DuraMAT
Durable Module Materials Consortium

Discover, Develop, and De-Risk module materials, architectures, accelerated testing protocols,data analytics, and financial models to reduce the LCOE of solar energy

Combined-Accelerated Stress Testing for Advanced Reliability Assessment of Photovoltaic Modules

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DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. **Module Testing: Module Prototyping and Combined-Accelerated Stress Testing (C-AST)**
5. Field Deployment
6. Techno-Economic Analysis

Capability Goals

Combining the stress factors of the natural environment, with fewer modules and with fewer parallel tests, it will be possible to discover potential weaknesses that are not known a-priori in new module designs, reduce residual risk, accelerate time to market and bankability, reduce costly overdesign, and apply known degradation rate equations to estimate service life for the degradation mechanisms observed in C-AST.

Milestones

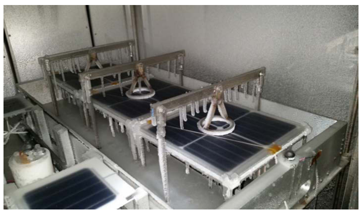
- C-AST tool brought to operational status
  - humidity, light, temperature, voltage & mechanical stress
  - automated, programmed stress cycle control, with database
- Build modules for C-AST backsheet experiment
- Indentation hardness testers differentiate backsheets
- Develop C-AST testing protocol
- Develop In-situ EL and IV capability

Outcomes and Impact

- Evaluation of backsheets as the vehicle for demonstration
- Show interactions between BOM and environmental stress
- Observation of failure mechanisms not seen in single factor tests, reducing risk.
  - exchange of samples with capability 3 and 5 for forensics and fielding

Capabilities and Test Protocol

- New and previously undiscovered degradation mechanisms continue to be identified after field exposure in new photovoltaic module designs or materials
- Oftentimes results in significant losses in investment
- This is despite passing certification tests. Testing is insufficient largely due to their single- or double-stress nature.
- A Combined-Accelerated Stress Test (C-AST) has recently been developed
- The test combines multiple stress factors of the natural environment to better replicate conditions experienced by modules in the field and detect mechanisms not *a-priori* known in new materials and designs



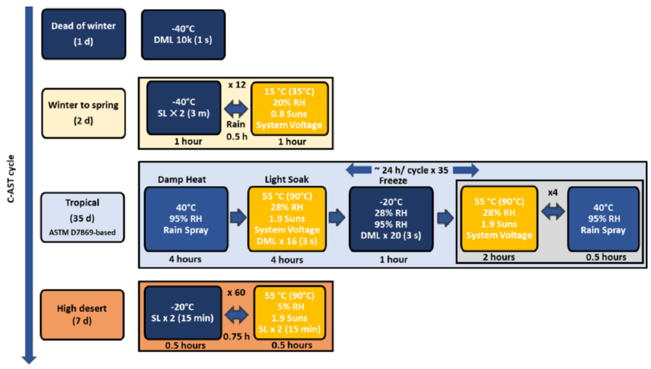
Inside the chamber during wet freeze stage

Modified Atlas XR-260 :

- -40°C to 90°C temperature control
- 5% to >95% relative humidity
- 2-sun Xe light exposure (4 lamps)
- Water spray (front and back)
- Mechanical loading
- System voltage (±1200 V)
- Reverse Bias*
- Variable load resistors
- Reflective troughs
- Keithley 2651a for EL/IV

*planned

- Module temperature monitored via T-type thermocouples on rear surface
- 6x LI-COR LI-61713 pyranometers positioned next to each sample
- LI-CORs monitored using National Instruments 9205 digital-to-analogue card with sampling rate of 2kHz



Multiple environment combined-accelerated stress testing (C-AST) cycle. Module temperature, when different from chamber air temperature, is shown in parenthesis. Ramp times are not necessarily included and shown time is sometimes rounded to the next higher integer unit.

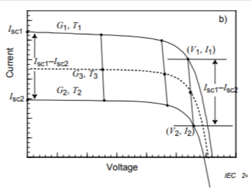
In-situ IV Curve

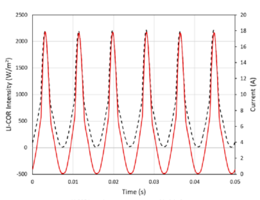
- Xe light source driven by AC supply means light fluctuates at ~100Hz
- Solution:
- Pulse voltage and take multiple current measurements (100kHz)
- Filter for highest current value where highest irradiance is known

Difficult to set lights such that peak irradiance = 1000W

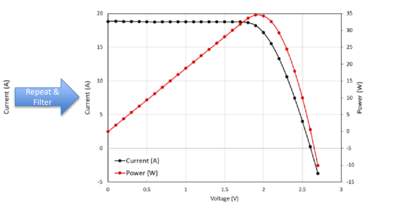
Tow curves measured at different irradiance

Curves at Standard Test Conditions can be interpolated/extrapolated from two IV curves using protocols outlined in IEC 60891





Current measurements for a 0.05s 0.1V pulse



Light-IV curve constructed from multiple pulses in 0.1V increments

$$V_3 = V_1 + a(V_2 - V_1)$$
$$I_3 = I_1 + a(I_2 - I_1)$$

$$a = \frac{G_3 - G_1}{G_2 - G_1}$$

I_1, V_1 = I-V points for G1
I_2, V_2 = I-V points for G2
I_3, V_3 = Corrected points for G3
G_1, G_2 = Irradiances for curves 1 and 2
G_3 = Target/corrected irradiance
a = interpolation constant

Acceleration Factor Modeling

Failure of AAA in 3000 hours C-AST testing

Example field-aged AAA

$$t_1 = t_2\left(\frac{L_2 I_2^x (b + mTOW_1)\left(T_f^{\left(\frac{T_2 - T_1}{10}\right)}\right)}{L_1 I_1^x (b + mTOW_2)}\right)$$

t_1 = time in test 1 (outdoors)
t_2 = time in test 2 (accelerated)
I_1 = actual irradiance in test 1
I_2 = actual irradiance in test 2
L_1 = light on fraction in test 1
L_2 = ligt on fraction in test 2
T_1 = specimen temperature in test 1
T_2 = specimen temperature in test 2
T_f = thermal acceleration per 10°C
TOW_1 = time of wetness for test 1
TOW_2 = time of wetness for test 2
X, b, m, T_f – extracted constants

R. M. Fischer and W. D. Ketola, "*Error Analyses and Associated Risk for Accelerated Weathering Results*," in 3rd International Service Life Symposium, 2004, no. February

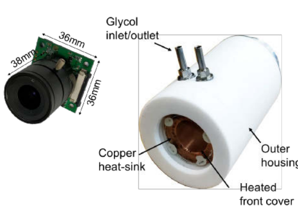
Location	Time in outdoors		Acceleration
	Hours	Years	Factor
Miami, Florida	36110	4.12	12.04
Phoenix, Arizona	36968	4.22	12.32
St. Paul, Minnesota	92438	10.55	30.8

3000 hours in C-AST tropical sequence represents ~4 years in worst-case locations for AAA

Lines up with reports of field failure of AAA within 4-5 years exposure

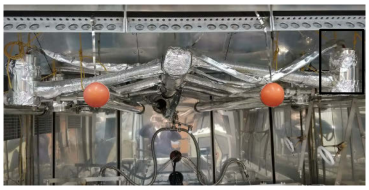
Calculated time-to-failure using Fischer equation based on time-to-failure in C-AST and field data from 3 locations. Calculated values based on mean extracted constants

In-Situ Electroluminescence Imaging



- Sony IMX219PQ 8.08Mpixel camera with an Arducam LS-61018CS lens is used for imaging
- Camera has small form factor (36mm x 36mm x 38mm) and is very low-cost
- Camera position is limited to 0.59m above the sample plane, so a wide-angle lens (70°) is used which introduces some lens distortion
- A custom-designed camera housing has been developed to protect camera from the harsh conditions of the chamber
  - PTFE outer housing
  - Copper heat-sink inner housing with ethylene glycol feed through for liquid cooling
  - Heated front cover for defogging

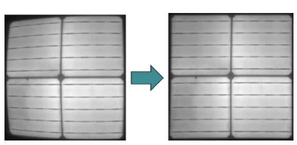
Image of cameras installed in all six locations in chamber



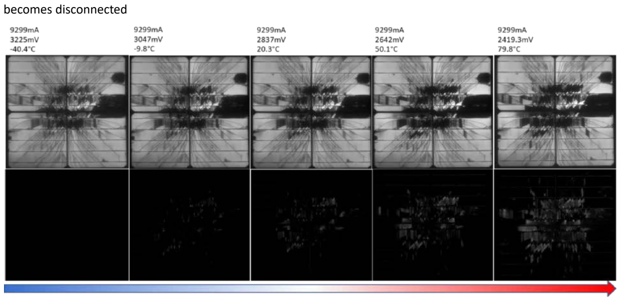
Lens Distortion Correction

Radial: $X_{corrected} = x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$
$Y_{corrected} = y(1 + k_1 r^2 + k_2 r4 + k_3 r6)$

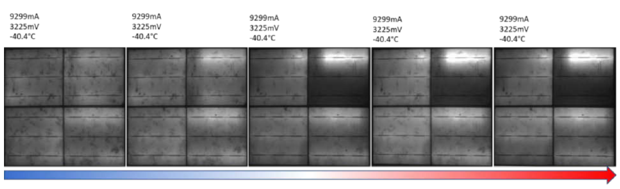
Tangential: $X_{corrected} = x + [2p_1 xy + p_2(r^2 + 2x2)]$
$Y_{corrected} = y + [p_1(r^2 + 2y^2) + 2p_2 xy]$



Severely cracked glass-glass module. As temperature increases, cracks can be seen to open and more of the cell area becomes disconnected



Module with degraded solder bonds. Solder bonds open and close depending on temperature



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