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Innovation for Our Energy Future

National Center for Photovoltaics

Quantifying the Weather: an analysis for thermal fatigue

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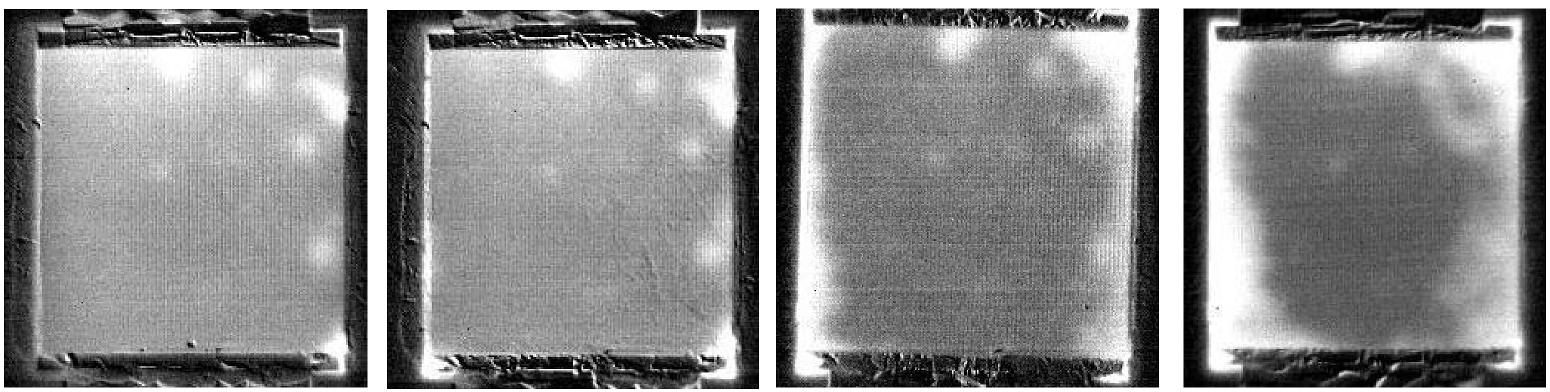
This presentation does not contain any proprietary or confidential information.

quantifying the weather

Problem:

- Thermal fatigue will cause die-attach failure.
- How can we predict this failure if it’s driving force is weather?



initial | 500 cycles | 1000 cycles | 1500 cycles

- Progression of IR images illustrating die-attach cracking through thermal cycling [1]

quantifying the weather

Questions:

- Can we quantify the amount of thermal cycling damage a deployed module will accumulate?
- If known, can we relate this damage to that incurred during accelerated testing?
- Will a life-time prediction result?

quantifying the weather

Can we quantify the amount of thermal cycling damage a deployed module will accumulate?

- What is the cell/ module temperature when in service?
- As this temperature changes, how do we quantify those changes (cycles)?
- Once known, how can we relate those changes to module damage?

quantifying the weather: temp model

What is the cell/ module temperature while in service?

Given local metrological data, models exist to estimate cell temperature:

Steady State Models

$$T_{cell} = T_{amb} + E\exp\left(a + bW\right) + ER$$

$$T_{cell} = T_{amb} + E\exp\left(a + bW\right) + \frac{E}{E_o}\Delta T$$

D. L. King, W. E. Boyson, and J. A. Kratochvil, "Photovoltaic array performance model," Sandia National Laboratories SAND2004-3535, 2004.

Non-Steady State Model

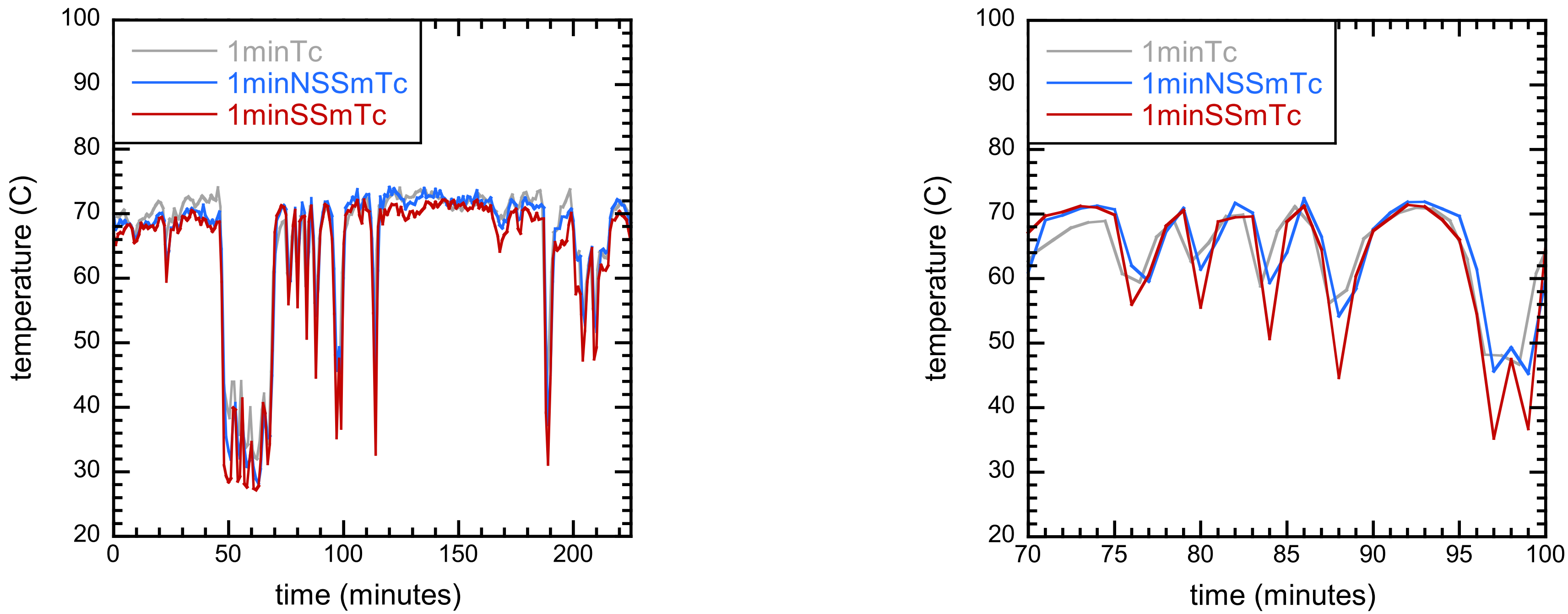
$$T_{cell}\left(t+1\right) = T_{cell}\left(t\right) + \frac{dT_{cell}}{dt}$$

$$\frac{dT_{cell}}{dt} = f\left(E, A, \varepsilon, T_{amb}, T_{cell}, h_c, C_m\right)$$

A. D. Jones and C. P. Underwood, "A thermal model for photovoltaic systems," *Solar Energy,* vol. 70, pp. 349-359, 2001

quantifying the weather: temp model

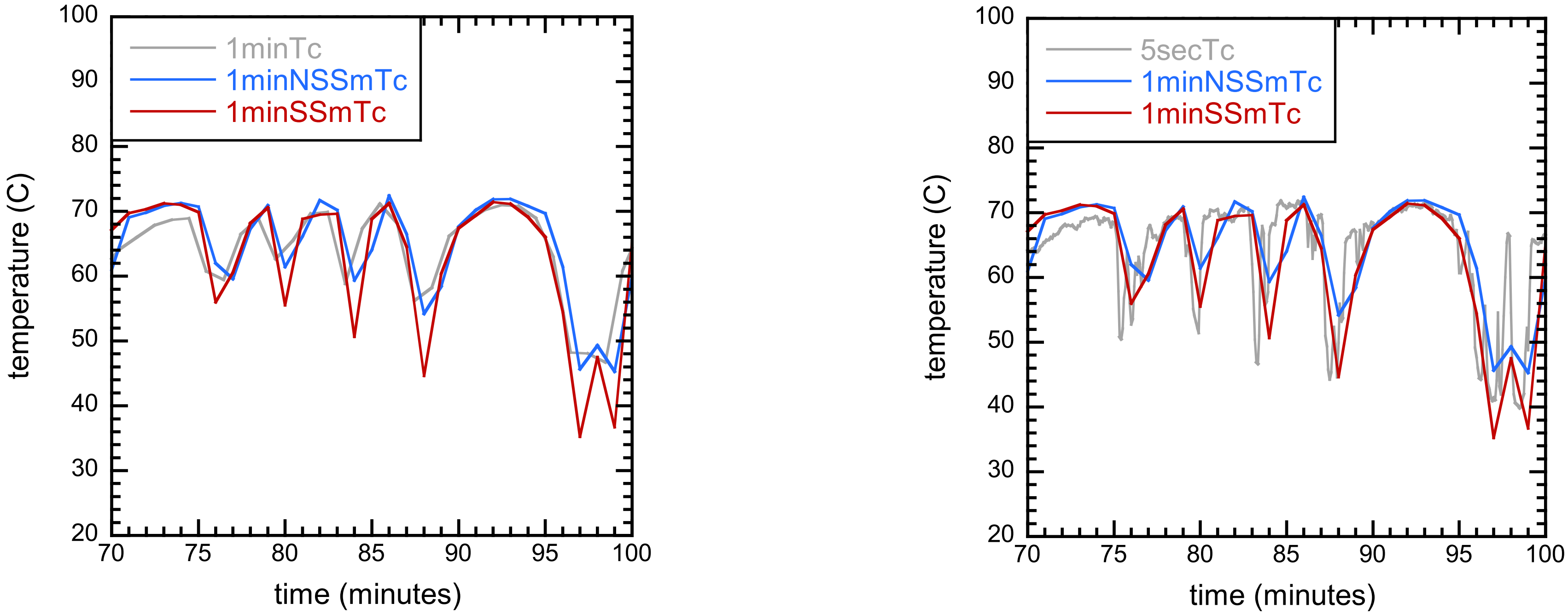
Comparison of temperature models



- The non-steady state model estimates the 1 minute average data well.
- The steady state model underestimates temperature “valleys” since it assumes an equilibrium condition has been reached.

quantifying the weather: temp model

Comparison of temperature models

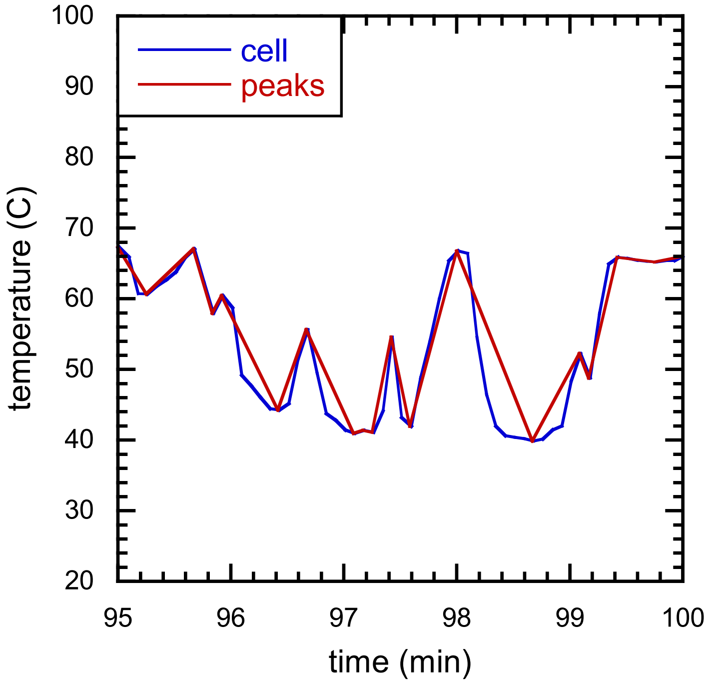


- When considering 5 sec. data, the steady state model fits better (and is used for this study).
- Note 5 sec. data reveals detail not captured with with the less frequent data.

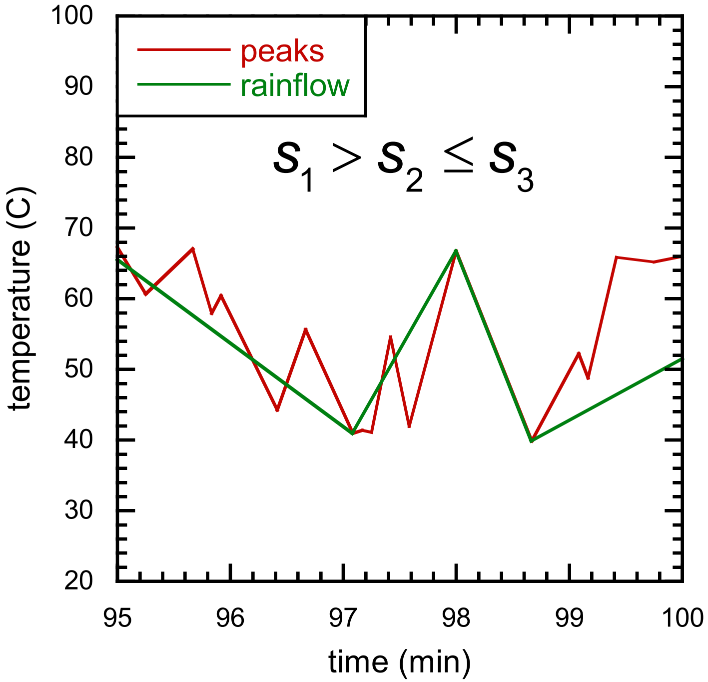
quantifying the weather: rainflow

As this temperature changes, how do we quantify those changes?

1. Peak and Valley



2. Rainflow count



- See and references [2&3] for more details on the rainflow counting algorithm.

1. maximum temperature T_{max}
2. temperature change ΔT
3. transition time t_t

thermal fatigue modeling

Once known, how can we relate those changes to module damage?

Damage: Thermal fatigue of solder die attach

I :<u>Engelmaier thermal fatigue model</u>

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma_p}{2\varepsilon_f}\right)^{\frac{1}{c}}$$

where

$$\Delta\gamma_p = \frac{\sqrt{2}FL}{2h}\Delta\alpha\Delta T$$

$$c = -0.422 - 6\cdot10^{-4}T_{mean} + 1.74\cdot10^{-2}\ln\left(1+\frac{360}{t_d}\right)$$

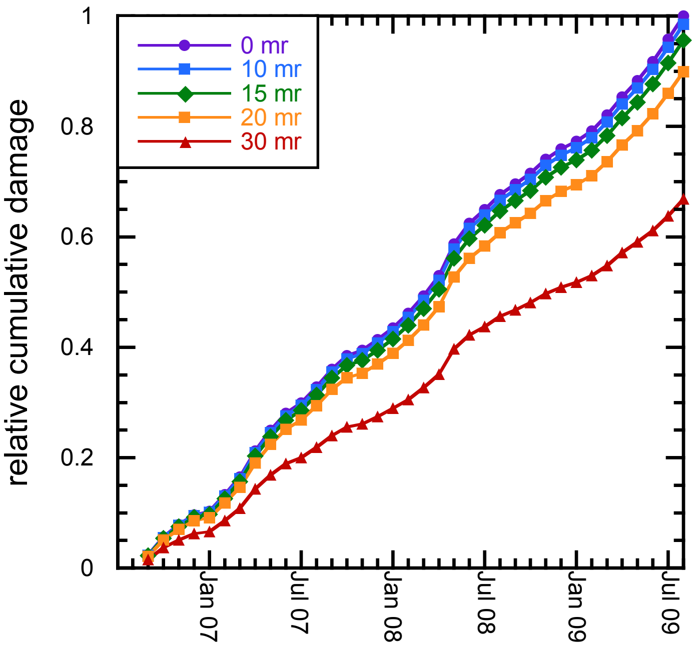
II: <u>Palmgren-Miner rule</u>

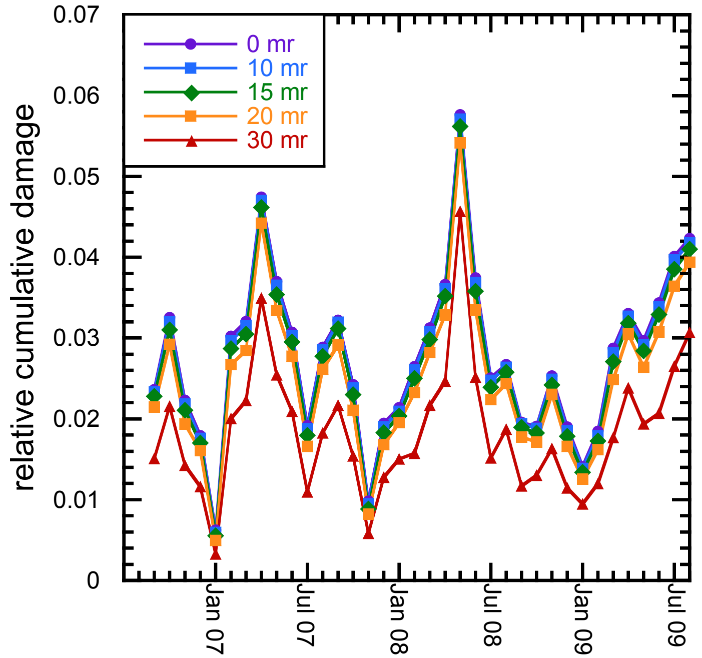
$$D = \sum_i \frac{n_i}{N_i}$$

$$\boxed{D = \sum_i \Delta T_i^{-\frac{1}{c_i}}}$$

damage analysis

3 years in Golden, CO: damage accumulation

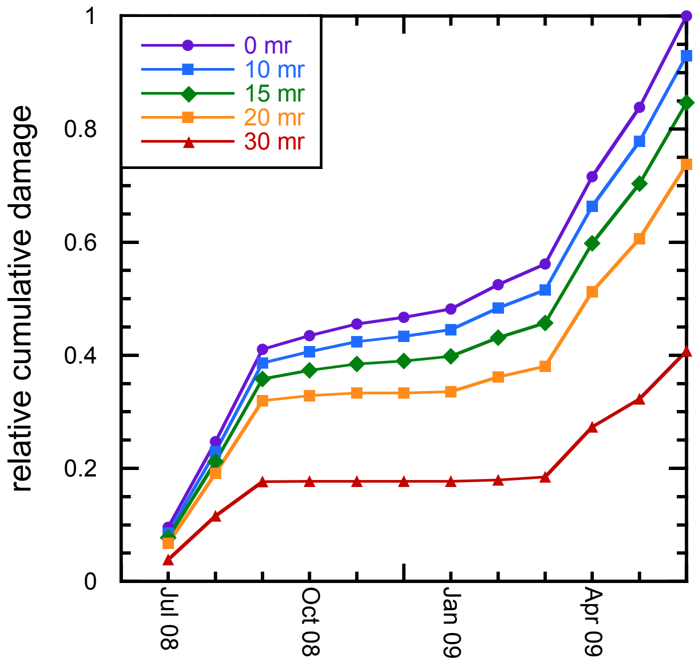


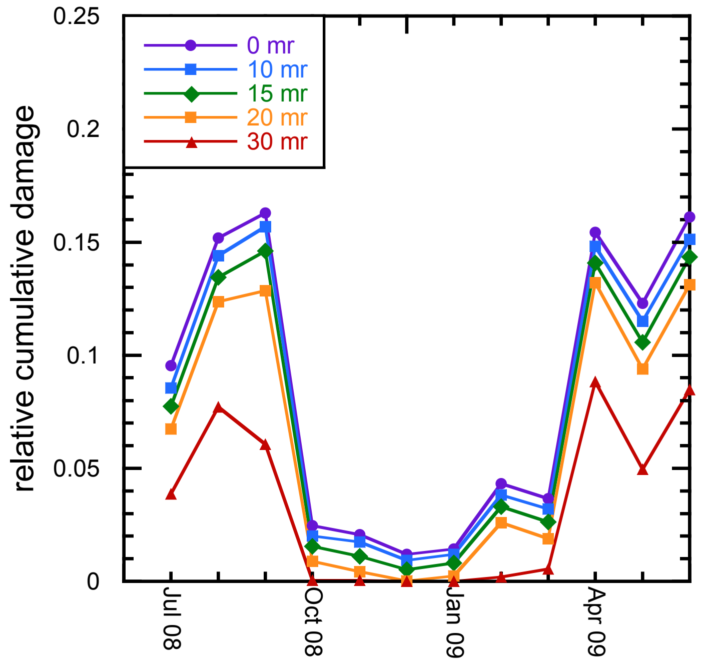


- Separate curves represent that only cycles with that minimum temperature range are considered in the calculation.
- For instance, ~67% of the damage is done by cycles with a temperature range of 30 C or greater (red curve).

damage analysis

1 year in Sanary, France*: damage accumulation

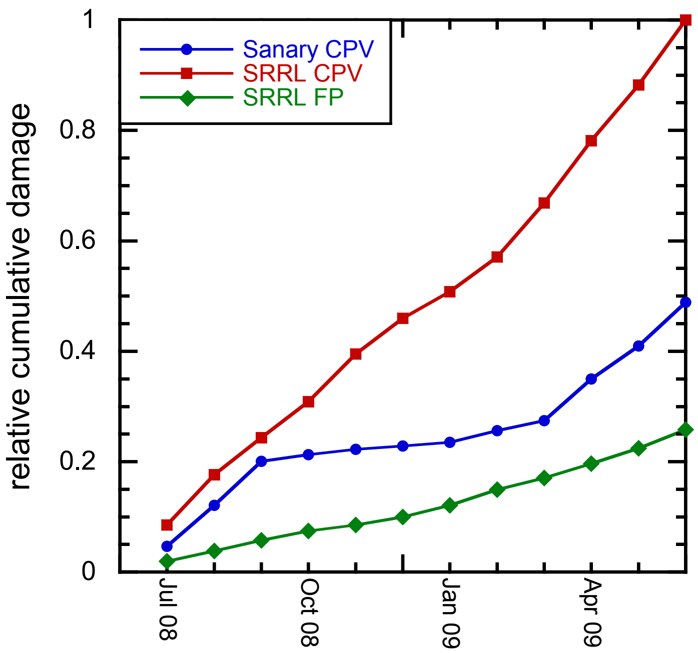


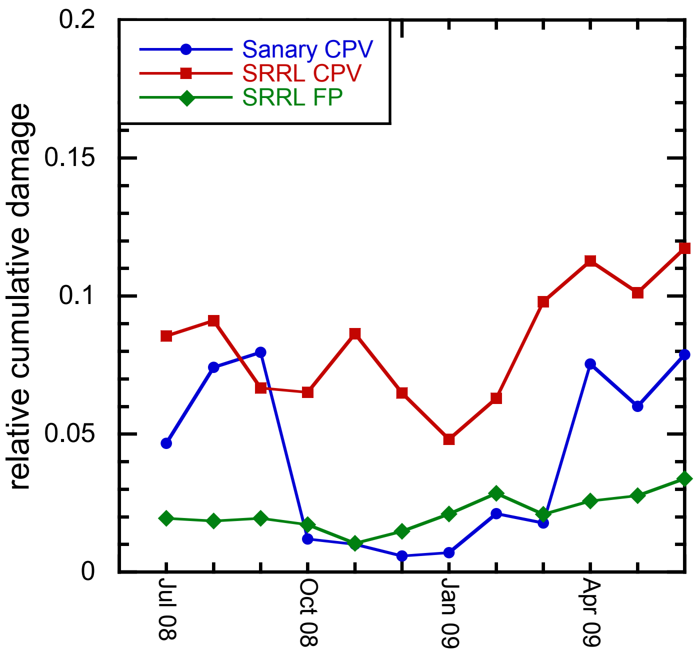


***Weather data courtesy of Atlas Testing Services, Atlas Material Testing Technology LLC.**

damage analysis

comparison: Sanary and Golden

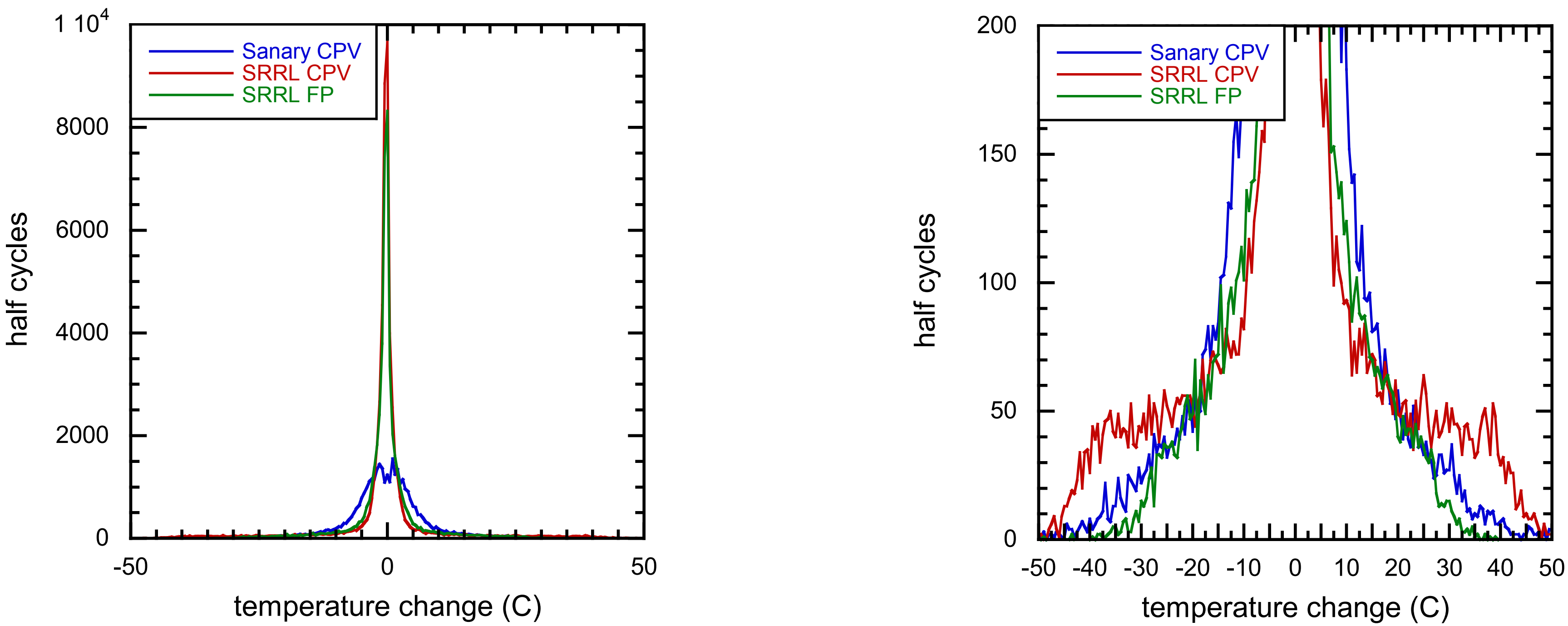




- Golden, CO is roughly twice as damaging to a CPV module as Sanary, France.
- A flat plate module will only accumulate ~25% of the damage of a CPV if both where deployed in Golden, CO.

rainflow count analysis

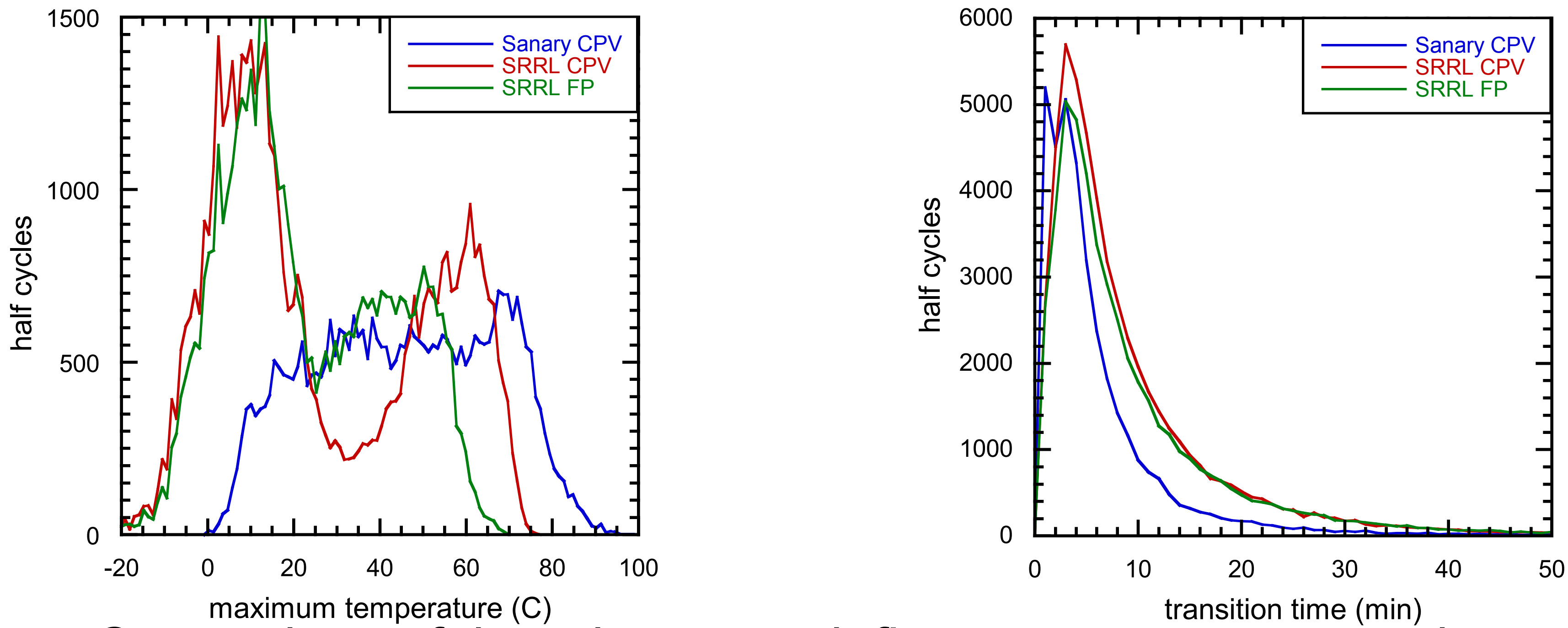
comparison: Sanary and Golden



- Temperature range output from the rainflow count illustrates the higher number of large temperature ranges experienced in Golden, CO.

rainflow count analysis

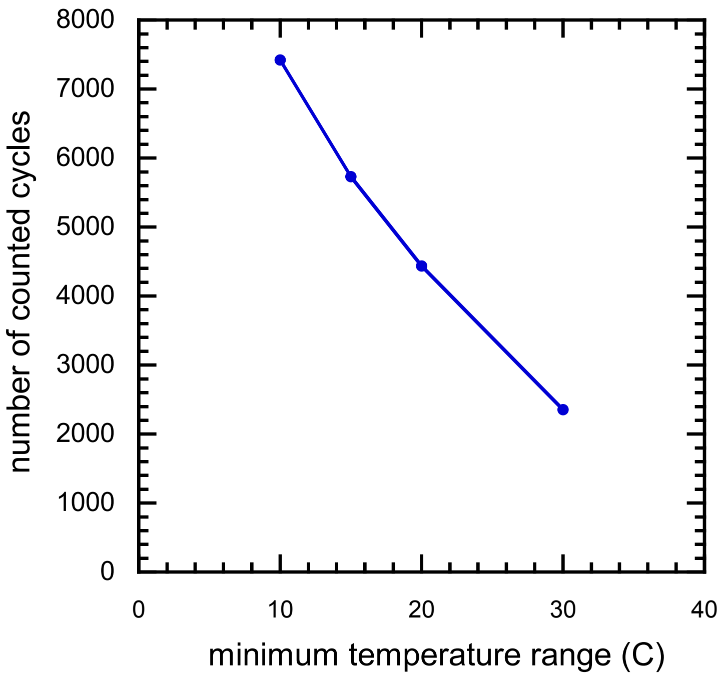
comparison: Sanary and Golden



- Comparison of the other two rainflow count outputs: maximum temperature and transition time.

rainflow count analysis

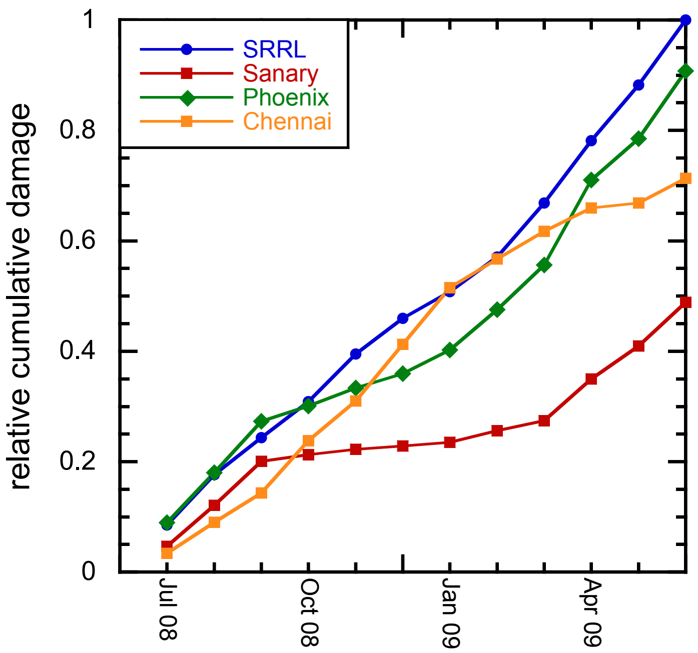
temperature cycles in one year in Golden

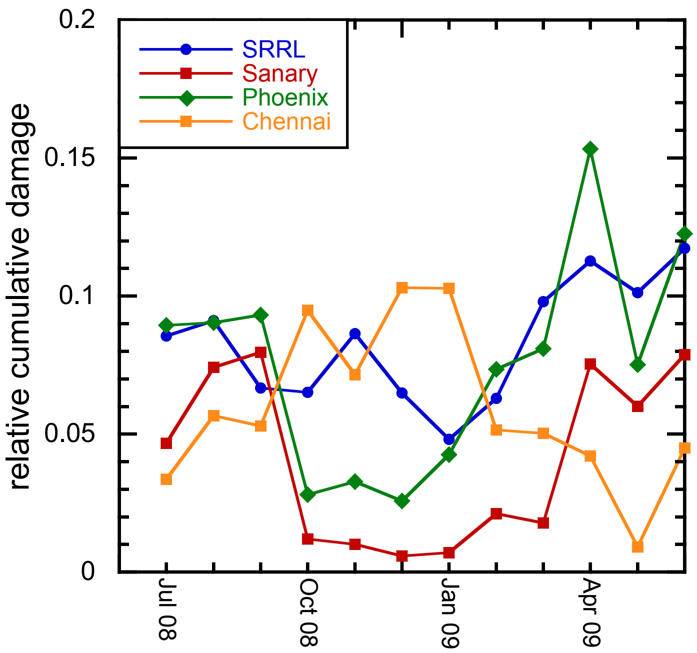


- Illustration of the number of cycles counted in the analysis.
- Roughly 20/day of a 10 C change or greater for the year considered.

rainflow count analysis

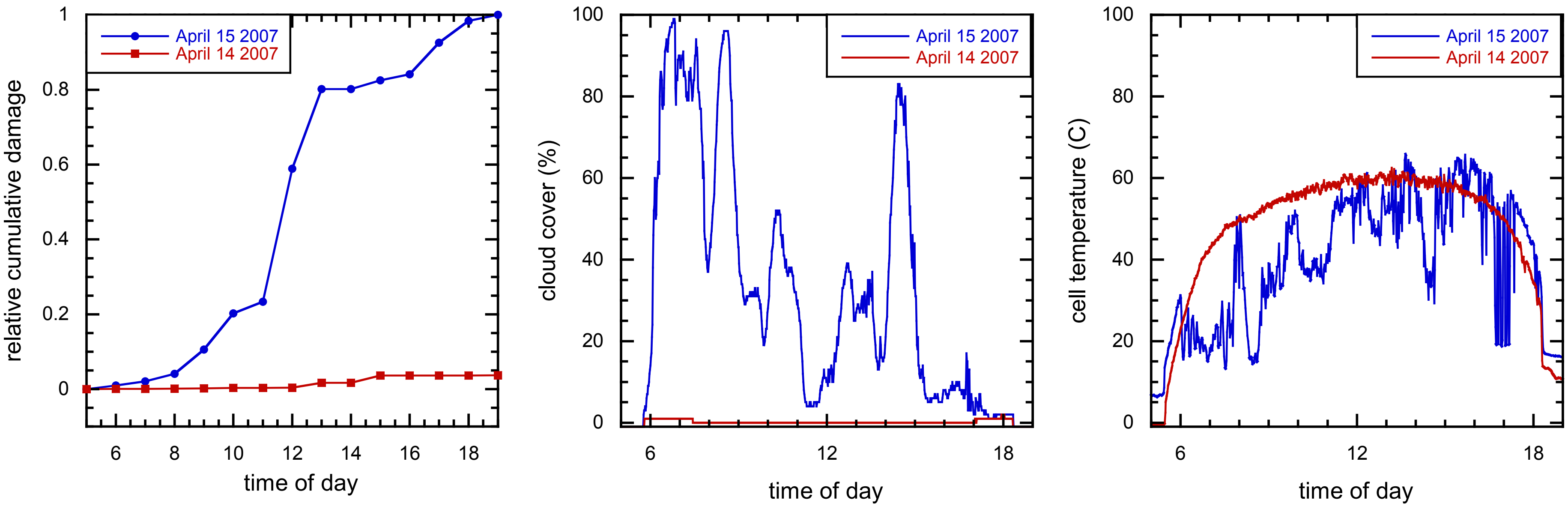
comparison





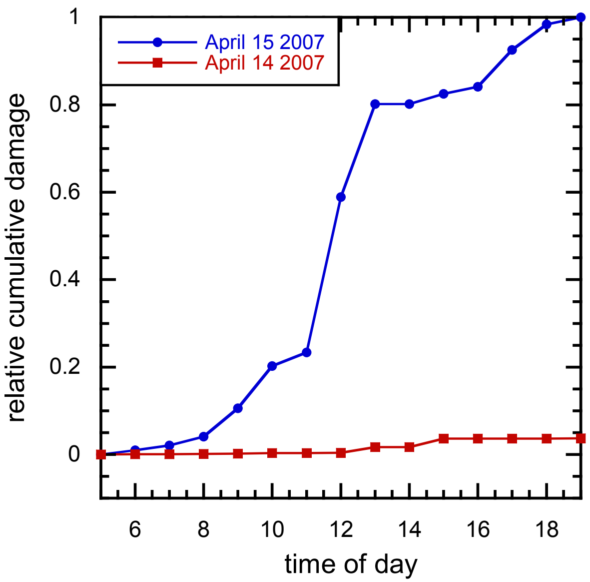
***Weather data courtesy of Atlas Testing Services, Atlas Material Testing Technology LLC.**

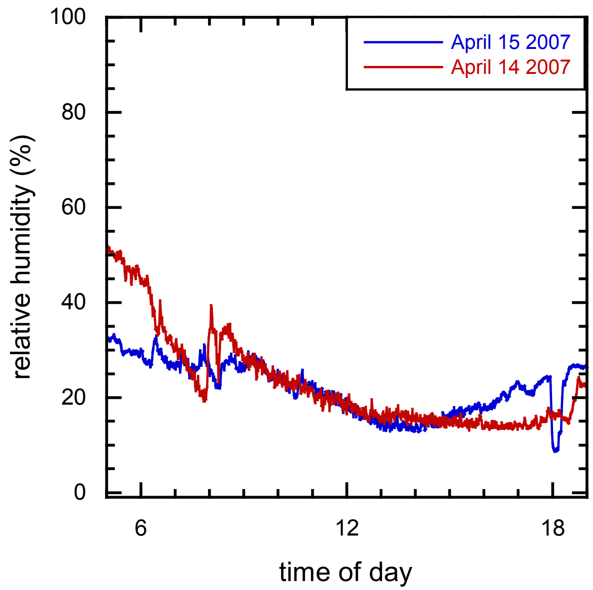
a really bad day

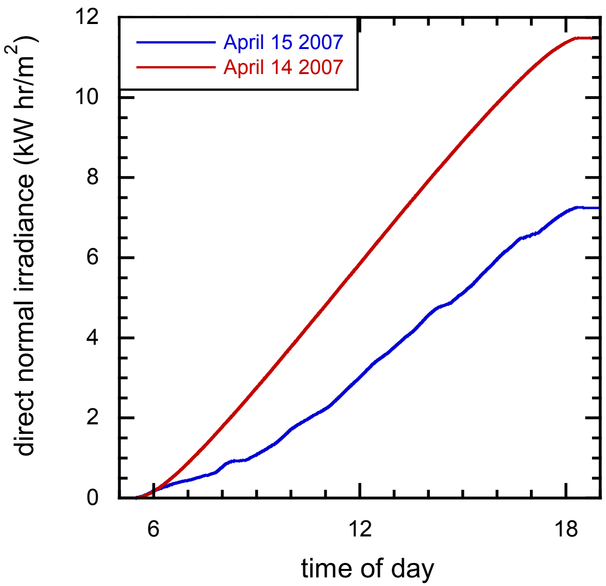


- Clouds are the key to a damaging day.

a really bad day





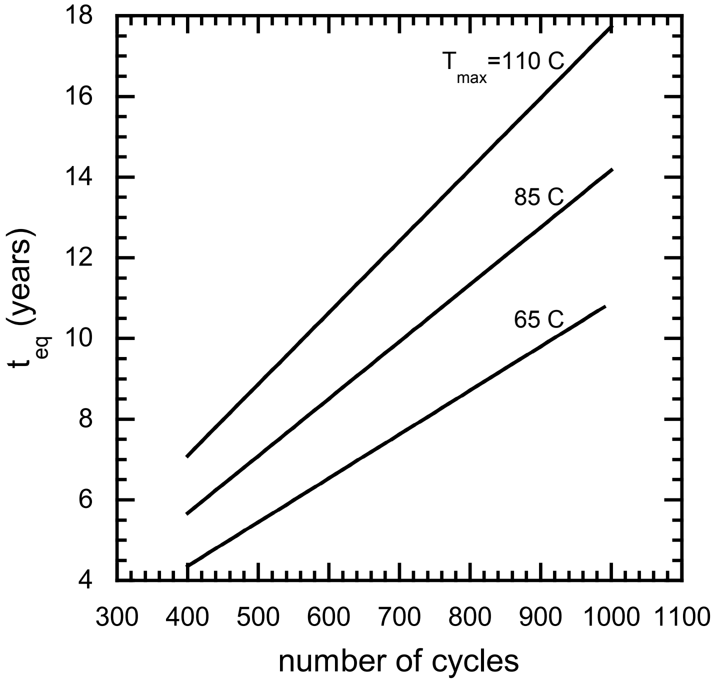


- It is difficult to determine if a day is damaging without high frequency data.

qualifications and predictions

If known, can we relate this damage to that incurred during accelerated testing?

Standard	Option	T_{max} ºC	T_{min} ºC	T_d min	n	t_{eq} SRRL years	t_{eq} Sanary years	observed years
IEC 62108	TCA-1	110	-40	10	500	8.9	18.2	
	TCA-2	85	-40	10	1000	14.2	29	
	TCA-3	65	-40	10	2000	21.8	44.6	
IEC 61215		85	-40	10	200	11		10*



*J. Wohlgemuth, D. Cunningham, D. Amin, J. Shaner, Z. Xia, and J. Miller, "Using Accelerated Tests and Field Data to Predict Module Reliability and Lifetime," *23rd European Photovoltaic Solar Energy Conference and Exhibition,* pp. 2663-2669, 2008

future work

- Outdoor testing to refine thermal fatigue and damage model.
- High frequency data.
- Analyze many locations: create a lifetime map.

1. Bosco, N.S., Sweet, C.,Kurtz, S., “Reliability Testing the Die-Attach of CPV Cell Assembles”, 34th IEEE Photovoltaic Specialists Conference, 7-12 June 2009, Philadelphia, Pennsylvania
2. A. Ramakrishnan and M. G. Pecht, "A life consumption monitoring methodology for electronic systems," *Components and Packaging Technologies, IEEE Transactions on,* vol. 26, pp. 625-634, 2003
3. "Standard practices for cycle counting in fatigue analysis," ASTM International Standard E 1049-85, West Conshohocken, PA 2005.