Reliability Modeling for Photovoltaic Modules

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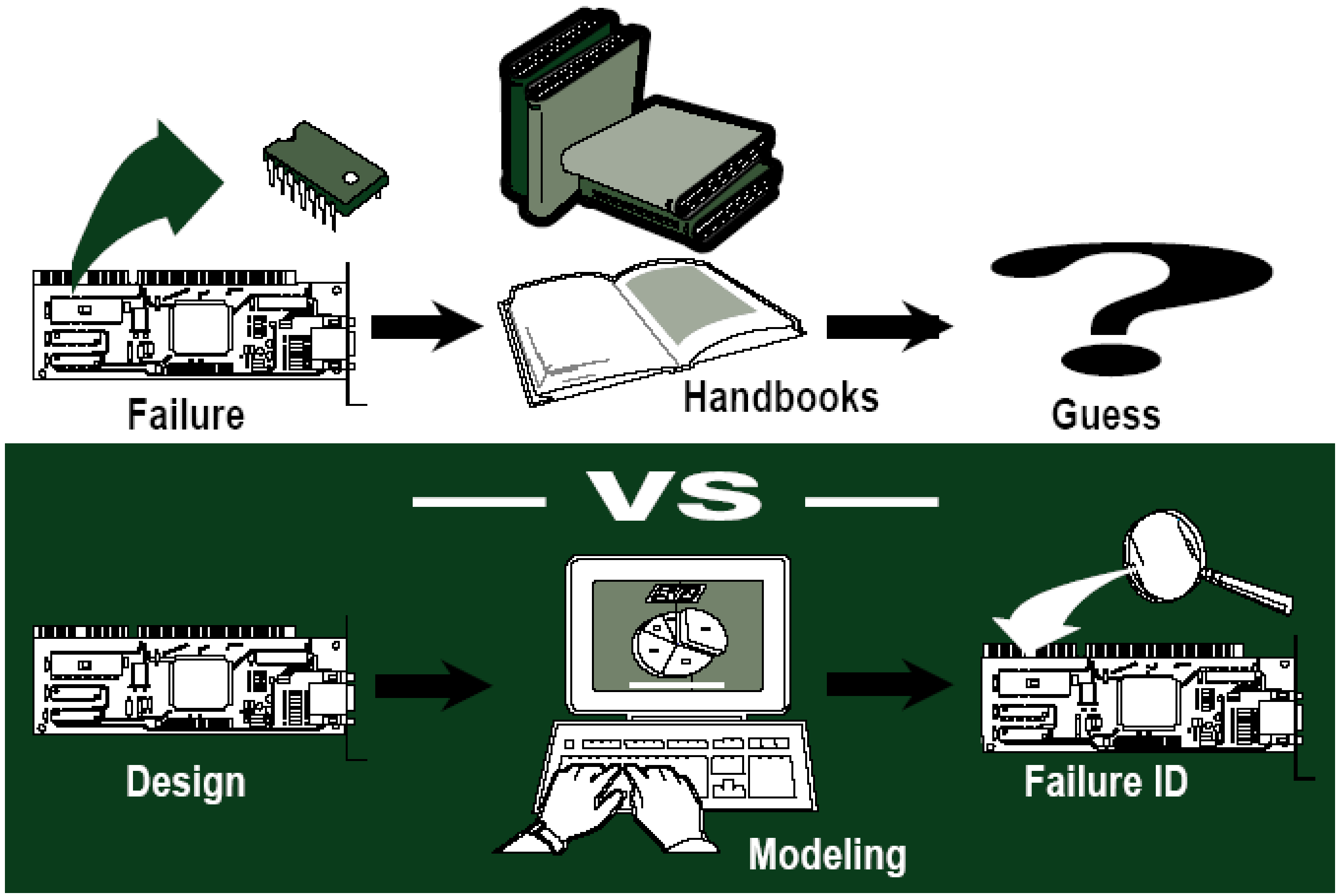
Elements of Reliability Estimation

- To produce an understandable and credible estimate, a reliability assessment must contain the following elements:
  - The specific purposes of the reliability estimate results (i.e. How the reliability assessment is intended to be used).
  - How the reliability assessment shall not be used
  - Where precautions are necessary
  - Definition of failures and failure criteria
    - Failure modes
    - Failure mechanisms
    - Physical parameter values that constitute a failure (voltage level, crack delamination area, etc.)
  - Description of the process to develop the estimation
    - Assumptions
    - Methods and models
    - Source of data
  - Required assessment format
    - Metrics
    - Confidence level

IEEE 1413

Empirical methods vs. Physics of Failure



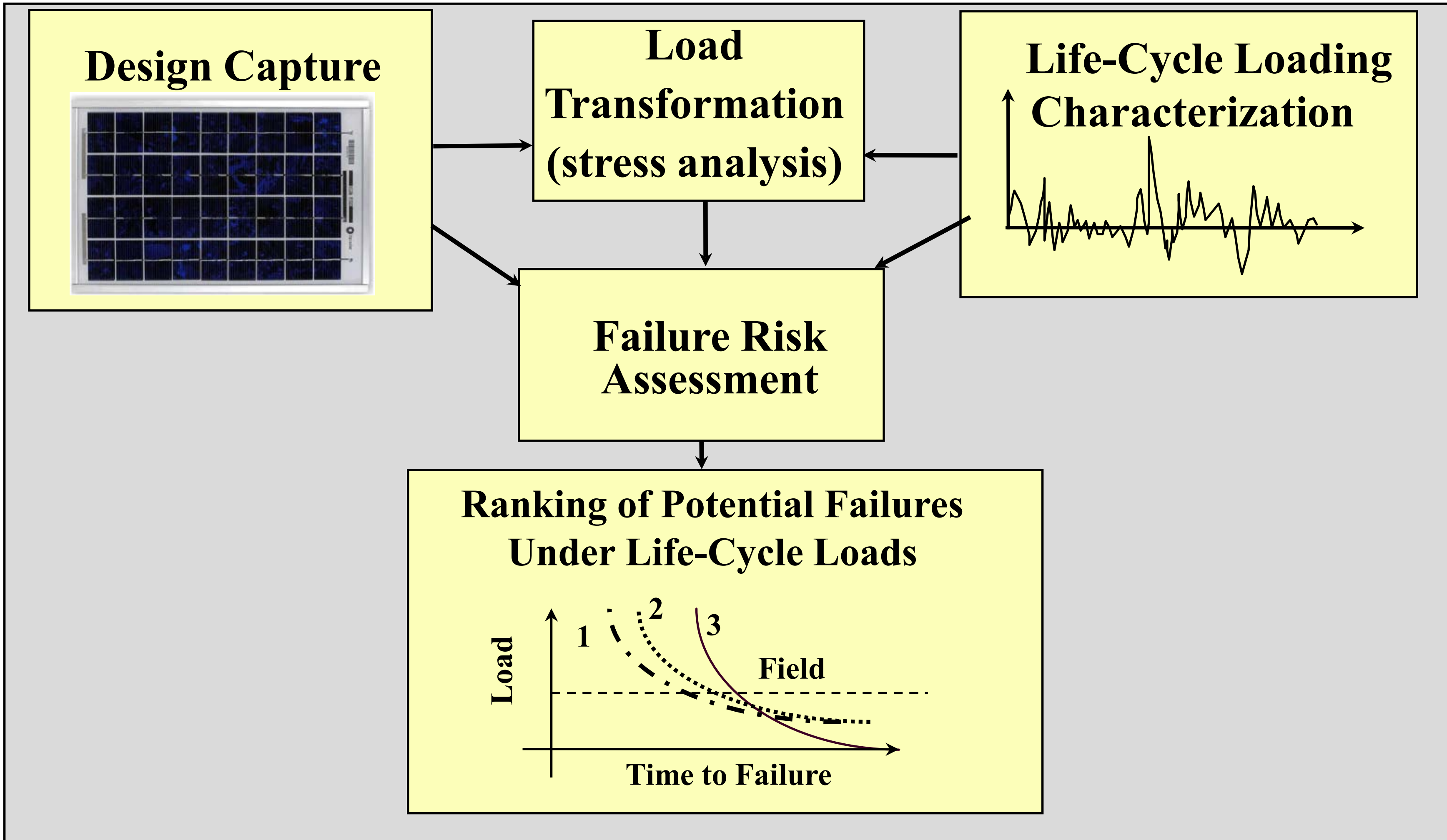
Reliability Assessment Uses and Timing

When selecting a reliability assessment method it is important to consider
- Why the assessment is conducted
- When in the system life cycle the assessment is conducted
- Which parts of the system are being assessed

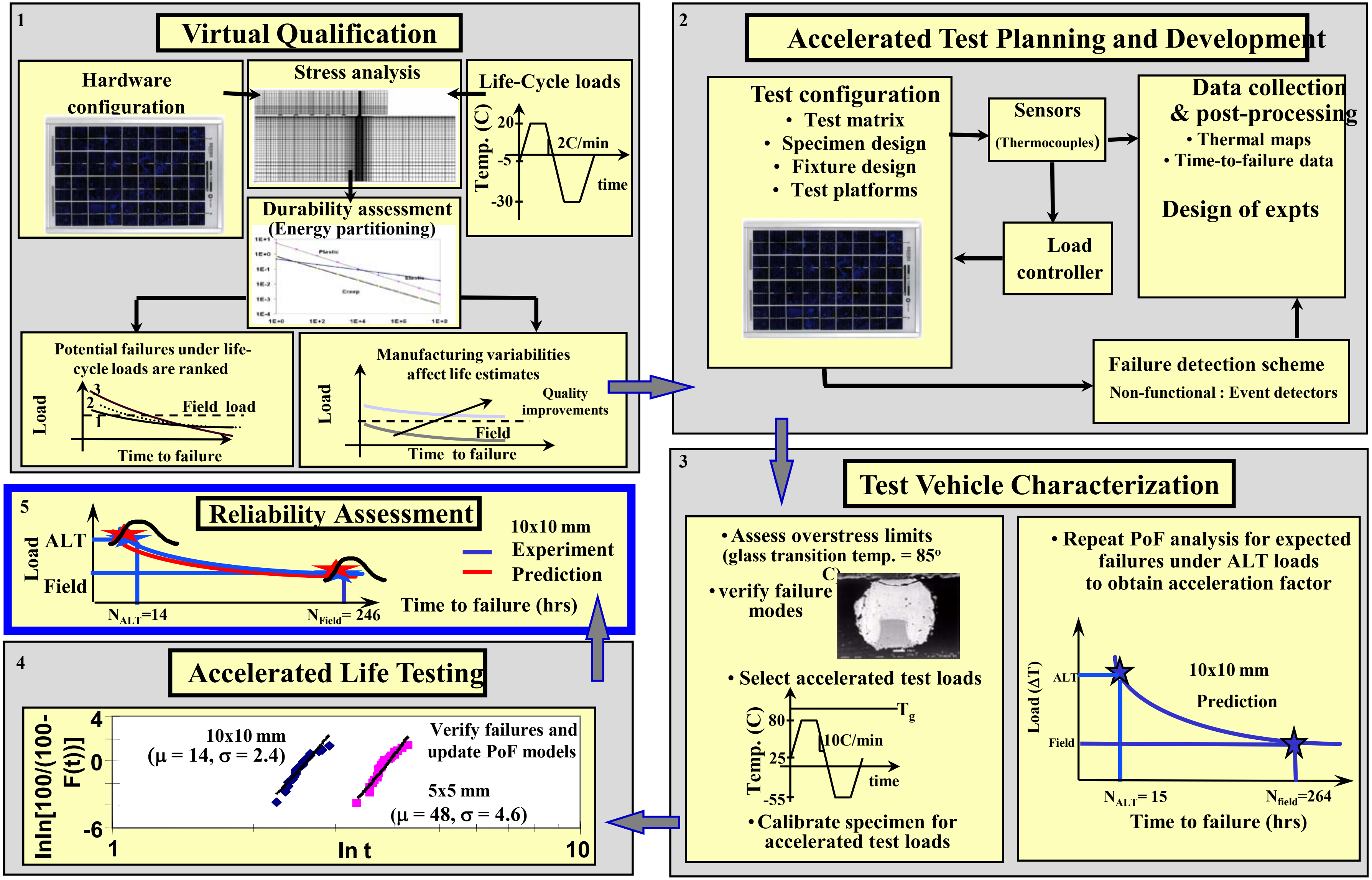
In the reliability assessment, the following steps must therefore be taken:

1. Identification and description of the item for which an estimate is made
   - Definition of realistic product reliability requirements
   - Definition of the usage profile.
     - Defines the specific thermal, mechanical, electrical, and chemical loads over time.
   - The specific characteristics of the product design and the manufacturing/assembly process.
2. Results of a virtual qualification assessment
   - Identification of potential failure sites and mechanisms
   - Estimates of time to failure under field and test conditions
3. An accelerated test plan
   - Test vehicle characterization for individual failure mechanisms (STIM not SIM)
   - Conditions for an accelerated life test, and determination of overstress and destruct limits
4. Results of the complete reliability assessment
   - Confidence in estimate, sources of uncertainty, limitations, and repeatability

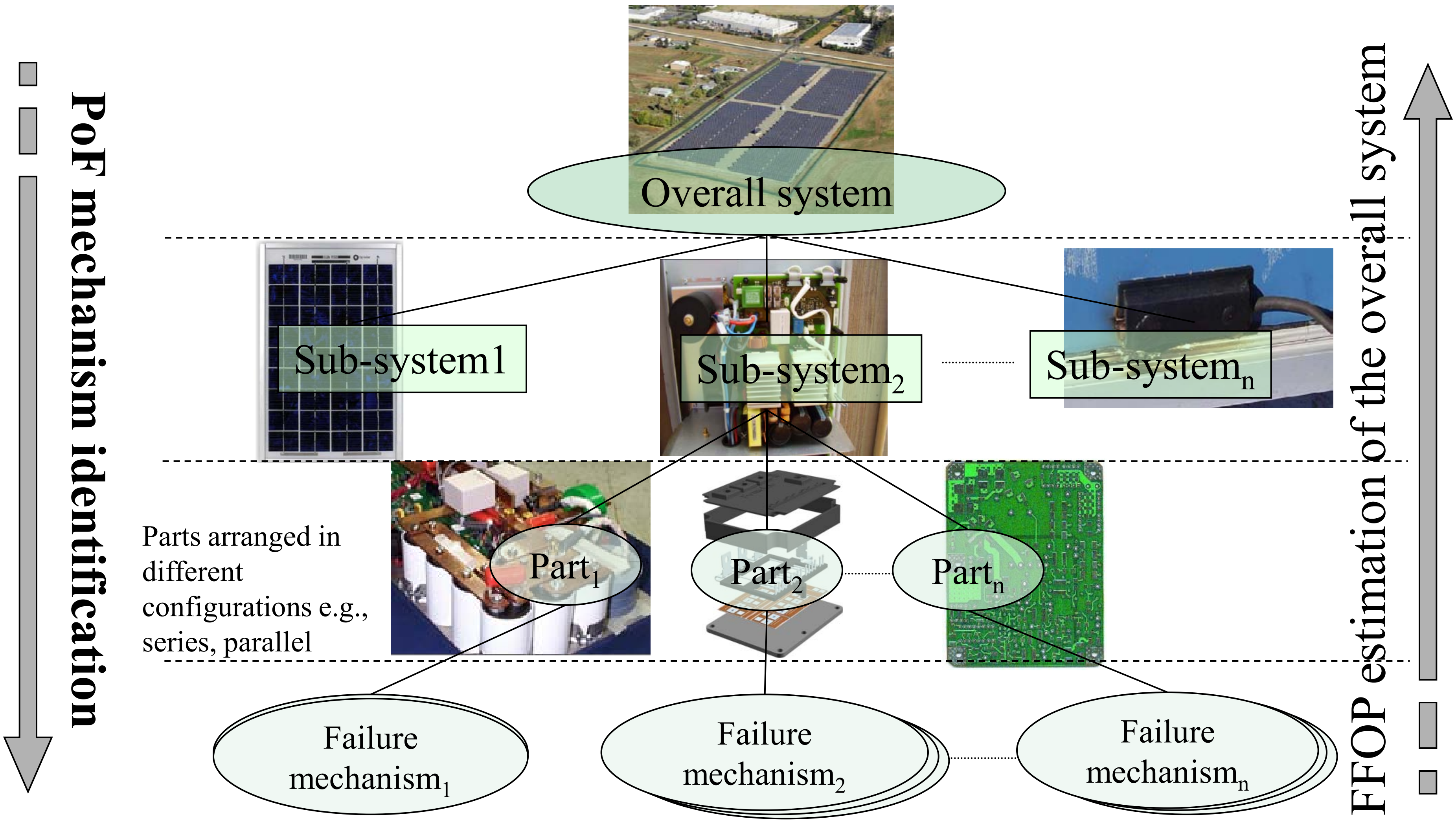
PoF Reliability Assessment Methodology



Accelerated Product Qualification



Comprehensive System Reliability Assessment



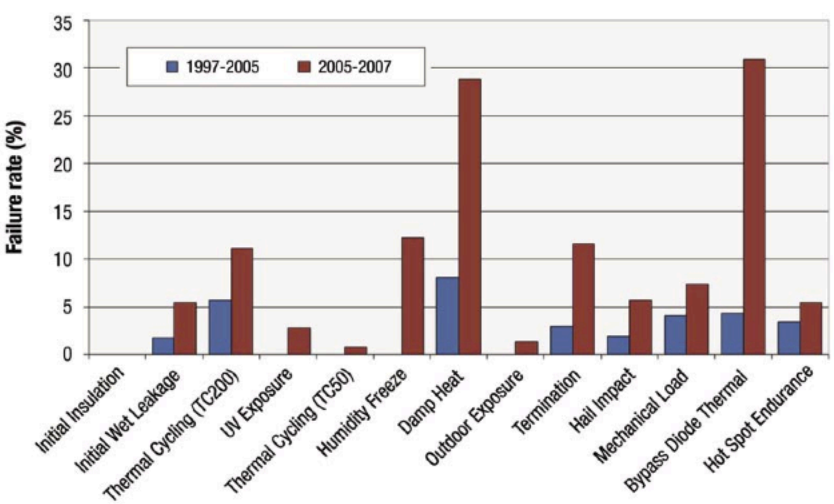
$$L = L_r\left(\frac{V_r}{V_0}\right)\times 2^{\left(\frac{T_r - T_A}{10}\right)}$$

$$\varepsilon = \frac{(R-\rho_f)d\psi}{\rho_i\psi_i} \approx \frac{(\bar{r}-\rho_f)d\psi}{\rho_i\psi_i} = \frac{r(\psi_i-\psi_f)}{\rho_i\psi_i}$$

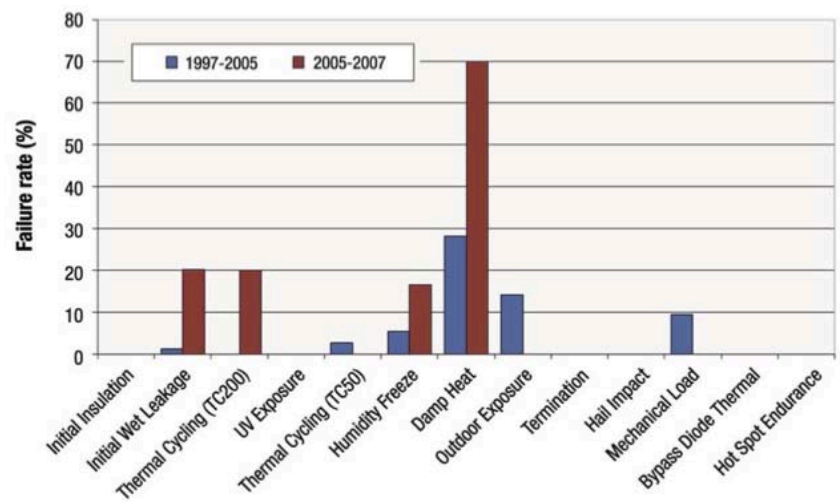
$$Nf = 0.5\ (\Delta\gamma/2\varepsilon_f)^c$$

Quality issues are occurring in the PV Module

- IEC 61215 Qualification and safety certifications are not a replacement for reliability testing and can only highlight initial design quality issues.
- Failure rates by Arizona State University Photovoltaic Testing Laboratory have shown historically that as an industry failure rates of minimum certification testing has increased.
  - Expansion of the market by new manufactures is largely responsible.
- An increase in certification failures highlights the potential for other reliability issues to increase in the field as new manufacturers enter the market.



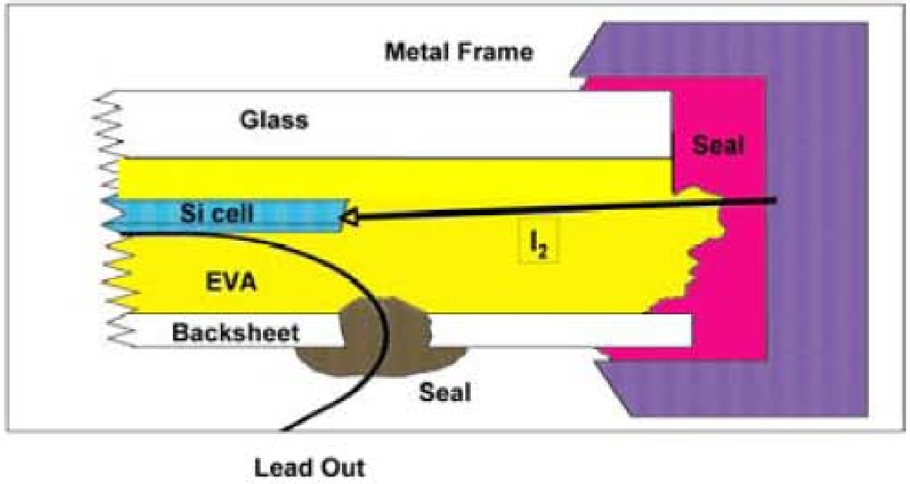
Crystalline Silicon PV

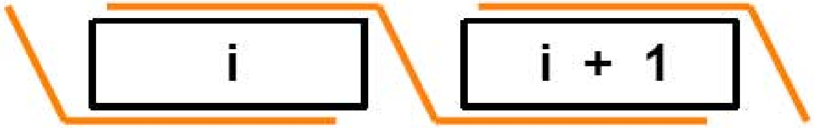


Thin Film PV

G. Tamizhmani, B. Li, T. Arends, J. Kuitche, B. Raghuraman, W. Shisler, K. Farnsworth, J. Gonzales, A. Voropayev, Failure analysis of design qualification testing: 2007 vs. 2005, Photovoltaics International, August 2008.

Design Capture
Wafer Type Module

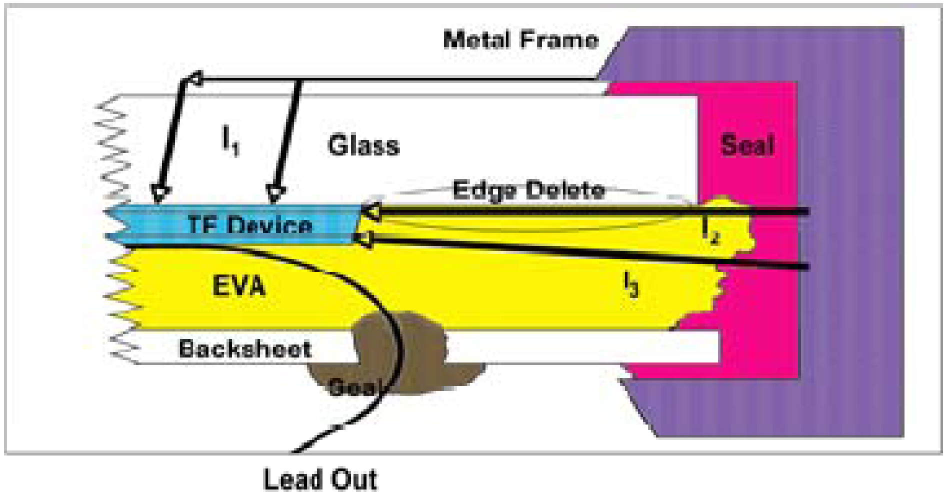


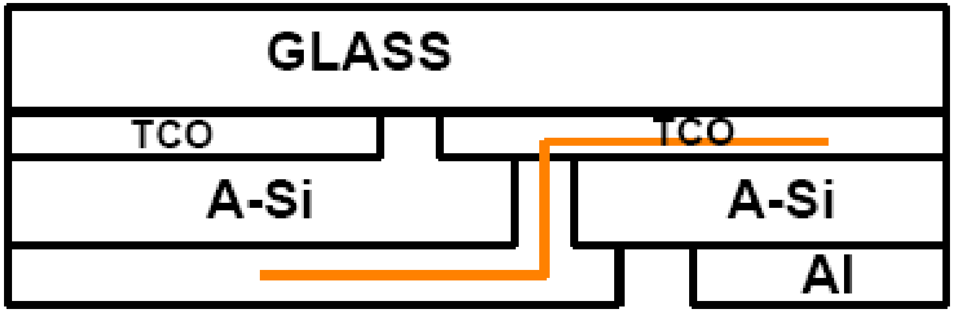


Cell Interconnect

T. McMahon and C. Osterwald, NREL

Design Capture
Thin-Film Type Module





Cell Interconnect

T. McMahon and C. Osterwald, NREL

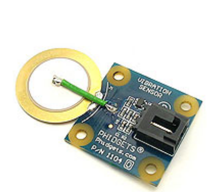
Mission Profile Collection

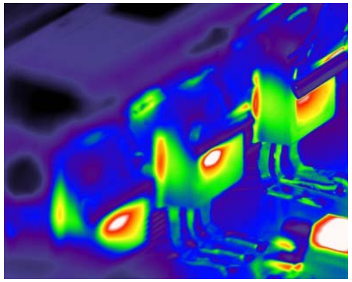
The physical environment describes the operating conditions and loads under which the system operates. It includes temperature, humidity, shock and vibration, voltage, UV radiation, power, contaminants, and so forth. It also includes loads applied in packaging, handling, storage, and transportation.

Temperature: Boundary conditions on temperature can be measured via a diverse array of sensors. Temperature profiles at each component can then be determined by thermal modeling.

Vibration: Vibration can be sensed by as displacement, velocity, or acceleration at specific locations in the system. This can then be translated to vibration at components of interest using vibration modeling.

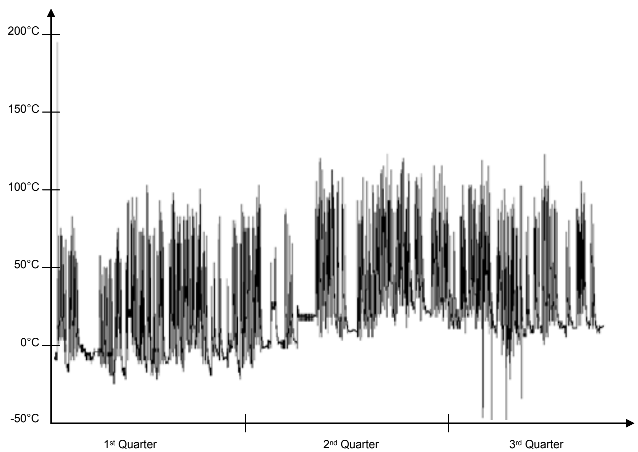
Corrosion: Characterizing this environment for later qualification testing can be performed through methods that include measuring moisture and temperature.



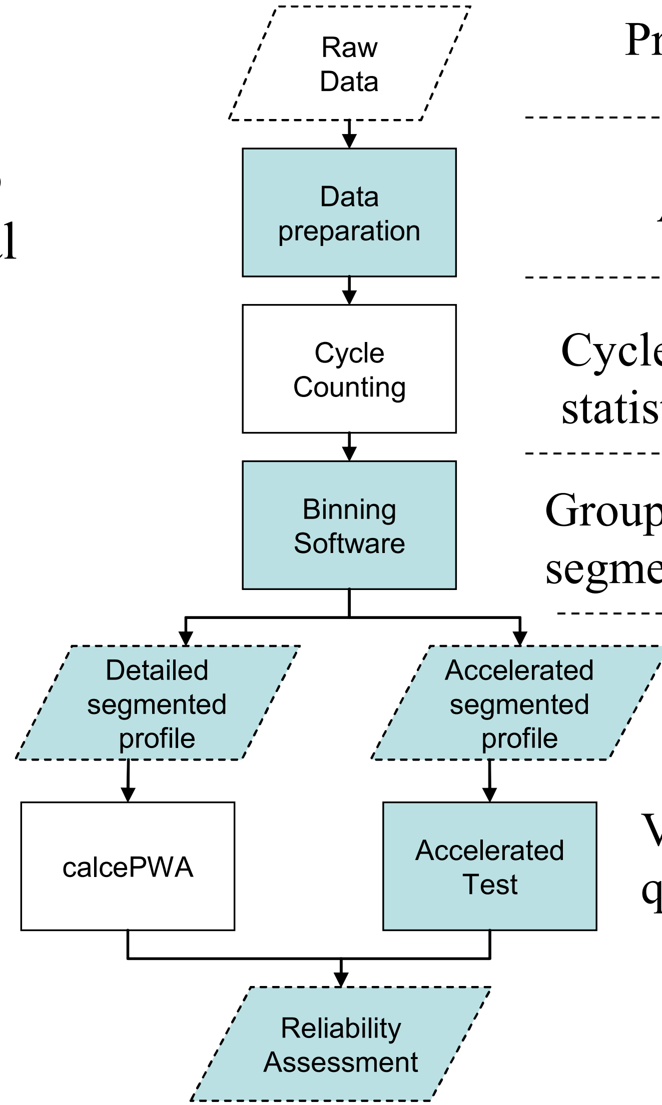


Mission Profile Creation

- A methodology is needed to create a segmented life cycle profile from raw field data to be used as an input for virtual qualification and reliability assessment.



Raw Data



Provided by user

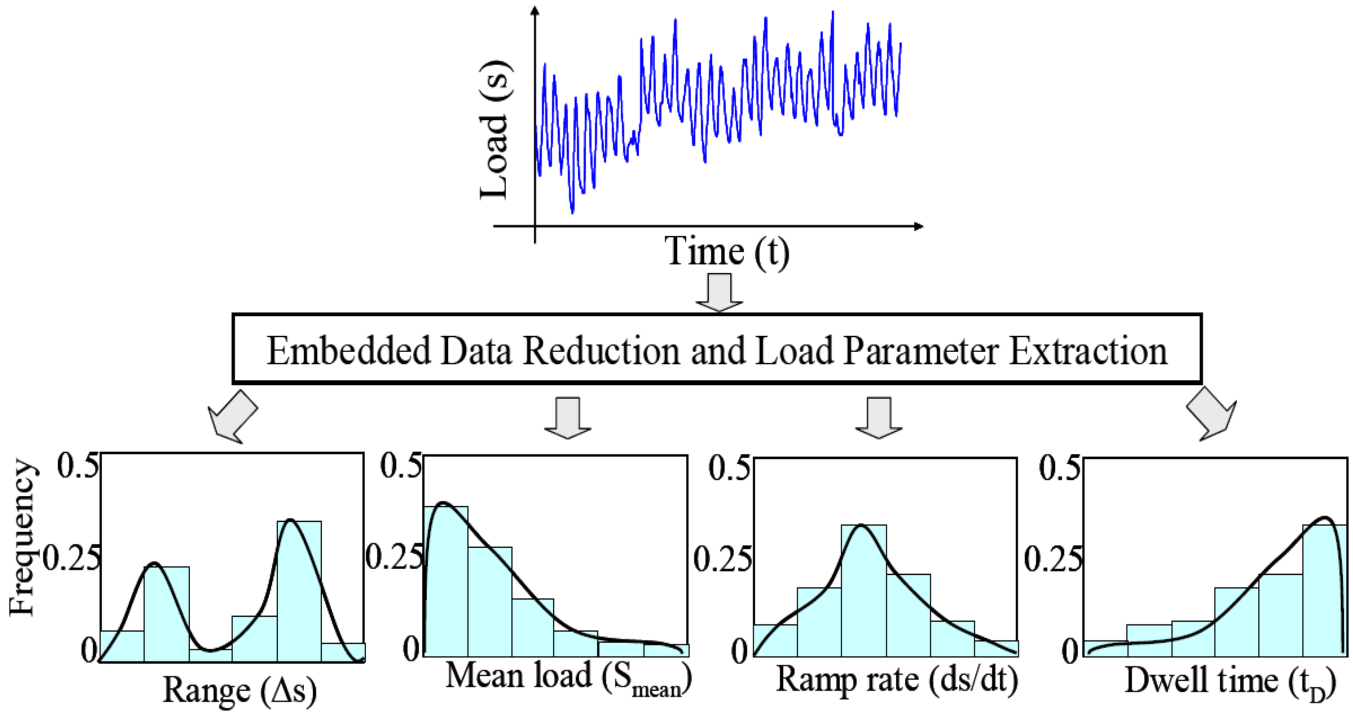
Add time stamps

Cycle counting, descriptive statistics and distributions

Group individual cycles into segments based on parameters

Virtual and experimental qualification

Load Parameter Extraction



- CALCE software was used to derive cycle characteristics and statistics.
- The software uses a moving average filter to reduce noise above 1 Hz

Binning Tool

- Accesses the output file of the cycle counting software containing the cycles with their respective ranges, means and ramp rates.
- Groups cycles in segments according to their range, mean and ramp values.
- Sorts the segments according to the amount of damage they inflict
  - Damage estimate based on the solder fatigue model
- Reduces the profile to contain only its most damaging segments
- User sets
  - Bin width - influences number and resolution of the segments
  - Accuracy - determines how many of the less damaging segments will be discarded
- Output
  - All segments in a plain textfile
  - A calcePWA compatible CSV file with the most damaging segments

Failure Mechanisms

- Failures can be described by their relation to failure precipitation.
  - **Overstress failure:** A failure that arises as a result of a single load (stress) condition. Examples of load conditions that can cause overstress failures are shock, temperature extremes, and electrical overstress.
  - **Wearout failure:** A failure that arises as a result of cumulative load (stress) conditions. Examples of load conditions that cause cumulative damage are temperature cycling, abrasion and material aging.
  - **System functional failure:** A failure that arises as a result of an anomalous condition of the system output. Examples of anomalous conditions that cause system functional failure are under-voltage input signals, mismatched switching speeds, and sneak paths.

Photovoltaic Failure Mechanisms

- Degradation of Semiconductor Device
- Degradation of Packaging Material
  - Material Aging
    - Encapsulant Discoloration – reduced light efficiency
  - Loss of Adhesion
    - Front Surface – Electrical open
    - Back Surface – Poor Heat Transfer, Hot Spots
  - Moisture Intrusion – increased corrosion and leakage currents
    - Backsheet Cracking and Lamination Disintegration
    - Edge Sealing
- Degradation of Cell/Module Interconnects
  - Solder joint fatigue
    - Metal segregation
    - Grain boundary coarsening/cracking
    - Increase series resistance and heating

Field Failures Observed in PV Modules

- From 1994 to 2002, BP Solar Collected Return Data on 2,000,000 modules. Returns were 0.13% or one module per 4200 module years of operation. No increase in failure rate at end of 10 year warranty period. [1]
- NREL did study indicating 0.7%/yr degradation in performance over time.
- Tests prescribed by IEC 61215

Types of Failure	%	Stressors	Accelerated Test
Corrosion	45.3	Moisture Penetration	85°C-85% RH Damp Heat (with UV) for greater than 1000 hrs.
Cell or Interconnect Break	40.7	Thermal expansion or contraction	-40°C to +85°C Thermal cycling (at peak power)
Delamination of Encapsulant	3.4	Moisture Penetration	Humidity Freeze

Other failures were related to leads, wires, junction box, and bypass diodes

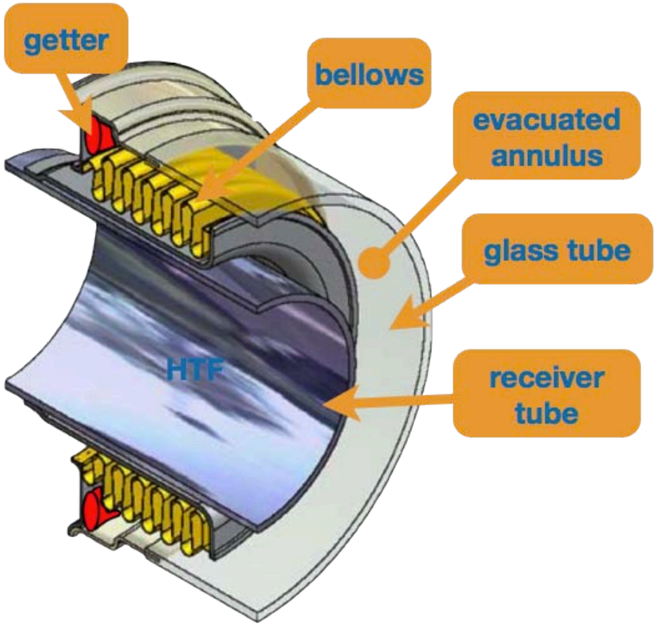
[1] J. H. Wohlgemuth, "Long Term Photovoltaic Module Reliability, NCPV and Solar Program Review Meeting 2003 NREL/CD-520-33586, p/179

Failure Mechanism Models – PV Module

Failure Mechanism	Failure Site	Failure Mode	Relevant Stresses	Environment Test	Model
UV Reaction Discoloration	EVA Encapsulation	Lower light efficiency	T, Intensity. Frequency	UV Exposure at Temp	Arrhenius Exp (-Ea/kT)
Deadhesion	Front Surface	Electrical Open	ΔT, H, ΔH	Damp heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Deadhesion	Back Surface	Poor Heat Transfer	ΔT, H, ΔH	Damp heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Corrosion	Front Surface Interconnects	Open Circuit Incr. Resist.	M, ΔV, T, impurities	Powered damp heat at Temp	Eyring $(V)^n(RH)^n e^{-Ea/kT}$
Fatigue Disintegration	Backsheet Lamination	Cracking	ΔT, ΔH	Damp Heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Fracture	Glass	Cracking	Mech Load	Mech Load	Paris Law $N=C(\Delta K)^n$
Fatigue	Edge Sealing	Cracking Voiding	ΔT,ΔH	Damp Heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Metal Segregation	Solder Connection	Voiding Intermetallic	T, J	Powered Temp Aging	Eyring (Black) $J^n e^{-Ea/kT}$
Fatigue	Solder or Cell Connection	Loss of connection	ΔT, ΔV	Powered Temp cycle	Coffin-Manson $N = C(\gamma)^n$

CPV - Trough Collectors – Receivers

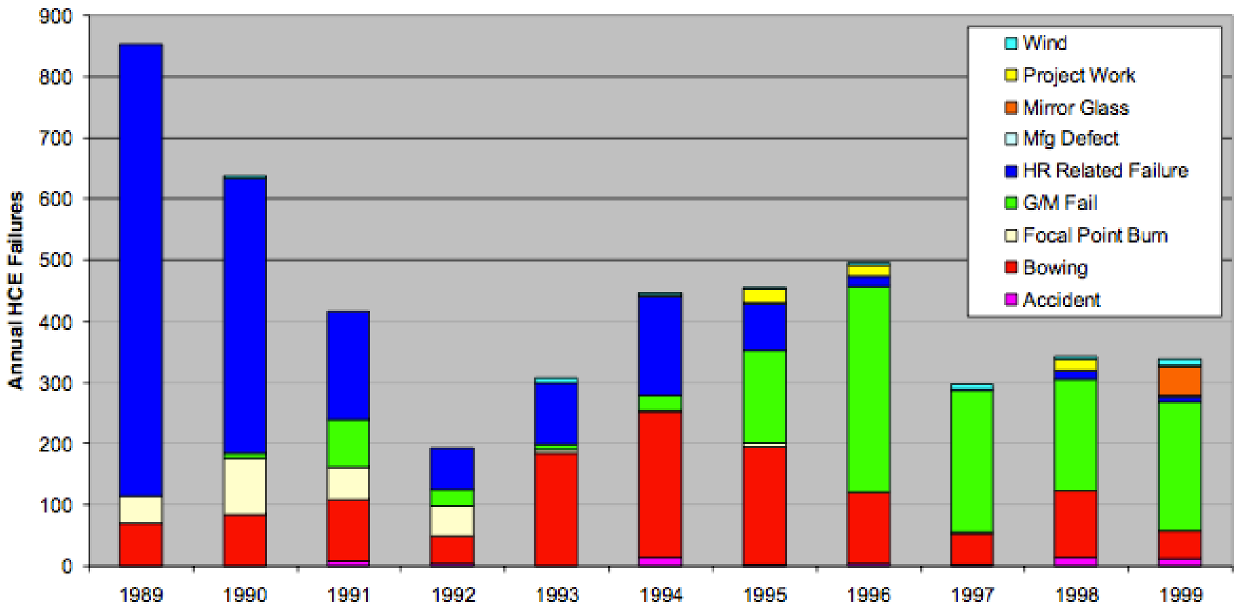
- Key parameters:
  - High solar absorbance
    - Efficient absorber coating, high transmittance of glass
  - Low thermal losses
    - Low absorber emissivity, vacuum
  - Minimal shading
    - Short bellows
  - Long operating life
    - Durability of glass to metal seal (low break rate)
    - Sustainment of vacuum (low hydrogen permeation, correctly sized getter)
    - Durability of absorber coating
    - Abrasion resistance of anti-reflective glass coating



http://www.lehigh.edu/imi/docs_pitt/pdf_Pitt/T1f_Marker.pdf

CPV - Trough Collectors – Receivers

- Receiver failure and degradation is the largest cost factor in plants
  - 30-40% failure at SEGS VI-IX in first 9-11 years of operation
  - Cases include inability to remove hydrogen from vacuum, glass/metal seal failure, coating degradation, and broken glass
  - Receiver replacement is approximately $1,000 each, accounting for 0.5 cents/kWh in O&M



http://www.nrel.gov/csp/troughnet/pdfs/mahoney_receiver_devel.pdf

Failure Mechanism Models - CPV

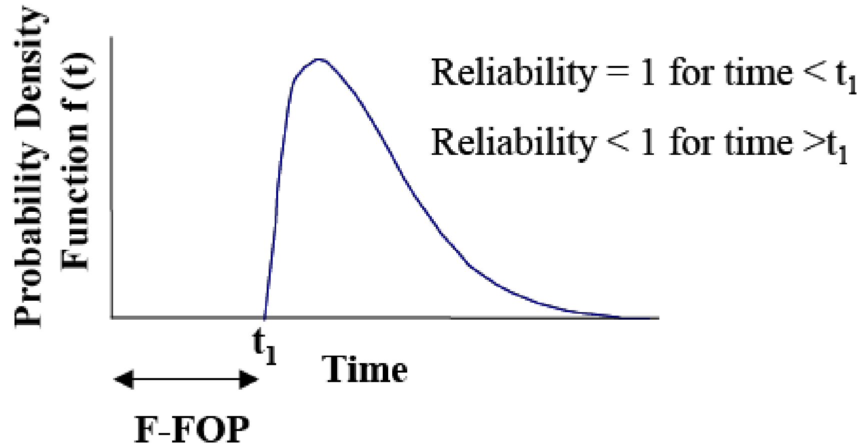
Failure Mechanism	Failure Site	Failure Mode	Relevant Stresses	Environment Test	Model	Ref
Abrasion of Optics	Glass, Coating Encapsulant	Loss of Optical output	Scratching UV	UV Exposure Abrasion	Wear Models	1
Delamination	Cell to Heat Sink	Thermal Overload	ΔT, J	Powered Temp cycle	Coffin-Manson $N = C(\gamma)^n$	1
Fracture	Glass	Cracking	Mech Load	Mech Load	Paris Law $N = C(\Delta K)^n$	2
Delamination	Glass to Metal Seal	Moisture, H Ingress	ΔT	Temp cycle	Coffin-Manson $N = C(\gamma)^n$	2
UV Degradation	Reflectors	Loss of Reflectance	UV	UV Exposure	Arrhenius Exp (-Ea/kT)	3

(1) S. Kurtz, J. Granata, M. Quintana, “Photovoltaic Reliability R&D toward a Solar Powered World, Proc. SPIE 7412, 74120Z-2
(2) http://www.nrel.gov/csp/troughnet/pdfs/mahoney_receiver_devel.pdf
(3) T. Fend, B. Hoffschmidt, G. Jorgensen, et al., Comparative Assessment of Solar Concentrator Materials, 2003

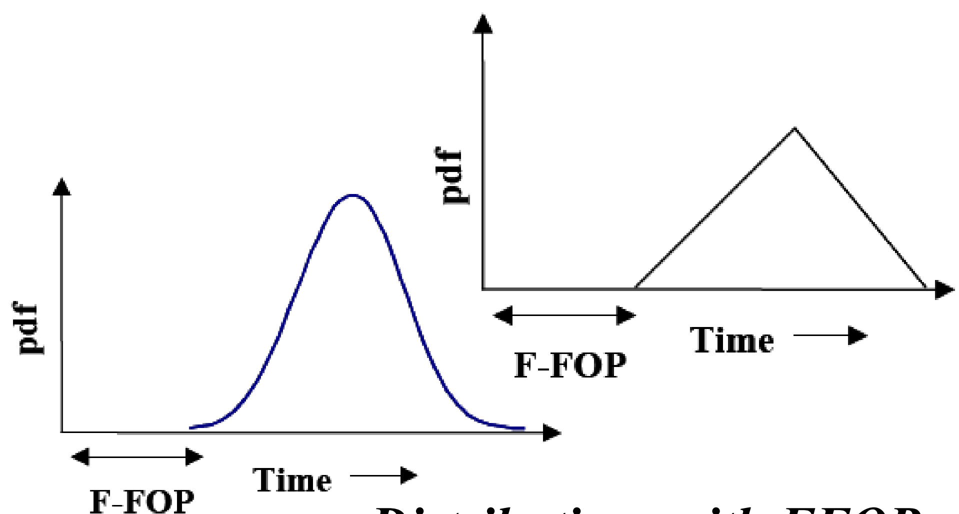
Measuring Reliability

- The preferred metric is Failure Free Operating Period.
- Failure free operating period (FFOP) of a system is defined as:

  "a period of time (or appropriate units) during which the system, operating within specific environmental conditions, is functional without encountering failures."
- There are many distributions that can be used to represent the failures. Exponential, normal, log normal, gamma, Weibull etc. are examples of such distributions. Failure free operating period is a period of time when the probability density function is zero.

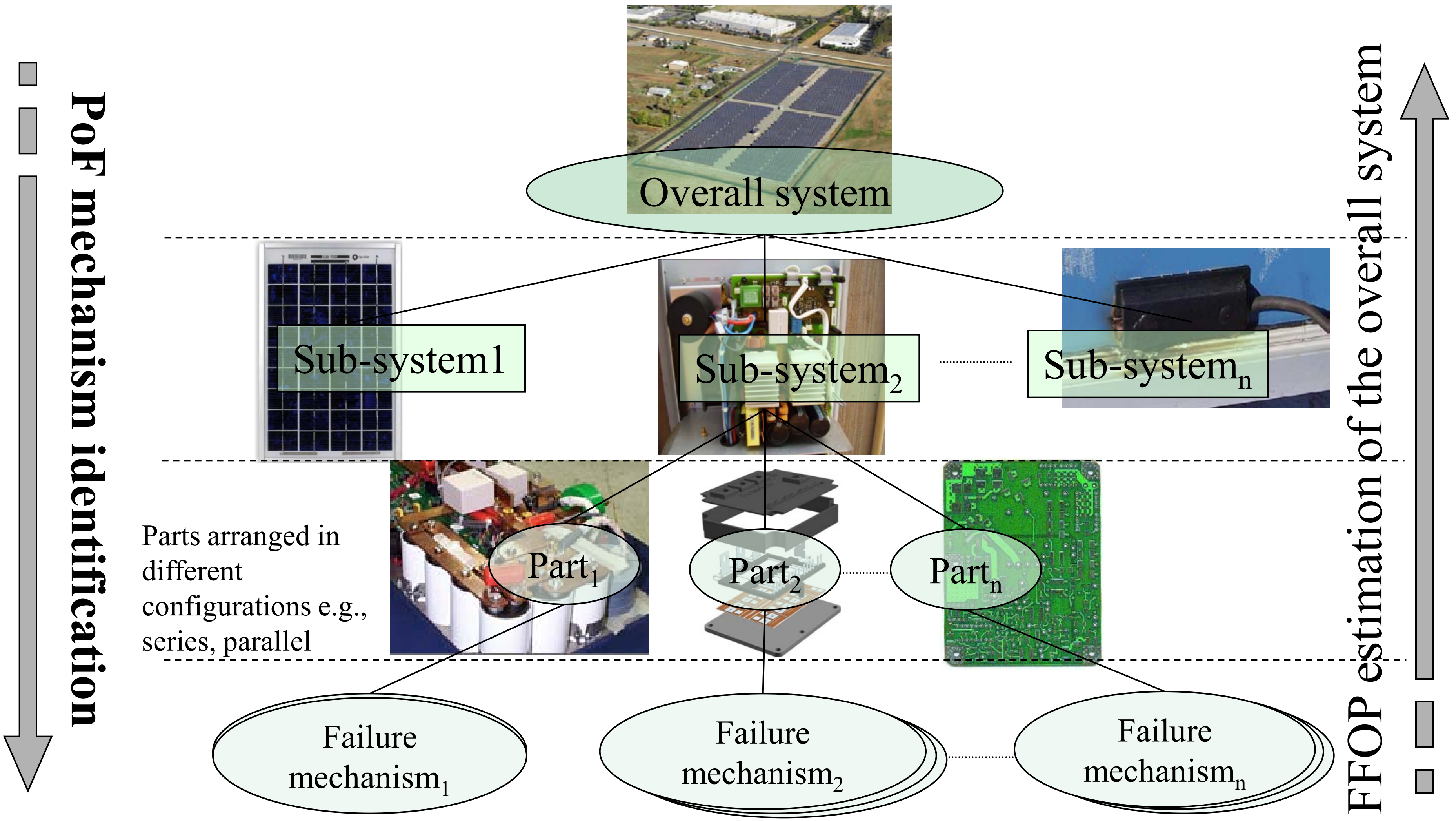


Probability Density Function for FFOP



Distributions with FFOP

Comprehensive System Reliability Assessment



$$L = L_r \left(\frac{V_r}{V_0}\right) \times 2^{\left(\frac{T_r - T_A}{10}\right)}$$

$$\varepsilon = \frac{(R-\rho_f)d\psi}{\rho_i\psi_i} \approx \frac{(\bar{r}-\rho_f)d\psi}{\rho_i\psi_i} = \frac{r(\psi_i-\psi_f)}{\rho_i\psi_i}$$

$$Nf = 0.5\ (\Delta\gamma/2\varepsilon_f)^c$$