

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 $\leq 2\%$ achieved, in successive intervals of $\sim 43 \text{ kW-h/m}^2$ 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

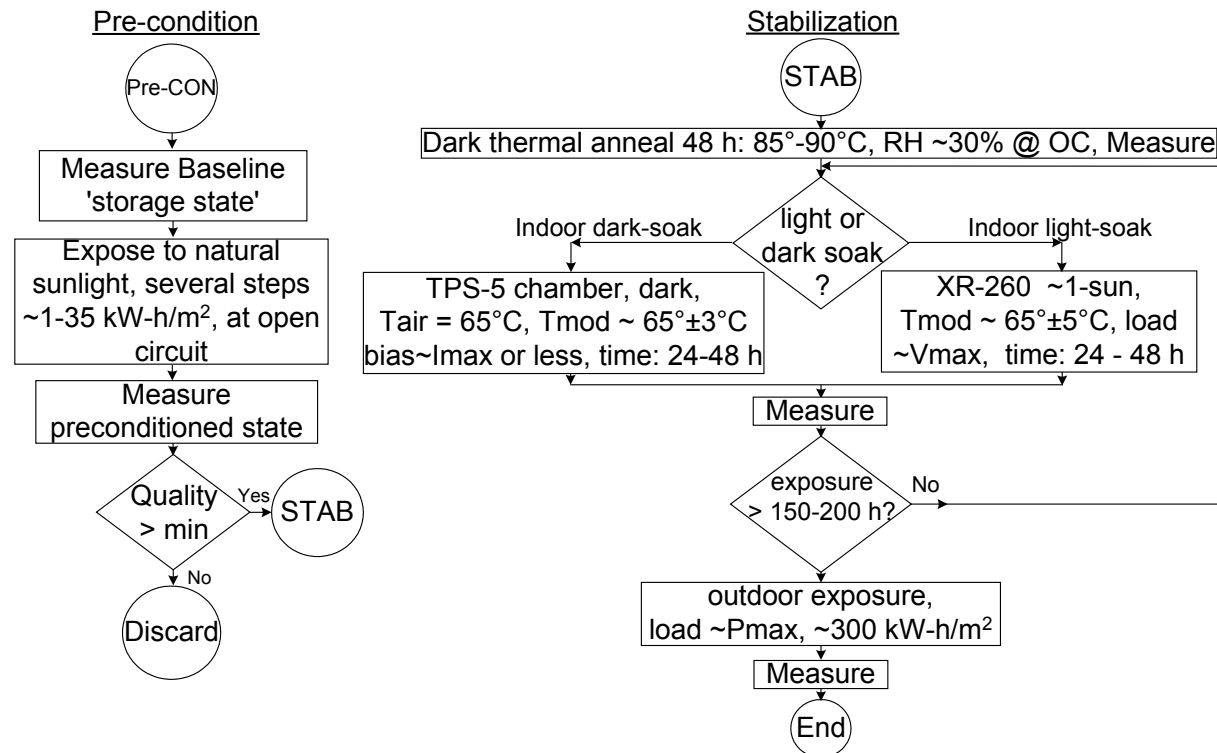
Preconditioning /Stabilization Study Plan

□ 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, $\sim 65^{\circ} \pm 5^{\circ} \text{ C}$
- Current-soak in dark is advantageous because of ease and lower cost of implementation
- Final Outdoor exposure $\sim 300 \text{ kW-h/m}^2$ 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 vice 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)

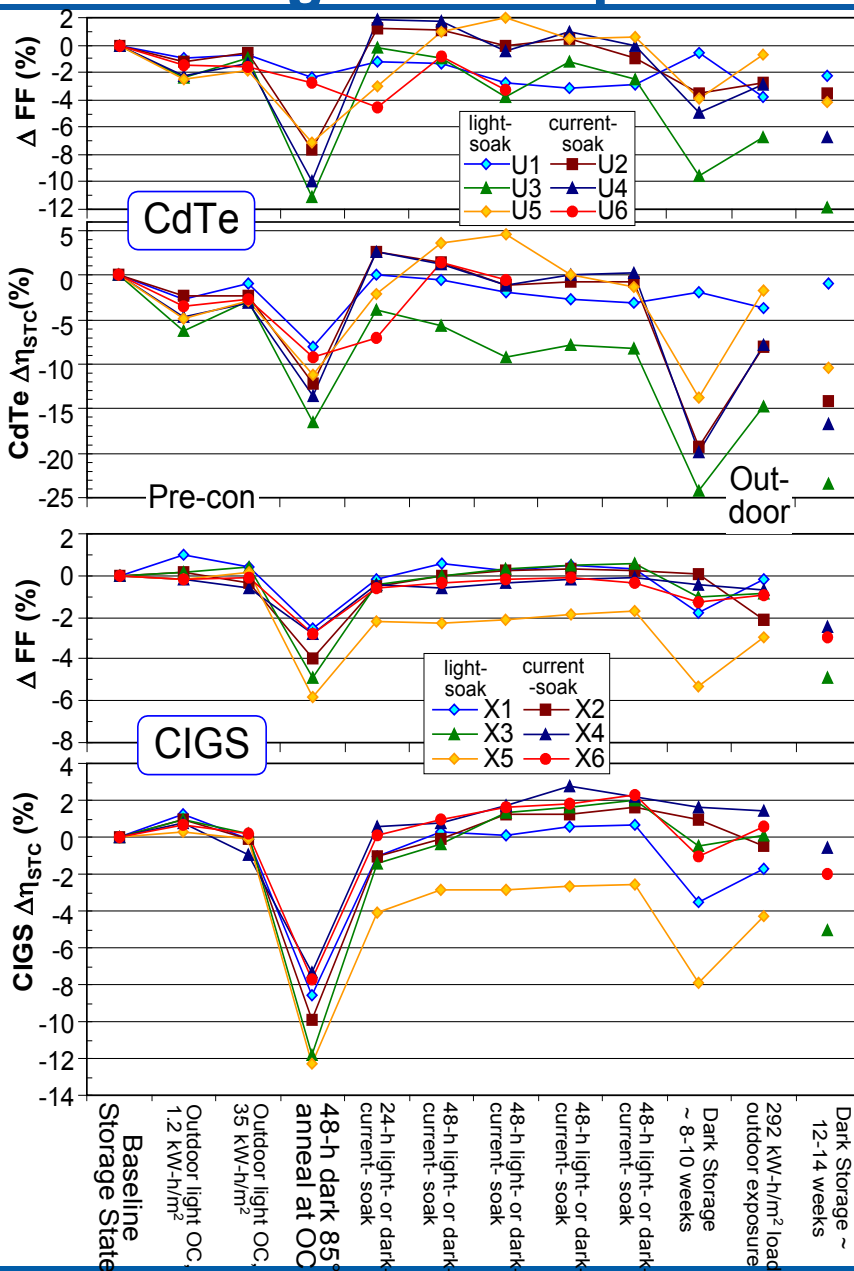
- used 3 test-beds SPIRE, LACSS & SOMS outdoor for baseline performance at standard test conditions (STC)
- used large area continuous solar simulator (LACSS) test-bed for incremental I-V performance tests; estimate I_{sc} accuracy $\sim \pm 1\%$
- power parameter changes depicted $\Delta = X_t/X_0 - 1$, 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 R_{se} & diode A , dJ/dV for G_{sh})

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

Important summary of group 1 exposures & performance changes

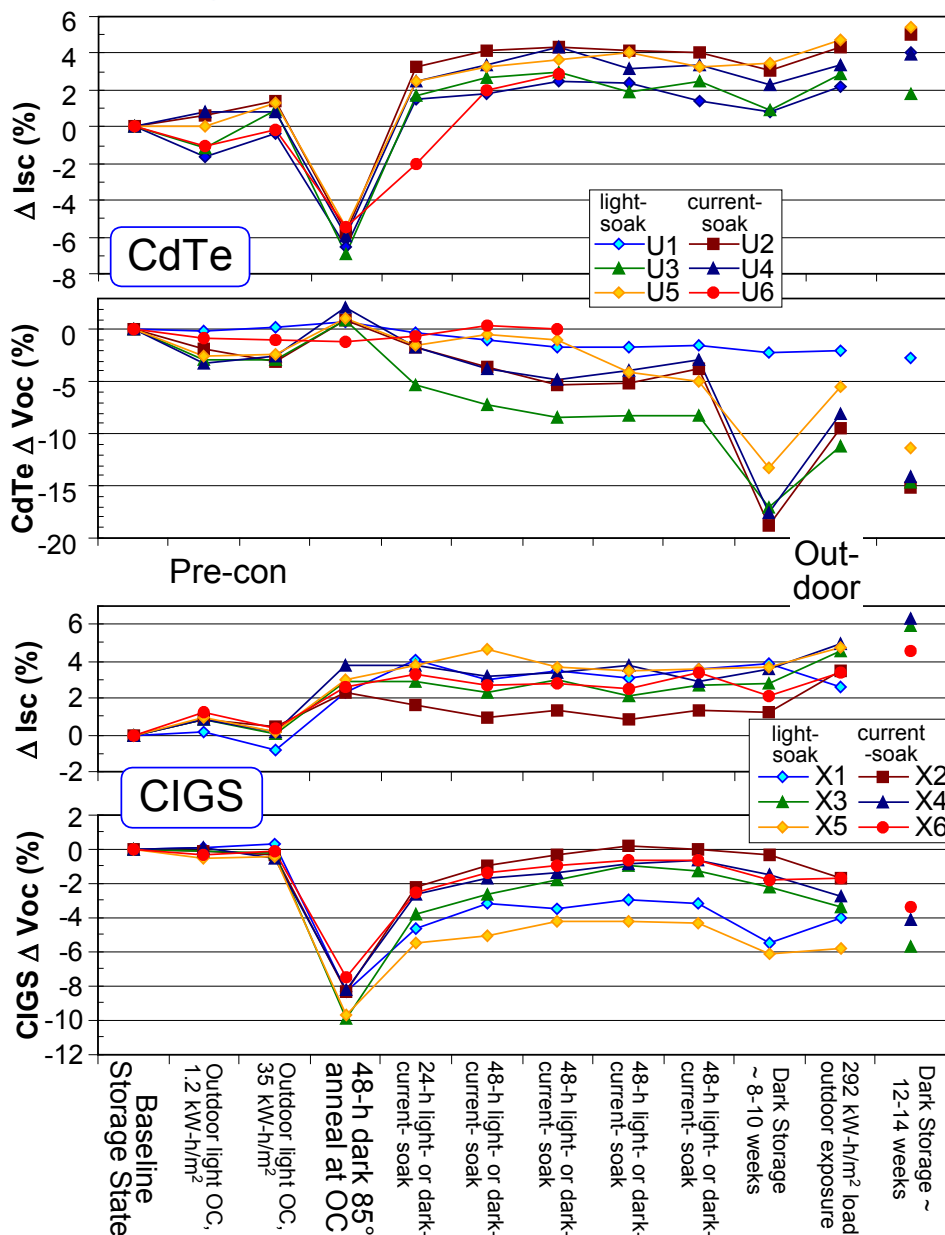
- ❑ dark thermal (85° -90° C, 48h OC) anneal
 - Typically see FF loss as largest source of degradation
 - Voc changes: all CdTe improve ~ 2%-8%, All CIGS ~ 2%-3%
- ❑ chamber current-soaks in forward bias in dark
 - phase I
 - ❖ V_{bias} chosen ~ halfway between V_{max} & V_{oc} , $I_{bias} < 20\% I_{max}$,
 - ❖ might have stifled stabilization
 - phase II
 - ❖ V_{bias} closer to V_{oc} than phase I, $I_{bias} \sim 80\% I_{max}$
 - ❖ 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



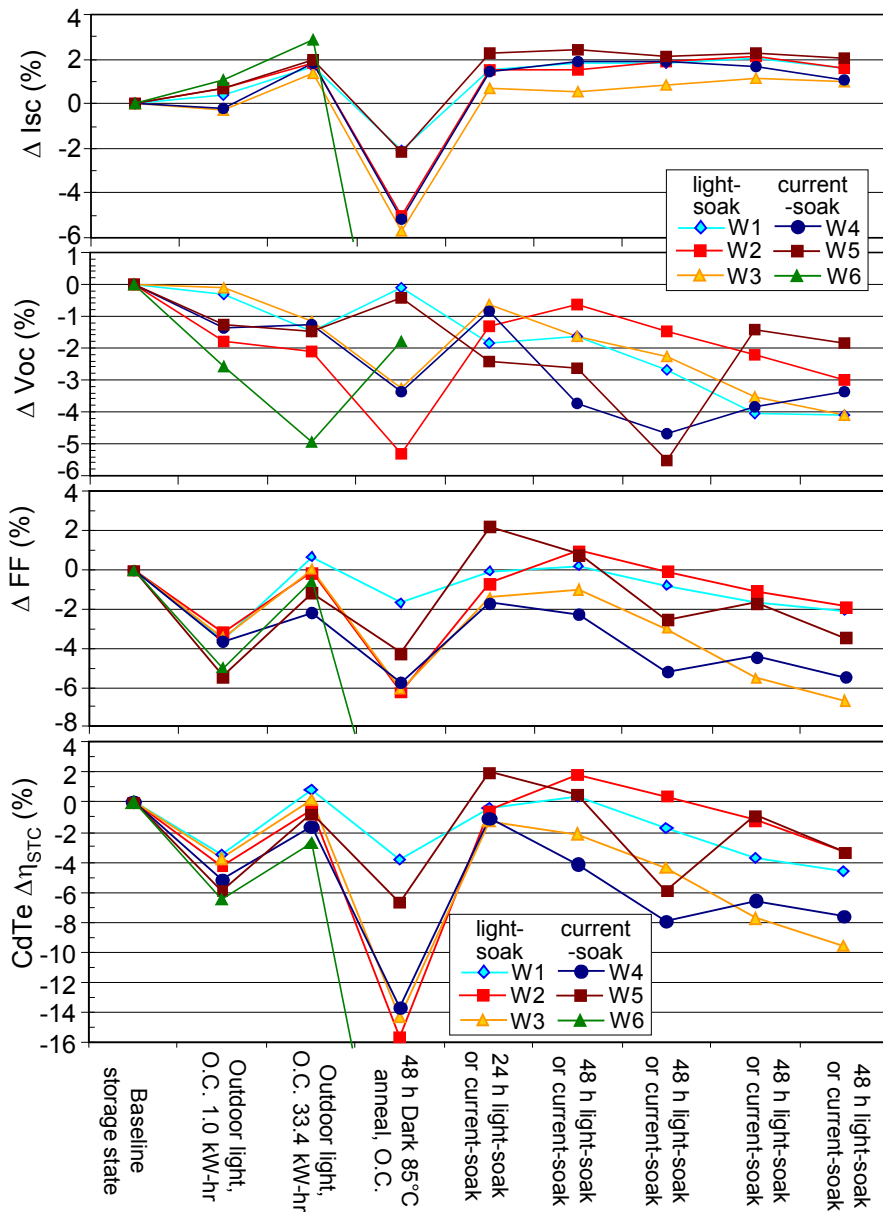
- Preconditioning 1, 35 kW-h lowers η_{STC} slightly ~ 0%-1% in CIGS X, moderately ~1%-5% in CdTe U
- Dark anneal degrades η_{STC}
 - CIGS X by 8%-12%, CdTe U by 8%-17%
 - FF loss accounts for half the loss in CIGS
 - Similar FF loss in CdTe U except for 1 & 6
- subsequent light or dark current soaks
 - 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/m²

➤ 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 $\Delta\eta_{\text{STC}}$ ~ $\pm 2\%$ ambiguous due to opposing FF, Voc changes

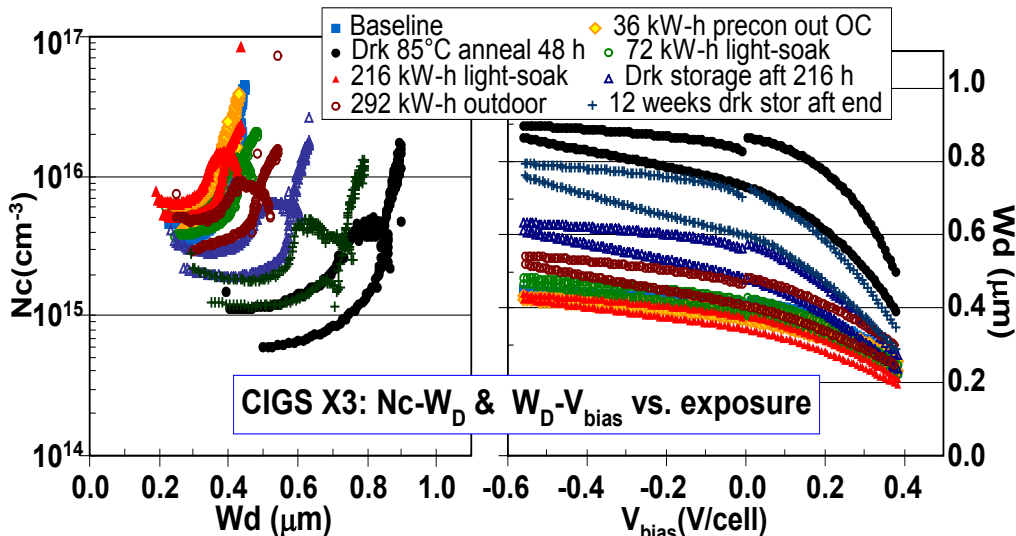
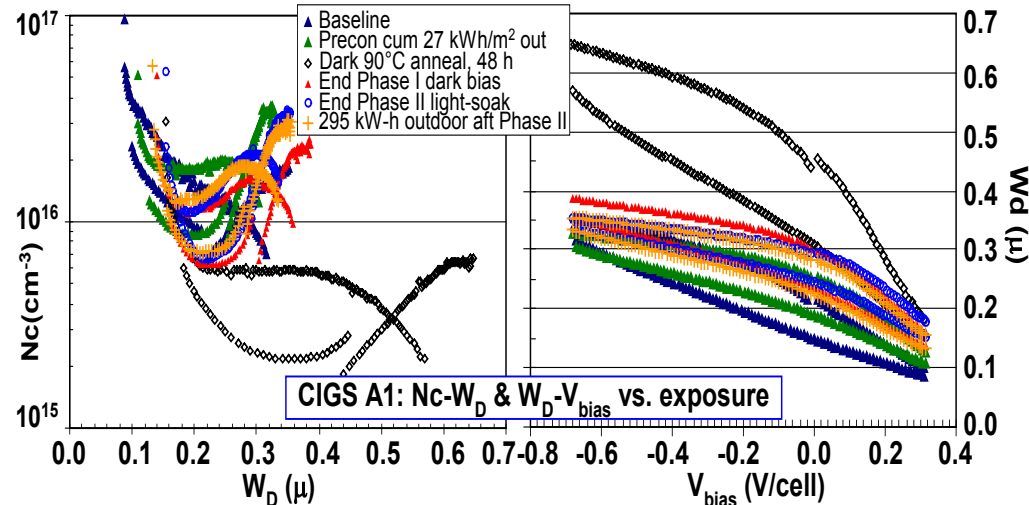
➤ 3rd 48-h $\Delta\eta_{\text{STC}}$ range -2% to -6%, mostly via Voc, FF losses in either light/current soak,

➤ 4th 48-h $\Delta\eta_{\text{STC}}$ ~ +2% to +6% in current soak, but -2% to -3% loss in light-soak

❖ Gains in current-soak from Voc

□ 5th 48-h $\Delta\eta_{\text{STC}}$ ~1%-2% further losses maybe stabilization reached

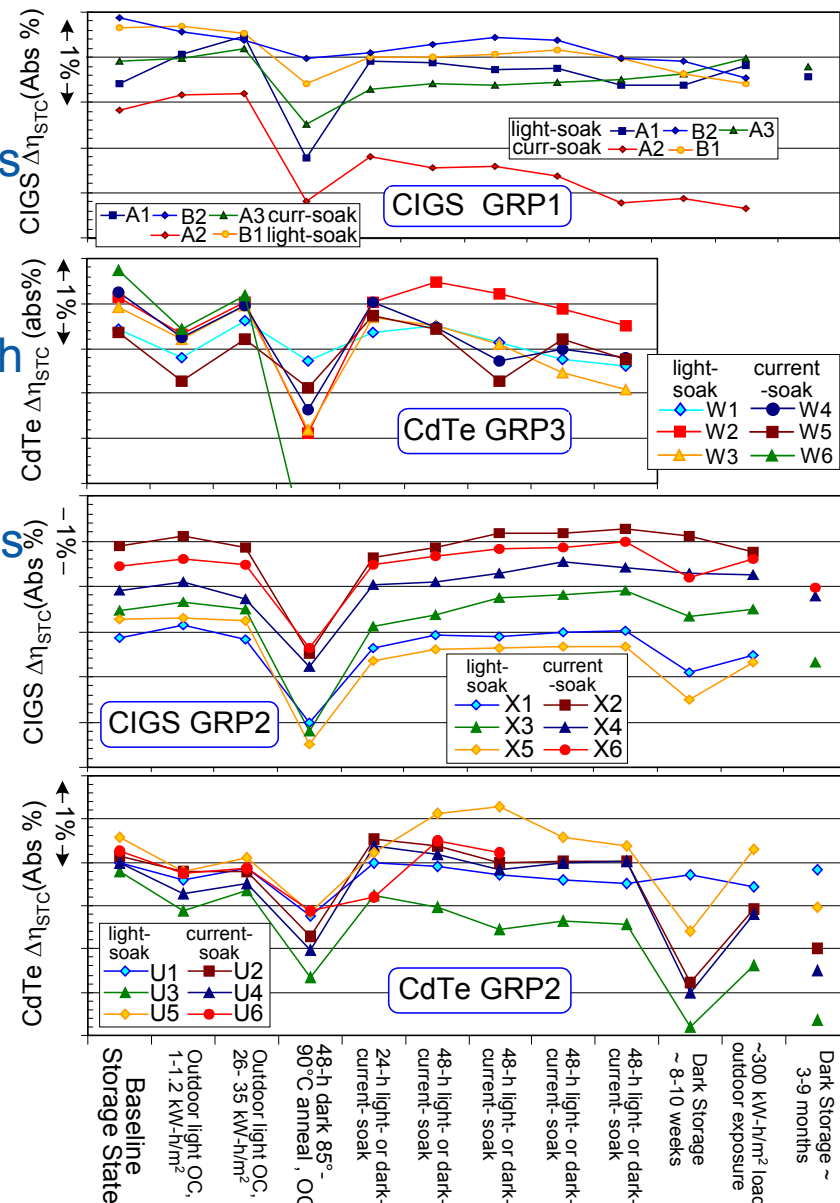
Sample C-V profile data: CIGS A & U modules derived depletion widths (W_D) and Carrier densities (N_c) data



- 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 N_c
- Dark thermal anneal large effect:
 - displaces W_D up by 2X to 3X & increases hysteresis
 - Drops N_c by factor 5 -10 to 10^{15}
- Indoor exposures drive W_D & N_c 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 $\Delta\eta_{STC} \leq \frac{1}{2}\% - 1\frac{1}{2}\%$
 - 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 $\eta_{STC} \sim \frac{1}{2}\%$ 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), $65^{\circ} \pm 5^{\circ} \text{ C}$
- ❑ if current stabilization criterion used, $\Delta\eta \leq 2\%$ between successive intervals:
 - Current- or light-soaks capable of stabilizing CIGS modules, after $\sim 150 \text{ h}$ at 65° C
 - ❖ current-soak in dark should be performed with $I_{\text{bias}} \sim 80\%-90\% I_{\text{max}}$ 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 $\sim 150\text{-}200 \text{ h}$ 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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