Solar Durability and Lifetime Extension Center at Case Western Reserve University: Degradation of Acrylic Polymer and Acrylic Mirrors

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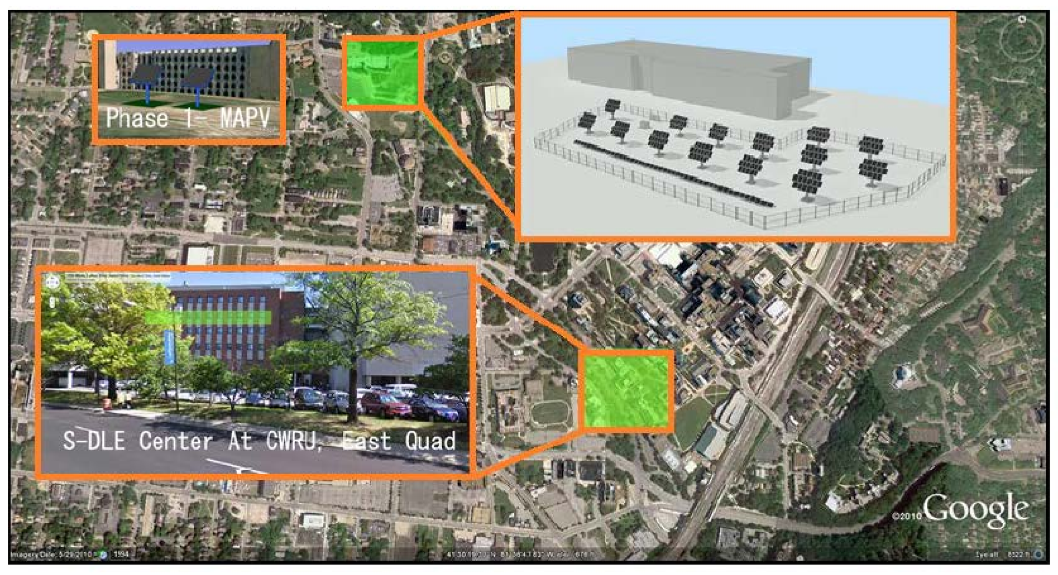
Solar Durability and Lifetime Extension (SDLE) Center

Determining Lifetime and Degradation Science for Photovoltaics



Motivation: Lifetime & Degradation Science for Photovoltaics

2010 Science For Energy Technology Workshop
- Convened by U. S. DOE, Basic Energy Sciences

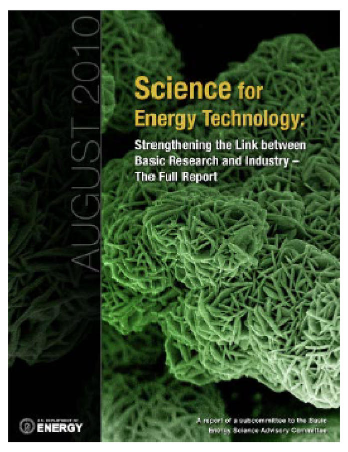
Science challenges across 9 areas of energy

PV prioritized research directions
- Photovoltaic **module lifetime and degradation science**
- Fundamental properties of photovoltaic interfaces
- Advanced photovoltaic analysis & computational modeling for scale-up

Qualification testing of systems
- Is not sufficient for reliability & lifetime
- To avoid excessively high degradation rates
- Dramatically reduced service lifetimes

Determine degradation mechanisms and rates
- Scientific underpinning of reliability and qualification standards

Quantitative degradation rate modeling
- Connects materials, components, system
- To overall degradation rate, linearity, reciprocity
- And system lifetime performance



Overview of the SDLE Methodology

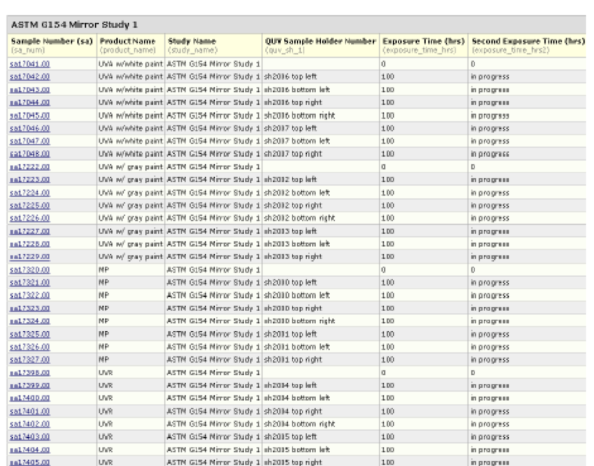
Does Current Qualification Testing Advance PV Reliability & Lifetime?
- Provides no lifetime validation
  Only pass/fail results
- Testing doesn't produce scientific insights
  Into degradation mechanisms and rates
- Reliability testing not founded
  In the physics of failure
- Qual. testing doesn't advance PV research

Lifetime and degradation science
- A scientific foundation for advancing PV lifetime
- Quantitative degradation mechanisms & rates
- Real time and accelerated testing
- Single and multi-factor studies

Material, component & system approach
- Causation of failure arises in
  complete systems and their interactions
- Must study component and material degradation
  To identify degradation mechanisms

Structured approach: study protocols
- For exposures and evaluations

Development of new study protocols
- For lifetime qualification standards



Engineering epidemiology
- For lifetime prediction
  e.g. PV Power degradation rates

SDLE Exposure Capabilities

Outdoor Testing
- SDLE SunFarm
  Irradiance
  Temperature and Humidity
  Yang Hu et. al. in Silicon Poster Session

Indoor Testing
- Irradiance
  Newport Solar Simulator 1-50x Suns
  SpectroLab XT 30 CW 100-1200x Suns

Irradiance, Temperature, & Humidity
- Q-Labs QUV/Spray Weathering Chamber
- Q-Labs Q-Sun Weathering
- CSZ ETC 100 cu. ft. with 1 Sun Light Rack

Temperature & Humidity
- CSZ ETC 8 cu. ft.

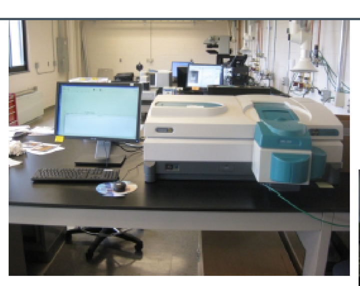
SDLE Evaluation Capabilities

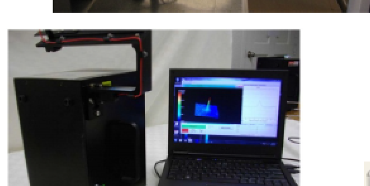
Optical Properties
- Cary 6000i with DRA-1800
- Filmetrics PARTS-UV
- HunterLabs UltraScan Pro
- Woollam VUV-Vase
  Spectroscopic Ellipsometer

Light Scattering Properties
- ScatterMaster 3D
- Wyatt Dawn Helios II

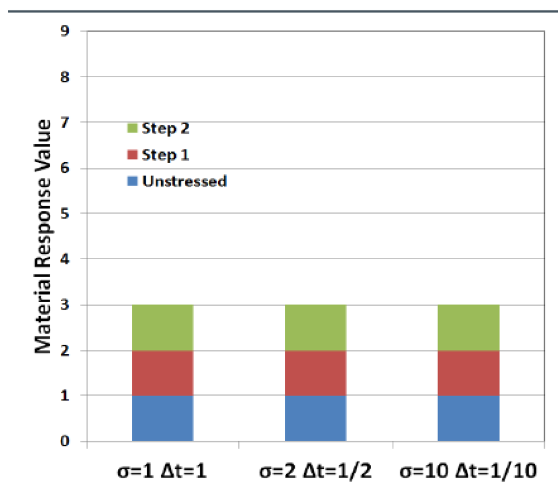
Surface and Bulk Properties
- Kruss DSA Surface Chemistry
- Olympus Confocal Microscope
- PHI VersaProbe XPS Microprobe

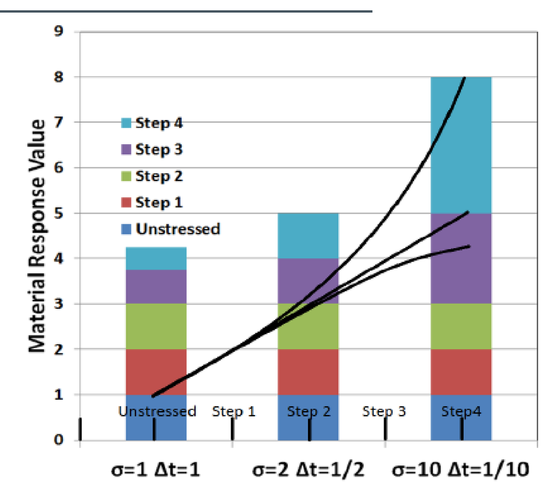
Mechanical Properties
- Nanoindentation
- Peel Strength





Stress Response Framework for Lifetime & Degradation Science





System response to applied stress

Study response of system
- At many stress levels
- With many applied stresses (multi-factor)

If system is only linear response
- Then increased stress rate
- Reduces time required for given net stress

If systems response is non-linear
- Then sub-, supra-linear response observed

Cross-correlation of stress/response
- Defines the system's response function
- Captures linear and non-linear phenomena
  As a matrix transform of stress to response

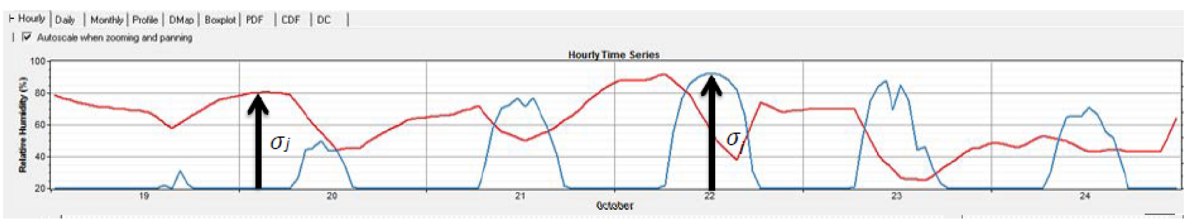
Stressors: How to Quantify Damaging Conditions

Stress Intensity (σ)
Graph of daily irradiance TMY3

Net Stress is a Stress Intensity over time

$$S = \int \sigma \, dt$$

Perform stress tests with
Higher Net Stress
AND Higher Stress intensity



Real world exposures have more than one stressor

$$\sum S = \int (\sigma_i \otimes \sigma_j \ldots \otimes \sigma_n) dt$$

Graph is of daily Irradiance and Relative Humidity TMY3

10.2 Times Higher AM1.5 Irradiance

$$A_\sigma = \frac{AM1.5}{UVA340} = \frac{618.3\ MJ/m^2}{60.65 MJ/m^2}$$

9.0 Times Higher AM1.5 Dose

$$A_\sigma = \frac{\mathbf{AM1.5}}{\mathbf{UVA340}} = \frac{\mathbf{977.6MJ/m^2}}{\mathbf{108.7MJ/m^2}}$$

Responses: Materials change as a function of stressors

Various levels of stress
- Stress intensity σ and integrated stress **S**
  Such as solar irradiance and solar dose

Measure responses
- Optical responses: abs/cm, index of refraction, YI, haze …
- Mechanical: embrittlement, crazing, haze …

Cross-correlation defines transferability
- Reciprocity between irradiance and time
- Linearity over dose or time
- Additivity over wavelength

Determine range of applicability of materials, components, systems
- Not just applicability to one set of stresses

Response a function of
- Stress level σ
- Net stress S

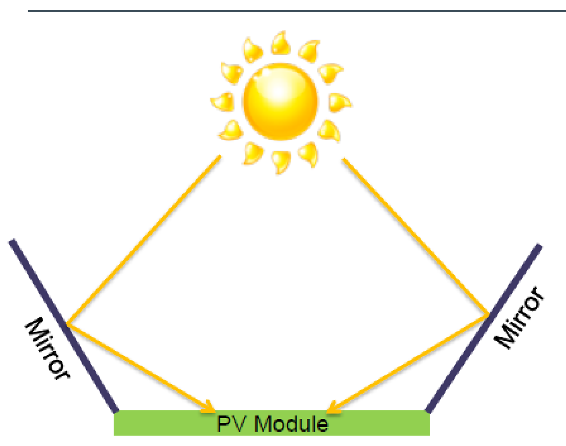
$$R = f({}^{\sigma}S) = \int f(\sigma)\sigma dt$$

Materials show many responses
1) Fundamental Absorption Edge
2) Light Stabilizer Package
3) Visible Yellowing

Expansion to multiple stresses gives:

$$R(S_i, S_j, \ldots S_n)$$
$$= f(\sigma_i, \sigma_j, \ldots \sigma_n) \int (\sigma_i \otimes \sigma_j \ldots \otimes \sigma_n) dt$$

Case Study: Mirror Augmented PV (MAPV) with Acrylic Mirrors



MAPV Value Proposition
- Increased irradiance on PV module
- Decreases LCOE
- Mirrors cost less than modules

Components in Acrylic:
- 1) Base resin
  Residual monomer
- 2) Light stabilizer package
  UV absorbers, radical scavenger

Acrylic Back Surface mirrors
- Use acrylic transmission
- To reduce UV and IR load on module

Durability Questions
- Are acrylic mirrors durable for 25 years?
- Do increased module stressors decrease service life

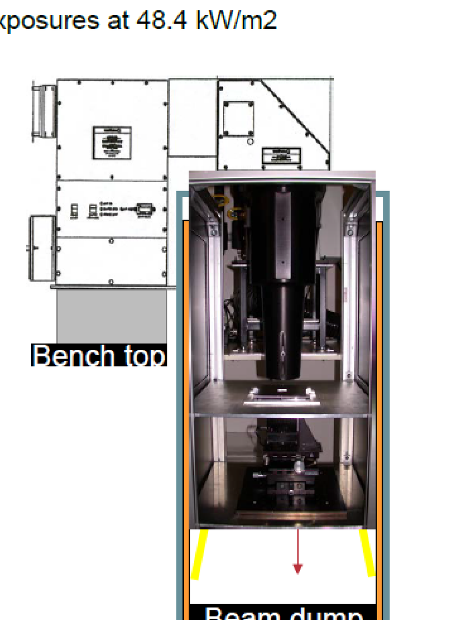
REPLEX PLASTICS

Stressors: Inducing Responses in Materials

Compare 2 irradiance tools
- Full spectrum Xe AM1.5D
- Fluorescent UVA 340

QUV at 1.55W/m² at 340 nm
Fluorescent weathering chamber
Outfitted with UVA 340 Lamps
Exposures at 1.55 W/m2 @ 340 nm

48.4 kW/m² Newport Solar Simulator
- Diverging Xenon Arc AM1.5
  With 13X Concentrator
- Exposures at 48.4 kW/m2



Compare MP Responses: For 3 Degradation Mechanisms

Incremental absorbance to dose

$$Incremental \frac{Abs}{cm} per \frac{GJ}{m^2} Dose$$
$$= \frac{Abs_{i+1}(\lambda)/cm - Abs_i(\lambda)/cm}{Dose_{i+1} - Dose_i}$$

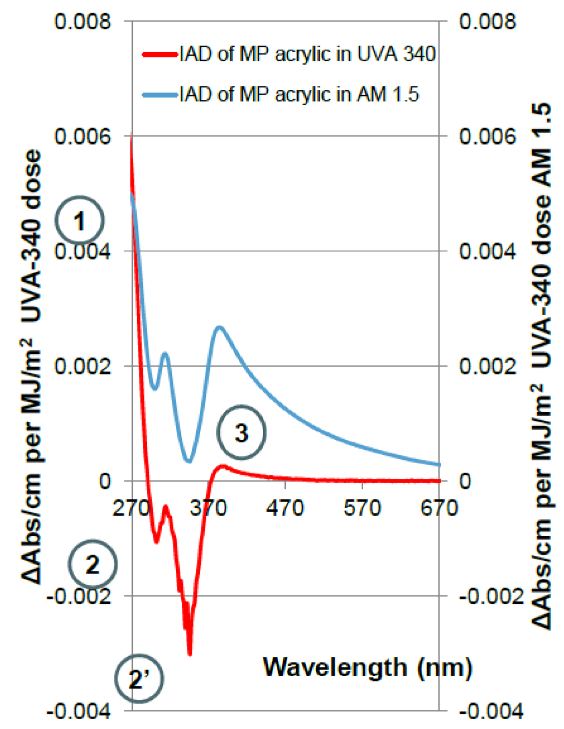
For AM1.5 and UVA-340 Experiments

1) Base resin photodegradation
Agreement in IAD rate
For Mechanism 1

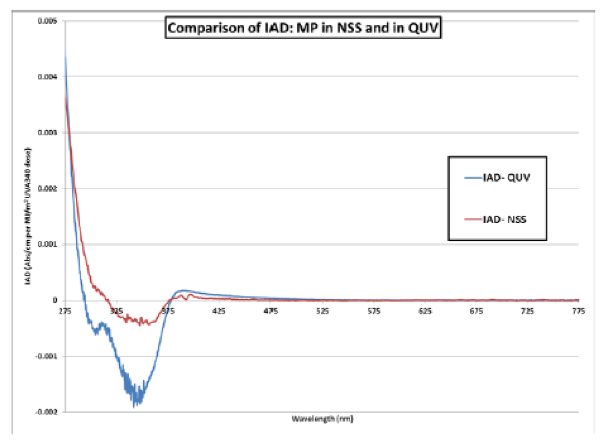
2) Stabilizer package bleaching
- Photobleaching Rates Comparable
- Rates Determine Package Lifetime

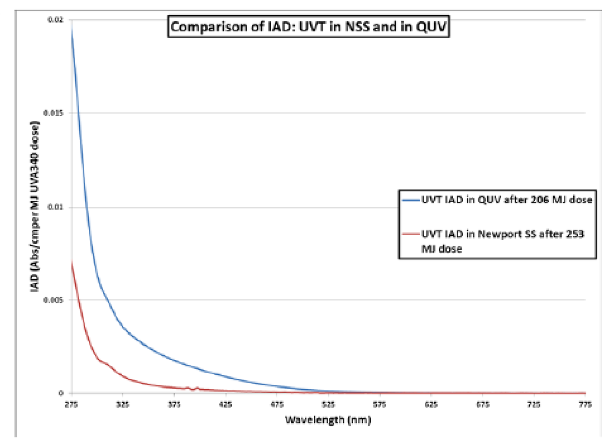
3) Visible region yellowing
- AM1.5 Yields Greater YI Yellowing
- Spectral Differences AM1.5 vs UVA340
  Produce different amounts of yellowing

Degradation Mechanisms & Rates
- To Estimate Lifetime Performance



Comparison of 2 Different Types of Acrylic



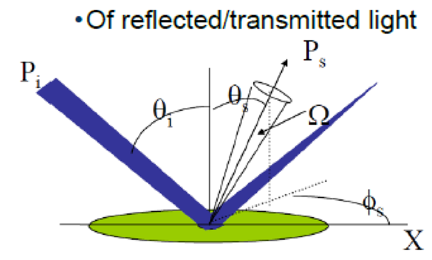


IAD Results for Multipurpose Acrylic
- Two different stress conditions
  Newport Solar Simulator
  QUV Weathering Chamber
- QUV 206 MJ dose
- NSS 253 MJ dose

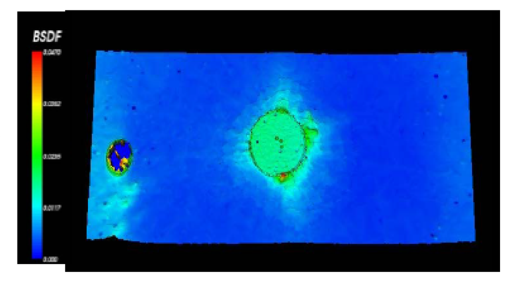
IAD Results for Ultra-violet Transmitting Acrylic
- Two different stress conditions
  Newport Solar Simulator
  QUV Weathering Chamber
- QUV 206 MJ dose
- NSS 253 MJ dose

Acrylic Mirrors after Exposure to Corrosive Environment

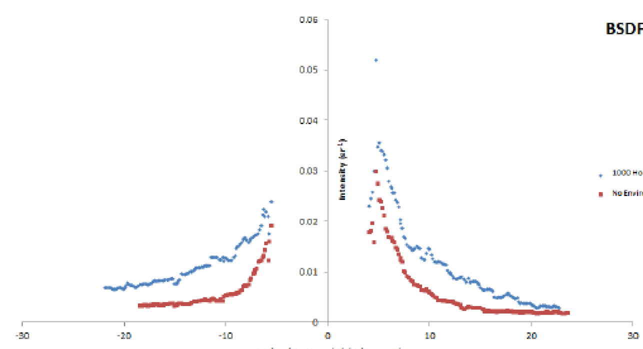
Bidirectional Scatter Distribution Function (BSDF)
- Of reflected/transmitted light

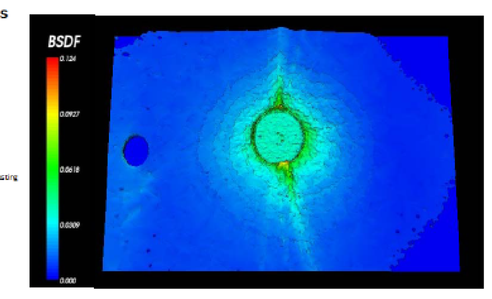


$$BRDF = \frac{Ps/\Omega}{Pi \cos\theta s}$$
$$CCBRDF = \frac{Ps/\Omega}{Pi}$$



Baseline Mirror Response





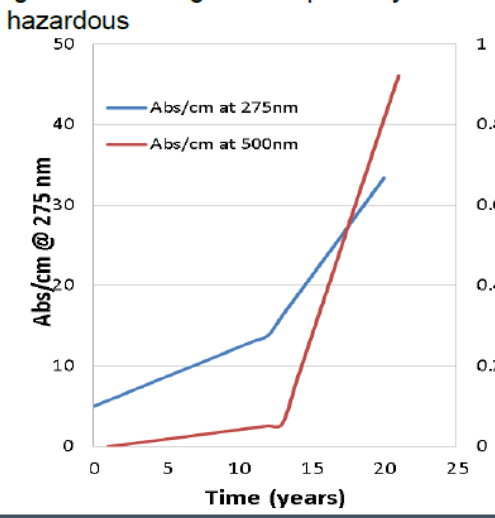
Mirror Response after 1000 hours of salt fog corrosion in a Q-Fog

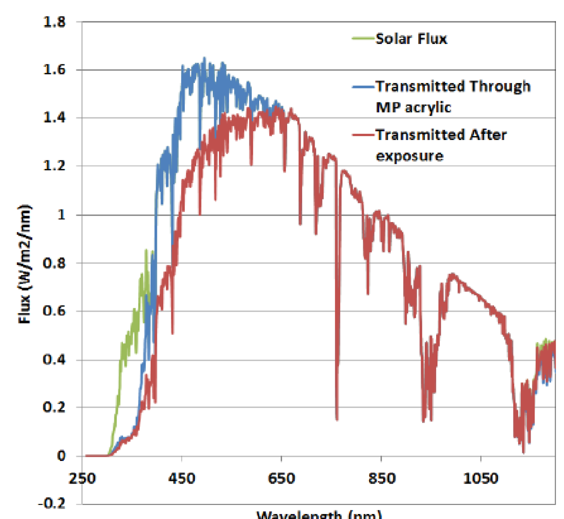
Examples of Lifetime Prediction Metrics for MAPV

Lifetime Prediction: After 12 years
- Optical absorbance will increase like UVT
- Due to consumption of stabilizers

PV technologies rely on 25 year warranted lifetimes
- Ignorance of degradation pathways is hazardous

Leading to 7% loss in transmitted flux
- after 76 MJ/m² flux
- 8 years 1 sun exposure





Conclusions

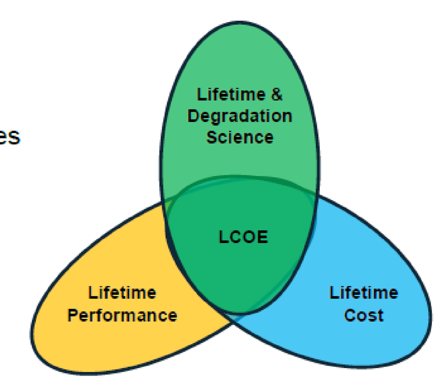
Lifetime and Degradation Science
- Furthers the understanding of PV reliability
- Determine degradation mechanisms and rates
- Beneficial for achieving 25 year lifetimes in PV modules

Current qualification testing
- Doesn't advance PV research

SDLE Center
- Significant Outdoor and Indoor Testing Capabilities
- Optical, Light Scattering, Surface & Bulk, Mechanical
  Evaluation Capabilities

Stress/Response Framework
- Cross-correlation of stress/response defines the system's response function

Acrylic Case Study
- Compare 2 different types of acrylic in 2 different types of stresses



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