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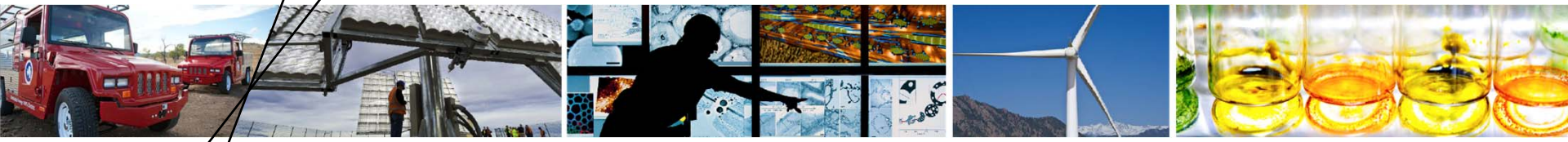
Comparison of accelerated testing with modeling to predict lifetime of CPV solder layers



2012 PV Module Reliability Workshop

Timothy J Silverman, Nick Bosco, Sarah Kurtz

March 1, 2012

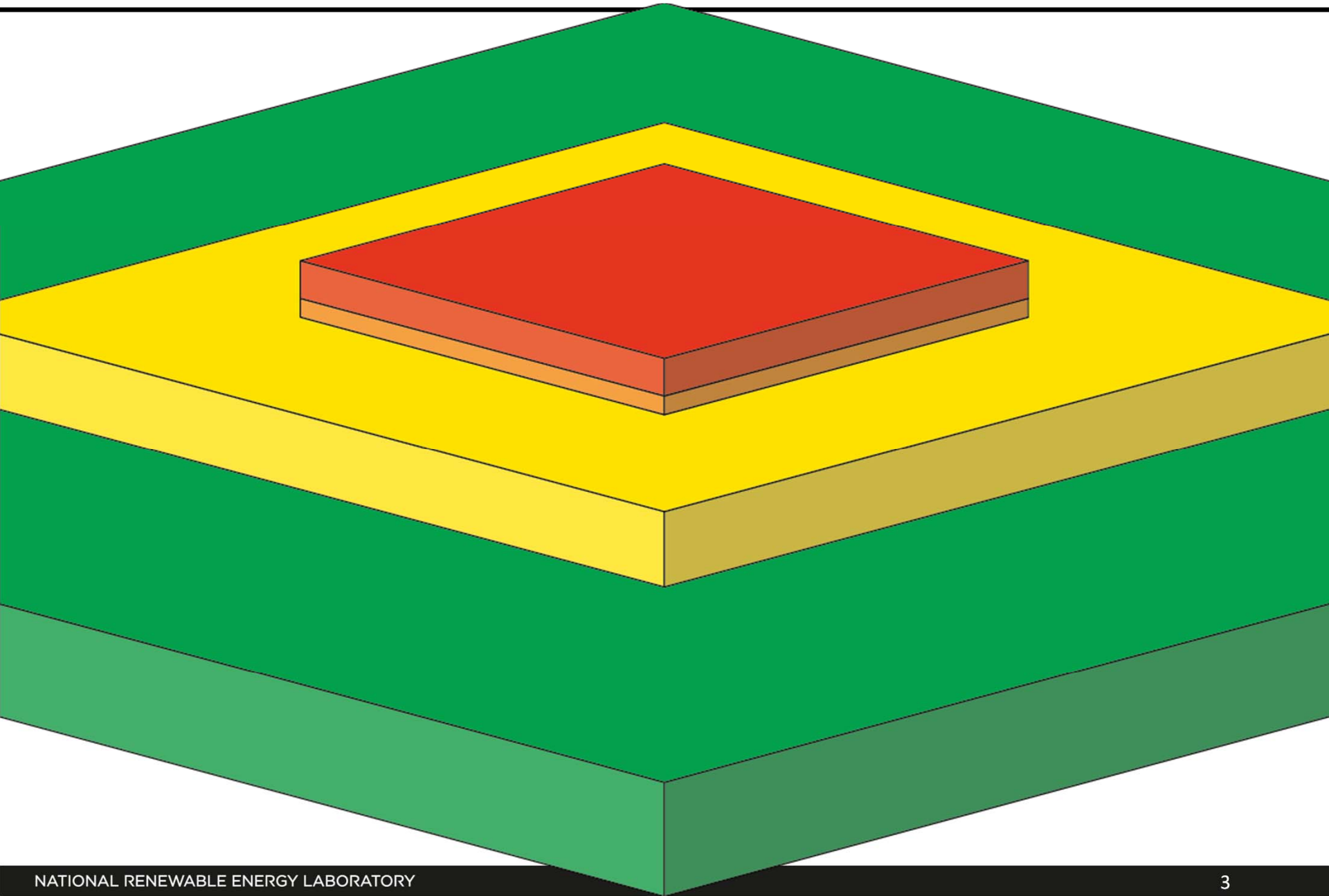
NREL/PR-5200-54677

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

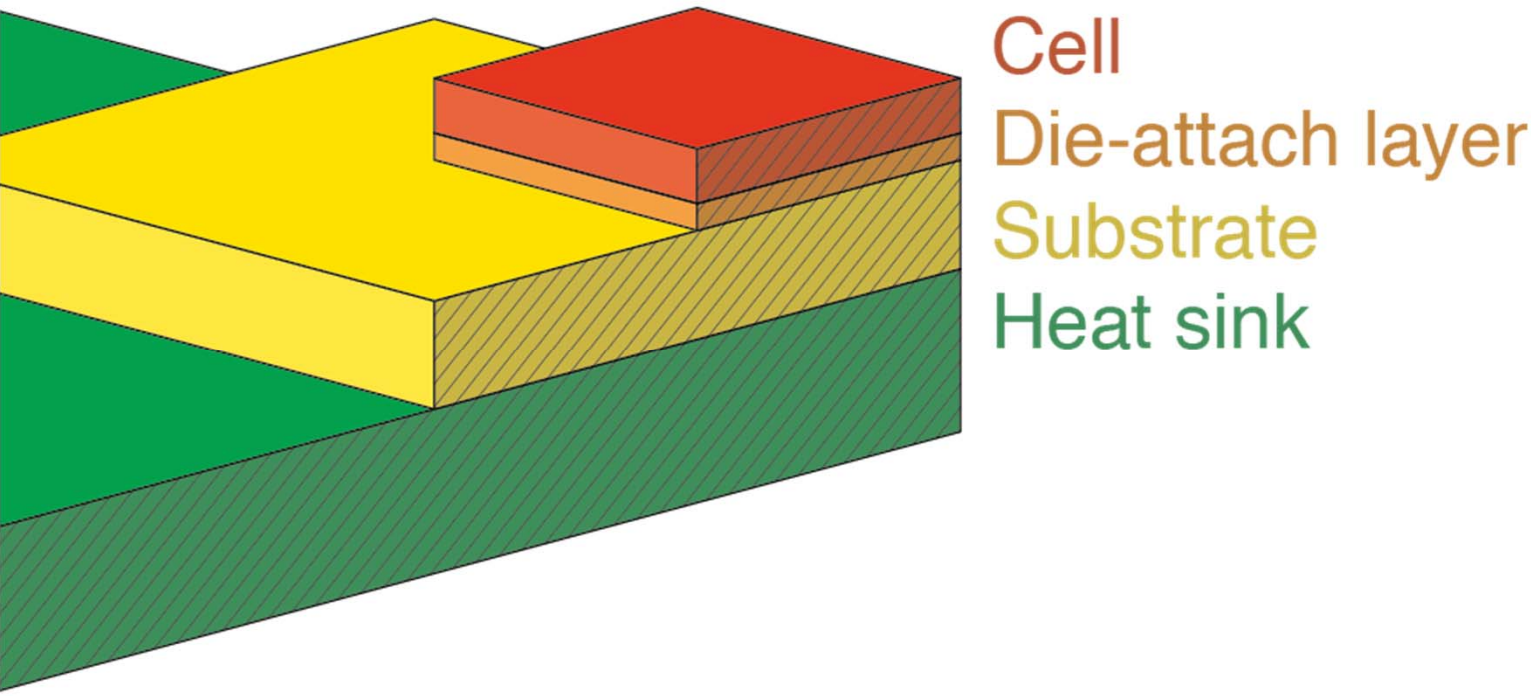
Agenda

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

The CPV solder layer

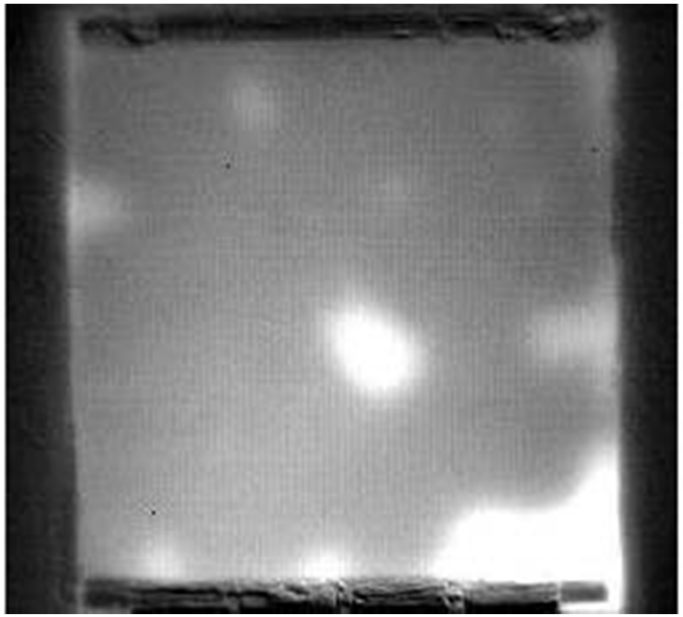


The CPV solder layer



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

Cracks kill



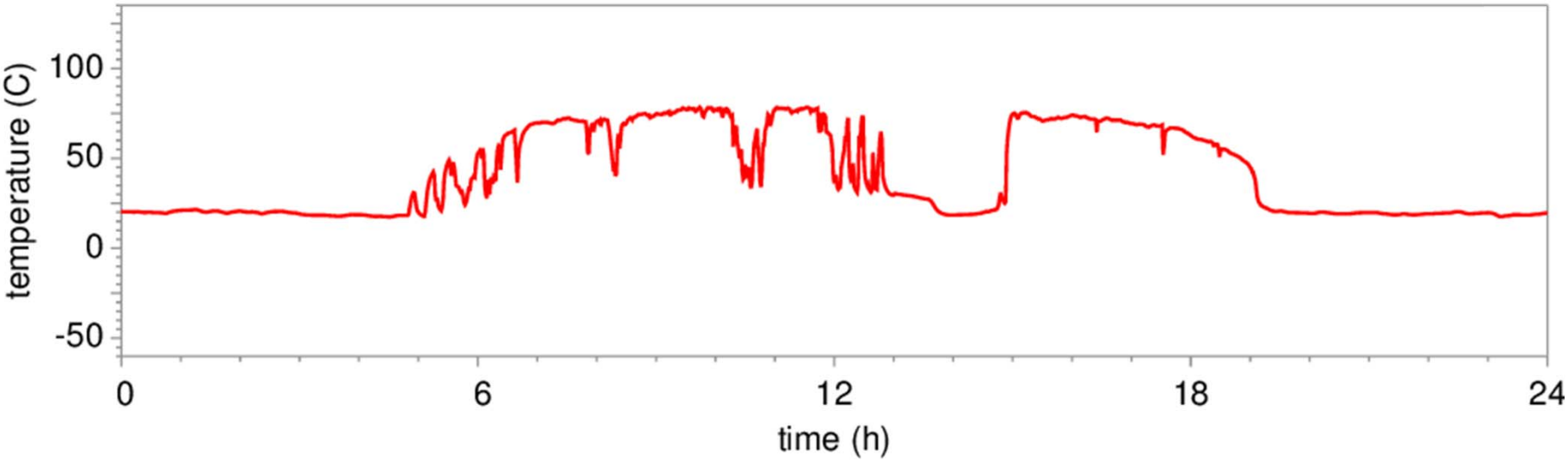
Transient IR image showing cracks from thermal cycling

Steady-state IR image showing shunt caused by sun exposure

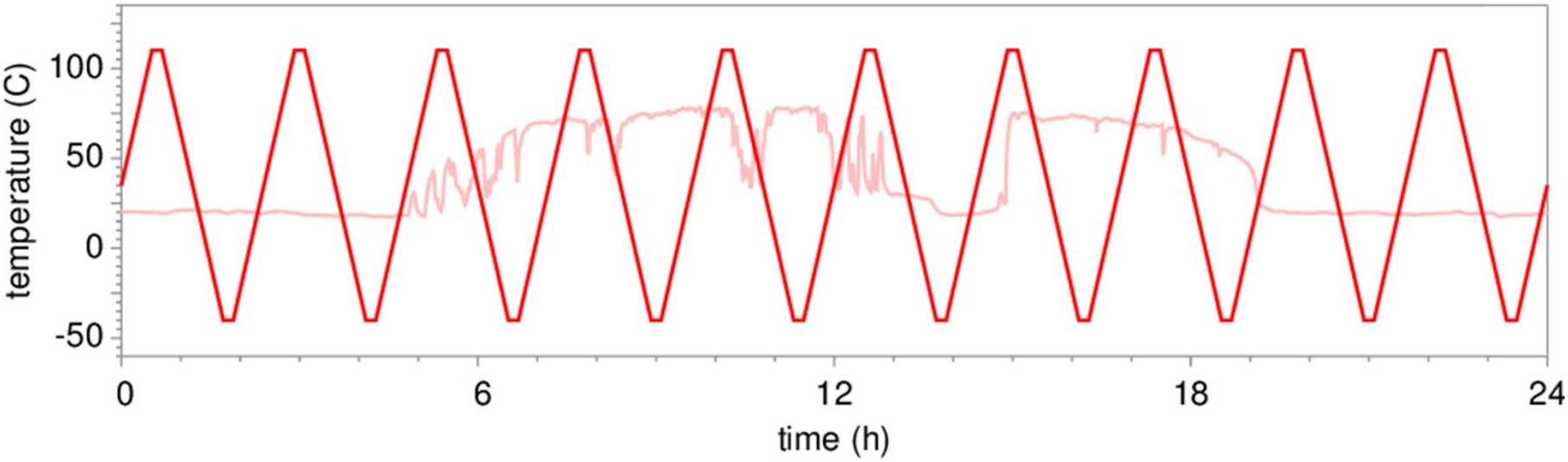
The mechanical integrity of the die-attach layer is critical for the removal of heat

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

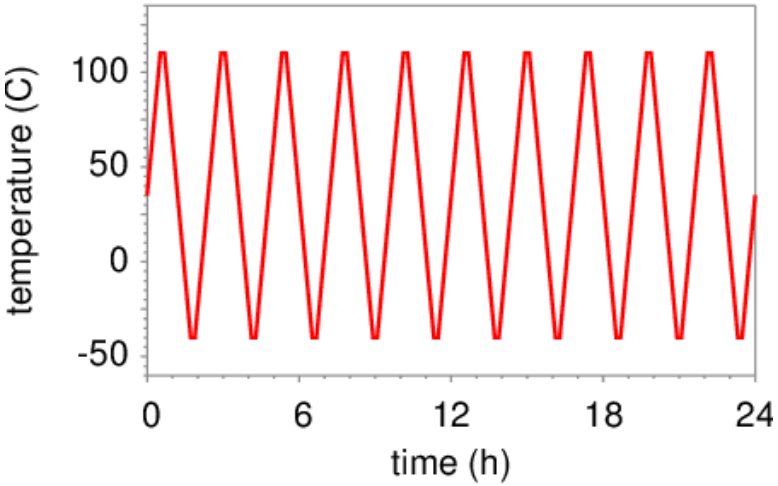
Weather is thermal cycling



Accelerated testing is a shortcut



How much damage does a day do?



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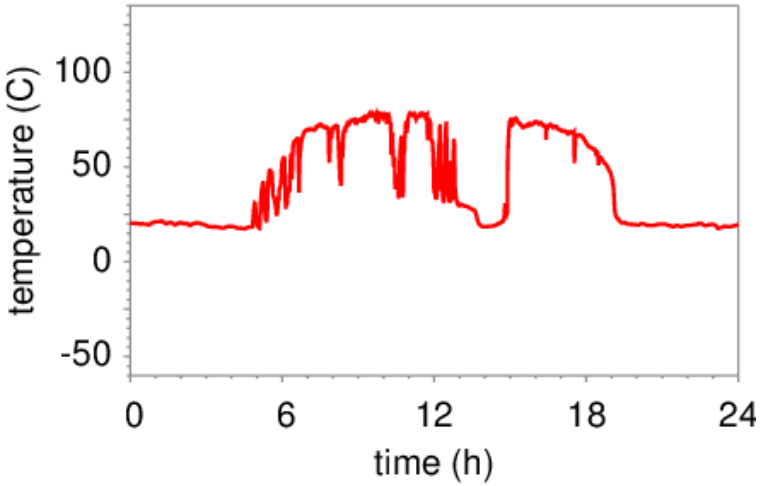
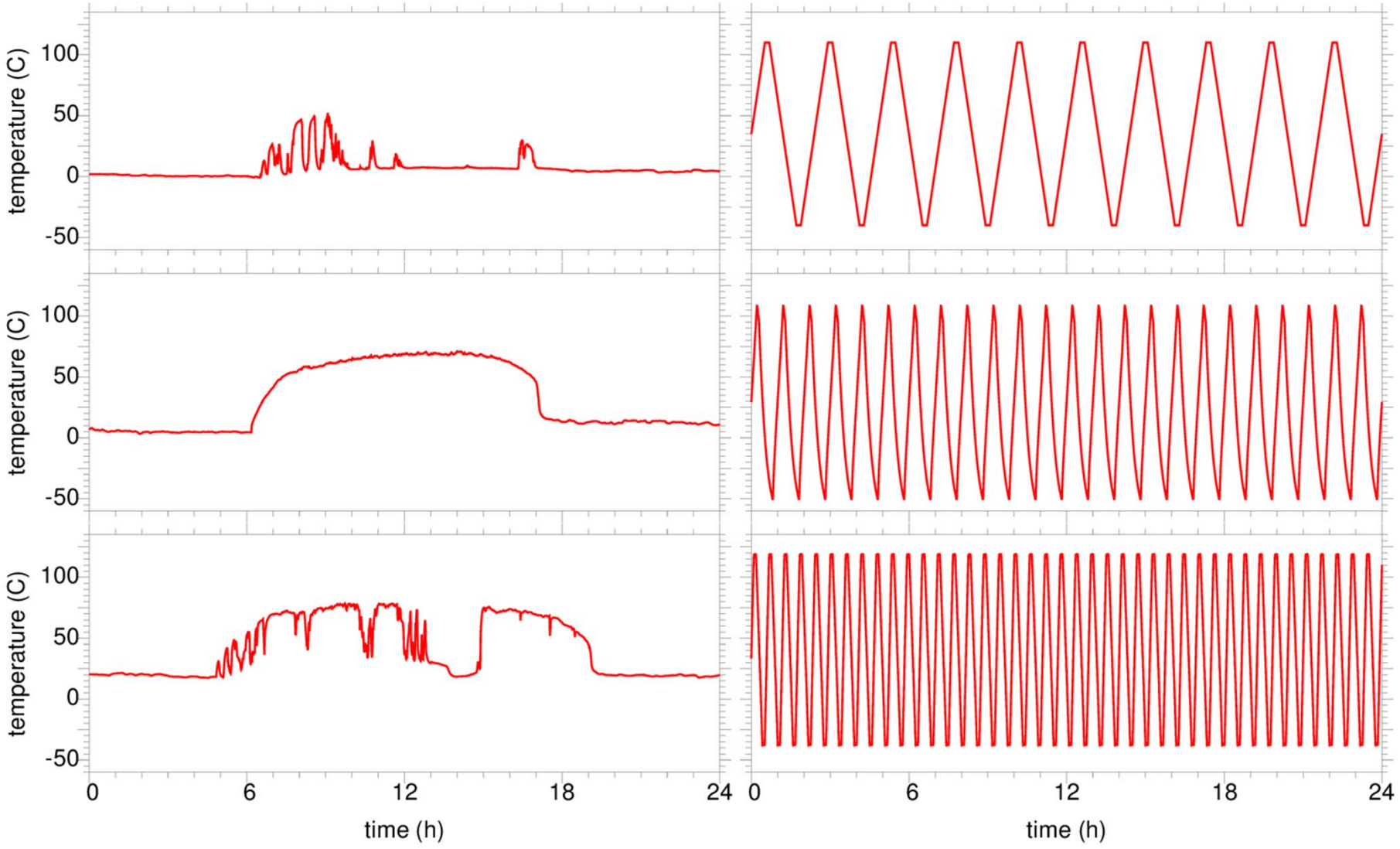


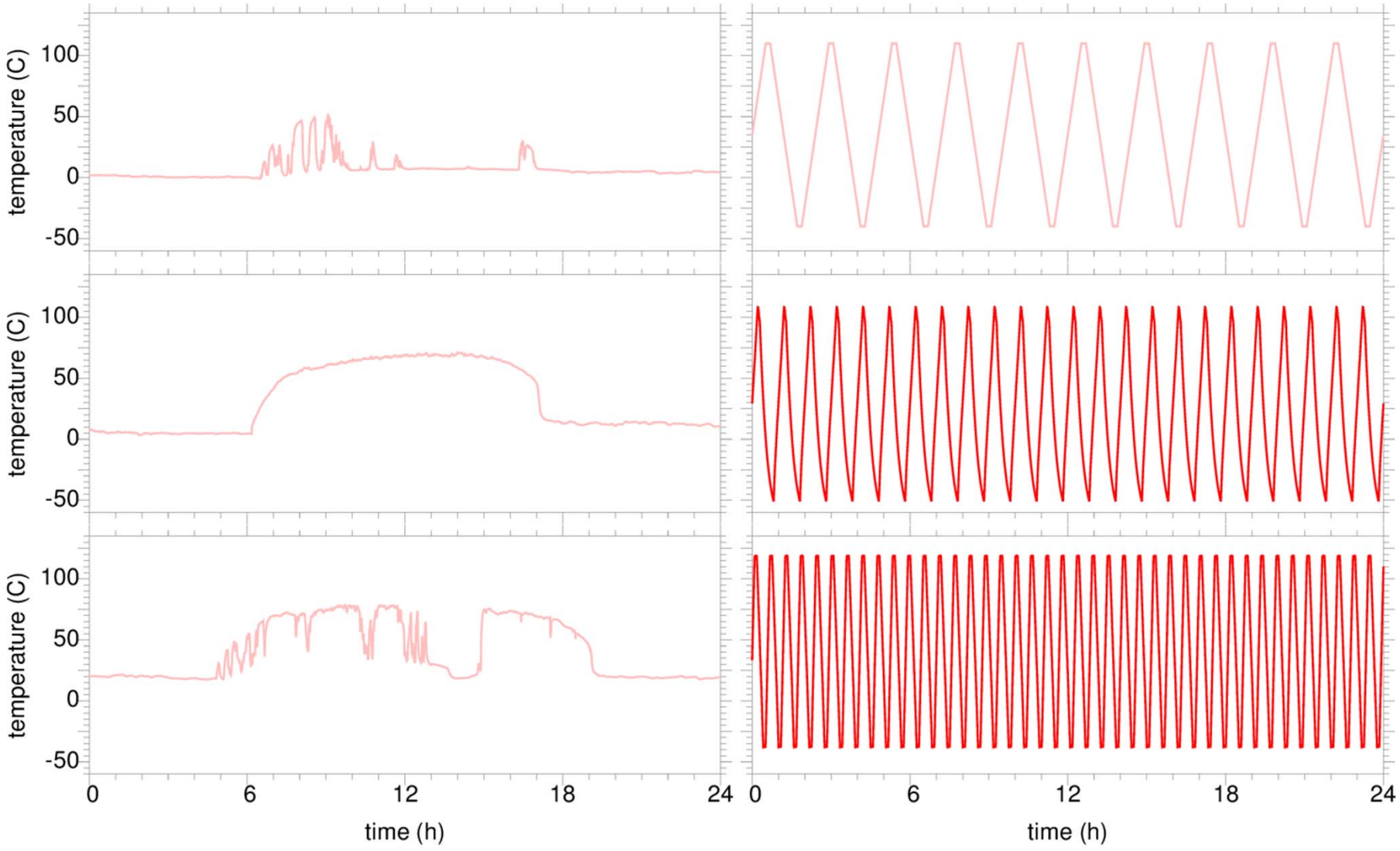
The answer: It depends

Which day?

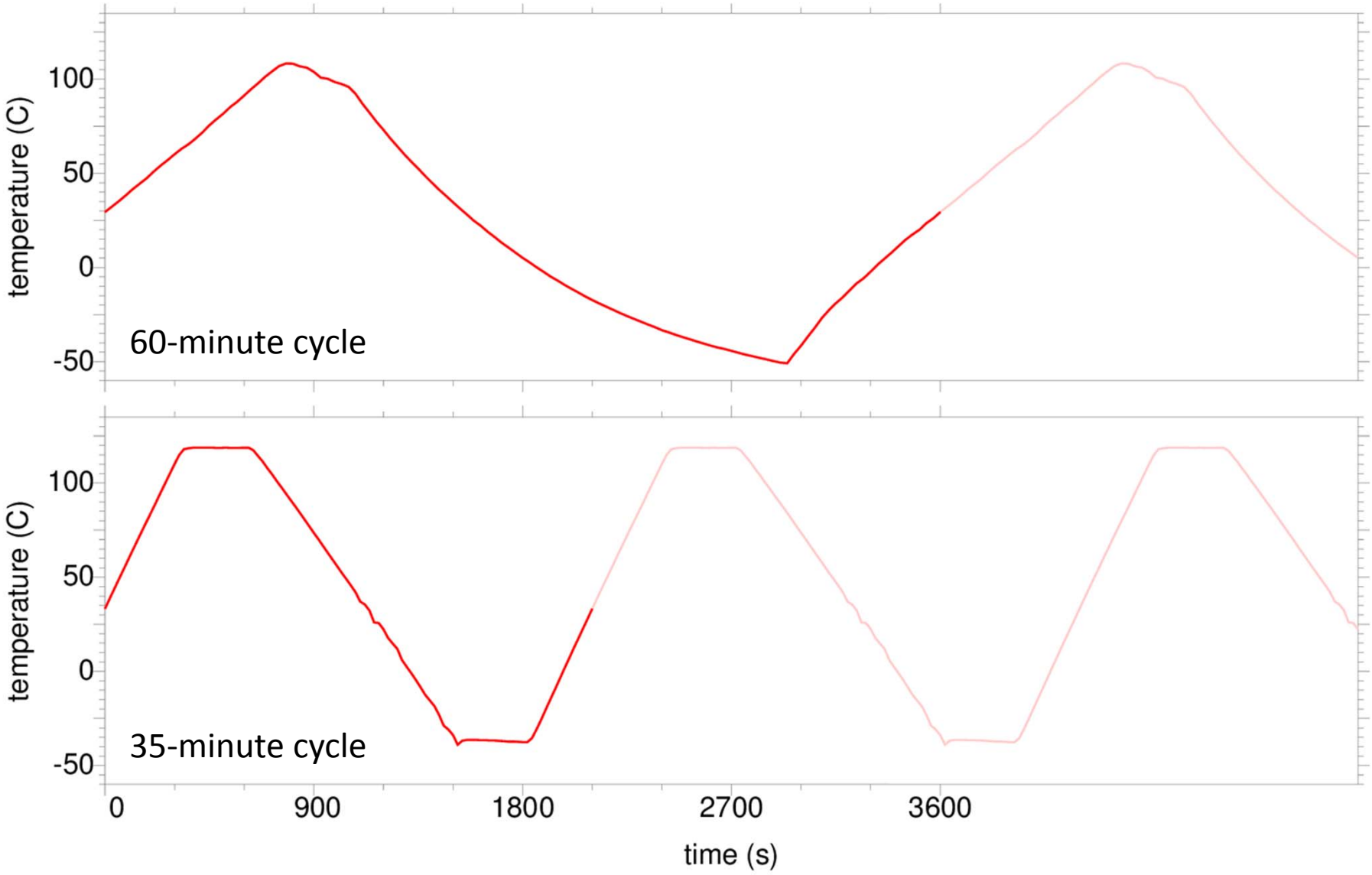
Which cycle?



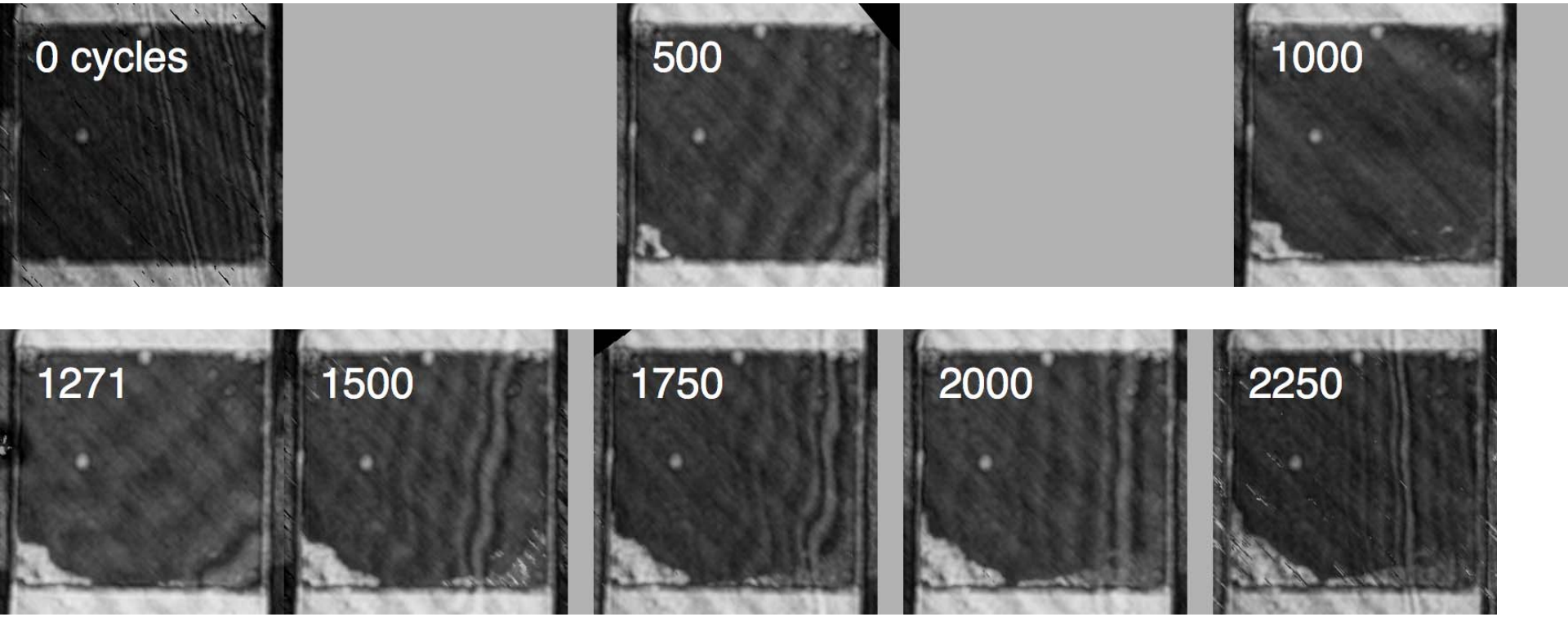
Crack growth experiments with two cycle types



How damaging are these two cycles?

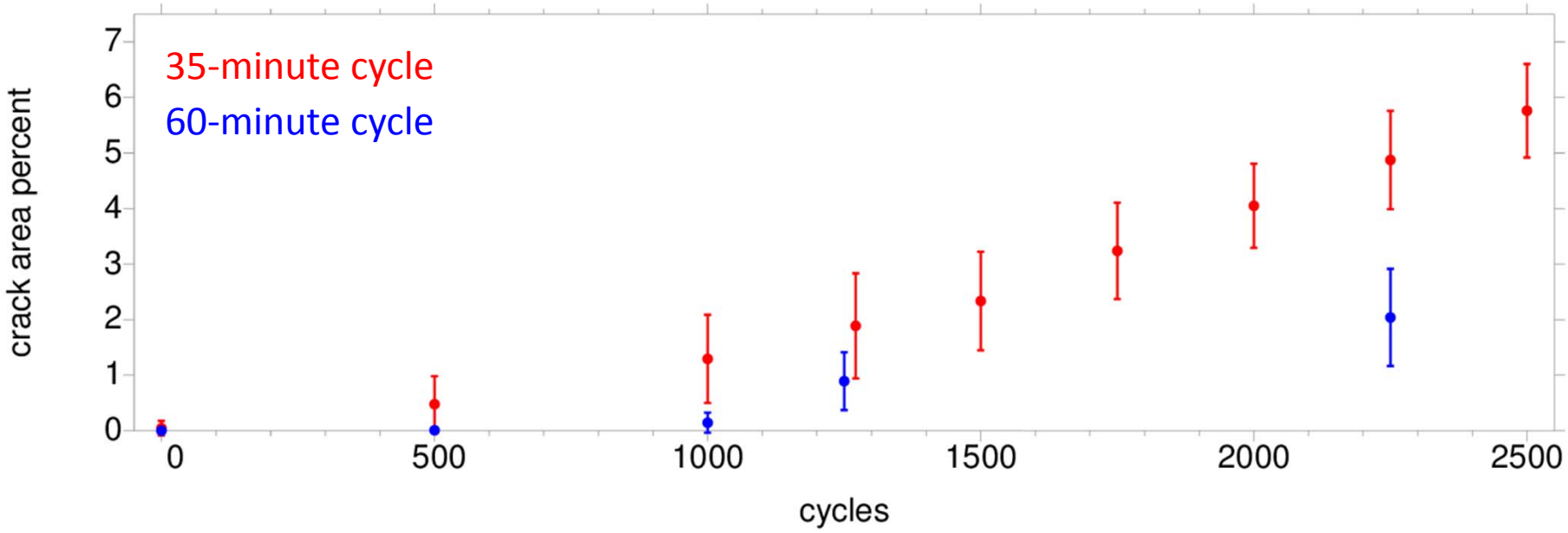


Measuring crack area acoustically



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

Crack growth due to thermal cycling



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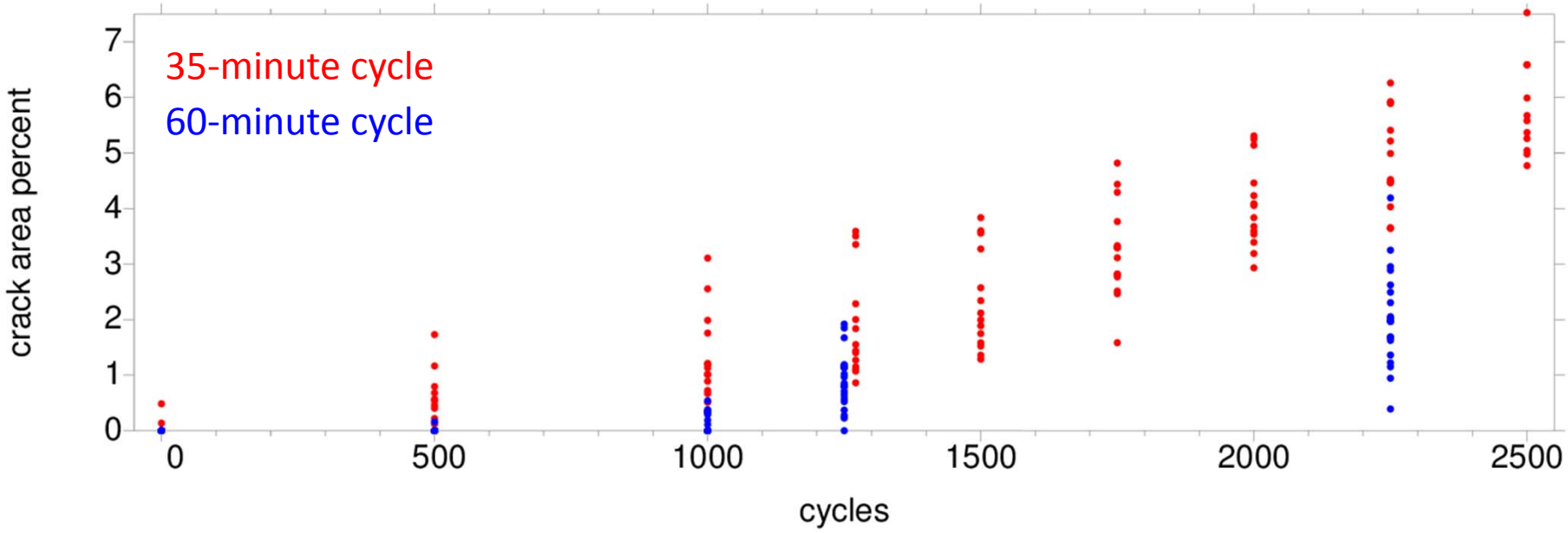

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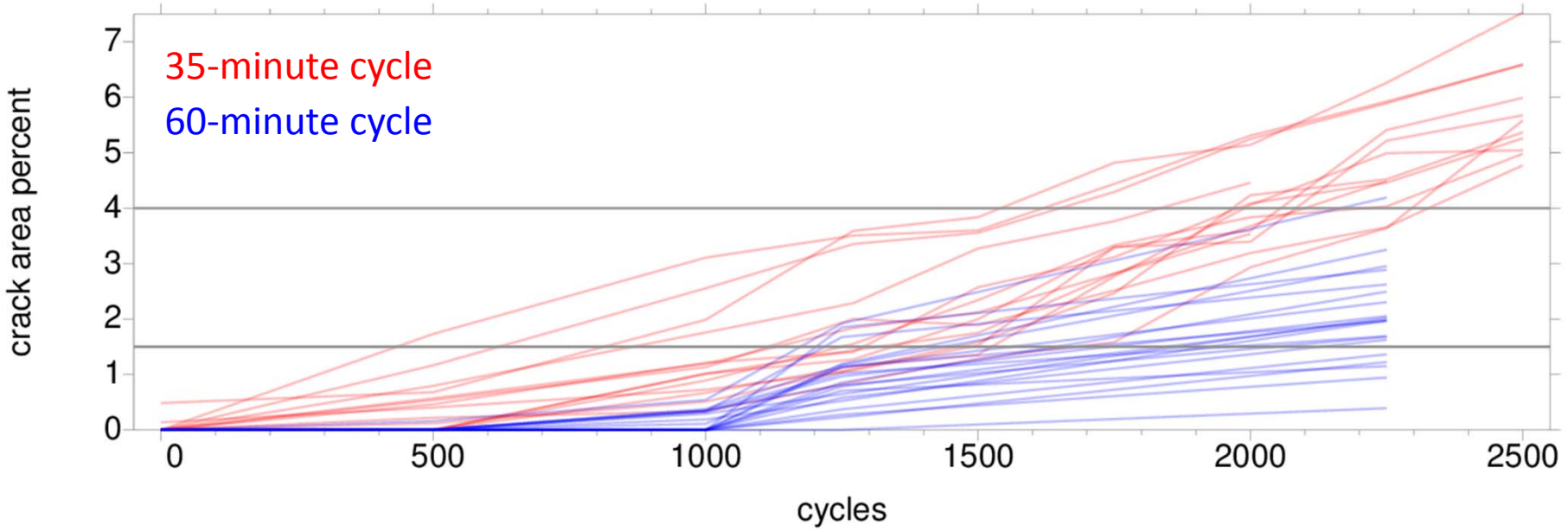
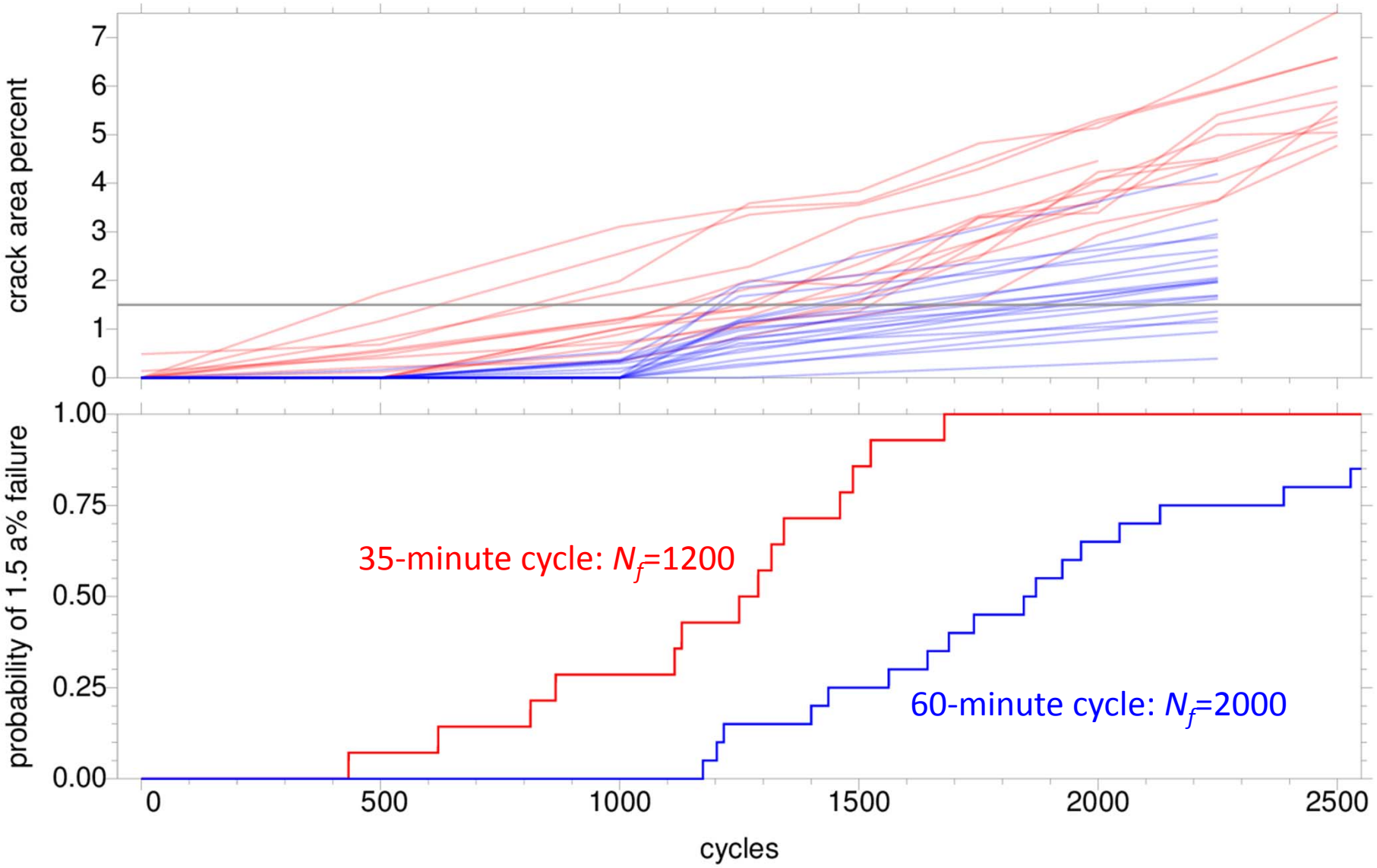
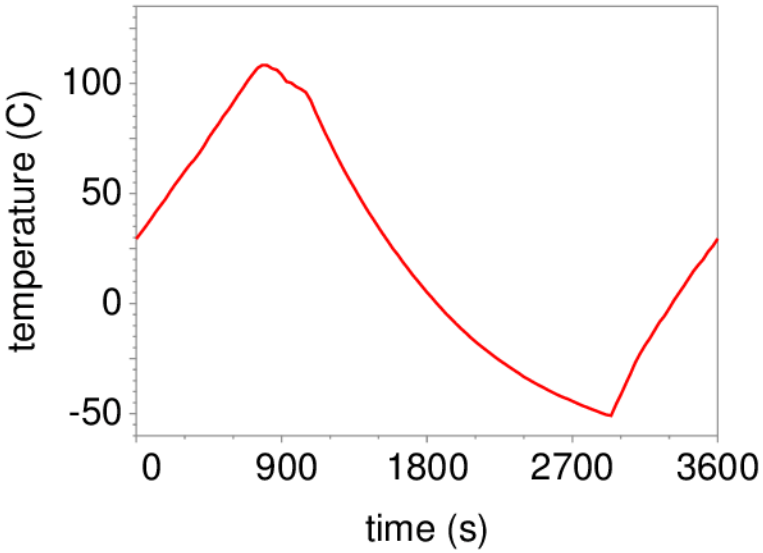


Crack growth due to thermal cycling



Connecting the two cycle types



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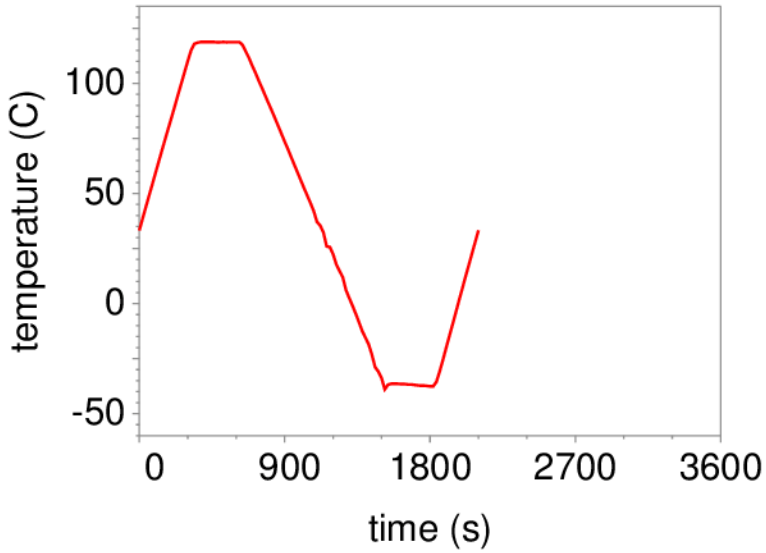
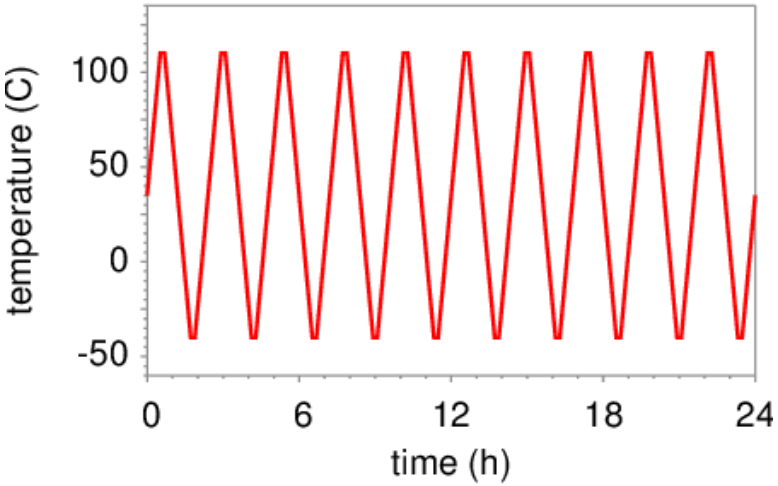


How much damage does a day do?



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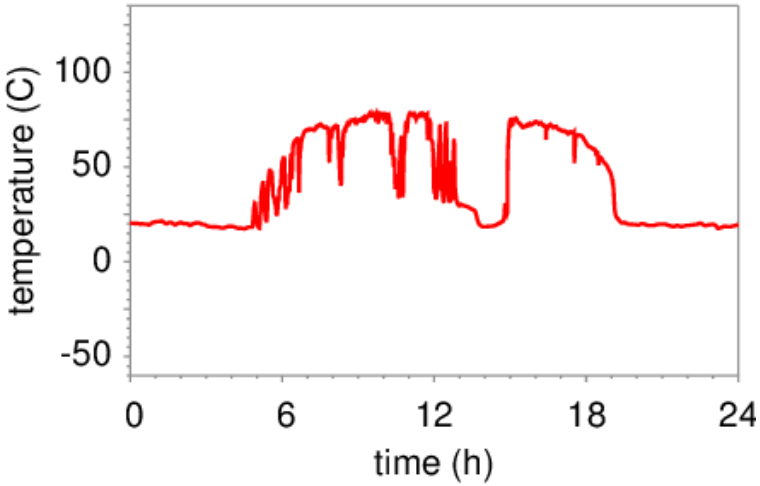
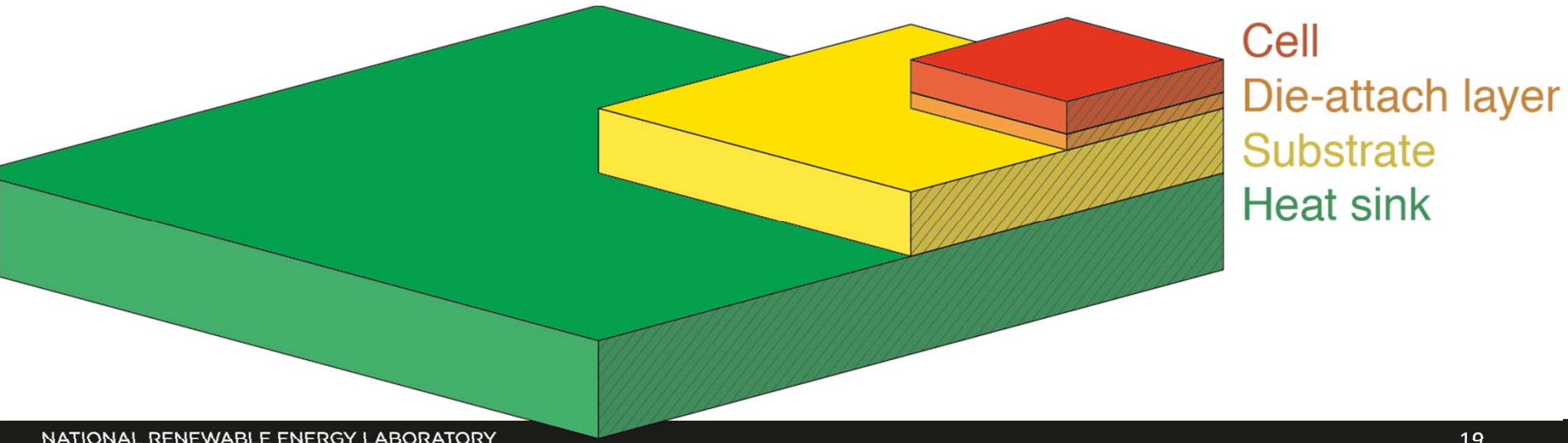


Numerical model

- 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



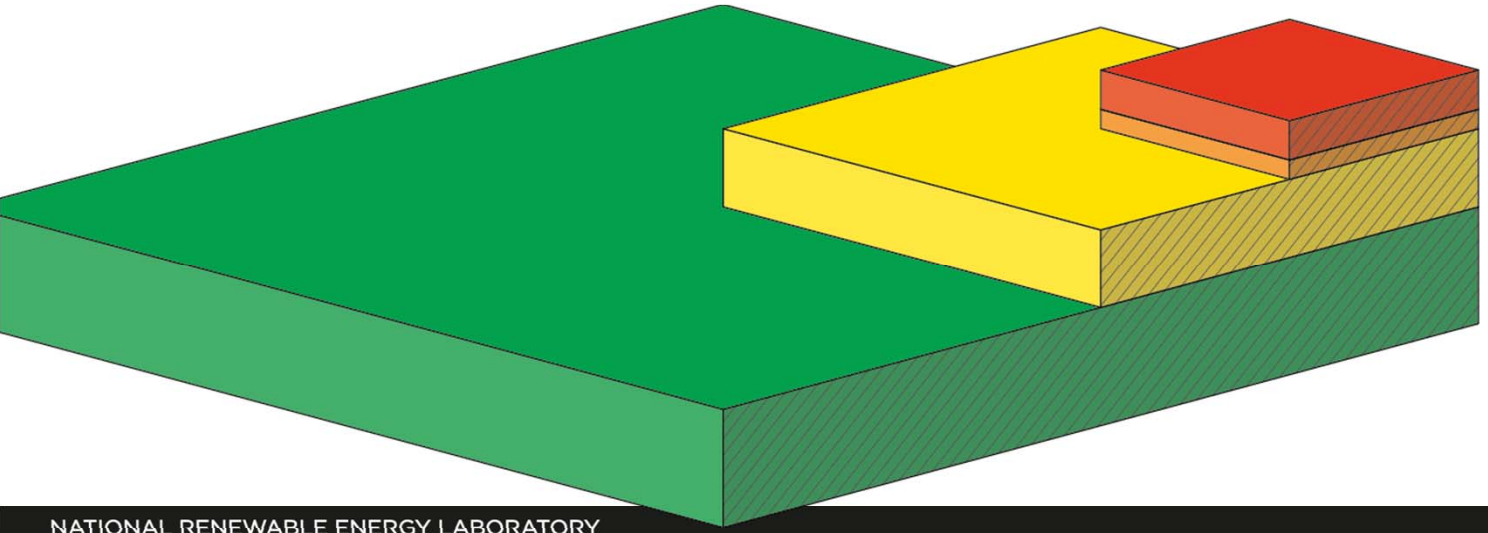
Numerical model

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

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

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

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



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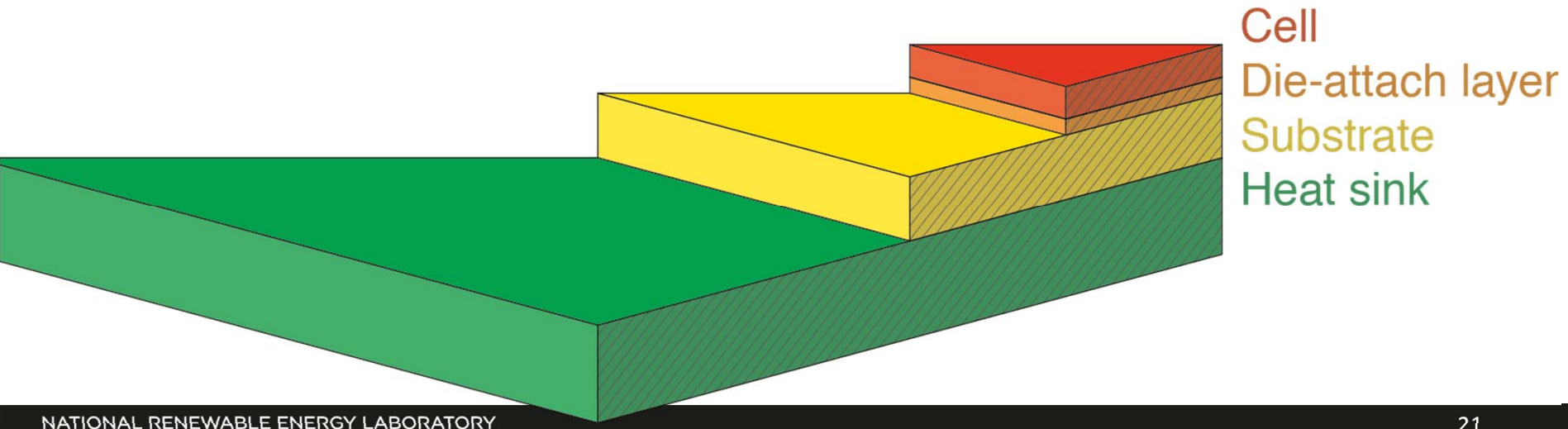
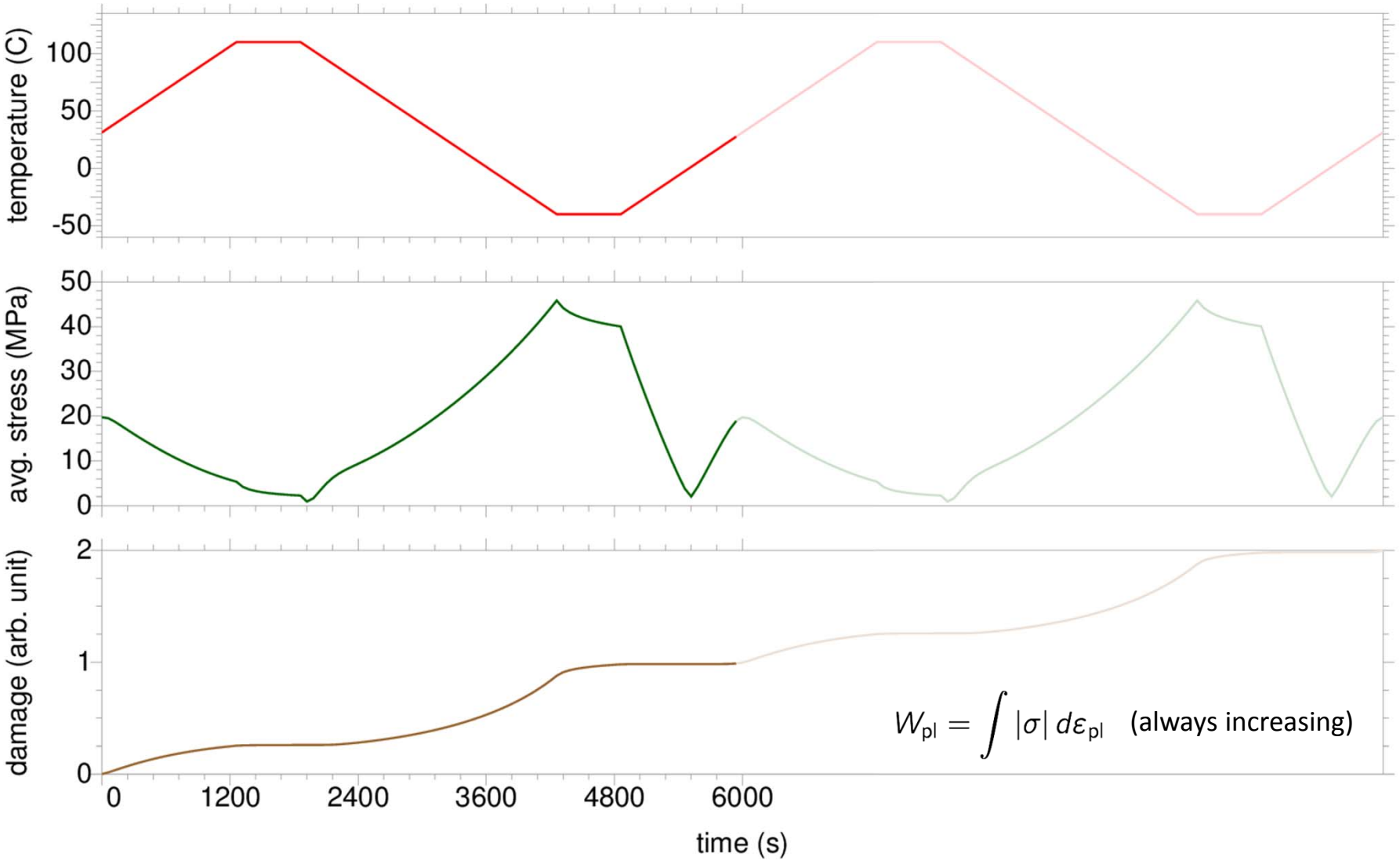
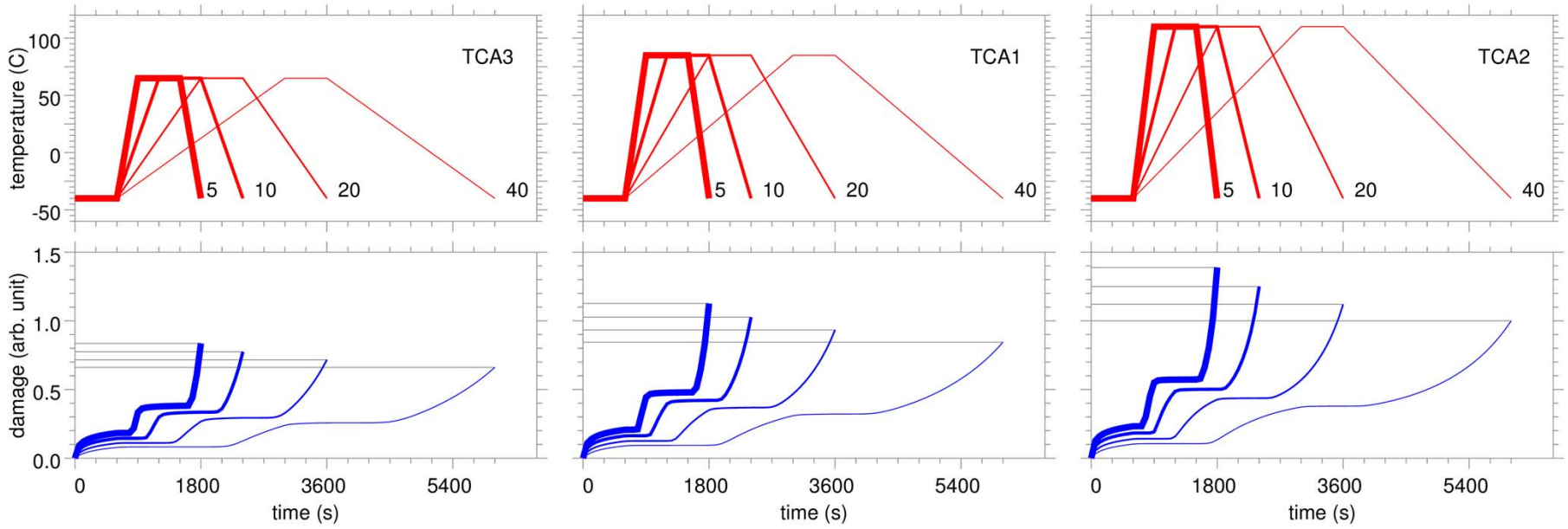


Damage: Progress toward failure



Comparing various thermal cycles



5, 10, 20, 40-minute ramps

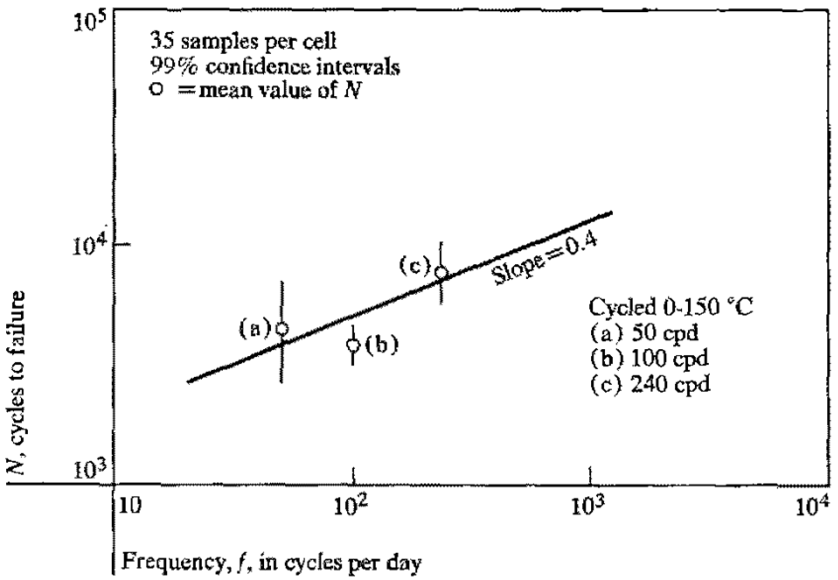
Faster cycles cause more damage per cycle

Larger-amplitude cycles cause more damage per cycle

Lifetime dependence on cycle frequency

$$N \propto f^k$$

$$0 \leq k \leq 1$$



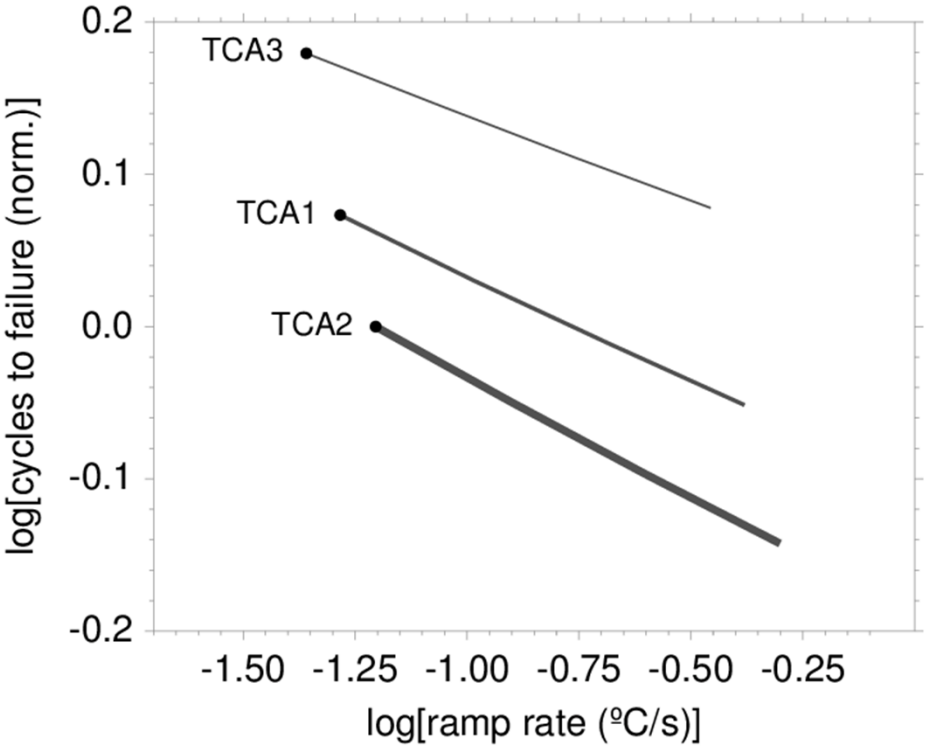
Norris, KC et al., IBM J Res Dev 13:3, 1969

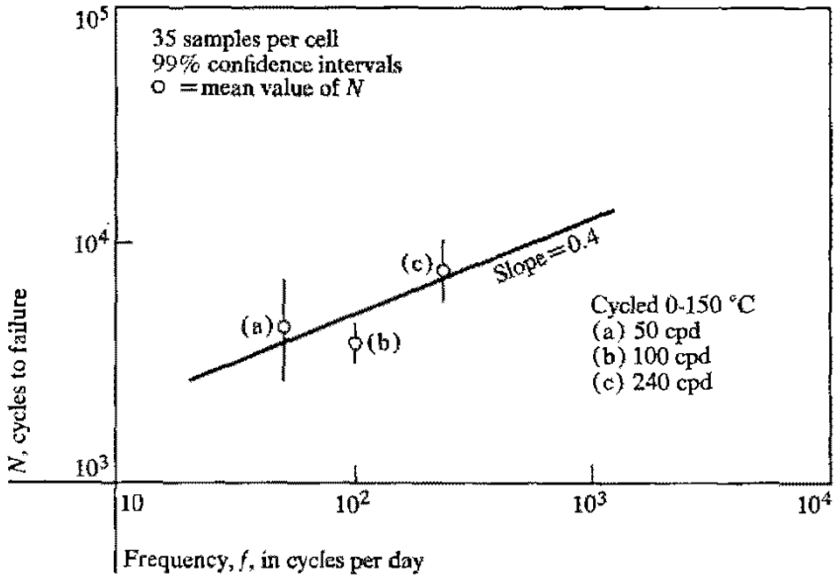
Empirical fatigue models say that faster cycles do less damage

Lifetime dependence on cycle frequency

$$N \propto f^k$$

$$0 \leq k \leq 1$$

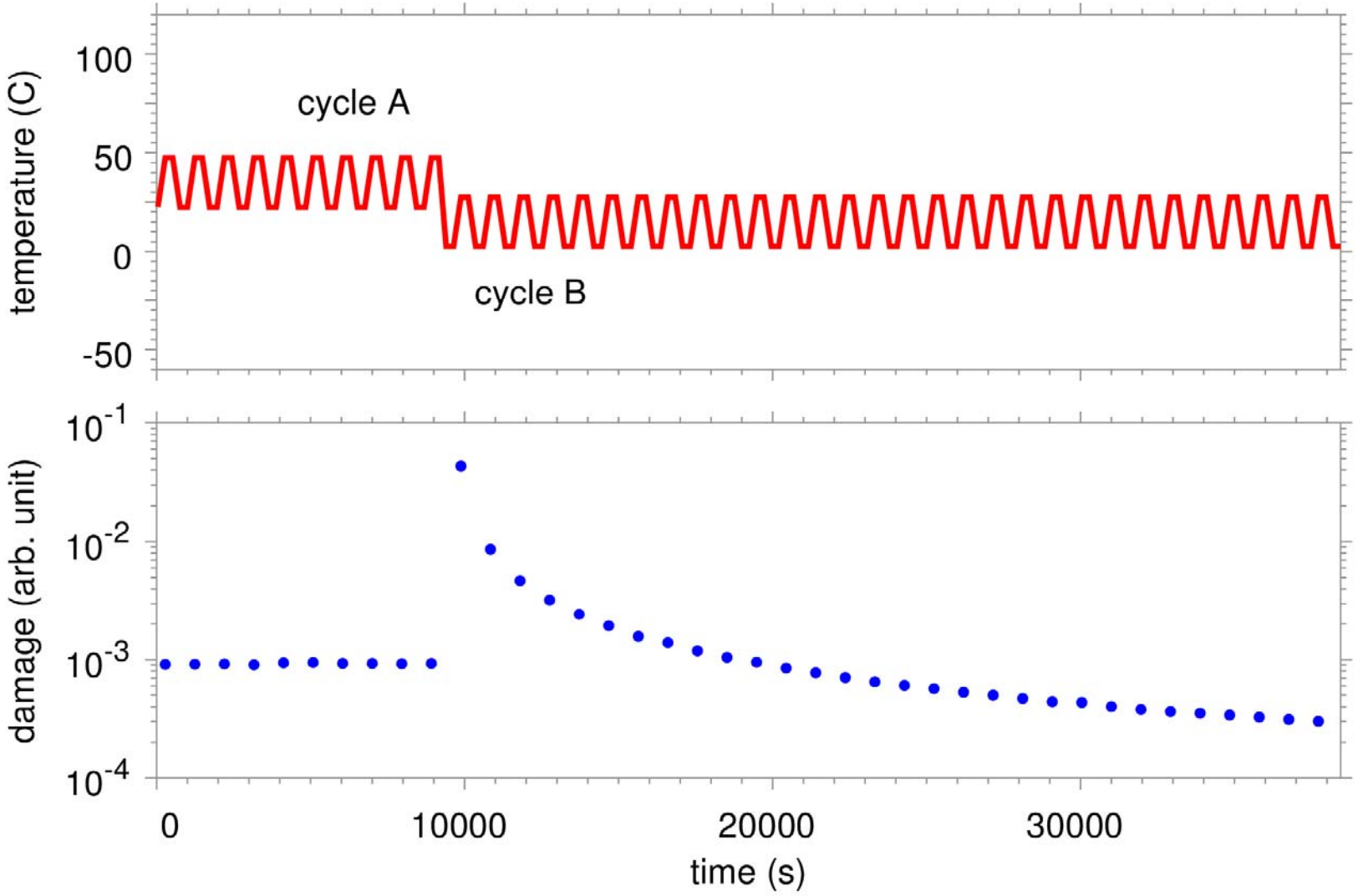




Norris, KC et al., IBM J Res Dev 13:3, 1969

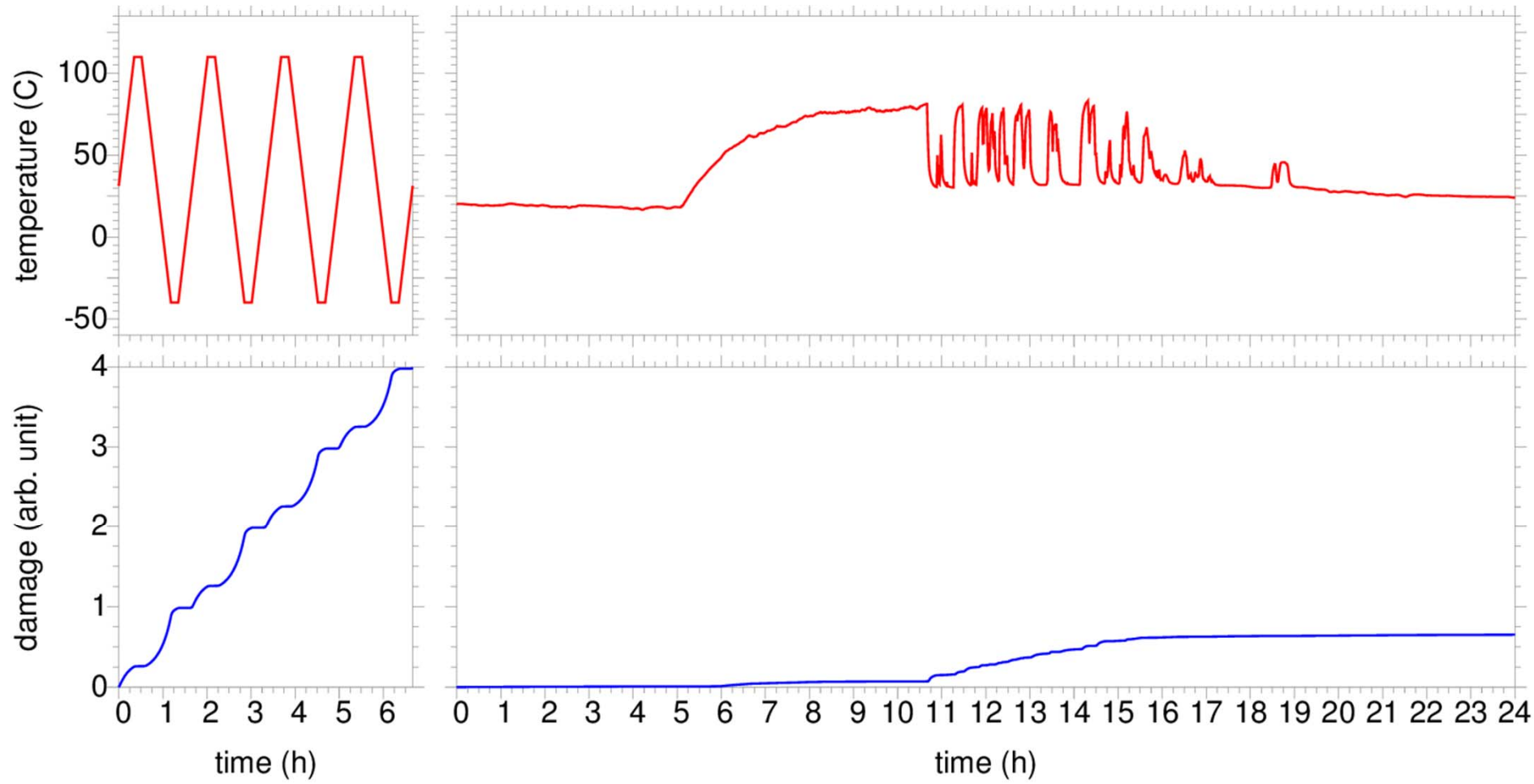
For every cycle we tested, faster cycles caused more damage per cycle

Weather is irregular



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

Long-time simulations

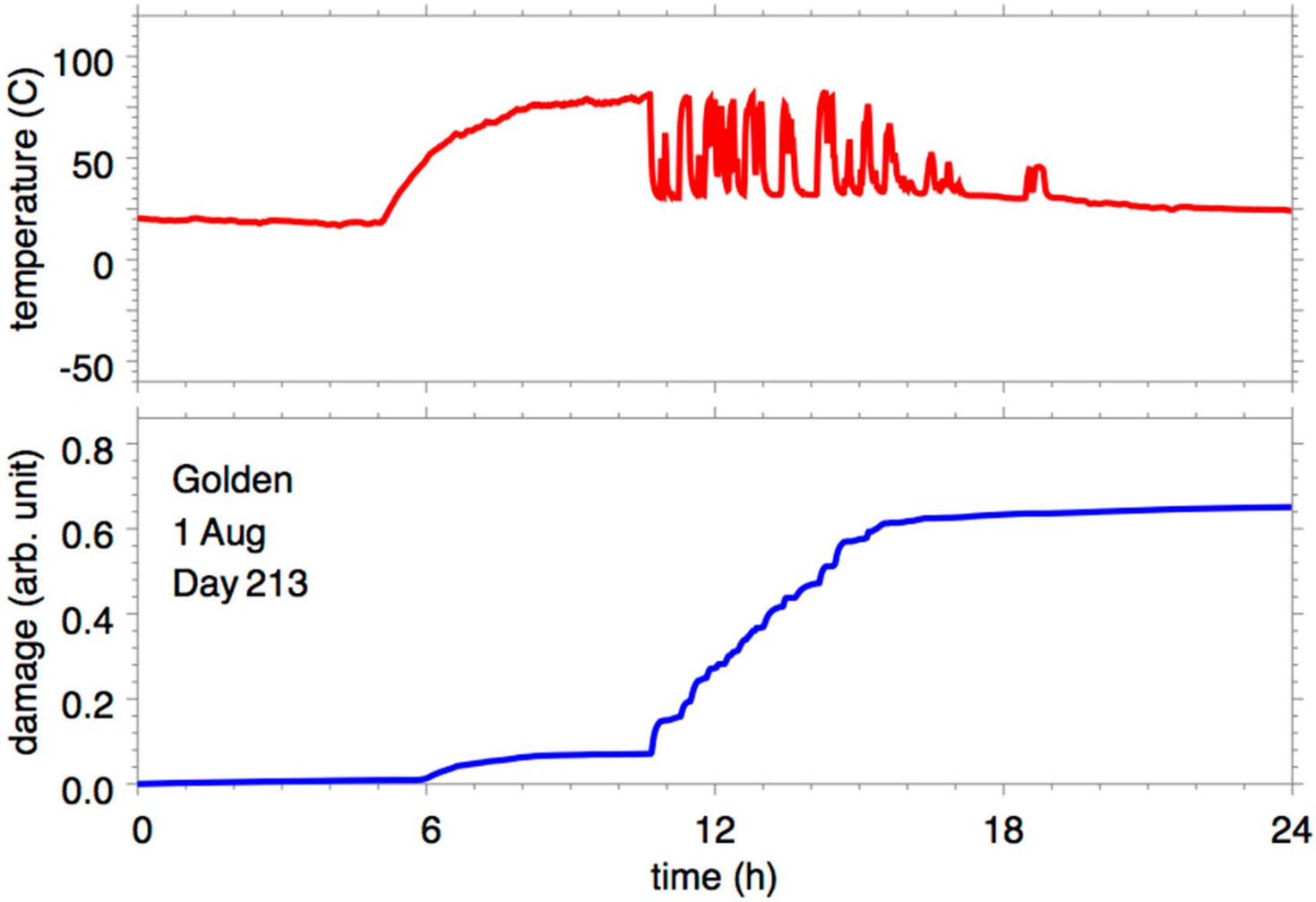


Typical fatigue models simulate only a few hours

Characterizing the weather requires a much longer simulation

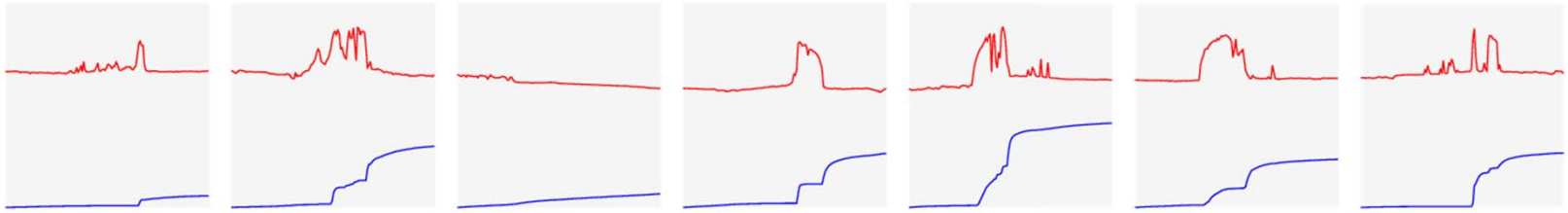
Cell temperature history can have more fast variation during outdoor exposure

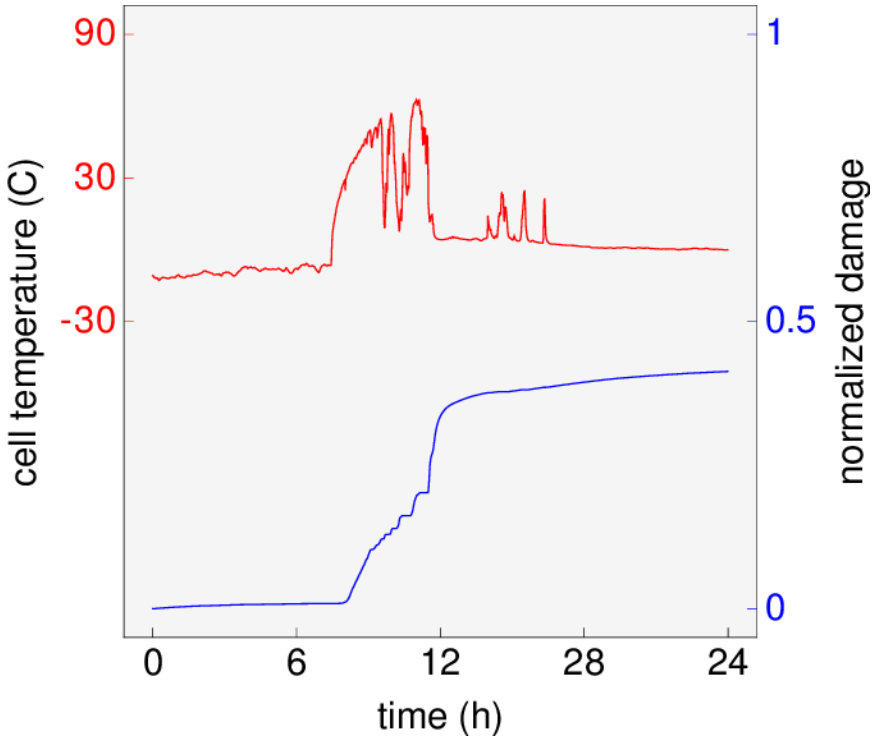
Simulating a day of outdoor exposure



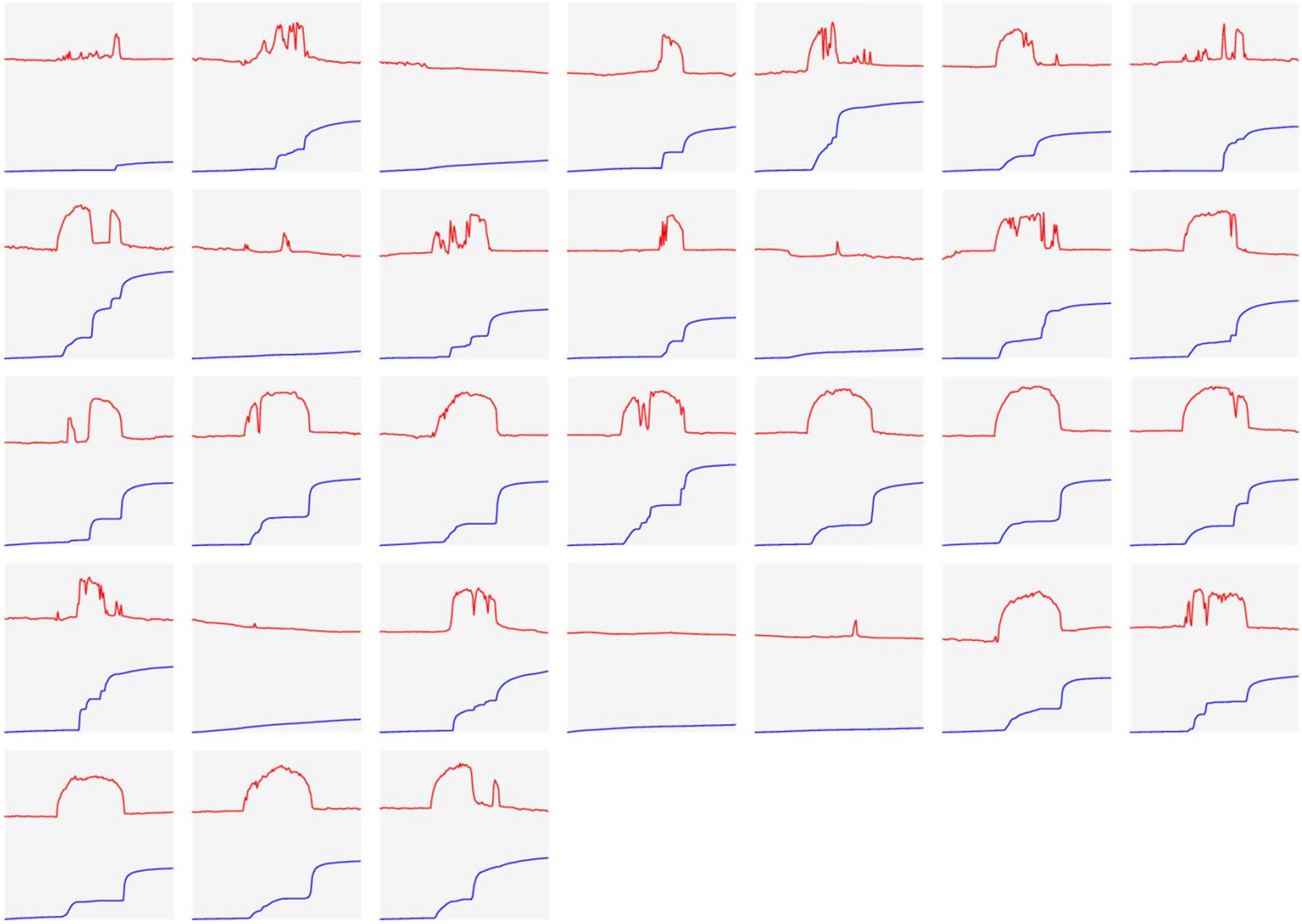
Cell temperature is derived from one-minute samples of meteorological data

Simulating several days

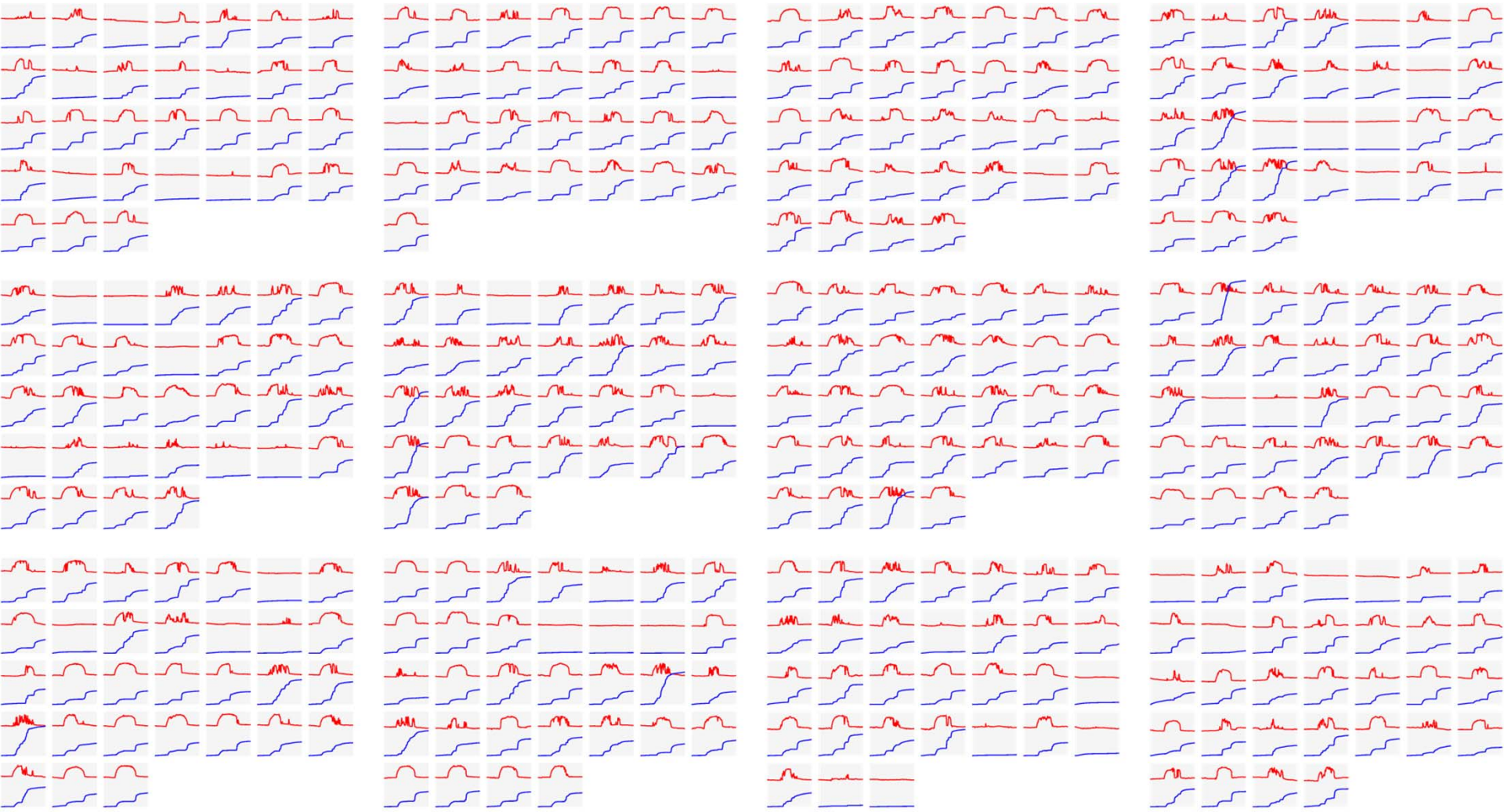




Simulating several days



Simulating an entire year



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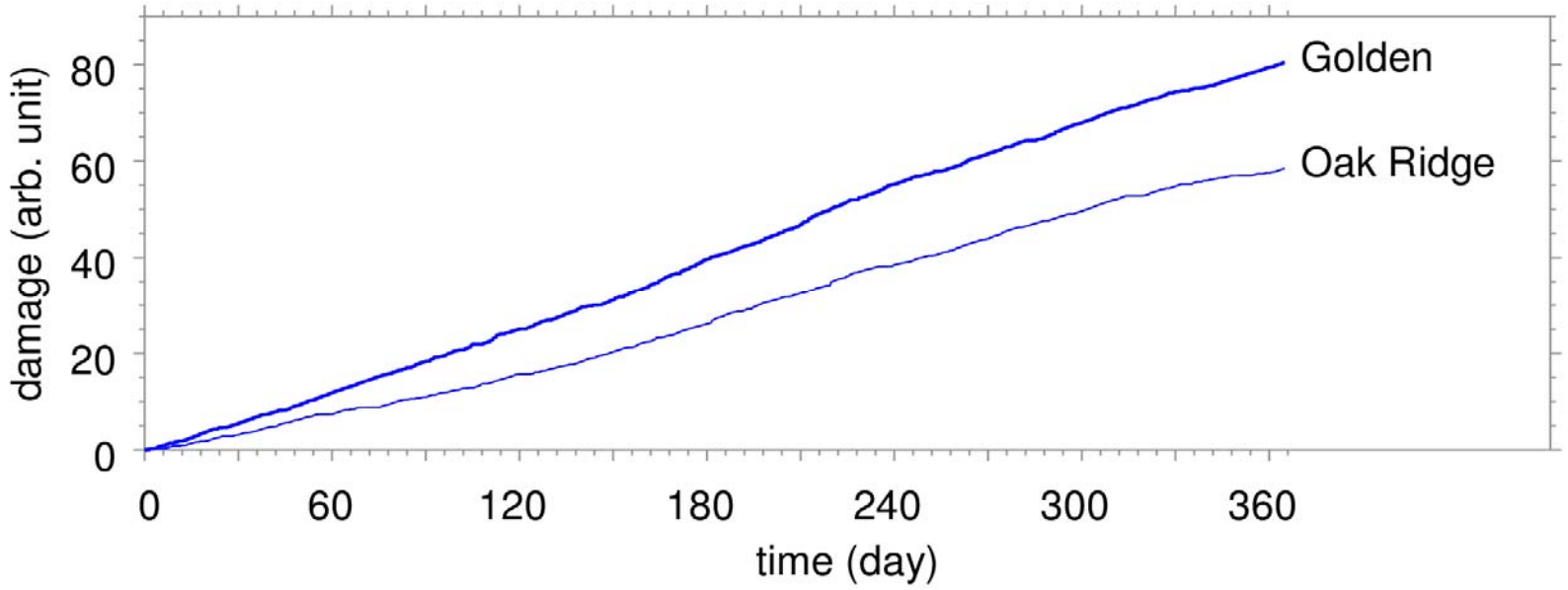
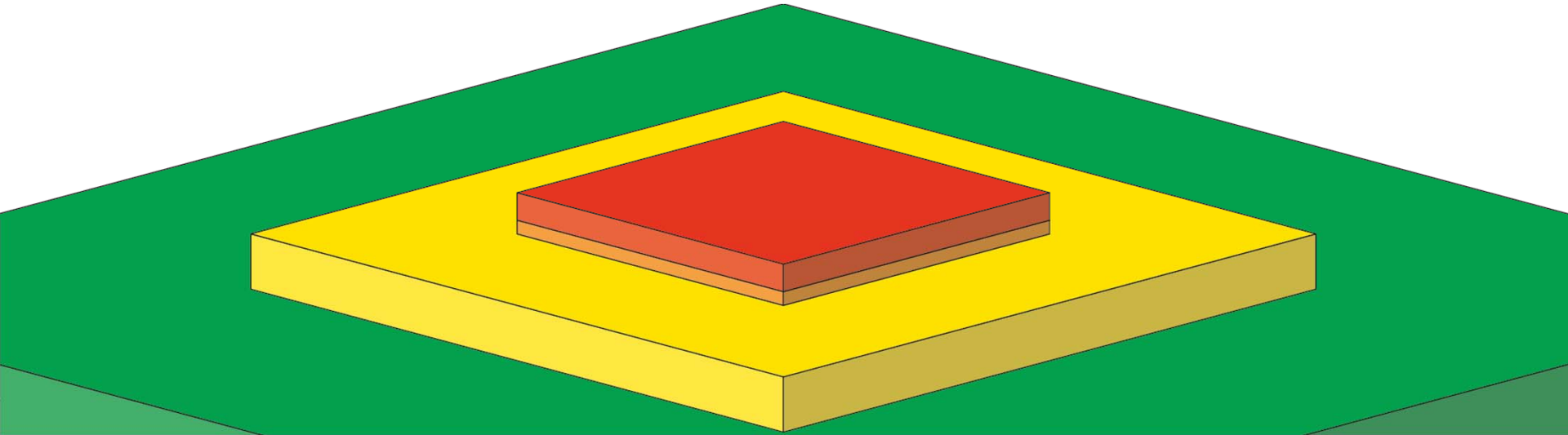


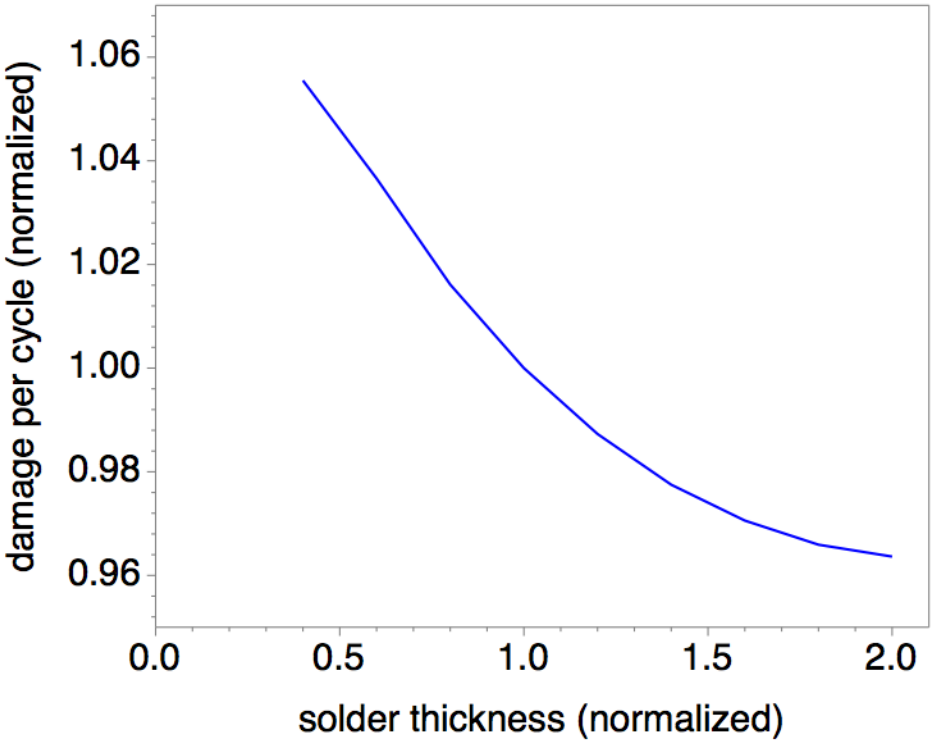
A year in Oak Ridge, Tenn. does 70% as much damage as a year in Golden, Colo.

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

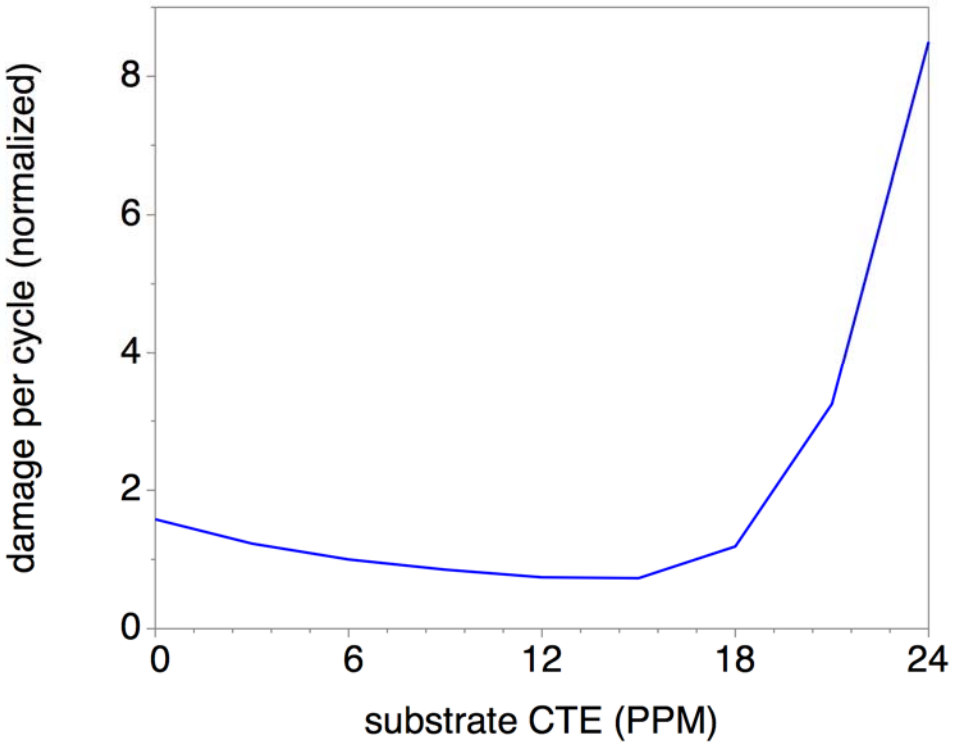


Improving the model: Geometric effects



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

Improving the model: Material effects



Fixed substrate thickness and stiffness; variable CTE

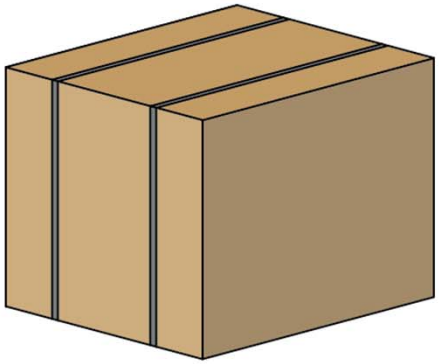
Substrate thermal expansion has a strong effect on the rate of damage accumulation

Improving the model: Material properties

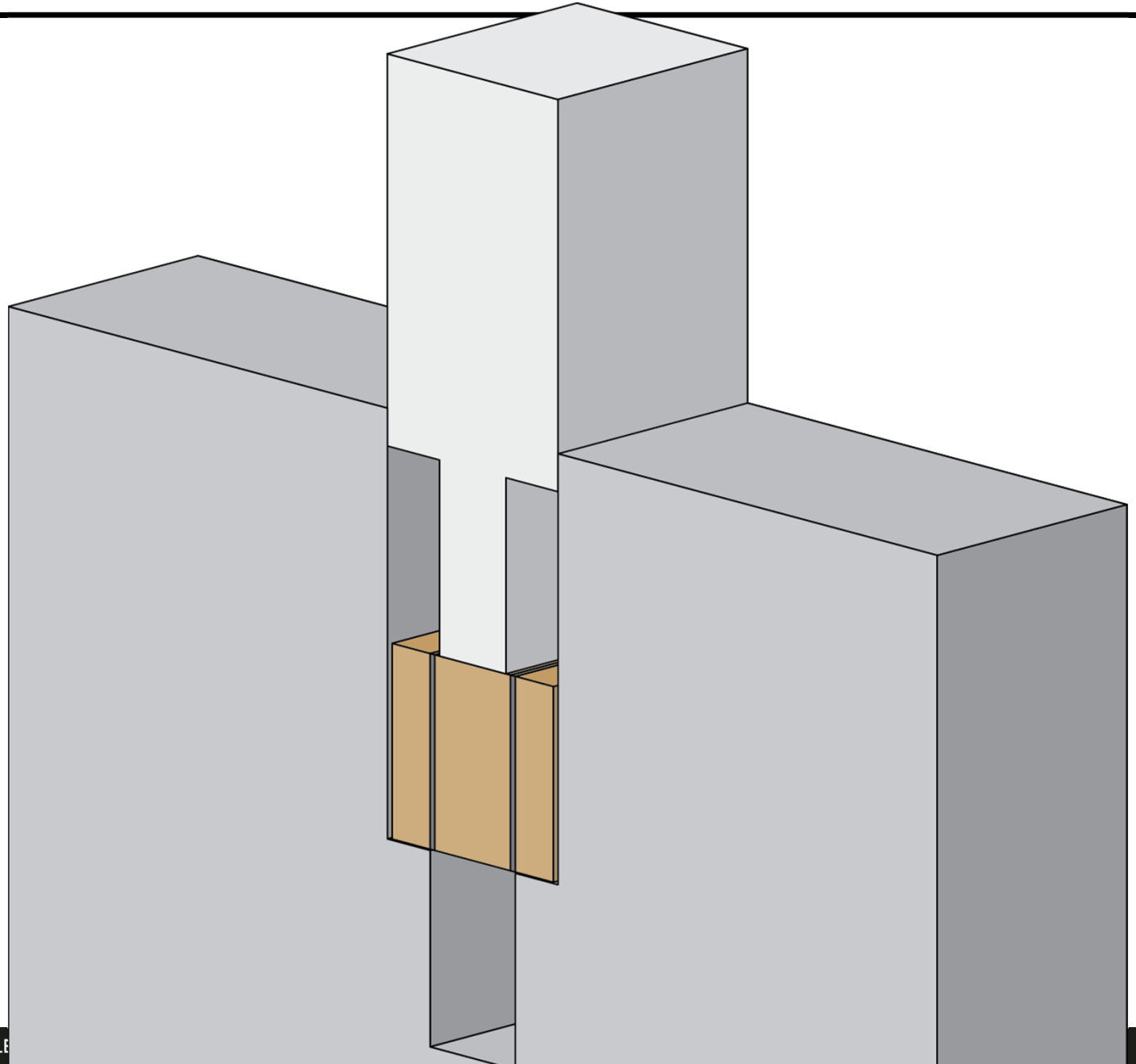
$$\dot{\varepsilon}_{\mathrm{pl,eq}} = A \exp\left(\frac{-Q}{RT}\right)\left[\sinh\left(\xi\frac{\sigma_{\mathrm{eq}}}{s}\right)\right]^{\frac{1}{m}}$$

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

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



Improving the model: Material properties



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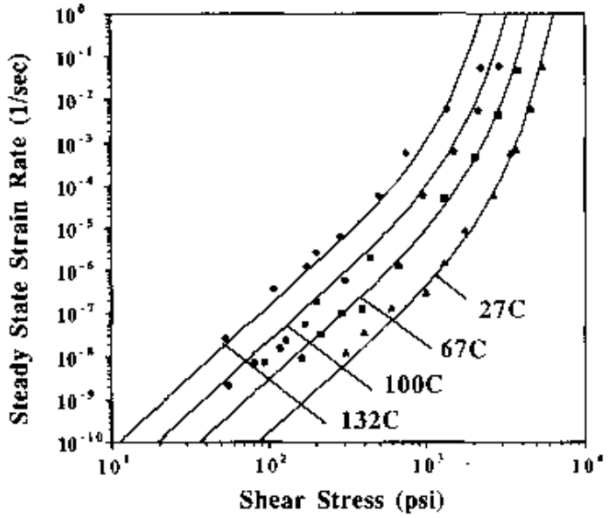


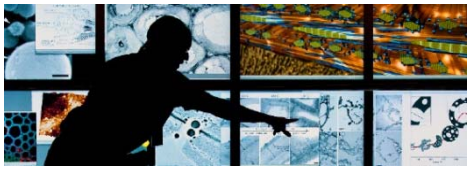
Darveaux, R. et al, IEEE J Compon. Hybr. 15:6, 1992.

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

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

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

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