Analysis of Alternate Methods to Obtain Stabilized Power Performance of CdTe and CIGS PV Modules

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Outline

- Challenge: Transitory performance of CIGS & CdTe PV
- Study plan to probe metastable behavior
  - comprising preconditioning, thermal stress, indoor light or current soak in dark at 65° C, subsequent long-term outdoor exposure
- Modules used in study:
  - Group 1 – ended beginning of last year
  - Group 2 – finished end of last year
  - Group 3 – started end of last year, currently ongoing indoor exposures
- Cursory review of earlier Group 1 data
- Analysis of Group 2 data
- Update Status of Group 3 data
- C-V profiling data possible signature or metastability
  - carrier concentrations, depletion widths on CIGS & CdTe modules
- Summary

Issue: Transitory Electrical Behavior

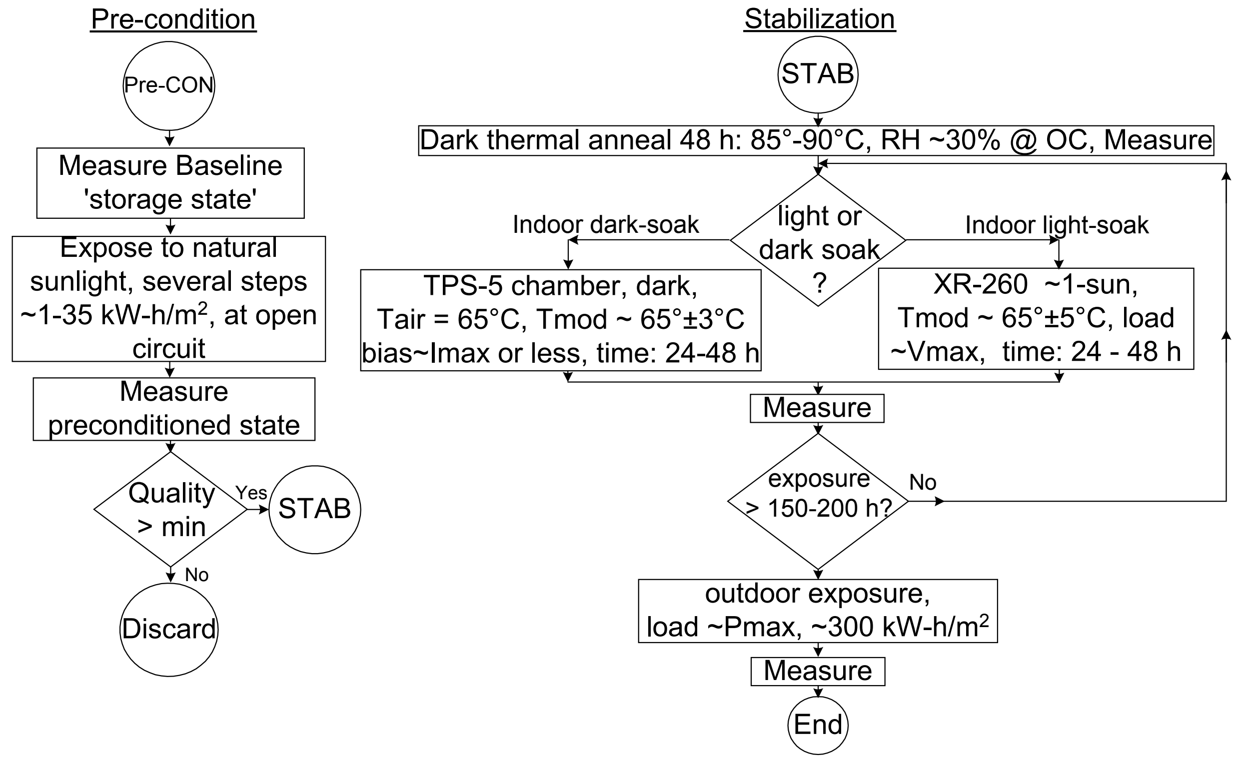
- High efficiency CdTe & CIGS thin-film PV devices exhibit transitory changes in electrical performance (I-V) at rapid (secs) & longer-term (hrs-weeks) time scales, specially after dark thermal stress or bias/light exposures
  - presents challenge assessing performance if I-V traces not consistent
  - prior history makes time between exposure and I-V measurement critical
- IEC 61646 certification standard for stabilizing thin-film PV calls for light-soaking until changes in power ≤ 2% achieved, in successive intervals of ~43 kW-h/m^2 of integrated irradiance
  - designed for a-Si, where defect mechanism is creation of dangling-bonds via light-induced Staebler-Wronski effect (SWE),
  - probably inadequate for CIGS or CdTe as these devices have different defect mechanisms
  - may even be inadequate for a-Si, because to get past SWE one really needs at least 400 h light exposure before testing for power changes between small intervals(43 kW-h)

Solution: practical preconditioning/stabilization steps

- Stabilization procedure is better if it addresses:
  - Reduced error assessing performance & measurement of temperature coefficients
    - impacts accuracy of models for long-term energy yield, and/or reliability
  - Feasibility questions: How long does it take? Resources & costs involved?
  - May need to dissect ‘transitory’ behavior into parts, reflecting time:
    - Metastable: addressing slower (maybe reversible) changes (occurring over days/weeks) that saturate to and correlate with actual field performance
    - Transients: rapid changes occurring on time scales: seconds to minutes
      - ✓ Short preconditioning step may stabilize fast/large transients & allow for manufacturers to (who must) count Watts-out per unit time from production
      - ✓ May be possible to establish correlation factor between performance assessed after preconditioning & that after stabilization steps,
        - thereby providing more accurate watts-out/time count from preconditioned state measurements
    - Instability: longer time scale, likely mostly irreversible change

Preconditioning /Stabilization Study Plan

- Preconditioning steps:
  - Wring out rapid transients, outdoor exposure at open circuit (OC) w/o temperature control
- Main Stabilization Sequence:
  - dark thermal anneal, emulates short version of stress tests in IEC certification
  - Studied two branches: 1) light soak & 2) current-soak in forward-bias in dark, ~65° ±5° C
  - Current-soak in dark is advantageous because of ease and lower cost of implementation
  - Final Outdoor exposure ~ 300 kW-h/m2 to correlate and validate indoor & outdoor stabilization



Modules Studied Groups 1, 2 and 3

- Group 1: diverse set of CdTe & CIGS mostly older modules
  - Some stored previously as controls, un-exposed; some pre-exposed outdoors; some light-soaked indoors; some new
- Group 2: 6 CIGS & 6 CdTe, identical models each type
- Group 3: 6 CdTe identical modules

Module Type	Group	Quantity	Configuration	Pre-existing exposure conditions
CdTe A	1	2	Glass-superstrate-glass laminate, monolithically interconnected	Yes, outdoors 3 years
CdTe B	1	2	Glass-superstrate-glass laminate, monolithically interconnected	Unexposed
CdTe C	1	1	Glass-superstrate-glass laminate, monolithically interconnected	Yes, indoor light-soak, 1130 kW-h in 2002
CIGS A	1	4	Glass-substrate-glass laminate, monolithically interconnected	Unexposed, 3 controls from 2003
CIGS B	1	2	Glass-flexsubstrate-glass laminate, solder bond interconnect	Unexposed, new
CdTe U	2	6	Glass-superstrate-glass laminate, monolithically interconnected	Unexposed, new
CIGS X	2	6	Glass-substrate-glass laminate, monolithically interconnected	Unexposed, new
CdTe W	3	6	Glass-superstrate-glass laminate, monolithically interconnected	Unexposed, new

Module Groups 1, 2 & 3: Prior & Present Exposure Steps

- Group 1
  - Initial CdTe A, C or CIGS A performance 5-6 years prior to baseline, was higher due to exposures outdoor or indoor
  - Phase I: part of the modules went through light soaking, part went into current soaking in dark forward-bias in;
  - Phase II: swapped modules, e.g., those previously in light-soak went to through dark current-soak and vise versa
  - Final outdoor exposure ~ 295 kW-h (after phase II) under load

- Groups 2 & 3
  - No prior exposures
  - Preconditioning, thermal anneal
  - Indoor chambers: start 3 in Light soaking, 3 in forward-bias current soaking in dark consisting of 5 steps (24-h, 48-h, 48-h, 48-h, 48-h)
  - Group 2, has final outdoor exposure 292 kW-h
  - Group 3 data up to 5th indoor increment, outside stabilization in progress

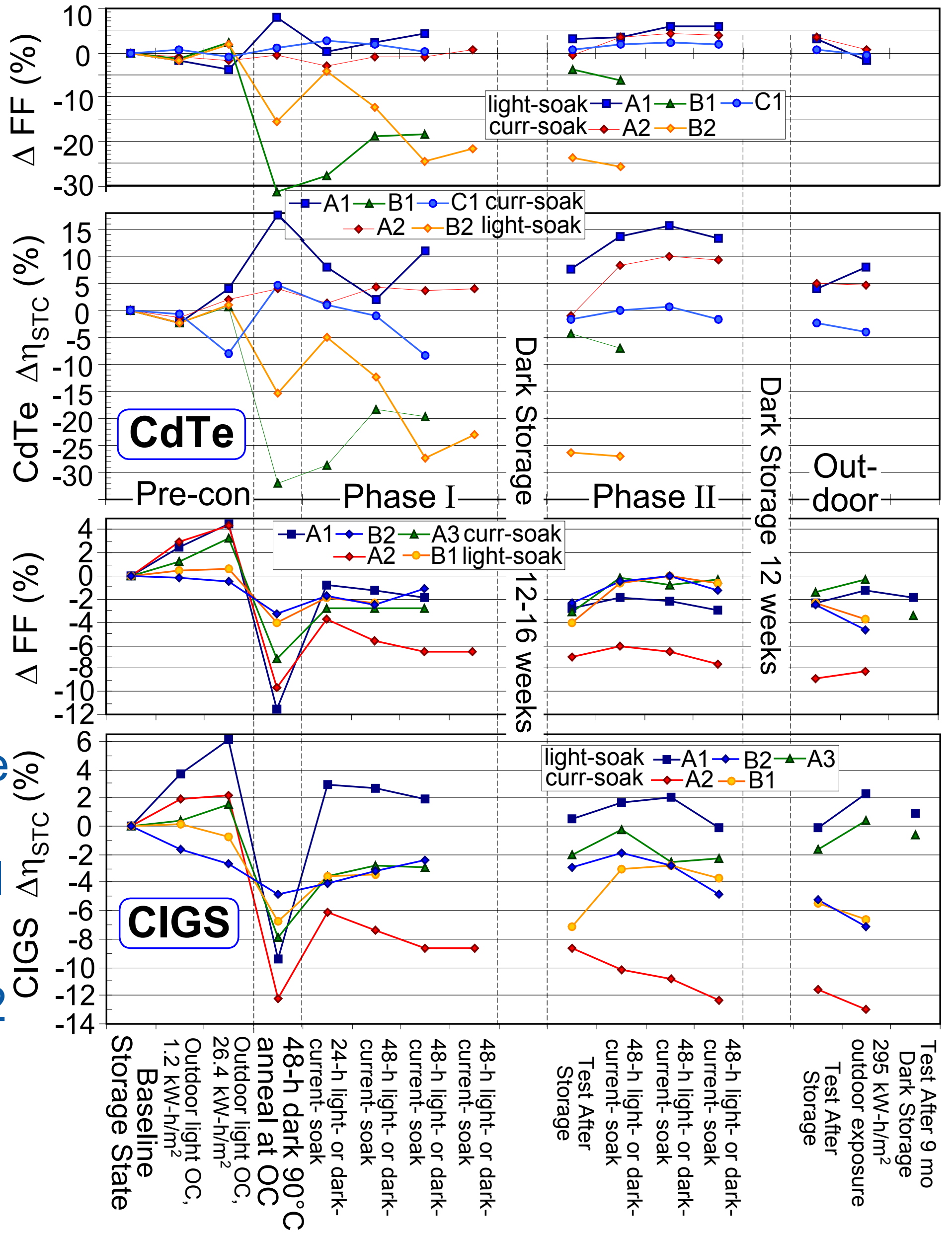
Module characterization tests

- ❑ Current-Voltage (I-V)
  - ➢ used 3 test-beds SPIRE, LACSS & SOMS outdoor for baseline performance at standard test conditions (STC)
  - ➢ used large area continuous solar simulator (LACSS) test-bed for incremental I-V performance tests; estimate Isc accuracy ~ ±1%
  - ➢ power parameter changes depicted $\Delta = X_t/X_0 - 1$, where X_0 , X_t = parameter at baseline, or time t
  - ➢ dark / light (STC), power parameters plus 2nd metrics from diode eqn. analysis (e.g., dV/dJ vs. 1/J for series Rse & diode A, dJ/dV for Gsh)

- ❑ C-V profiles measured exhibit correlations with performance changes, cursorily presented if time allows

Group 1 CIGS & CdTe Module Performance: Efficiency & FF changes vs. exposure relative to baseline

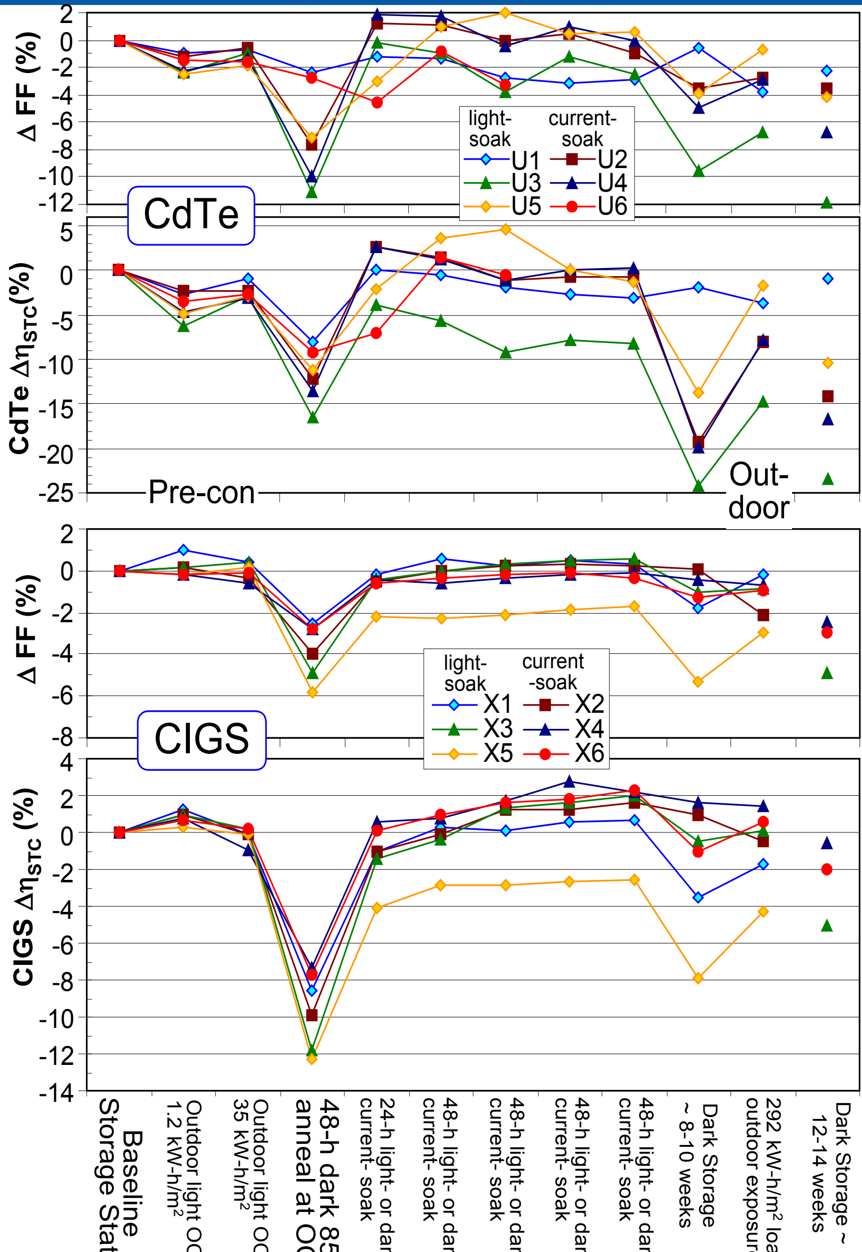
- ❑ precondition outdoor for 1, 26 kW-h/m^2
  - ❖ η_{STC} slight to moderate changes, but changes seen after 1kW-h precondition
- ❑ after dark thermal anneal , $\Delta\eta_{STC}$
  - ❖All CIGS + CdTe B drop ⇨ FF
  - ❖CdTe A & C improve
- ❑ Phase I steps: 4 light /3 dark soak
- ➢ CIGS stabilize ($\Delta \eta \leq 2\%$) in light or dark
- ➢ CdTe mixed, some stabilize (B1, A2)
- ❑ dark storage: CdTe's change 3%-5%, CIGS less ~1%-2%
- ❑ Phase II swap: 3 light/dark steps 48 h ea.
- ➢ CIGS change some, most close to stabilize
- ➢ CdTe: A stabilize per pre-existing prior to baseline, C stabilizes near baseline, Bs fail
- ❑ Final outdoor 295 kW-h exposure, loaded
  - ➢CIGS appear stabilized $\Delta \eta$~2%, but A2 shows continuing $\Delta \eta$ loss ~2%
  - ➢CdTe A2, C1 stabilize, not A1



Important summary of group 1 exposures & performance changes

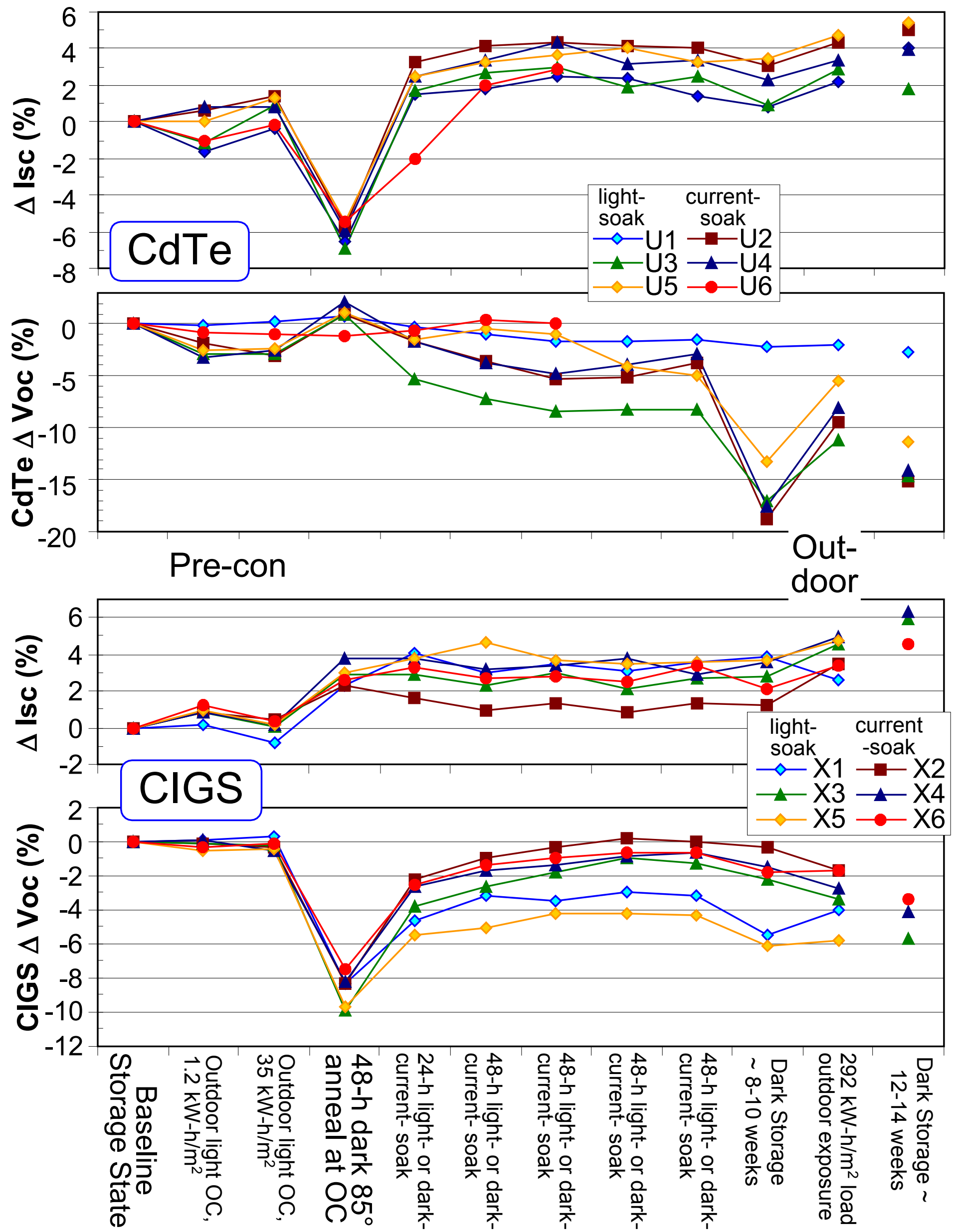
- dark thermal (85°-90° C, 48h OC) anneal
  - Typically see FF loss as largest source of degradation
  - Voc changes: all CdTe improve ~ 2%-8%, All CIGS ~ 2%-3%
- chamber current-soaks in forward bias in dark
  - phase I
    - V_{bias} chosen ~ halfway between Vmax & Voc, I_{bias} <20% I_{max},
    - might have stifled stabilization
  - phase II
    - V_{bias} closer to Voc than phase I, I_{bias} ~ 80%* Imax
    - probably accelerated stabilization & changes
- dark storage intervals between phases
  - Improve Voc in CIGS A by 2%, diminish Voc in CdTe A 3%-5%
- outdoor exposure
  - CIGS A stabilize near levels after phase II, light soaking or current-soak appear to work equally well
  - CIGS B met stabilization criteria~ 2% light/dark-soak, but trends in same direction as changes in phase II so may not have stabilized
  - CdTe A,C mixed: light soak may work better, but sizable changes in Voc appear after dark

Group 2 CIGS X & CdTe U Module Performance: Efficiency & FF changes vs. exposure relative to baseline



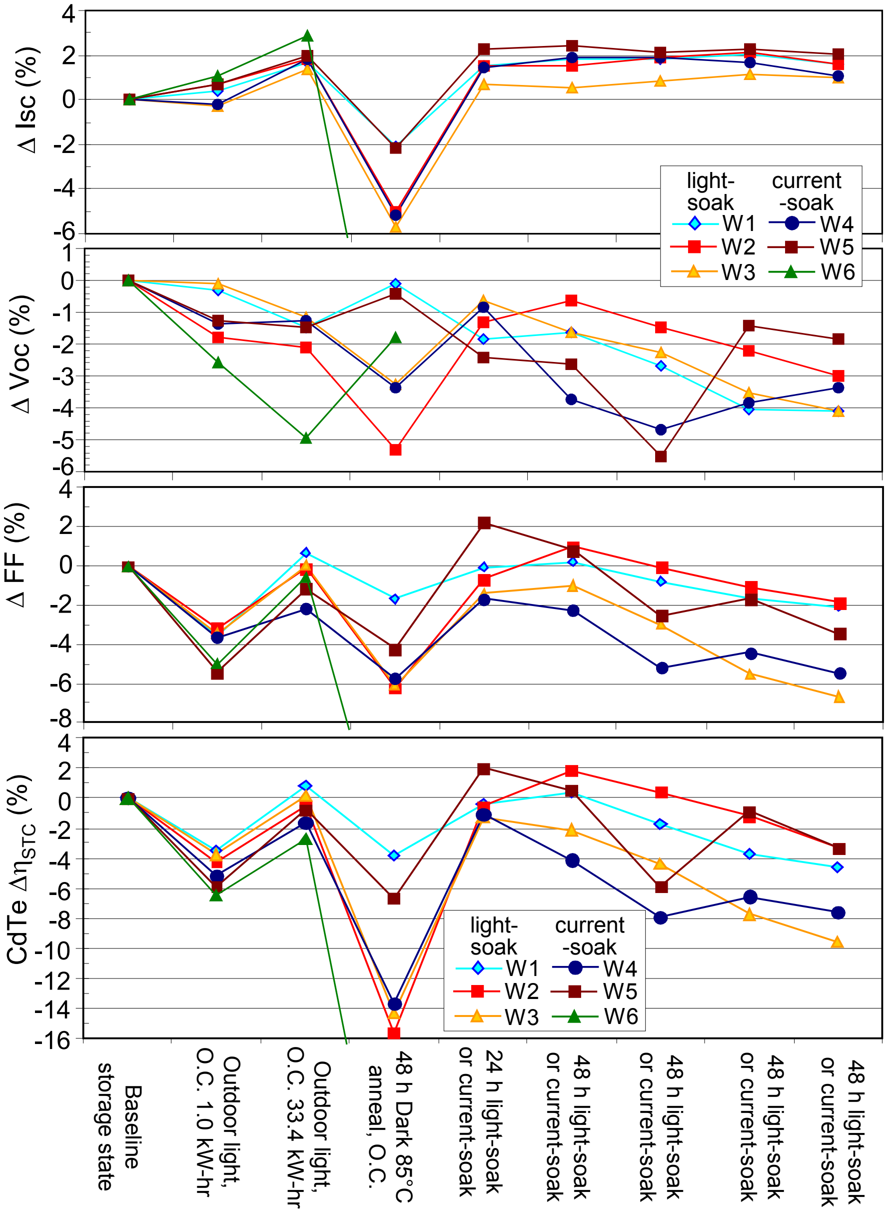
- Preconditioning 1, 35 kW-h lowers η_{STC} slightly ~ 0%-1% in CIGS X, moderately ~1%-5% in CdTe U
- Dark anneal degrades η_{STC}
  - CIGS X by 8%-12%, CdTe U by 8%-17%
  - FF loss accounts for half the loss in CIGS
  - Similar FF loss in CdTe U except for 1 & 6
- subsequent light or dark current soaks
  - 1st 24-h incr. recovers η_{STC} loss in CIGS to within 4%, in CdTe to +2% to -4%
  - either stabilize equally η_{STC} & FF in CIGS <1% after 96 h or CdTe after 200 h
- Dark storage drops performance
  - In CIGS X: modestly 1%-5% largely FF
  - In CdTe U: 13%-20%, some by FF
- Outdoor exposure validates stabiliz'ng η_{STC} using either light/current soak for CIGS, may indicate light-soak more effective for CdTe
- Changes still observed in dark storage at end

Group 2 CIGS X & CdTe U Module Performance: Voc & Isc changes vs. exposure relative to baseline



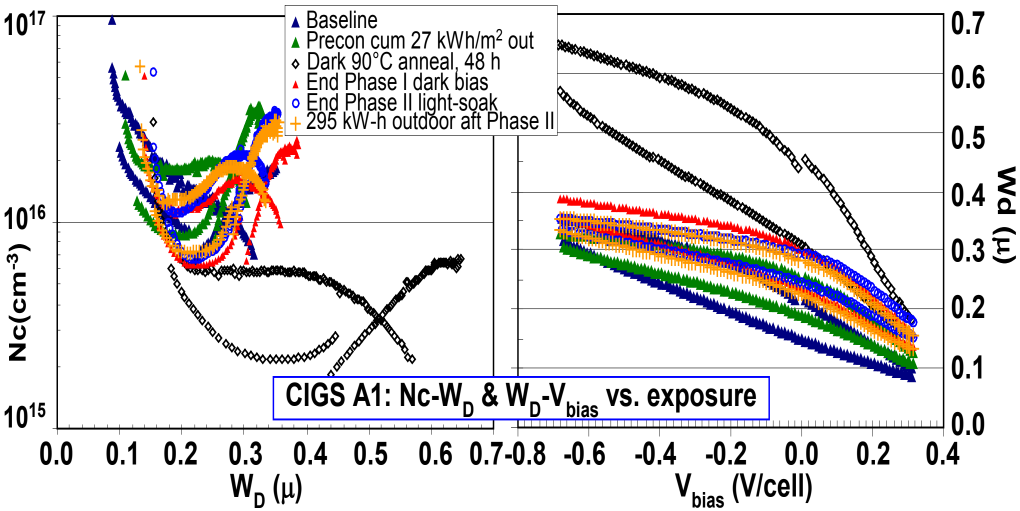
- Preconditioning 1, 35 kW-h: slight changes in Voc in CIGS X but larger ΔVoc in CdTe U; slight ΔIsc both
- Dark thermal (85° C) anneal
  - CIGS X , drops Voc by 8%-10%, bumps Isc up by 2% to 4%
  - CdTe U, drops Isc by 5%-7%, Voc ±1%
- sequel light or current soaks:
  - both seem to stabilize Voc & Isc
  - current-soak recovers more Voc in CIGS, less in CdTe, Isc responds to both
  - CdTe recovers slight better in light soak
- Dark storage diminishes Voc:
  - for CdTe ~12%-18% except U1;
  - for CIGS ~1%-2%
- Outdoor exposure
  - recovers Voc loss in CdTe U
  - Bumps Isc in both CIGS & CdTe by 2%,

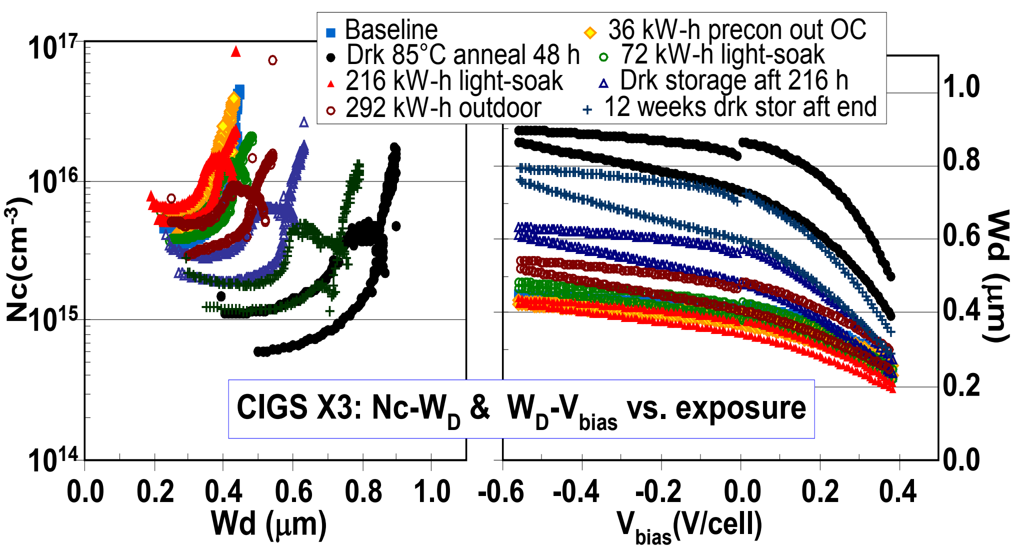
Group 3 CdTe W Module Performance: η_{STC}, FF Voc & Isc changes vs. exposure relative to baseline



- Preconditioning 1, 33 kW-h/m^2
  - 1st incr. drops η_{STC} ~3%-7%, then mostly thru FF & Voc loss
  - 2nd incr. recovers loss for total change -5% to +1% largely due to FF or Isc, not Voc
- Dark thermal anneal drops η_{STC} ~5-15%,
  - thru various combination FF, Voc, Isc loss
  - Isc loss in all, quite large (10%) for W2,W3
- post-thermal anneal light/current soaks incrs.
  - 1st 24 h recover most η_{STC} loss via FF, Isc
  - 2nd 48 h $\Delta\eta_{STC}$ ~ ±2% ambiguous due to opposing FF, Voc changes
  - 3rd 48-h $\Delta\eta_{STC}$ range -2% to -6%, mostly via Voc, FF losses in either light/current soak,
  - 4th 48-h $\Delta\eta_{STC}$ ~ +2% to +6% in current soak, but -2% to -3% loss in light-soak
    - Gains in current-soak from Voc
- 5th 48-h $\Delta\eta_{STC}$ ~1%-2% further losses maybe stabilization reached

Sample C-V profile data: CIGS A & U modules derived depletion widths (W_D) and Carrier densities (Nc) data

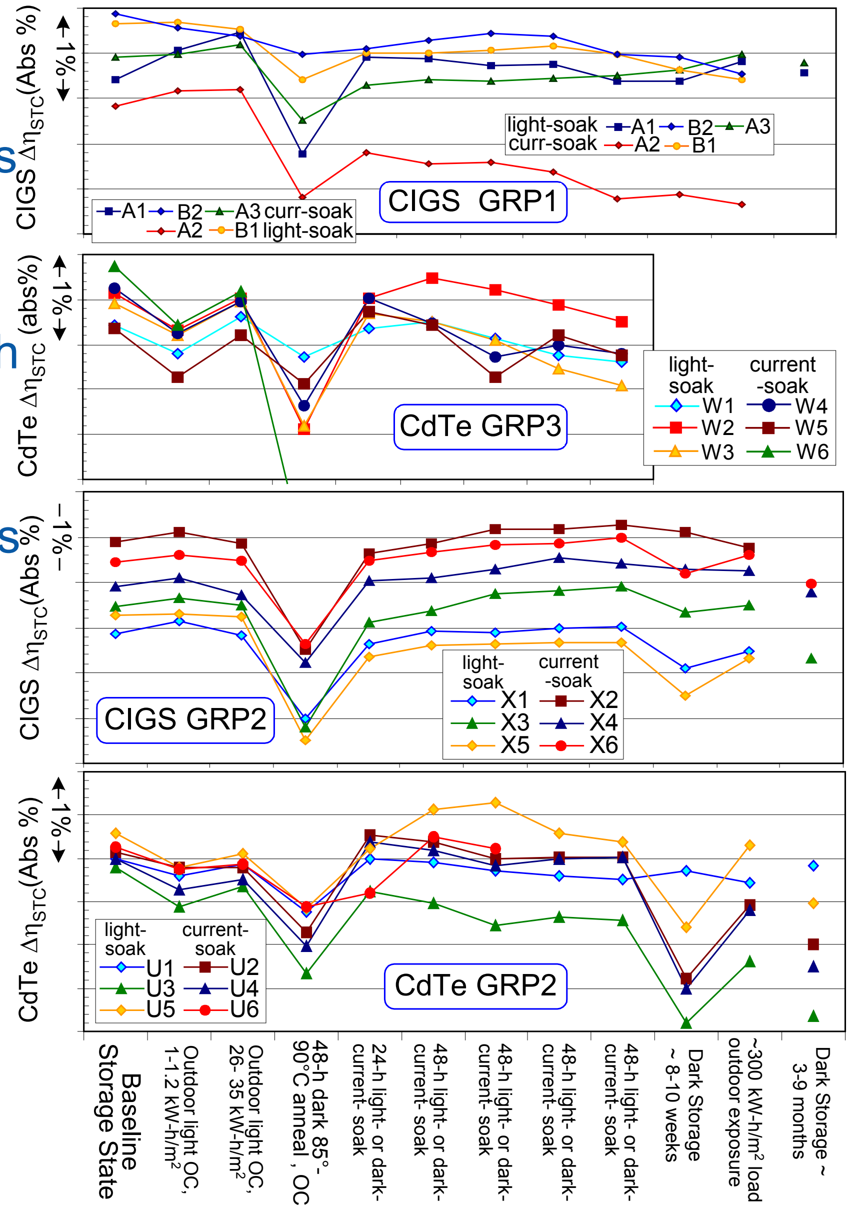




- CIGS A1 top, X3 at bottom
- Baseline W_D : similar ranges 0.1-0.3 μ for A1, 0.2-0.4 μ for X3
- Preconditioning has slight: widening on W_D ; lowers max Nc
- Dark thermal anneal large effect:
  - displaces W_D up by 2X to 3X & increases hysteresis
  - Drops Nc by factor 5 -10 to 10^{15}
- Indoor exposures drive W_D & Nc profiles to levels @ precon or base
- Outdoor exposure shifts A1 profiles closer to precon/baseline

Group 1, 2, 3 module absolute changes Eff η_{STC} plotted

- Plots vs. precondition, stress & exposures
  - grp 1 CIGS A & B at top, grp 3 CdTe 2nd from top panel, grp 2 CdTe & CIGS bottom 2 panels
  - groups begin with range $\Delta\eta_{STC} \leq 1\%$ abs., end with range $\Delta\eta_{STC} \leq$ ½% - 1½%
  - Preconditioning should be > 10 kW-h to quench transients, 1 kW-h does not seem enough
  - Dark thermal anneal drops most η_{STC} 1%-2% that seems recoverable after light/current soaks for most but not all, specially CdTe
  - Some modules (CIGS A2, CdTe U3) exhibit longer-term instability beyond metastability, which challenges notion that longer term outdoor exposures reflect performance better
  - Stabilizing w current soak in dark bias seems
    - ❖as good as light soak in CIGS
    - ❖feasible in CdTe but not as good as light
  - dark storage alters η_{STC} ~½% after outdoor stabilization past end or between exposures



Summary

- Thin-film CIGS & CdTe PV show transitory electrical performance ranging from fast (secs) transients to long (hours-days) time scales
  - Specially after dark thermal stress (85°C or more) or exposure
- Fast transients, may be quenched by preconditioning (20-30 kW-h) using outdoor light exposure, less may be possible, but need more than 1 kW-h

- For newer CIGS: preconditioned η_{STC} values are close to end-of-exposure levels; seem to stabilize after 100-150 h exposures at 65°C

- CdTe modules exhibit more variation in stabilization behavior than newer CIGS, thru variations in all power parameters, may need more like 200+ h exposure to stabilize
  - It's possible that we don't yet know what a representative sample size for CdTe modules is (to determine stabilization behavior).
  - To determine more representative sample size for CdTe, it may be better to deploy and monitor I-Vs in larger set, perhaps ~25-100 outdoors

- Time between measurement of I-V characteristics after stabilization procedures should be kept as short as possible, at least less than 1-2 hours

Summary

- ❑ Implemented two types stabilization procedures using : 1) light soak at 1-sun and 2) current-soak (forward bias dark), 65° ±5° C
- ❑ if current stabilization criterion used, $\Delta\eta \leq 2\%$ between successive intervals:
  - ➢ Current- or light-soaks capable of stabilizing CIGS modules, after ~150 h at 65° C
    - ❖ current-soak in dark should be performed with I_{bias} ~80%-90% I_{max} for acceleration
  - ➢ light soak may be more efficient than current soak for stabilizing CdTe, but higher temperature or larger current bias (in dark) may speed it up
  - ➢ CdTe probably needs even longer exposure than CIGS to stabilize

- ❑ Recommend IEC stabilization protocol be refined to require minimum ~150-200 h exposure for all thin-film modules,
  - ➢ specially if they are poly-c thin film & undergo dark thermal exposure
  - ➢ avoid successive steady low relative loss trends from biasing stabilization

- ❑ Will soon deploy group 3 CdTe set outdoors for 6-10 weeks to validate efficacy of light- or dark current- exposures against outdoor stabilized performance…Will next start testing newer CIGS (group 4) module set

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