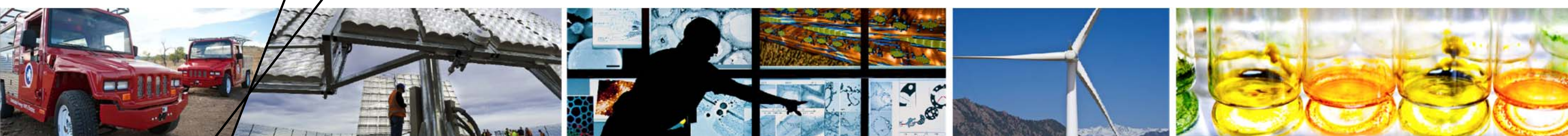
NATIONAL RENEWABLE ENERGY LABORATORY

Comparison of accelerated testing with modeling to predict lifetime of CPV solder layers



2012 PV Module Reliability Workshop

Timothy J Silverman, **Nick Bosco, Sarah Kurtz**

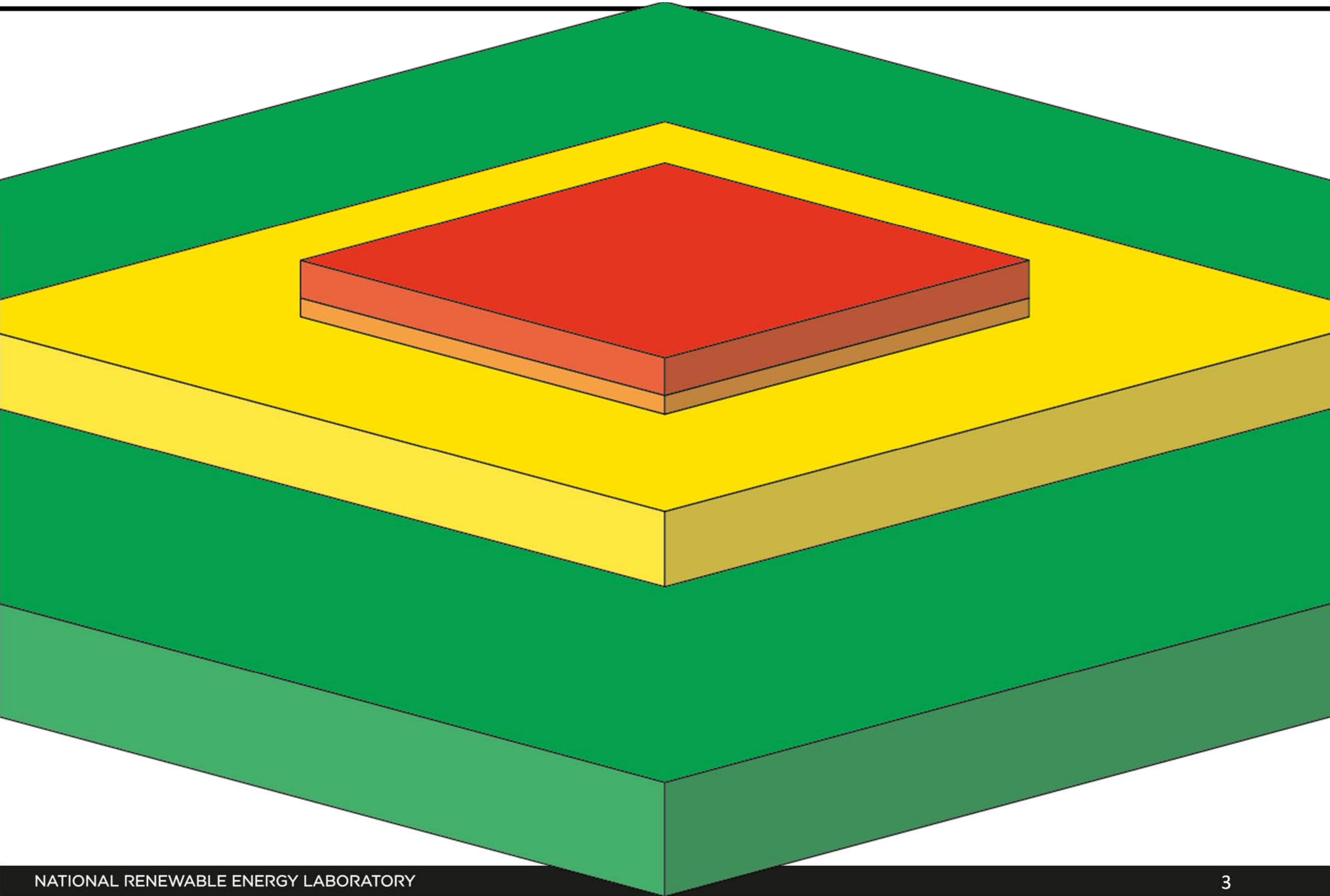
March 1, 2012

NREL/PR-5200-54677

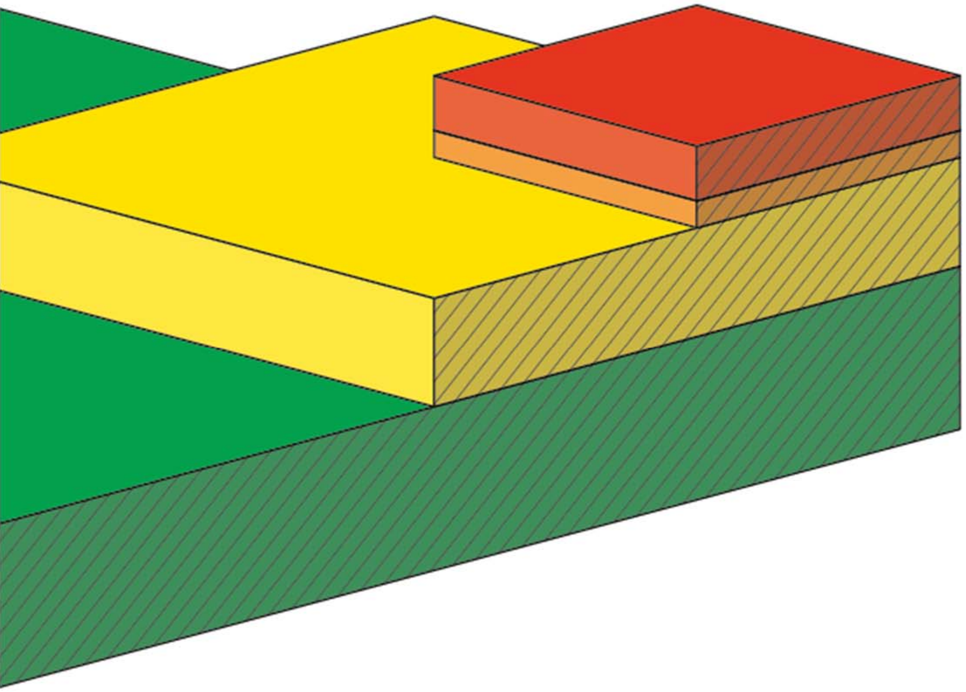
Agenda

- Motivation for studying CPV die-attach reliability
- Experiments with accelerated testing
- Computer simulation of thermal cycling
- Computer simulation of weather

The CPV solder layer

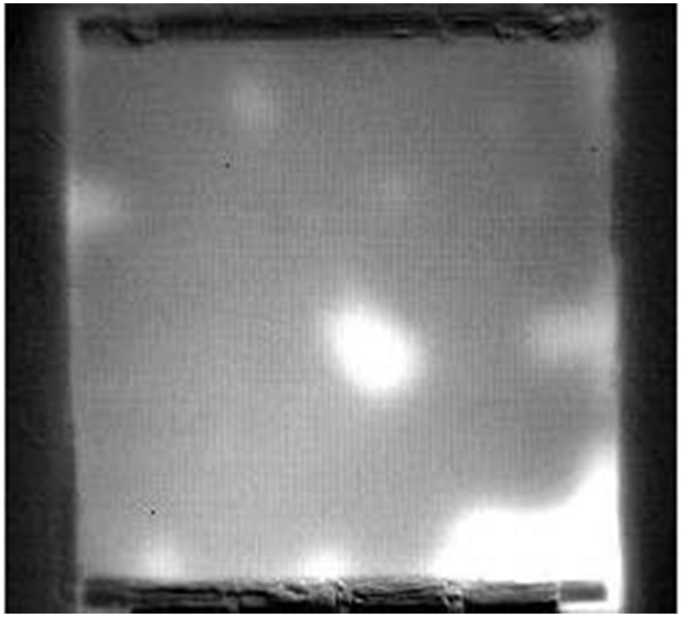


The CPV solder layer



The mechanical integrity of the die-attach layer is critical for the removal of heat

Cracks kill



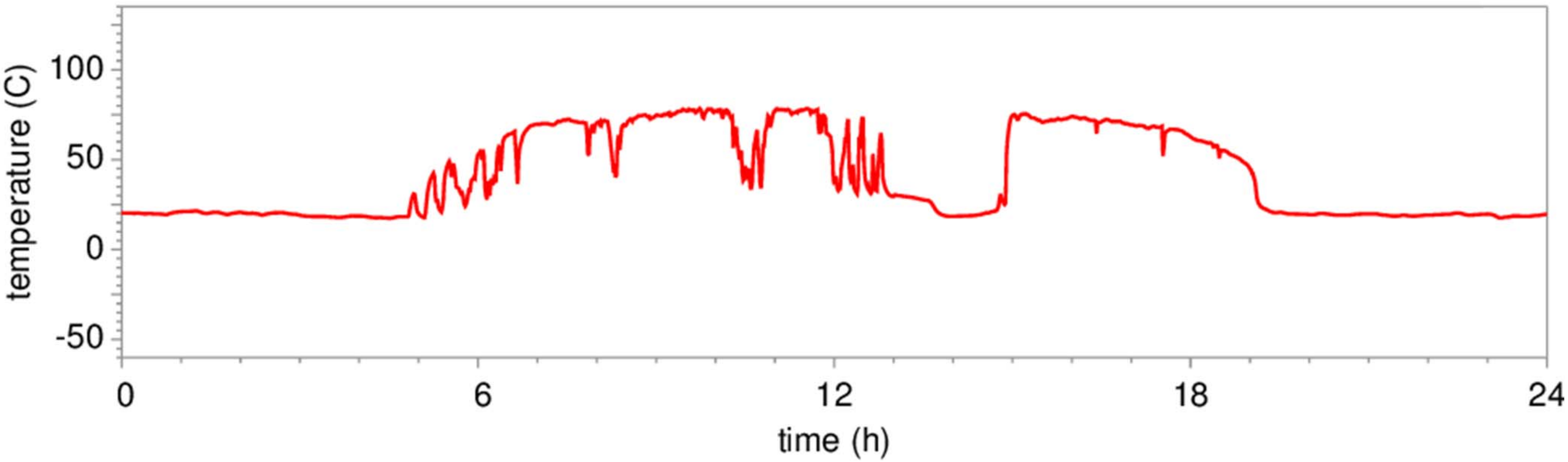
Transient IR image showing cracks from thermal cycling

Steady-state IR image showing shunt caused by sun exposure

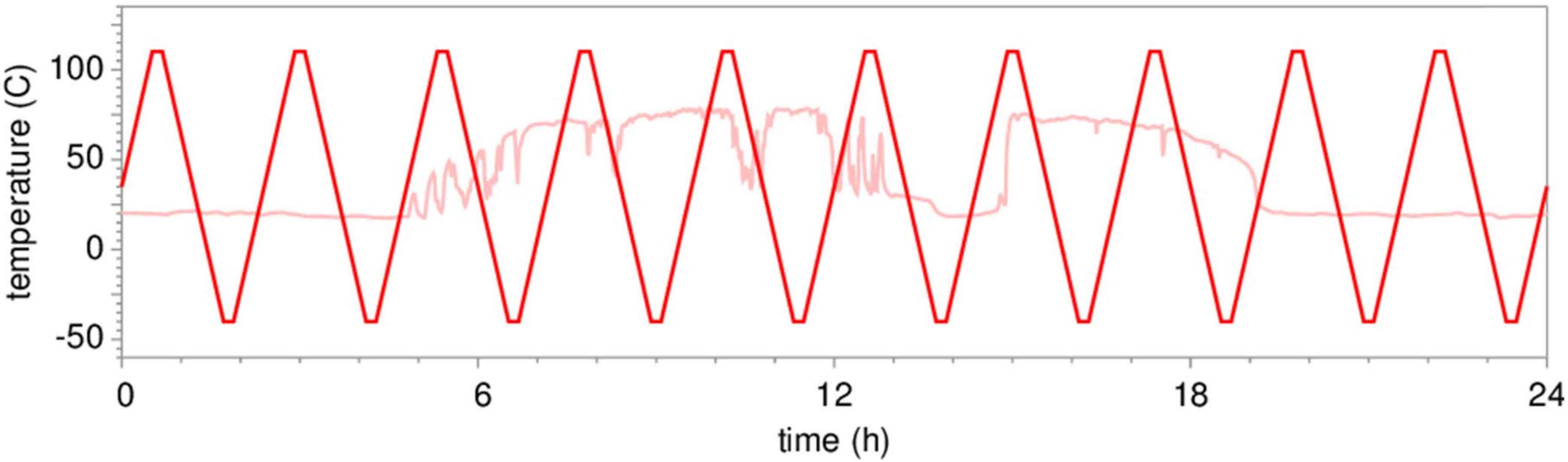
The mechanical integrity of the die-attach layer is critical for the removal of heat

Bosco, N. et al., NREL Report No. PR-5200-49243

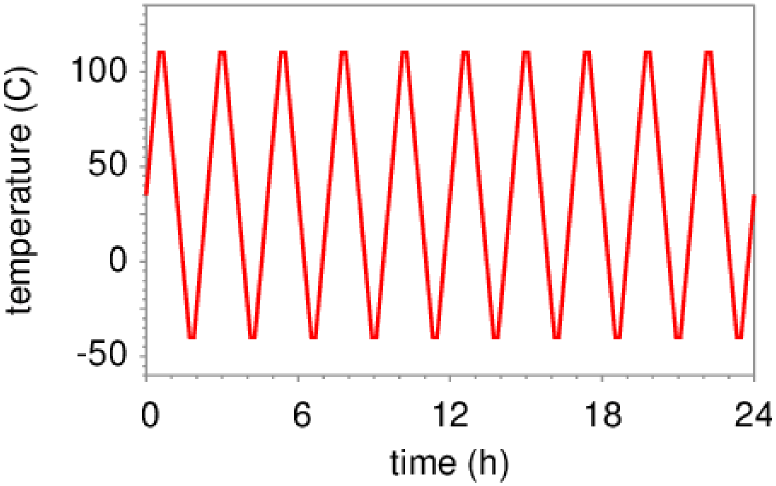
Weather is thermal cycling



Accelerated testing is a shortcut



How much damage does a day do?



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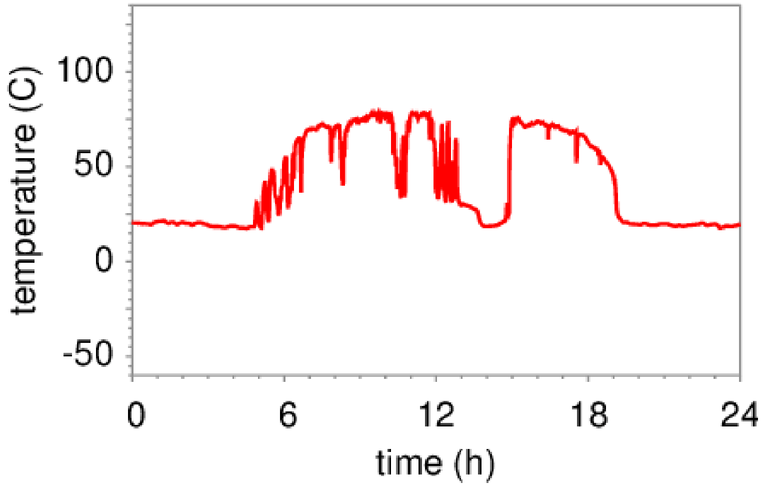
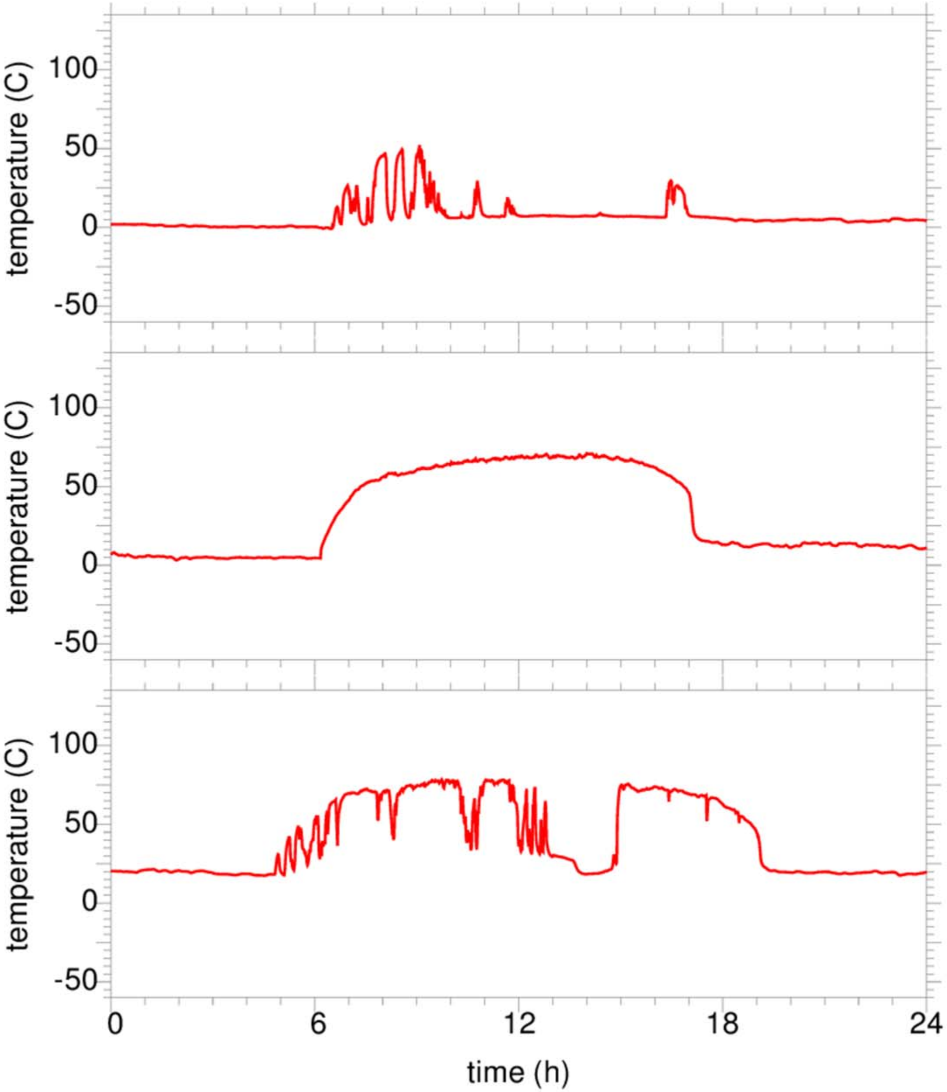
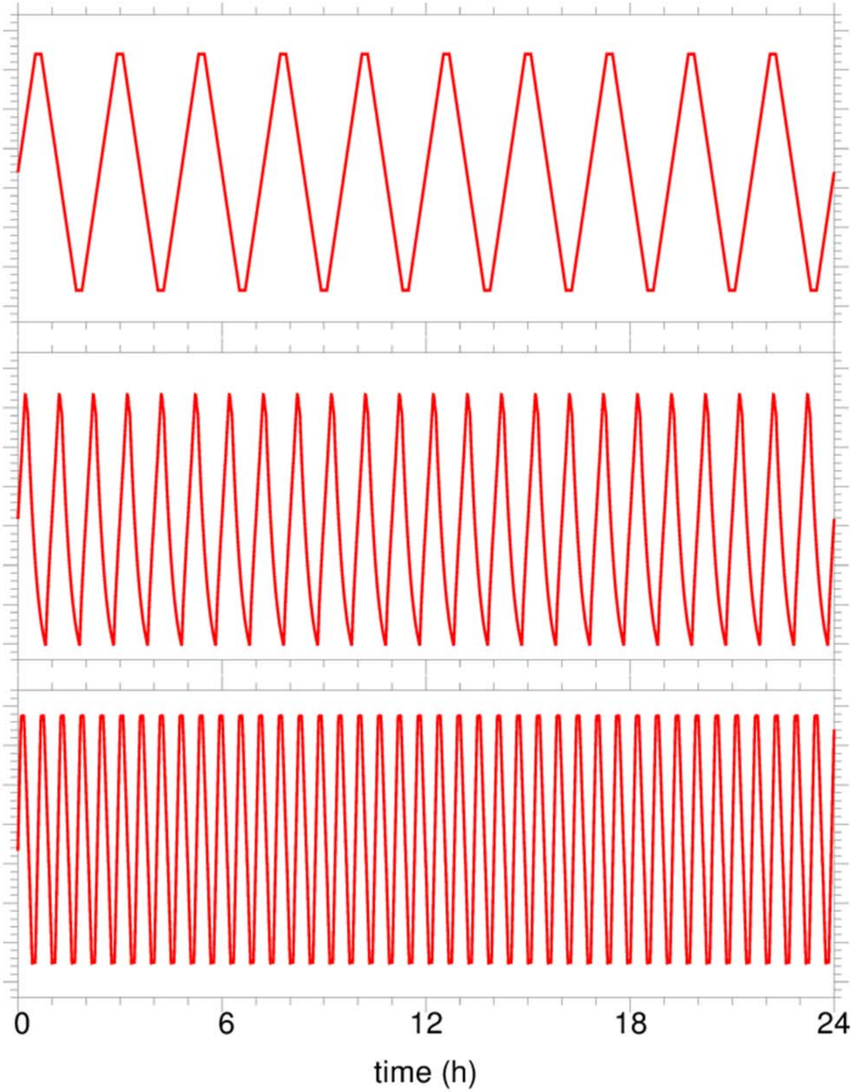


The answer: It depends

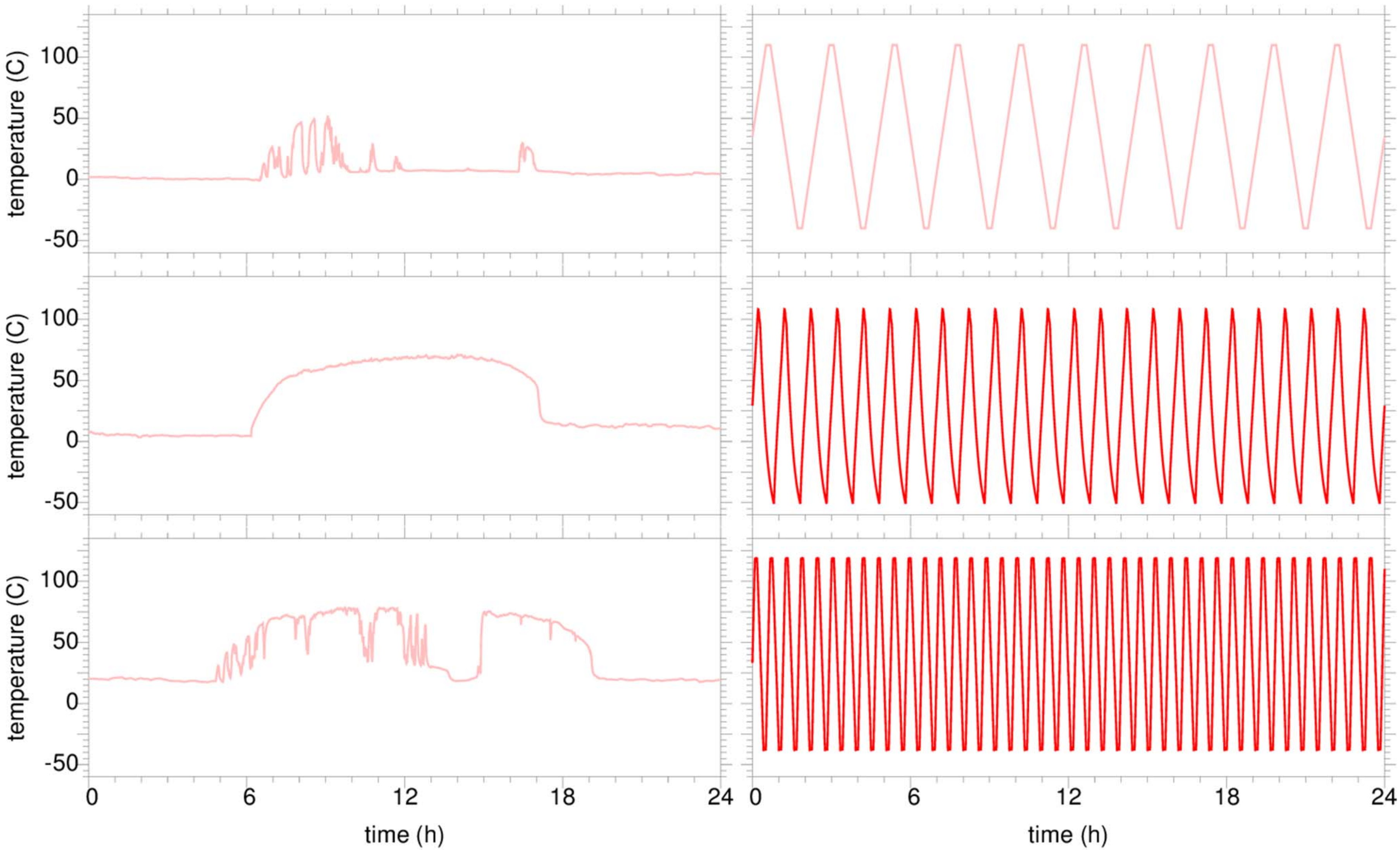
Which day?



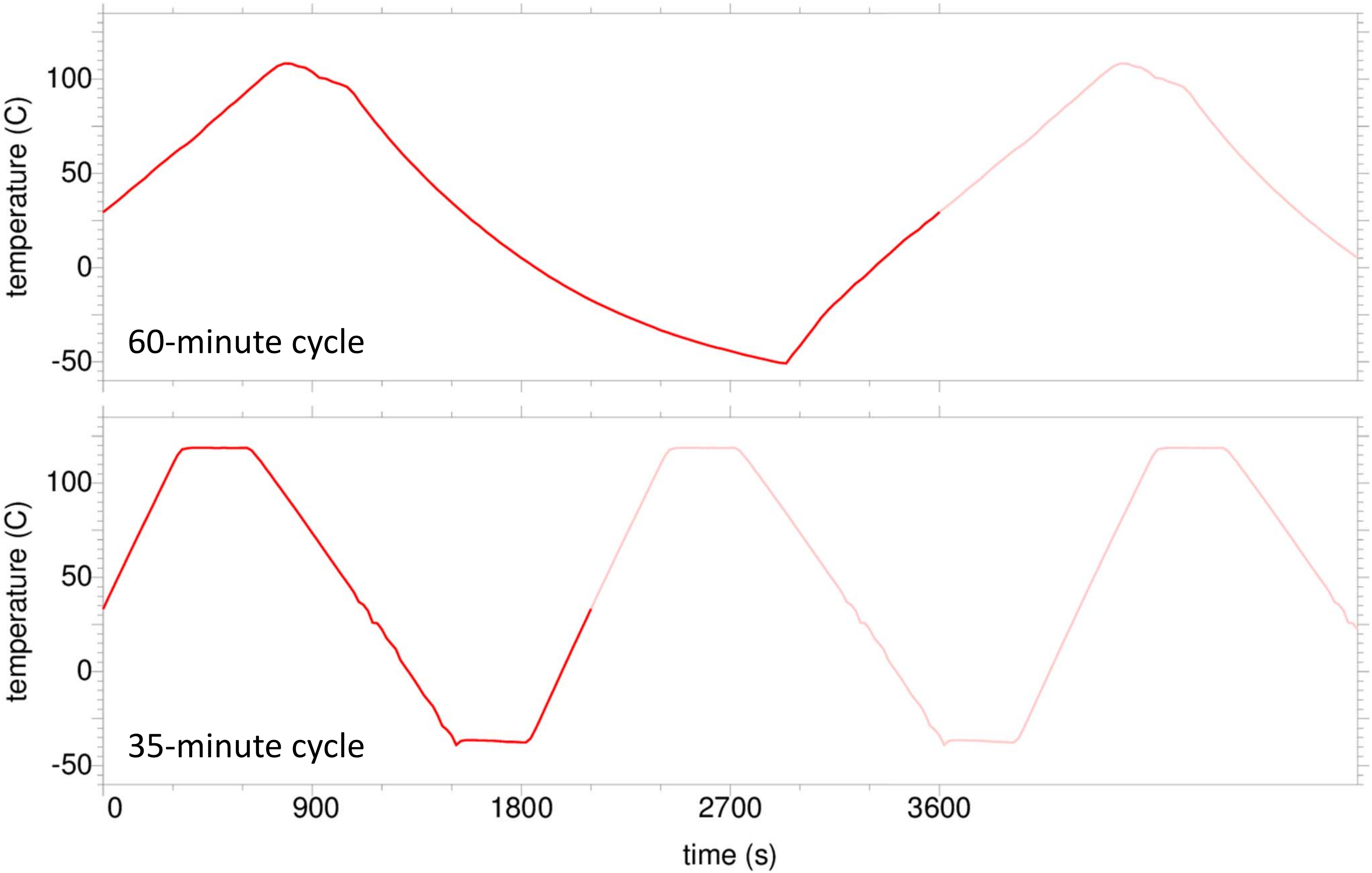
Which cycle?



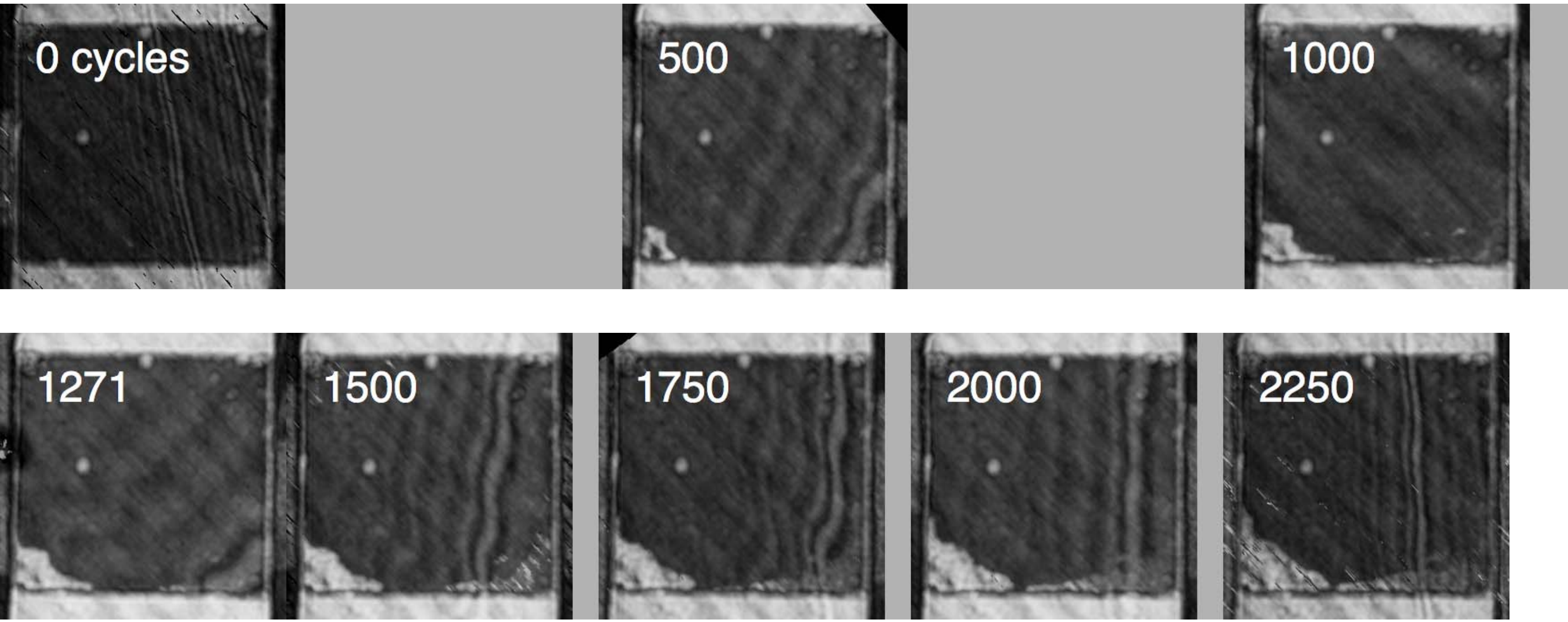
Crack growth experiments with two cycle types



How damaging are these two cycles?

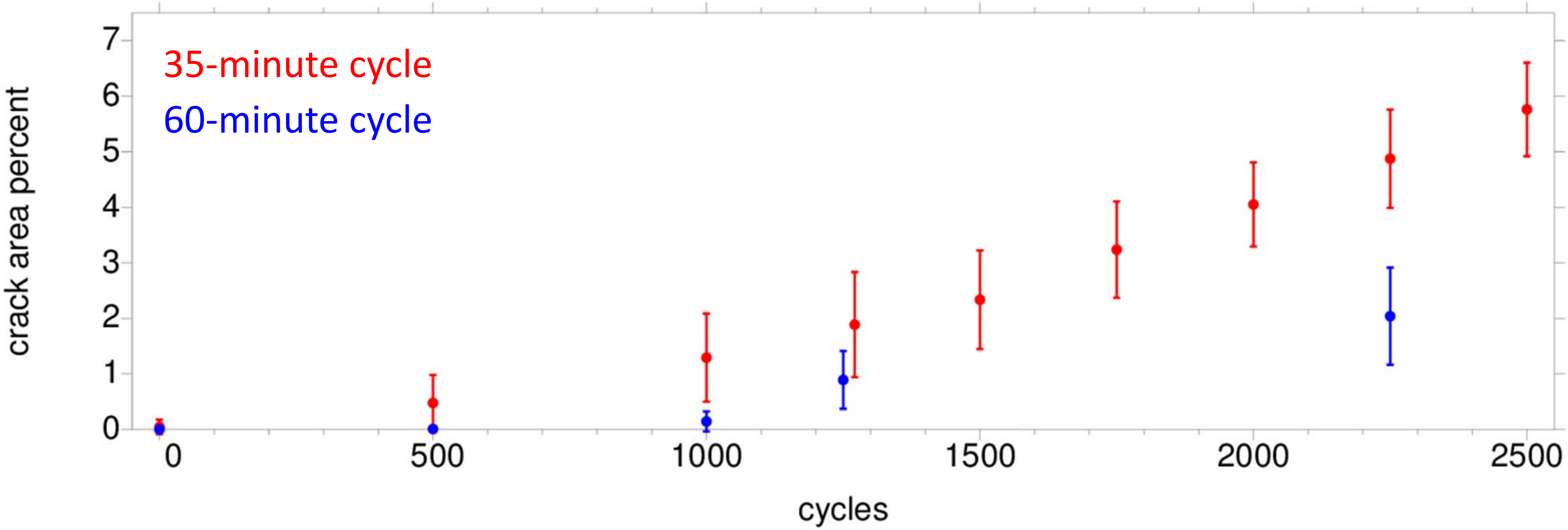


Measuring crack area acoustically

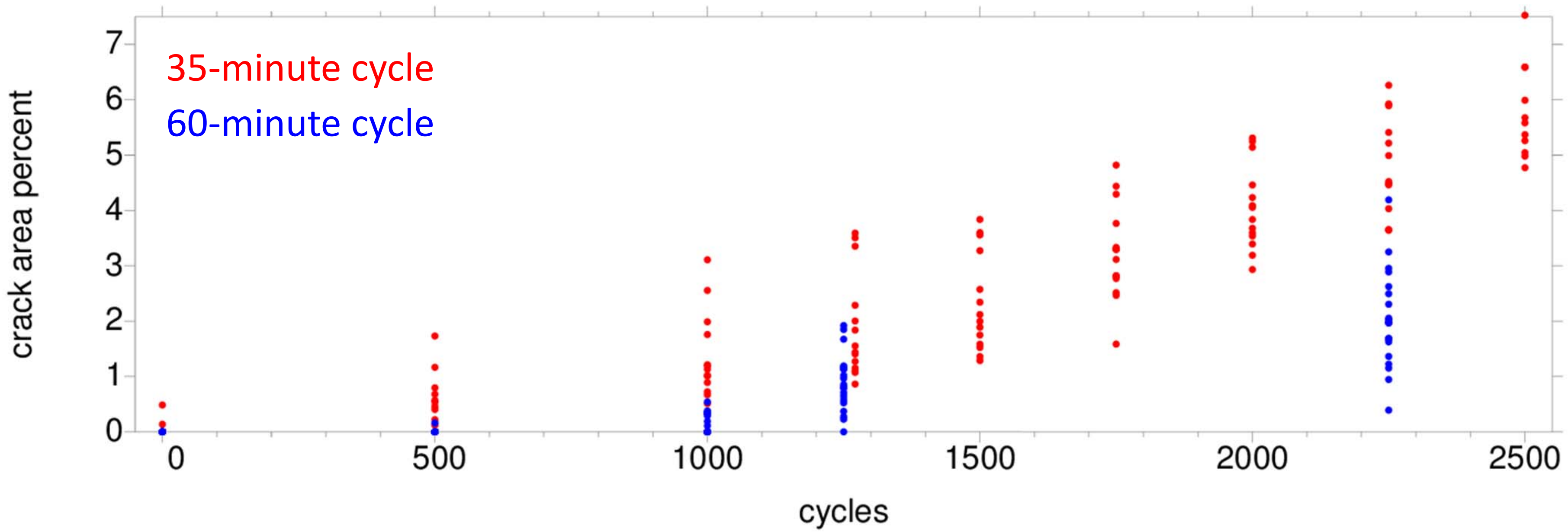


This is a test article intended to accumulate damage quickly
Crack measurement algorithm is still under development

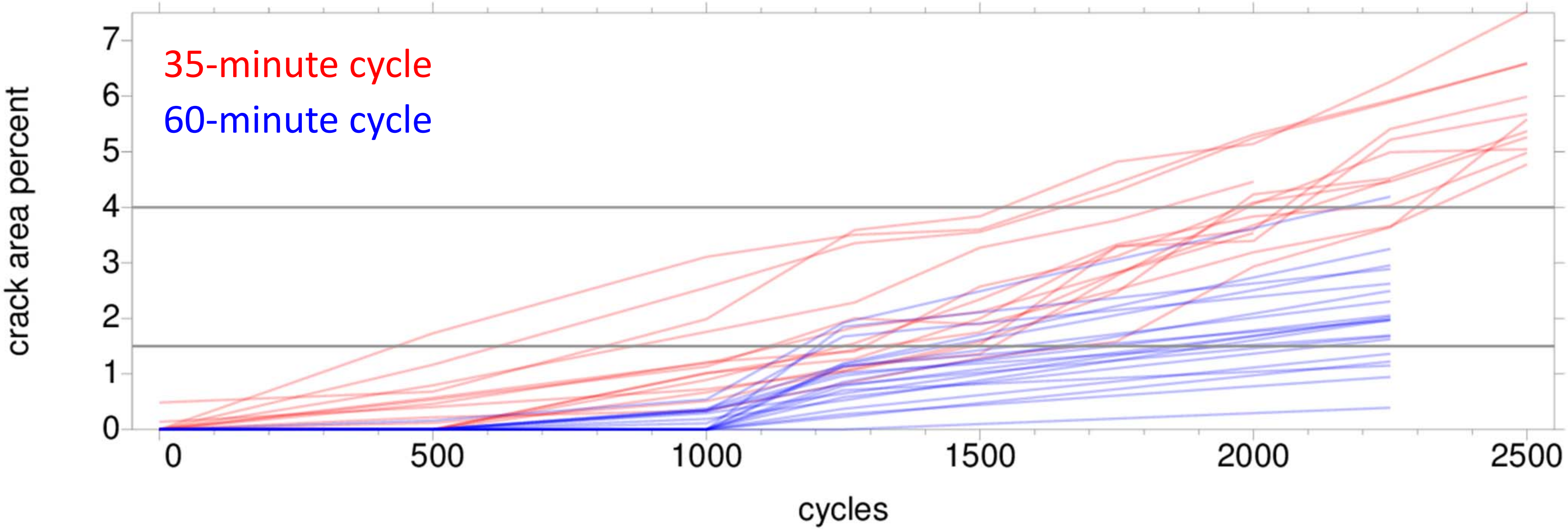
Crack growth due to thermal cycling



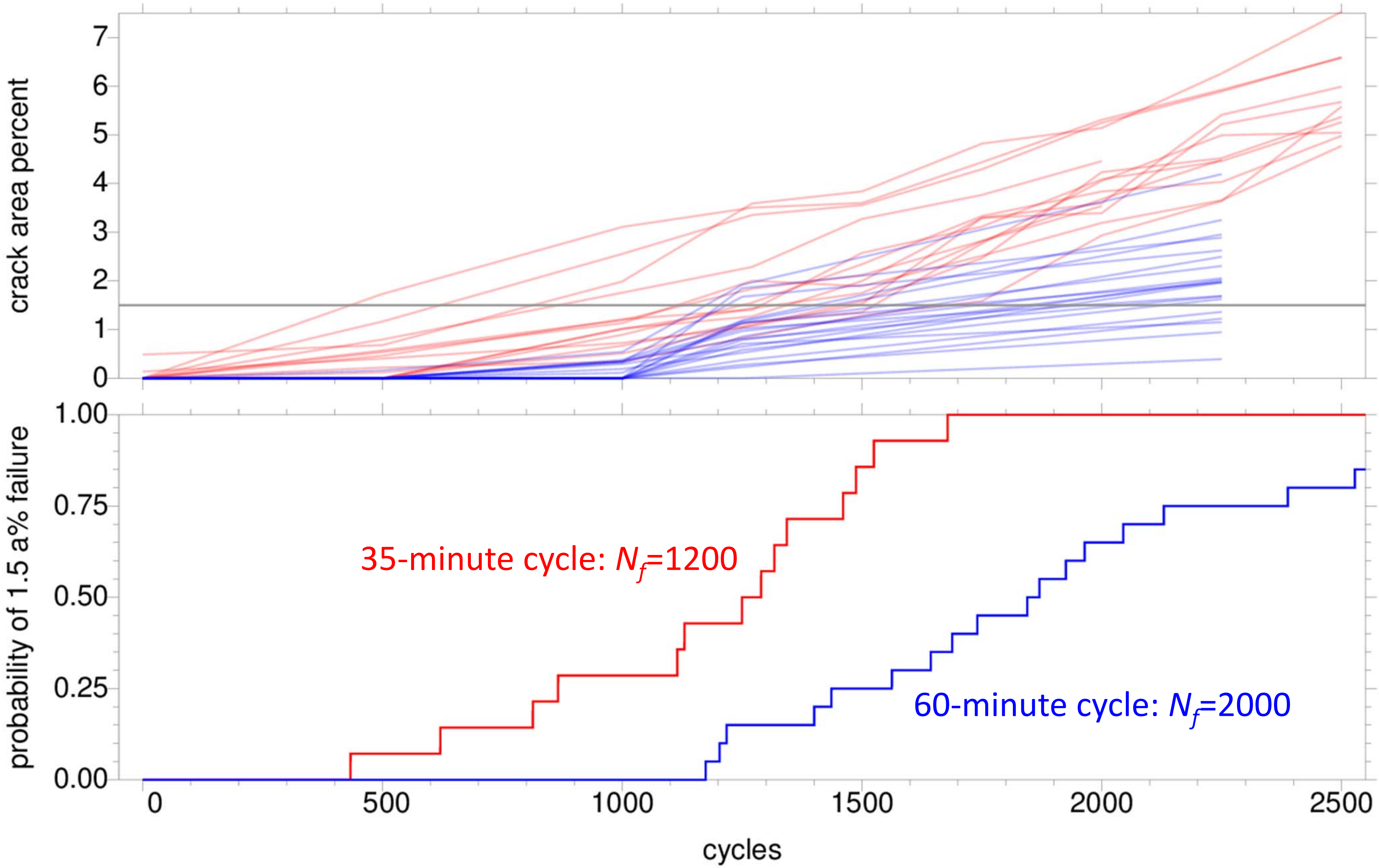
Crack growth due to thermal cycling



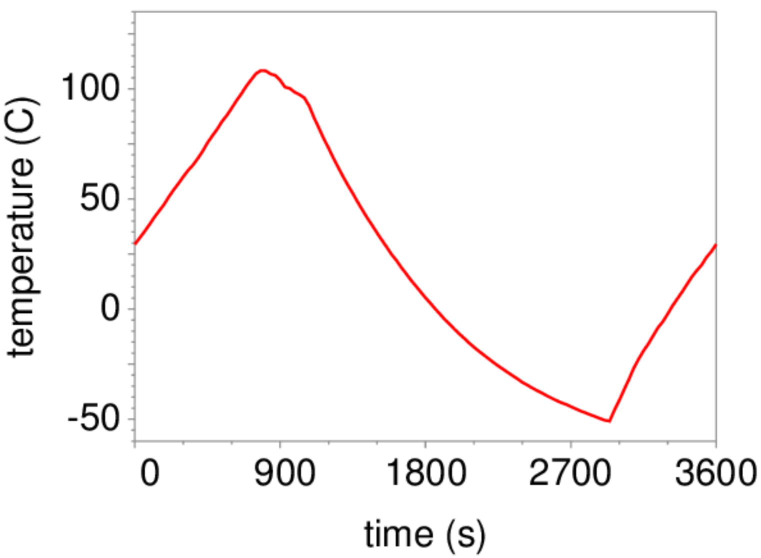
Crack growth due to thermal cycling



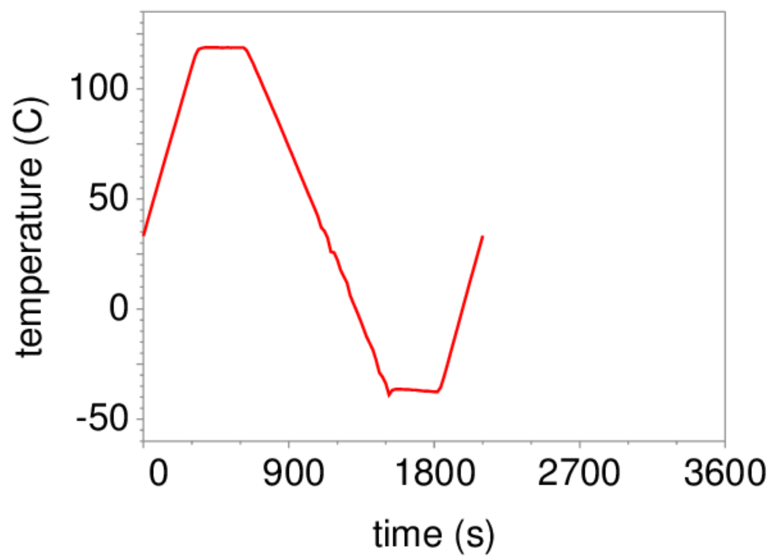
Crack growth due to thermal cycling



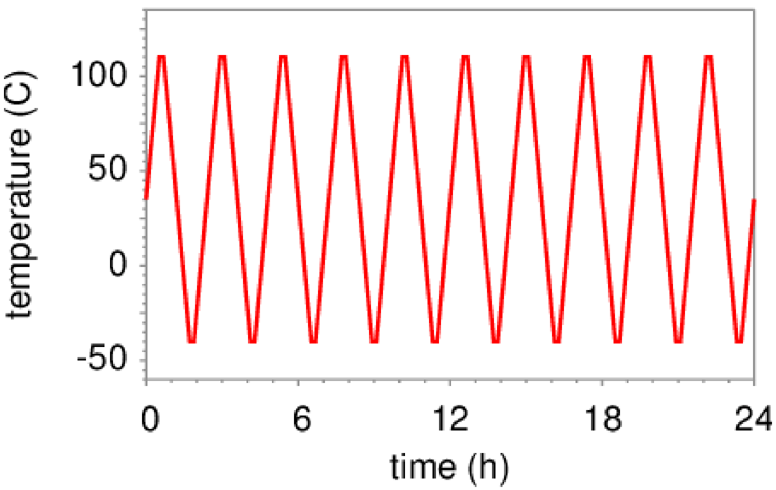
Connecting the two cycle types



= 0.6 ×



How much damage does a day do?



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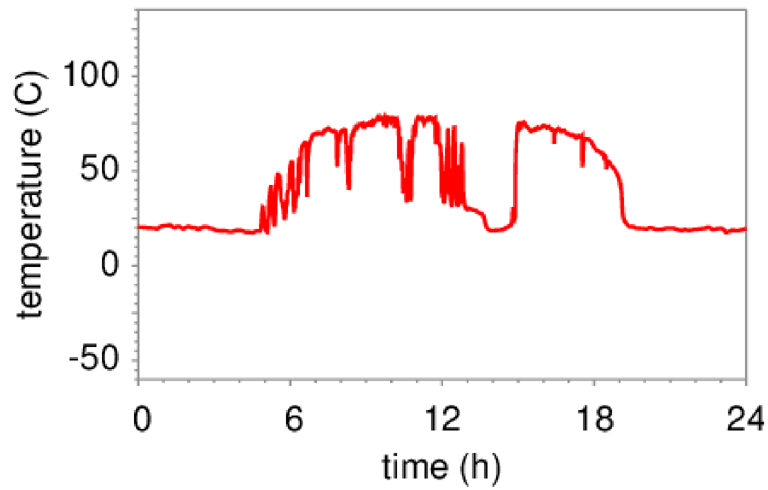
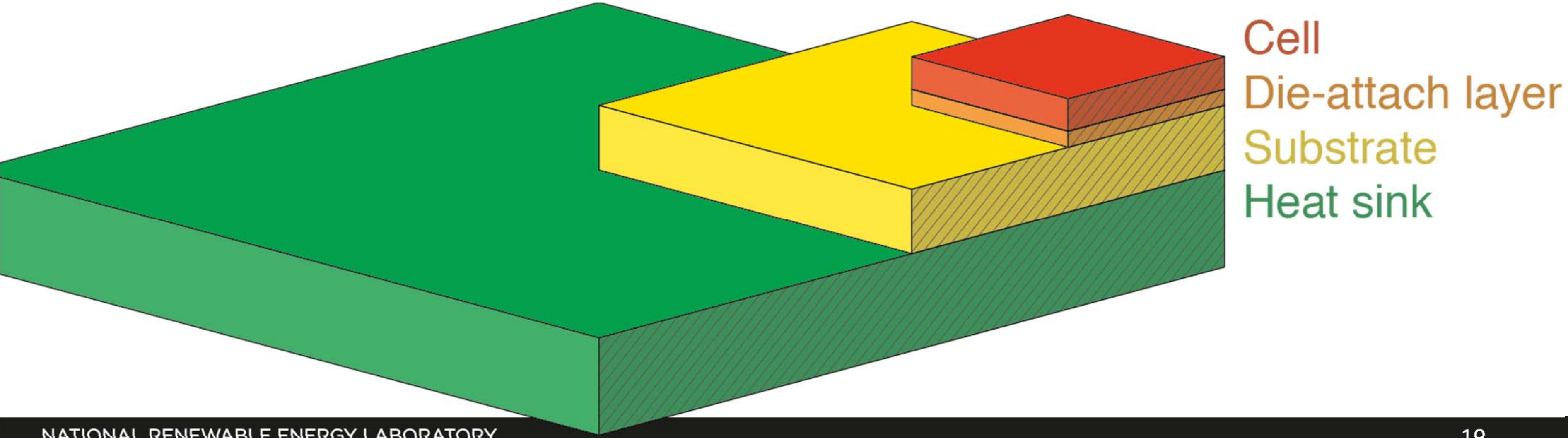


Numerical model

- Finite-element method
- Driven by arbitrary temperature history
- Viscoplastic constitutive behavior (Anand model)
- Inelastic deformations and isotropic resistance to hardening
- Geometrically flawless solder layer
- Damage metric: Average inelastic strain energy density



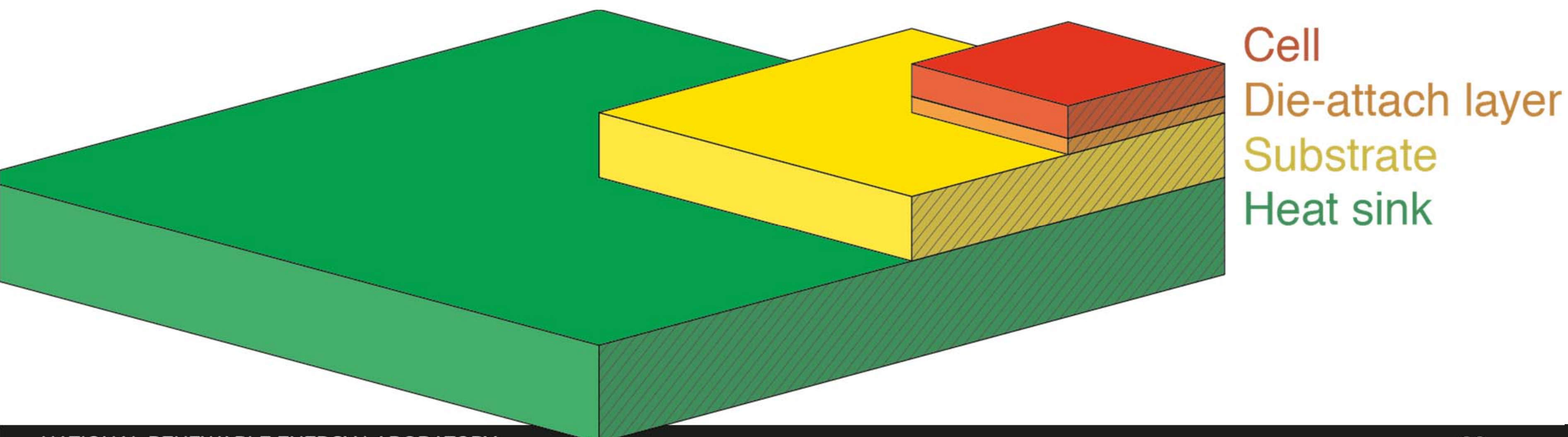
Numerical model

$$\dot{\varepsilon}_{\mathrm{pl,eq}} = A \exp\left(\frac{-Q}{RT}\right) \left[\sinh\left(\xi \frac{\sigma_{\mathrm{eq}}}{s}\right)\right]^{\frac{1}{m}}$$

$$\dot{s} = \dot{\varepsilon}_{\mathrm{pl,eq}} \; h_0 \left|1 - \frac{s}{s^*}\right|^a \; \mathrm{signum}\left(1 - \frac{s}{s^*}\right)$$

$$s^* = \hat{s}\left[\frac{\dot{\varepsilon}_{\mathrm{pl,eq}}}{A} \exp\left(\frac{Q}{RT}\right)\right]^n$$

$$W_{\mathrm{pl}} = \int |\sigma| \, d\varepsilon_{\mathrm{pl}}$$



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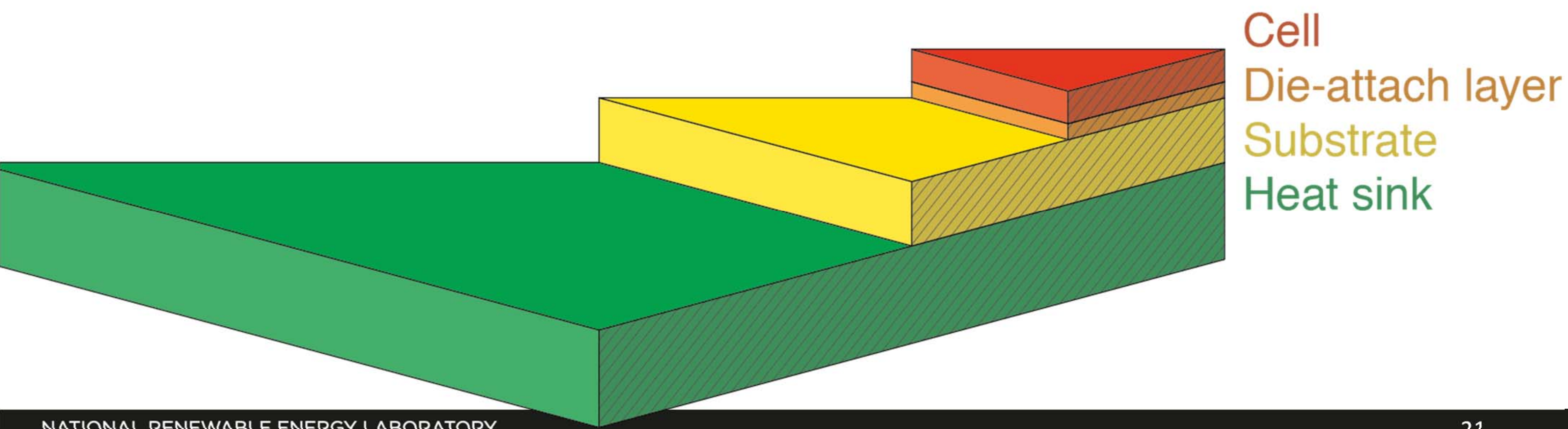
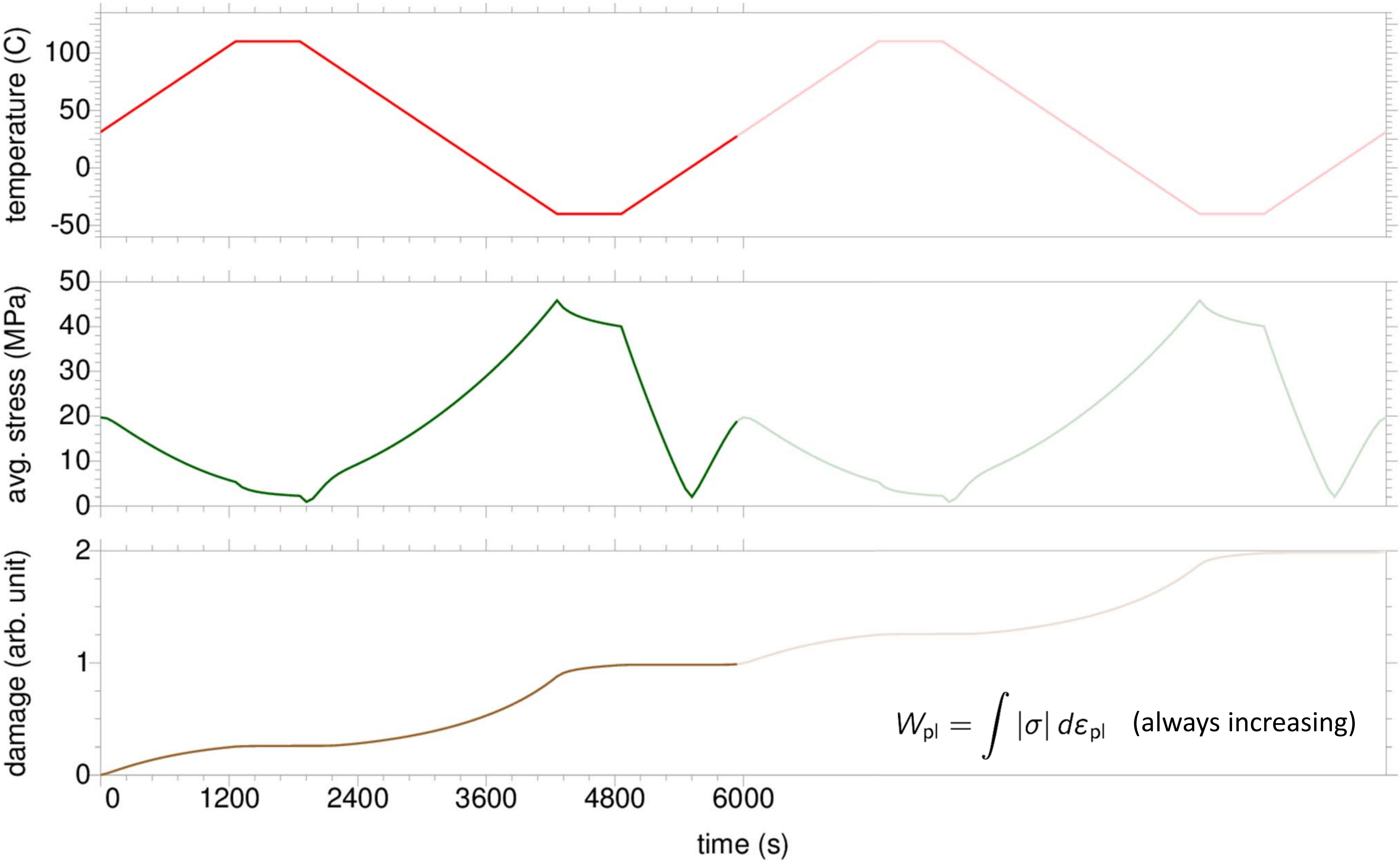
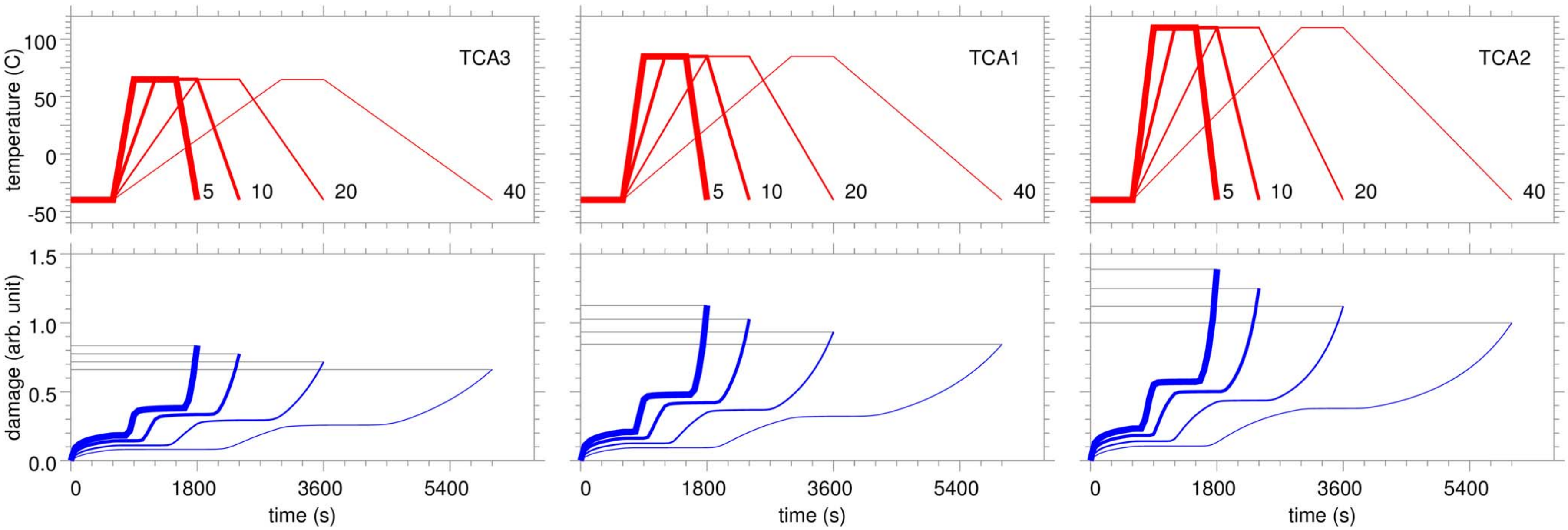


Damage: Progress toward failure



Comparing various thermal cycles

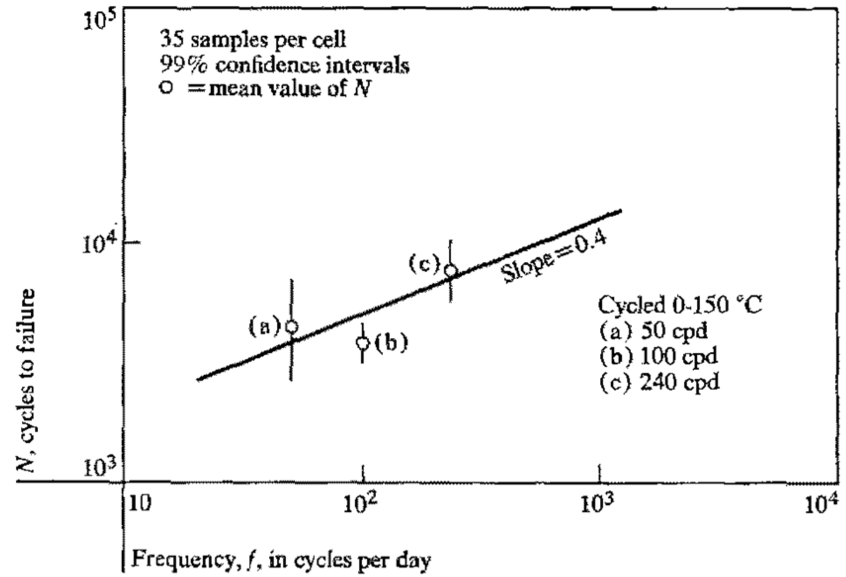


5, 10, 20, 40-minute ramps
Faster cycles cause more damage per cycle
Larger-amplitude cycles cause more damage per cycle

Lifetime dependence on cycle frequency

$$N \propto f^k$$

$$0 \leq k \leq 1$$



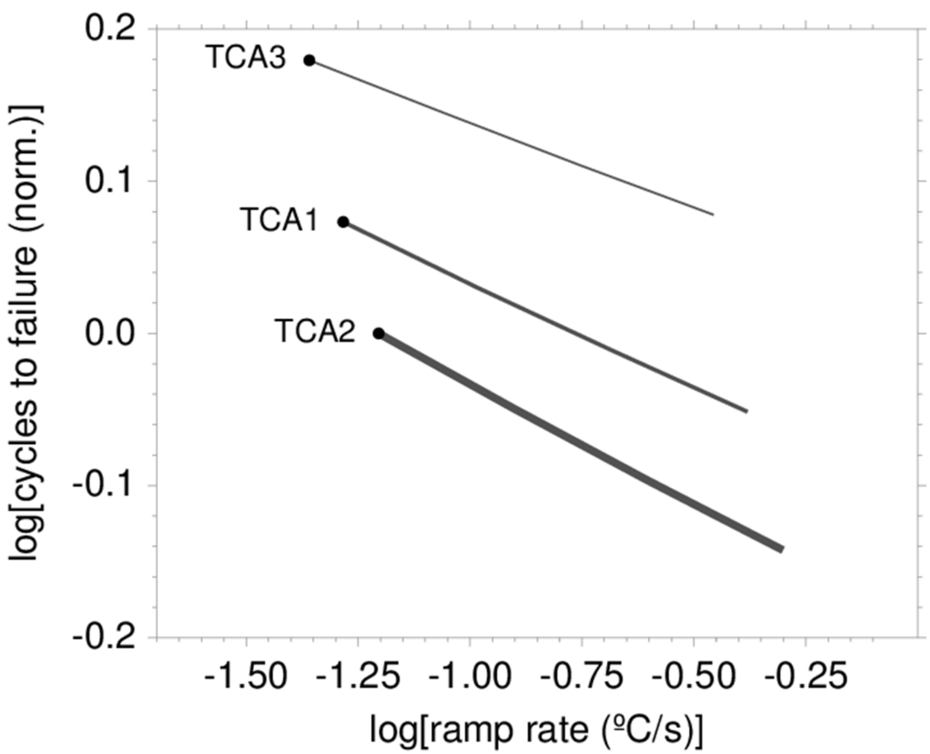
Norris, KC et al., IBM J Res Dev 13:3, 1969

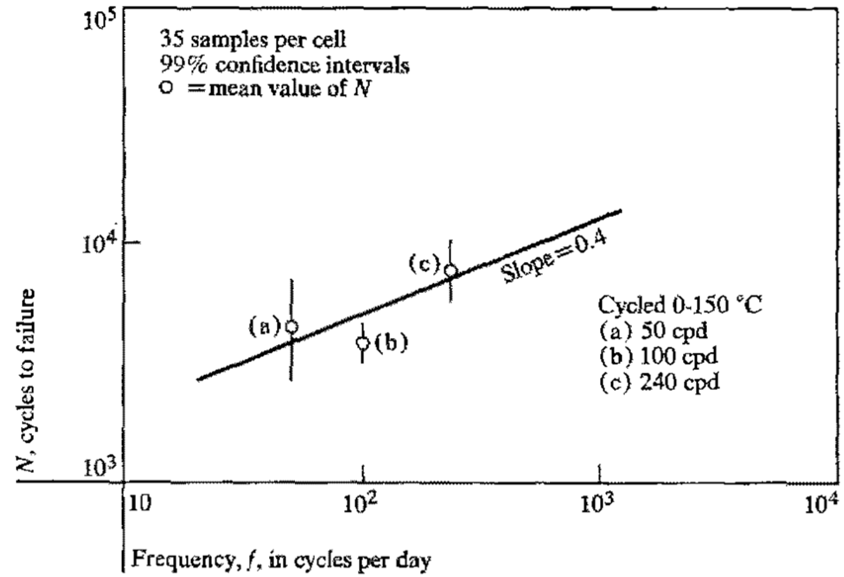
Empirical fatigue models say that faster cycles do less damage

Lifetime dependence on cycle frequency

$$N \propto f^k$$

$$0 \leq k \leq 1$$

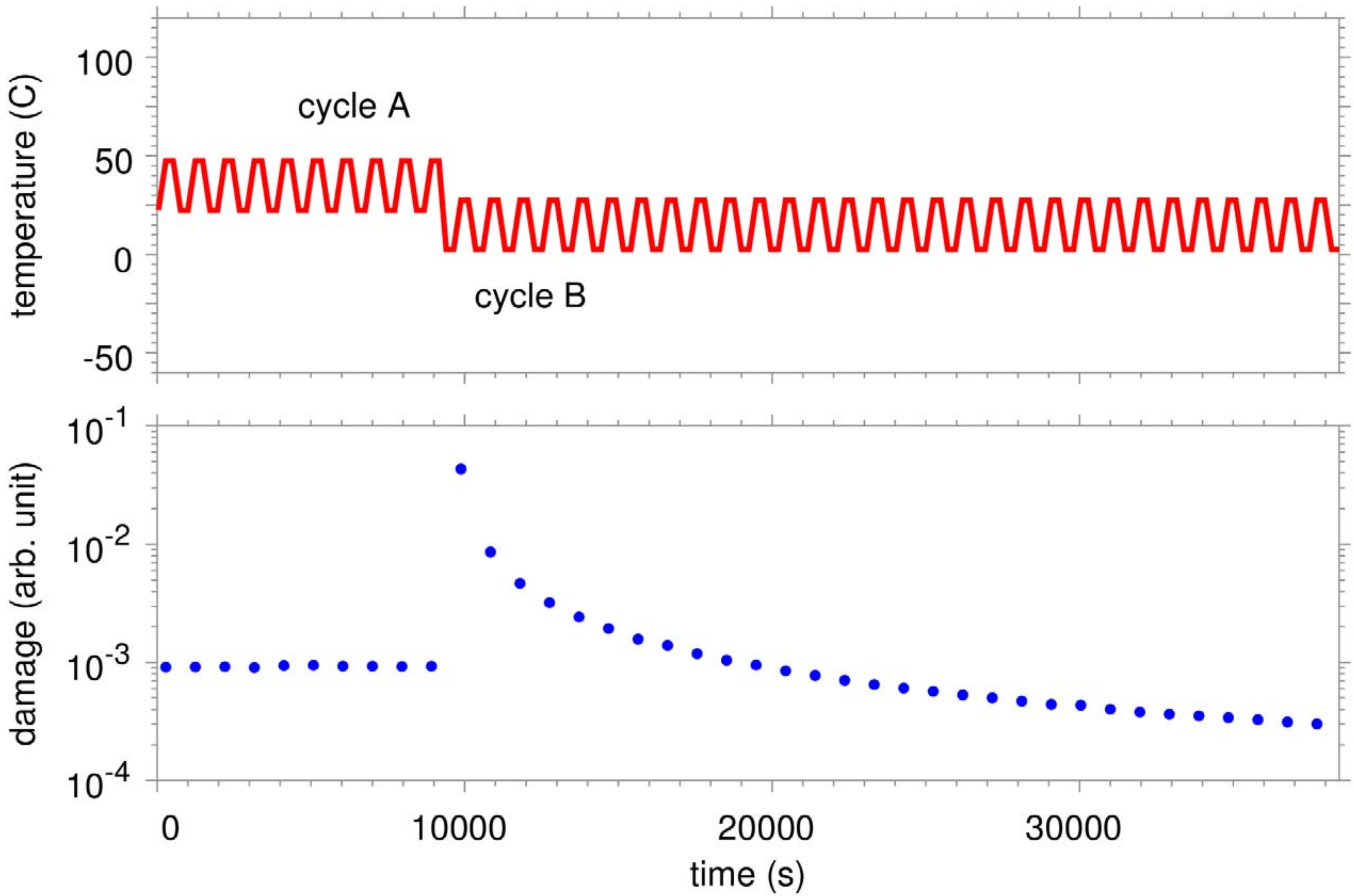




Norris, KC et al., IBM J Res Dev 13:3, 1969

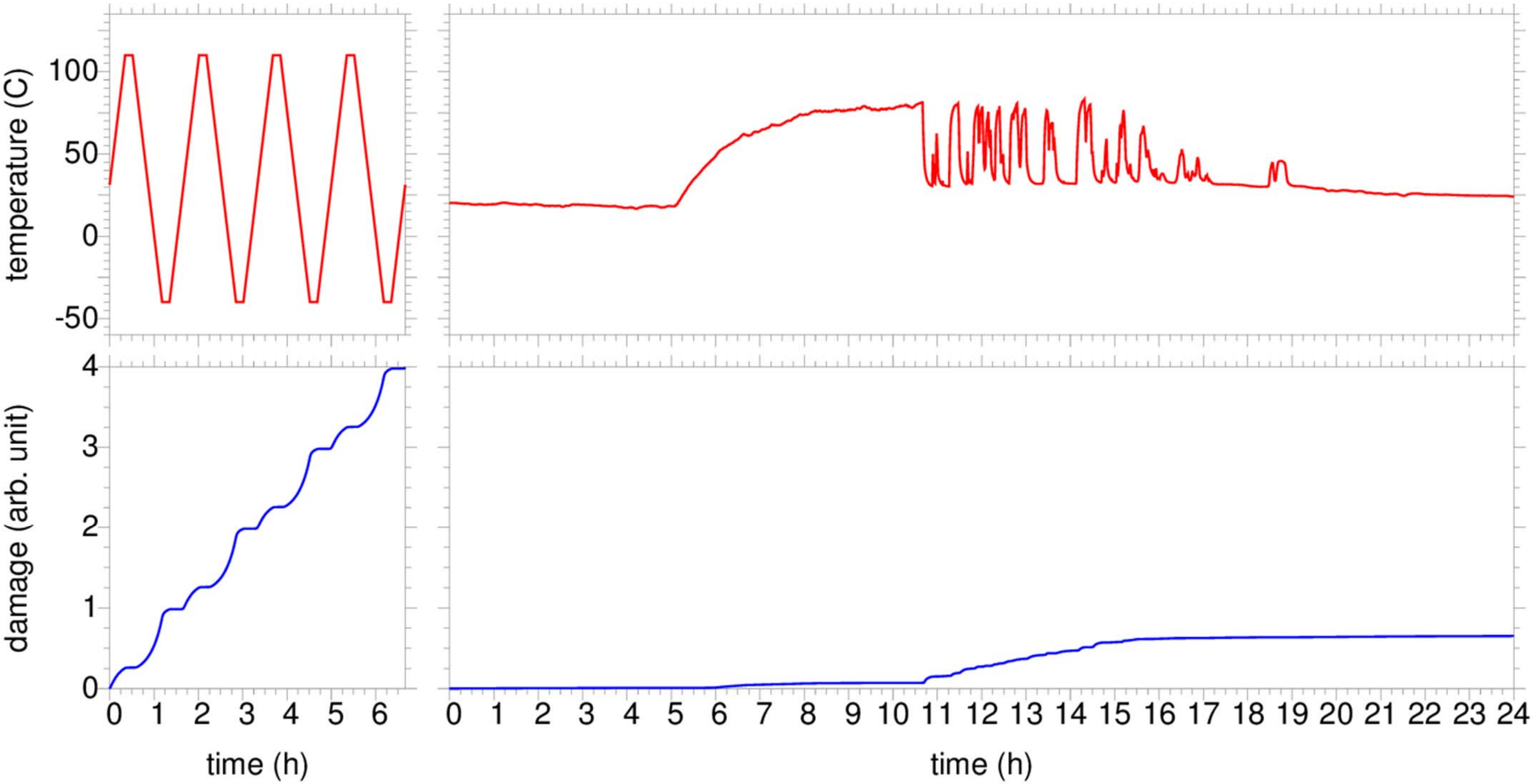
For every cycle we tested, faster cycles caused more damage per cycle

Weather is irregular



Repeating cycles each do the same damage only after a long sequence

Long-time simulations

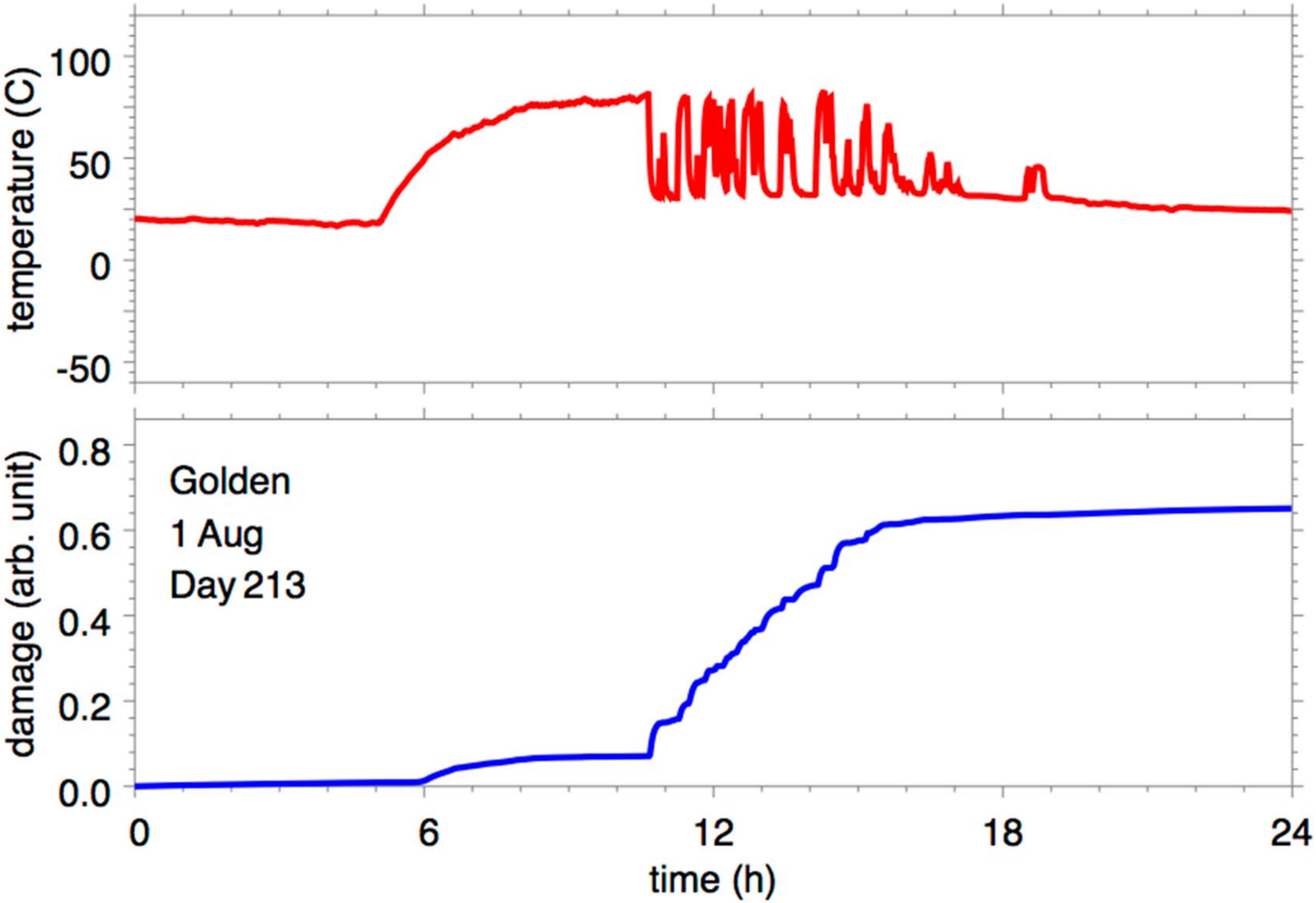


Typical fatigue models simulate only a few hours

Characterizing the weather requires a much longer simulation

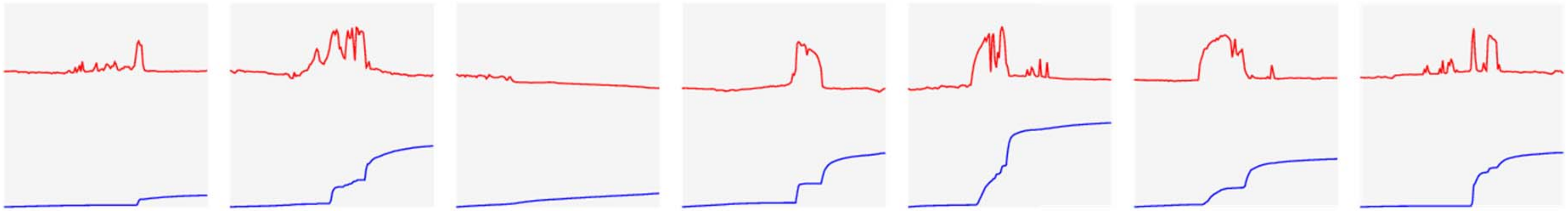
Cell temperature history can have more fast variation during outdoor exposure

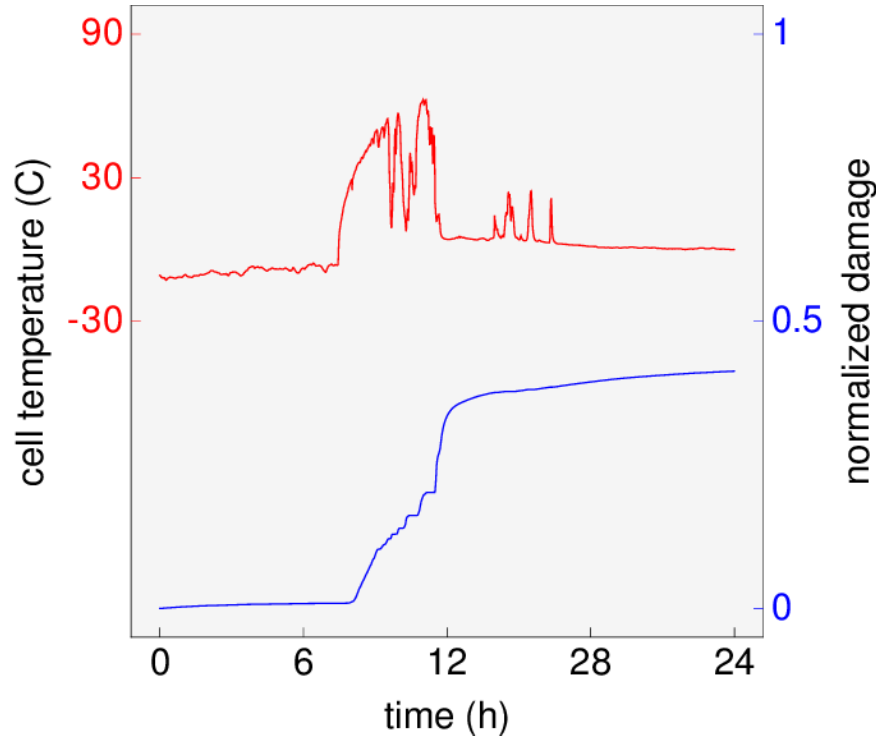
Simulating a day of outdoor exposure



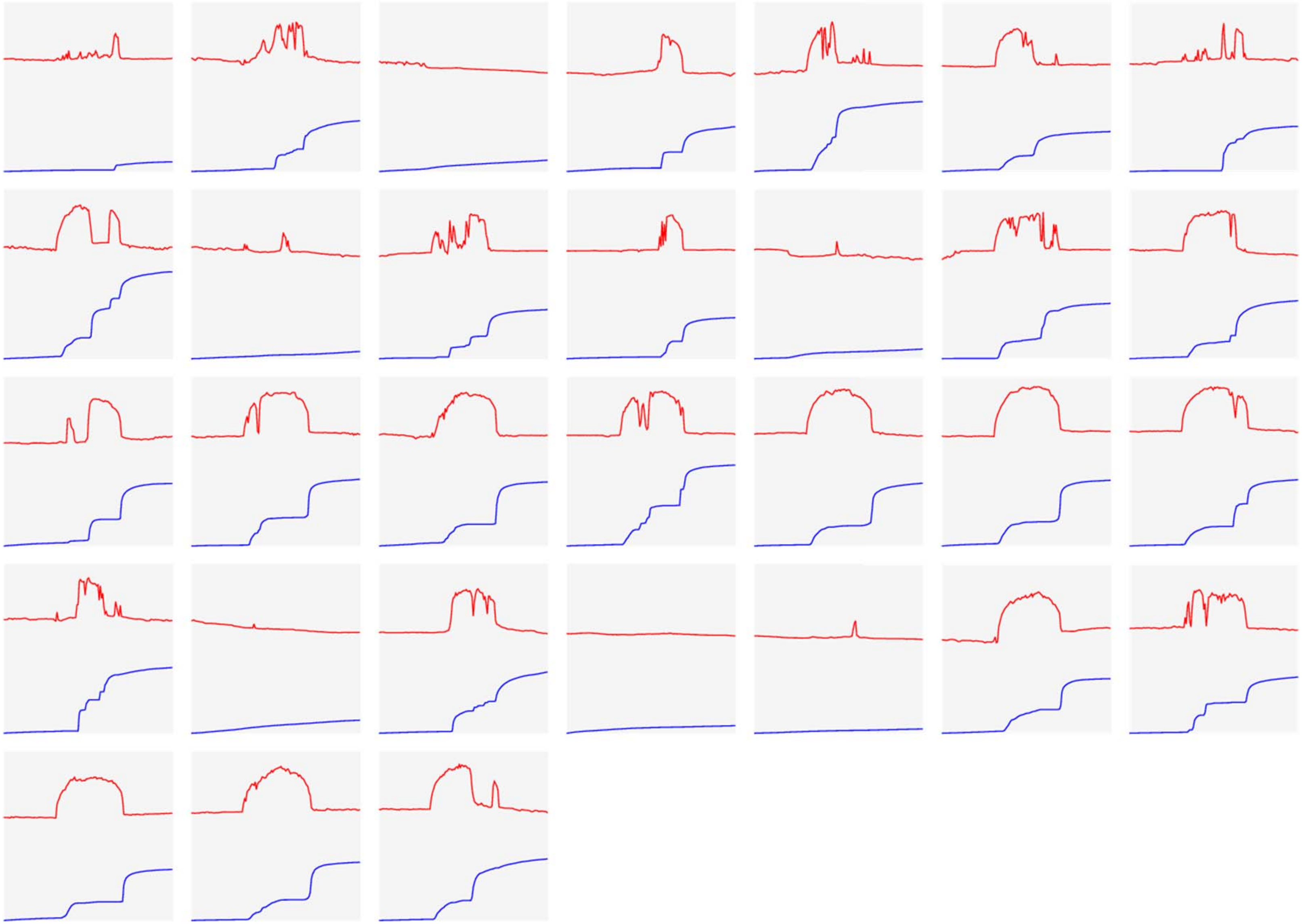
Cell temperature is derived from one-minute samples of meteorological data

Simulating several days

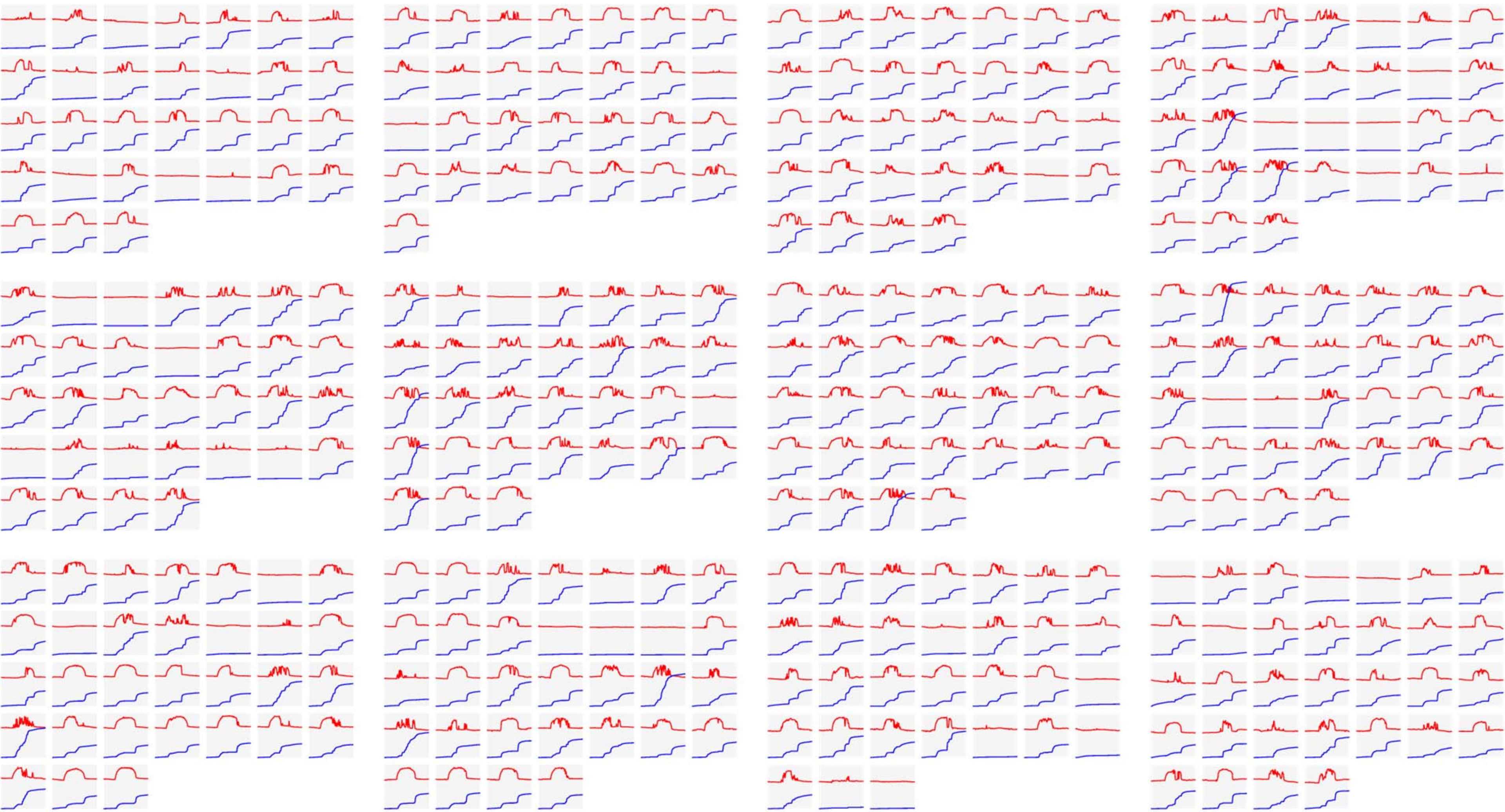




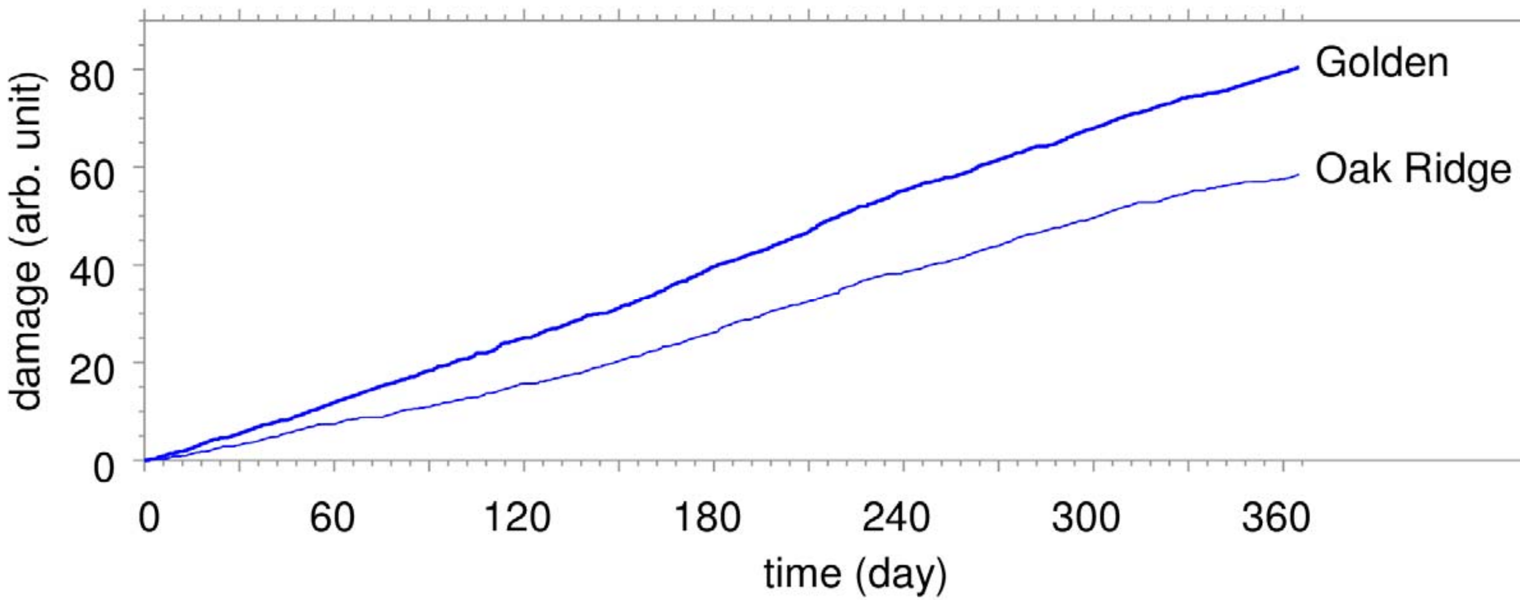
Simulating several days



Simulating an entire year



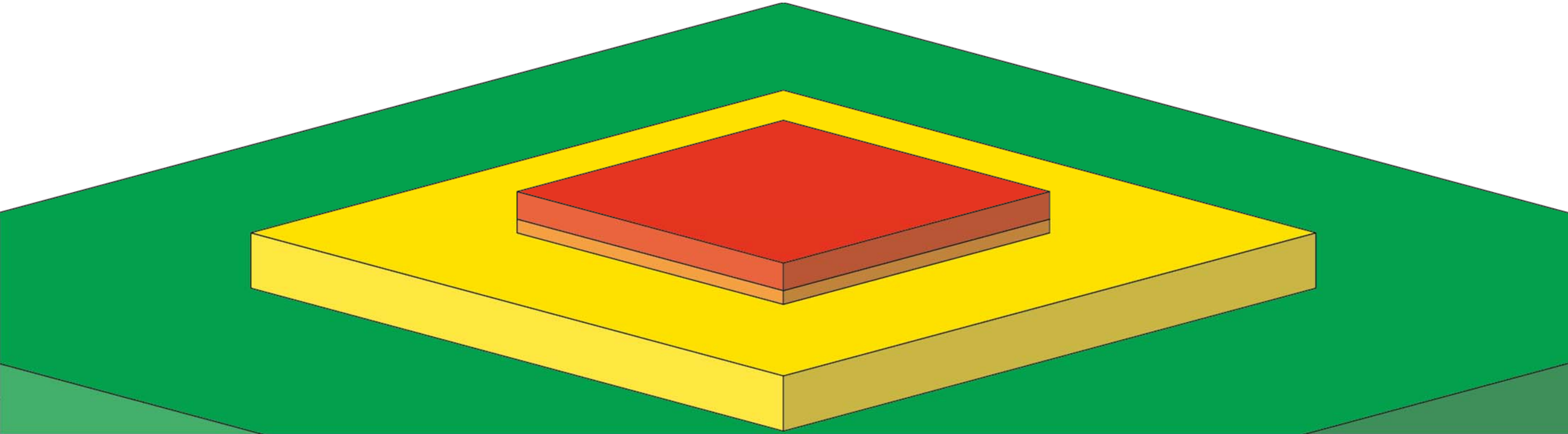
Simulating an entire year



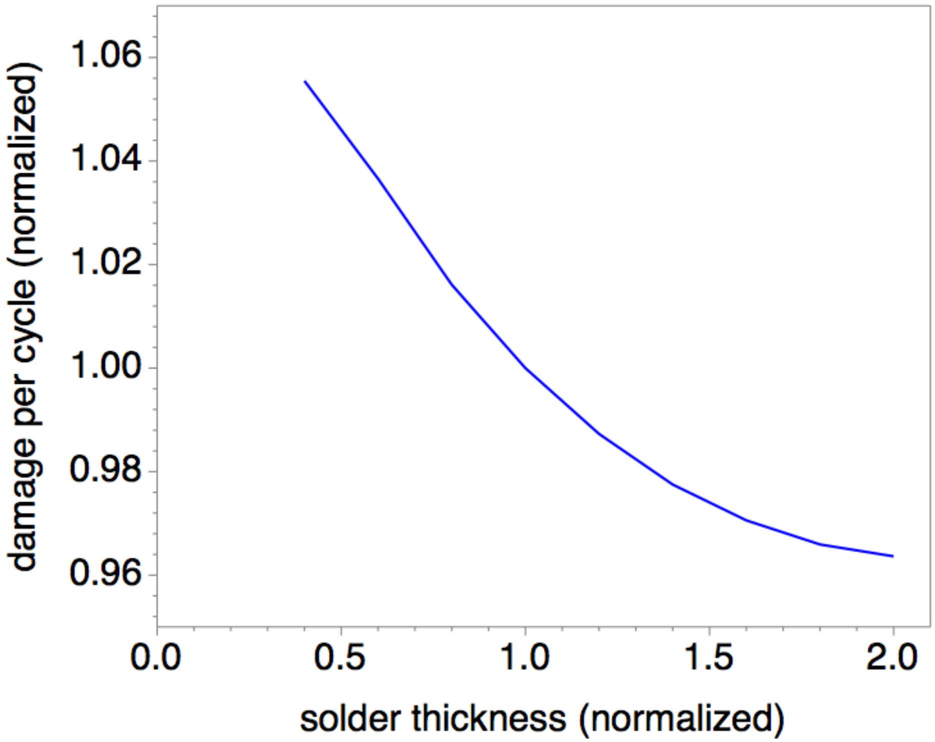
A year in Oak Ridge, Tenn. does 70% as much damage as a year in Golden, Colo.

Improving the model

- More accurate temperature input data
- Understanding of sensitivity to geometry and materials selection: Do these results apply to your cell assembly?
- Improved measurements of material properties

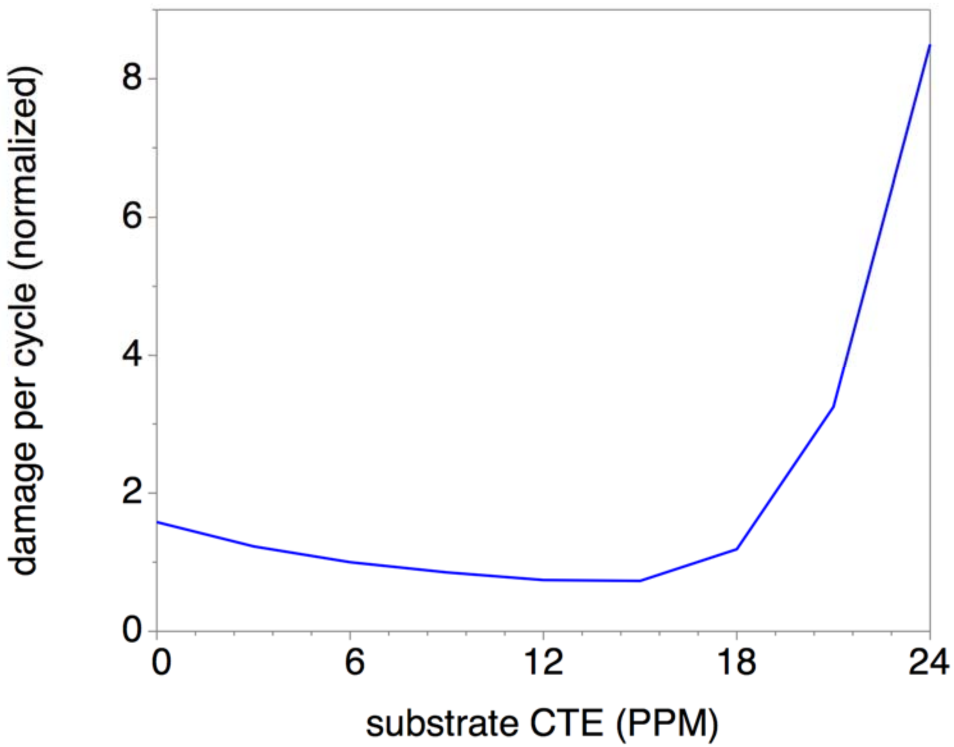


Improving the model: Geometric effects



Solder thickness has a modest effect on the rate of damage accumulation

Improving the model: Material effects



Fixed substrate thickness and stiffness; variable CTE

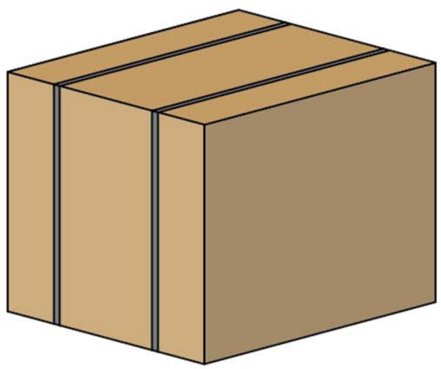
Substrate thermal expansion has a strong effect on the rate of damage accumulation

Improving the model: Material properties

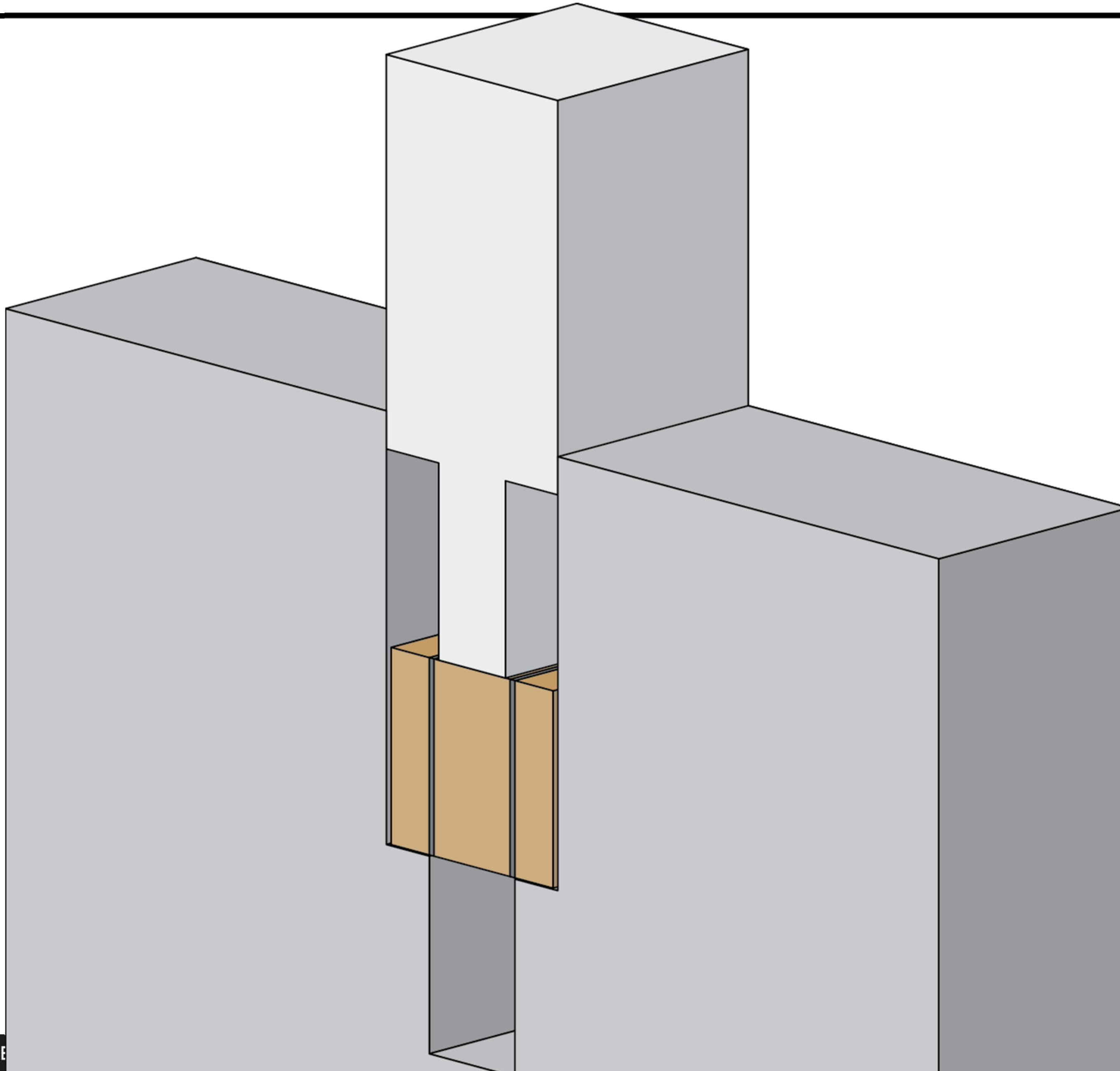
$$\dot{\varepsilon}_{\mathrm{pl,eq}} = A \exp\left(\frac{-Q}{RT}\right) \left[\sinh\left(\xi \frac{\sigma_{\mathrm{eq}}}{s}\right)\right]^{\frac{1}{m}}$$

$$\dot{s} = \dot{\varepsilon}_{\mathrm{pl,eq}} \; h_0 \left|1 - \frac{s}{s^*}\right|^a \; \mathrm{signum}\left(1 - \frac{s}{s^*}\right)$$

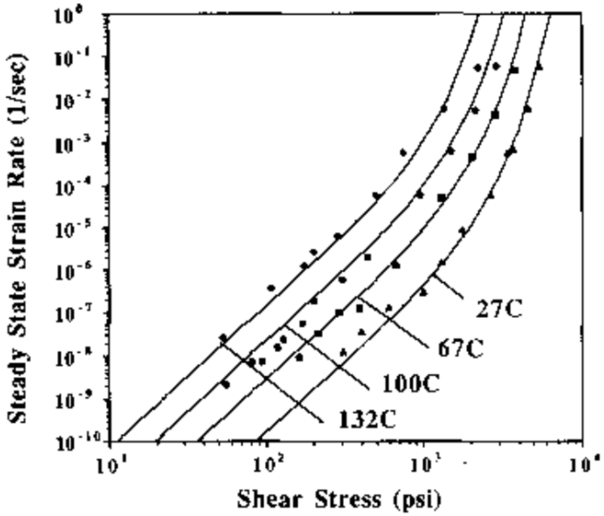
$$s^* = \hat{s} \left[\frac{\dot{\varepsilon}_{\mathrm{pl,eq}}}{A} \exp\left(\frac{Q}{RT}\right)\right]^n$$



Improving the model: Material properties



Improving the model: Material properties



Darveaux, R. et al, IEEE J Compon. Hybr. 15:6, 1992.

$$\dot{\varepsilon}_{\mathrm{pl}} = \dot{\varepsilon} = A \exp\left(\frac{-Q}{RT}\right) \left[\sinh\left(\xi \frac{\sigma^*}{s^*}\right)\right]^{\frac{1}{m}}$$

$$s^* = \hat{s} \left[\frac{\dot{\varepsilon}_{\mathrm{pl,eq}}}{A} \exp\left(\frac{Q}{RT}\right)\right]^{n}$$

Material properties are fitted to a set of constant-strain-rate or constant-load tests

Summary and conclusion

- By experiment and simulation, fast thermal cycles cause more damage per cycle
- Our model is efficient enough to simulate thousands of cycles or entire years of exposure
- A year in Golden causes more damage than a year in Oak Ridge
- Simulations have come a long way, but need additional refinement before they can be used for absolute lifetime prediction
- Further experiments and model improvements could enable estimation of lifetime from simulation and limited experiments