PV Reliability Development Lessons from JPL's Flat Plate Solar Array Project

Dr. R.G. Ross, Jr.

FSA Engineering and Reliability Mngr, 1975-1990

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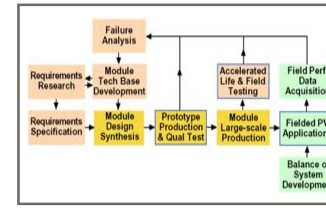
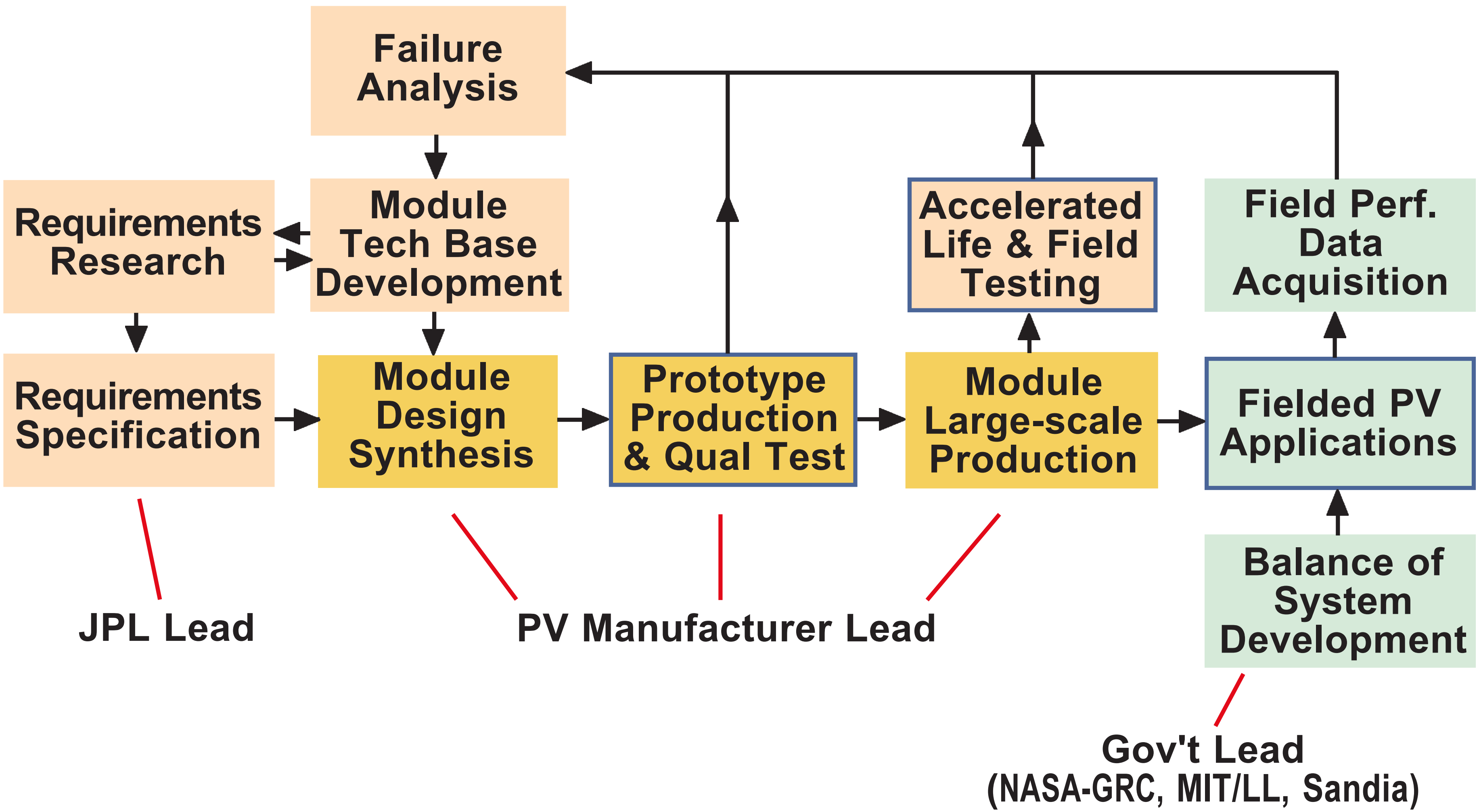
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Topics

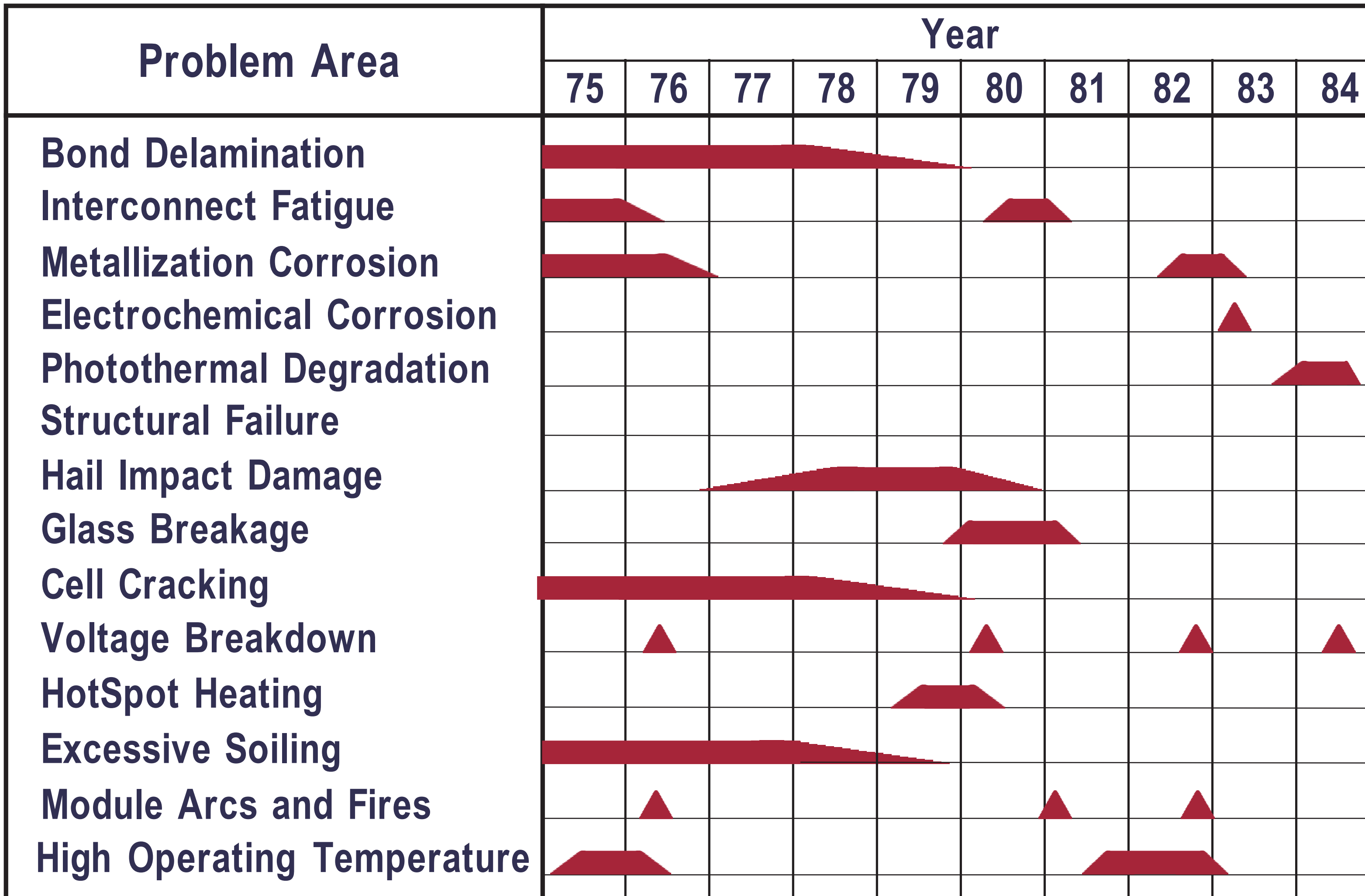
- **Overview of the FSA Program Approach**
  - Closed-loop module development process
  - Program players and roles
- **Reliability Management Lessons**
  - Closed-loop process
  - Defining reliability requirements
  - Measuring reliability against requirements
- **Reliability Development Lessons**
  - Large applications for problem identification
  - Computer simulations for life prediction
  - Failure analysis and reliability physics research
  - Qual tests for rapid product assessment
- **Summary Observations**



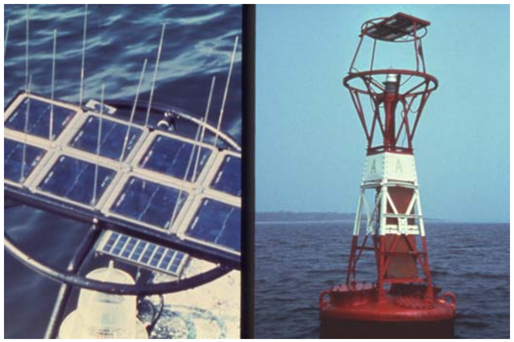
DoE / FSA Program Approach to PV Module Development



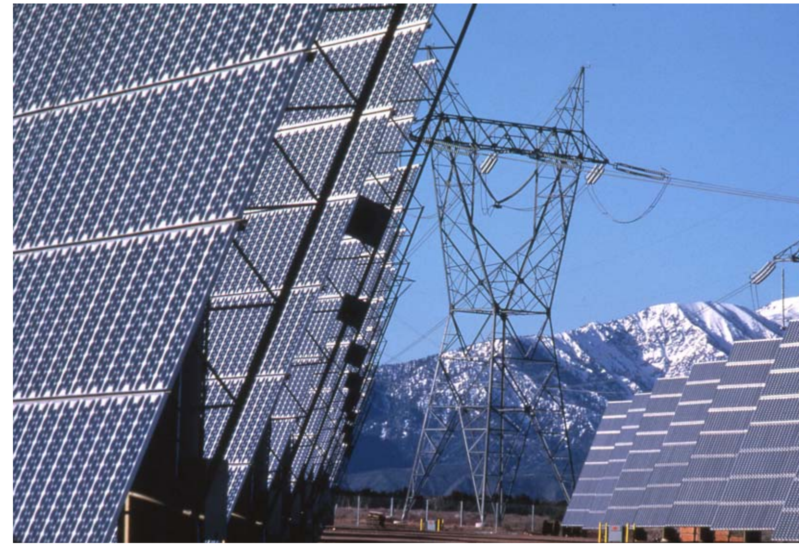
Evolution of Reliability Issues during FSA Project (1975-1985)



By the mid 1980s we'd Completed Some Big Full-Scale Systems

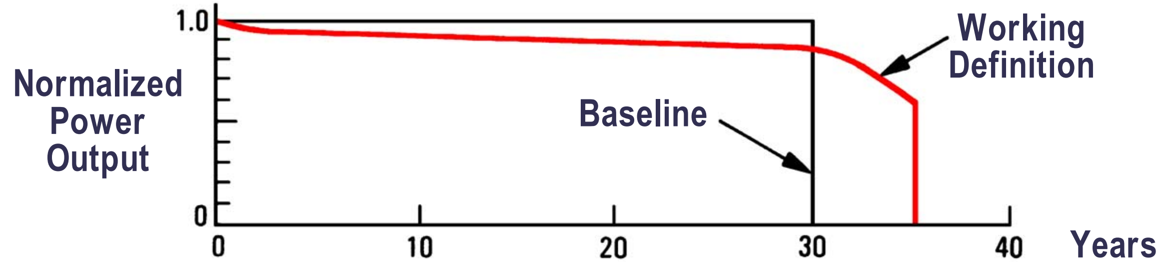


1975



1985

Example Reliability Requirements at System & Components Level



Type of Degradation	Failure Mechanism	Units of Degradation	Level for 10% Energy Cost Increase*		Allocation for 30-year Life Module†	Economic Penalty
			k=0	k=10		
Component failures	Open-circuit cracked cells	%/yr	0.08	0.13	0.005	Energy
	Short circuit cells	%/yr	0.24	0.40	0.050	Energy
	Interconnect open circuits	$\%/yr^2$	0.05	0.25	0.001	Energy
Power Degradation	Cell gradual power loss	%/yr	0.67	1.15	0.20	Energy
	Module optical degradation	%/yr	0.67	1.15	0.20	Energy
	Front surface soiling	%	10	10	3	Energy
Module failures	Module glass breakage	%/yr	0.33	1.18	0.1	O&M
	Module open circuits	%/yr	0.33	1.18	0.1	O&M
	Module hot-spot failures	%/yr	0.33	1.18	0.1	O&M
	Bypass diode failures	%/yr	0.70	2.40	0.05	O&M
	Module shorts to ground	$\%/yr^2$	0.022	0.122	0.01	O&M
	Module delamination	$\%/yr^2$	0.022	0.122	0.01	O&M
Life-limiting wearout	Encapsulant failure due to loss of stabilizers	years of life	27	20	35	End of life

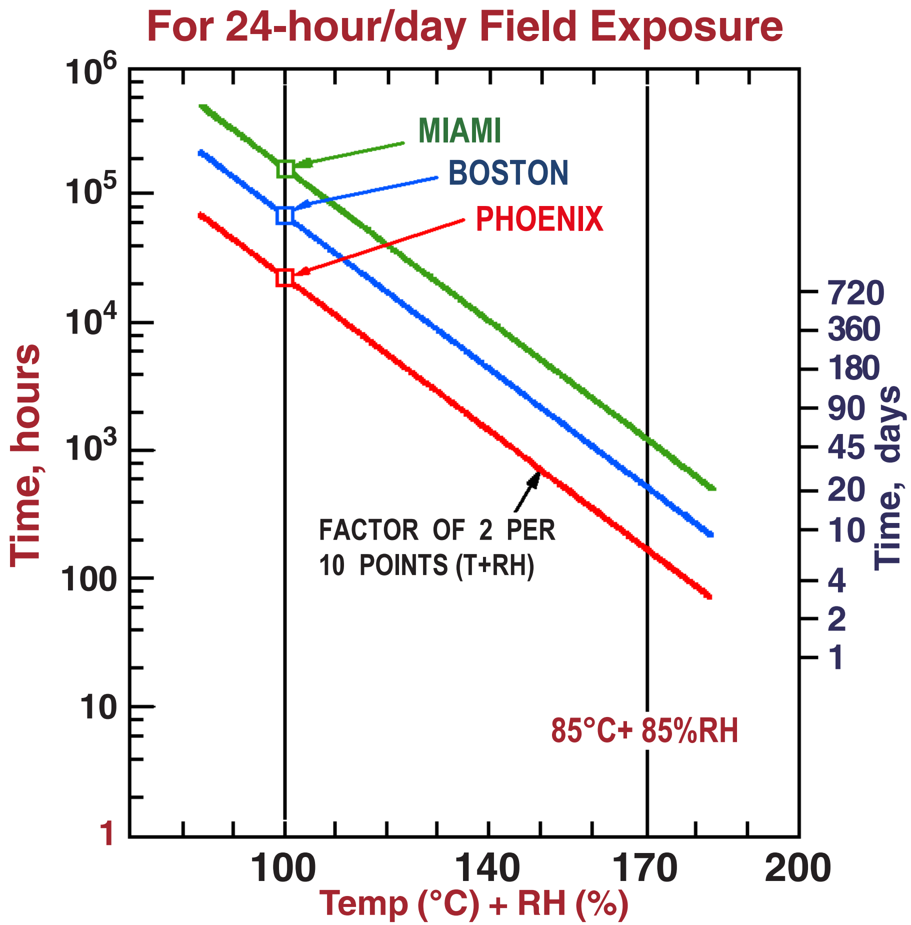
* k=discount rate, †Very difficult to measure in module level testing

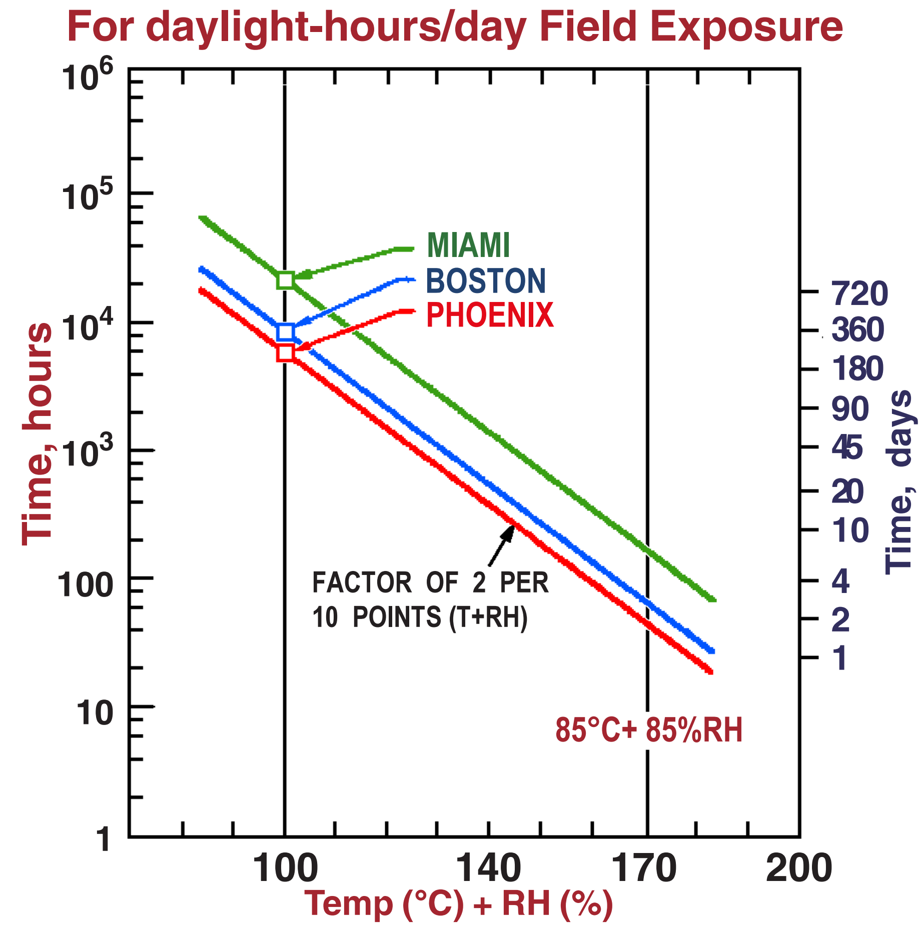
Reliability Requirements Ranked by Difficulty

- System Operating Voltage
  - Large number of series cells magnifies component failure effects
  - High voltage exacerbates corrosion and safety issues
- Operating Temperature and Temperature Cycles
  - Accelerates nearly all failure mechanisms
  - x2 life reduction for each 10°C increase in Temperature
- Ambient Humidity Level
  - x2 life reduction for each 10% increase in Relative Humidity
- Ultraviolet Exposure Level
  - Encapsulant degradation (highly nonlinear with UV level)
- Ambient Soiling Level
  - Much worse in urban environments
- Maximum Hail Size
  - Site specific, a problem with early applications in central US
- Presence of Salt Fog
  - Very specific to marine locations
- Maximum Wind & Snow Loads
  - Site specific, generally not a significant issue

Site Specific Effects of Temperature, Humidity and Voltage

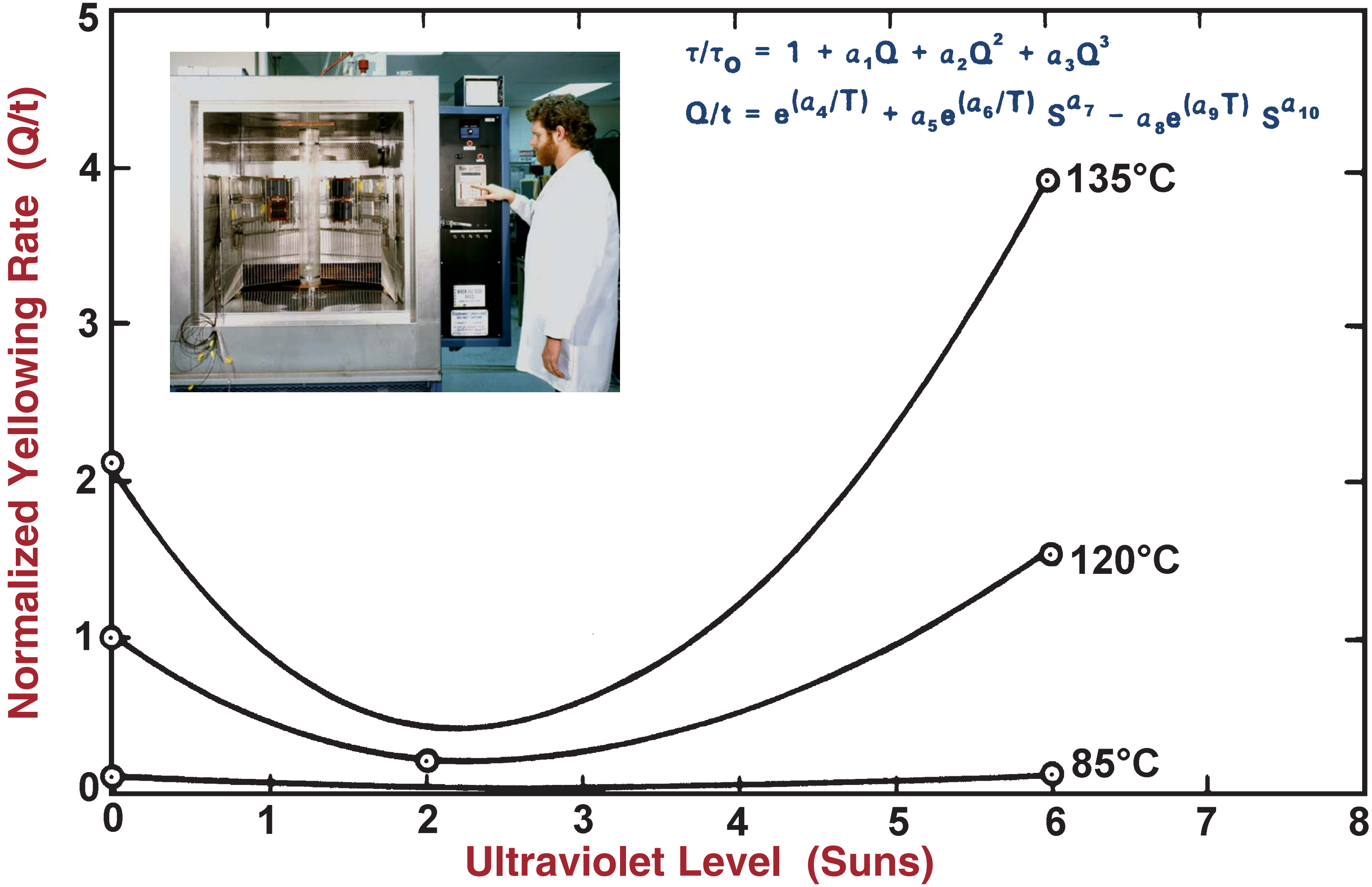
Plots of Temp/Humidity chamber exposure equivalent to 20-year field exposure at indicated sites based on integrating SOLMET hourly weather data





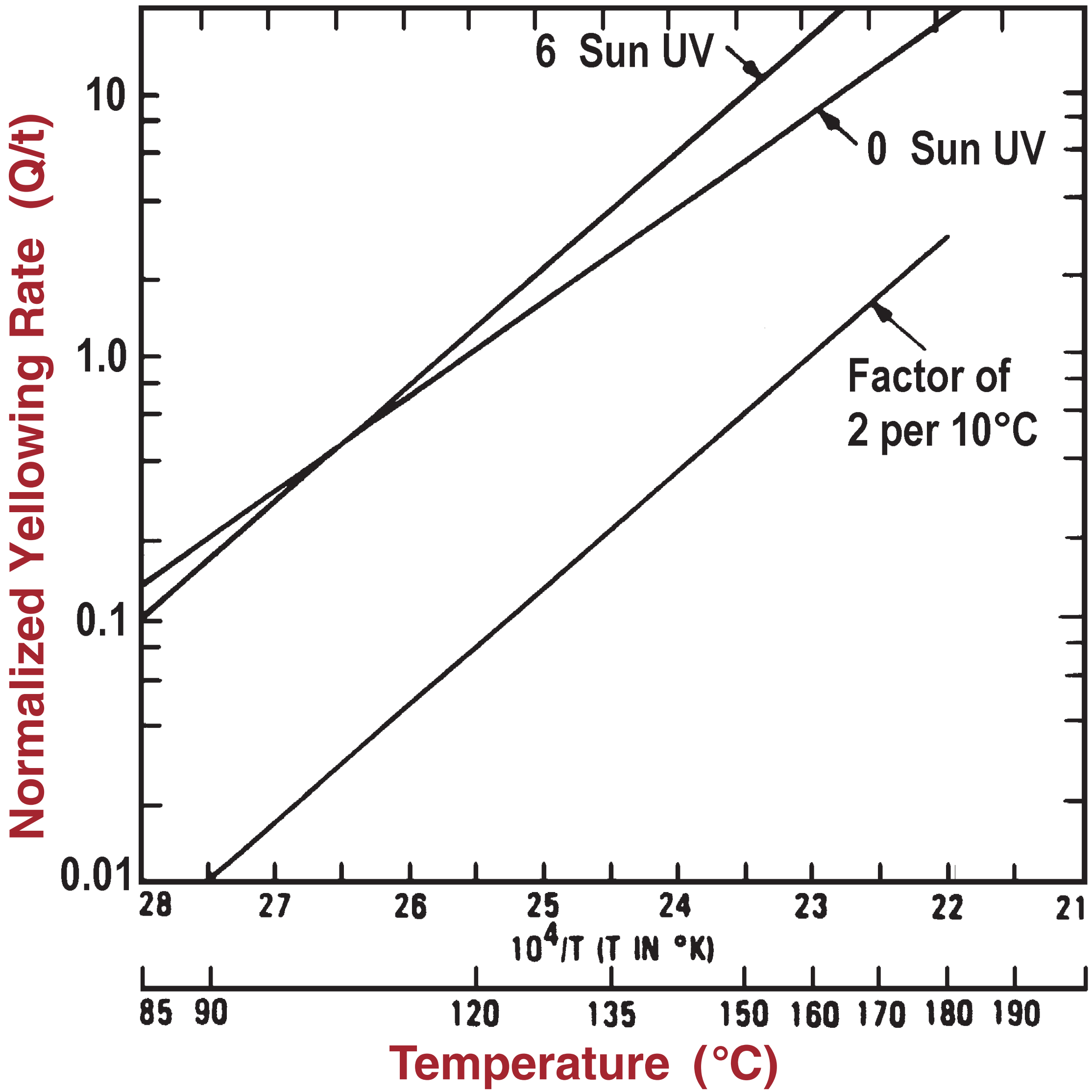
Bottom Line: 10°C increase in Temp or 10% increase in RH drops life by factor of 2

Transmission Loss through EVA vs Temperature and UV Level



UV response is very nonlinear and difficult to accelerate

Transmission Loss through EVA Increases Arrheniusly with Temp



- Thermal response is relatively predictable (typically Arrhenius with approx. rate doubling each 10°C)
- Accurate regulation of temperature is critical to successful UV testing

Hourly Calculation of EVA Yellowing Rate in Phoenix

From curve-fit of parametric UV-Temp Yellowing data for EVA

Cell temperature, °C	Yellowing Rate at each Temperature-UV Level: UV level in suns											
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15
75	65	61	58	55	52	49	46	44	41	39	37	35
65	33	31	29	28	26	25	24	23	21	20	19	18
55	16	15	14	13	13	12	12	11	11	10	10	9
45	7	7	7	6	6	6	6	5	5	5	5	4
35	3	3	3	3	3	3	2	2	2	2	2	2
25	1	1	1	1	1	1	1	1	1	0.9	0.9	0.9
15	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1

From SOLMET hourly weather records for Phoenix

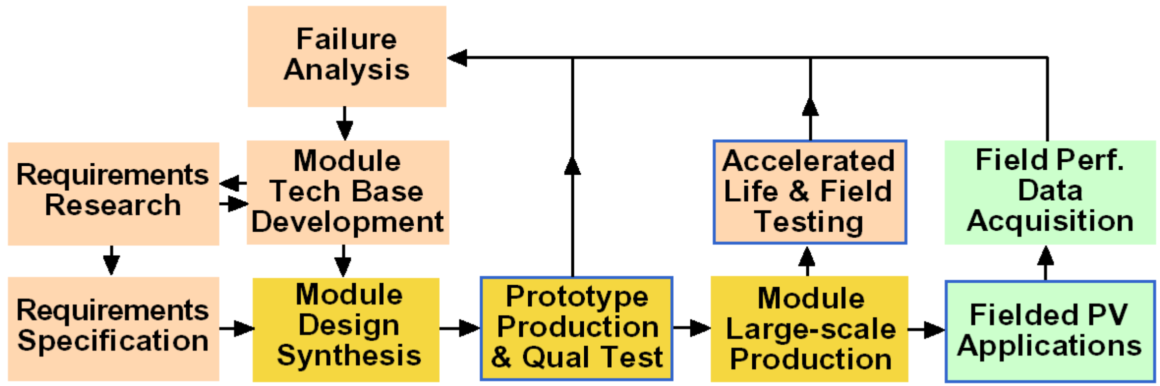
Cell temperature, °C	Annual Hours at each Temperature-UV Level: UV level in suns											
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15
75	0	0	0	0	0	0	0	0	0	11	4	0
65	0	0	0	0	0	1	17	24	107	294	167	6
55	0	0	0	32	18	56	130	81	201	142	177	17
45	22	74	32	110	62	84	144	73	172	154	55	1
35	134	131	63	124	97	93	113	49	53	17	0	0
25	190	129	92	86	53	21	22	0	0	0	0	0
15	129	94	36	35	8	0	0	0	0	0	0	0
5	55	20	3	0	0	0	0	0	0	0	0	0

Predicted power loss after 30-years in Phoenix:

- **Ground-mounted array = 3.5%**
- **Roof-mounted array = 7.9%***

* Because roof array operates at higher temperature

FSA Project Relied on a Variety of Test methods



- **Large Application Experiments** that include all system-level interfaces
  - Extremely valuable for quantifying reliability of mature designs and identifying failures driven by complex interfaces
  - Outdoor Test Racks of minimal value: unaccelerated and lack key system voltage-current interface conditions
- **Laboratory Research and Life Tests**
  - High value for quantifying reliability physics parameter dependencies and resolving reliability problems
- **Qualification (or screening) Tests**
  - High value for screening new designs for known failures

Full-Up System-Level Testing Objectives and Attributes

OBJECTIVE

- To accurately assess hardware functionality and reliability in big systems with emphasis on system synergisms, interactions, and interfaces

ADVANTAGES

- Complete system interfaces and operating conditions provides reliable assessment of subsystem compatibility issues and degradation mechanisms associated with large numbers of modules with real system interactions and operational stresses
- Inclusion of balance-of-system (BOS) hardware provides data and confidence in complete functional system

LIMITATIONS

- Requires complete system with all important balance-of-system components and interfaces
- Occurs very late in the design cycle; problems at this point are highly visible and expensive
- Added complexity in constructing and testing complete system

Characterization and Accelerated Life Testing Objectives and Attributes

OBJECTIVE

- To understand and quantify the fundamental interdependencies between performance (failure level), environmental and operational stress level, hardware materials and construction features, and time

UV-Temp-Humidity Exposure Chamber

ADVANTAGES

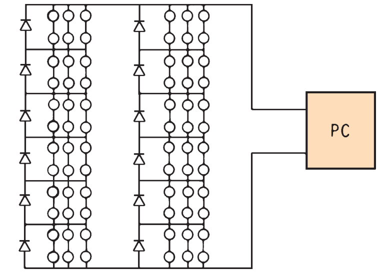
- Mechanism-level understanding achieved by selecting specialized tests and facilities targeted at specific degradation stress environments and construction material parameters
- Carefully controlled parameters (generally at parametric levels) with acceleration consistent with accurate extrapolation to use conditions

LIMITATIONS

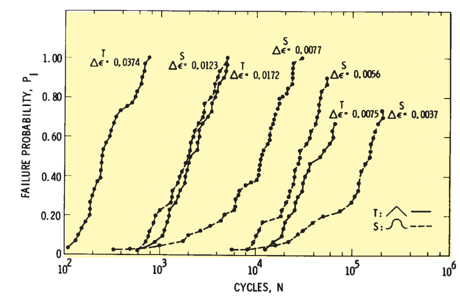
- Expensive and time consuming — requires specialized testing equipment and modestly long test durations (2 weeks to 5 years)
- Requires multiple tests to address the total spectrum of degradation mechanisms and levels
- Number of specimens insufficient to quantify random failures

Key Output of Reliab. Physics Testing was TechBase for Module Design

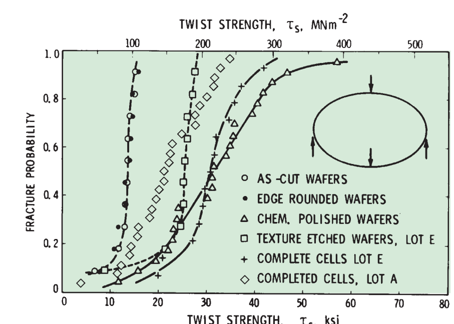
- **New lamination adhesives**, primers, and stabilizers (PVB, EVA, EMA) for lower cost and improved weathering
- **Circuit redundancy configurations** for controlling cell cracking and broken interconnects
- **Interconnect design and test methods**
- **Cell attachment techniques** to minimize losses due to cell cracking
- **Glass strength** calculation methods
- **Bypass diode design** and hotspot test methods
- **Hail resistance data** and test methods
- **Cell fracture strength** and test methods
- **Voltage breakdown data** and test methods
- **Electrochem corrosion** Data and test methods
- **UV-thermal durability data** and test methods



Circuit designs



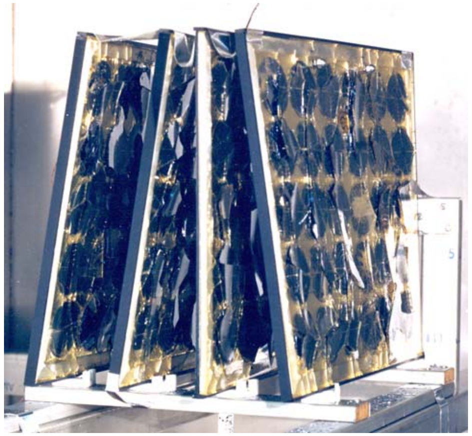
Fatigue strength



Cell strength

Qualification Testing Objectives and Attributes

OBJECTIVE



- To rapidly and economically screen module designs for prominent failure mechanisms
- To rapidly assess the relative durability of alternative designs

ADVANTAGES

- Quick turnaround — relatively inexpensive
- Relatively standard procedures allows inter-comparison with historical data
- Separate tests for important environmental and operational stresses aids identification of high-risk mechanisms

LIMITATIONS

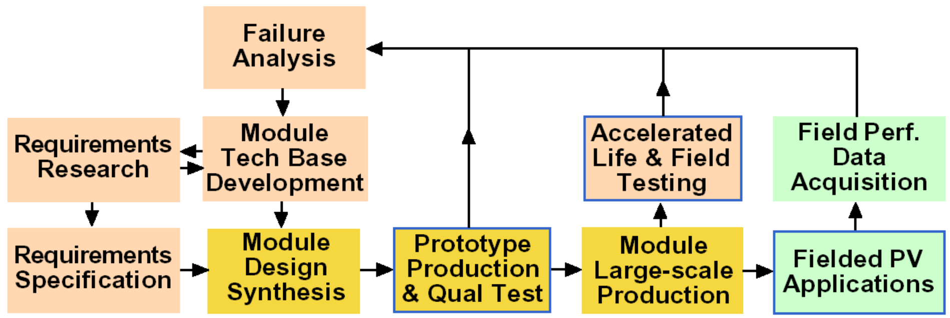
- Minimal life-prediction capability (a relative measure of robustness, generally does not quantify life attributes)
- Requires multiple tests and specialized facilities to address the total spectrum of stressing environments
- Number of specimens insufficient to quantify random failures

Evolution of Qualification Tests during FSA Project (1975-1985)

QUAL TEST	I	II	III	IV	V	NOTES
THERMAL CYCLING						
Range (°C)	-40 to +90	-40 to +90	→	→	→	
Number cycles	100	50	→	→	200	
HUMIDITY CYCLING						
Relative Humidity	90	→	→	→	85	
Temp. Range (°C)	+70*	-23 to +40	→	→	-40 to +85	*No cycling, 70°C Constant for 168 h
Number cycles	-	5	→	→	10	
MECHANICAL CYCLING*						*Excluding shingle modules
Pressure (kPa)	-	±2.4	→	→	→	
Number Cycles	-	100	→	10,000	→	
WIND RESISTANCE (kPa)	-	-	-	1.7*	→	*Shingles only
TWISTED MOUNT (mm/m)	-	20	→	→	→	
HAIL IMPACT						
Diameter (mm)	-	-	-	20	25.4	
Terminal Velocity (m/s)	-	-	-	20.1	23.2	
Num. Impacts	-	-	-	9	10	
HOT-SPOT HEATING (h)	-	-	-	-	100	
ELECTRICAL ISOLATION (volts)	-	1500	→	2000*	3000*	*1500 for resid. modules

JPL's Role in National PV Program Sunsetted in the Early 1990's

Summary Lessons from 20 years developing PV



- **Overall closed-loop performance measurement process is critical to reliability identification & quantification**
  - Full-up systems providing definitive operational feedback
  - Mechanism-level & life testing for root-cause identification
  - Qual tests for quick production screening
- **Module Technology Devel. is critical to reliability growth**
  - Encapsulation systems development (EVA, Tedlar, primers, etc)
  - Requirements Refinement (natural environments, UL 1703, NEC 690)
  - Engineering Tech Base Development (fatigue, corrosion, glass strength, hail resistance, hot-spot heating, voltage breakdown, electrochemical corrosion, UV-thermal degradation, etc)
  - Improved failure analysis and measurement techniques

Summary Lessons (Con't)

- Rapid open communication between all stakeholders is critical to rapid reliability improvement
  - Rapid Problem Identification and communication
  - Resolution Teamwork across many organizations

    (JPL FSA project had 131 organizations under contract; Engineering (ES&R, Module Proc, & Encapsulation) had a total of 37 organizations under contract)

- In total, over 380 of the key reports resulting from the Engineering and Reliability activities of the FSA Project are cataloged on the JPL web site:

  http://www2.jpl.nasa.gov/adv_tech/photovol/PV_pubs.htm