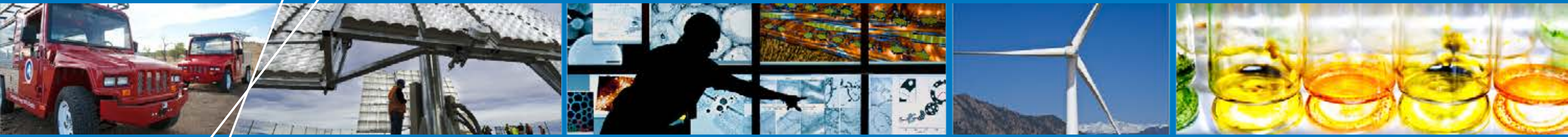
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

IEC Quality Assurance Task Group 5: UV, Temperature, and Humidity



SOPHIA Workshop for PV-Module Reliability

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Tuesday, 2014/6/03, 13:00-13:20 pm
SolarInfoCenter (SIC), Room 1G
Freiburg, Germany
NREL/PR-5200-62228

This presentation contains no proprietary information

Topics Covered Today

- Motivation: Goals and activities for QA TG5
- E_a interlaboratory experiment (TG5 US)
  - Motivation and background
  - Some details of the E_a experiment:
    - Encapsulation discoloration
    - Encapsulation adhesion
    - Edge seal adhesion
- Timeline for TG5

Goal and Activities for QA TG5 (UV, T, RH)

- IEC qualification tests (61215, 61646, 61730-2) presently prescribe up to 137 days field equivalent (IEC 60904-3 AM 1.5) UV-B dose.
- **Goal**: develop UV- and temperature-facilitated test protocol(s) that may be used to compare PV materials, components, and modules relative to a field deployment.

Core Activities:

1: Consider weathering literature and climate meteorology (*location-dependent information*).
    e.g., known benchmark locations…Miami, FL; Phoenix, AZ

2: Leverage existing standards, including other industries.
    - summary exists from Kurt Scott *et al.*

3: Improve understanding of existing PV UV tests.

4: Improve understanding of module durability.
  4-1 Collect information about observed failure modes.
    e.g., the literature, site inspections
  4-2 Confirm appropriate models for aging.

5: Verify suitable UV sources.
    - summary of *module* capable equipment from David Burns *et al.*

6: **Generate test procedure for UV-related accelerated service aging.**

7: Perform laboratory verification of proposed test standard/failure mode.
    - mini-module study (Japan), SoPhia round-robin (Europe), E_a interlaboratory study (US)

Motivation for the E_a Interlaboratory Experiment (TG5 US)

- Knowing E_a (for rate of change in a characteristic) is critical to prescribing and interpreting a *UV- and temperature*-mediated test.
- Unfortunately, E_a is not known for the common UV-related PV degradation modes.

$$k = A\left[\frac{T}{T_0}\right]^n e^{\left[\frac{-E_a}{RT}\right]}$$

The modified Arrhenius equation

Critical unknowns
(Goals for the interlaboratory experiment):

1. Quantify E_a so that applied test conditions can be interpreted.
2. Provide a sense of the range of E_a that may be present by examining “known bad,” “known good,” and “intermediate” material formulations.
3. Determine if there is significant coupling between relevant aging factors, *i.e.,* UV, temperature, and humidity.
   What factors does TG5 need to consider?
4. Investigate the spectral requirements for light sources by comparing E_a for different sources, *i.e.*, Xe-arc, UVA 340.
   Is visible light required in addition to UV light?

Interlaboratory Participation Enables a Wider Range of Study

- Indoor aging is expensive. No one institution has all the resources to apply the complete set of factors we would like to examine.
- Discoloration and adhesion will be studied in detail at (9) -*volunteer*- institutions using similar makes and models of instrument (*e.g.*, Ci5000, QUV).
- This overcomes the difficulty of limited availability of aging equipment.

LIGHT SOURCE, FILTER	Xe Arc (right-light/cira filter) or (Suga-Q/#295/Ircut)					UVA 340 fluorescent (no filter)		UVA 340 fluorescent (no filter)	No light			field deployment (outdoors)
UV LIGHT INTENSITY	NOMINAL (102 W•m^{-2} for 300≤λ≤400)					NOMINAL (1.0 W•m^{-2} @ 340 nm)		NOMINAL (~150 W•m^{-2} for 300≤λ≤400)	0 W•m^{-2}			
CHAMBER RELATIVE HUMIDITY {%}	30 ("low")			50 ("high")		~7% ("very low")		60 ("high")	30 ("low")			ambient
CHAMBER TEMEPRATURE {°C}	40	60	80	40	60	40	60	60→ 80 → 40	40	60	80	ambient
PARTICIPANT (INSTRUMENT MODEL)	3M (Ci5000)	3M (Ci5000)	3M (Ci5000)	Mitsui (SX120)	NREL (Ci5000)	QLAB (QUV)	QLAB (QUV)	Fraunhofer (custom)	NIST (custom)	NIST (custom)	NIST (custom)	ATLAS (EMMA in Phoenix)
		QLAB (QSUN XE3)			QLAB (QSUN XE3)	ATLAS (UVTEST)	NREL (custom UV suitcase)					CWRU (5x in Cleveland)
		ATLAS (SunTest XXL)					Fraunhofer (customized)					ATLAS (rack in Phoenix)
		Suga (SX75)					Suga (FDP)					ATLAS (rack in Miami
							CWRU (QUV) @1.55 W·m-2 @ 340 nm					NREL (rack in Golden)

Summary of participating laboratories and test conditions

- A standard condition (60°C chamber ambient) allows a broad variety of other instruments (light sources) to be compared.

- Rate of degradation will be compared against field data to allow site-specific acceleration factors to be determined.
- Outdoor data will verify the validity of the test.

- Separate experiment at NIST (same EVAs) will examine action spectrum.

Materials Used in the E_a Experiment

- Discoloration has been studied in the literature:
  - We have a sense of the general rate of degradation.
  - We have a sense of the sorts of formulations used (historical and contemporary).
  - We have prescribed known bad and known improved formulations of EVA.
  - A TPU formulation is chosen as a known bad material.

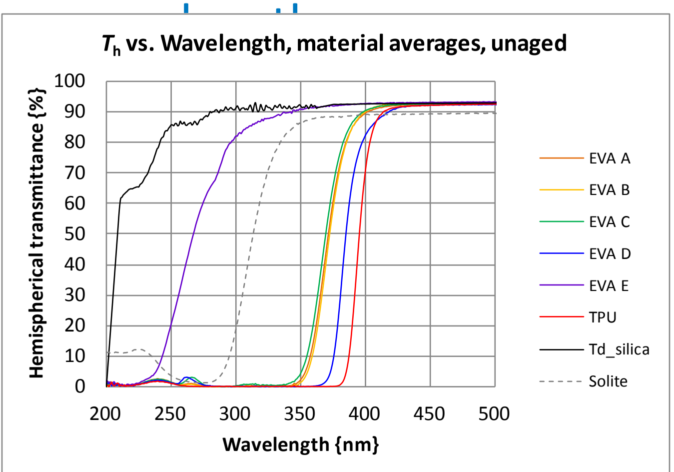
Ingredient	Comment	Mass {g}	Mass {g}	Mass {g}	Mass {g}	Mass {g}	Mass {g}
Elvax PV1400	Dupont EVA resin, 33 wt% VAc	100	100	100	100	100	N/A
Dow Corning Z6030	Silane primer, gama-methacroyloxy propyl trimethoxysilane	0.25	0.25	0.25	0.25	0.25	?
Tinuvin 770	Hindered amine light stabilizer (HALS)	0.1	0.1	0.1	N/A	N/A	?
Tinuvin 123	Non-basic aminoether-hindered amine light stabilizer (NOR-HALS)	N/A	N/A	N/A	0.1	0.1	?
TBEC	Curing agent, OO-Tertbutyl-O-(2-ethyl-hexyl)-peroxycarbonate, 0.133kPa at 20C.	N/A	1.5	1.5	1.5	1.5	?
Lupersol 101	Curing agent, 2,5-Bis(tert-butylperoxy)-2,5-dimethylhexane	1.5	N/A	N/A	N/A	N/A	?
Naugard P	Phosphite anti-oxidant (AO)	0.2	0.2	N/A	N/A	N/A	?
Tinuvin 329	Benotriazole UV absorber (UVA)	N/A	N/A	N/A	0.3	N/A	?
Cyasorb 531	Benzophenone UV absorber	0.3	0.3	0.3	N/A	N/A	?
Comments		Material A "known bad", "slow cure"	Material B "intermediate", "fast cure"	Material C "intermediate", "fast cure"	Material D "known good"	Material E "modern, no UVA"	TPU (known bad)

Encapsulation materials being compared in the transmittance (discoloration) experiment.
The encapsulation adhesion experiment examines Material B only.

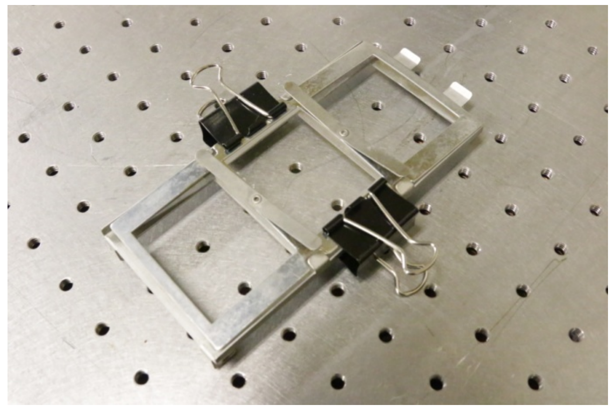
- Degradation of adhesion is not well known for PV encapsulation or edge seals.
  - First study a limited set of materials to get a sense of the degradation rate and relative importance of factors (UV, T, %RH).
    - (1) EVA formulation used to study encapsulation adhesion.
    - (2) Edge-seal formulations used to study edge-seal adhesion.

Details of the E_a Methods and Experiment: Encapsulation Transmittance Test

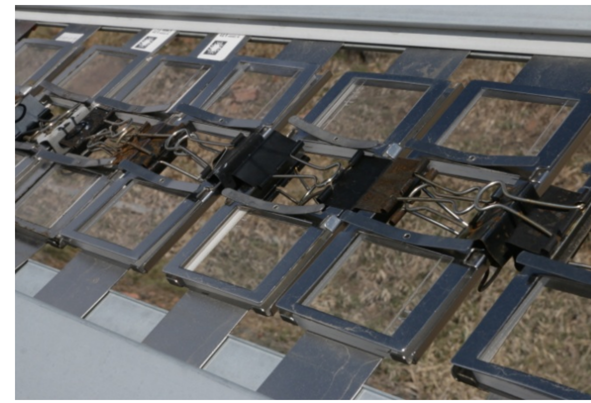
- Coupon specimens will be measured using a spectrophotometer (with integrating sphere)
- Measure at specimen center (anaerobic, no O_2) and edge (aerobic)
- Analyze: solar-weighted transmittance, yellowness index, and UV cut-off



Transmittance will be examined using silica/polymer/silica samples.



Specimen in sample holder for indoor aging at NREL.



Specimens on outdoor rack, aging in Golden, CO at NREL.

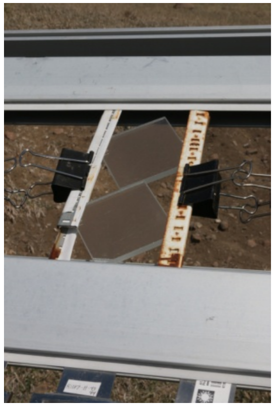
User summary:

- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 2” x 2”
- Quantity: 3 replicates of 6 materials (pre-conditioned), and 1 reference (not pre-conditioned)
- Aging: 0, 15, 30, 45, 60, 75, 90, 120, 150, 180 cumulative days (indoors) or 0, 1, 2, 3, 4, 5 years (outdoors)
- Measurements (non-destructive): repeatedly age and measure at each laboratory/test site

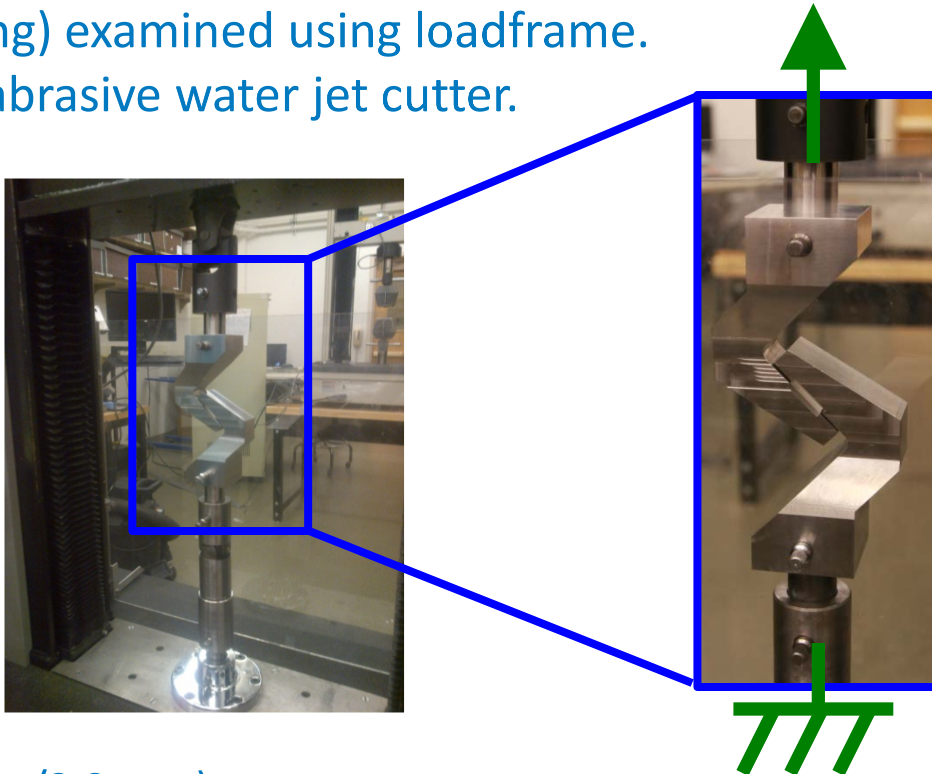
Details of the E_a Methods and Experiment: Encapsulation CST Adhesion Test

- 25 mm square specimens (diced, after aging) examined using loadframe.
- Pristine edge quality is critical. Dice using abrasive water jet cutter.

Sample holder configuration for indoor aging at NREL.



Specimens on outdoor rack, aging in Golden, CO at NREL.



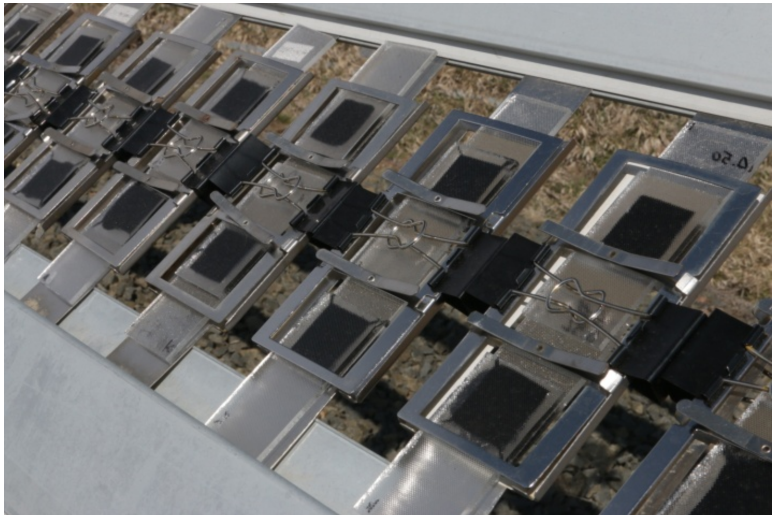
The CST will be used to examine the attachment of EVA. Method from: Chapuis et al., PIP, 22 (4), 2014, pp.405–41. (EPFL)

User summary:

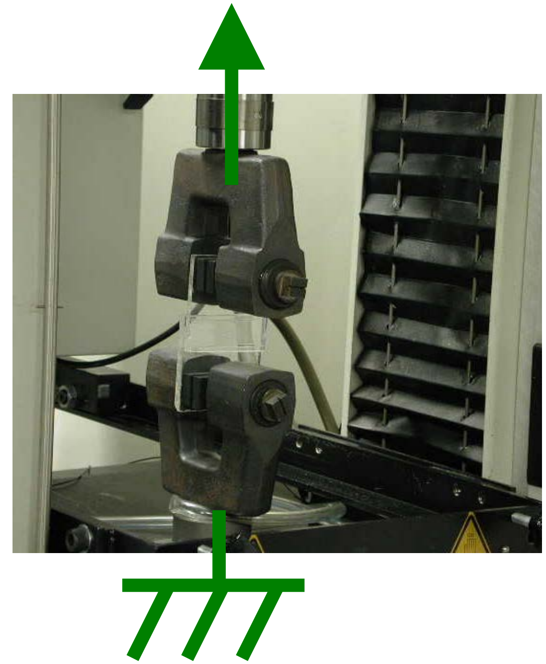
- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 3” x 3”
- Quantity: 10 replicates of 1 material (pre-conditioned), plus 5 extras (not pre-conditioned)
- Aging: 15, 30, 45, 90, and 180 cumulative days (indoors), or 1, 2, 3, 4, 5 years (outdoors)
- Remove 2 coupons at each increment
- Measurements(destructive): age at each laboratory/test site, then sent to NREL for measurement

Details of the E_a Methods and Experiment: Edge Seal Lap Shear Adhesion Test

- Lap shear is the standard test method for RTI and other certification protocols.
- Edge quality (handling of the glass specimens) is not as critical here.



Specimens on outdoor rack, aging in Golden, CO at NREL.

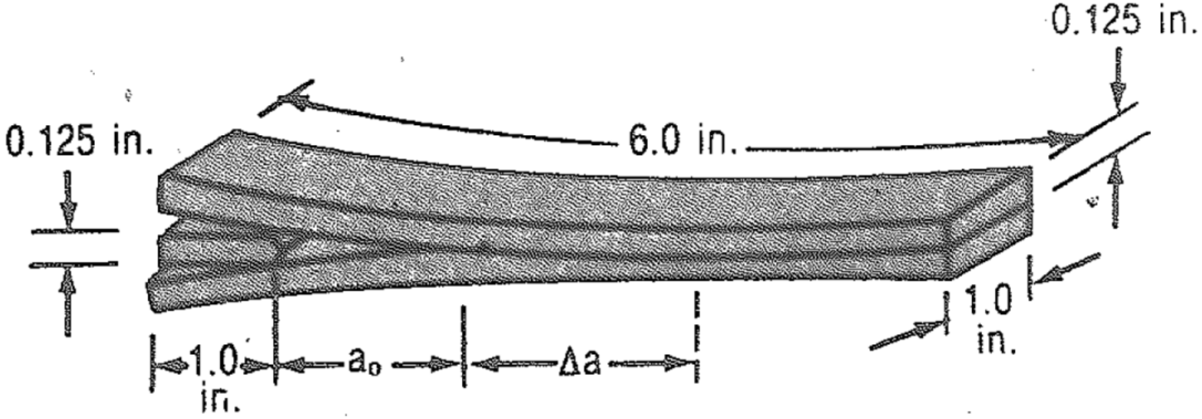


Testing Summary:

- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm). 25 mm X 25mm test area.
- Quantity: 10 replicates of 2 test materials
- Aging: 15, 30, 45, 90, and 180 cumulative days (indoors), or 0.5, 1, 2, 3, 4, 5 years (outdoors)
- Remove 2 coupons of each material at each increment
- Measurements (destructive): aged at each laboratory/test site, then sent to NREL for measurement
- Use a displacement rate of 10 mm·min^{-1}. Record σ_{max}, ε_{max}, and failure mode.

Details of the E_a Methods and Experiment: Edge Seal Wedge Adhesion Test

- Fracture mechanics test for interfacial adhesion ($J \cdot m^{-2}$), not an attachment strength test ($N \cdot m^{-2}$ or $N \cdot m^{-1}$) .
- Specimens will be examined visually and using a micrometer.



G = Fracture Energy

$$G = \frac{3Et^3h^2}{16a^4}$$

A DCB wedge test will be used to examine the attachment of edge seals.
Marceau *et al*., Adhesives Age, 1977, 28-34.
Also: ISO 10354, ASTM D3762.

User summary:

- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 1” x 9”
- Quantity: 2 replicates of 2 test materials
- Aging: 15, 30, 45, 90, and 180 cumulative days (indoors) or 0, 0.5, 1, 2, 3, 4, 5 years (outdoors)
- Measurements (semi-destructive): aged and measured at each laboratory/test site

Timeline and Goals for TG5

- NREL specimens are presently at 15 days (Ci5000) and 60 days (UV suitcase).
- Other institutions (including Fraunhofer) are beginning the experiment.
- Results will be used to assign t, T, %RH for a comparative UV test.

	Qualification	QMS	Comparative Rating	Service Life Prediction
Current status	Issued as standards	Revised NWIP submitted	Proposed as concepts	Concepts
2014 goal	Submit Ed 3 61215 Ed 2 61730	Publish new TS	Initiate E_a test. Create strawman UV standard.	Develop criteria to evaluate QMS related to service life; NWIP
2015 goal	Publish new editions	Start use of the TS in factory inspection	Submit UV standard NWIP. Create strawman test sequence standard. Complete E_a test.	
2016 goal		Revise QMS document to reflect feedback	Publish E_a results. Submit CD UV standard.	
Chamber test times	Modules: ~ 6 weeks	TBD	~6 months	~18 months

Conclusions/Goals (for the E_a Experiment)

- We have initiated a large interlaboratory experiment investigating the degradation kinetics (E_a) of encapsulation and edge-seal materials.
- We will investigate transmittance and adhesion as a function of exposure to heat, humidity, light, and light source.
- Hundreds of test samples were made and shared with multiple collaborators in the PV industry.
- The results of these experiments will enable the determination of acceleration factors facilitating the design of accelerated stress tests, with field-performance prediction capability.

Acknowledgements

- There has been fantastic participation in TG5.
  Thank you to the many participants for their ongoing support!
- If interested in TG5 or the experiments, please contact the corresponding regional TG5 leader. (See title slide)
- Let the speaker know if you are interested in any of the related material standards (encapsulation transmittance, encapsulation adhesion, edge-seal attachment).

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

NREL STM campus, Dennis Schroeder

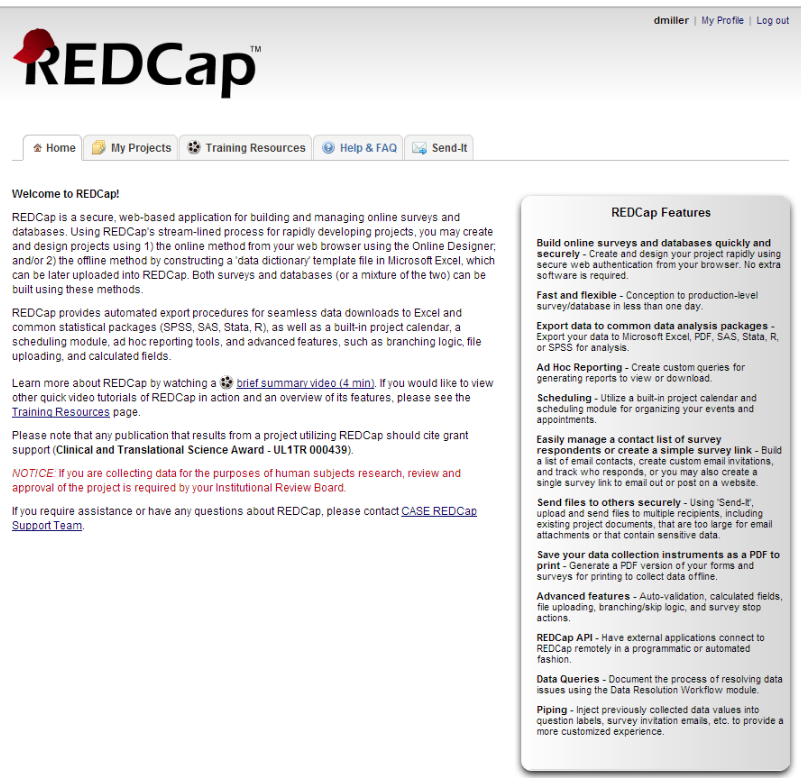
Additional Slides (for reference)

Use of REDCap Database for Transmittance Data

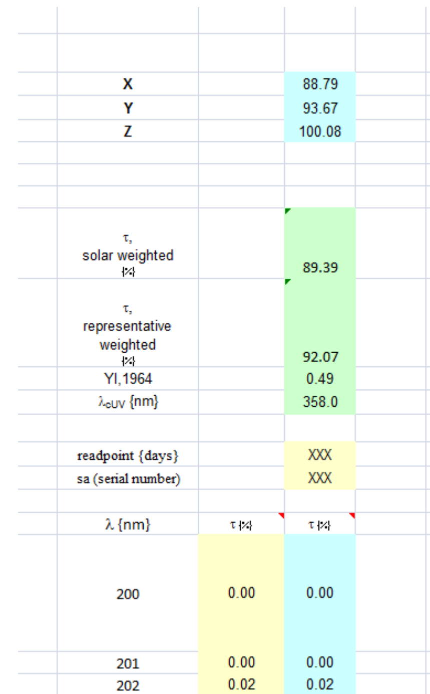
- LOTS of transmittance data will be generated for the experiment.
- Case Western Reserve University volunteered the REDcap database to TG5.
- REDCap comes from the medical (research) industry.

Benefits: Ensures designed experiments, high data capacity, simultaneous user access, automated data quality verification.

- REDCap allows users to view and analyze results in real-time.



Home screen for https://dcru.case.edu/redcap



Transmittance results will be uploaded to REDCap using an Excel template file.

Moisture Conditioning of Specimens

- Water content is a critical factor in the experiment.
- A set of 3 different conditions were applied to render an internal water content (ppm) similar to that in the aging chamber.
- Specimens were pre-conditioned for 1 month prior to distribution.
- Specimens need to be maintained with a water content during intermission (between aging and measurement).

for	condition at	NREL CHAMBER	equipment	total (3 replicates each)	total (3 replicates each) plus
40/20% & 60/20%	40/25%	S&TF 205	salt solution in oven	8	10
40/50% & 80/20%	40/46%	OTF bay	chamber	4	6
60/50%	45/85%	FTLB 158-03	chamber	3	6
80/50%	45/85%	FTLB 158-03	chamber	1	
reference	25/0%	N/A	dessicator	1	1
outdoor		N/A	CO ambient	6	
7%RH	ambient (25/low%)	N/A	CO ambient	8	
				31	23

Matrix for the pre-conditioning of samples for the TG5 experiment.

We Need Estimates of the Sample Temperature

- In weathering instruments, the sample is heated above the air temperature.
- We are sending thermocouple-equipped samples to the labs to evaluate the heating of their particular instruments.
- Depending on the sample and the chamber, they may be between 2°C and 18°C above the air temperature.