Model for the aging of temperature sensors under cyclic temperature loads for statements on durability above 10 years

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EMATEM
European Metrology Association for Thermal Energy Measurement

JUMO

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Global Development - Research & Test
Measures and Measuring Methods

Long term goals

- Determine factors affecting durability of temperature probes
- Build a model to calculate expected lifetime
- Develop accelerated test

What is already known in the literature

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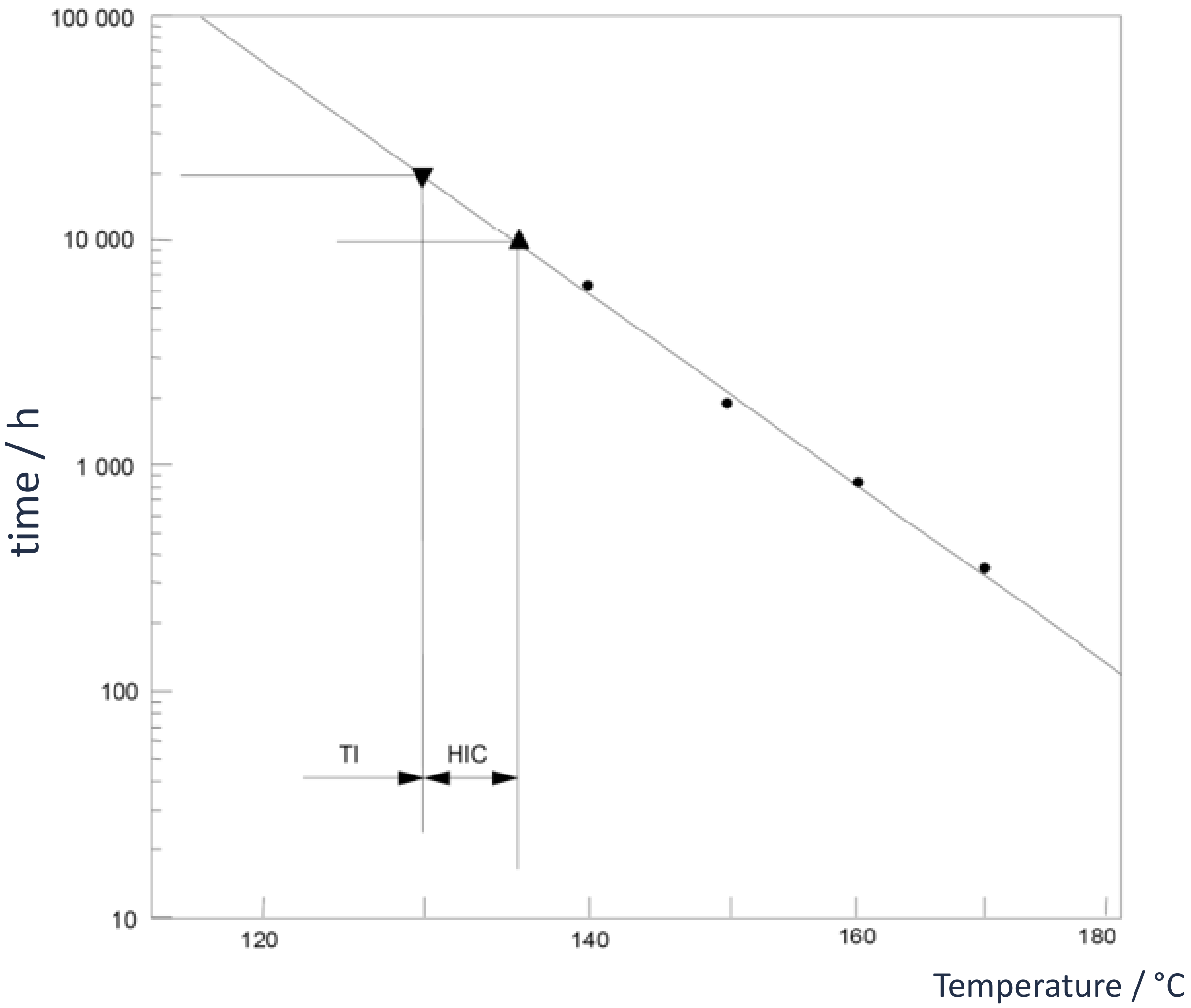
- Standards from other fields
- Several approaches to accelerated testing
- DIN EN 60216 “Electrical insulating materials – Thermal endurance properties”



Standards

- DIN EN 61709, IEC 61709:2011

- Tools for lifetime analysis of a device by lifetime analysis of components

- Definition of failure:

The end of the capability to fulfil its required function.

- One possible interpretation for heat metering of required function:

Thermometer pair is within 1 MPE

DIN EN 61709

- Lifetime for whole device can be calculated from the individual components

$$\lambda_{component} = \sum_{i=1}^{n} (\lambda_{mode})_i$$

- General models are not available. Fit to actual failure rates with known stressors:

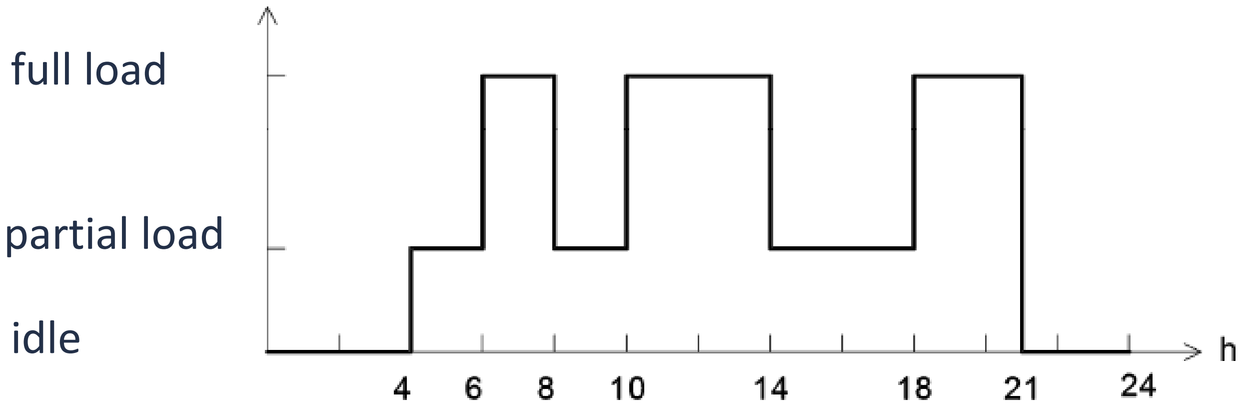
$$\lambda = \lambda_{ref} \cdot \pi_U \cdot \pi_I \cdot \pi_T \cdot \pi_E \cdot \pi_S \cdot \pi_{ES}$$

- Failure mechanisms are modelled, e.g.:
  Voltage, current, temperature, environment, duty cycle, electrical stress

DIN EN 61709

- Real life applications are not binary in stress

- Example from standard:

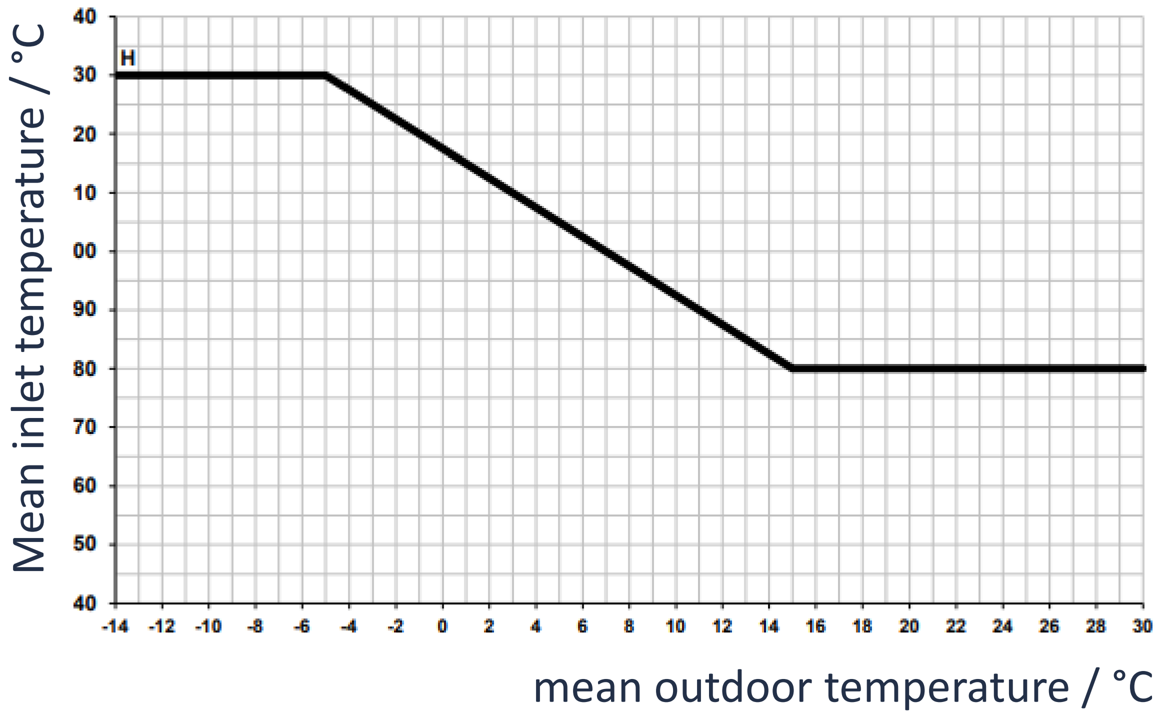


stress profile

$$\lambda_{as} = \frac{1}{t_f + t_p + t_i}\left(t_f \lambda_f + t_p \lambda_p + t_i \lambda_i\right)$$

Stress profile for heat meters?

- We have no access to data from the field
- Estimations based on open source material, e.g.:



Vattelfall ("Technische Anschlussbedingungen – Fahrkurve H")

Stress profile for heat meters?

- Mean outdoor temperatures comparison (source: www.klimatabelle.de) :

Month	Germany Frankfurt(Main)		Sweden Lulea	
	Outside temperature / °C	Inlet temperature / °C	Outside temperature / °C	Inlet temperature / °C
January	-2	108	-15	130
February	-1	107	-15	130
March	2	102	-10	123
April	6	95	-3	110
May	9	88	2	101
June	13	83	9	80
July	15	79	11	85
August	14	80	10	87
September	11	86	4	98
October	7	93	0	105
November	3	99	-6	116
December	0	105	-12	126

Stress profile for heat meters?

Temperature / °C	Germany Frankfurt(Main)	Sweden Lulea	China Harbin
130	0 %	33 %	42 %
120	0 %	17 %	0 %
110	33 %	17 %	17 %
100	25 %	8 %	8 %
90	33 %	25 %	8 %
80	8 %	0 %	25 %
70	0%	0 %	0 %

- There is no general stress profile

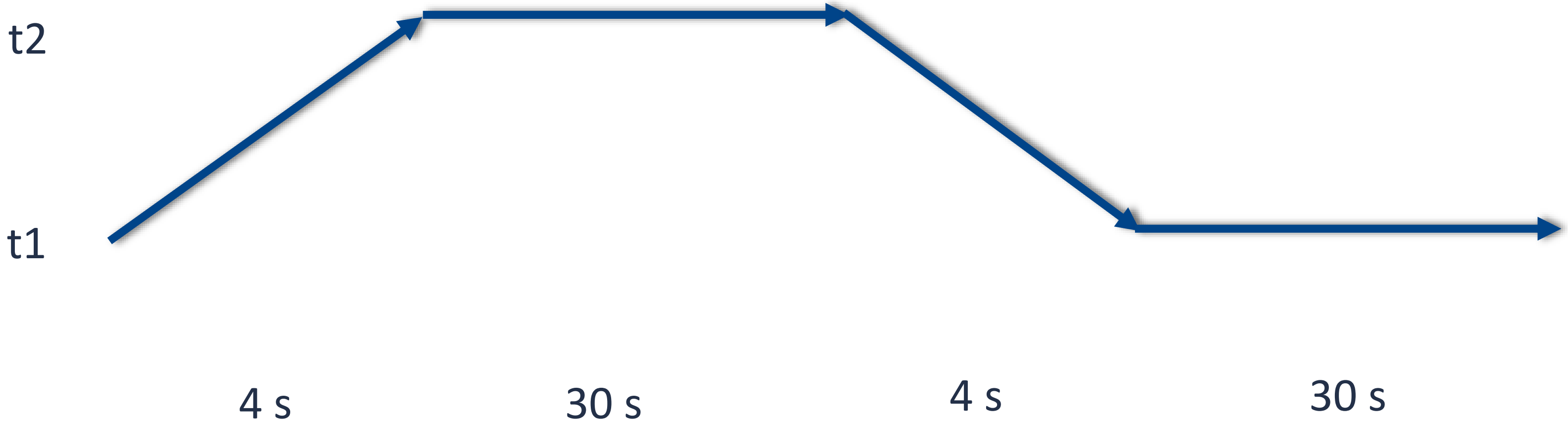
- Topic for standardisation: Definition of a standard profile

What we tested

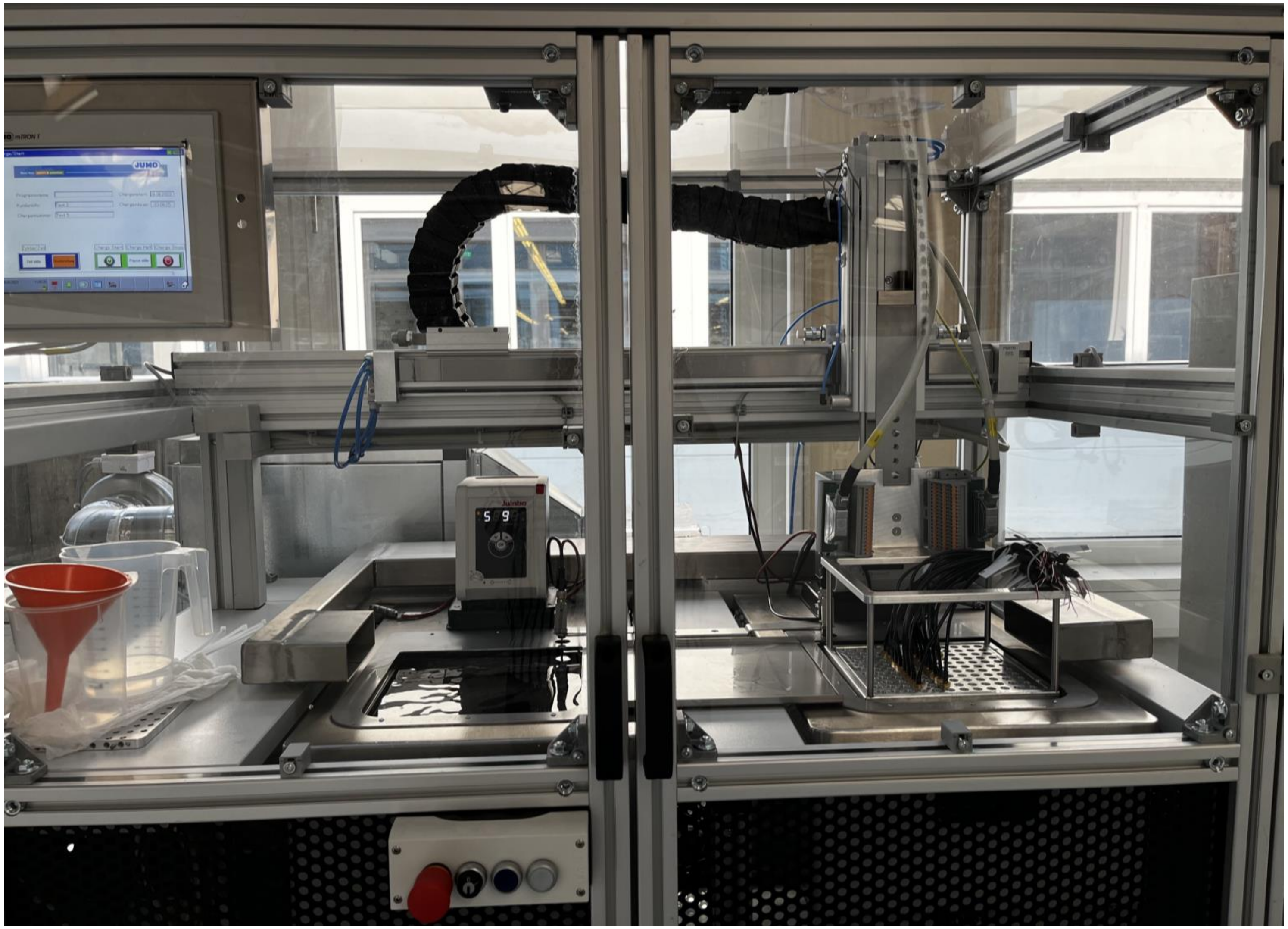
- JUMO temperature probes (902428/50)
- SMD Pt500

How we tested: Procedure

- Test procedure similar to EN 1434-4:2023 (7.8.3)
  - Cyclic temperature stress (*low temperature (LT)*)
  - Cyclic temperature stress (Max. temperature)



How we tested: Equipment



How we tested: Equipment

- Weiss Type vötschoven Lab 60 premium
- Temperature range RT+10 °C to 300 °C
- Temperature homogeneity ± 1 %
- Temperature stability ± 0.1 K

What we expected:

- Typical behaviour of temperature sensors (bare SMD chip): Exponential
- Typical behaviour for ageing in other fields is most likely either exponential (Arrhenius behaviour) or Weibull

$$\pi_T = \exp\left[\frac{E_{a1}}{k_0}\left(\frac{1}{T_{ref}} - \frac{1}{T_{op}}\right)\right]$$

$$f(x;\lambda,\beta) = \begin{cases} \frac{\beta}{\lambda}\left(\frac{x}{\lambda}\right)^{\beta-1} e^{-\left(\frac{x}{\lambda}\right)^{\beta}} & , x \geq 0 \\ 0 & , x < 0 \end{cases}$$

DIN EN 67109

Setup:

- Test for T_{max} and ΔT

No.	T_{min} / °C	T_{max} / °C
1	10	85
2	10	105
3	10	140
4	30	105

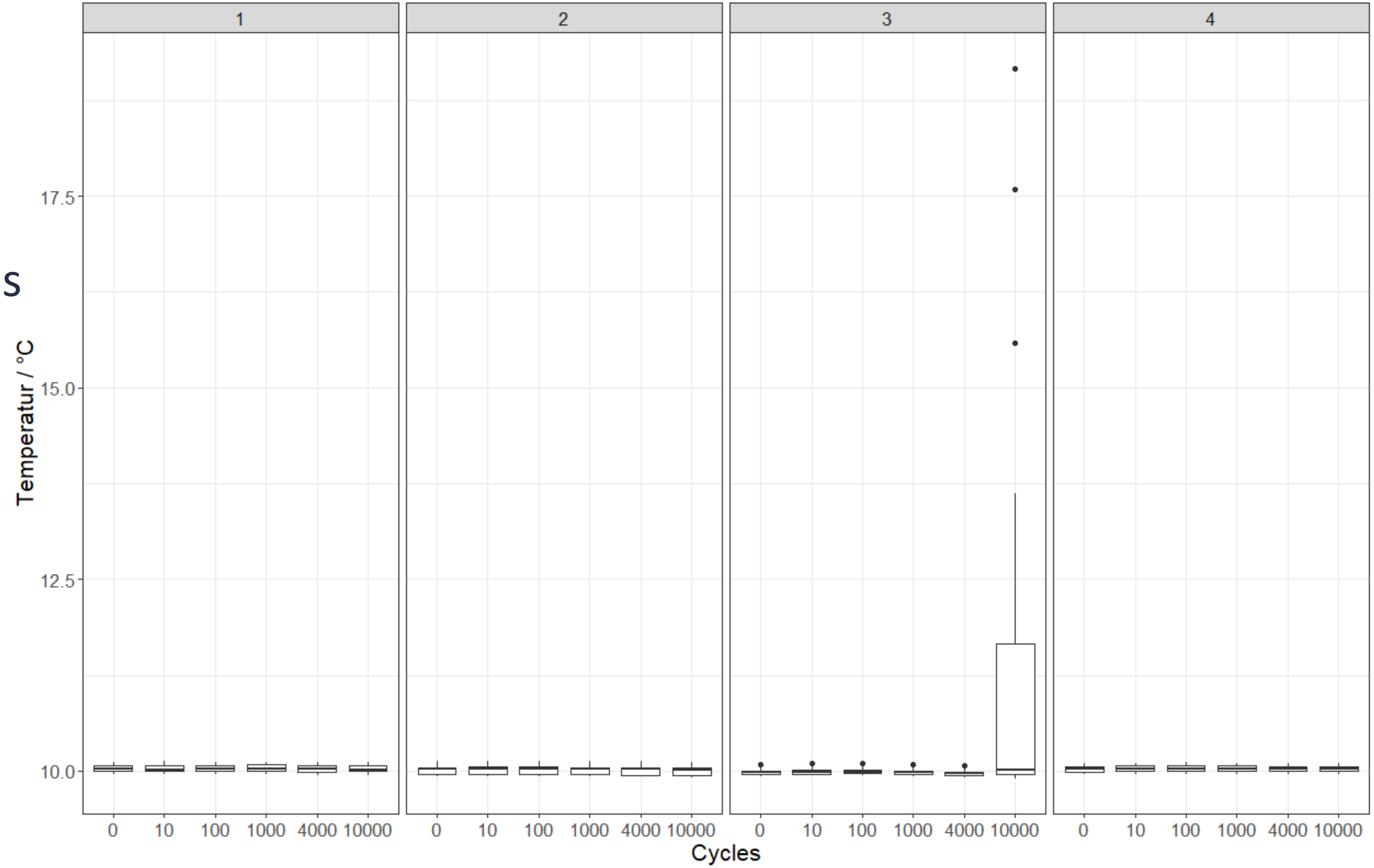
- Exponential behaviour expected. Measurements after 10, 100 , 1000 , 4000 and 10000 cycles

- After that a test with high temperature (150 °C): 22h T_{max}, 2h RT

Results: Temperature measuremet at 10 °C

Group 3 has significant failures

Soldering (cable to PCB) most likely cause for failure



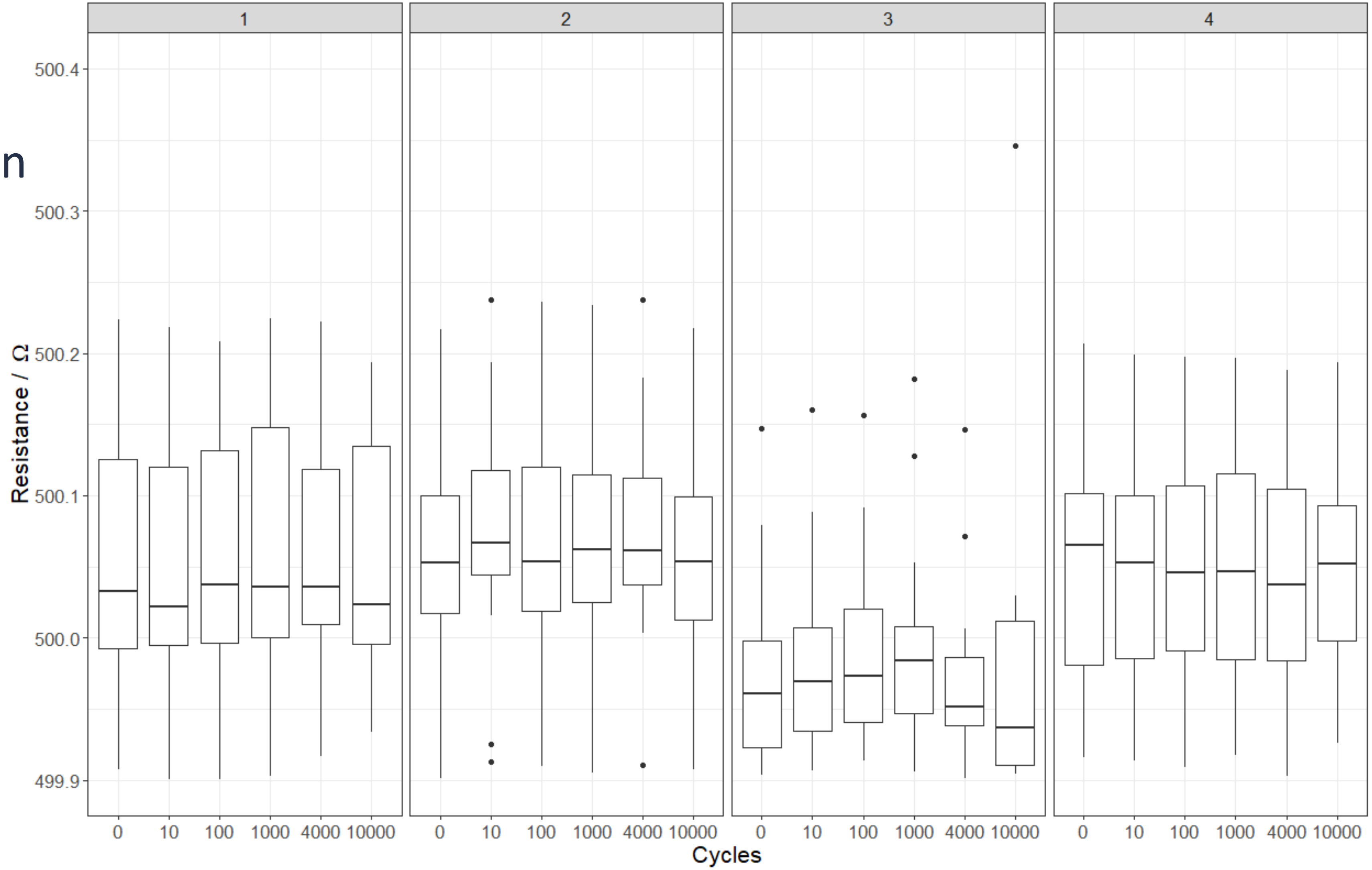
Results: Resistance at 0 °C

Group 3 has clearest indication for double exponential behaviour

Effect size small

Model with *one* exponential curve is not valid

Fit for double exponential model doesn't converge

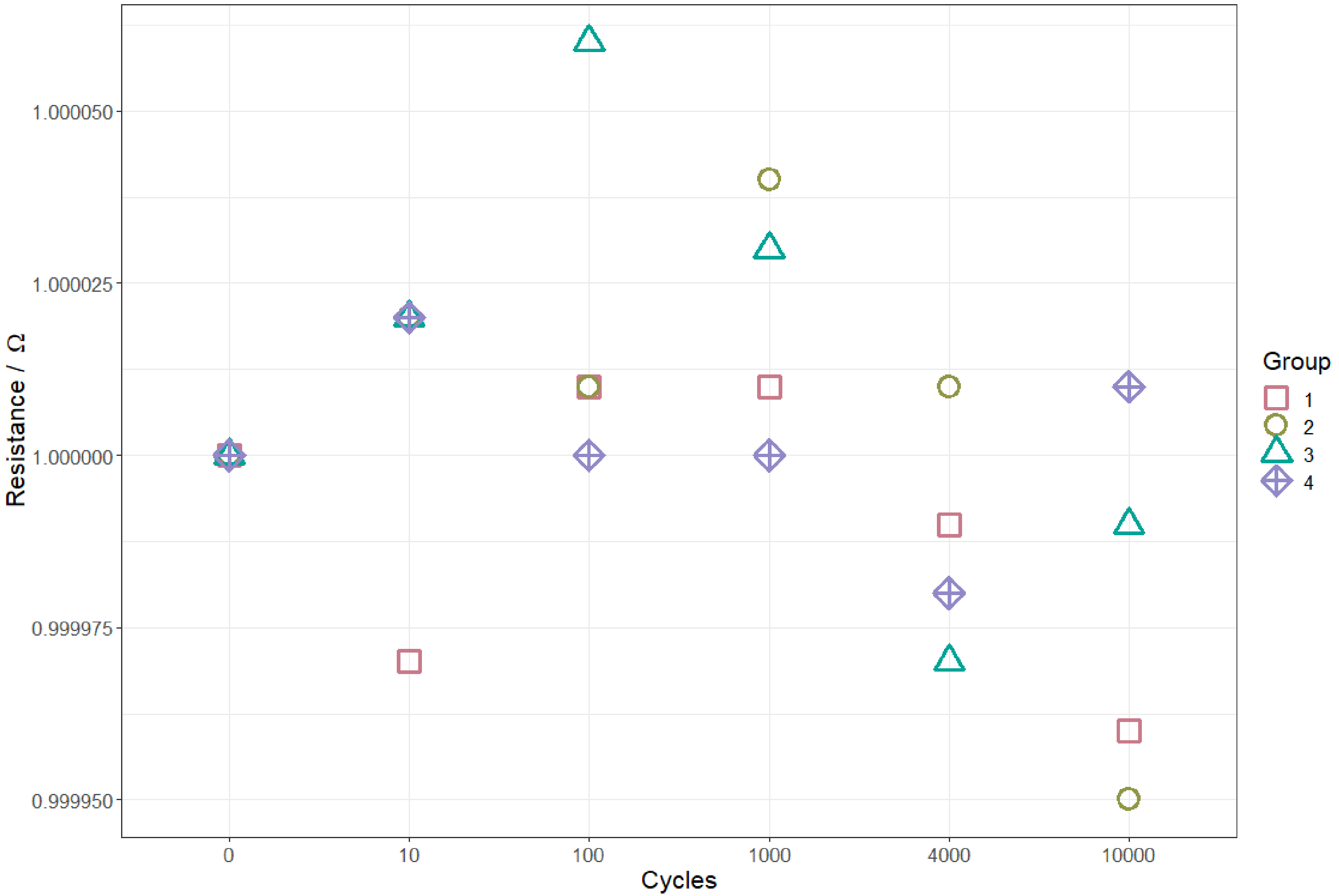


Results: Normalisation

Median values taken

Normalised to 0 cycles

There is a general trend observable

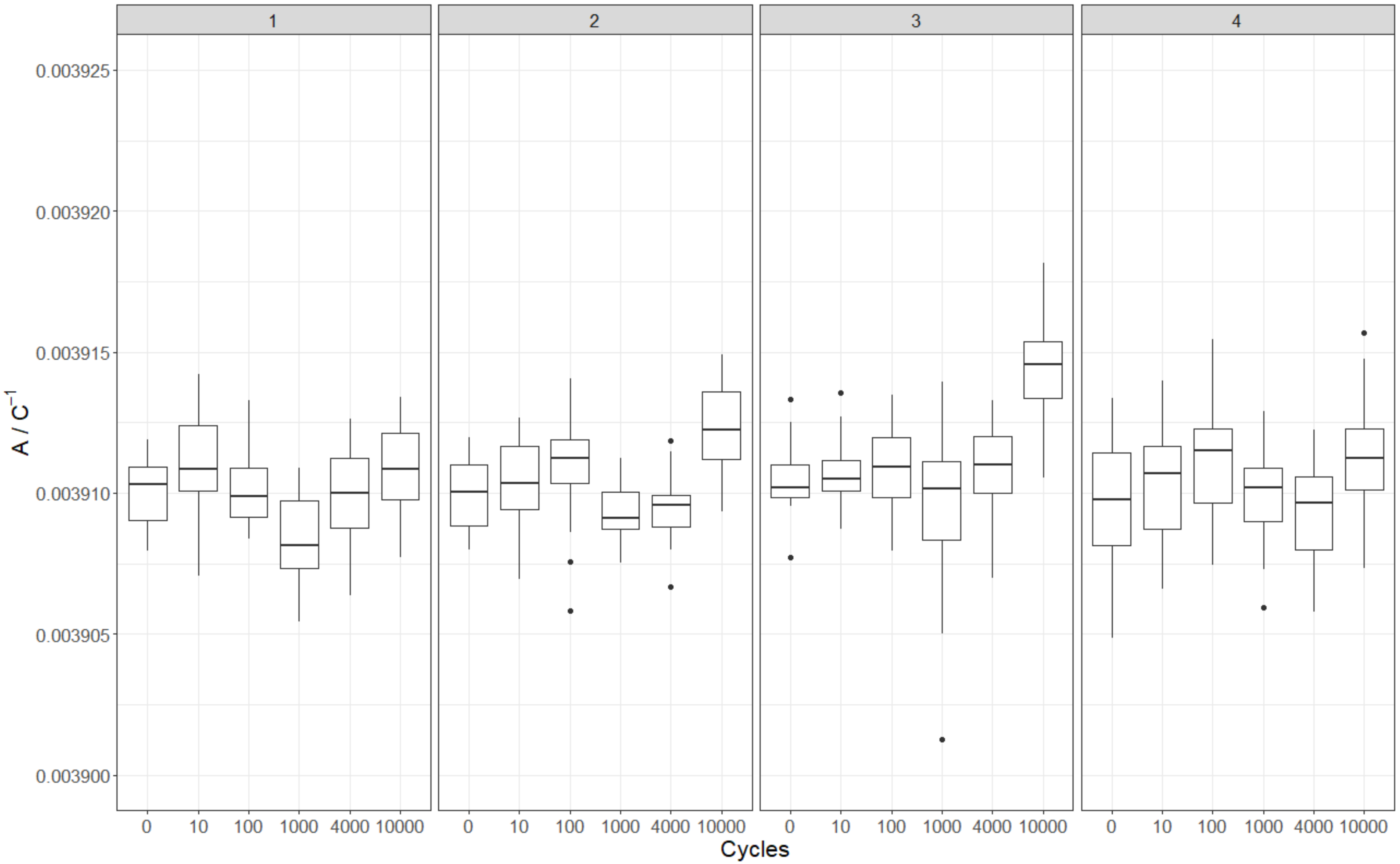


Results: A value

- $R(T) = R_0 \cdot (1 + AT + BT^2)$

Multiple ageing effects can be observed

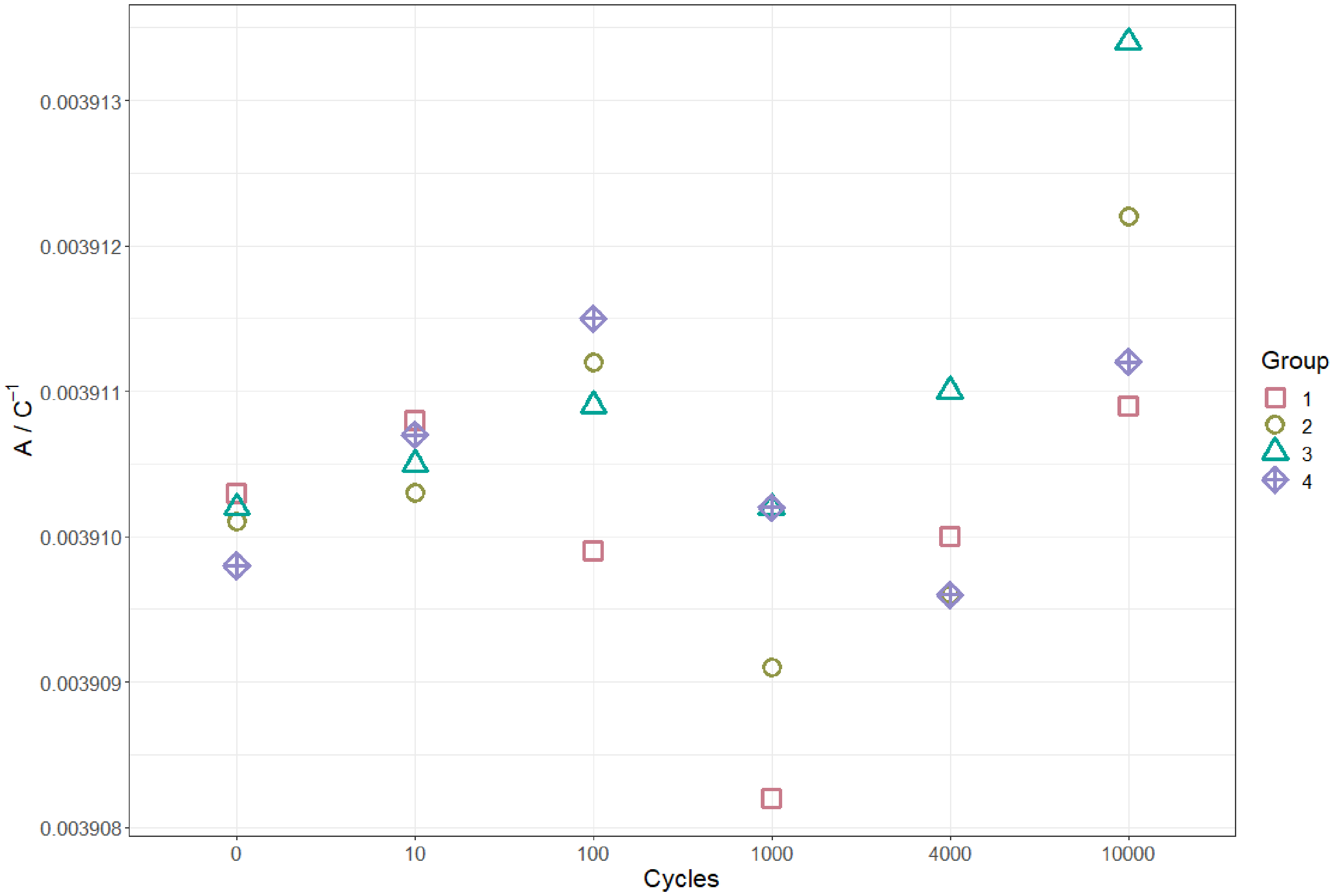
Pre-stages for failure at 10k cycles for high temperature stress can be observed



Results: Comparison of A values

Short term ageing can be distinguished from long term

Comparison of 0 cycles and 4k cycles measurement doesn’t reveal ageing



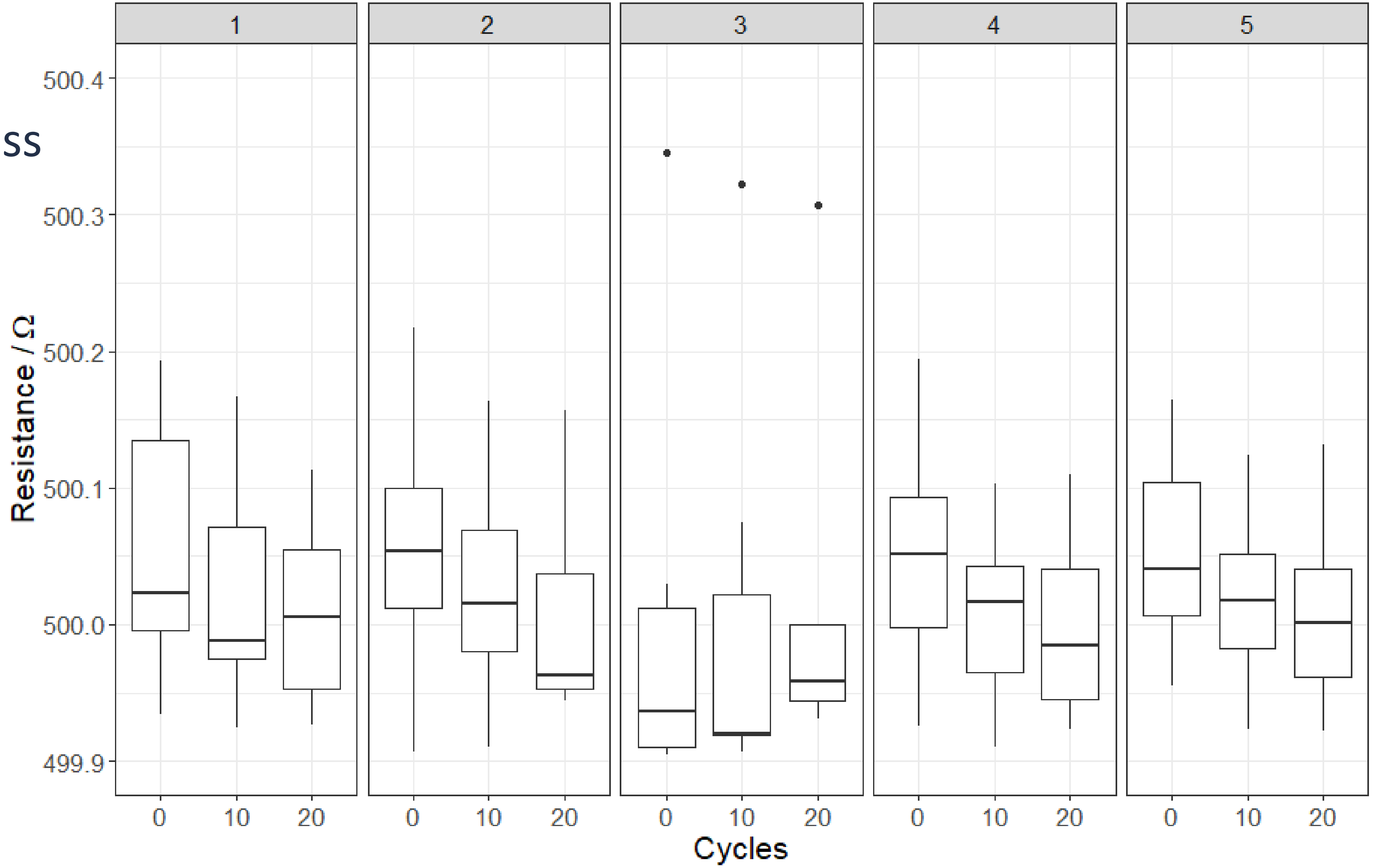
Results: High temperature stress

Group 5 has no LT cycle stress

0 cycles for group 1-4 is the last measurement for LT cycles

Group 3 has signs of catastrophic failure

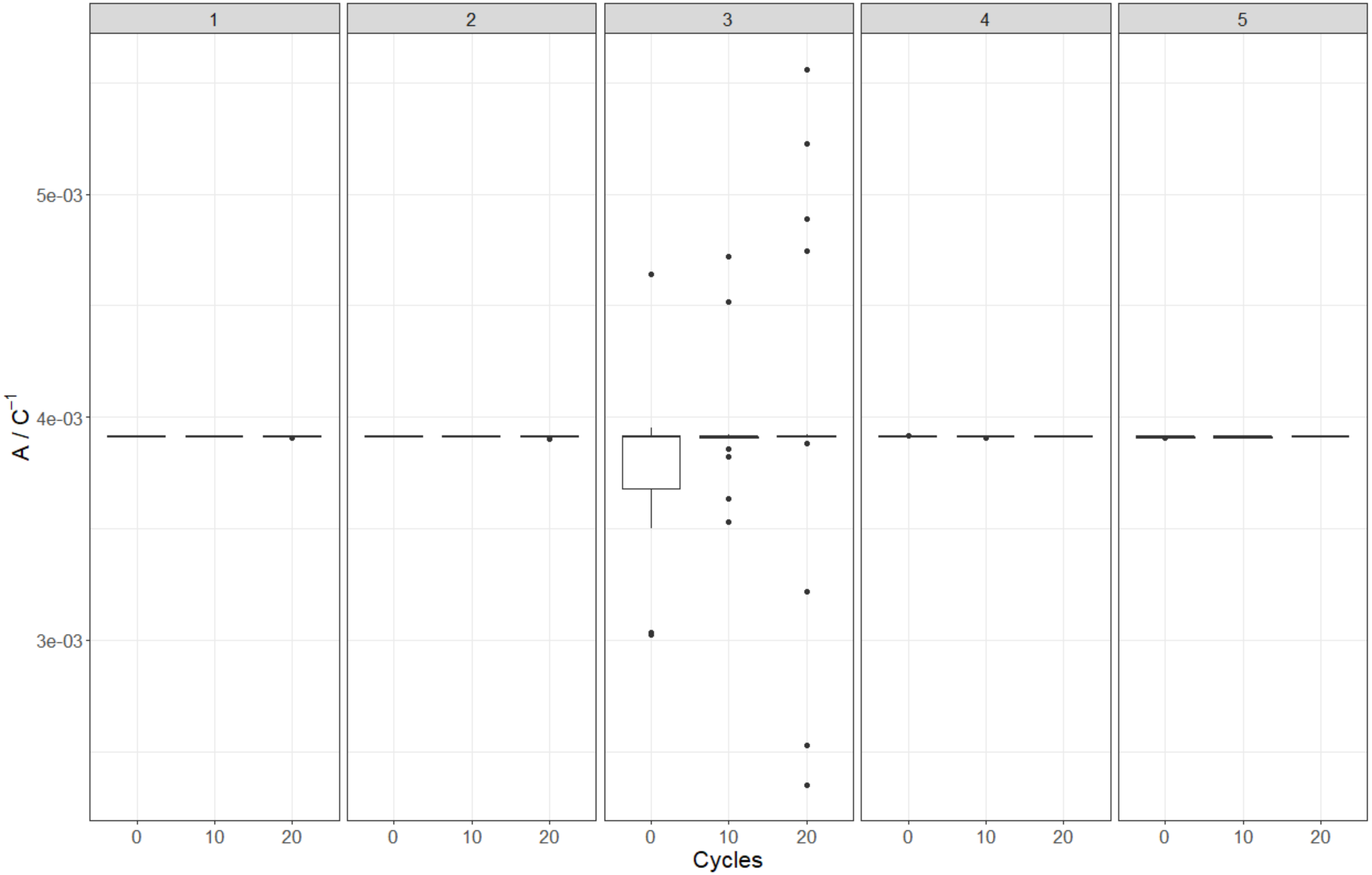
Other groups age



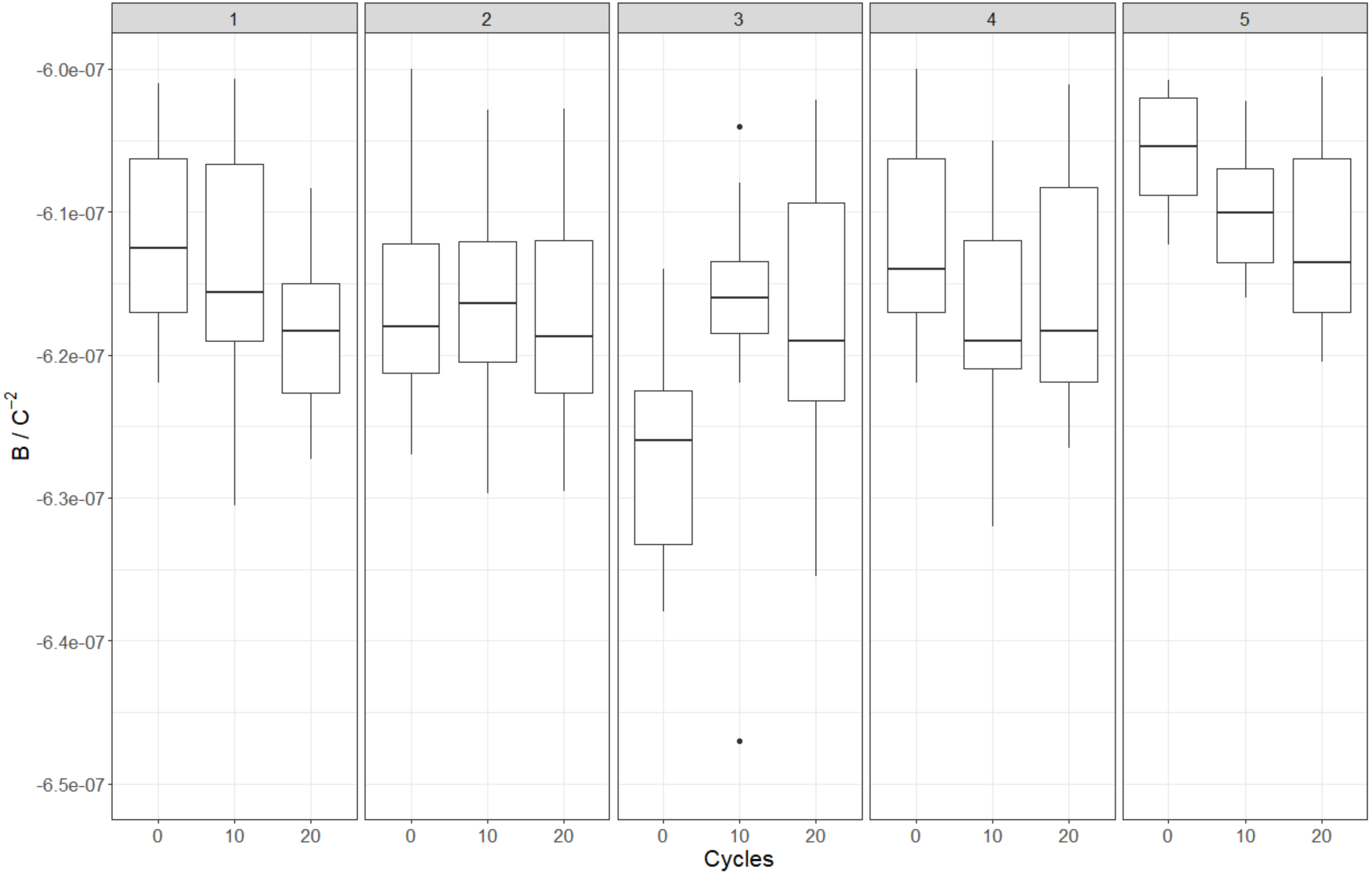
Results: High temperature stress

Group 3 has signs of catastrophic failure and it is getting worse

Other groups remain ok



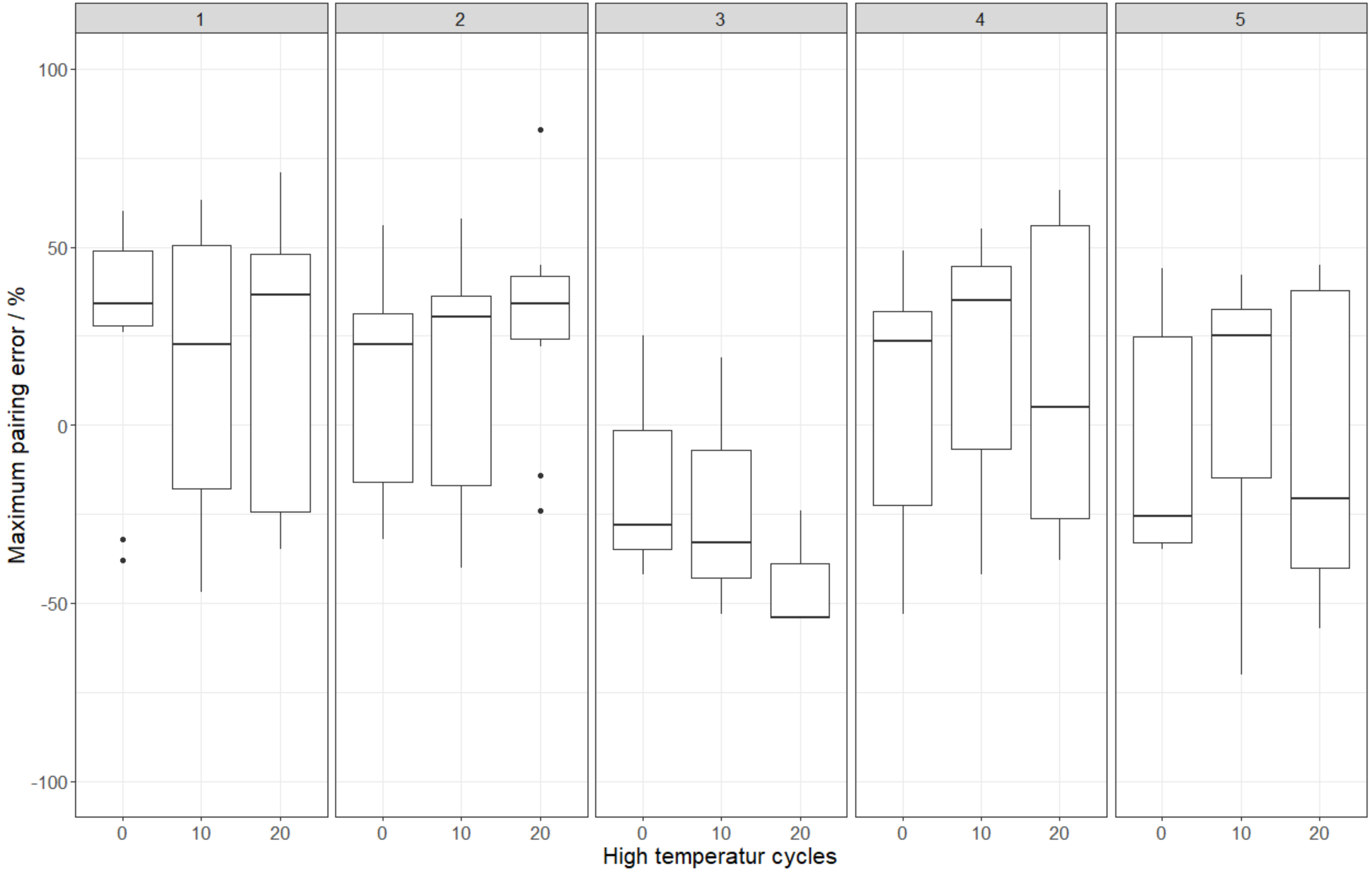
Results: High temperature stress



High temperature stress: B values

Results: High temperature stress

Pairs with ok sensor remain within 1 MPE ($\Delta\Theta_{min} = 3K$)



Results

- The expected exponential behaviour was not verified
- Double exponential behaviour is more difficult to model
- **A** value is an indicator for stress (ageing of individual components)
- Good thermometers remain pairs within 1 MPE

Outlook

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- Reproducibility needs to be checked
- This was one type of thermometer → Other types will be tested
- Work on a model with competing exponential behaviour

I look forward to your feedback!

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