DOE Photovoltaics Reliability Project

A Teamed Effort at:

Sandia National Labs and the National Renewable Energy Lab

Accelerated Aging and Reliability Workshop

Denver, CO April 1-2, 2008

Primary Team Members/Architects

<u>Sandia</u>

M. A. Quintana

N. R. Sorensen

D. R. Tallant

E. C. Collins

M. J. Mundt

J. R. Tillerson

<u>NREL</u>

S. M. Kurtz

D. R. Albin

T. M. McMahon

C. R. Osterwald

G. J. Jorgensen

How do you spell reliability?

1. System owner/operator with a Power Purchase Agreement
   - Availability?
   - Maintainability?
2. Integrators
   - No call backs?
3. Module manufacturers
   - Zero product returns?
   - No major recalls?
4. Inverter manufacturers
   - Zero product returns?
   - No major recalls?
5. BOS manufacturers
   - Not here?

Market segmentation and technology development are driving diverse and comprehensive needs.

DOE Labs Focus on Providing the Industry Information and Tools

Alex Mikonowicz (formerly Shell Solar now Solar World), AA I, Feb ‘06:

What we do not have?

- A meaningful test to predict end of life
- (As a manufacturer we have neither the resources or time to accomplish this).
- Suggested tests for life affected performance, i.e. UV degradation of polymers, cables, junction boxes etc.
- Suggested tests for EVA, back sheet materials, RTV etc.

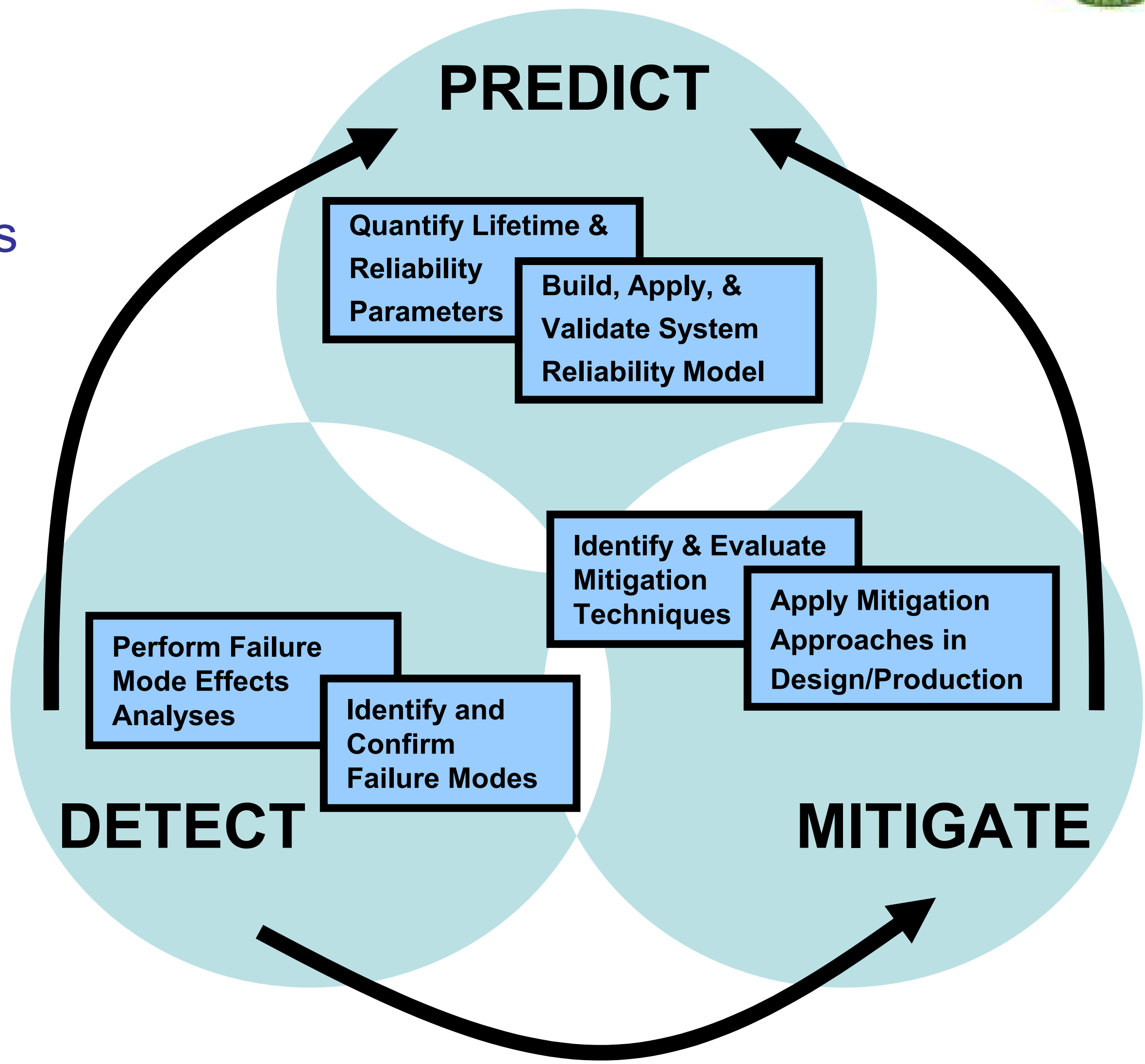
What can the labs do for manufacturers?

- Any series of “suggested” tests that can be correlated to the life expectancy of module performance (not standards)
- Operate long term site installations and measure performance over time
- Operate long term site installations and measure performance in several environments within the US

Proliferation of markets and technology make Alex visionary!

DOE has expanded and linked reliability across the entire PV program

Three major elements will be applied across materials, components and systems.



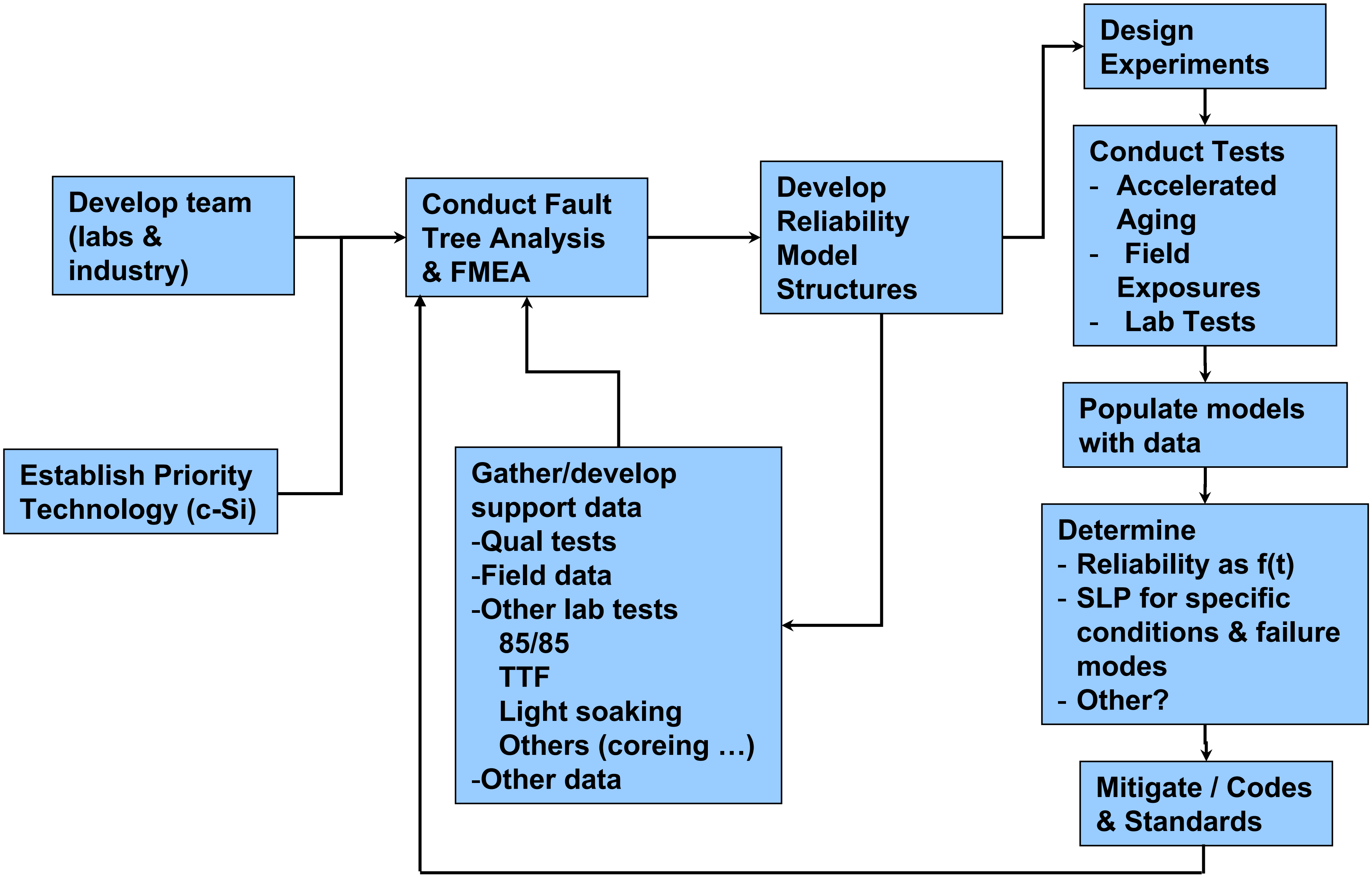
Project Objectives

- Accelerate development and adoption of methodologies that increase reliability of PV components/systems
- Develop and facilitate use of rigorous pre-qualification screening protocols
- Develop a predictive model capability that industry can own and apply
- Develop accelerated tests/standards that facilitate product development
- Develop system availability functions
- Develop criteria for design-for-maintainability strategies
- Identify barriers and solution-oriented R&D opportunities
- Assist SAI participants to meet Stage-Gates

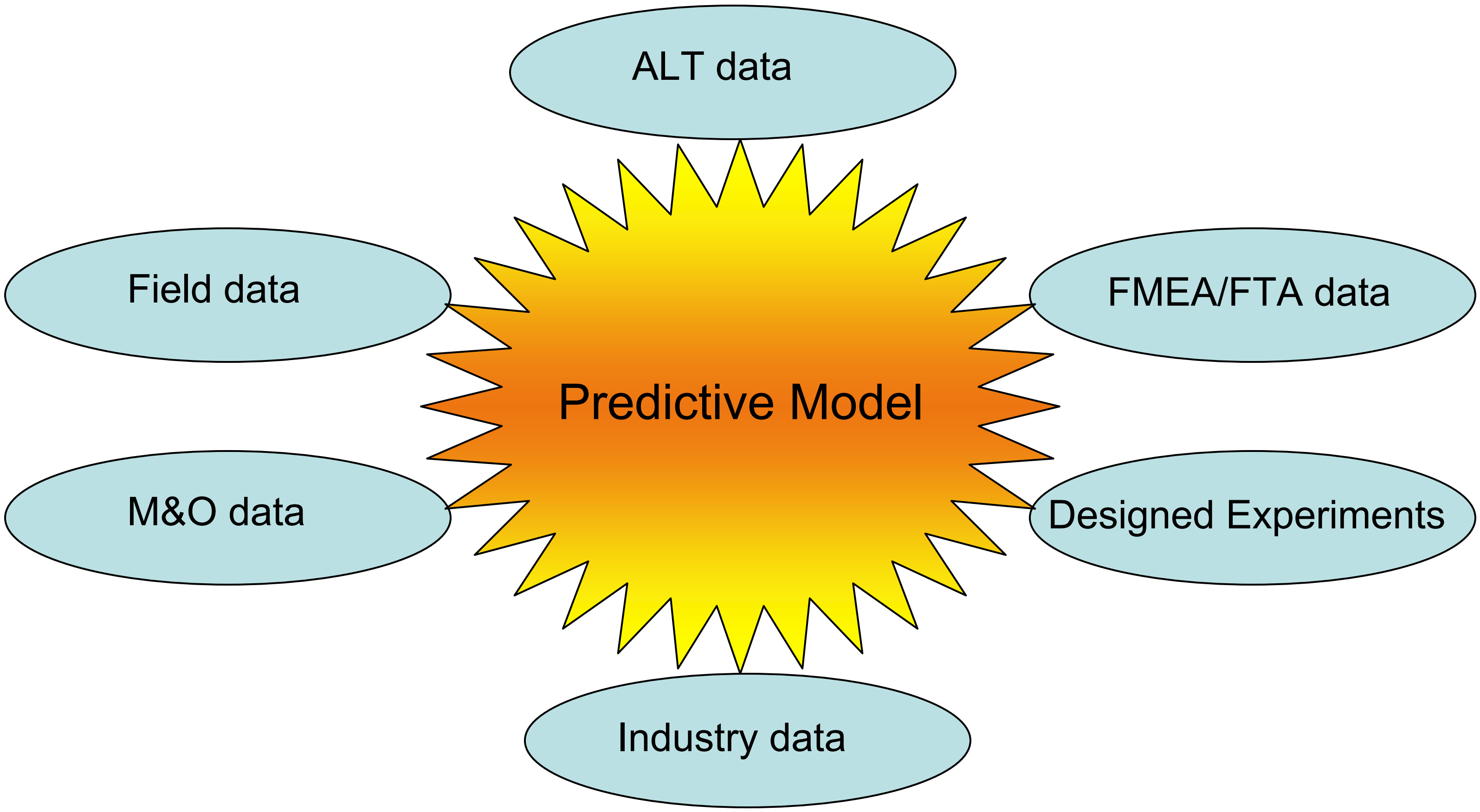
Project Scope for FY08

1. Failure Modes and Effects Analysis: Apply to c-Si modules, CIGS, and inverter to define and/or understand and review potential failure modes
    - Pursue commercial partners for FMEA application
2. Fault Tree Analysis: Define foreseeable/undesirable system events
    - Pursue commercial partner(s) to define inputs
3. Long-Term Exposure: Invest in understanding degradation of newer products/technologies
4. System Studies: Invest in field installation data to assess reliability issues
5. Accelerated Tests: Increase development of tests that address new technologies and greater understanding of mature technologies
6. Screening Protocols: Develop and apply protocols that provide valued pre-qualification T&E + diagnostics
7. Predictive Model: Develop data needs and model architecture
    - Pursue collaboration with commercial partner(s)

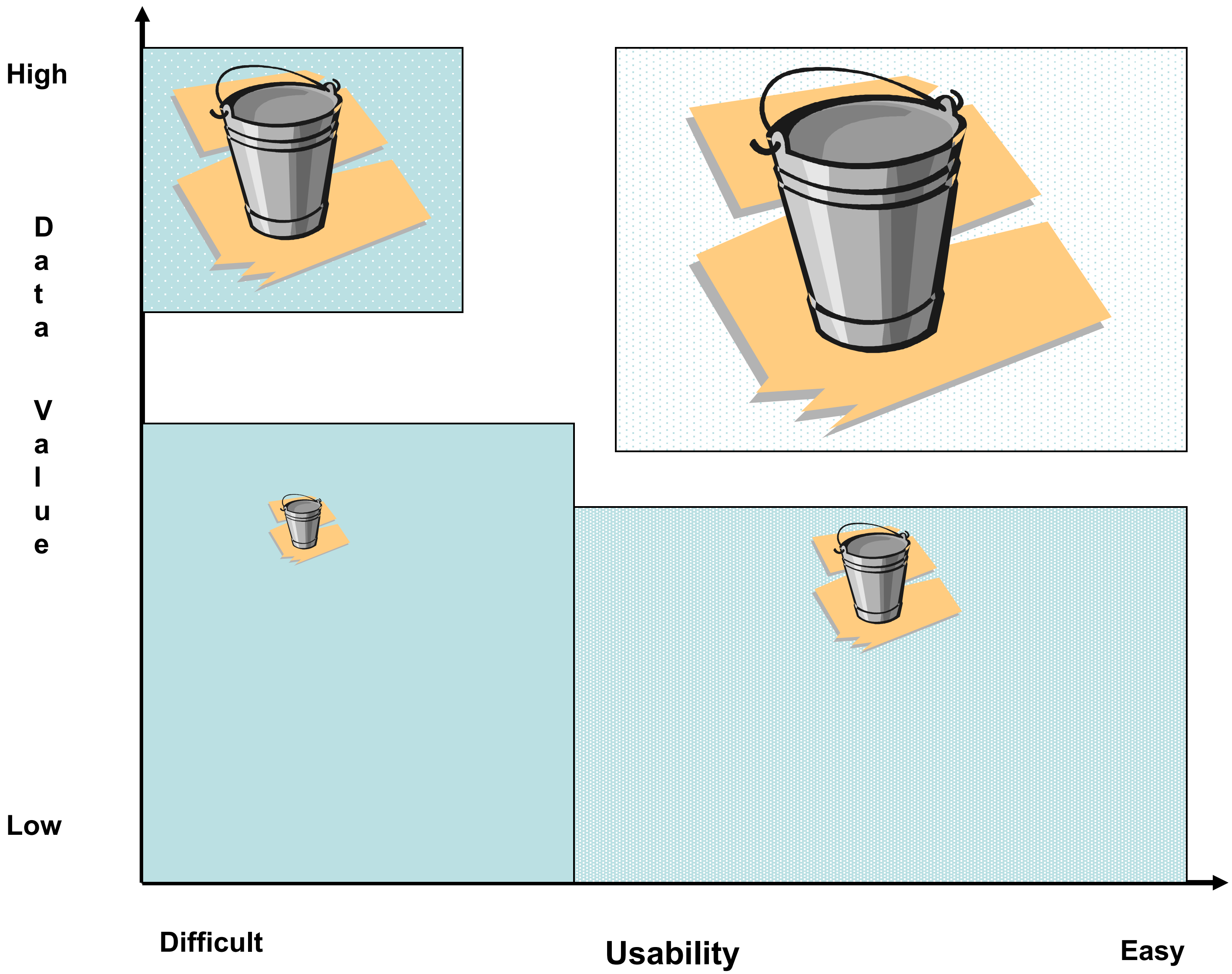
Reliability Project Flow Diagram



Data is the driver



Targeting data sources



Lab tests

Field tests

Owner data

Operator data

Manufacturers

Specifications

Codes and Stds

Physics Models

Failure Modes and Effects Analysis

FMEA is a bottom-up approach to systematically identify, analyze and document possible failure modes within a design and the effects of such failures on system performance and personnel safety.

Approach:

- Field data will be used to identify potential failure mechanisms
- Subject Matter Experts examine and review the materials used to build components
- Potential Failure Mechanisms will be identified and ranked based on perceived risk

Objectives:

- Identify dominant failure mechanisms
- Develop theoretical models that predict failure
- Identify candidate items for accelerated life tests

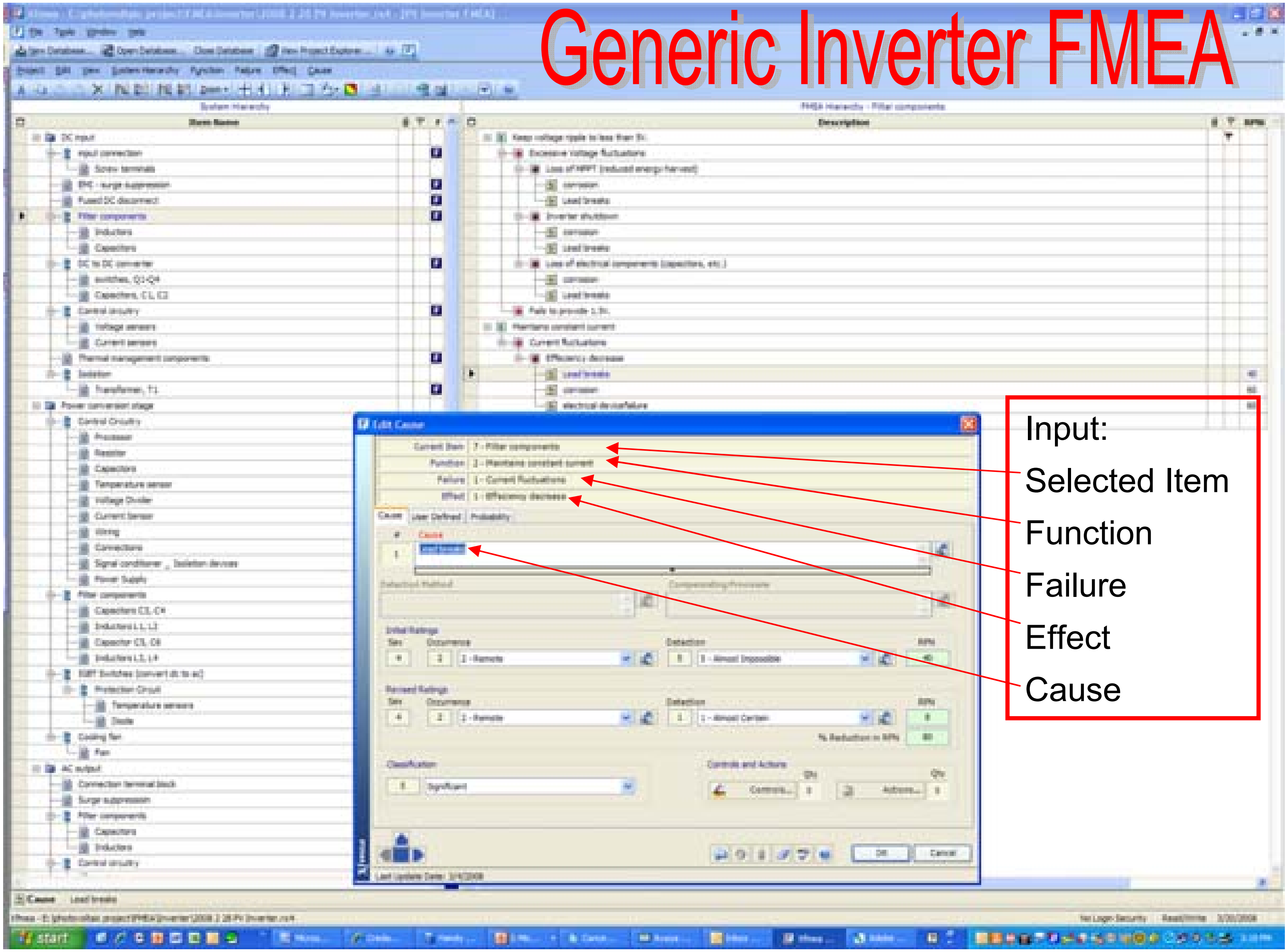
Failure Modes and Effects Analysis

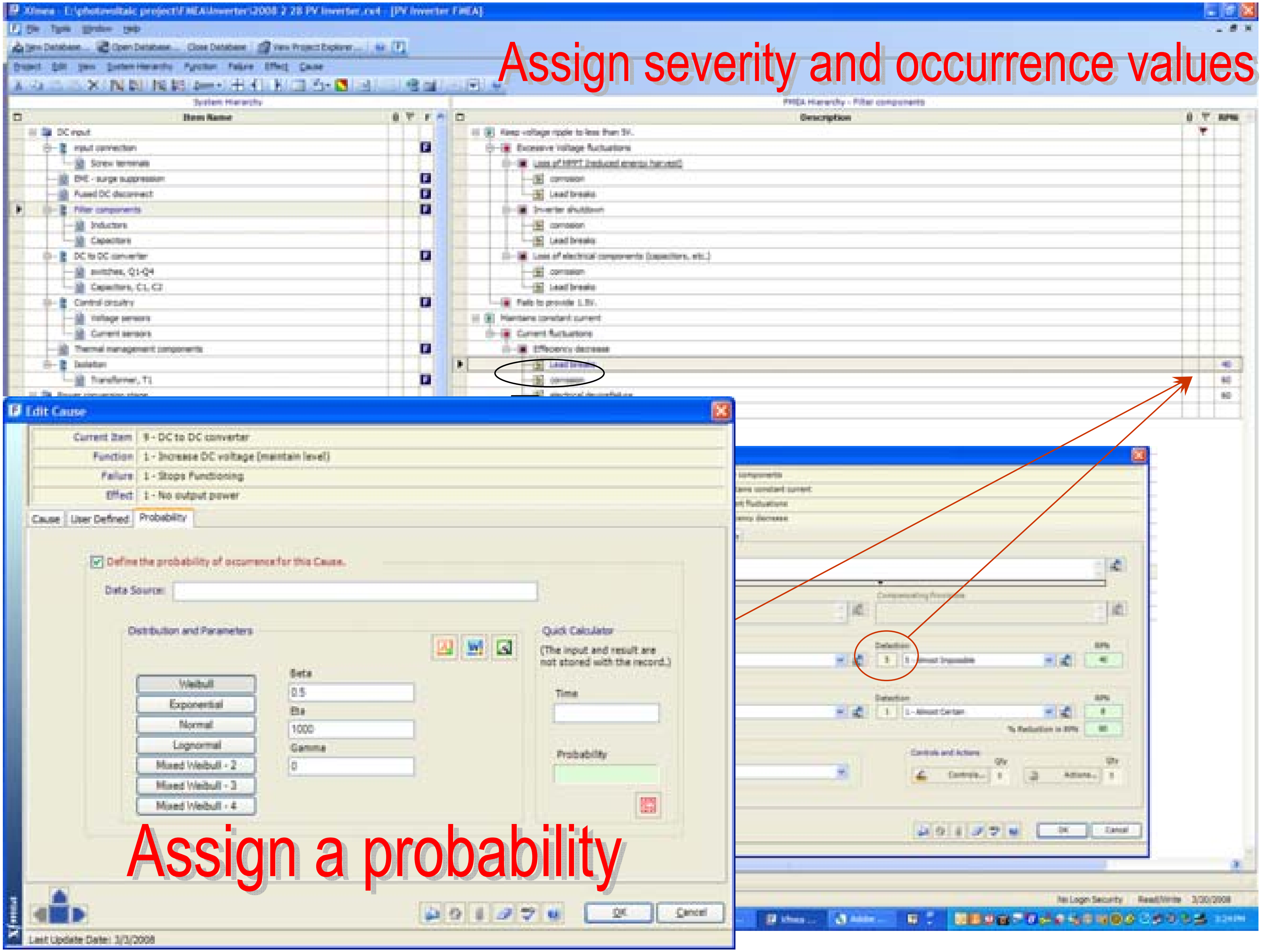
- FMEA includes “cost and actions” elements
  - Scheduled maintenance actions
  - Maintenance costs
  - Replacement schedules
- Tool: XFMEA (can be imported into ALTA and RBD packages)

✓Some Early Results Follow

✓We Will be Soliciting Review from Industry

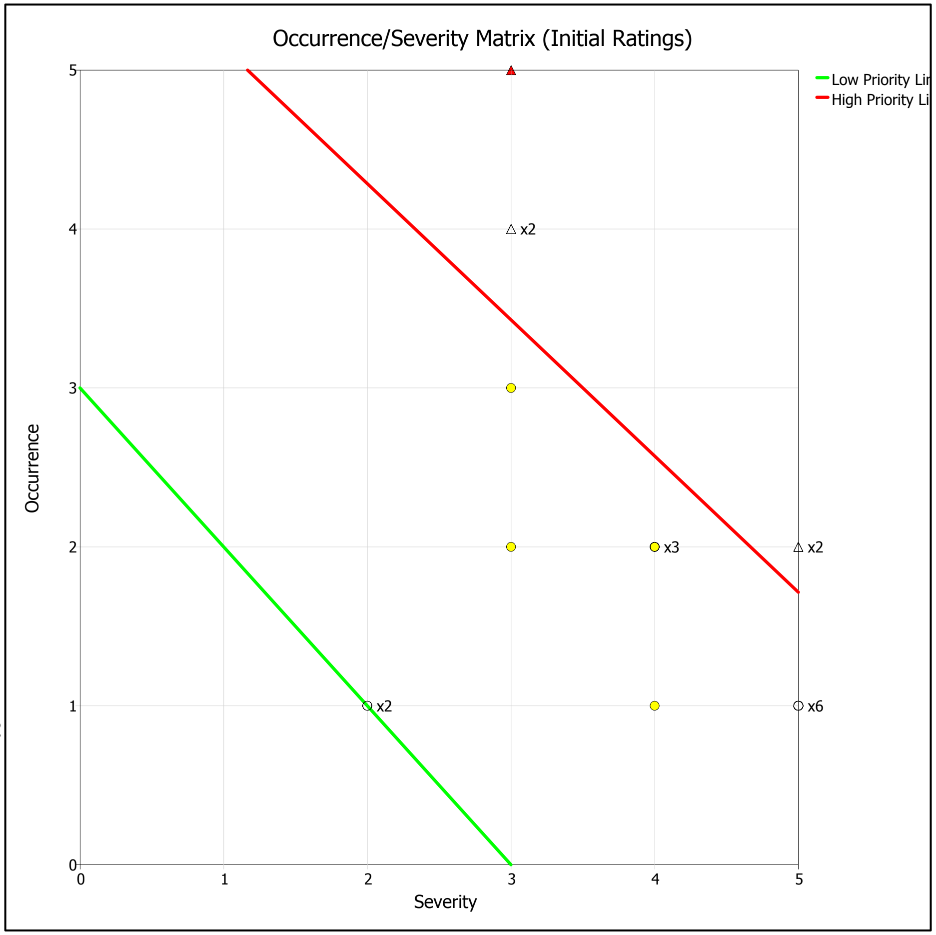
Applying XFMEA and Lab Expertise





Assign severity and occurrence values
Edit Cause
Current Item
9 - DC to DC converter
Function
1 - Increase DC voltage (maintain level)
Failure
1 - Stops Functioning
Effect
1 - No output power
Cause
User Defined
Probability
Define the probability of occurrence for this Cause.
Data Source:
Distribution and Parameters
Weibull
Exponential
Normal
Lognormal
Mixed Weibull - 2
Mixed Weibull - 3
Mixed Weibull - 4
Beta
0.5
Eta
1000
Gamma
0
Quick Calculator
(The input and result are not stored with the record.)
Time
Probability
OK
Cancel
Last Update Date: 3/3/2008
Assign a probability

Identifying High Risk Elements



Database: E:\photovoltaic project\FMEA\c-Si\Crystalline Silicon Device.rx4
Project: Crystalline Silicon Device

Selected Items:
3 - Cell Strings
3.4 - Ribbons
3.5 - Busbars
3.6 - Insulation (Dielectric Material)
3.7 - Solar Cell
3.7.17 - Silicon substrate
3.7.18 - Dopant
3.7.19 - Metallization lines
3.7.19.20 - Bus lines
3.7.19.21 - Gridlines
3.7.22 - Backsurface Field
3.7.24 - Silicon Nitride

High Priority Causes:

Medium Priority Causes:
electromigration (Item: 3 - Cell Strings) Sev = 5, Occ = 1
deterioration of metallization adhesion (corrosion) (Item: 3.7 - Solar Cell) Sev = 4, Occ = 2
metallization diffusion or migration (Item: 3.7 - Solar Cell) Sev = 4, Occ = 1
Cracked cell (Item: 3.7 - Solar Cell) Sev = 4, Occ = 2
Cracked cell (Item: 3.7 - Solar Cell) Sev = 5, Occ = 2
Full delamination of metallization lines (Item: 3.7 - Solar Cell) Sev = 5, Occ = 1
Partial delamination of metallization lines (Item: 3.7 - Solar Cell) Sev = 4, Occ = 2
Broken bus bar (Item: 3 - Cell Strings) Sev = 5, Occ = 1
Broken ribbon (Item: 3 - Cell Strings) Sev = 5, Occ = 1
Short circuit to ground (fault current) (Item: 3 - Cell Strings) Sev = 5, Occ = 1
Solder bond failure (Item: 3 - Cell Strings) Sev = 5, Occ = 2
Increased series resistance due to solder joint degradation & or failure at gridline interface (Item: 3 - Cell Strings) Sev = 3, Occ = 4
Decreased power in a single cell (Item: 3 - Cell Strings) Sev = 3, Occ = 3
Corrosion (Item: 3 - Cell Strings) Sev = 5, Occ = 1
Shunting (cell to cell shorting) (Item: 3 - Cell Strings) Sev = 3, Occ = 2
One or more cracked cells (Item: 3 - Cell Strings) Sev = 3, Occ = 5
Fatigue due to thermal cycling (Item: 3 - Cell Strings) Sev = 3, Occ = 4

Address highest priority issues!

Low Priority Causes:
encapsulation material leaching (Item: 3.7 - Solar Cell) Sev = 2, Occ = 1
contamination from plating or corrosion products (Item: 3.7 - Solar Cell) Sev = 2, Occ = 1

System Reliability Modeling

A system reliability model is a diagrammatic representation of all functions, in terms of subsystem or component events, that must occur for a successful system operation.

Approach:

- Reliability Block Diagrams and
- Fault Tree Analysis

Objective:

- Quantify reliability/availability for a system
- Determine life cycle cost of system

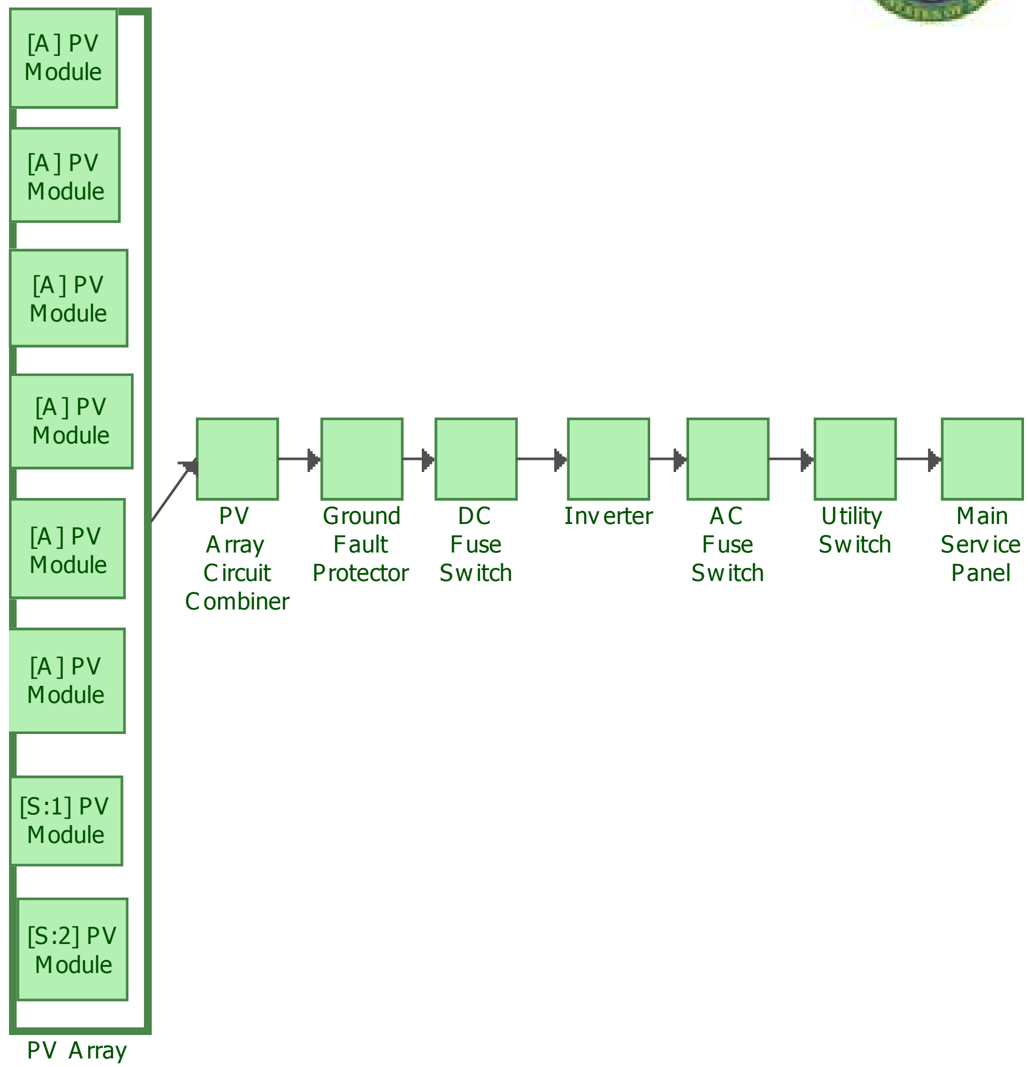
Tools:

- Reliasoft Block Sim 7, Weibull++, and ALTA
- Computer-Aided Fault Tree Analysis (CAFTA)

Service life prediction--a time period in which the system degrades to a specified unreliability

Reliability Block Diagram (RBD)

- RBD: used to quantify System Level Reliability for a specified period of time.
- Model can be used to predict the number of failures
  - Develop maintenance schedules/spares inventory
  - Identifies "weak link(s)"
  - Identifies designs for maintainability/availability
  - Identification of major contributors to the unreliability
  - trade-offs between cost and unreliability
  - predictions for unscheduled maintenance cost

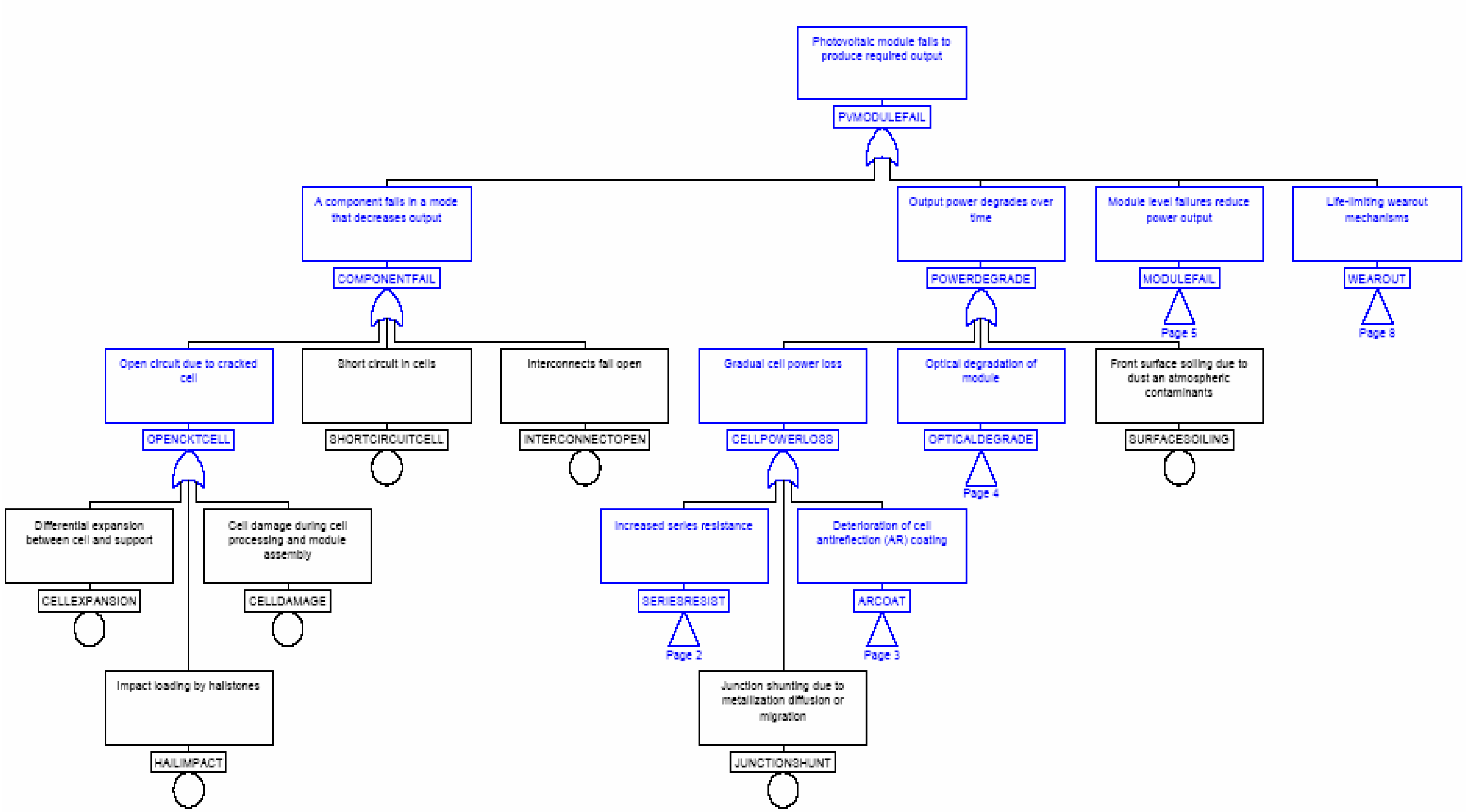


This is early work!

Fault Tree Analysis (FTA)

- FTA is a system-to-component top down analysis.
  - An undesired behavior event at the system level is hypothesized
  - Events at subsequent lower levels are then identified that can result in the undesired behavior
- Blocks in the RBD that do not have sufficient data available for quantification will be analyzed with FTA.
  - The objective is to identify lower level data that may be available to allow quantification.
- If the fault tree is developed sufficiently FTA may provide insight into those manufacturing processes that influence field reliability.

Initial Fault Tree Analysis



This is early work to be expanded in collaboration with PV community!

Accelerated Life Tests (ALT)

ALT's increase the rate of degradation processes such that quantifiable changes occur in months rather than years/decades to identify kinetics under accelerated aging conditions. Field validation tests plus these accelerated degradation rates are used to estimate service lifetimes under normal operating conditions—AF's.

Objective: Apply lab-based tests to increase use rate, aging rate or stress level of a product to quantitatively estimate long-term performance

Approach:

- Identify/prioritize failure modes using
  - FMEA
  - Field data
  - Physics models
- Identify mechanisms & associated stresses
- Accelerate aging without changing the mechanism or introducing other failure modes
- Correlate field data to ALT data to determine acceleration factors

Tools – ALTA, Design of Experiments

Accelerated Life Tests (ALT) - Step 1

Identify/prioritize failure modes

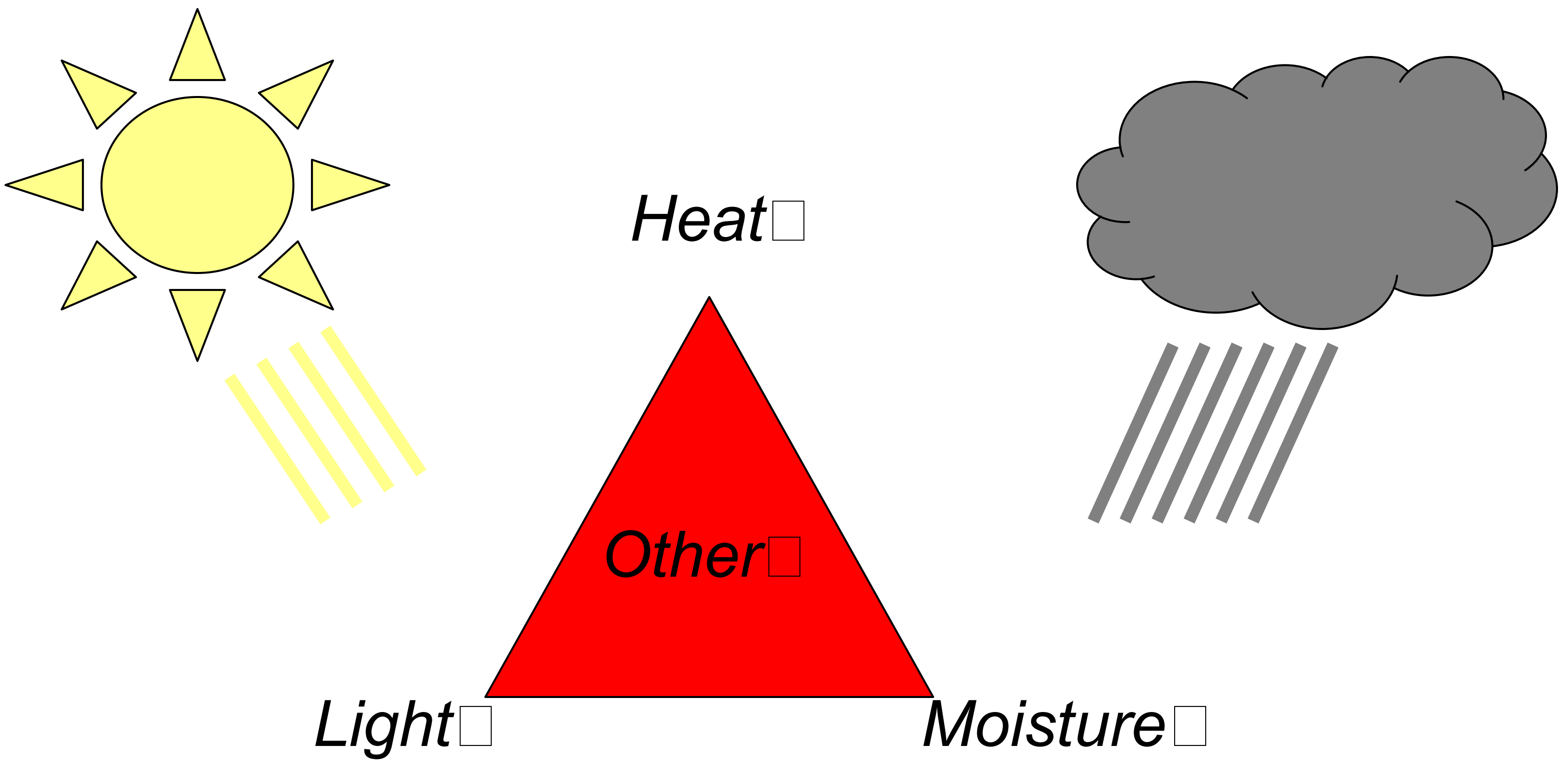
Table 1. Reliability Concerns Associated with PV Technologies

Technology	Known and Anticipated Failures & Degradation	Priority /Prob. of Success /Importance of work at Labs	Cell/ Module/ System	Diagnostic Technique / Qual Test? (e.g., chamber tests, HVTB)	Acceleration factor determination (schedule for development & validation) None? Start on?
Wafer Si	Wafer breakage issues during manufacture/handling etc. (highest priority for industry); cell cracking as wafer thickness is decreased	H/M/H	C/M	Flexing of cells	
	Improved reliability must accompany new processing innovations (reduced wafer breakage, tighter performance distributions, and higher throughput)	M/H/L	C		
	Development of encapsulation mat erials that r educe module cost and maintain reliability	H/M/H	M	UV and damp heat exposure	
	Wafer breakage caused by bonding of conductors (front contact, interconnects, etc.)	M/H/M	M	Thermo-mechanical stressing	
	Effect of lead-free solders (higher process temperatures)	L/M/L	M	SNL?	
	Corrosion of grid lines	M/M/M	M		
Film Si	Slow degradation of I_{sc}	M/M/L	C/M	Light soaking	
	Electrochemical corrosion of SnO_2:F	L/L/L	M	Voltage biased damp heat (1)	
	Initial light degradation (a-Si)	L/L/L	C/M	Light soaking	
	Annealing instabilities (a-Si)	L/L/L	C/M	Light soaking	
	Contacting of thin Si (breakage)	?/?/?	C/M		
	Reliable low cost packaging options	H/?/?	M		
	Corrosion of grid lines and solder	H/?/?	C/M	Damp heat	

Prioritize according to importance and needed R&D

Accelerated Life Tests - Step 2

Identify failure mechanisms & associated stress(es)

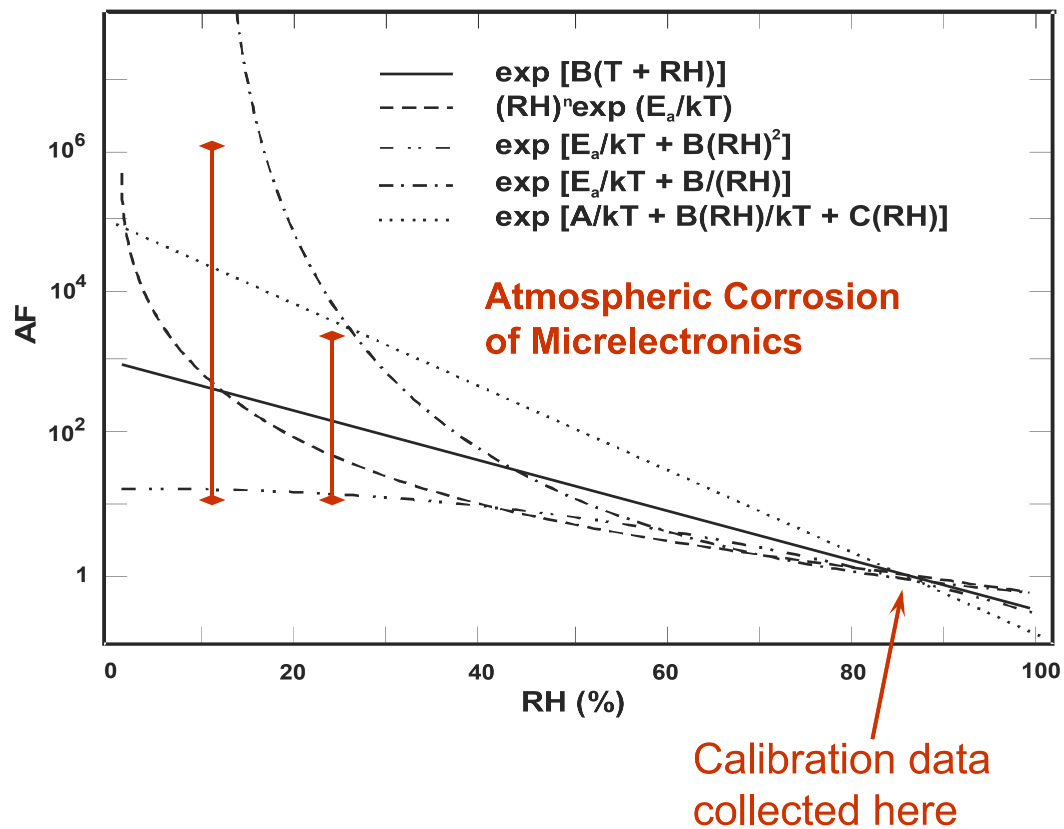


Accelerated Life Tests - Step 2

Identify Applicable Models

Example:

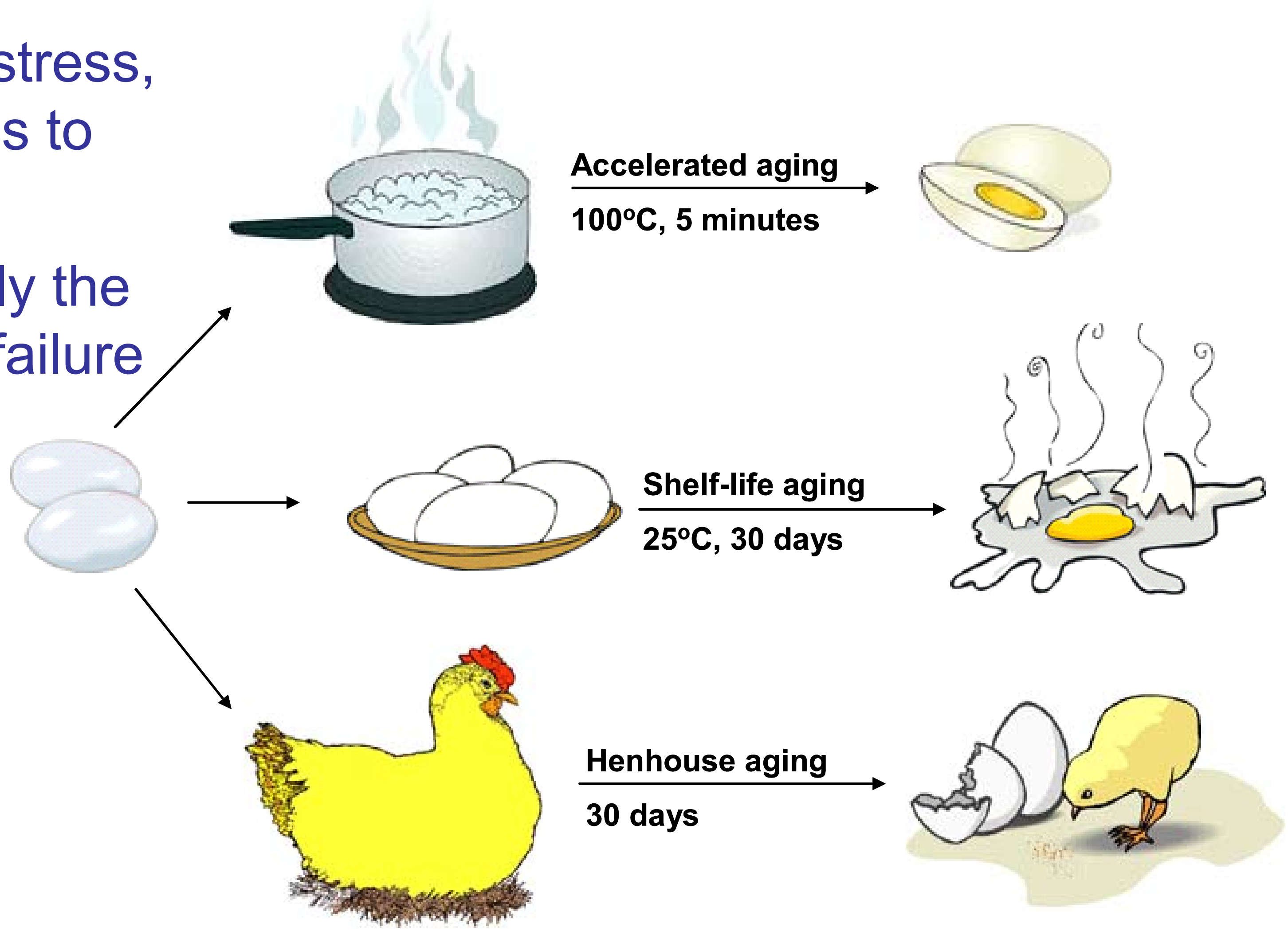
- Three recognized models for corrosion in micro-electronics
- All agree at 85%RH
- Disagreement at 10%-30% prevent uniform application of either model



Accelerated Life Tests - Step 3

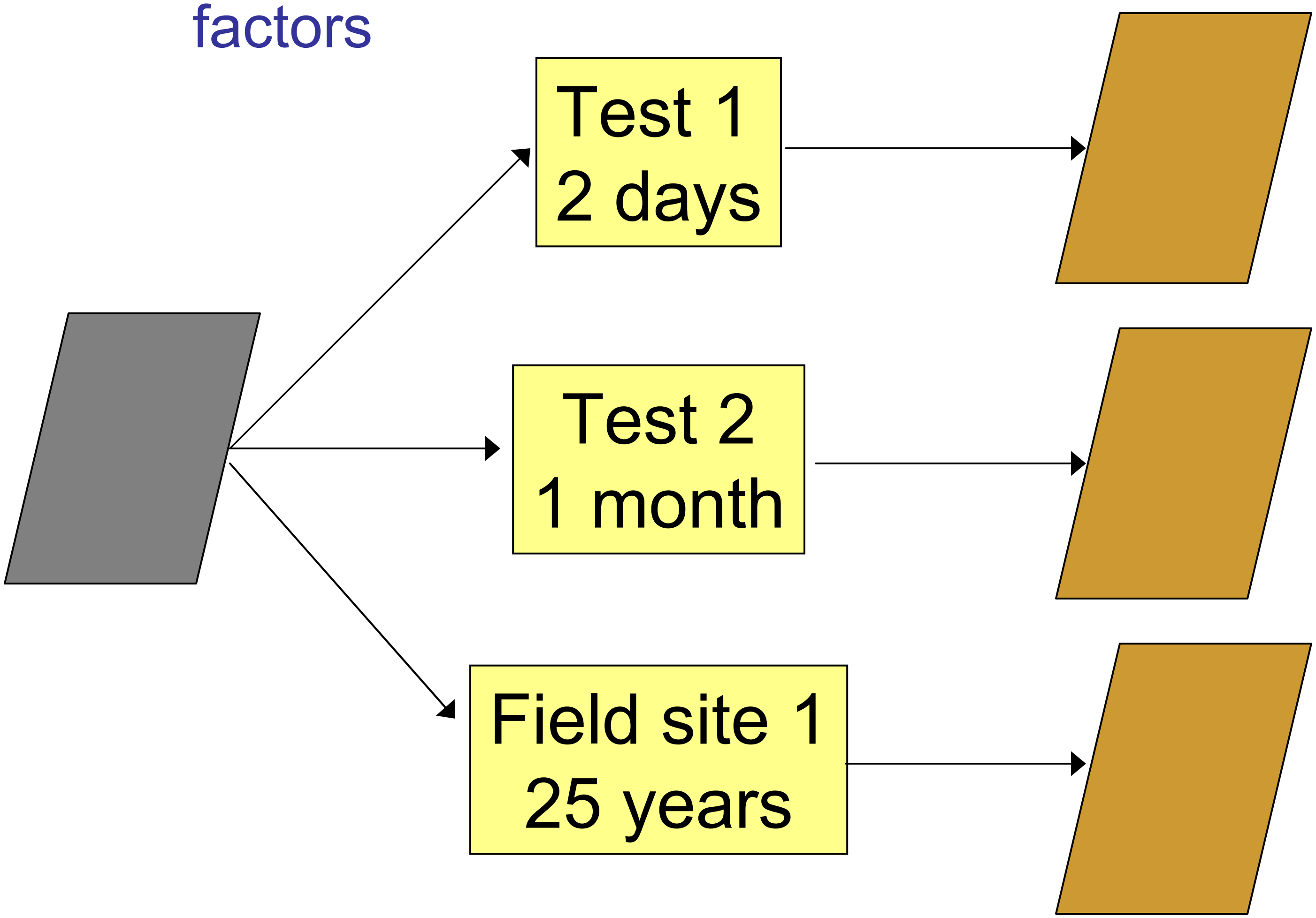
Develop ALT's that:

- Increase stress, sometimes to failure
- Stress only the intended failure mode(s)



Accelerated Life Tests - Step 4

Measure acceleration factors



Step 5. Apply acceleration factors to site-specific stresses

Test-to-failure protocol

Objective:

- Quantitative testing of failure rates
- Comparison of different designs

Approach:

- Leverages years of experience with qualitative testing
- Repeat test multiple times; record time of failure
- In-situ monitoring can pinpoint time of failure

Tools:

- Damp heat; temperature cycling

Details:

- Published at: http://www.nrel.gov/docs/fy08osti/42893.pdf

Comparison of these tests with field data will can yield acceleration factors

Field-based Surveillance Studies

- Module and inverter long term exposure in severe climates will be implemented to further develop data on degradation rates
- Industry return data will be mined—partners are being solicited
- Fielded systems will be evaluated for module, inverter and BOS data that assists analyses
- Validation tests will be conducted to assist in ALT and model development
- Coupon/samples will be fielded in extreme environments
- Short and intermediate outdoor exposure at labs

Summary

- The photovoltaics industry is evolving rapidly
- Reliability is a key element in everybody's growth plans
- DOE Labs are heavily invested in promoting robust reliability methodologies to:
  - Assist industry in meeting development needs
  - Assist DOE in administering the Solar America initiative
  - Elevate the value proposition that photovoltaics brings to America's energy landscape