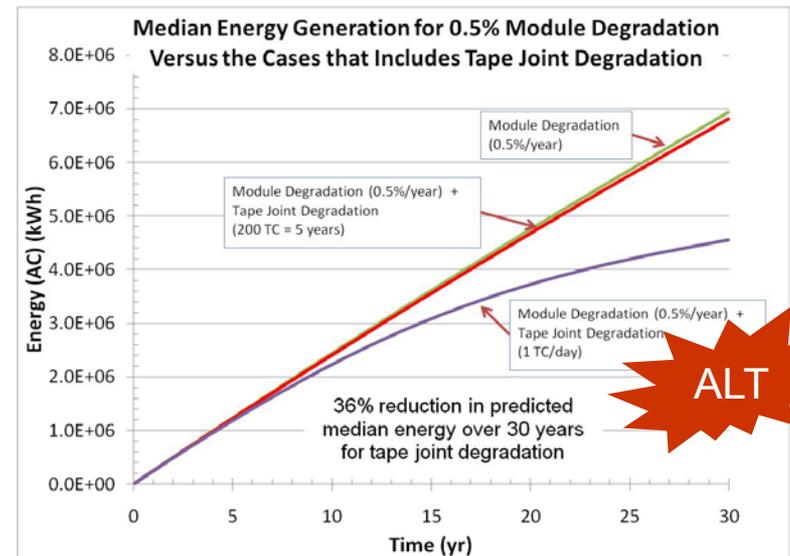
# Laboratory testing provides vital information for PV system reliability



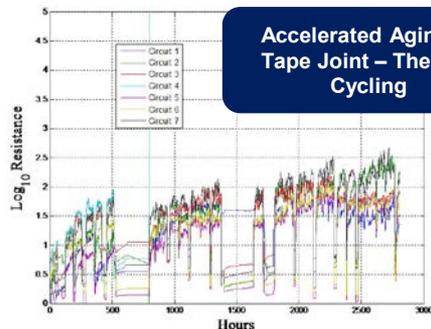
Field Data (O&M, Failures, ...)

Accelerated Testing / Lab Tests

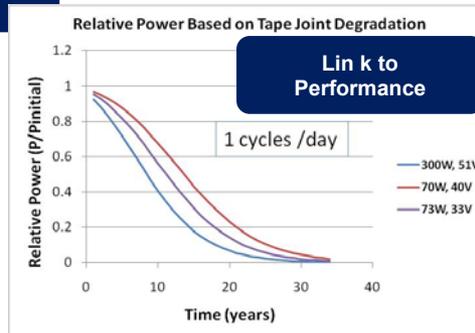
System performance model must include wear out (end of life) information



ALT



Accelerated Aging of Tape Joint - Thermal Cycling

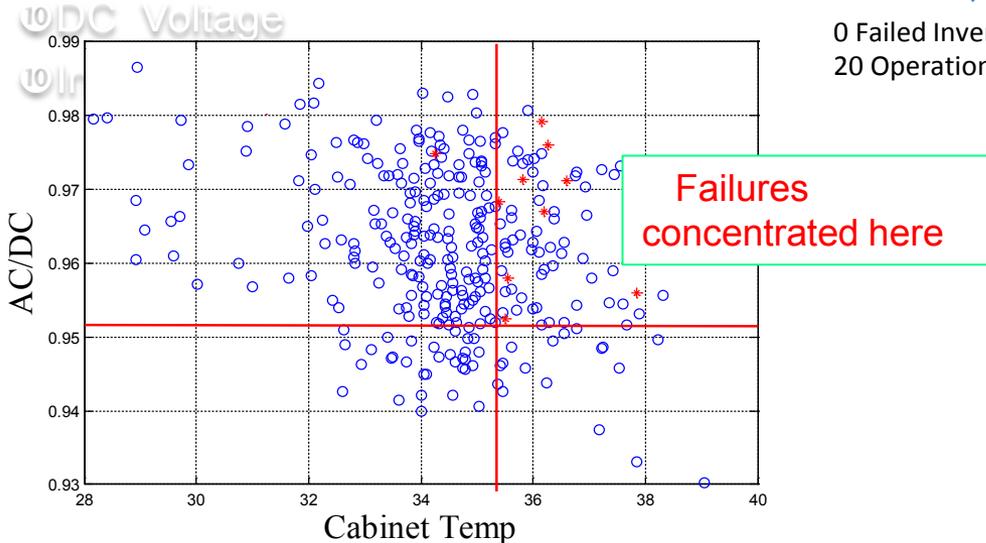
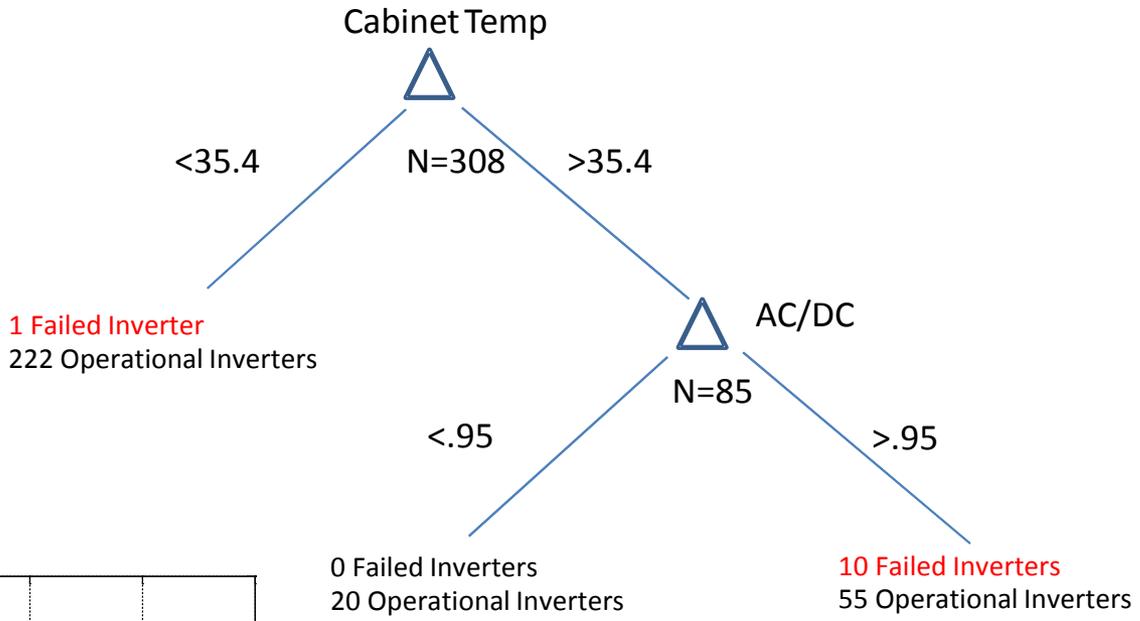


Link to Performance

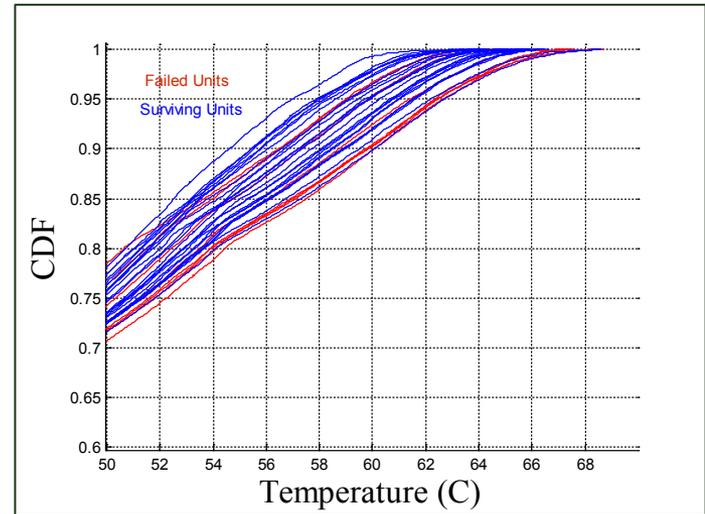
Acceleration Factors

# Field failure data from very large plants indicate correlation between temperature and failure

- Predictor Variables**
- AC\_Power
  - Cabinet\_Temp
  - Coolant\_Temp
  - DC\_AC
  - DC\_Current
  - DC\_Power

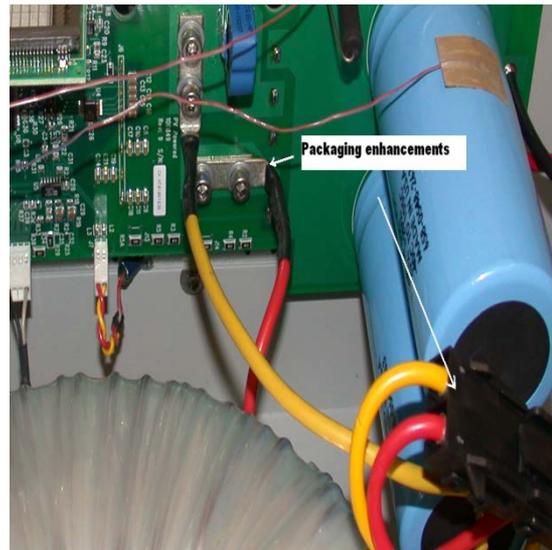
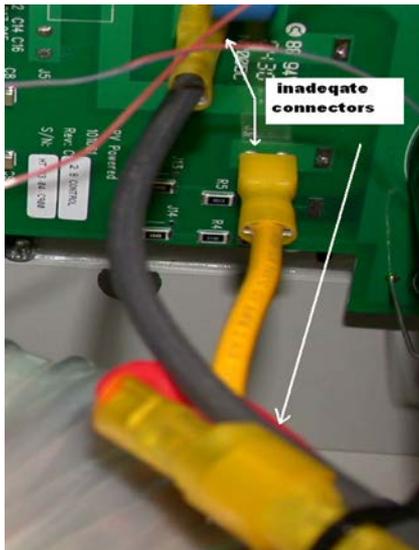


Data from large plant

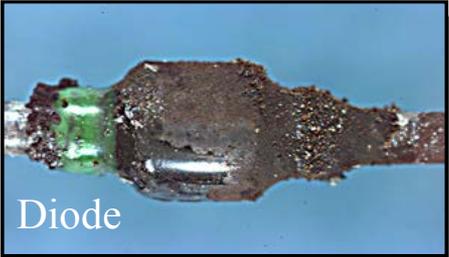
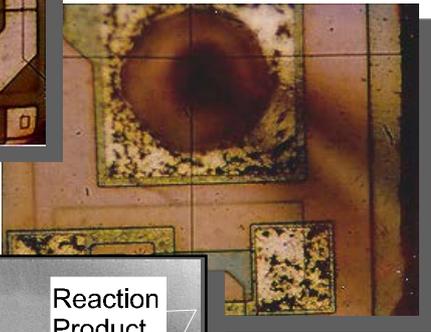
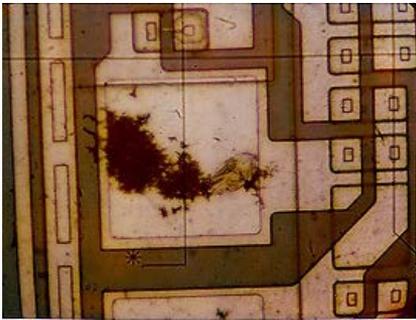


## Accelerated Aging for Inverter Development

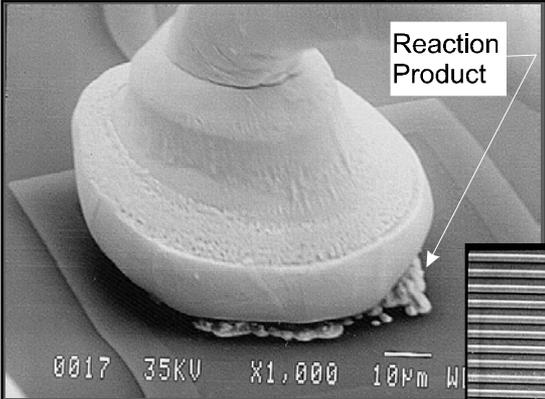
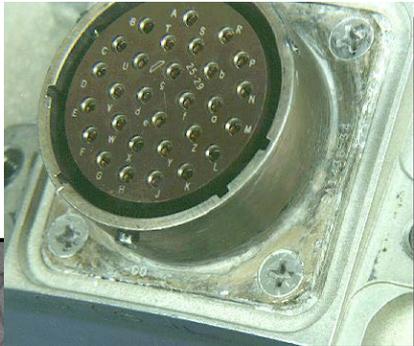
- No PV specific industry standard exists
- HALT testing is spotty; independently applied
- Separate needs identified for residential and commercial scale inverters
- Failure modes identified but not in a uniform program applicable across the industry
- System predictive models will require inputs for inverters



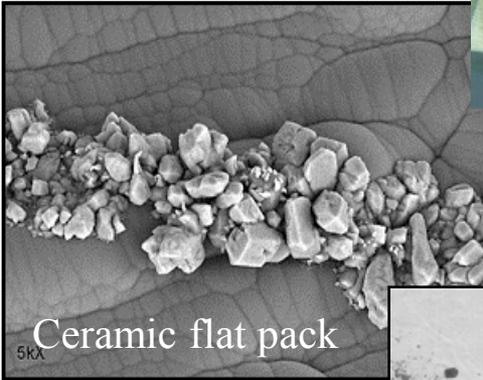
# Atmospheric Corrosion



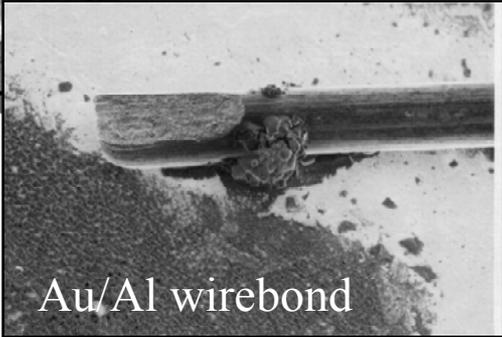
Diode



Reaction Product



Ceramic flat pack



Au/Al wirebond

# Examples of electrolytic migration

- LF amplifier - Puerto Rico
  - high humidity
  - seacoast environment (NaCl)
  - powered system
  - Ag used in ground plane
- Printed wiring boards
  - cyclic humidity
  - flux residue (activator)
  - powered electronics
  - Sn/Pb solder

