NATIONAL RENEWABLE ENERGY LABORATORY

National Center for Photovoltaics

Research Opportunities in Reliability of Photovoltaic Modules

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Catalyzing Innovation in PV Manufacturing - An NSF Workshop

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Overview

Research Opportunities in Reliability of Photovoltaic Modules

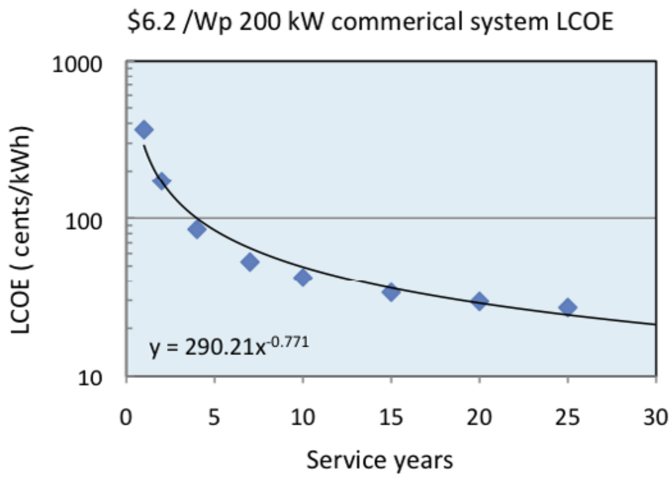
- Motivation
- Where we are today and how we got here
- Present needs – general and specific
- Jobs

Motivation for Reliability Research in PV Modules

- Reducing the levelized cost of energy through:
  - Increased performance, availability/uptime
  - Lower materials, operations, and maintenance costs
  - Reduced investment and customer risk, reduced cost of capital
- Forecasting for performance and reliability
  - Choose the relevant tests for materials and components to benchmark and improve reliability
  - Better confidence for module manufacturers in making projections for warrantee returns (standard is 25 years)

Value of Reliability

- Reliable products reduce Levelized Cost Of Energy (total lifecycle cost/total energy produced) over the long term
  - LCOE increases as system lifetime decreases (power law fit)

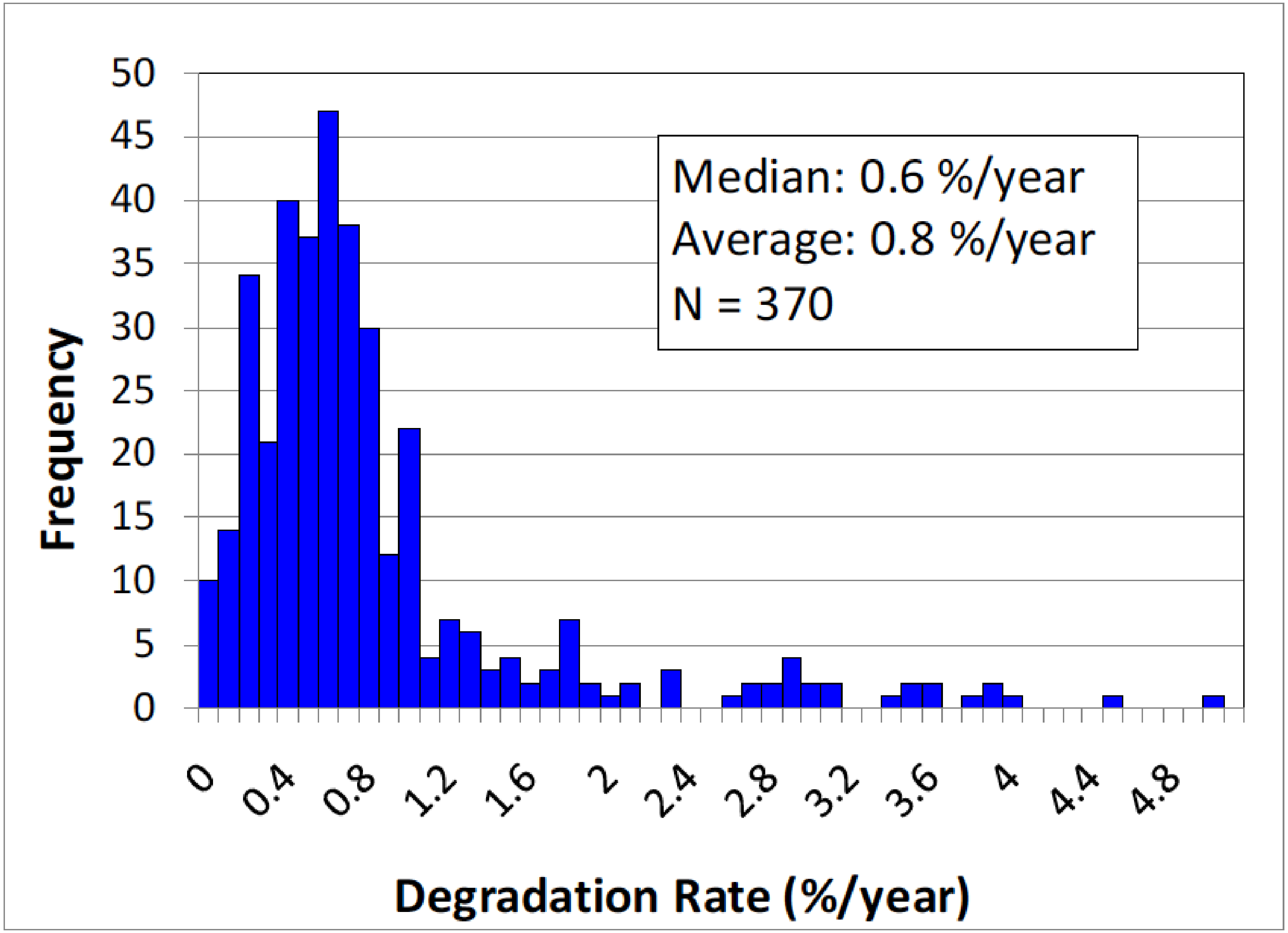


  - LCOE increases 10% per 1% increase in degradation rate
  - LCOE increases 2¢/kWh for each additional 1% per year of the initial capital expenditure for O&M
- Reliable products over the long term enhance the the amount of energy produced and delivered at reduced cost

Calculated by the Solar Advisor Model (SAM): www.nrel.gov/analysis/sam/
Based on Granata et. al. Sandia, IPRW(2009)

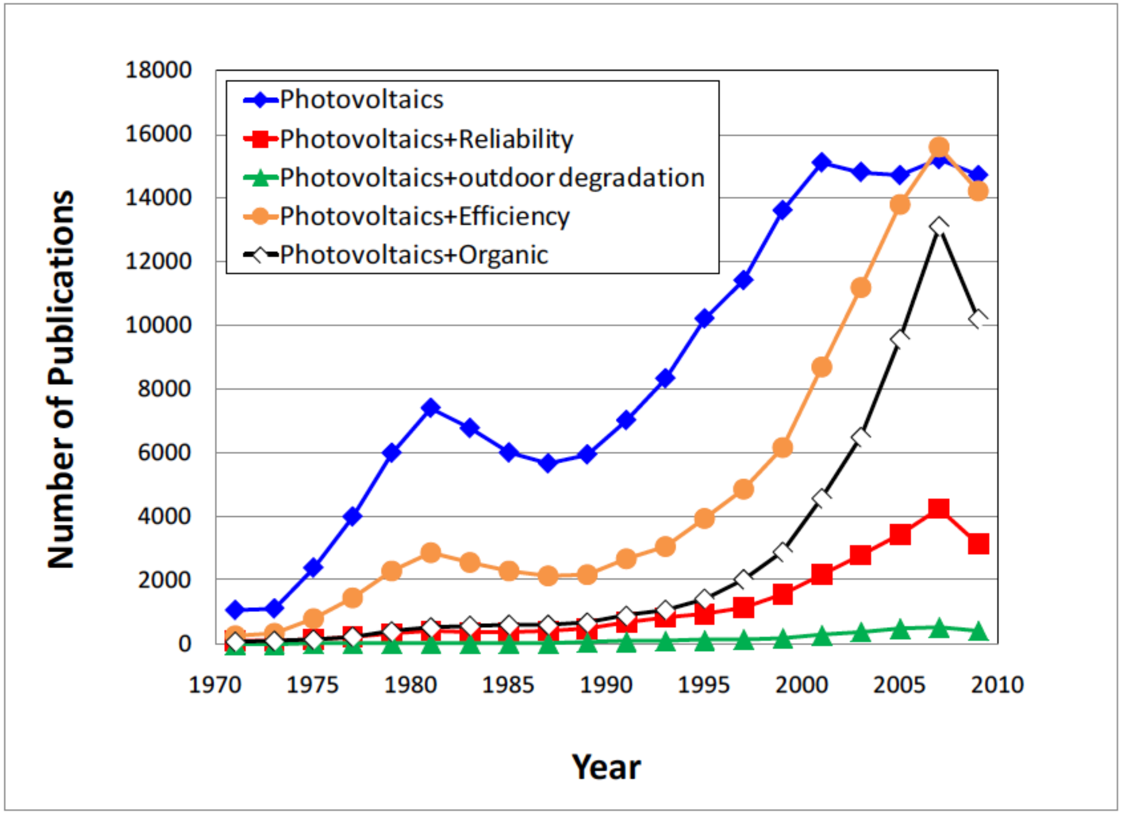
Historical Degradation Rates of Fielded Modules

Degradation Rates (R_d) most often reported



D. Jordan 2010 NREL PV Module Reliability Workshop (PVMRW)

The Reliability and Performance of PV Modules in the Field is Insufficiently Studied



Number of Publications on Google Scholar

Different search engine. Web of Science, Scirus, INSPEC etc. → vertical axis will be different

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Reliability Problems Can be Catastrophic

German blaze sparks BP Solar concerns

A fire at one of the world's largest roof-top solar installations has raised fresh concerns about BP Solar's panels. It destroyed around 200 sq m of a solar array on warehouses in Bürstadt, near Mannheim operated by Tauber Solar.

RELATED STORIES

- Q-Cells gobbles remaining shares of Solibro
- Solar firm a+f nabs installation contract in Italy
- Showa Shell, Aramco to start Saudi solar project

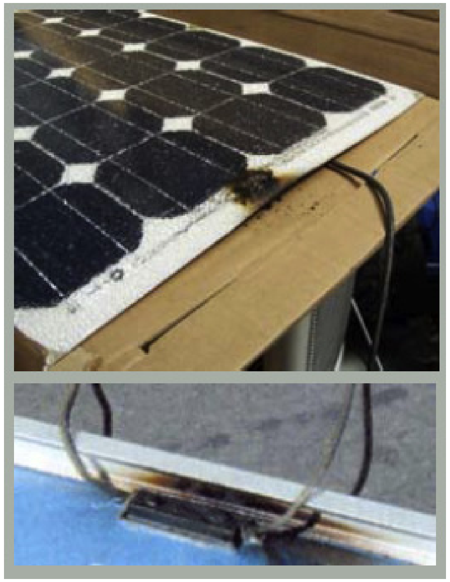
A source familiar with the incident says: "BP has been in the plant since the day after the fire and they have already told us the reason was the modules." She adds that BP Solar has said that it will pay for the damage and for the time that the 5 megawatt (MW) solar plant is out of action. "

The source says that the whole plant has been switched off while BP checks the panels "module by module" to make sure they are safe. But she adsds that the incident is unlikely to affect Tauber's relationship with BP. "BP has said it will pay compensation, and it has done so in the past so we have no reason to doubt them."

A BP spokesman says the fire affected "a small part of a very large roof installation." German authorities are investigating the cause of the fire and BP Solar is helping these investigations as well as carrying out its own probe. "This is something to be taken very seriously," if it is shown conclusively that the panels were responsively for the fire.

BP Solar was forced to review its solar panels in 2006 and 2007 due to a problem with junction boxes over-heating and carry out a recall of a large amount of panels, some 80% of them in Germany.

Source: http://www.rechargenews.com/energy/solar/article182054.ece



Source: IEC, Swisswafer, electrosuisse

Qualification Testing: First Threshold for Reliability

- **PV Module reliability and durability approach to date, while very helpful, has been phenomenological, empirical, and iterative as opposed to systems and model based**

Test	**Block I**	**Block II**	**Block III**	**Block IV**	**Block V**	**IEC 61215**
Year	1975	1976	1977	1978	1981	2009
Thermal Cycle (°C)	100 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	200 cycles -40 to +90	200 cycles -40 to +85 w current flow
Humidity or humidity/freeze (RH is relative humidity)	70 C, 90%RH, 68 hr	5 cycles 40 C, 90%RH to 23 C	5 cycles 40 C, 90%RH to 23 C	5 cycles 54 C, 90%RH to 23 C	10 cycles 85 C, 85%RH to -40 C	10 cycles 85 C, 85%RH to -40 C; 1000 hr 85 C, 85%RH
Hot spots	-	-	-	-	3 cells, 100 hrs	5 hr, worst case
Mechanical load	-	100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 cyc. ± 2400 P	10000 cyc. ± 2400 Pa	3 cyc. 2400 Pa
Hail	-	-	-	9 impacts 3/4" - 45 mph	10 impacts 1" - 52 mph	11 impacts 25 mm - 23 m/s
Insulation test	-	< 15 µA 1500 V	< 50 µA 1500 V	< 50 µA 1500 V	< 50 µA 2*Vs+1000	1 min at 2*Vs+1000, then measure @ 500 V: R X A > 40 $M\Omega \cdot m^2$

Sarah Kurtz, Jennifer Granata, and Michael Quintana, SPIE, (2009)

Steps to Improved PV Module Reliability

Qualification Test

Test-to-Failure

Lifetime Prediction

Field Reliability Experience

Present Research Opportunities

Module Materials

-Polymer encapsulants, how they fail as function of the temperature, UV light exposure, humidity, and physical stress

-Degradation in connectors, wires, and junction boxes – how they degrade when exposed to the elements

Reliability Engineering

-Mapping of failure mechanisms observed in the field to those obtained under accelerated lifetime testing

-Clarifying the failure mechanisms, assigning and validating their rate models

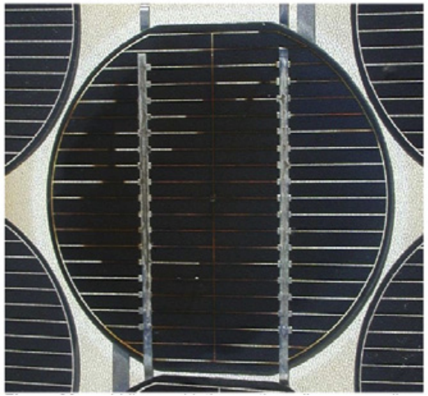
Quantitative reliability models for PV need further development

-Presently underrepresented stresses in accelerated testing: UV, electrical (system) bias

-Determining to what extent one can accelerate the degradation meaningfully

-Accounting for combined stress effects (delamination → moisture ingress → corrosion → current concentrations/ short circuits → power loss)

Corrosion in Modules



One of the key degradation mechanisms in modules responsible for power loss and failure in the field

–What are the mechanisms?

- Galvanic
- Electrolytic

–How are they activated?

- Acidity (from ethylene vinyl acetate encapsulant)
- Moisture ingress
- Electrical bias
- Galvanic potentials
- Catalytically induced

–What are the reactants, products?

–How does it lead to failure?

- Increased series resistance
- Shorts/shunts
- Current concentrations, hot spots (fire potential)

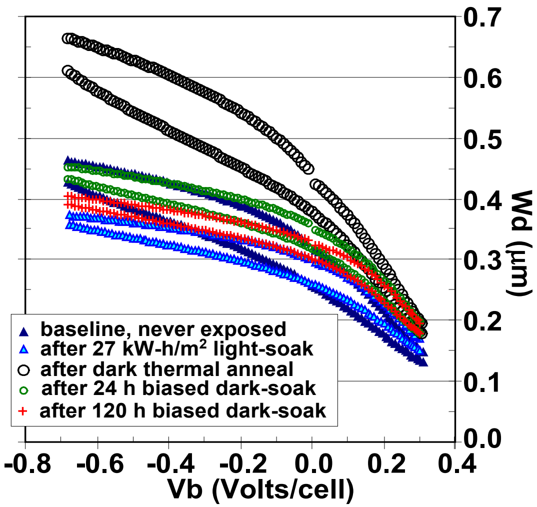
–How to characterize it?

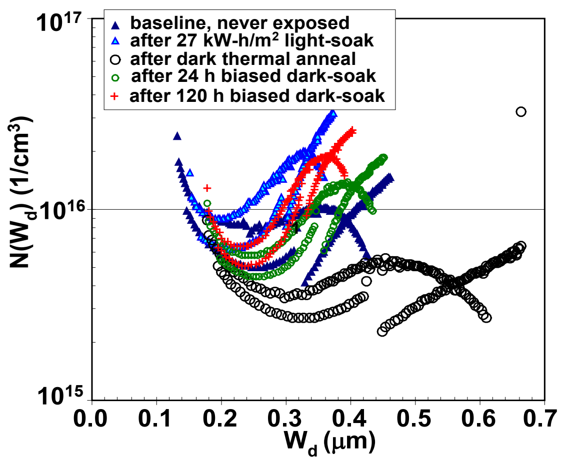
- Identification of the reaction equations associated with observed corrosion via identification of the species present
- Identification of encapsulant discoloration (ionic migration, reactions) via characterization of the species present
- Imaging for series resistance and shorts/shunts

–How to model the degradation?

- Chemical kinetics; Eyring Equation
- Diffusion (O_2, H_2O)
- Coulombs leaked under bias (electrolytic corrosion)
- Differences in galvanic potential
- Validate model in various field environments

Metastability in CdTe, CIGS, and CIS





Measured changes in depletion width (top) and carrier profiles (bottom) as a function of exposure (Capacitance measurements)

Thin film modules display metastability associated with their exposure (thermal, optical, electrical) history

- What are the mechanisms?
  - Diffusion of ionic species across the device, especially in the depletion region
  - Trap states capturing and releasing carriers
- How is it activated?
  - Heat
  - Light
  - Electric field
- What are the species involved?
  - Typically Cu, especially in CdTe
  - Other, Na? …TBD
- What is the reliability problem?
  - Power measurement variations on the order of $\pm$10%
  - Shows up predominantly in FF (junction related), V_{oc} (lifetime related), and I_{sc} as well
- How to characterize it?
  - Electron microscopy (SIMS, SEM, TEM)
  - Auger profiling
  - Deep level analysis (Drive level capacitance profiling)
- How to model it?
  - Ionic drift under electric field
  - Arrhenius equation

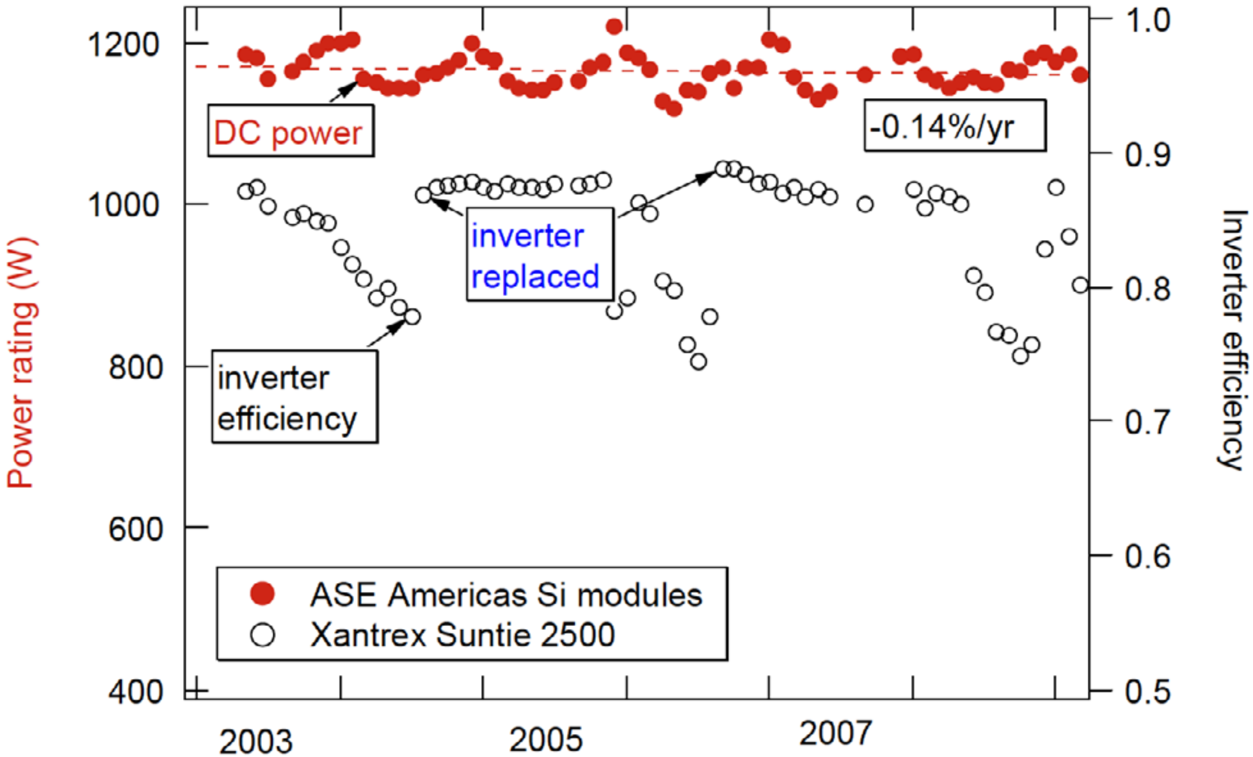
  - Could lead to better fundamental understanding and efficiency gains

Delamination & Loss of Elastic Properties

Loss of adhesion, elastic properties, and cracking of encapsulant, backsheet, and edge seal material lead to rapid degradation of module performance because of accelerated moisture ingress

- What are the mechanisms?
  - Hydrolytic reactions
  - Oxidation
- How is it activated?
  - Heat
  - Light
  - Electrical bias (tentatively)
  - Activity of water
- What are the species involved?
  - O_2, H_2O, reacting with the polymeric materials in the module package
- How does it lead to failure?
  - Moisture ingress through delaminated or cracked polymeric packaging leads to corrosion, and in turn series resistance, short and leakage currents, then current concentrations (fire potential)
- How to characterize it?
  - Infrared spectroscopy techniques
  - Imaging for series resistance, shorts/shunts
  - Mechanical testing
- How to model it?
  - Hydrolytic reactions – Arrhenius equation
  - Delamination -??

Inverter Failure



Of the system components, inverters have one of the shortest lifetimes

- What are the mechanisms?
  - Excess heat from losses in the semiconductor switches: long switching time, conductor power losses, putting the inverter in the sun, inadequate heat removal.
  - The capacitor bank is very sensitive to heat and charge surges (rule of thumb: 10°C increase leads to halving of the capacitor life), degrading dielectrics.
- How is it activated?
  - Heat
  - High voltage, current
- How does it lead to failure?
  - Reduced DC/AC conversion efficiency
- Characterization
  - Thermography
  - FET channel resistance/breakdown voltage
- How to model it?

Time to Move

Reactive → Proactive

Jobs: Who is Hiring Reliability Scientists and Engineers?

PV materials makers

Dow, DuPont …

PV module manufacturers

Calisolar, Evergreen Solar … (*all of them*)

Installers

SunEdison …

Vertically integrated PV companies

REC, Emcore, Amonix, SunPower … (*all of them*)

Testing companies

Underwriters Laboratories

<u>Hiring at many levels of the value chain</u>

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