Reliability R&D

DOE Program Review
for April 2007-March 2008

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Austin Airport Marriott South

Austin, TX April 22-24, 2008

Outline

Relevance to the SAI

- Key metric: levelized cost of electricity (LCOE)
- Reliability is needed to calculate LCOE
- Collaboration with SAI participants and other industry

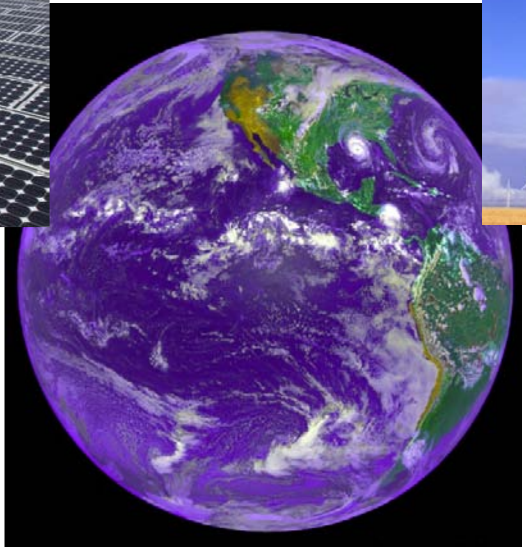
Project Specific Information

- Past year Activities
- Past year Accomplishments

Plans for coming year

- Planned support for SAI
- Other plans for coming year

SAI key metric is LCOE

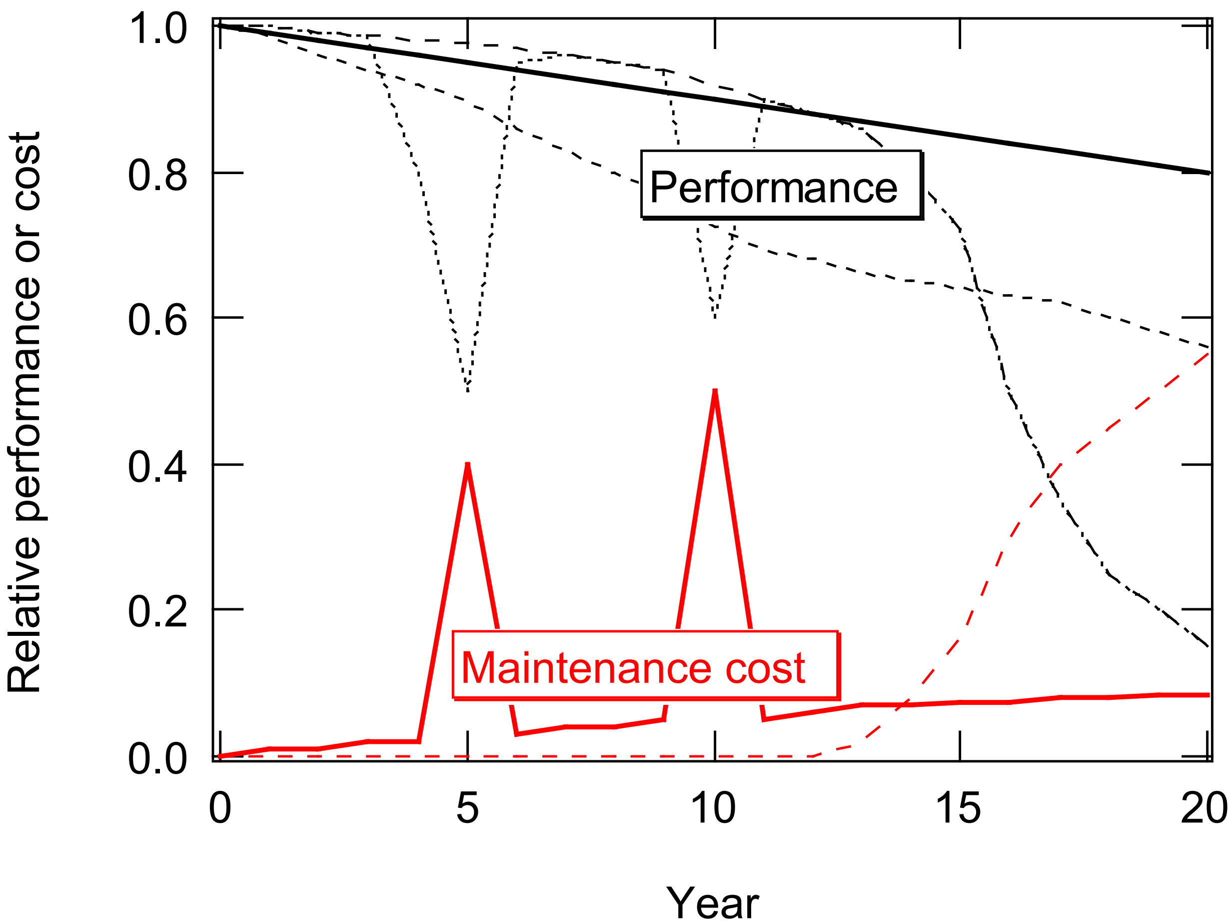


LCOE = total cost/total electricity

For this calculation we require:

- *Predictable performance*
- *Predictable cost*

Ideal Expectations vs Real Experience



Competitive LCOE:

- High energy production
- Low degradation rates
- High availability
- Low initial costs
- Low operational costs
- Low replacement costs

To predict LCOE we need to understand reliability

Understanding reliability needs

1. System owner/operator with a Power Purchase Agreement
   - Availability?
   - Maintainability?
   - Performance?
   - Good safety record
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
   - State of denial?

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

Continue to build consumer confidence with excellent reliability record

Relevance to the SAI

Roles for National Labs:

1. Assessment - support requirements of SAI deliverables
2. PV supply-chain support
   - Prototype development: **failure mechanism identification**; **accelerated testing**, and **field testing** to uncover the failures; summarize in standards
   - Commercialization: **failure analysis modeling**, **accelerated testing** to support industry's efforts to develop reproducible processes
   - Long term success: support industry in developing **predictive models** and the **field testing** data to support these

Working with industry:

We propose to balance

need for *secrecy* with

benefit of *sharing* information by:

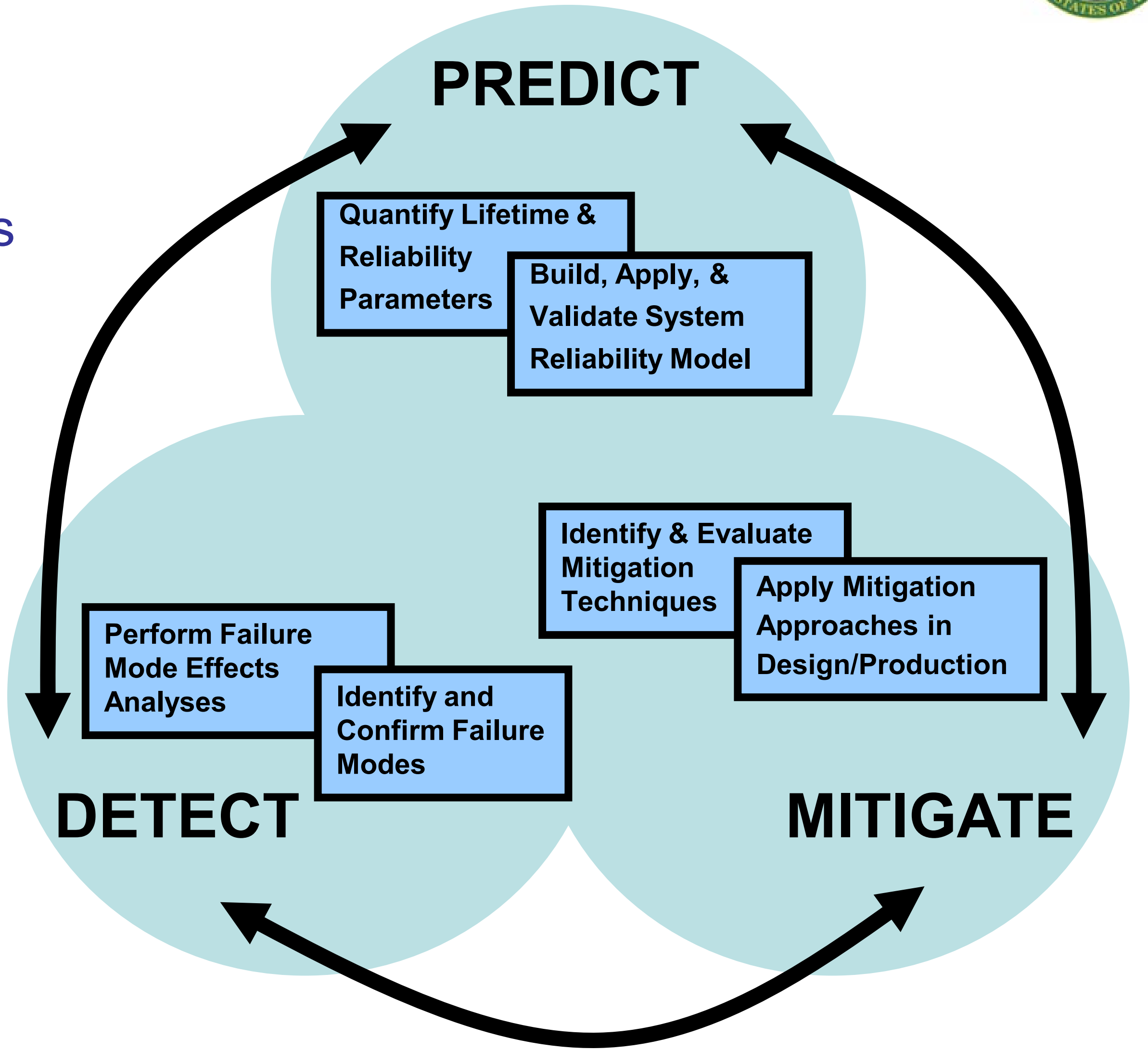
Keep proprietary:
- Existence of problem before solution developed
- Solutions to problems

Share:
- Possible failure modes
- Tests to identify failures

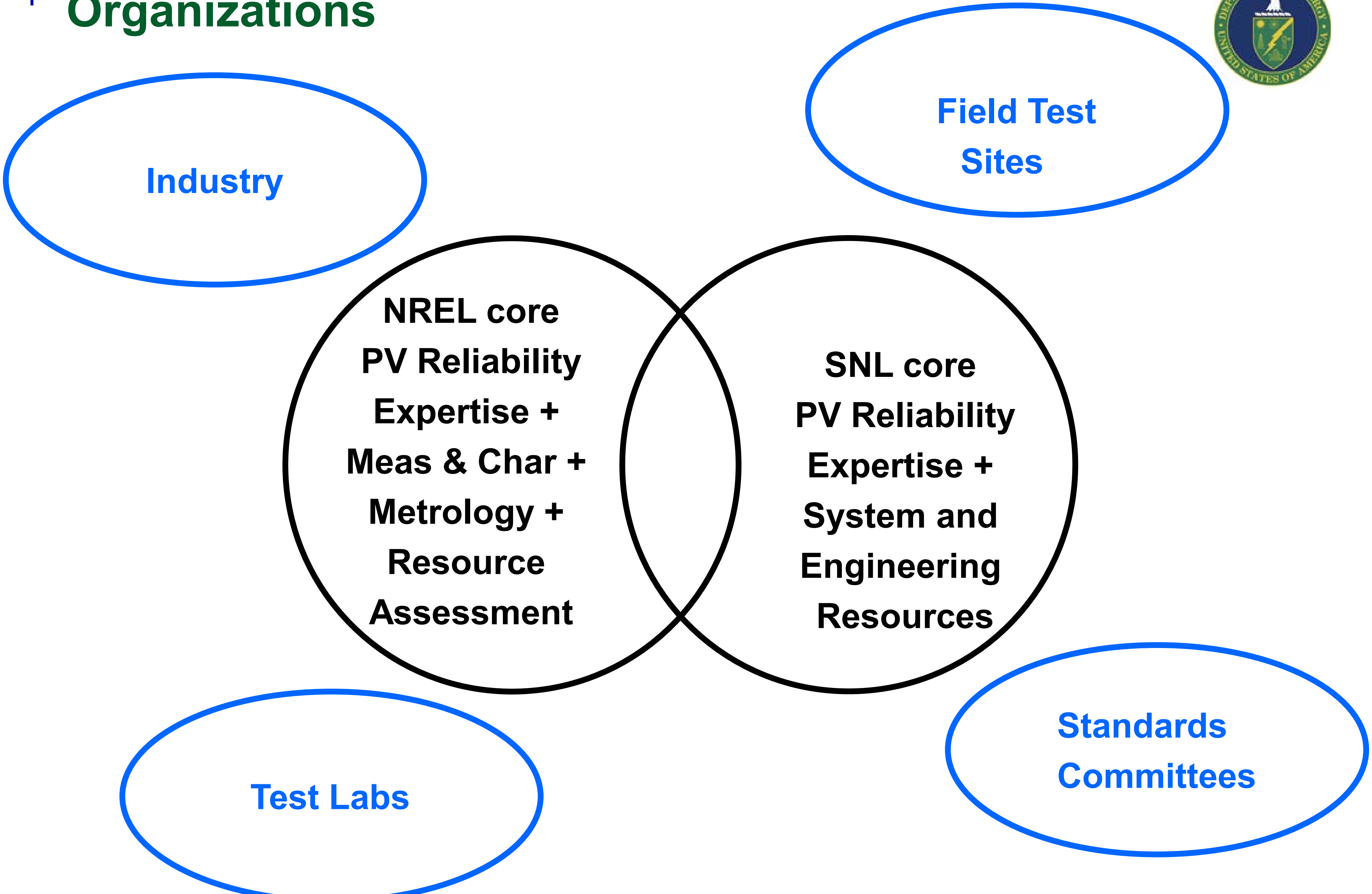
A clear, common understanding of this framework provides a strong foundation for partnerships

Reliability has been expanded and linked across the entire program

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



Reliability Program Interacts with Other Important Organizations



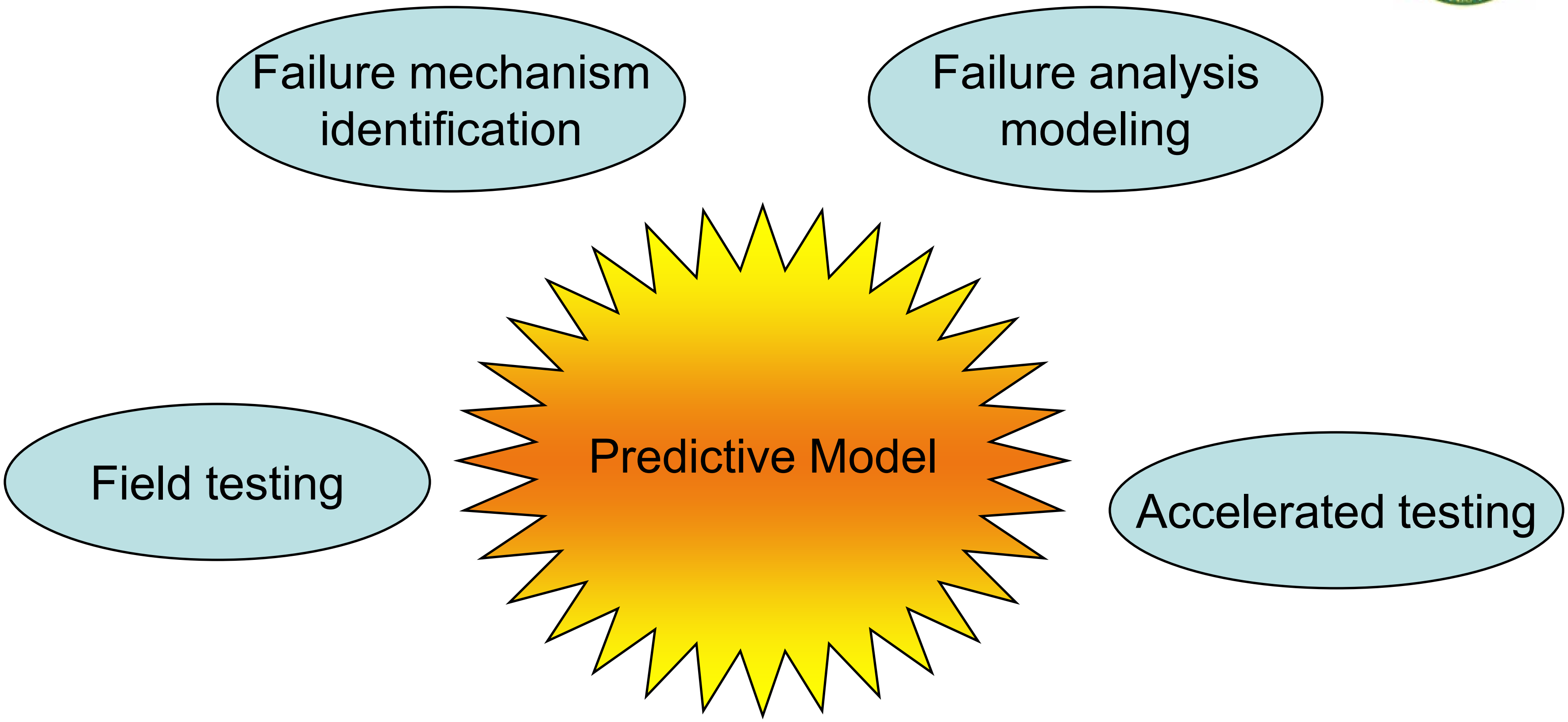
Project Scope - FY08

FY08 Plans

1. Failure Modes and Effects Analysis: Apply to c-Si modules, CIGS, and inverter to define and/or understand and review potential failure modes
2. Fault Tree Analysis: Define foreseeable/undesirable system events
3. Long-Term Exposure (field tests): Invest in understanding degradation of newer products/technologies
4. Accelerated Tests: Increase development of tests that address new technologies and greater understanding of mature technologies
5. Test-to-failure Protocols: Develop and apply protocols to quantitatively compare performance of different designs
6. Predictive Model: Develop data needs and model architecture

We seek commercial partner(s) for these

Project develops basis for predictive model



FY07/FY08 Budgets

FY07 Research Activities	Org.	Budget ($K)
Cell and Module Stability & Reliability	NREL	1219
Module and Array Testing (includes some T&E)	NREL SNL	1940 530
Module Failure Analysis	NREL	460

FY08 Research Activities	Org.	Budget ($K)
Accelerated Life Testing & Analysis	NREL SNL	1935 630
Industry Reliability & Codes	NREL SNL	475 445
Module Screening & Field Evaluation	NREL SNL	1945 320
SLP Model & Failure Analysis	SNL NREL	645 270

Accomplishments

Assessments in support of SAI:

1. Discussions/planning with most TPPs and incubators
2. Temperature cycling test completed for SolFocus
3. Module baseline testing and humidity freeze testing of junction boxes for GreenRay
4. Soliant reliability assessment (ongoing)

PV Supply-chain support:

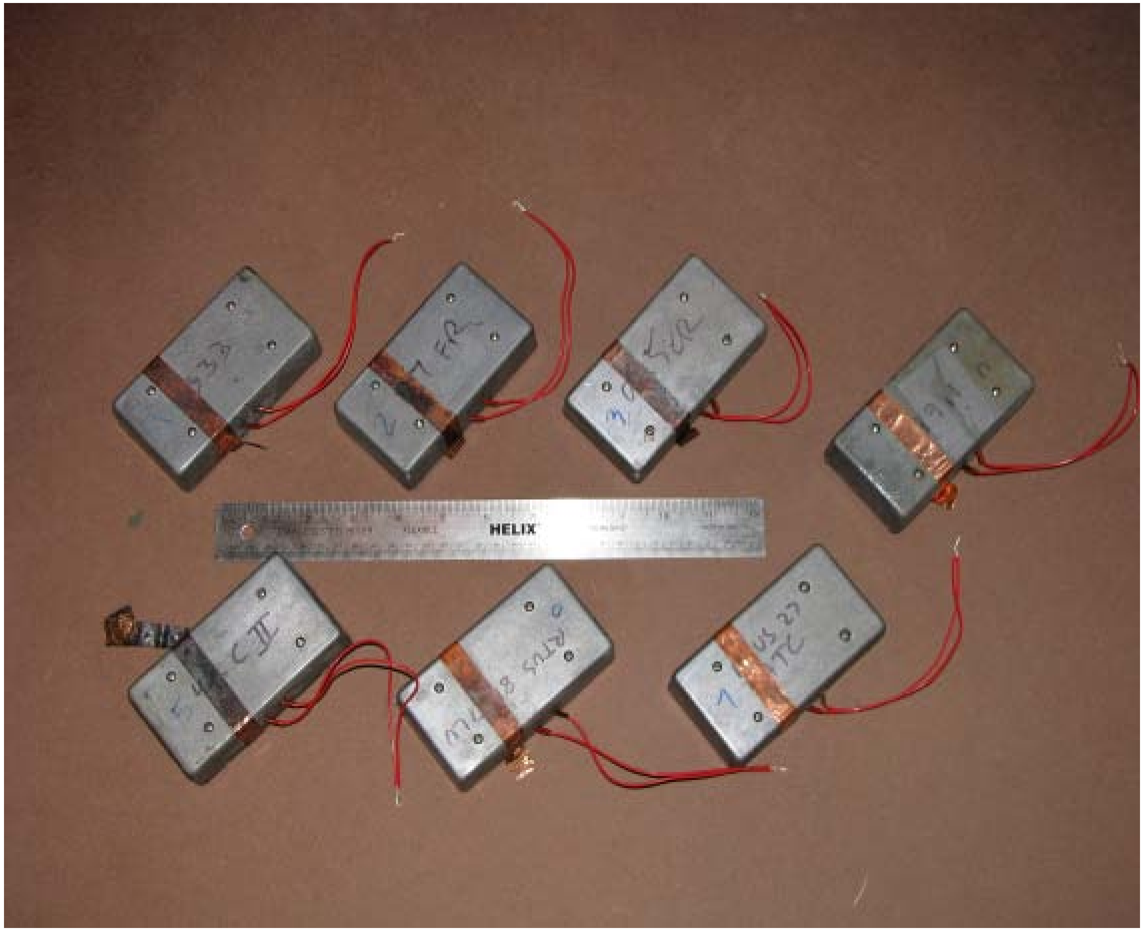
1. Accelerated Aging workshop
2. Accelerated testing
3. Test-to-failure protocol
4. Failure mode analyses begun (c-Si, CIGS, inverter)
5. Initiated model as basis for reliability prediction

SAI support - SolFocus (Incubator)

Stress: temperature cycling

Accelerated testing

SAI support - GreenRay (TPP)



SNL screened six junction box configurations.

Accelerated testing

Humidity freeze tests at Sandia

Accelerated Aging Workshop II

April 1-2, 2008

- 115 participants from ~50 companies
- CPV, CIGS, a-Si, CdTe, c-Si, inverter, BOS, materials, and systems companies
- All Technology Pathway Partners and Incubators represented
- Participants ranged from start-ups to mature companies
- Three universities represented

Accelerated Aging Workshop II

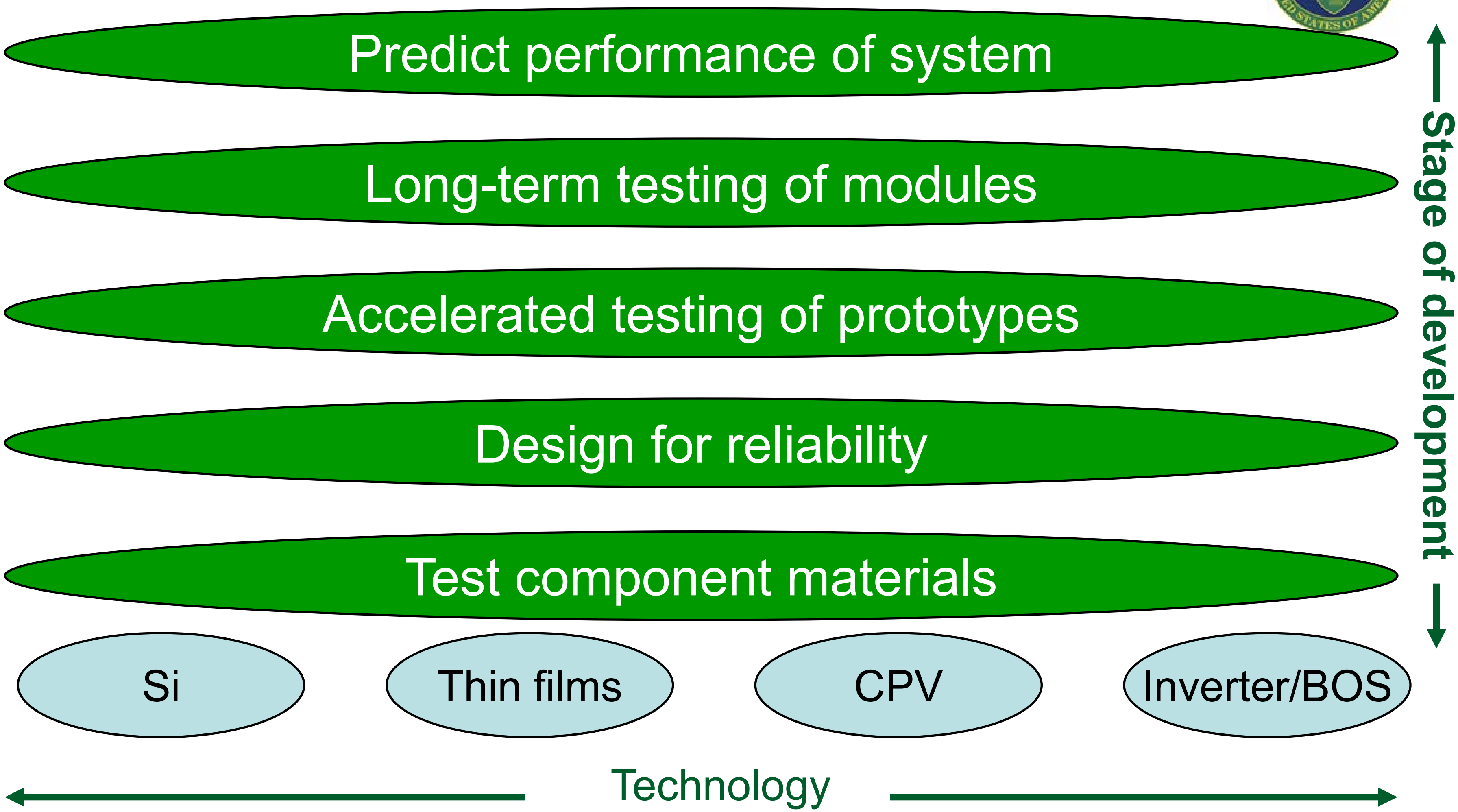
New areas of interest:

- Systems needs; replacement frequency, availability, maintainability
- Safety
- Surge/surge protection and diodes
- Arcing
- BOS components
- Database of failure modes
- Definition of use conditions
- Reliability testing of prototypes for start-up companies
- Cost of achieving reliability

Continued needs:

- Accelerated Life Tests for development purposes

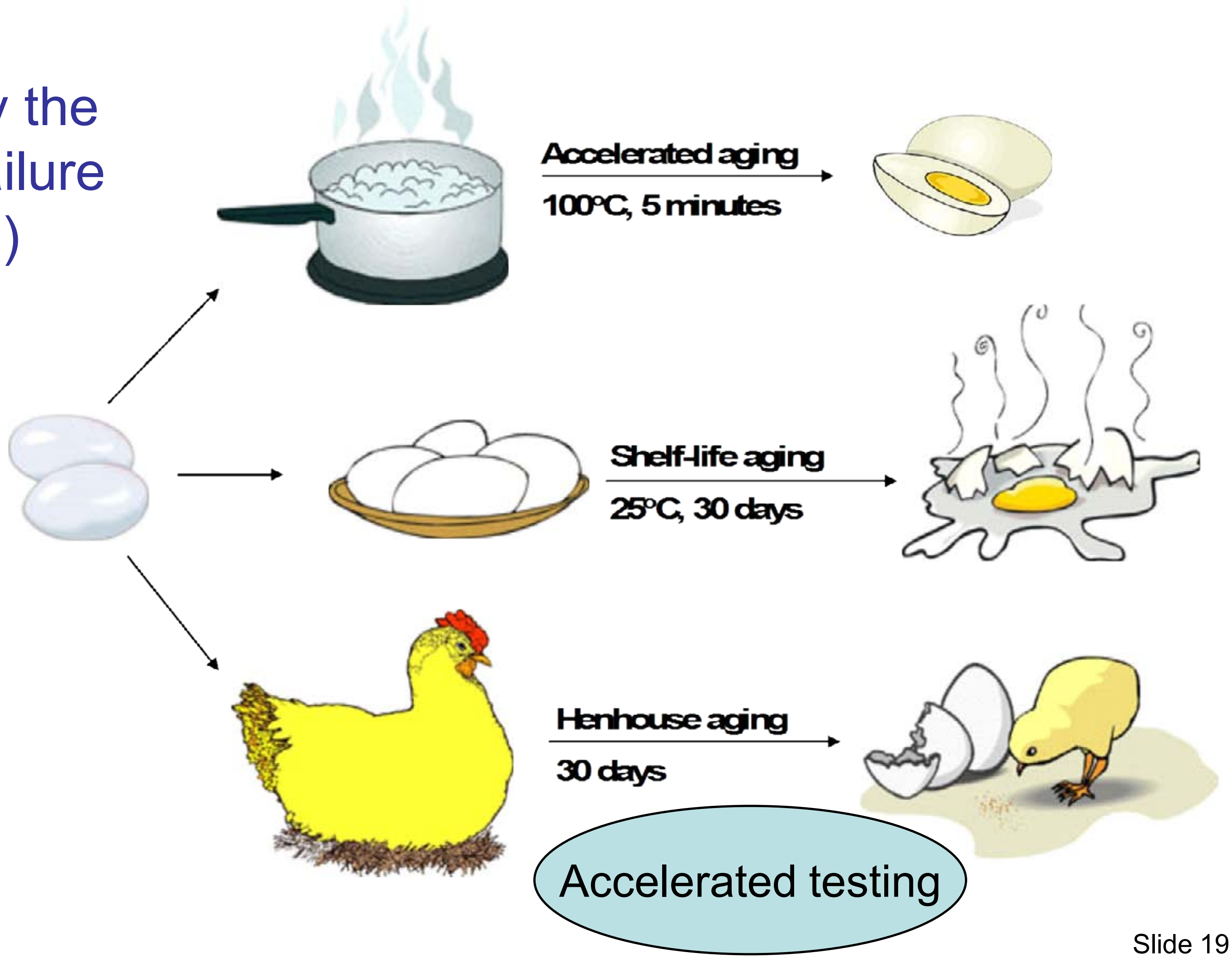
Accelerated aging workshop: portfolio



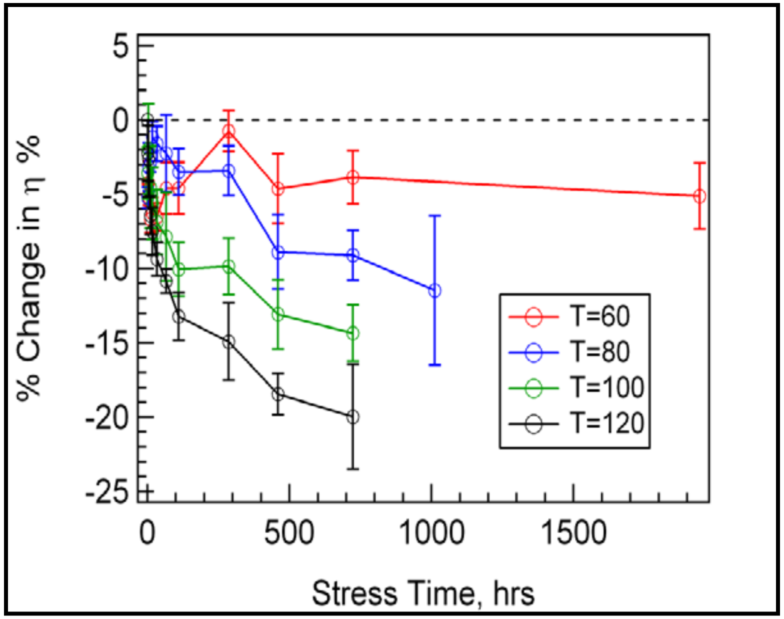
Consumer relies on all of the above to assess LCOE

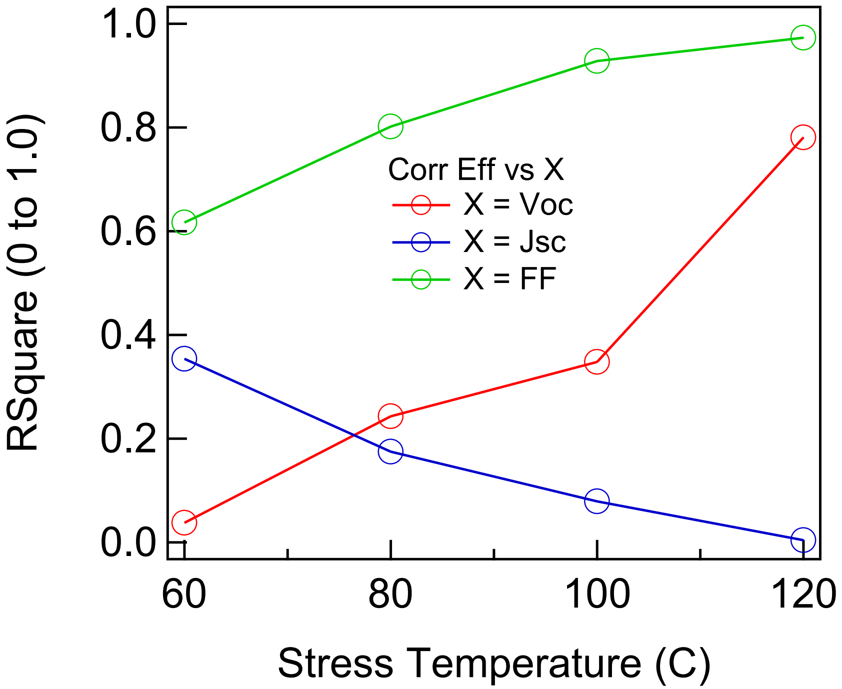
Accelerated testing

Stress only the intended failure mode(s)



CdTe accelerated stress testing dependence on temperature





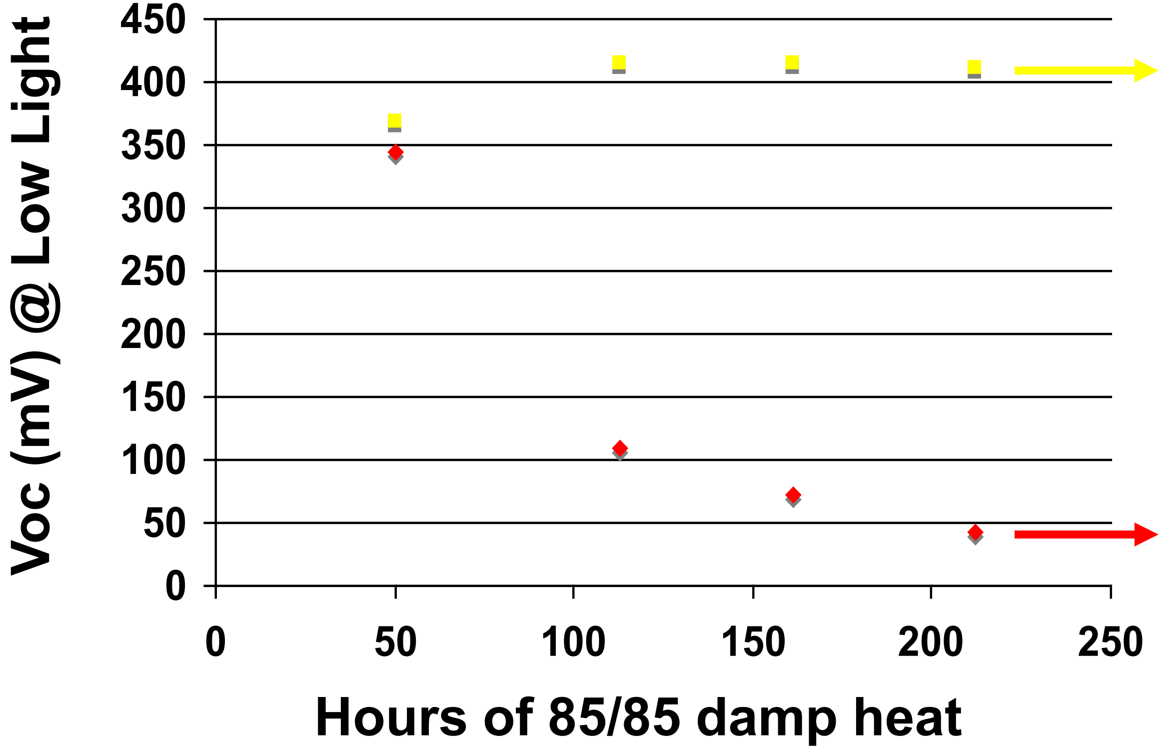
At 120°C, degradation correlates with Voc, but at 60°C, the mechanism is different; which is relevant to the field?

Albin, et al, SPIE, 2008

Accelerated testing

Stability of 2 Konarka OPV cells

1-sun I-V data not yet available



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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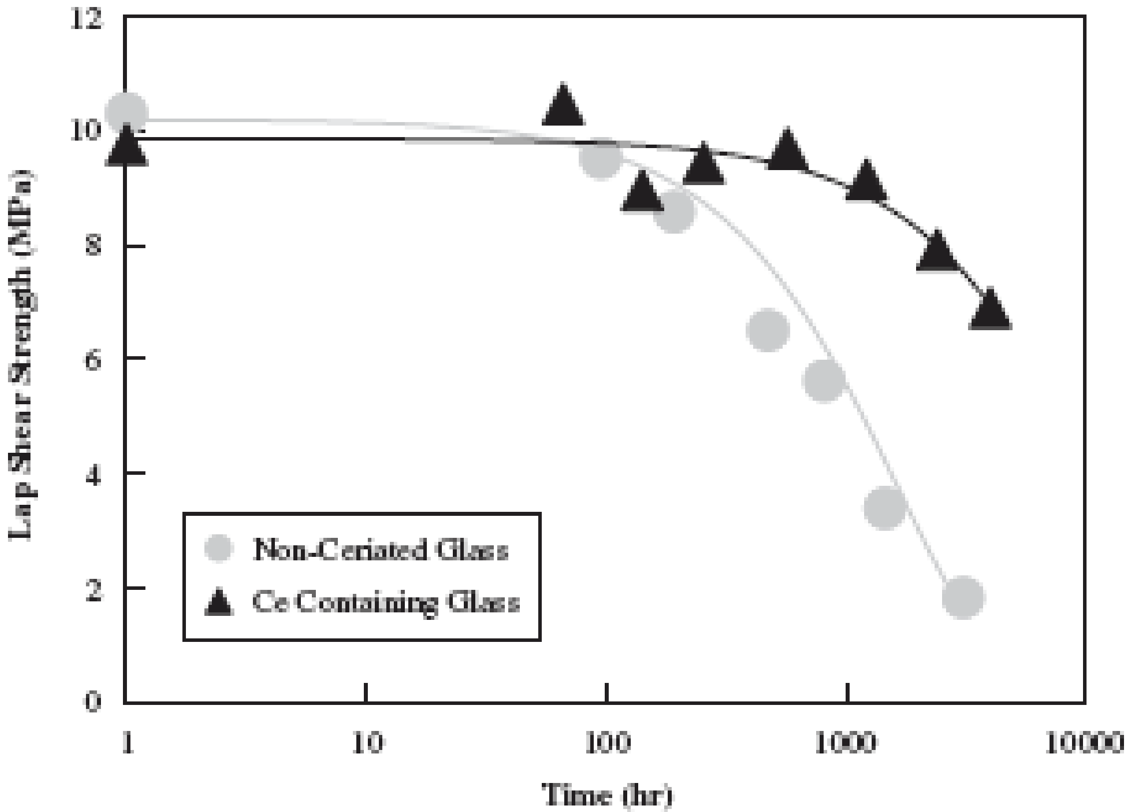
Low light Voc and IR images predict future failure of 1 cell

IR images, forward bias

McMahon & Konarka, unpublished

Accelerated testing

Study of encapsulant adhesion



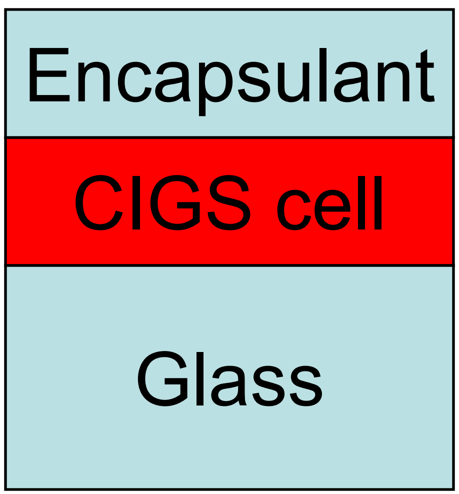
60°C/60% humidity; 2.5 suns UV

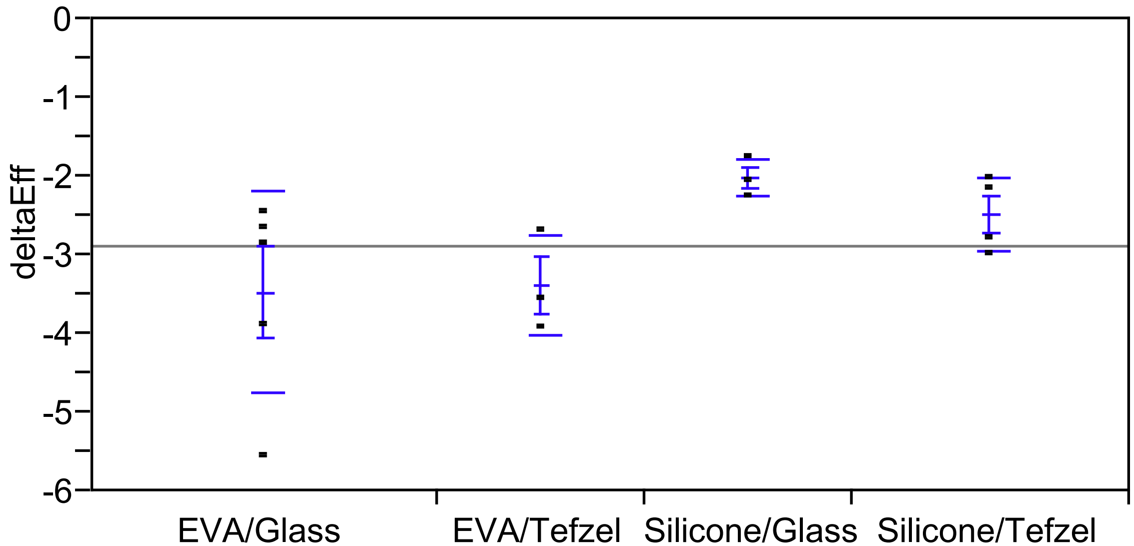
Adhesion retained longer when glass contains Ce that blocks UV B radiation

Accelerated testing

Kempe, et al, Solar Energy Materials 91, (2007) p. 315-329

Study of encapsulant effect on cell efficiency after 8800 hrs @ 85°C/0% humidity





Cells encapsulated with silicone are more stable than those using EVA

Accelerated testing

Kempe, et al, IEEE PVSC, 2008

Outdoor Exposure

Field testing

- Time consuming, but absolutely vital
- May uncover problems not seen with accelerated tests
- Degradation rates - only way to validate

Field testing

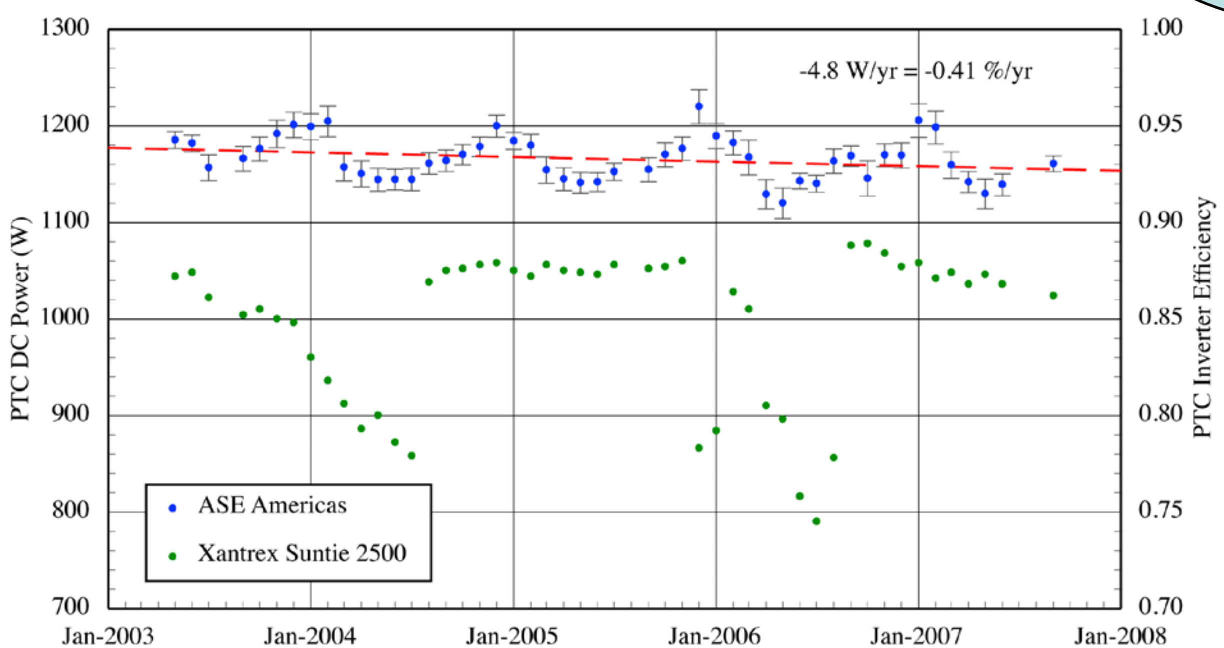
SunPower system installed fall 2007

Module/array degradation rates

Degradation rates calculated from monthly linear regression

- Power rating @ 1000 W/m^2, 20°C ambient, 1 m/s wind speed
- For Schott Solar, > four years of data implies -0.4%/yr
- Enables LCOE calculation

Field testing



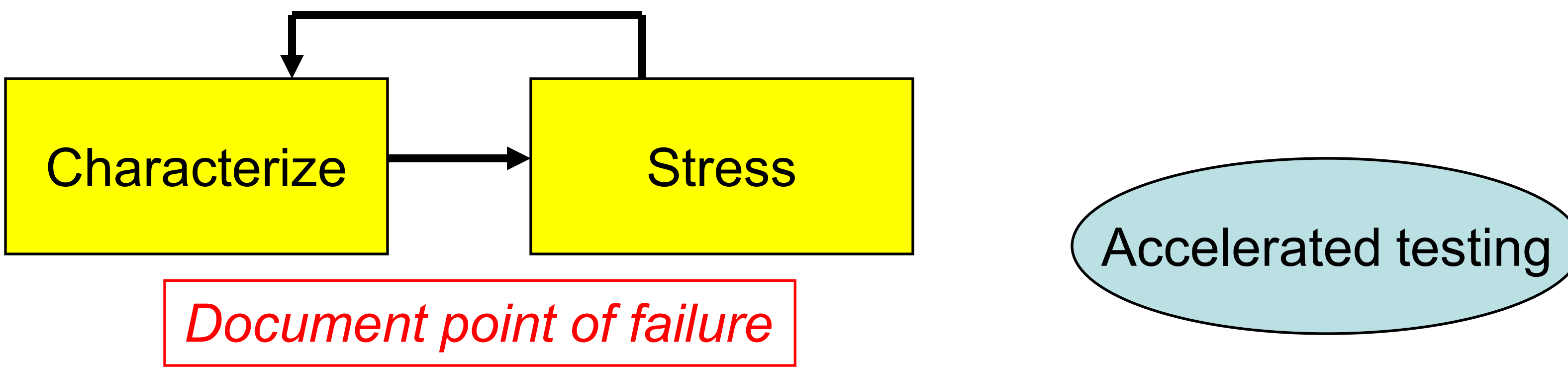
Test-to-failure protocol

Objective:

- Quantitative testing of failure rates

Approach:

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



Osterwald, http://www.nrel.gov/docs/fy08osti/42893.pdf

Two new environmental chambers

Will be able to handle up to 6' X 12' module

Osterwald, et al.

Accelerated testing

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.

Objectives:

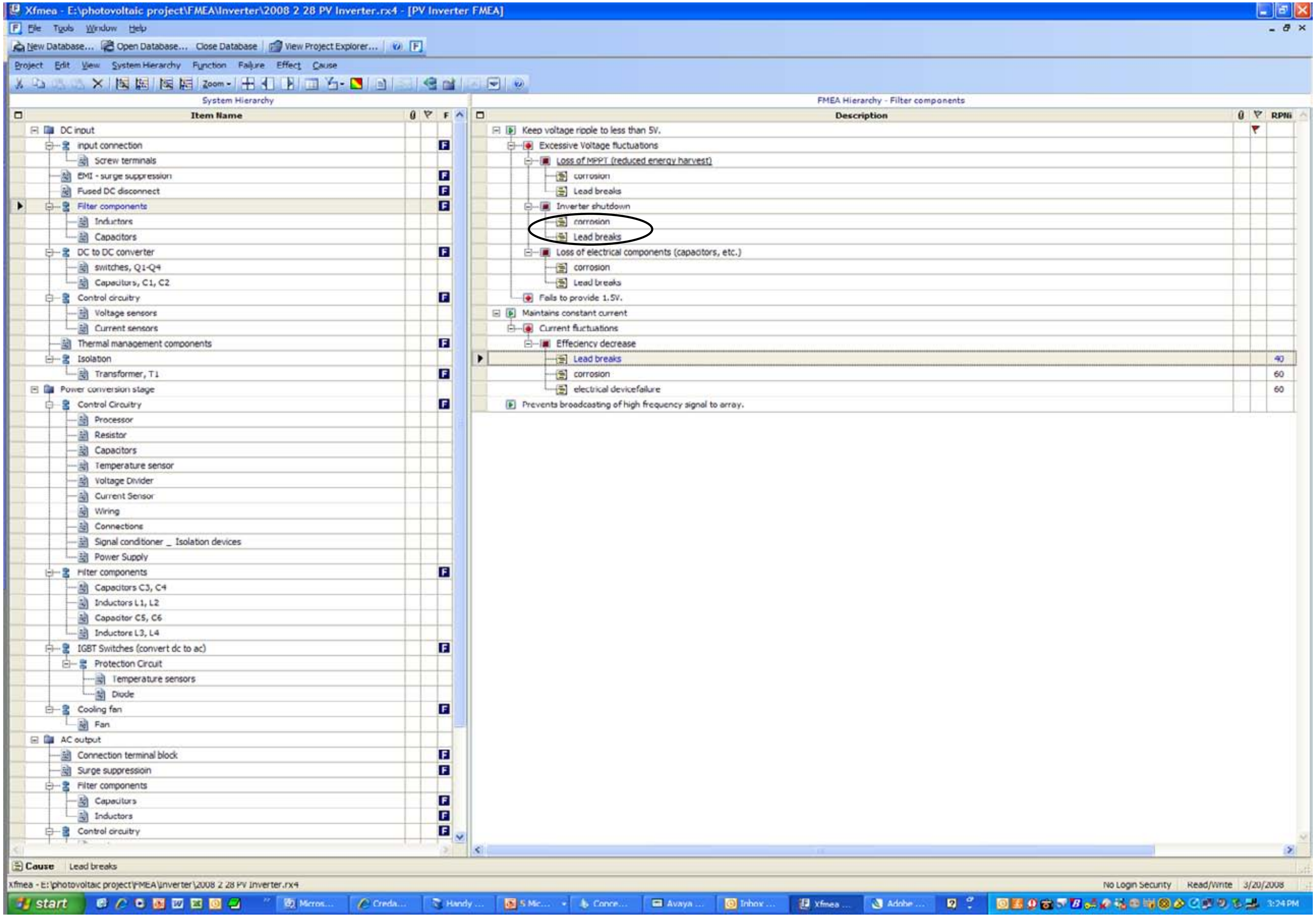
- Identify dominant failure mechanisms
- Develop theoretical models that predict failure
- Identify candidate items for accelerated life tests
- Identify "costs and actions"—operations/maintenance/replacements

Failure analysis modeling

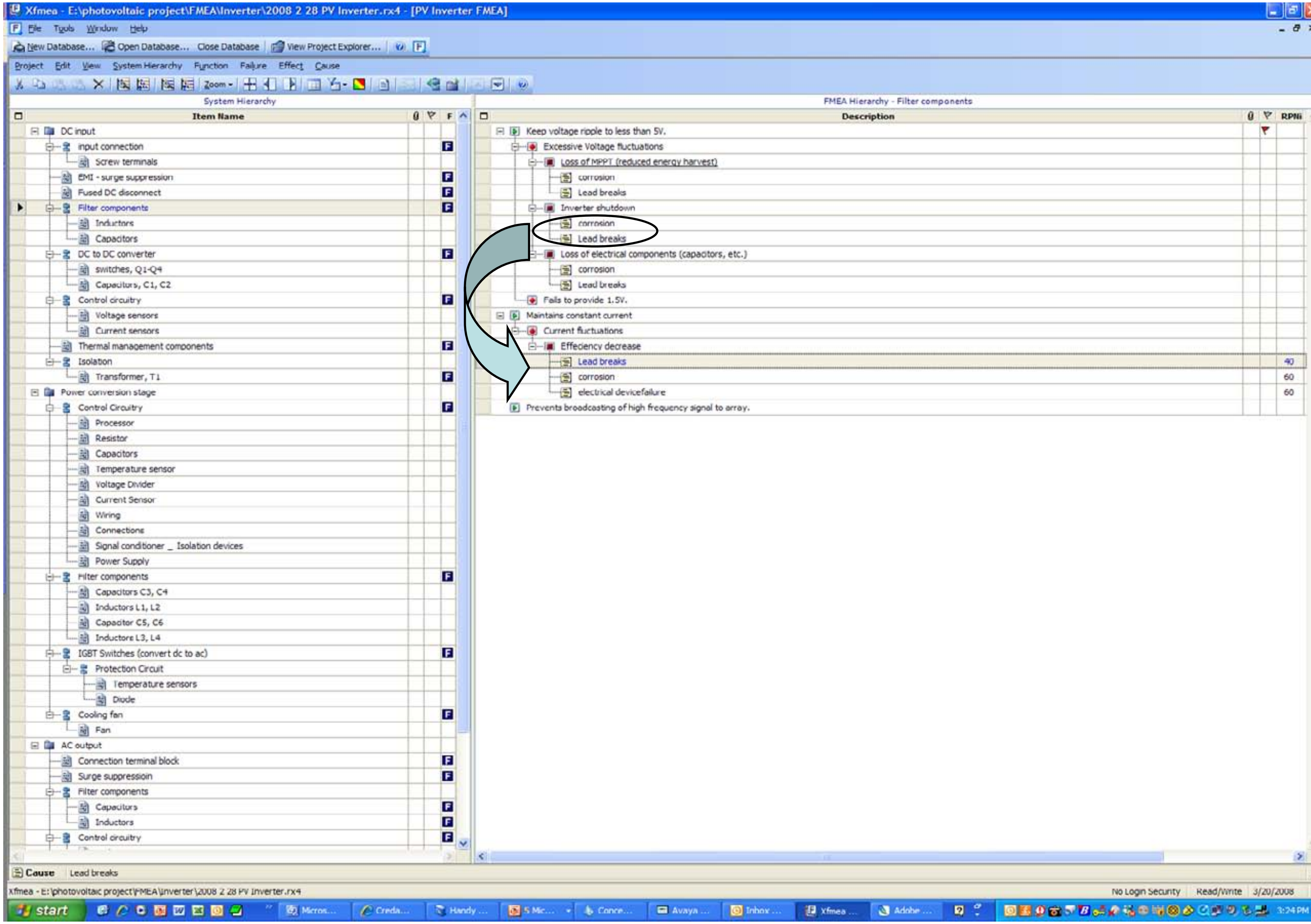
Approach:

- 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

Applying XFMEA and Lab Expertise



Applying XFMEA and Lab Expertise



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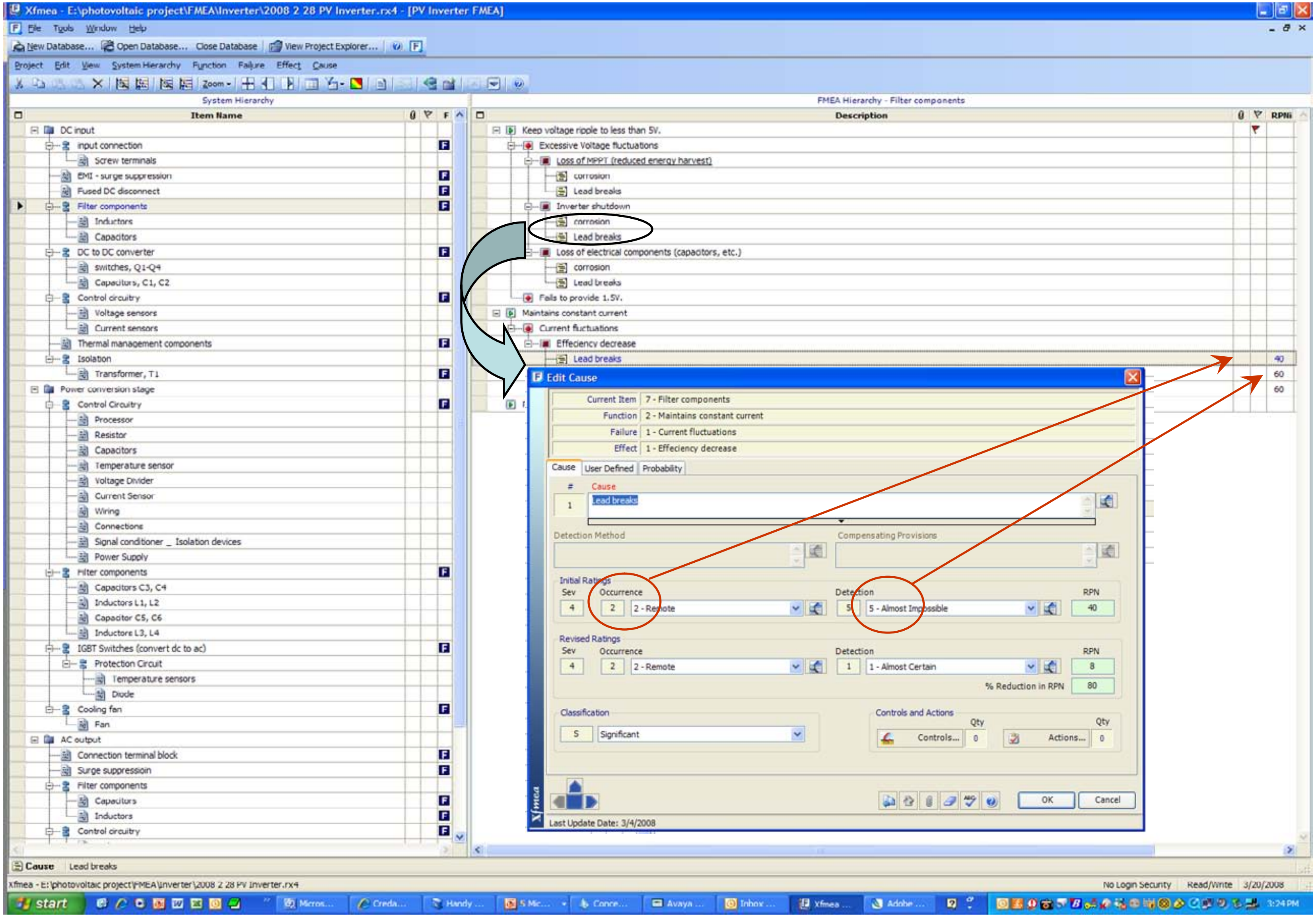
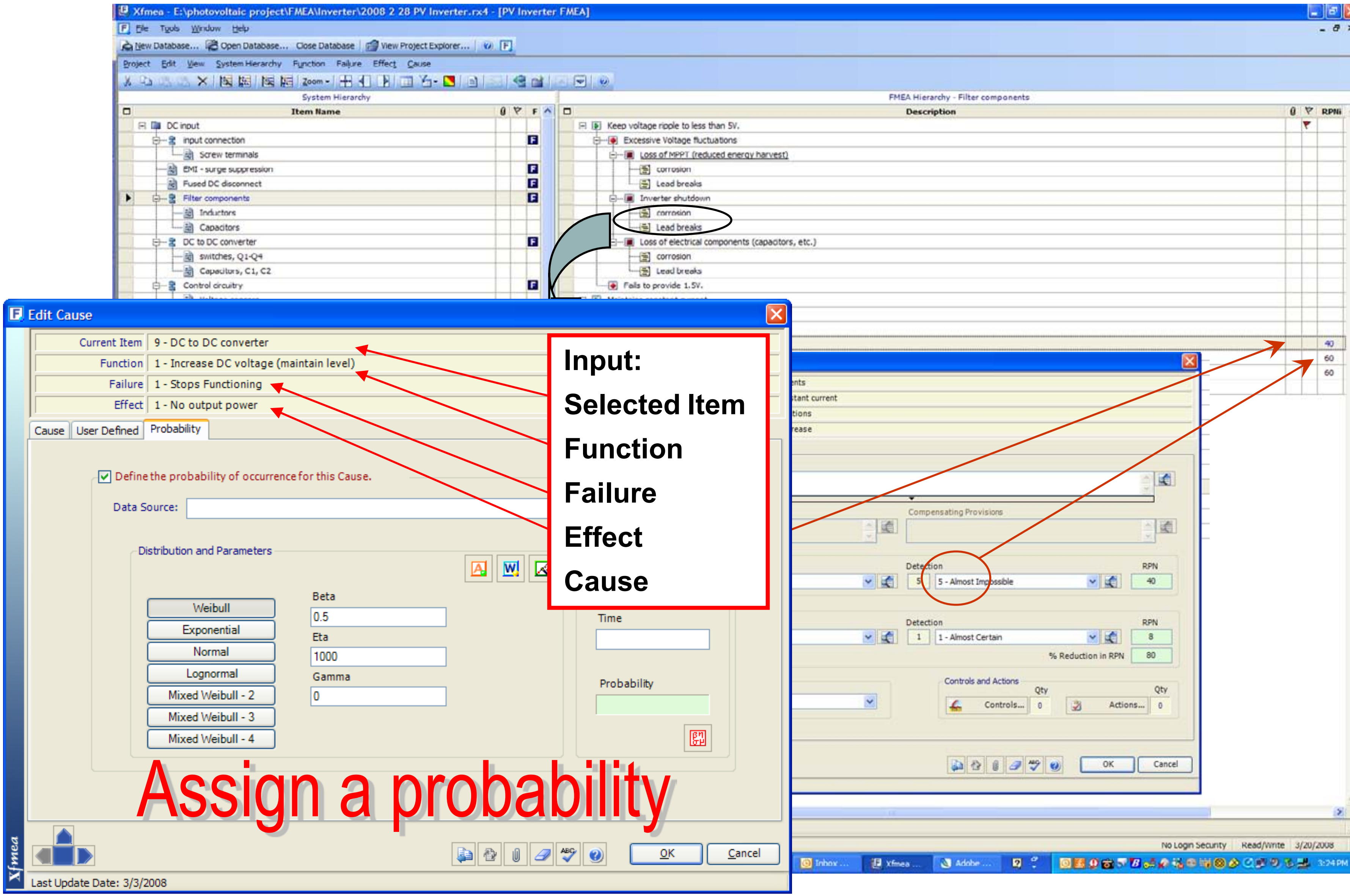
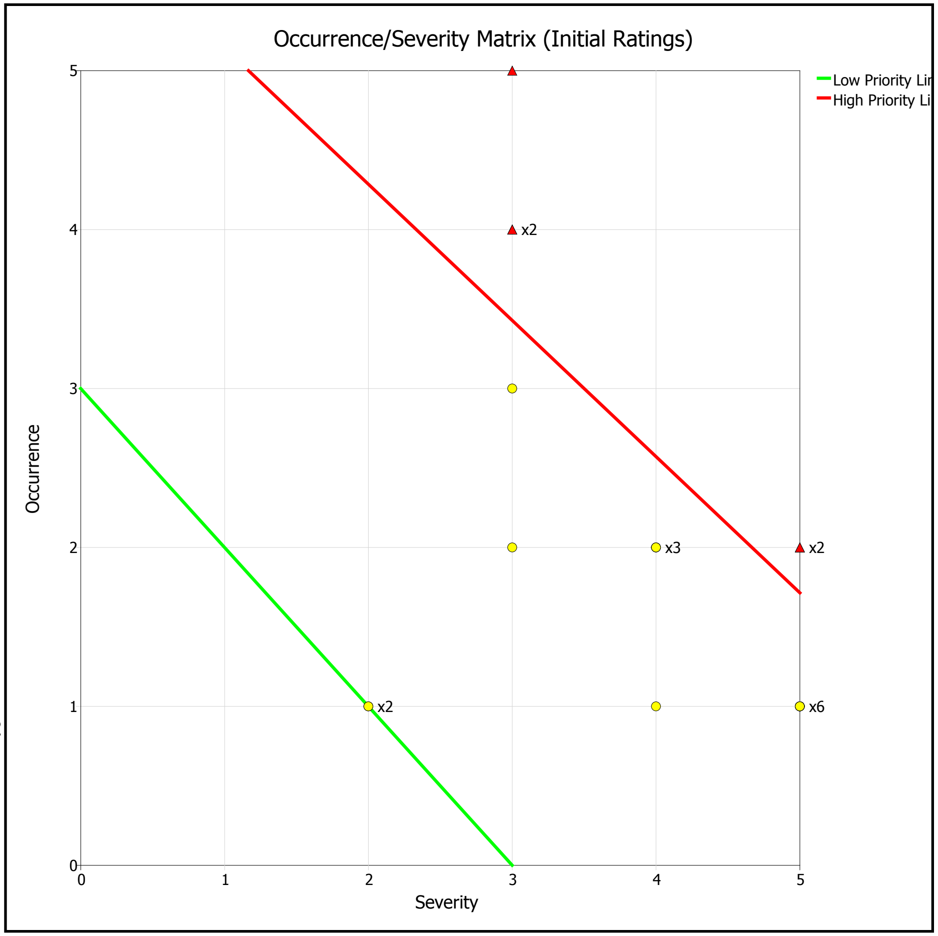


Applying XFMEA and Lab Expertise



Identifying High Risk Elements

Output allows prioritization of highest level risks based on occurrence and severity



c = 2

rface (Item: 3 - Cell Strings) Sev = 3, Occ = 4

Address highest priority issues!

= 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.

Objective:

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

Approach:

- Reliability Block Diagrams and
- Fault Tree Analysis

Tools:

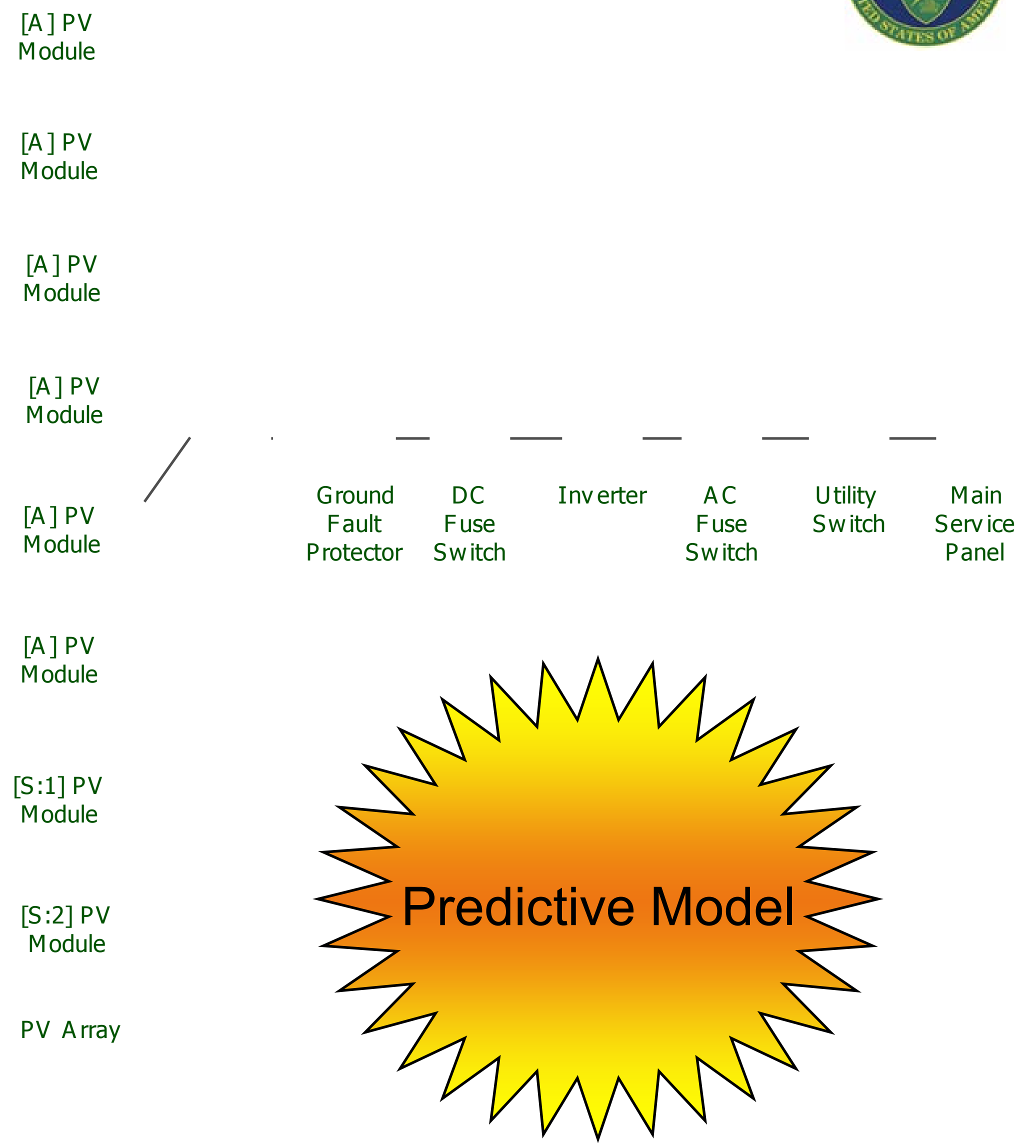
- Reliasoft Block Sim 7, Weibull++, and ALTA
- Computer-Aided Fault Tree Analysis (CAFTA)

Predictive Model

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**



Field-based Surveillance Studies

Field testing

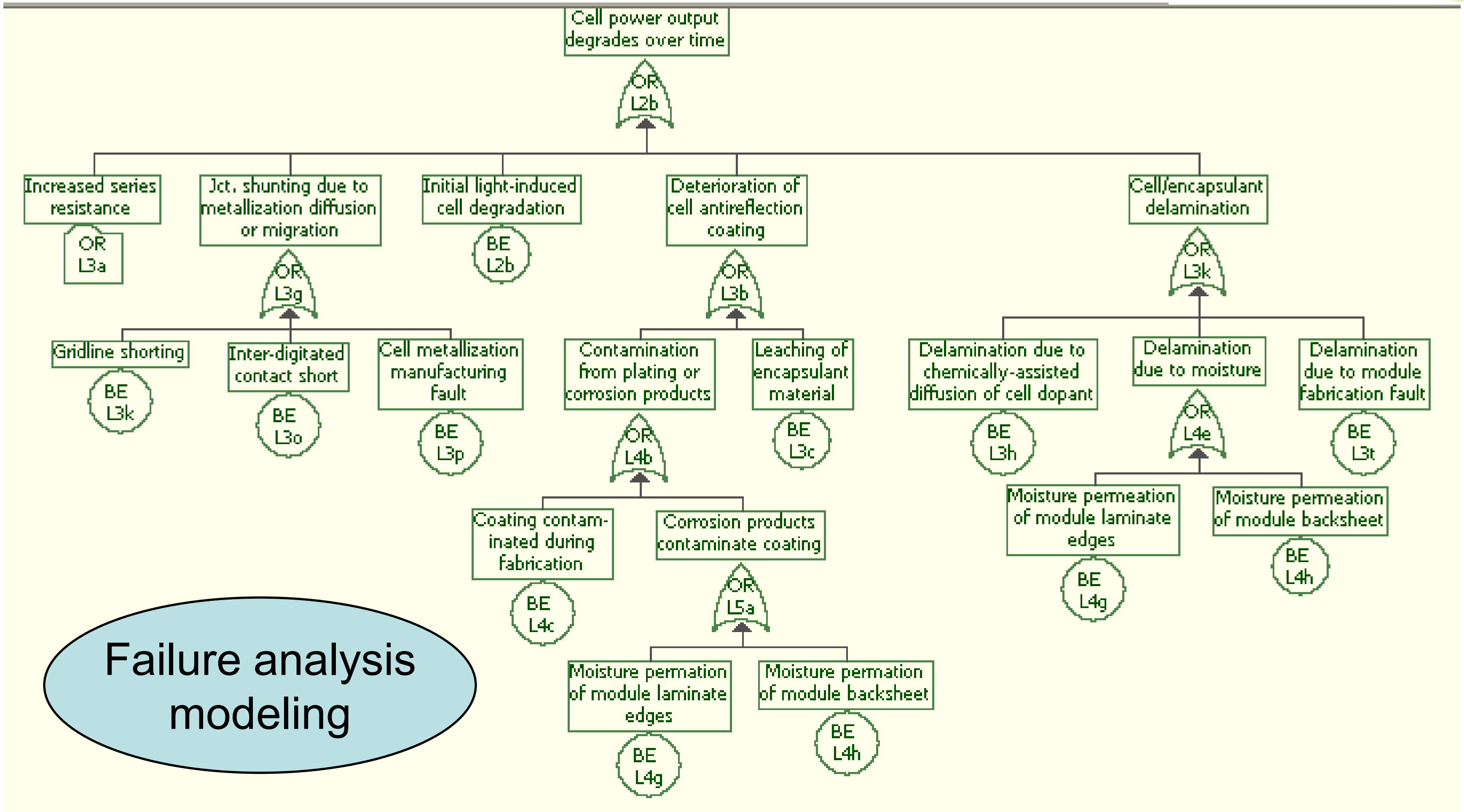
- Re-investment in long-term exposure in severe climates has begun; pursuit of degradation rates on newer technologies
  - FSEC outdoor exposure facility reconfigured
  - Continued long-term inverter testing
- Industry return data being pursued
- Continued short and intermediate outdoor exposure at labs

Fault Tree Analysis (FTA)

- FTA is a system-to-component top down analysis.
  - Undesired behavior/event at the system level is hypothesized
  - Events at subsequent lower levels are identified that can produce undesired behavior
- Blocks in the RBD that do not have enough data available for quantification will be analyzed with FTA.
  - 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.

Failure analysis modeling

Example of Early Fault Tree Analysis



FTA can be applied to the component or the system level

Looking Forward - multiyear milestones

2009	Document completed qualification testing scheduled for first-year stage-gates for the TPPs
2010	Achieve first validated module/system lifetime predictive model [f(t) in specified environment for applicable modes]
2012	Document service life prediction for the least LCOE system produced in TPP phase 1 activities
2012	Attain industry adoption of PV reliability methodology

Prioritize activities based on feedback from Workshop

SAI support - in FY08 and into FY09

Failure mechanism identification

Assessments planned in support of SAI:

1. AVA - (1-3 kW outdoor, damp heat, hi pot, IR camera)
2. DOW - (ALT, FMEA, baseline tests)
3. Soliant- reliability assessment
4. GreenRay- environmental tests
5. GE- Inverter tests
6. Enfocus - (outdoor, start August)
7. Global Solar - (~ 1 kW outdoor, start August)
8. Others…

Failure analysis modeling

Accelerated testing

Field testing

Looking Forward

SNL

1. Complete generic FMEA's for Inverters, c-Si, and CIGS and obtain industry input
2. Develop accelerated tests based on FMEA analyses
3. Continue to work with Tucson Electric on FTA for system model and pursue alternative partner(s) as appropriate
4. Continue development of predictive model architecture developing data needs (field/accelerated test data) and integrating needs into the rest of the reliability effort
5. Capture data/information that provides a better understanding of emerging systems reliability issues with proliferation of PPA business models
6. Increase fielded installation assessments to capture real-world system reliability experience/issues

Looking Forward

NREL

1. Identification and analysis of failure mechanisms in collaboration with industry
2. Accelerated testing to provide understanding of importance of stress factors
3. Accelerated testing to define time-to-failure
4. Field testing to define long-term degradation rates
5. Partnerships to help the community benefit from collective field data

Adjust project direction to reflect workshop input

- Adjust programmatic direction to address issues (leveraging investments when possible):
  - Partner with companies that have interest/information to provide early responses and long term solutions
  - Pursue needs that create market and/or technology growth
  - Facilitate solutions that the PV community is best suited to address
- Follow-on activities
  - Complete report on FY08's accelerated aging workshop
  - Develop smaller forum(s) to expand technology specific needs in FY09
  - Conduct short reliability seminars for Market Transformation, Systems Engineering, and Systems Modeling teams to create synergy, leverage investments, and eliminate any duplication of efforts

Sharing the wealth of information

Share reliability data to better understand long-term reliability

1. Define data to be collected
2. Define data collection method
3. Identify how to protect proprietary data
4. Implement plan

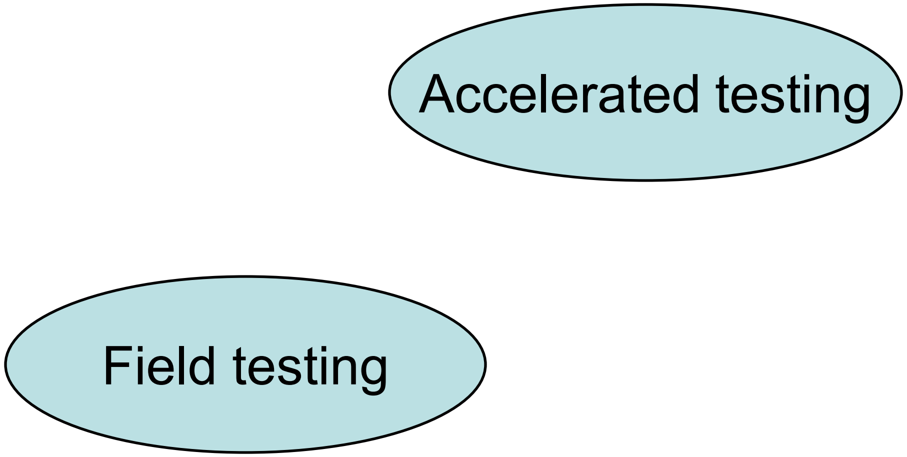
Field testing

Industry participation is vital!

Expand CPV testing

CPV participation at Accelerated Aging Workshop was new this year and enthusiastic - National Labs will respond to this

1. Cell testing
2. Accelerated testing
3. Outdoor testing



Summary

- Reliability needs span the entire breadth of the supply-chain
  - Materials➔Components ➔Systems ➔Users/Owners/Purchasers
- Needs are not uniform across technologies or applications
- Finite funding will require prioritization
- SAI needs are increasing demands on the reliability project
- Accelerated Aging Workshop has provided a wealth of input as well as opportunities