Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

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Probabilistic Analysis of Accelerated Life Tests for Thermal Barrier Coatings

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Research Center Karlsruhe,
Institute for Materials Research II

Research Center Jülich,
Institute for Materials and Processes of Energy Systems 2

Siemens AG, Energy
Gas Turbine Engineering

Overview

Motivation

- for Accelerated Life Testing
- for Probabilistic Analysis
- for Bayesian Approach

Application to Thermal Barrier Coatings (TBCs)

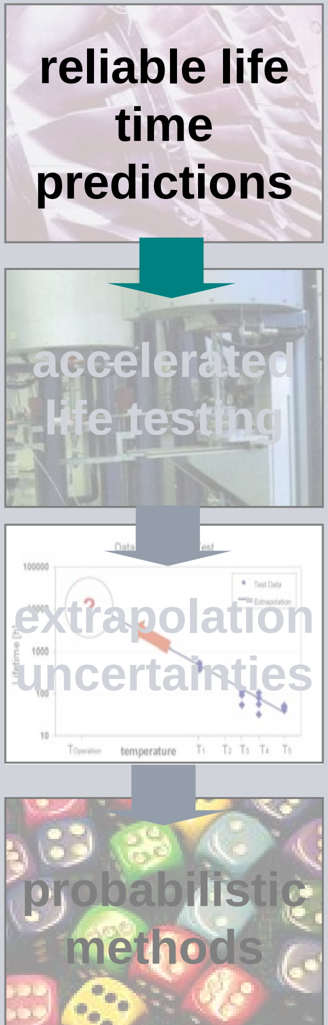
- Cyclic Oxidations Test

Bayesian Statistics

- Basic Ideas
- Application to Cyclic Oxidation Test Data

Uncertainties in Lifetime Prediction

Motivation



Increasing turbine inlet temperatures require prime reliant TBCs for turbine blades and vanes.

→ **Reliable Thermal Barrier Coatings**

→ **Reliable Lifetime Tests**

Testing under real gas turbine conditions is

- **difficult to realize**
- **too time consuming**

→ **Accelerated Life Testing**

Motivation

Accelerated Life Testing:

tests under overload conditions

e.g. non stop operation,
lower/higher temperature,
higher stress levels,
more agressive environment, ...

extrapolation from overload conditions to operating conditions

→ **Extrapolation Uncertainties**

Motivation

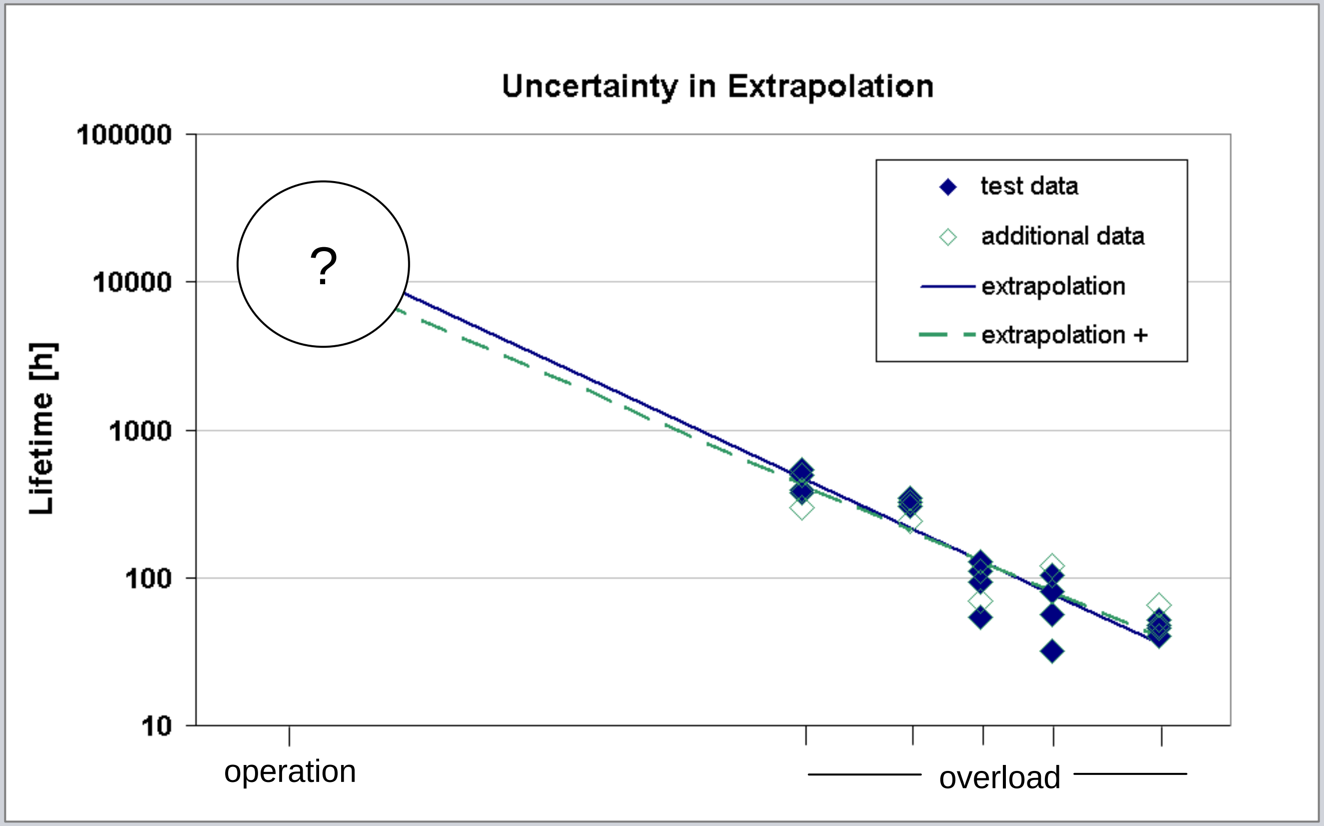
reliable life time predictions

accelerated life testing

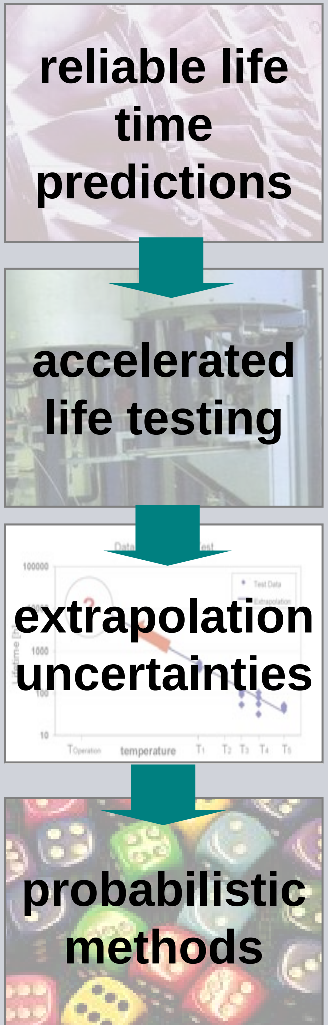
extrapolation uncertainties

probabilistic methods

typical test data contain scatter and uncertainties:

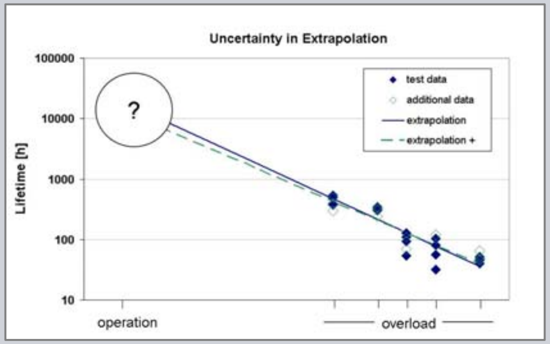


Motivation



Extrapolation Uncertainties

- natural scatter in material
- scatter in test data
- uncertainties in acceleration model



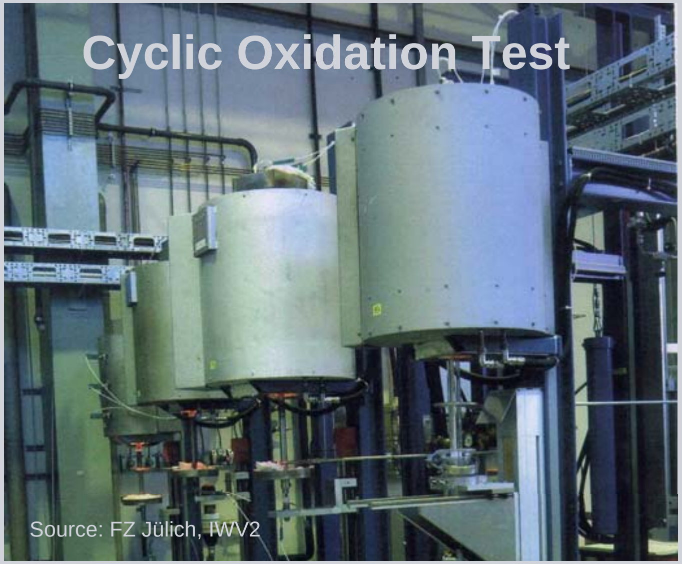
→ **high uncertainties in extrapolation**

Lifetime prediction should

- be precise
- be reliable
- consider uncertainties

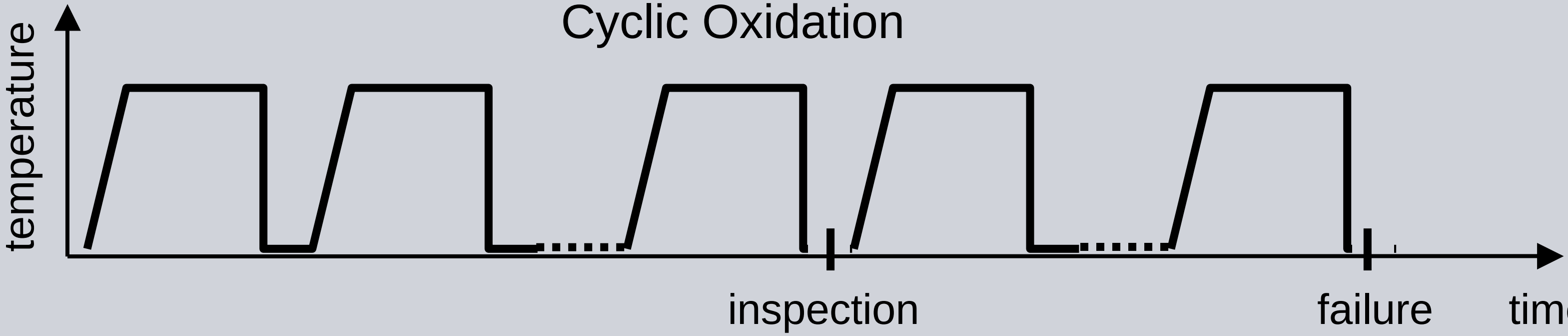
→ **Probabilistic Methods**

Accelerated Life Test for Thermal Barrier Coatings



Failure detected by visual inspection:

Bond Coat Oxidation
Crack Initiation
Spallation



Test Results
Extrapolation from Overlaod to Operating Conditions

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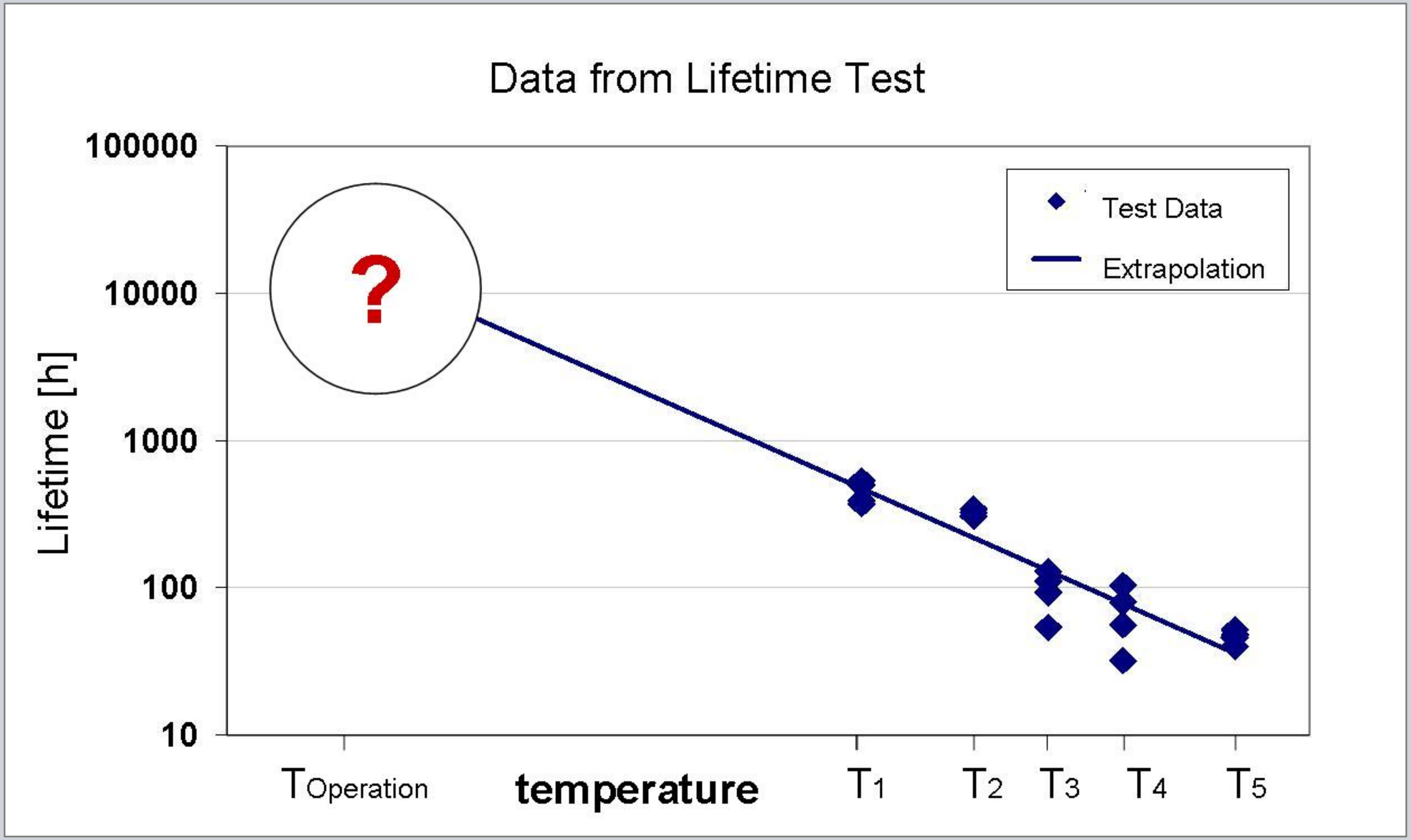
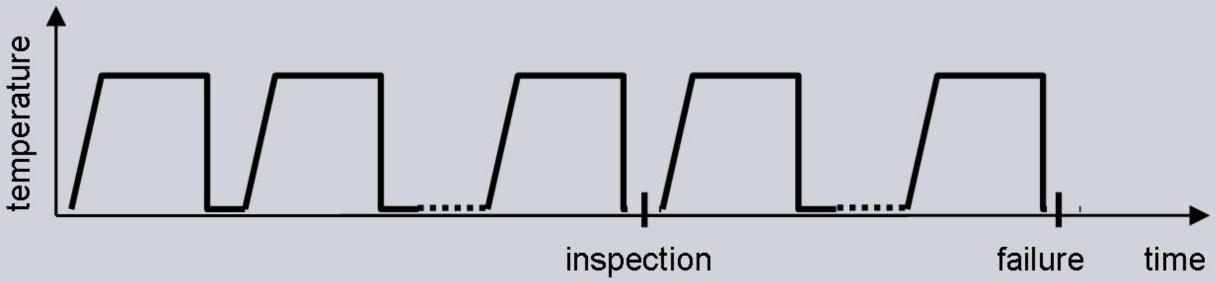


Requirements for a Probabilistic Approach

- low number of specimen
- censored data (inspection intervals)



nice to have:

- easy to include new data points
- considering single data points in analysis
- no further assumptions, except probability distribution type

Application of Bayesian-Statistics

lifetime prediction under operating conditions

a-posteriori-probability
this value is derived from data analysis

lifetime data from cyclic oxidation test at several temperature levels

Likelihood:
information from data analysis

$$P(\lambda \mid D, H) = P(\lambda \mid H) \cdot \frac{P(D \mid \lambda, H)}{P(D \mid H)}$$

model quality

evidence:
normalization

λ estimated parameter
D information from data
H additional information (hypothesis)

a-priori-probability:
value from prior knowledge

no previous knowledge: P(λ|H)=1

Application on Cyclic Oxidation Test

given from test data: temperature level T_i , i=1,...,5
lifetime t_i
failure rate λ_i

Likelihood Function for Exponential Distribution

$$P(D \mid \lambda_i, H) = P(x_1,\ldots,x_n \mid \lambda_i, H)$$

$$= \prod_{k=1}^{n} P(x_k \mid \lambda_i, H) = \prod_{k=1}^{n} \lambda_i \exp(-x_k)$$

Application on Cyclic Oxidation Test

Arrhenius-Approach for Acceleration Function

$$\lambda_i = \lambda_0 \cdot \exp\left(-\frac{B}{R}\left(\frac{1}{T_i} - \frac{1}{T_0} \right) \right)$$

given:
operating temperature T_0
temperature level T_i
failure rate λ_0
failure rates λ_i
universal gas constant R

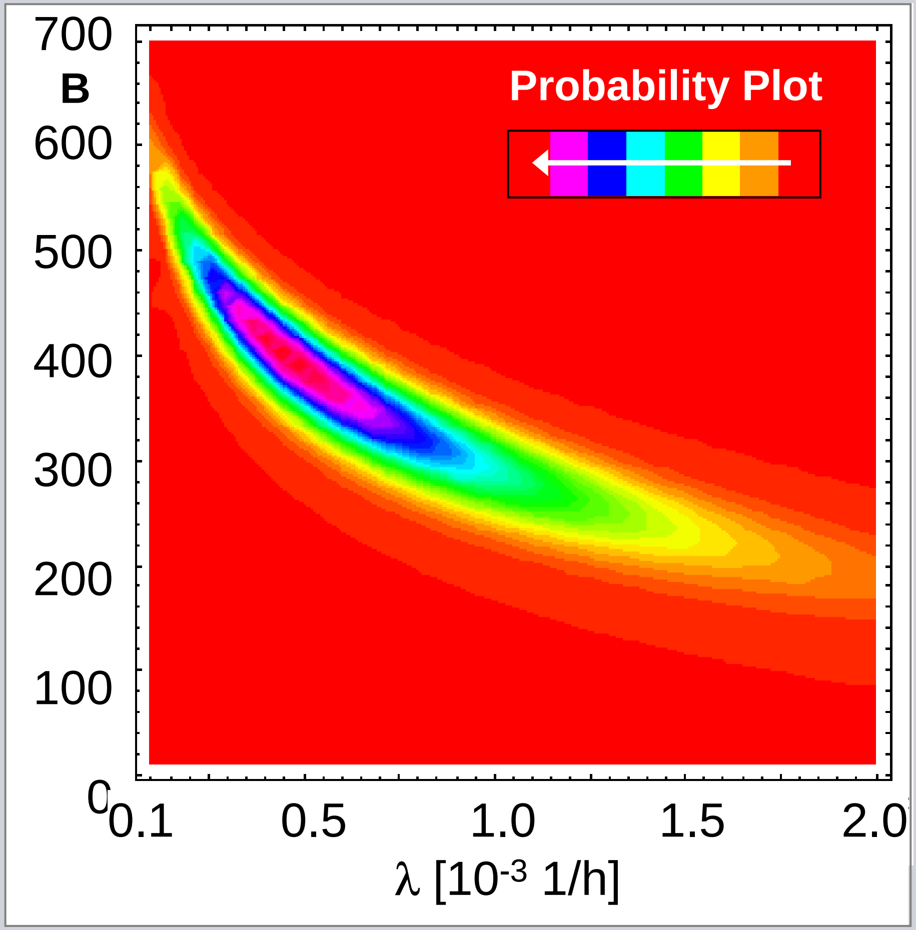
Likelihood Funktion for Lifetime Prediction

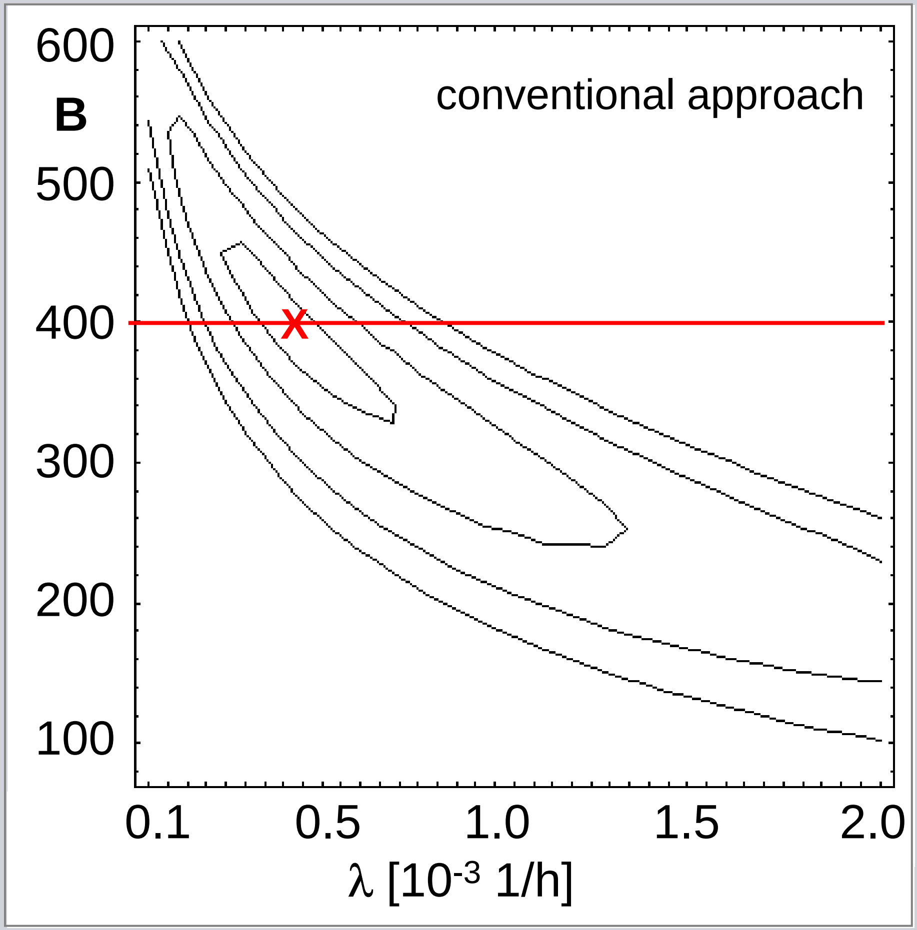
$$P\left(D \middle| \lambda_0, B, H\right) = \lambda_0^n \cdot \exp\left(-\lambda_0 \cdot \sum_{i=1}^{n} \exp\left(-\frac{B}{R}\left(\frac{1}{T_i} - \frac{1}{T_0} \right) \right) \cdot t_i - \sum_{i=1}^{n} \frac{B}{R}\left(\frac{1}{T_i} - \frac{1}{T_0} \right) \right)$$

wanted: failure rate λ_0

unknown: parameter B

Prediction of Failure Rate λ





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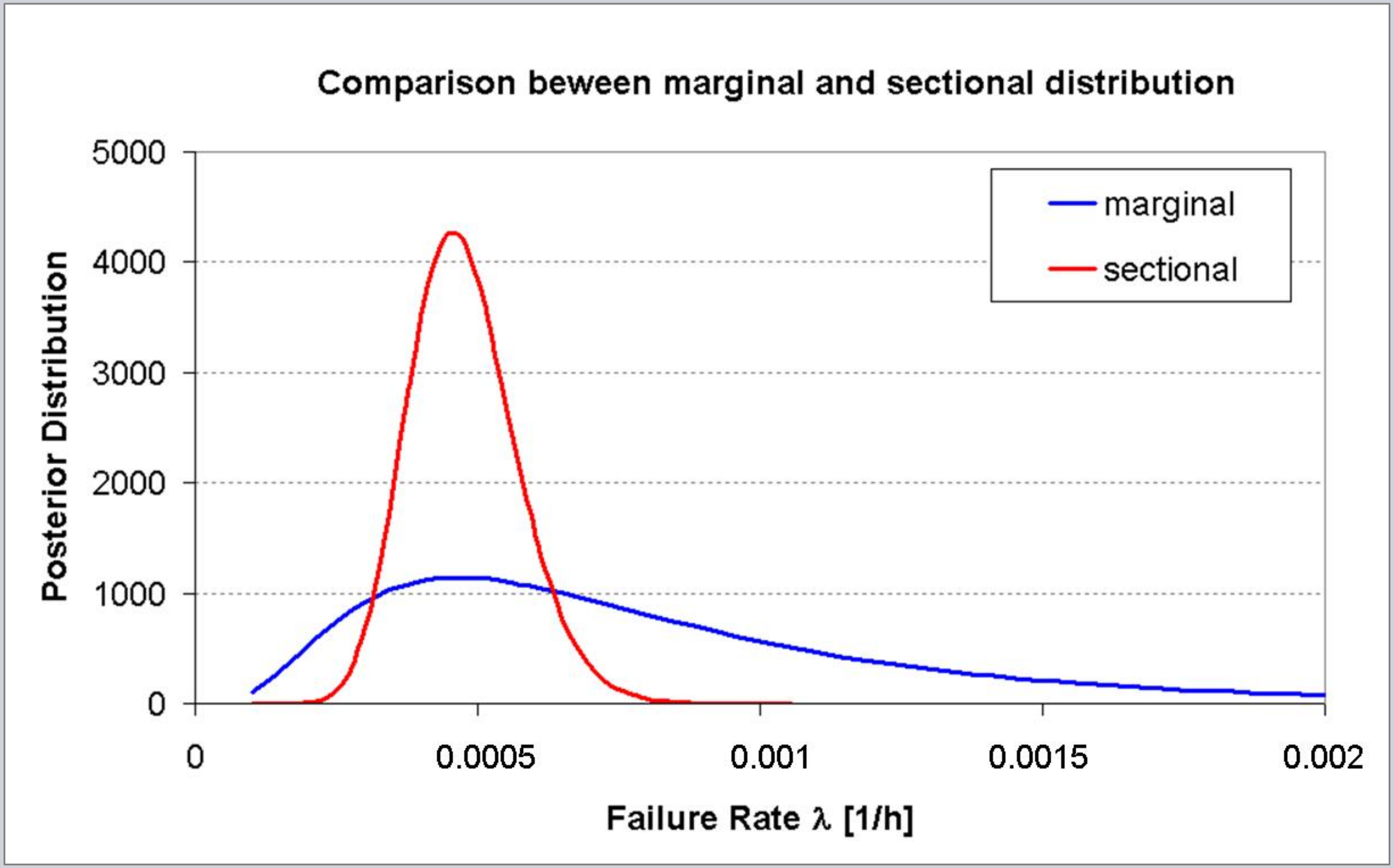
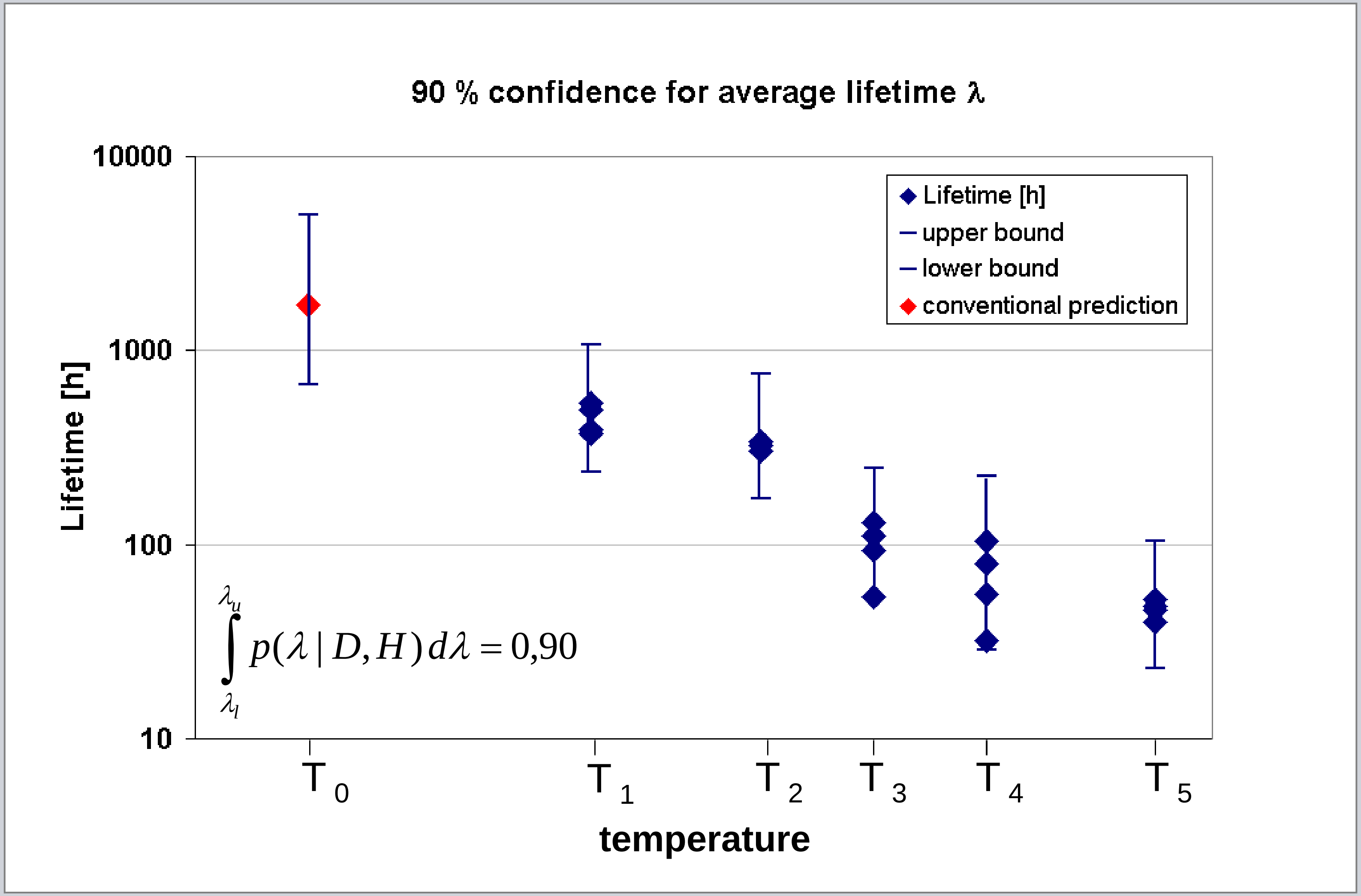
Comparison of Failure Rate Distribution



Uncertainties in Lifetime Prediction



Conclusion

- A probabilistic evaluation of Accelerated Life Testing was performed based on a Bayesian approach.
- The Bayesian set up has a lot of advantages compared to the „conventional“ probabilistic approach.
- Marginalization allows to eliminate nuisance parameters, while still taking into account their uncertainty.
- Results show high uncertainties in test data.
- High uncertainties in lifetime prediction were quantified.

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Thank you

for your attention!