Reliability Overview for Electronic Systems in Solar Applications

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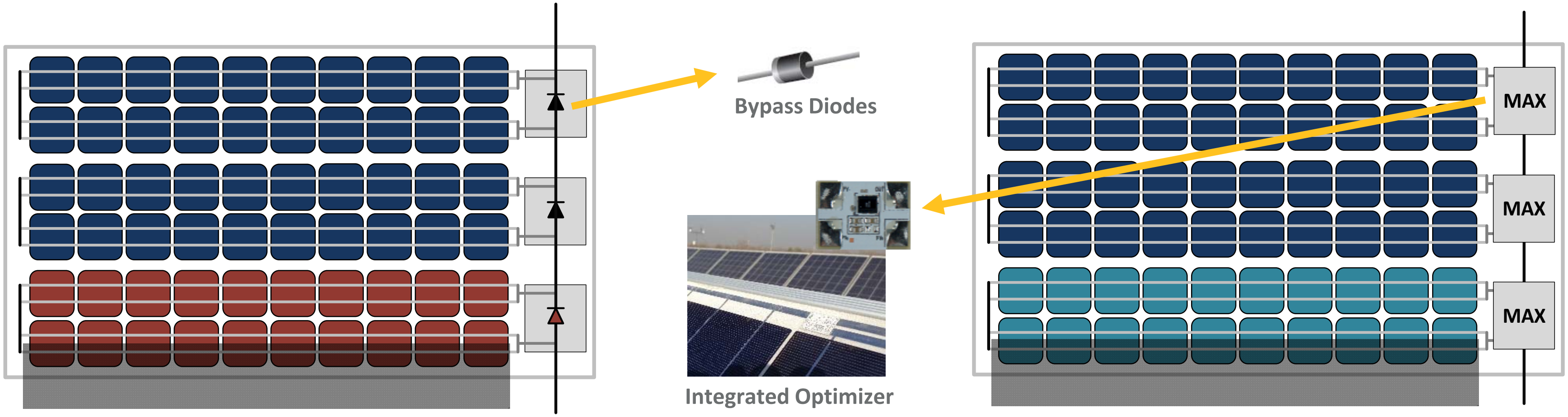
Maxim Cell-String Optimizer



Bypass Diodes

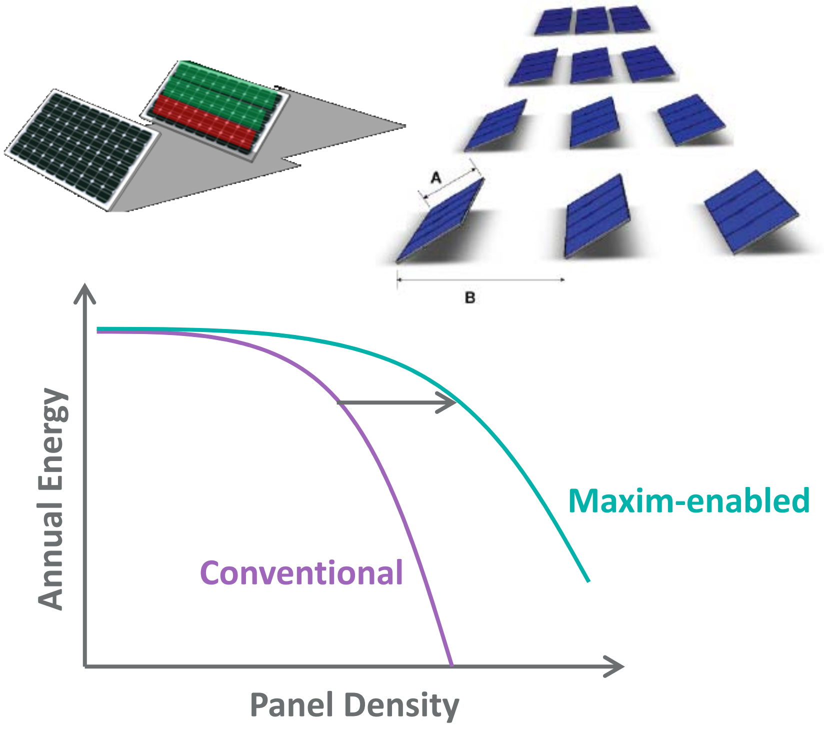
Integrated Optimizer

Conventional Solar Panels

Maxim Enabled Solar Panels

- Single-chip power converter performing MPPT on individual cell-strings
- High level of integration leads to high reliability and low cost
- Cell-string granularity offers concrete benefits scaling from unshaded utility scale arrays to shaded residential systems

The Benefit is Lower Cost of Energy

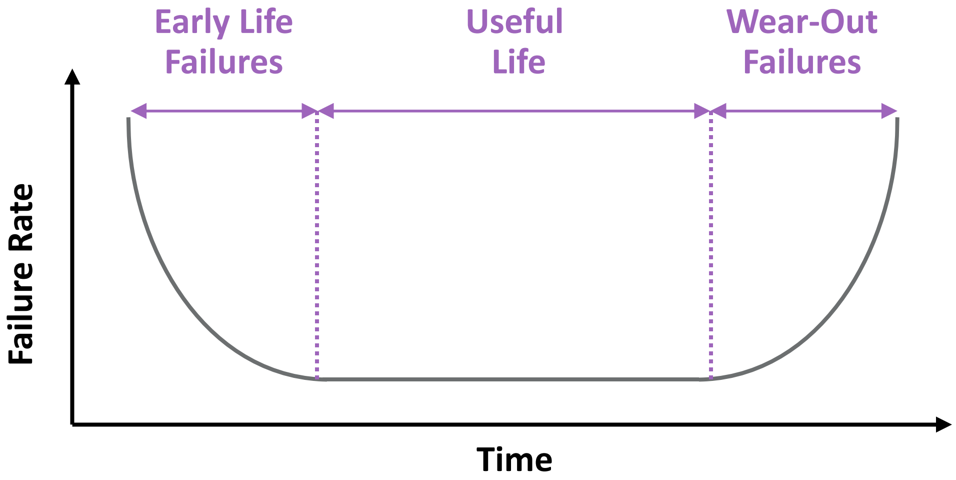


- Self-shading is the primary factor to determine # of panels in a system
- Maxim technology provides higher shade tolerance and therefore higher density
- Denser and larger systems can reduce the CAPEX and LCOE up to 20%

Agenda

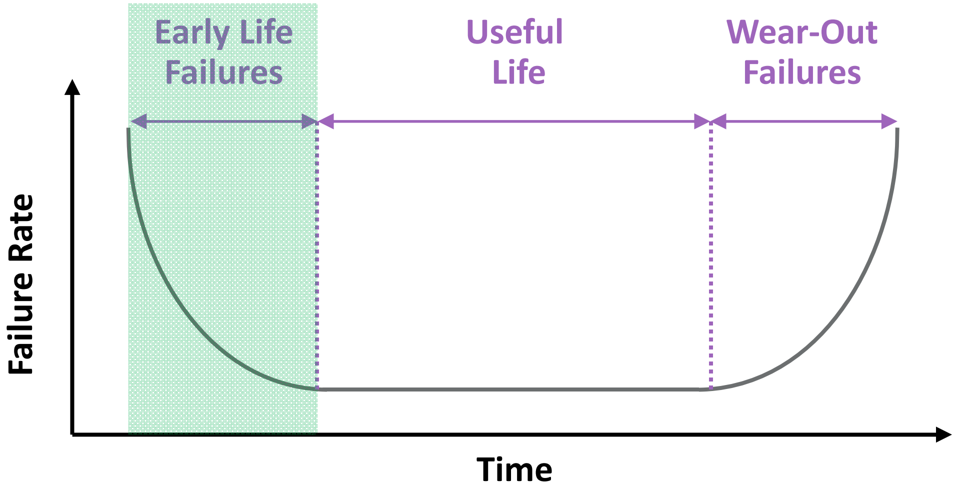
- Sleazy marketing pitch (done)
- What do we mean by reliability?
- How do we estimate reliability?
- Example related to electronics in Solar applications

The Bathtub Curve



- Reliability: the probability of a product meeting its performance specifications under normal usage conditions versus time
- The "bathtub curve" plots failure rate versus time; shows three distinct regions
  - Early life failure region
  - Useful life region
  - Wear-out region

Early Life Region



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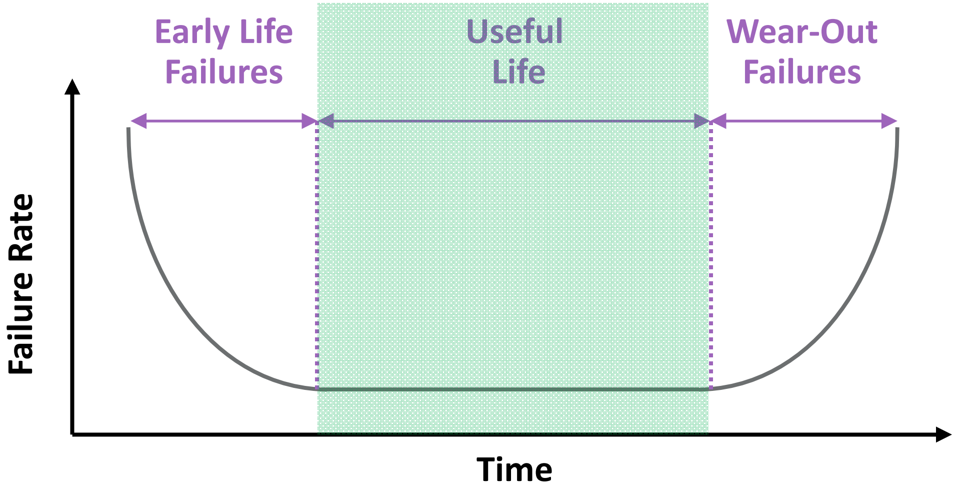
Useful Operating Region



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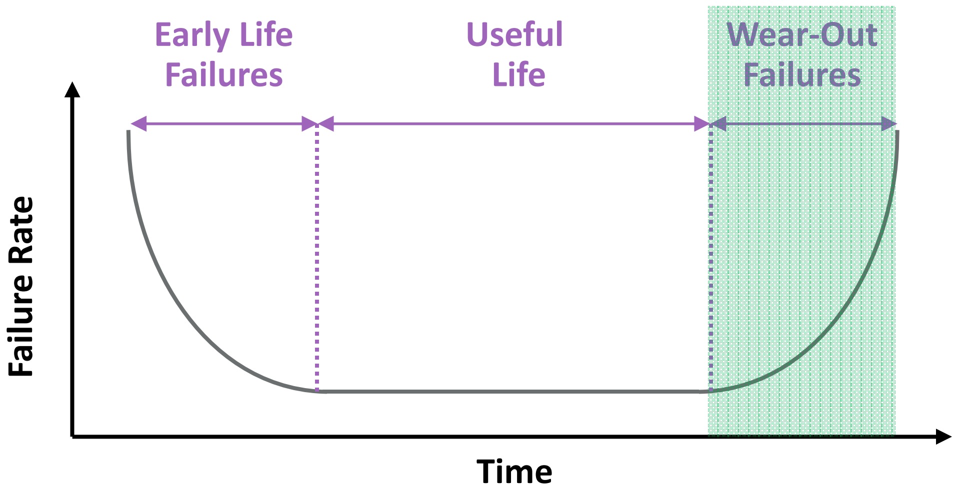
Wear-Out Region



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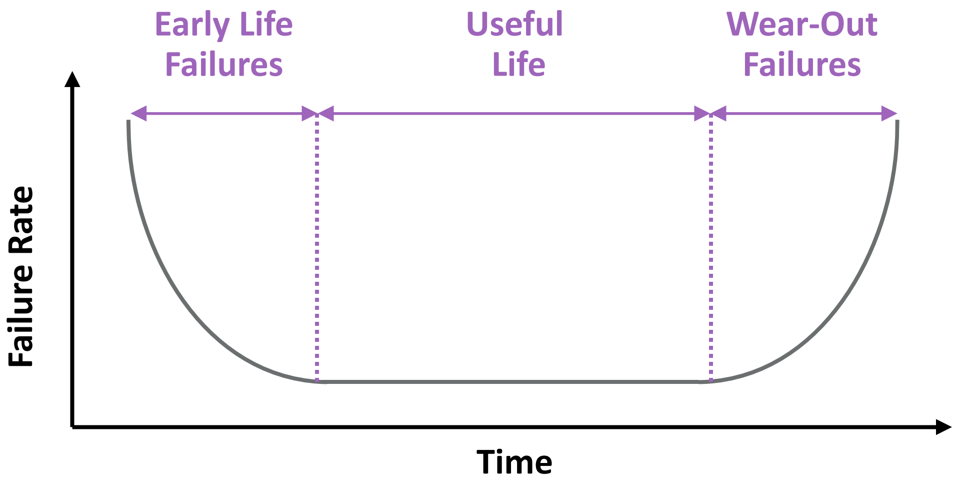
Common Semiconductor Reliability Tests



Early Life

- Electrical Test Coverage
  - Wafer
  - IC
  - PCA
  - PV Panel

- Handling / Assembly
  - X-ray inspection
  - Optical inspection

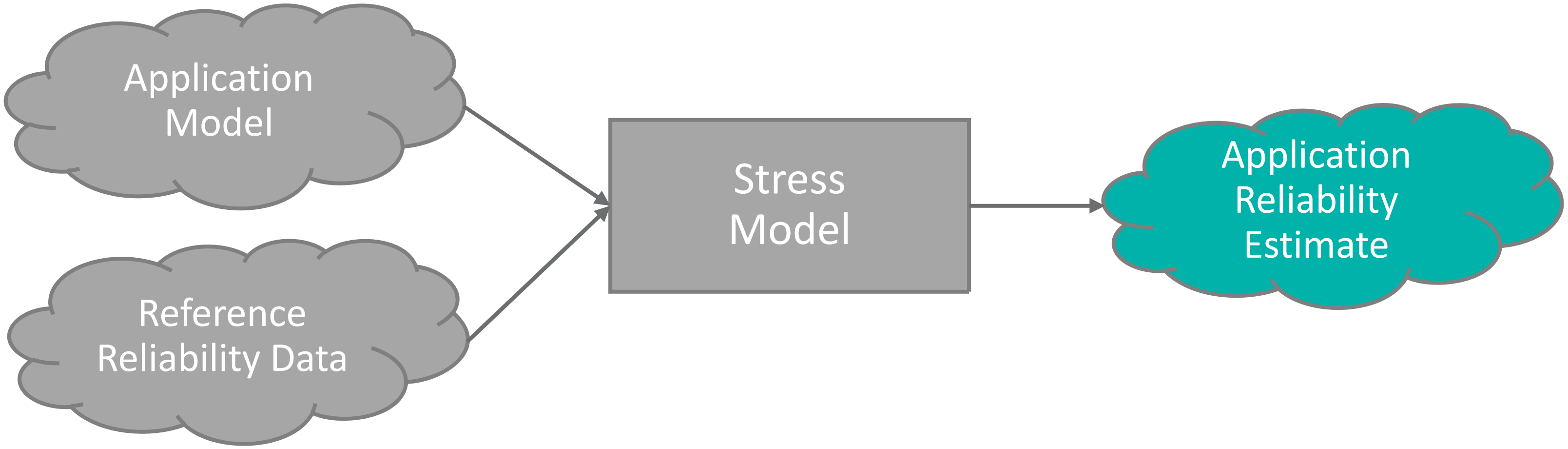
Useful Life

- Stress Tests
  - Voltage Acceleration
  - Temperature Acceleration

Wear Out

- Stress Tests
  - Temperature Cycling
  - Electromigration
  - TDDB
  - HCI
  - Humidity Bias

Estimating Useful Life Failure Rate



Application Model

Reference Reliability Data

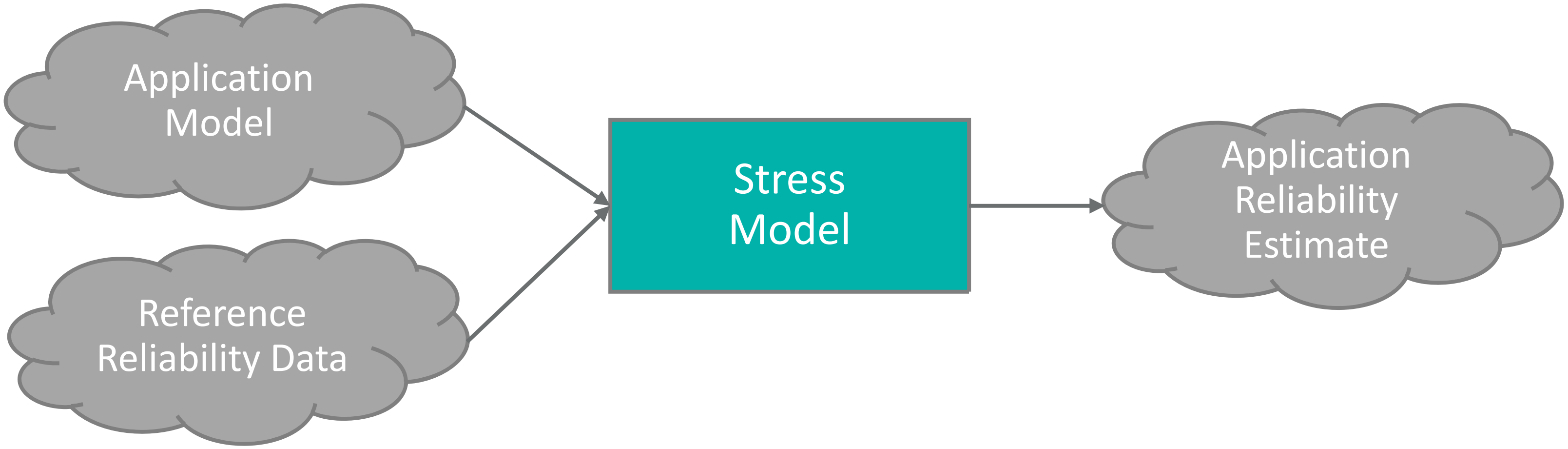
Stress Model

Application Reliability Estimate

- We need three basic components to estimate the device FIT rate
  1. A stress model
  2. An application model
  3. Reference reliability data

> Discussion focused on Useful Life FIT but also applies to other regions
> FIT = Failure In Time; # of failures per Billion operating hours
> MTTF = 1 / FIT

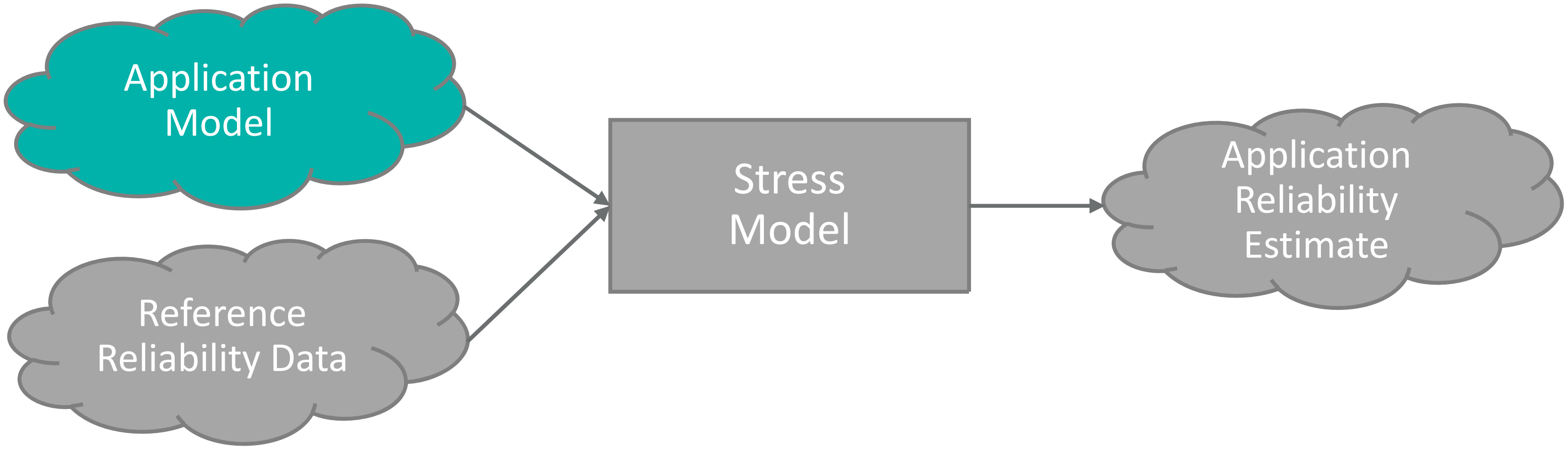
Estimating Useful Life Failure Rate



- We need three basic components to estimate the device FIT rate
  1. A stress model
  2. An application model
  3. Reference reliability data

  > What is the relationship between usage conditions and reliability?
  > Can describe electrical, mechanical, or other physical relationships

Estimating Useful Life Failure Rate

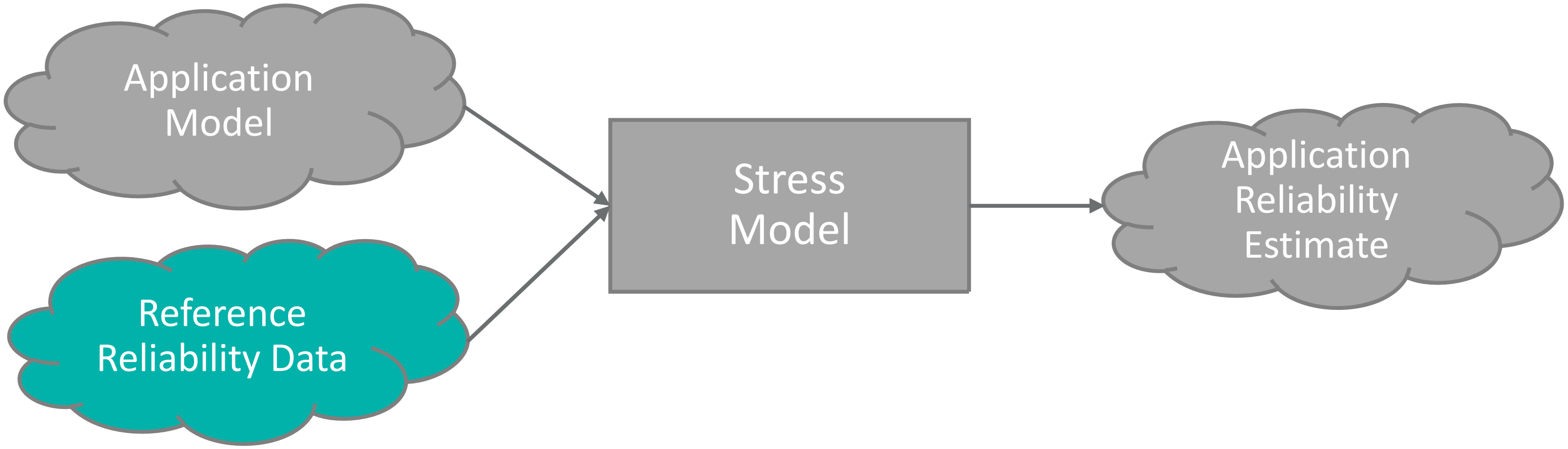


- We need three basic components to estimate the device FIT rate
  1. A stress model
  2. An application model
  3. Reference reliability data

  > What are the usage conditions in the application?

  > This could be a typical usage model or historical data

Estimating Useful Life Failure Rate



- We need three basic components to estimate the device FIT rate
  1. A stress model
  2. An application model
  3. Reference reliability data

  > Data sourced from product qualification or technology characterization

  > Data sourced from the field (operational data)

  > Data of either type sourced from similar technology / products

Stress Model

- Must identify the stress impact of each parameter and failure mechanism

- Acceleration Factors relate reliability in one condition to another

$$AF = \frac{\lambda_{USE}}{\lambda_{REF}} = e^{\left[\frac{-E_A}{k}\left(\frac{1}{T_{USE}}-\frac{1}{T_{REF}}\right)\right]} \cdot e^{[\alpha(V_{USE}-V_{REF})]}$$

Example for Silicon Devices[1]

$$AF = \frac{\lambda_{USE}}{\lambda_{REF}} = \left[\frac{V_{USE}}{V_{REF}}\right]^{\alpha} \cdot 2^{\left[\frac{T_{USE}-T_{REF}}{10}\right]}$$

Example for MLCC Capacitors[2]

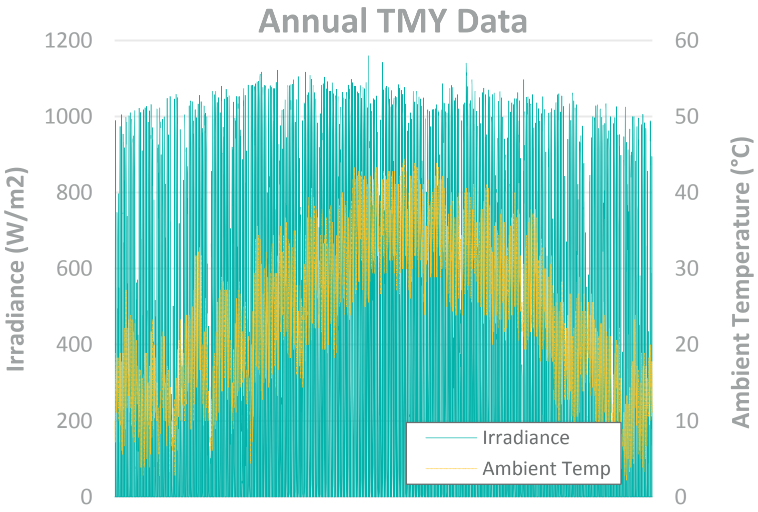
Where λ is the failure rate

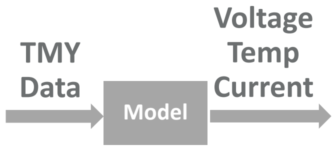
- With time varying conditions, a Net Acceleration Factor can be calculated as a time weighted average of individual usage conditions

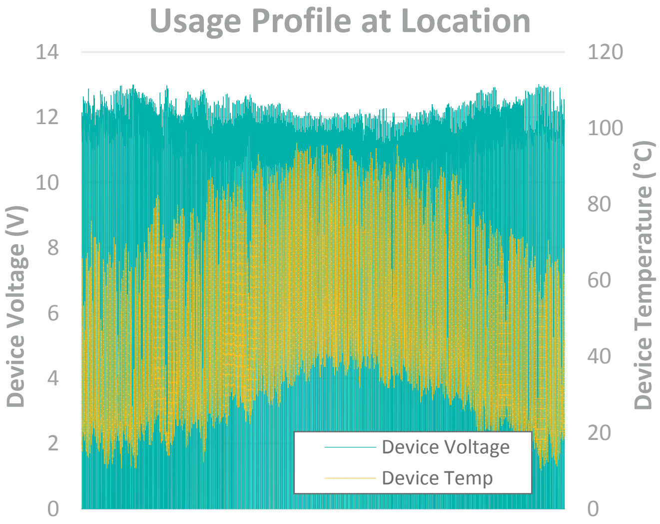
$$AF = \sum_{t=1}^{T} \frac{AF(t)}{T}$$

1. **JEDEC Standard JEP122, Failure Mechanisms and Models for Silicon Devices**
2. **Multilayer Ceramic Chip Capacitors FIT Data and MTTF/MTBF, http://product.tdk.com/capacitor/mlcc/en/faq/faq00024.html**

Application Model







- TMY dataset is used to predict long term reliability in Solar applications
- TMY data converted to component voltage, current, and temperature conditions

$$T,V,I = f_{TMY}\left(T,G\right)$$

Reference Reliability Data

- Failure rates can be determined experimentally or operationally[1]

$$\lambda_{\mathrm{CL}} = \frac{\chi^{2}_{\%CL,2f+2}}{2 * device - hours * \mathrm{AF}}$$

$X^2_{\%CL,2f+2}$ is the chi-squared statistic with confidence internal *%CL* and *f* failures

- Typical reliability statistics can then be calculated

$$FIT = \lambda \cdot 10^9$$

$$MTTF = \frac{10^9}{FIT \cdot 24 \cdot 365}$$

- Failure rates for complex electronic systems are calculated by summing the failure rate of each individual components[2]

$$\lambda_{SYSTEM} = \sum_{1}^{N} \lambda_{COMPONENT}$$

for each component N

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1. **JEDEC Standard JESD74A, Early Life Failure Rate Calculation Procedure for Semiconductor Components**
2. **JEDEC Standard JESD85, Methods for Calculating Failure Rate in Units of FITs**

Practical Example

- As an example, assume we have the following reference data points

1. Burn-In: 500 devices at 15V / 125°C for 1k hours with 0 failures
2. Other Application: 5M devices at 12V / 75°C for 10 years and 8 hr/day with 2 failures

- We can calculate the relative stress between each and the Phoenix solar application

$$AF = \frac{1}{8760} \cdot \sum_{t=1}^{8760} e^{\left[\frac{-\mathrm{E}_A}{k}\left(\frac{1}{\mathrm{T}_{TMY}} - \frac{1}{\mathrm{T}_{REF}}\right)\right]} \cdot e^{\left[\alpha\left(V_{TMY} - V_{REF}\right)\right]} \cdot \left[\frac{V_{TMY}}{V_{REF}}\right]^{\alpha} \cdot 2^{\left[\frac{T_{TMY} - T_{REF}}{10}\right]}$$

1. Burn-In: 92x more stressful than Phoenix solar application
2. Other Application: 4.0x more stressful than Phoenix solar application

- Relative to the Phoenix solar application, the references provide the following data:

1. Burn-In: 46 million device-hours with zero failures
2. Other Application: 584 billion device-hours with two failures

Practical Example

- With the data translated to the Phoenix solar application, we can then calculate FIT

$$\text{Chi-Squared Statistic:} \quad \chi^2(90\%\ \text{Confidence, 2 failures}) = 10.65$$

$$FIT = \frac{10^9 \cdot \chi^2}{2 \cdot device - hours \cdot AF} = \frac{10^9 \cdot 10.65}{2 \cdot 584.046x10^9\, hours \cdot 1} = 0.0091$$

The example data suggests 0.0091 failures per billion device operating hours in Phoenix

- If this sounds unreasonably low, consider the results with respect to a 10MW field:

$$10MW \cdot \frac{1\,panel}{300W} \cdot \frac{3\ devices}{panel} = 100{,}000\ devices$$

$$25\,years \cdot \frac{365\ days}{year} \cdot \frac{24\ hours}{day} = 219{,}000\ hours$$

$$10MW \cdot 25\,years = 219\ \text{billion device-hours}$$

$$219\ \text{billion device-hours} \cdot \frac{0.0091\ \text{failures}}{\text{billion device-hours}}$$

$$1.996\ failures$$

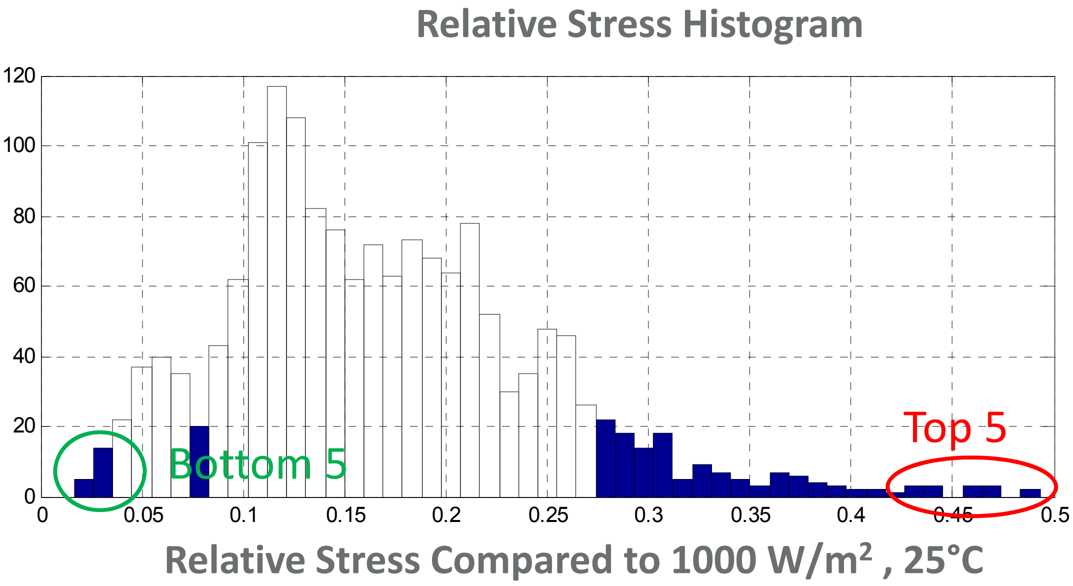
The example data suggests 2 failures in a 10MW field operating 25 years in Phoenix

Summary

- We have shown how to extend semiconductor industry reliability methods to the Solar application
- An example calculation was used to estimate useful life field failure rates
- Similar techniques can be used to calculate onset of wear-out
- Takeaways:
  - > Semiconductor industry standard accelerated stress models can be directly used in Solar reliability analyses
  - > Solar TMY datasets can be used to estimate long term electromechanical stress to devices deployed in the Solar application
  - > The three components needed for this methodology are reference reliability data, a stress model, and application conditions

Thank You

Appendix



Rank	Location	Stress
1	USA TX Abilene Regional Ap [ut] (TMY3).csv	0.493
2	Australia AUS Port_Hedland (INTL).csv	0.492
3	United Arab Emirates ARE Abu_Dhabi (INTL).csv	0.471
4	Egypt EGY Aswan (INTL).csv	0.47
5	USA CA Needles Airport (TMY3).csv	0.467
…		
1615	USA AK Deadhorse (TMY3).csv	0.025
1616	USA AK Shemya Afb (TMY3).csv	0.024
1617	Canada NT Resolute (INTL).csv	0.019
1618	USA AK Barrow (TMY2).csv	0.017
1619	USA AK Barrow W Post-w Rogers Arpt [nsa - A	0.017

- Calculation of relative stress operating at TMY locations compared to reference panel operating on-sun at a constant 1000 W/m^2 + 25°C
- Interesting Facts
  - > Highest: Abilene TX Regional Airport, 0.493x stressful as reference
  - > Lowest: Barrow Alaska , 0.017x stressful as reference
  - > Range: 29x difference in stress between highest and lowest stress TMY locations
  - > Phoenix is a decent proxy for “worst-case” studies: #9 , 0.443x stress