Probabilistic RPV Integrity Assessment: Safety Margin Quantification and Integration of Thermal-Hydraulic Uncertainties

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ISPMNA-5, Tokyo, Japan, October 2024

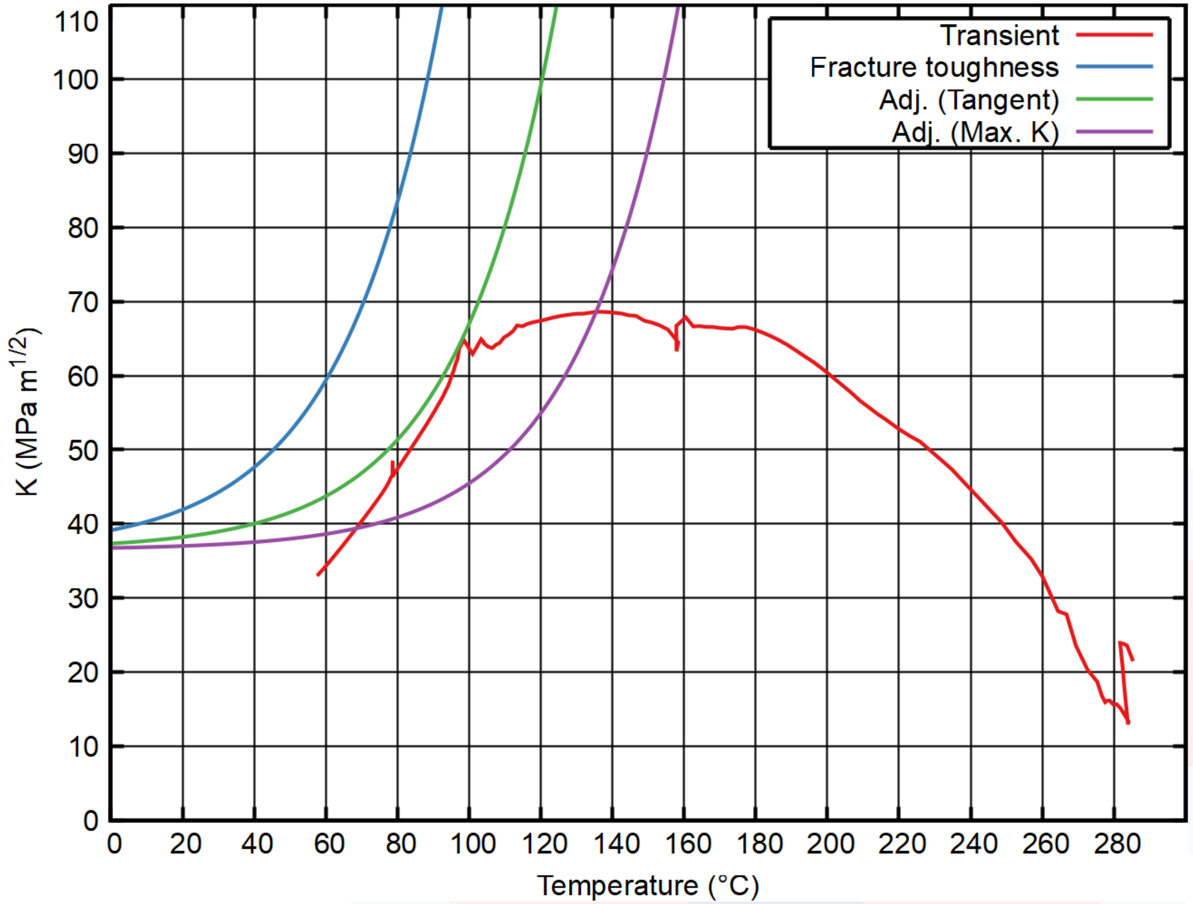
APAL has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945253.

Outline

- Introduction: Probabilistic RPV integrity assessment
- PART I: Probabilistic margin concepts
  - 3 concepts
  - Demonstration cases
  - Conclusions
- PART II: Thermal-Hydraulic Uncertainties
  - Probabilistic margin assessment including thermal-hydraulic uncertainties
  - Probabilistic assessment of set of transients
  - Vision of fully integrated assessment
- Final Summary

Introduction: RPV integrity assessment

- RPV Integrity assessment
  - Pressurized thermal shock (PTS)
- Fracture-mechanics assessment
  - Crack postulate (TCC, UCC, EC)
  - Fracture toughness curve
- Deterministic margin
  - Maximal allowable adjusted reference temperature (Max. all. ART)
  - Depends on initiation criterion
    - Tangent
    - Max. K WPS



PART I:
Probabilistic margin assessment using 3 different concepts

Introduction to probabilistic margin concepts

Probabilistic margin concepts

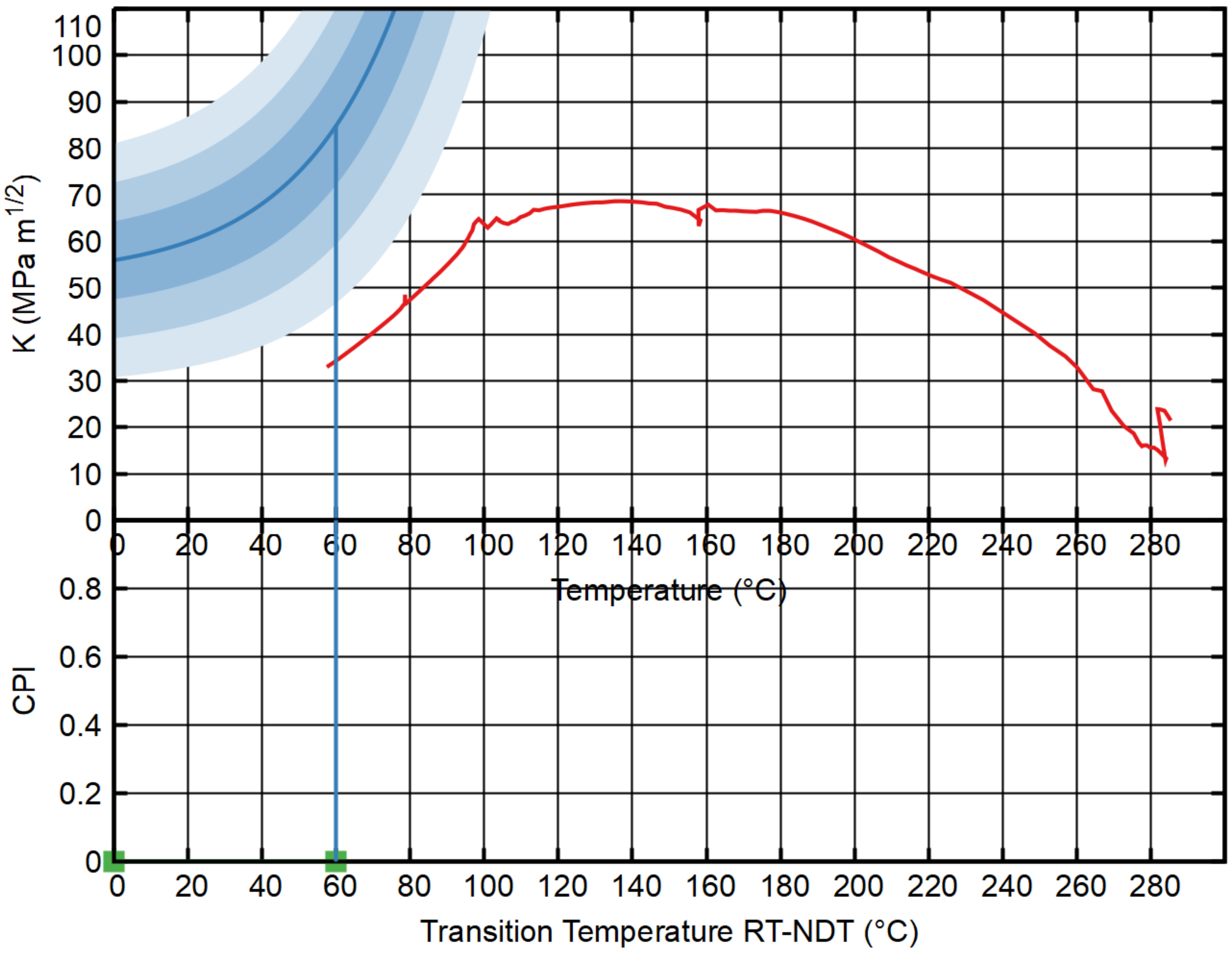
i. Assessment based on maximal allowable adjusted reference temperature
ii. Assessment based on lifetime
iii. Assessment based on reliability theory

Common background: Probabilistic acceptance criterion

- Marginally acceptable transient:
  - Conditional probability of initiation 2.28e-4

Max. all. ART

- Distribution of fracture toughness
  - ASME-Curve: truncated normal distribution
- CPI depends on RT_NDT
- Adjust transition temperature RT-NDT
- Find intersection point with target CPI
  - APAL-specific target for this type of transient: 2.28 e-4



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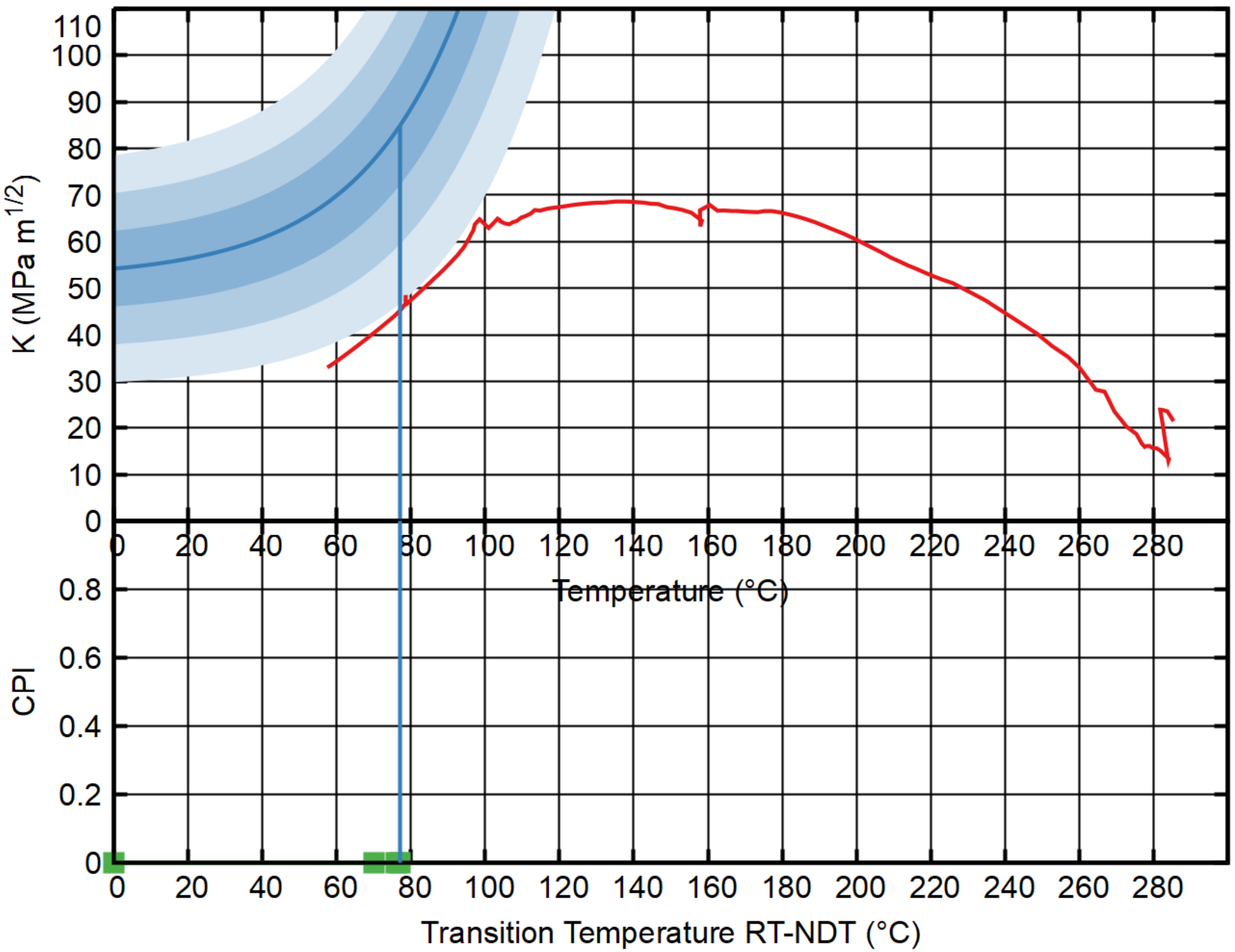

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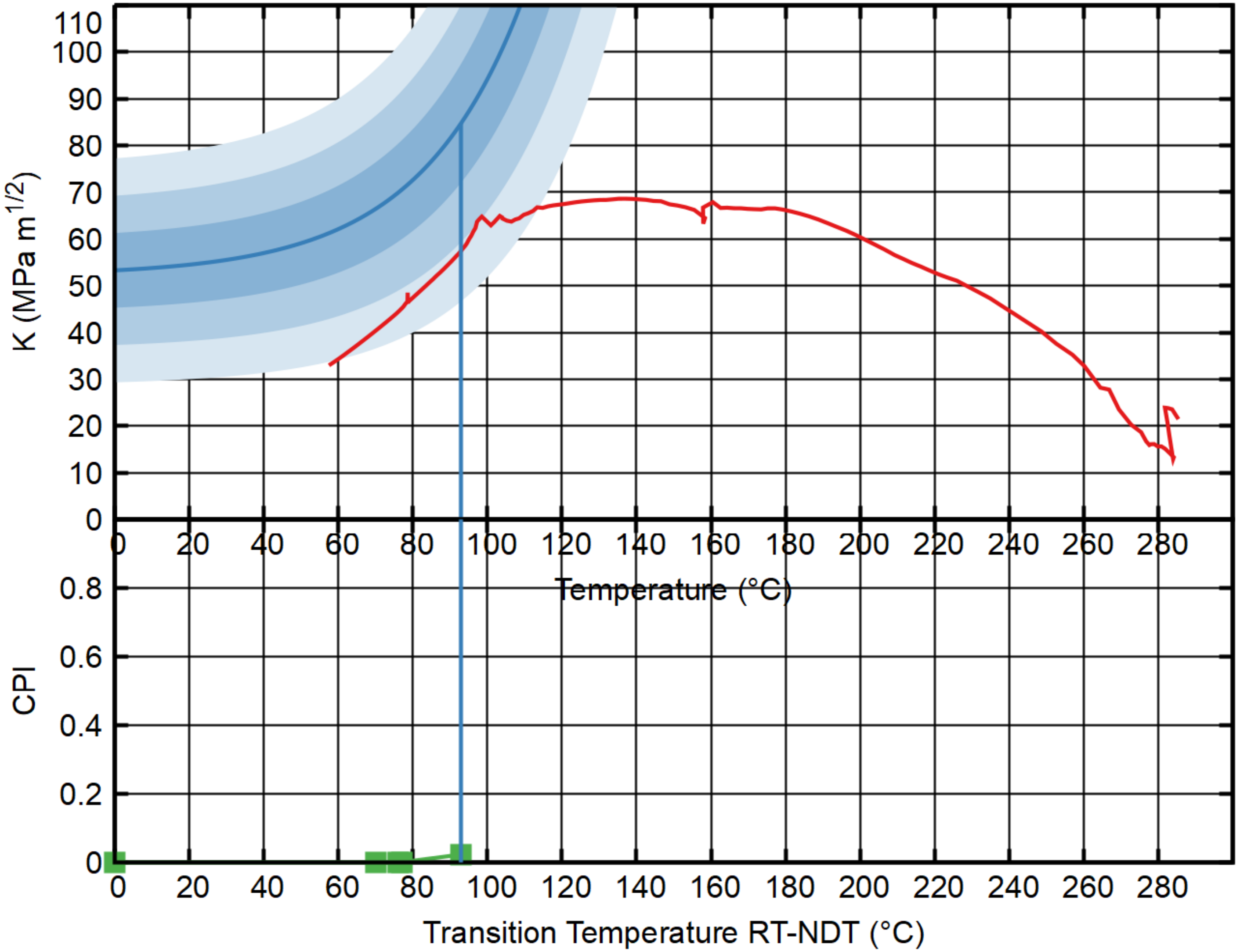

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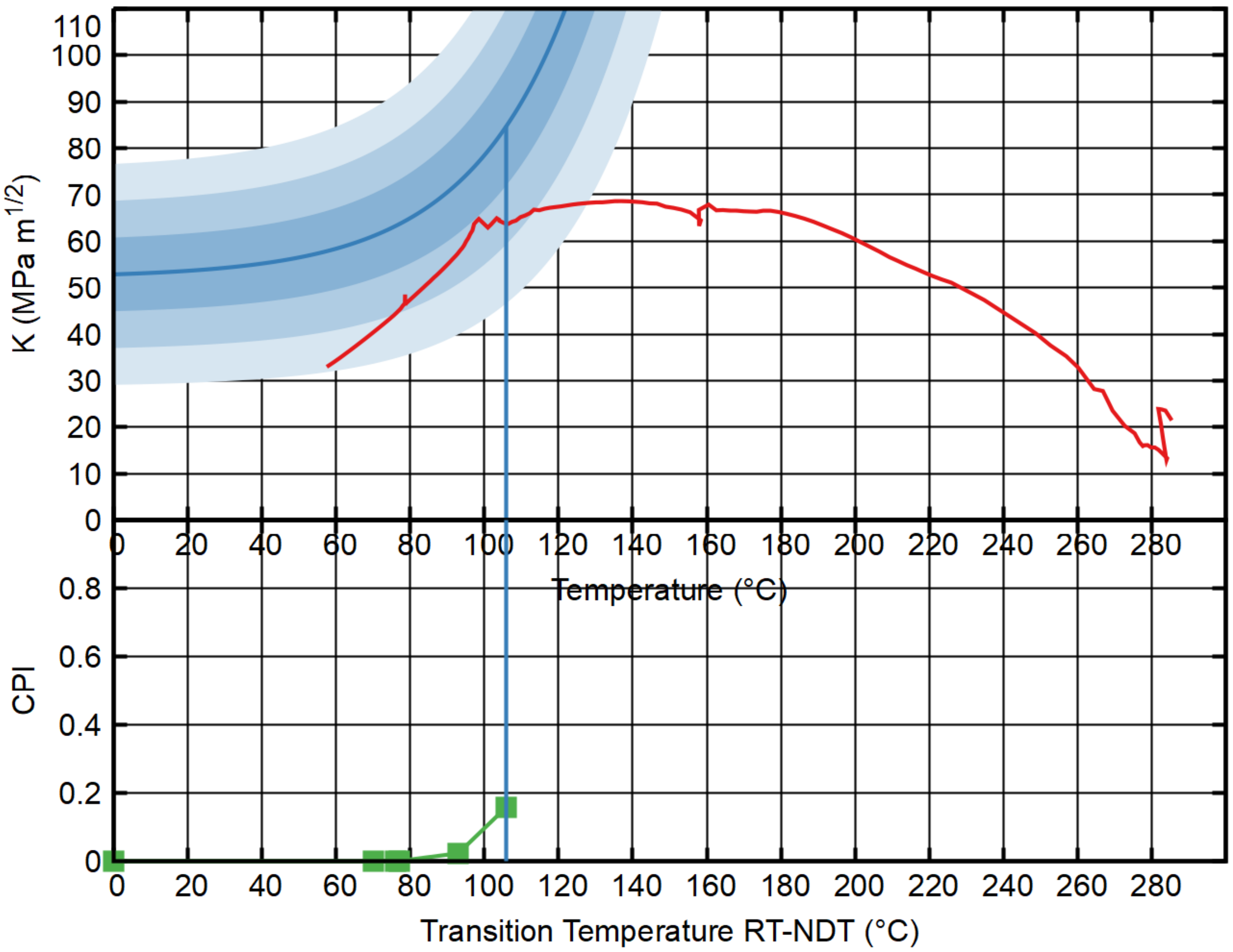

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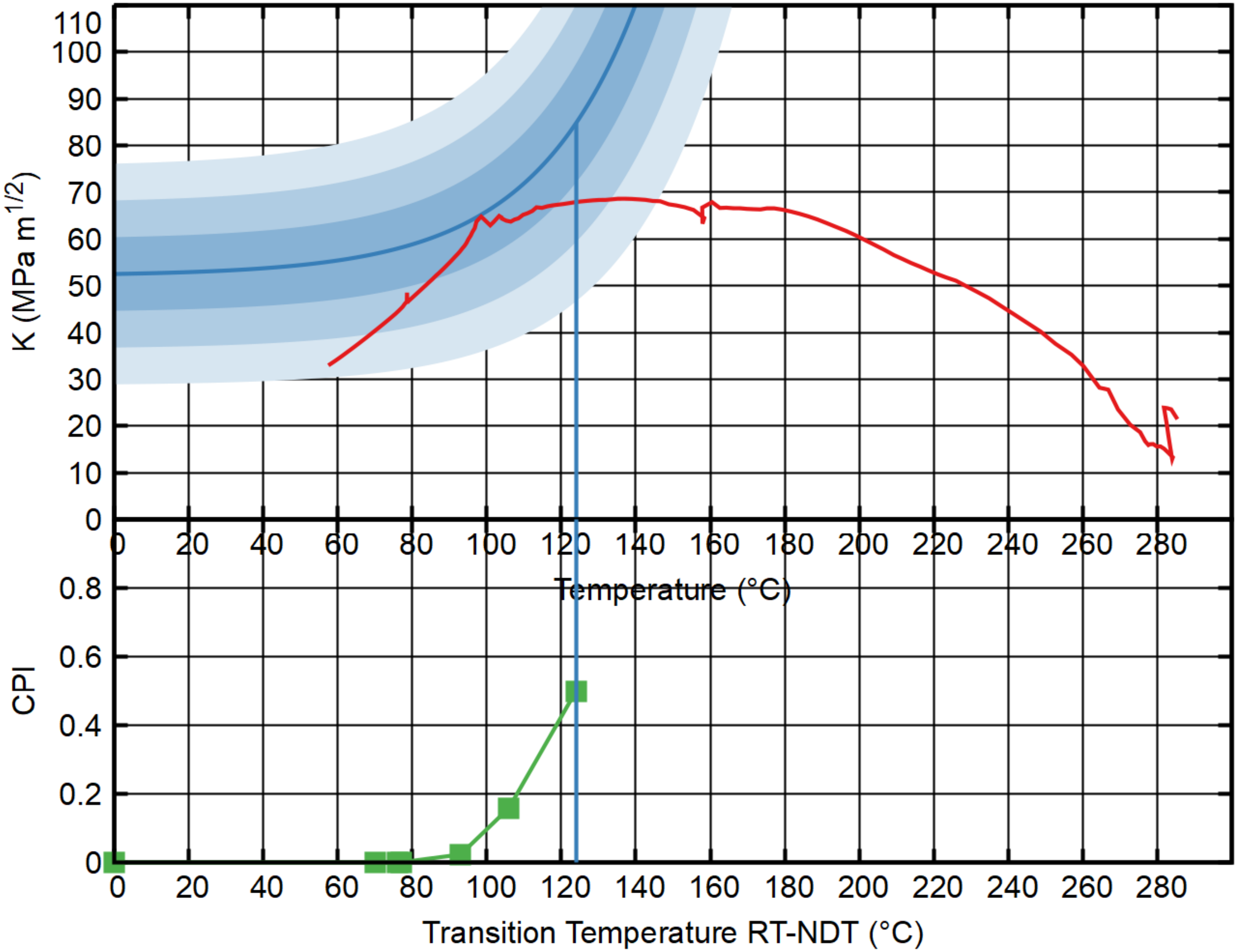

Max. all. ART

- Distribution of fracture toughness
  - ASME-Curve: truncated normal distribution
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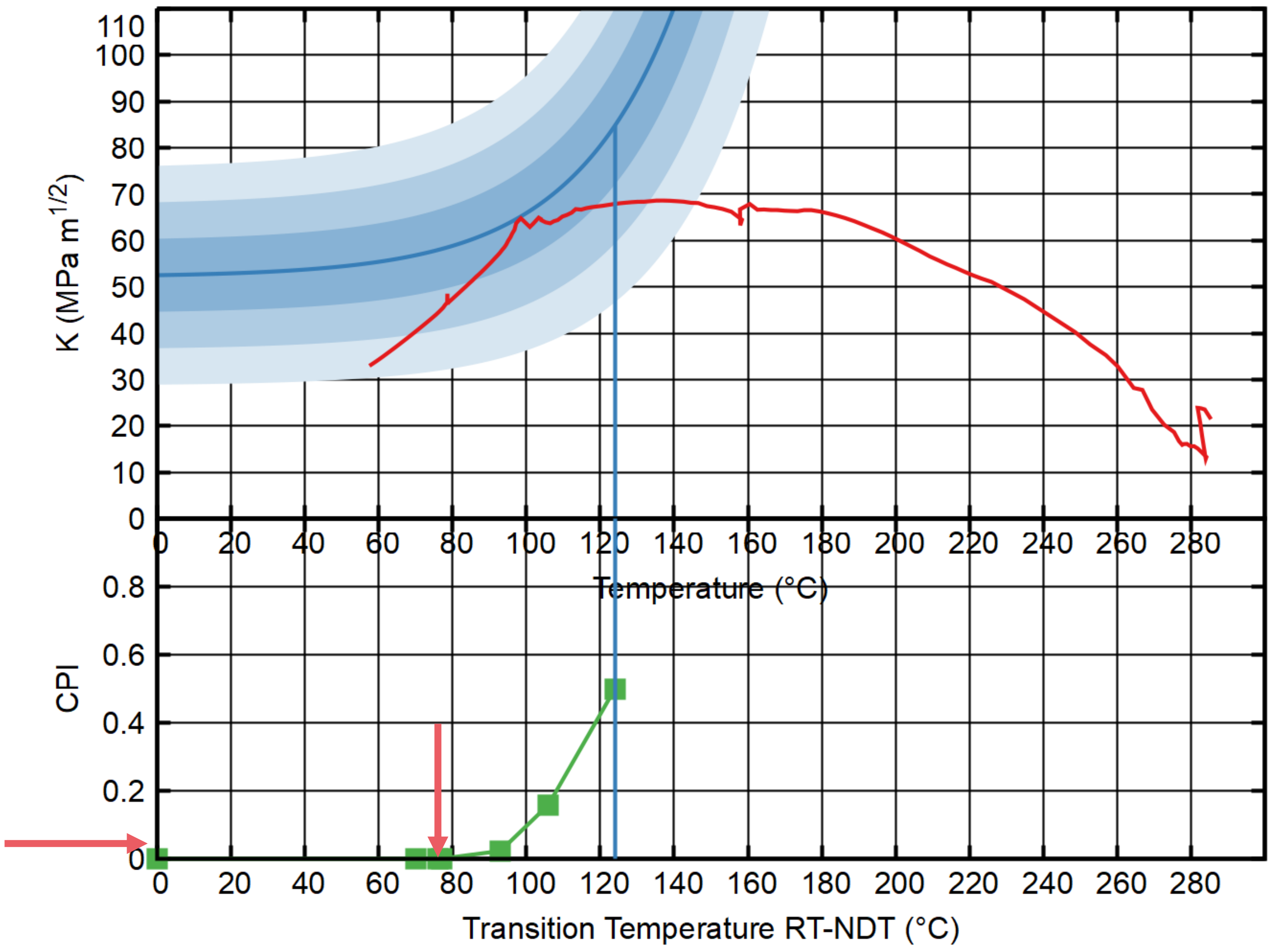
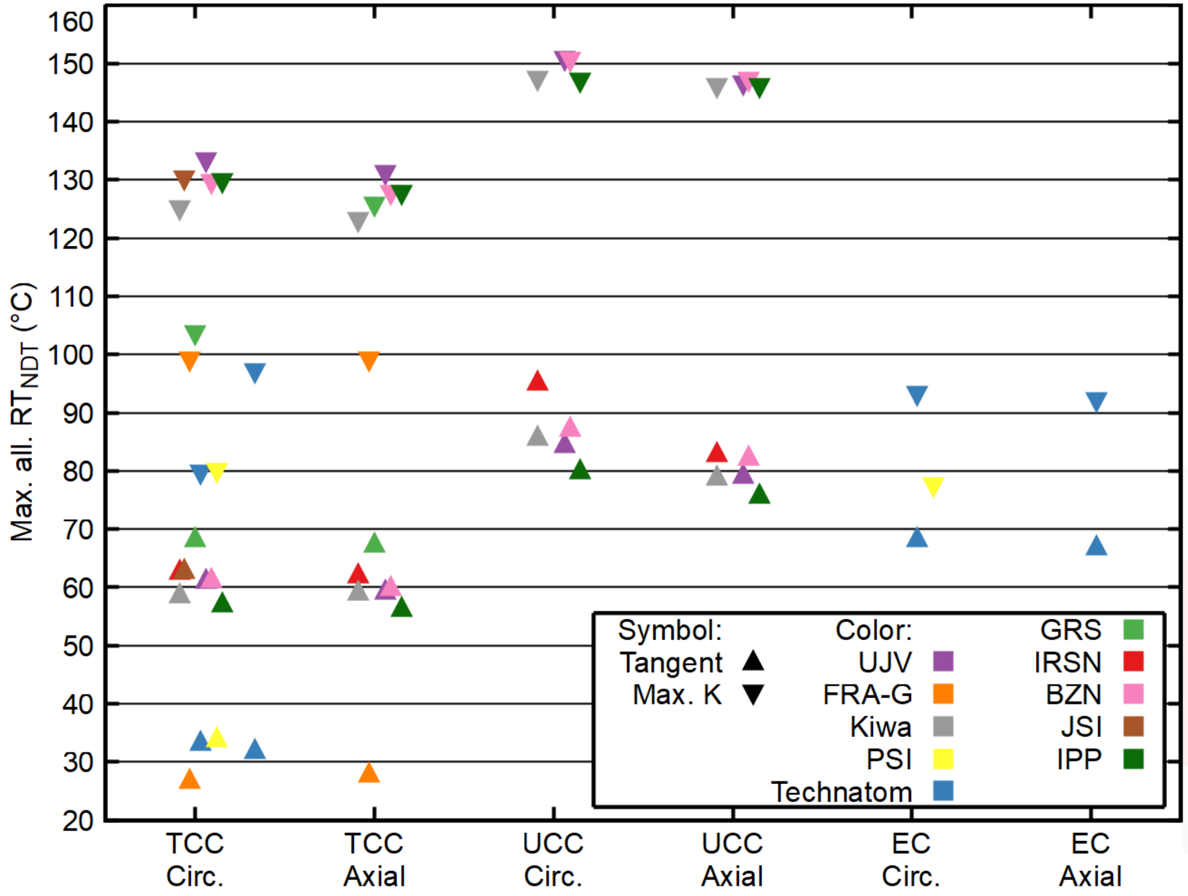
- Adjust transition temperature RT-NDT
- Find intersection point with target CPI: 77°C
  - APAL-specific target for this type of transient: 2.28 e-4



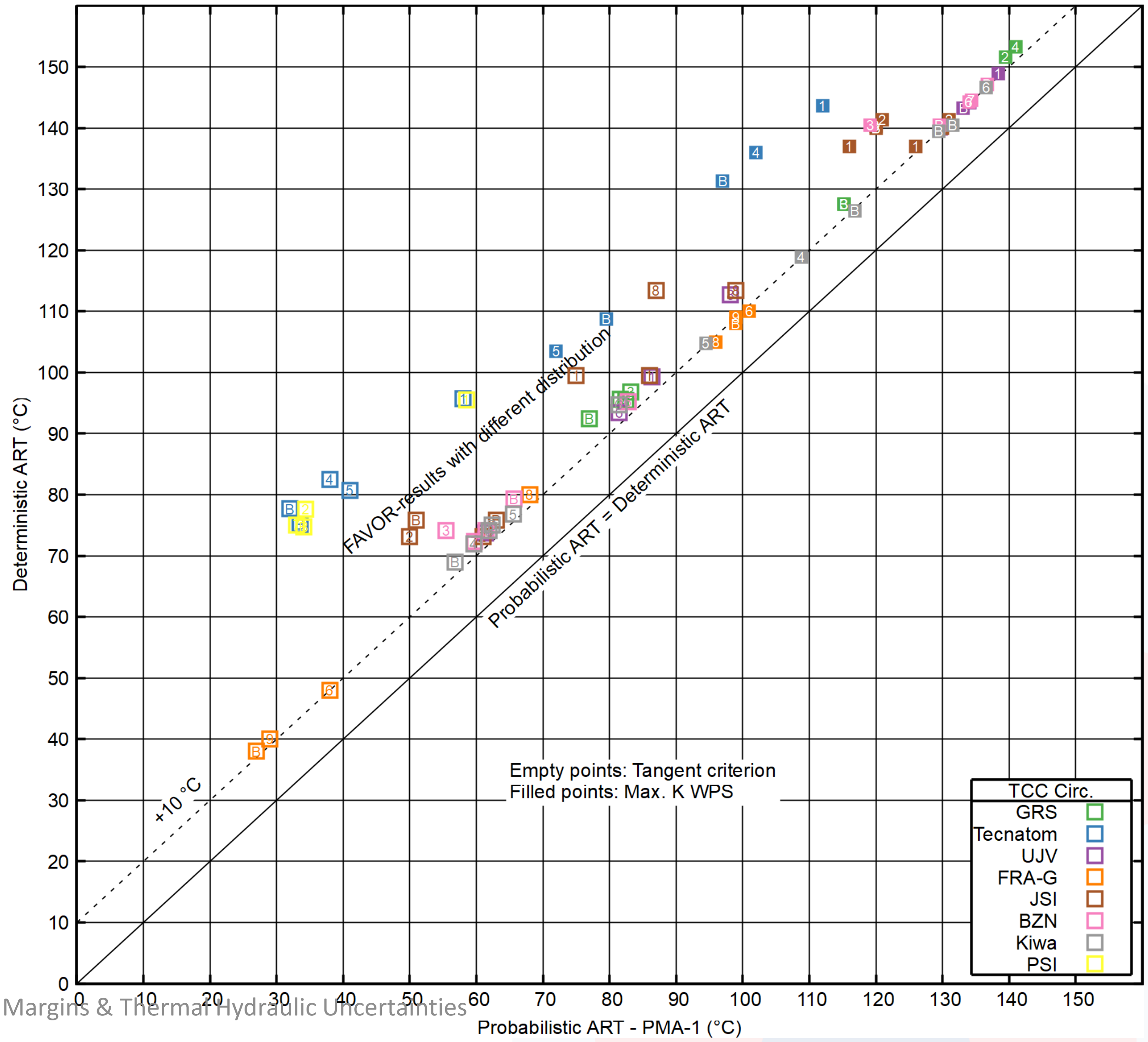
Application cases

- „Baseline“ cases from APAL project
  - TCC, UCC; EC
  - Different TH system codes
  - Tangent vs. max. K WPS
- Agreement
  - TH code influence
  - Conservative trend for some participants
- Remark
  - Low max. all. ART with tangent crit.



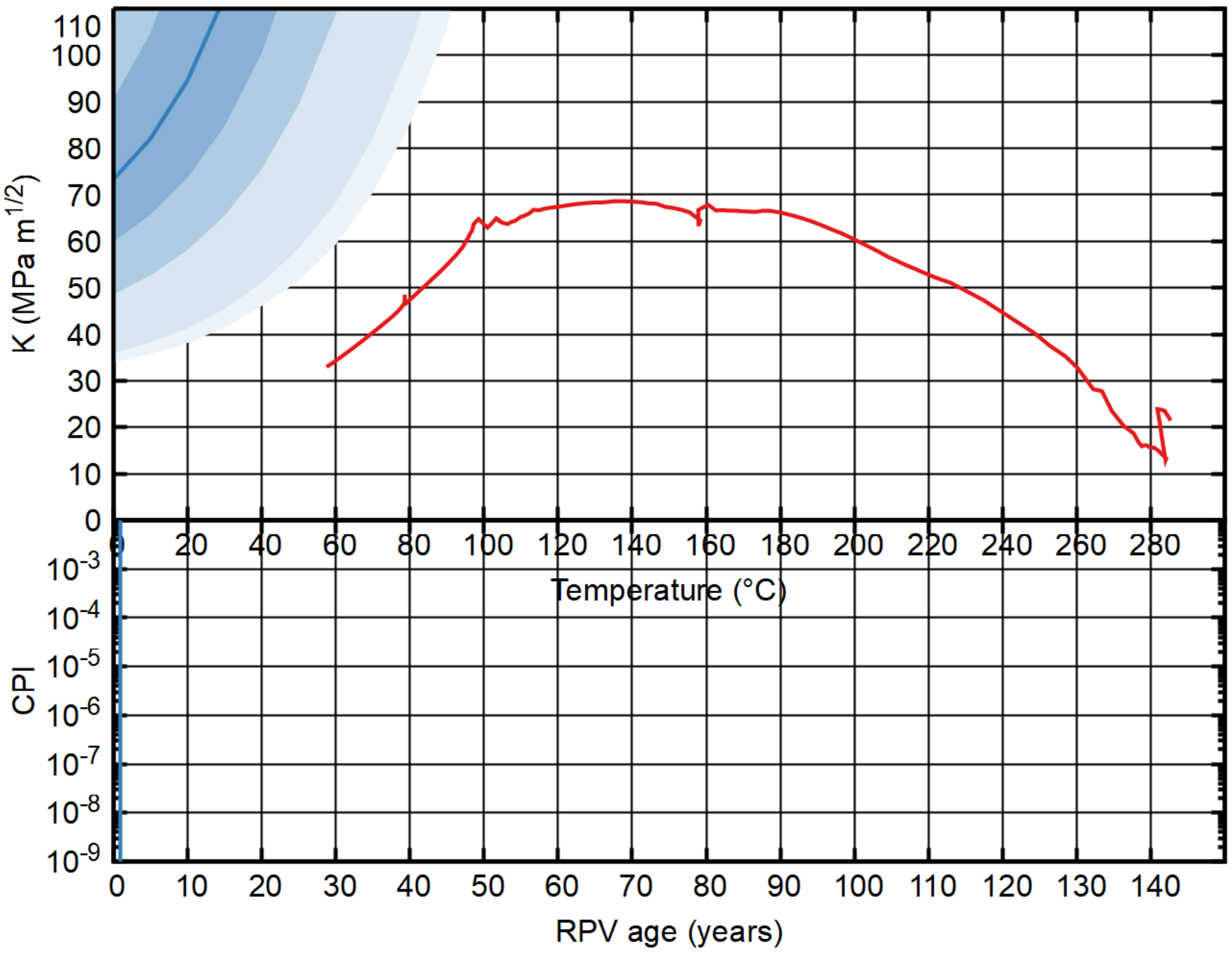
Probabilistic vs. Deterministic margin

- Selection of different transients
- Simple relation
  - Exception: FAVOR users with Weibull distribution and different crack assumptions
- Trend note
  - Deterministic not envelope



Lifetime

- Distribution of fracture toughness
  - Fracture toughness level (as before)
  - Uncertainties in predicted RT-NDT
    - Due to chemistry, fluence, intial conditions
- Fluence depends on lifetime
  - Right-shift of fracture toughness
  - → CPI depends on lifetime
  - Find intersection point with target CPI



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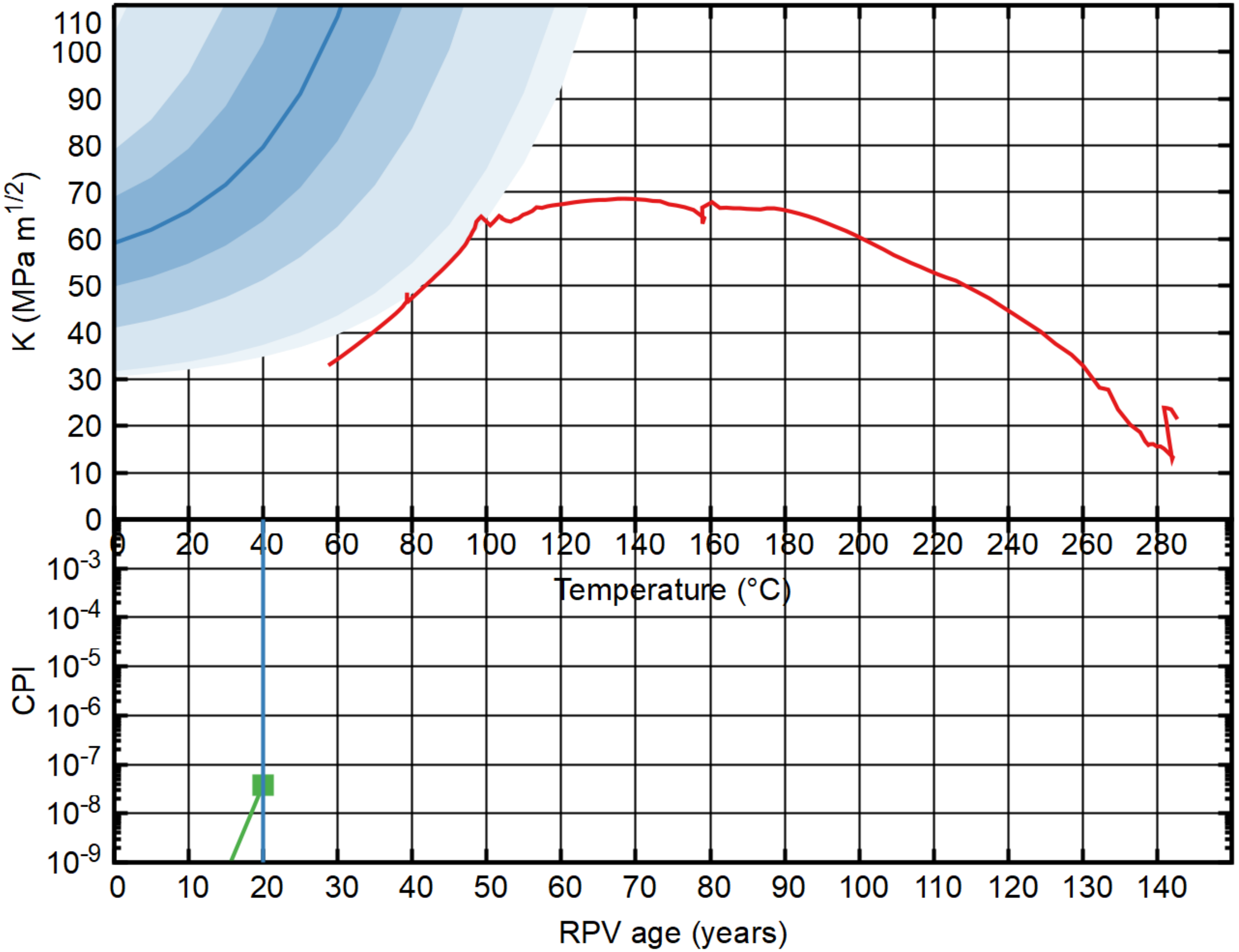

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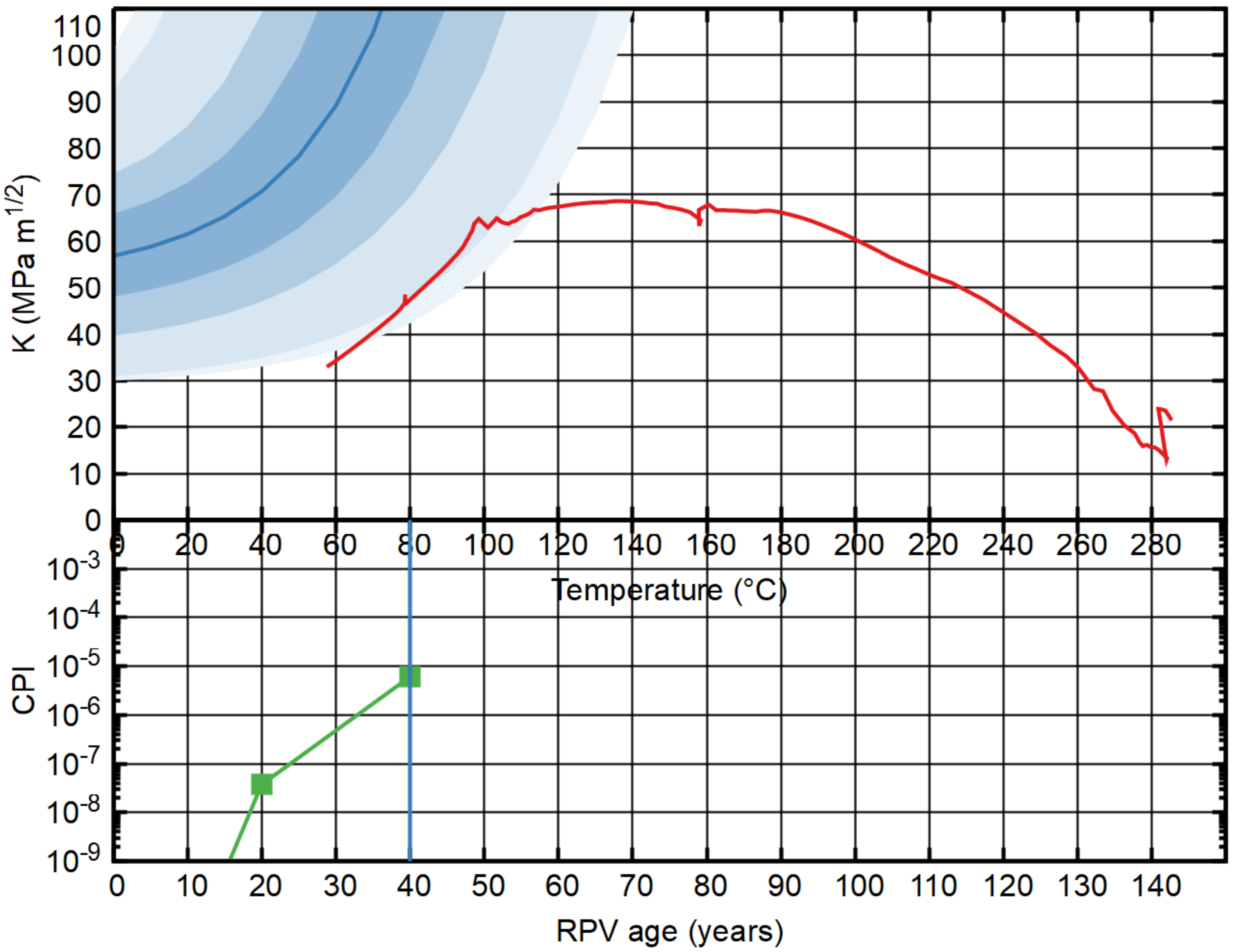

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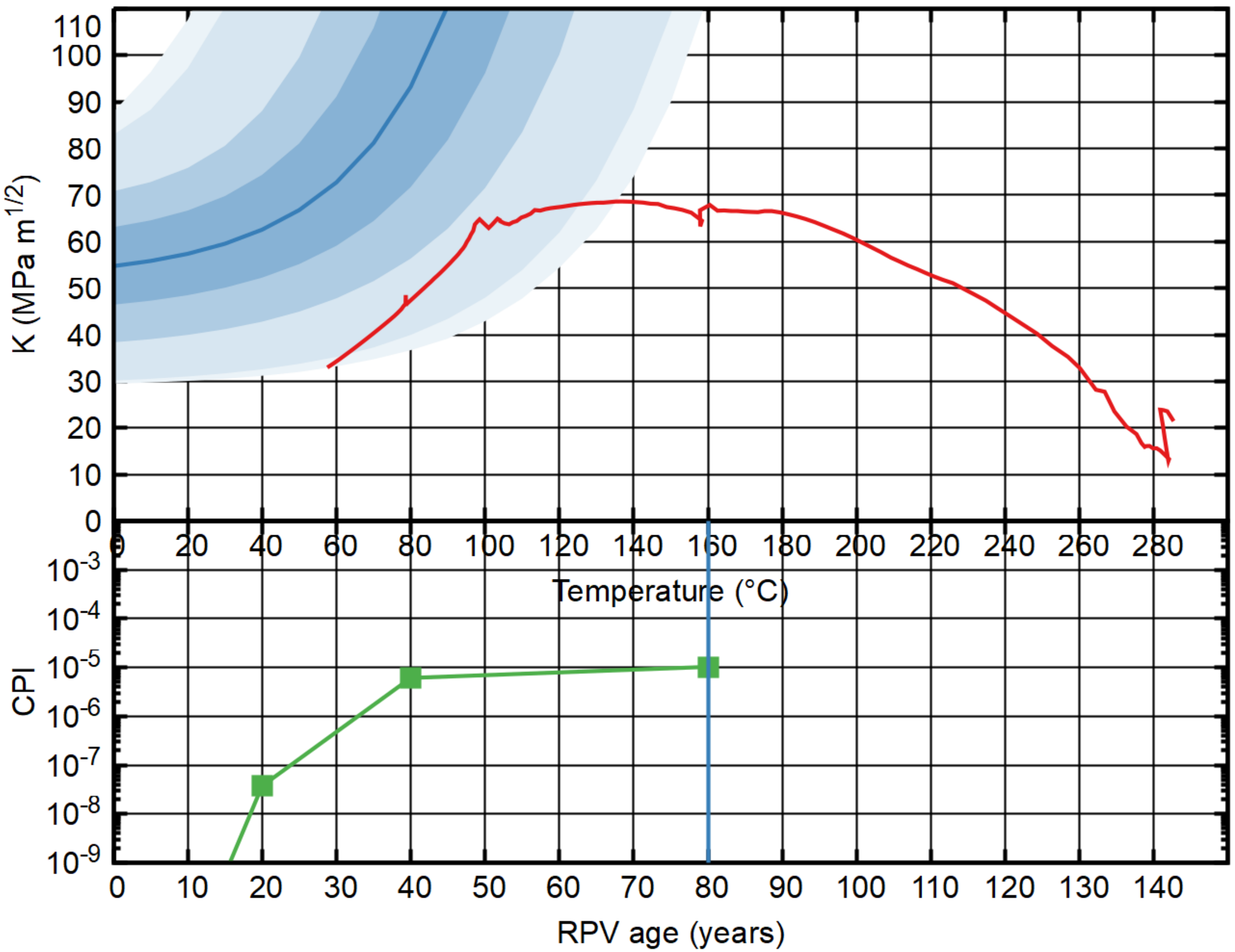

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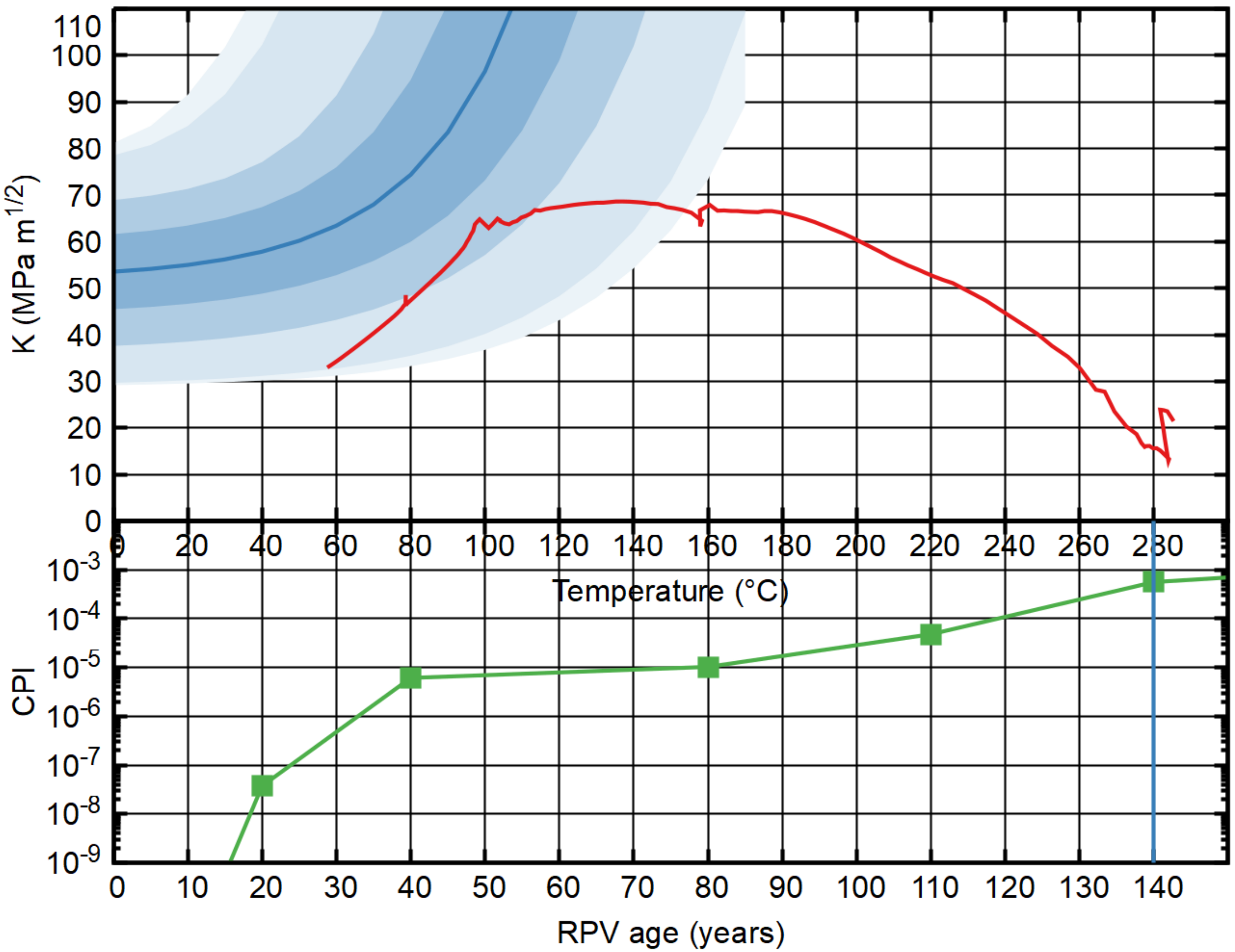

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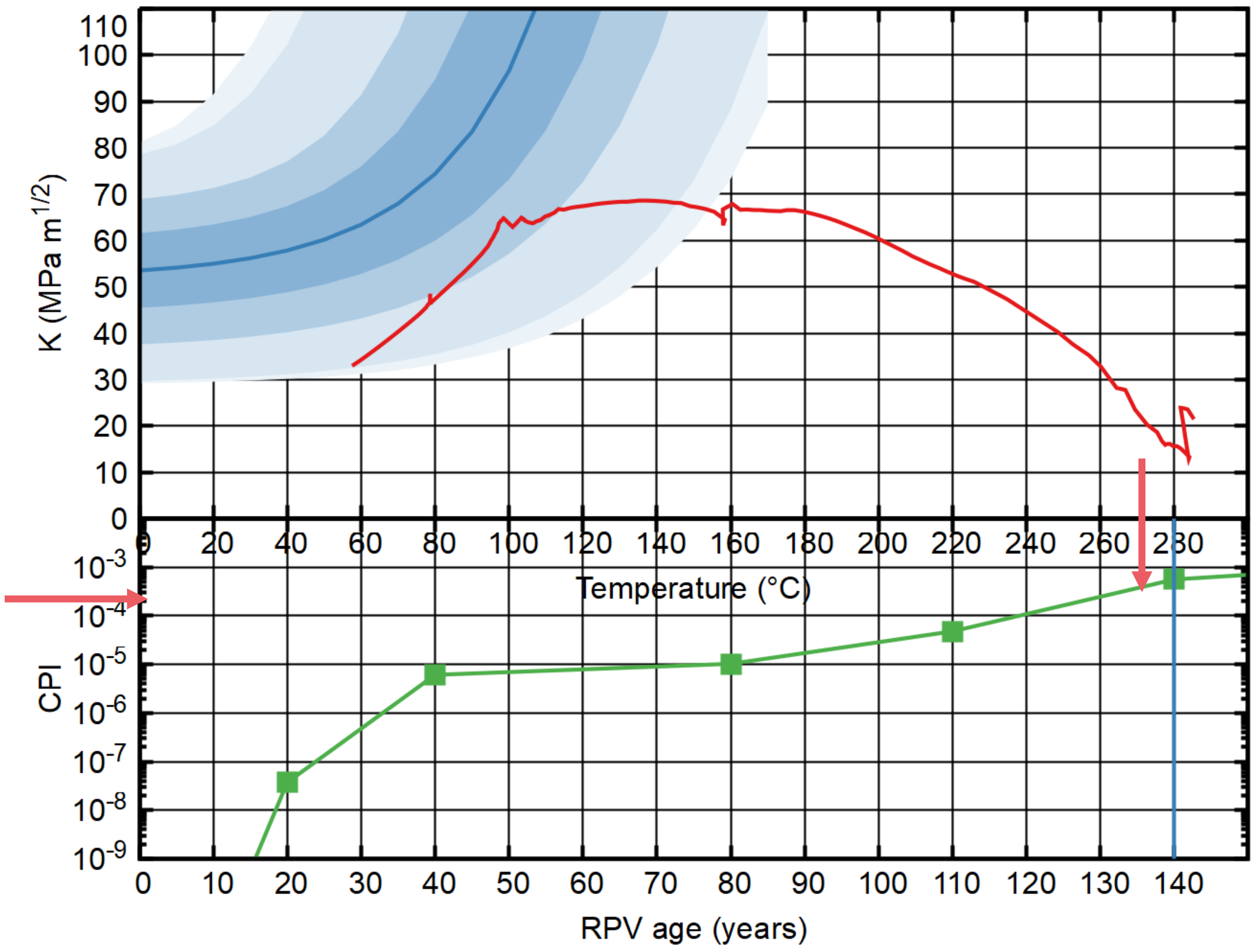
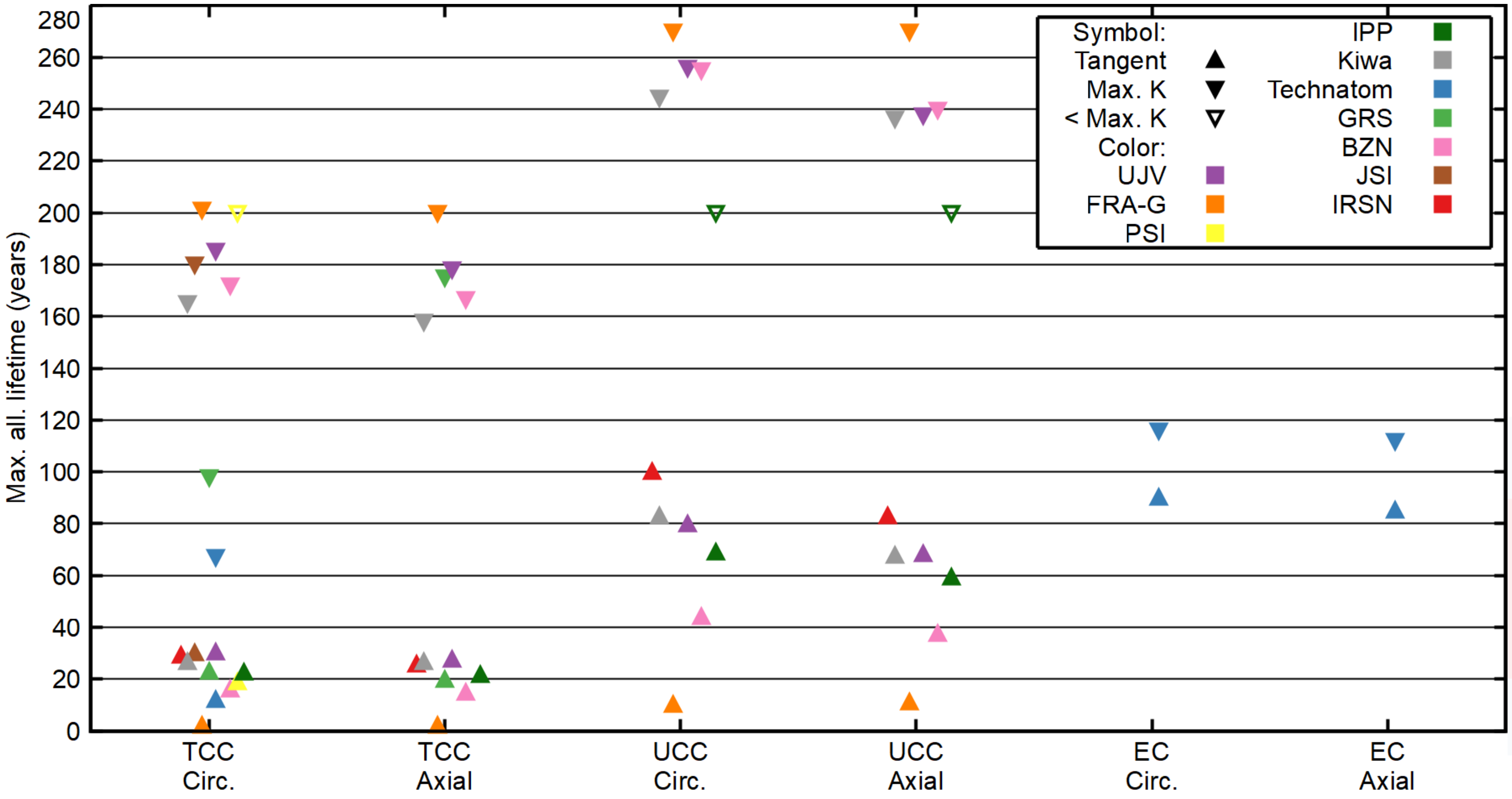
  - → CPI depends on lifetime
  - Find intersection point with target CPI: ~135 years



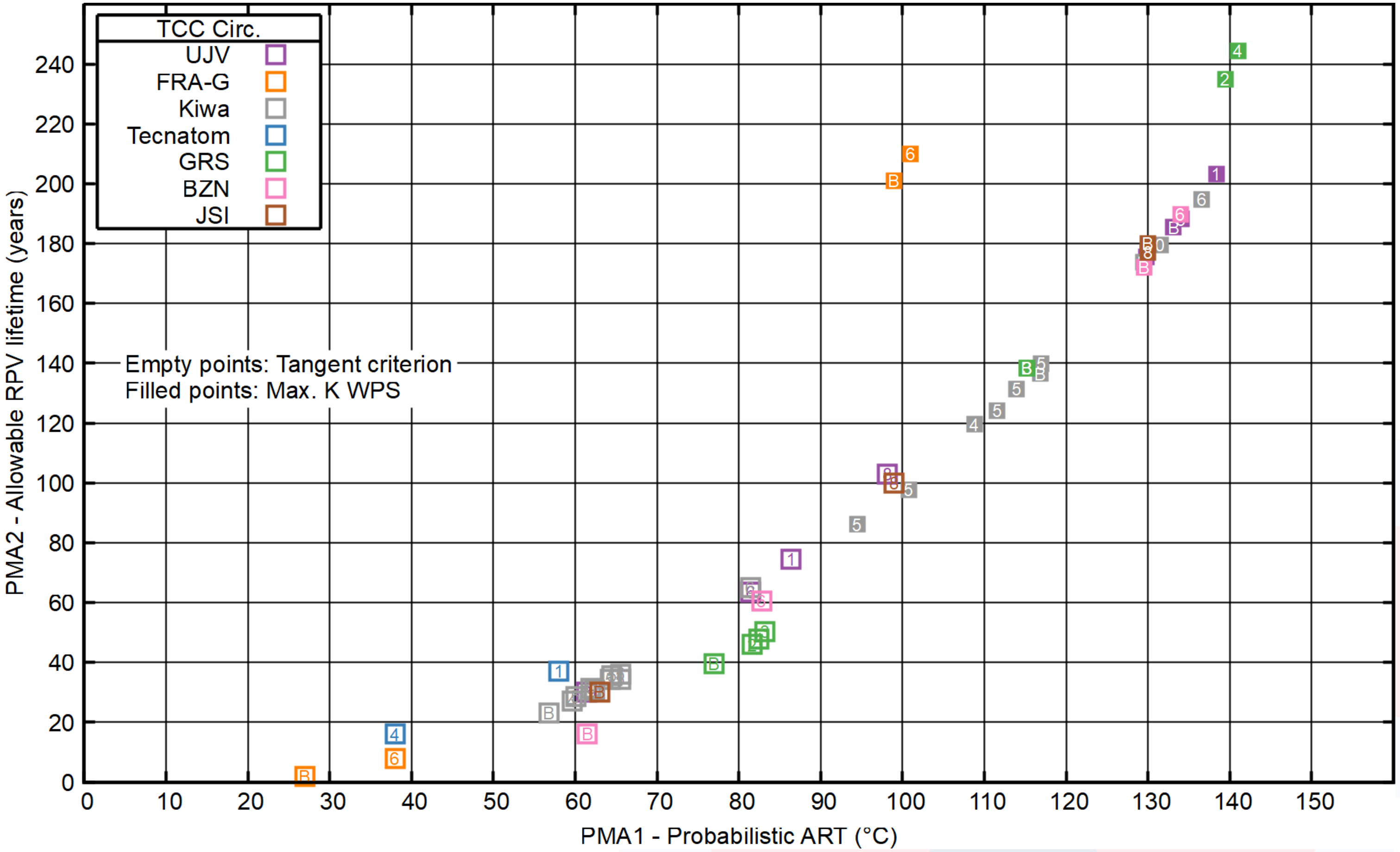
Examples for lifetime margin

- Trends in agreement with max. all. ref. temperature
- Low allowable lifetime with tangent criterion
- High allowable lifetime with max. K WPS criterion



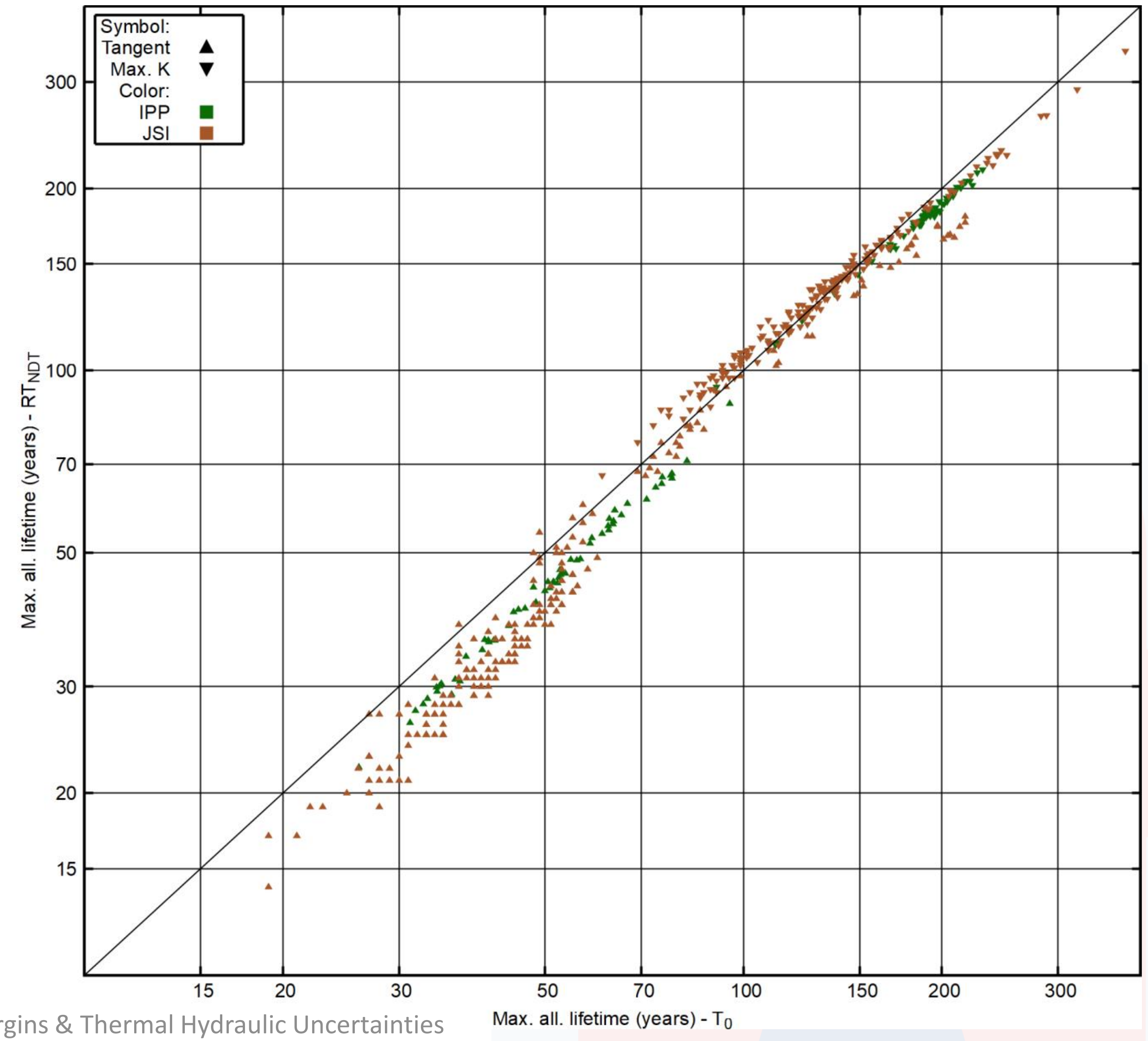
Lifetime vs. max. all. ref. temperature

- Comparison of probabilistic margins
- Selection of different transients
- Result
  - Non-linear relation
  - Monotonic behavior
- Important for conclusion:
  - Different margin concepts lead to same ranking



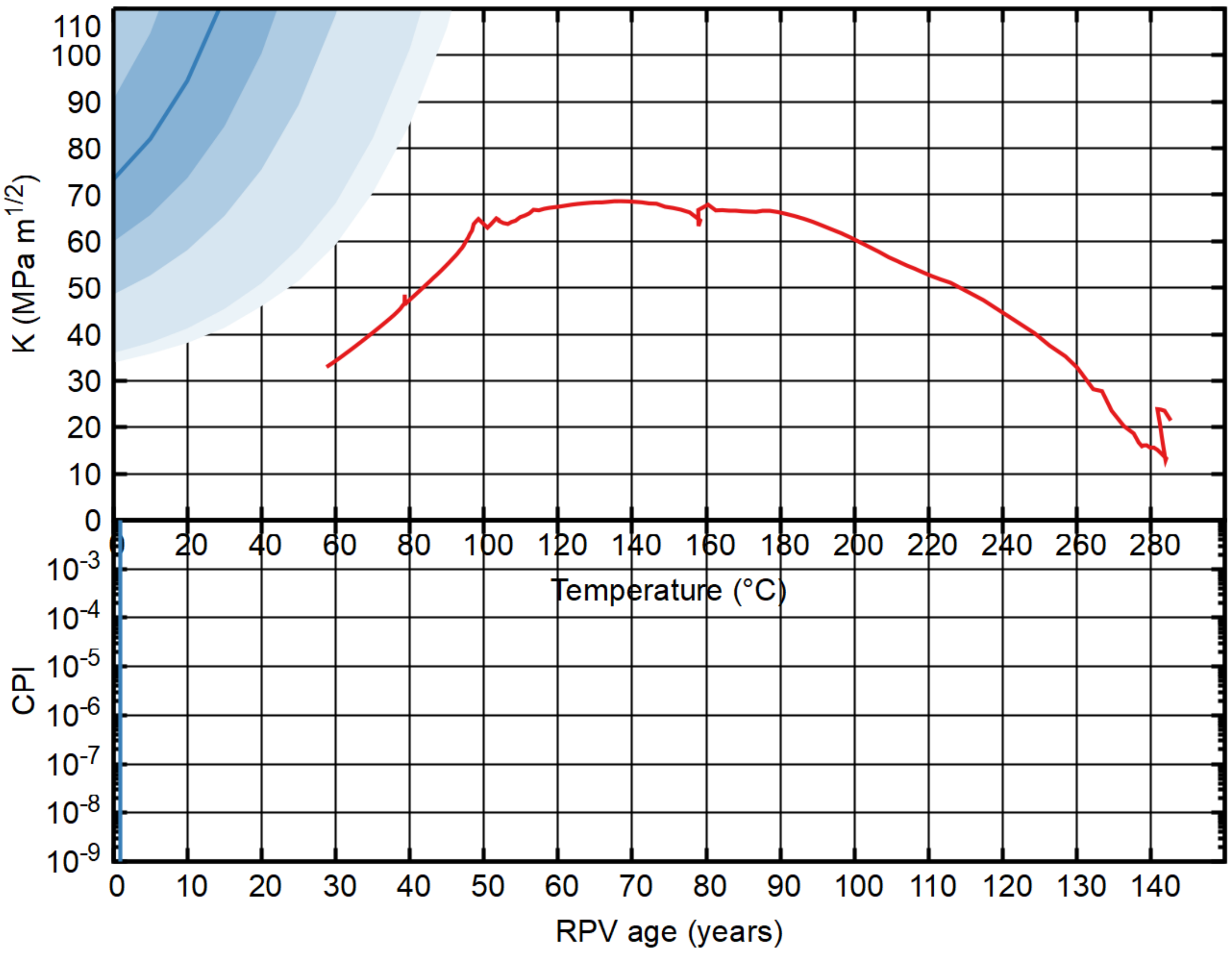
Influence of fracture toughness curve

- Larger set of transients
- Compute lifetime with…
  - ASME curve
  - Master curve
- Dependence is implicite
  - Both enter in lifetime
- Slight differences



Reliability and sensitivity

- Distribution of fracture toughness
  - 7 different parameters
- Limit state function and failure area
  - Visualization for 2 dimensions
- Transformation to std. normal space
- Most probable failure point (MPFP)
- Importance factors
  - $|MPFP_i|/\beta$
  - Ranking of relevant parameters



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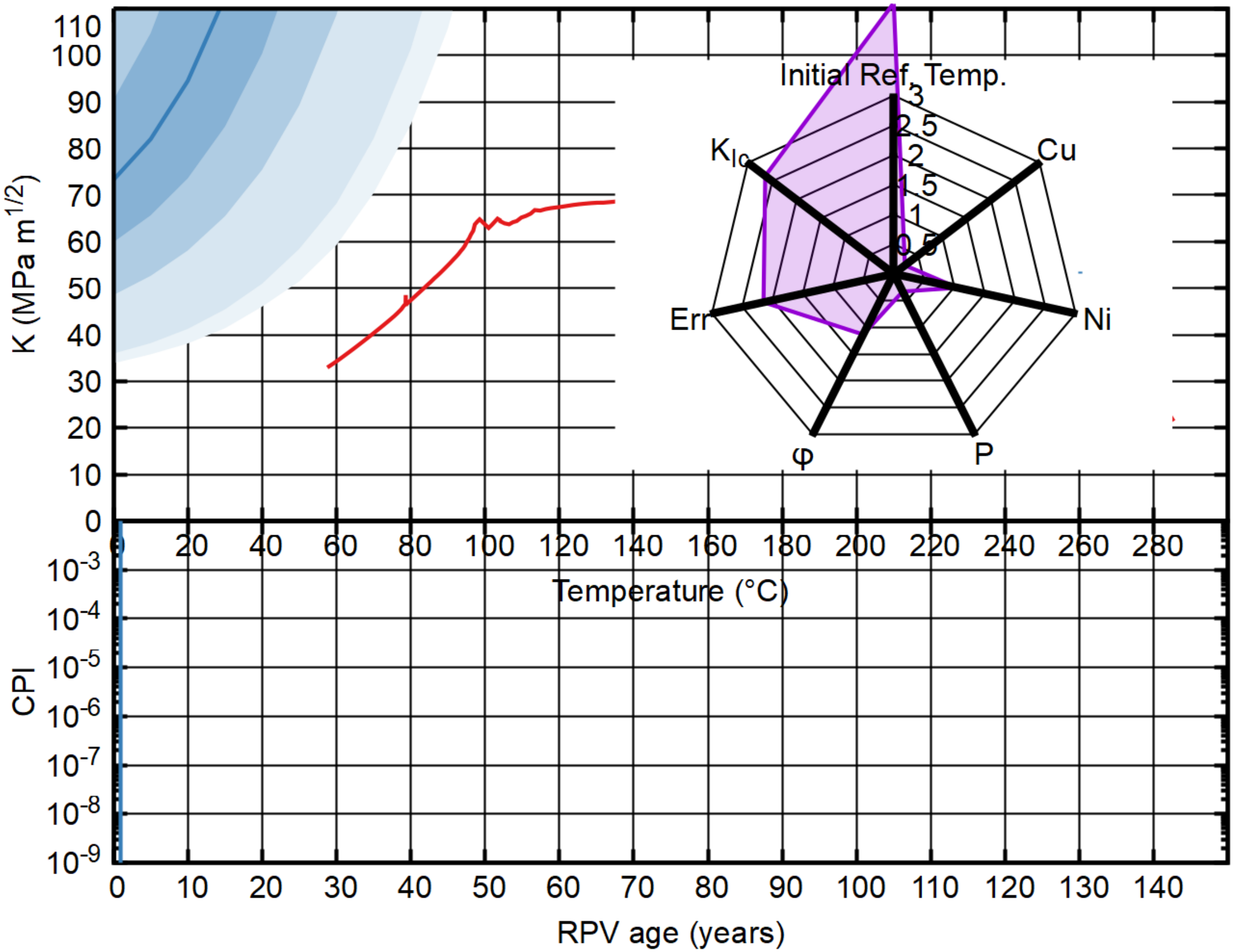

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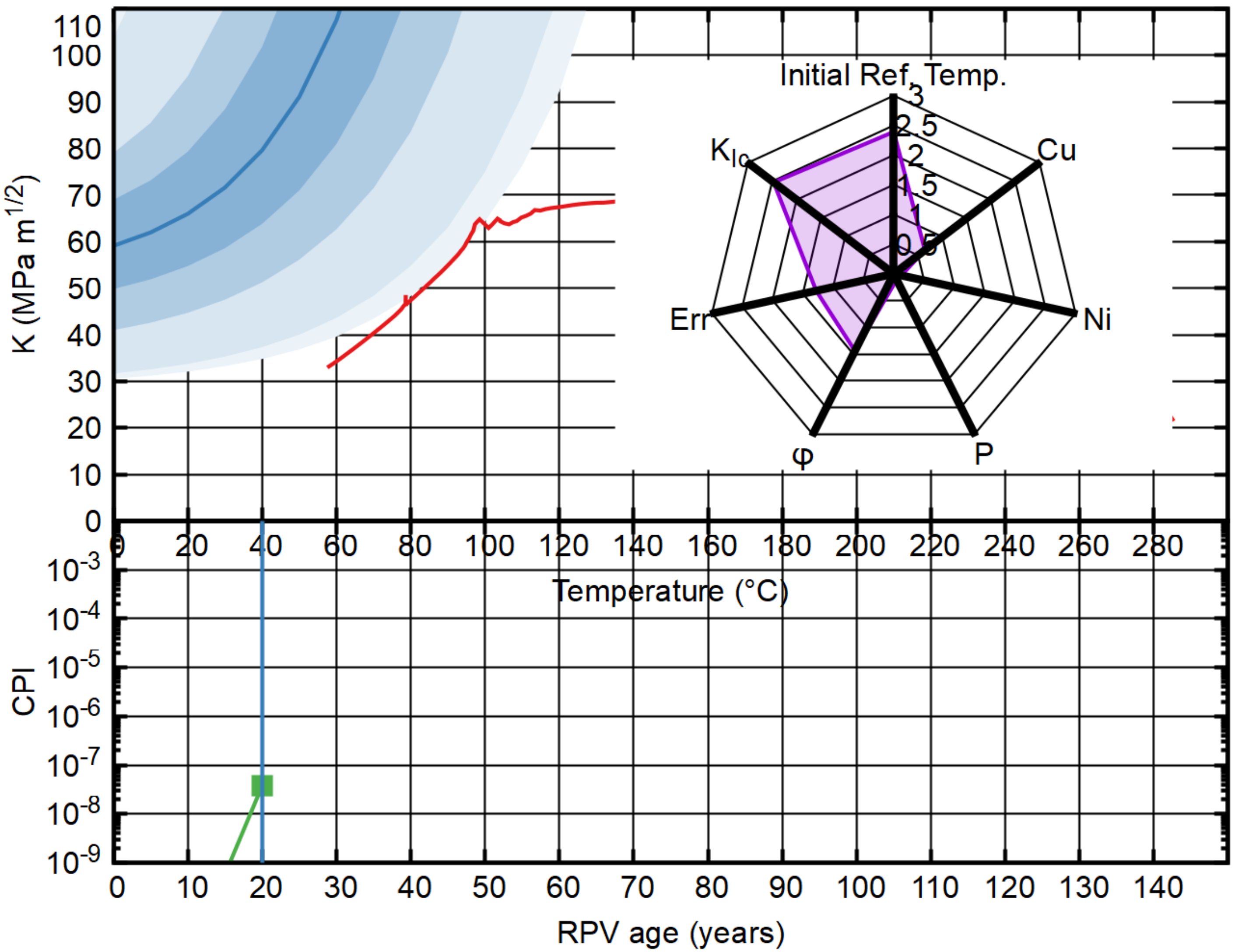

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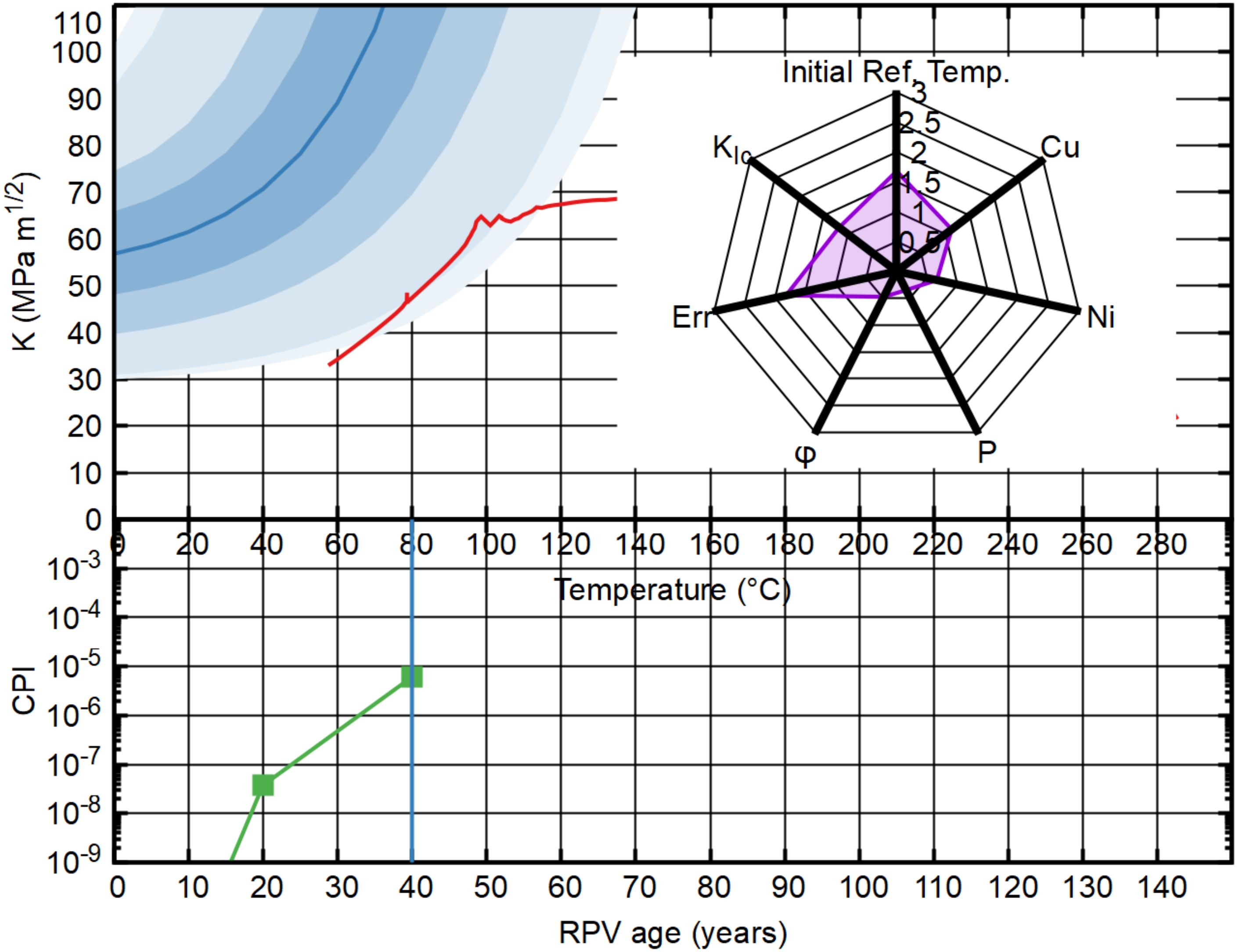

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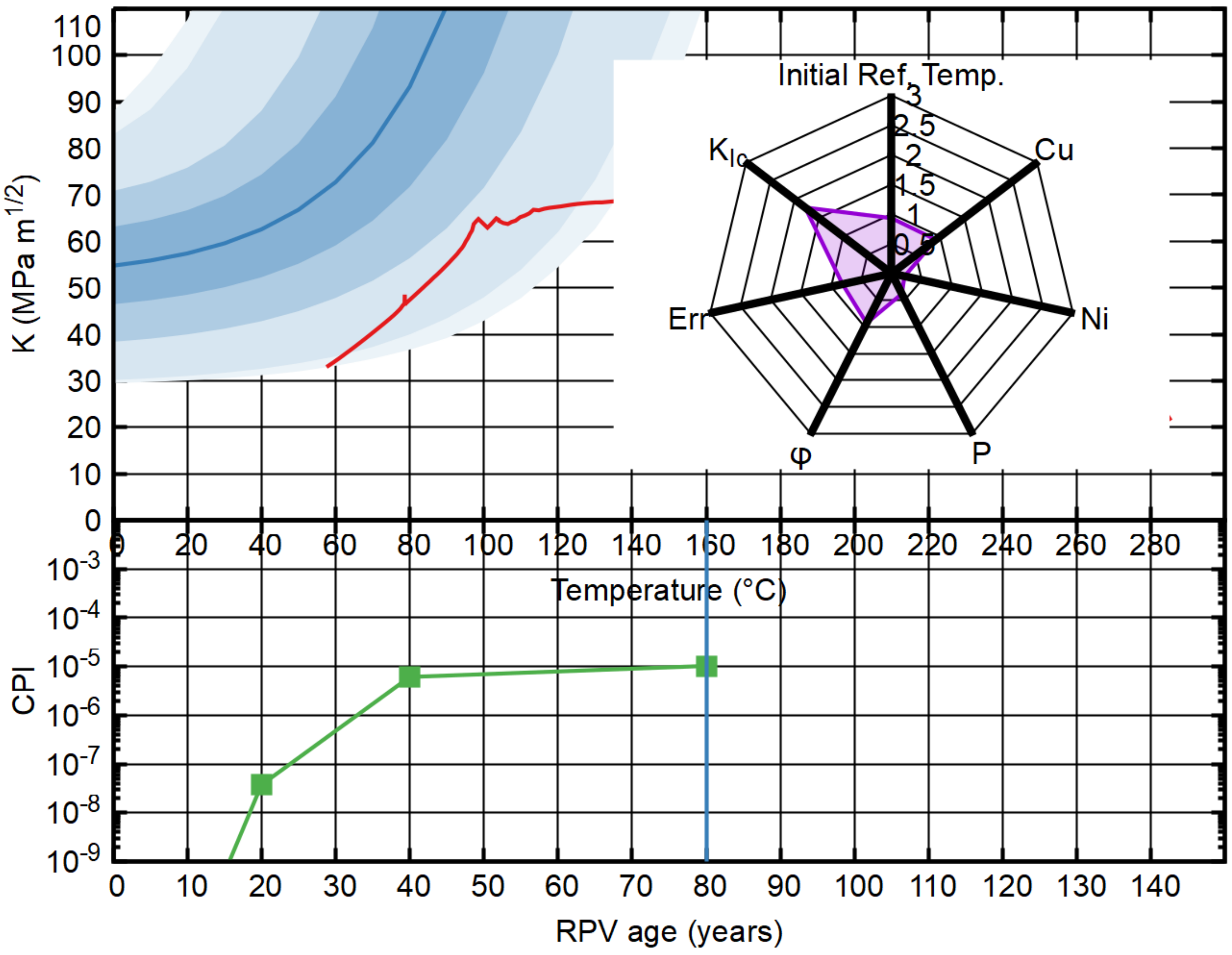
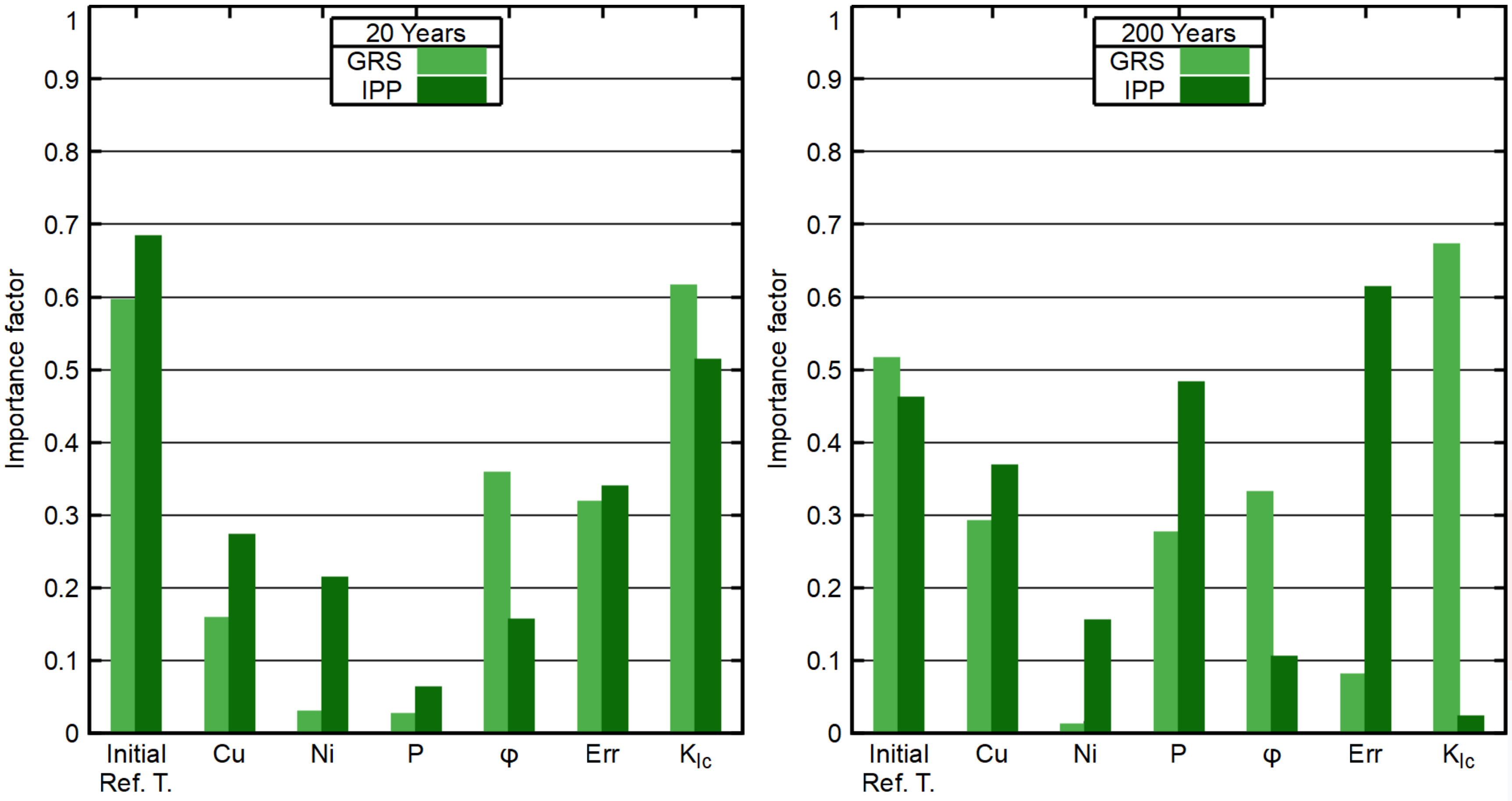


PMA-4: Importance factors

- Importance factors
  - $|MPFP_i|/\beta$
  - Ranking of relevant parameters
- Selected ages
  - 20 years
  - 200 years
- Agreement
  - For 20 years
  - Difference for 200 – but high probability



Methodology conclusion

- **Fracture toughness margin**
  - Very limited additional information, compared to deterministic assessment
  - Remark: No crack size distribution was considered in the presented cases
  - Result would be less trivial for distributed crack size + fracture toughness based margin assessment
- **Lifetime margin**
  - Clear quantification of safety margin (lifetime)
  - Remark: Dependence on embrittlement model
- **Reliability and sensitivity margin**
  - Similar to PMA-2, understanding of mechanisms and risks
  - Generalization beyond initiation (i.e. crack arrest) open
- Relation between margin approaches
  - Monotonic relations (or even linear relations)
  - Consequence: Transients can be ranked/rated on deterministic level
    - (monotonic relation deterministic → fracture toughness → lifetime)

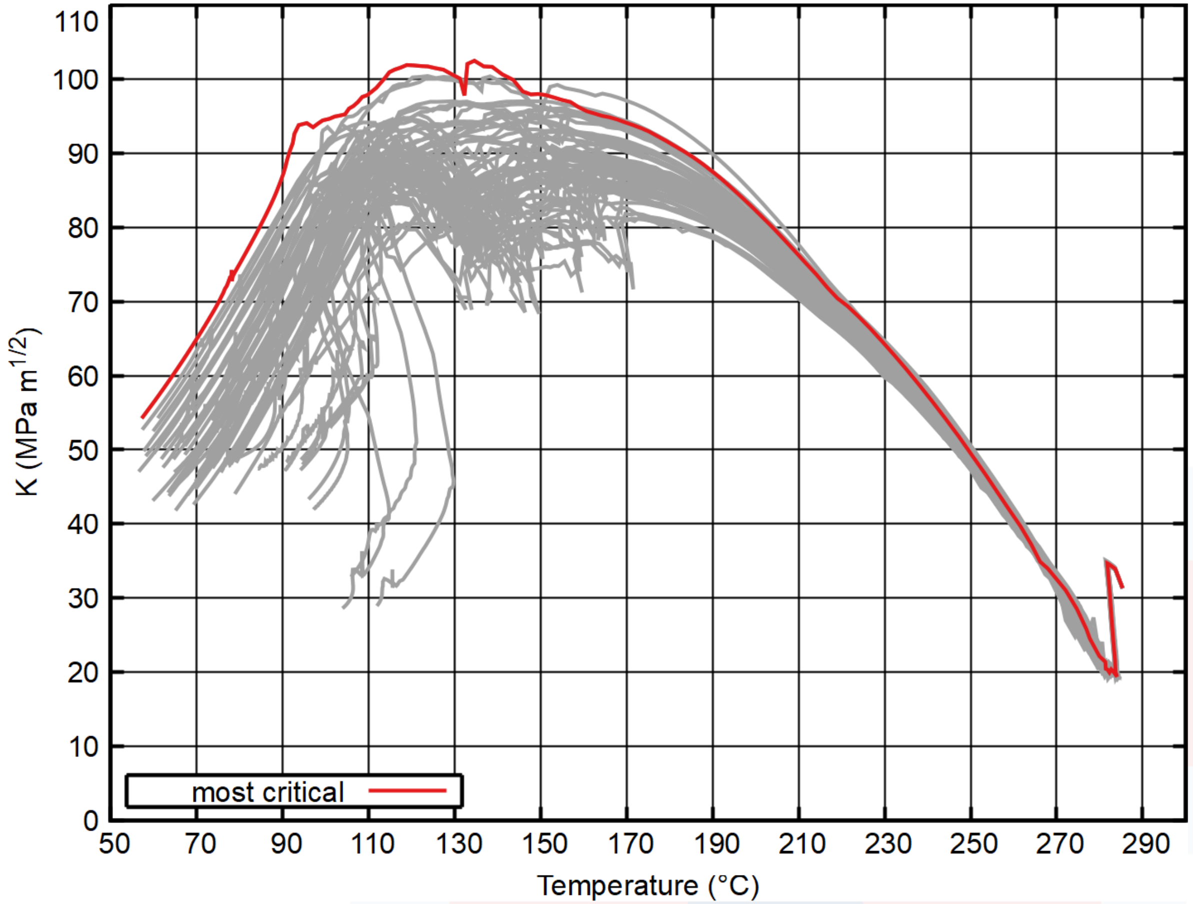
PART II:
Thermal-Hydraulic Uncertainties

and their inclusion in probabilistic margin assessmemt

Thermal-hydraulic uncertainties: Introduction

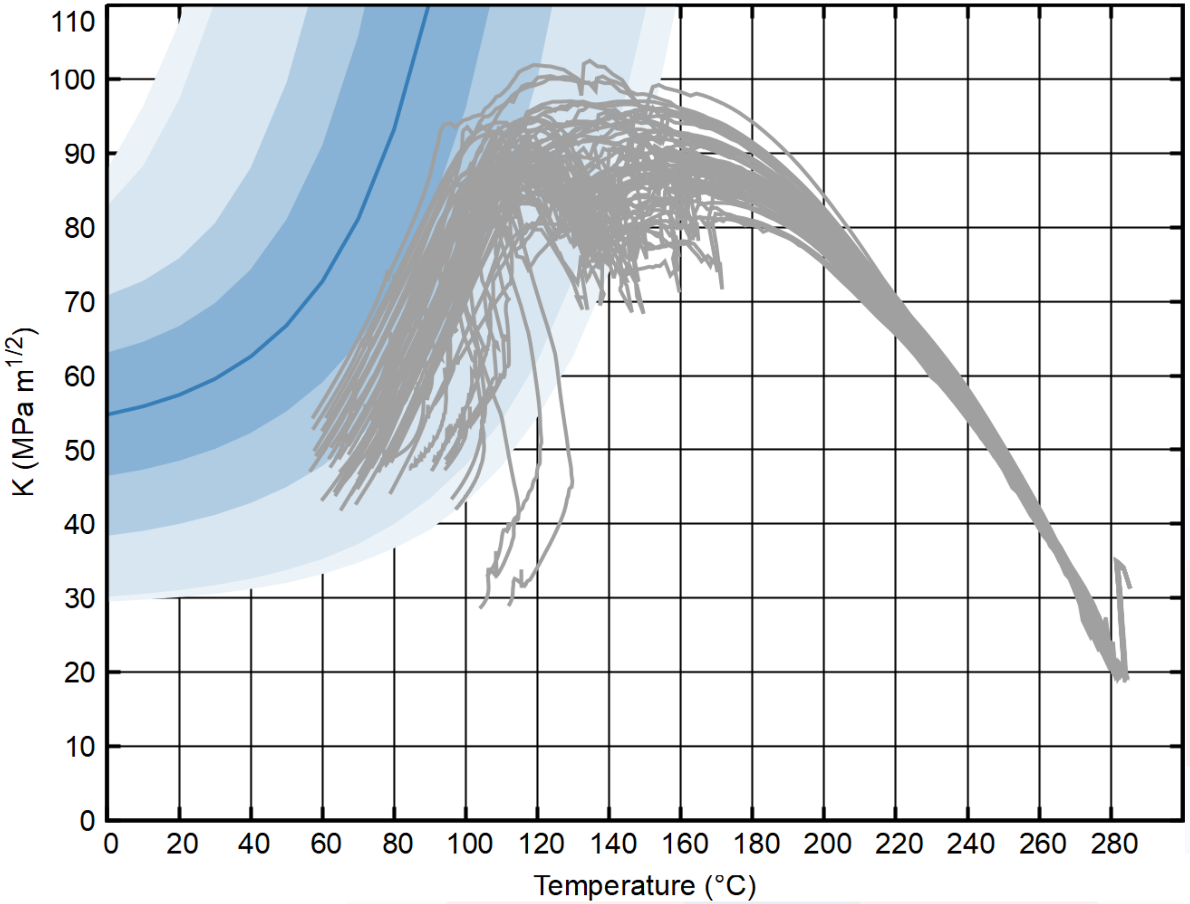
Introduction

- Consideration of different sets of TH parameters
- Wilks argument: one-sided tolerance limit, lower bound
- Set of transients, depending on
  - Number of distributed parameters
  - Tolerance limit, lower bound
  - Rank
  - Usually: 59-130 transients



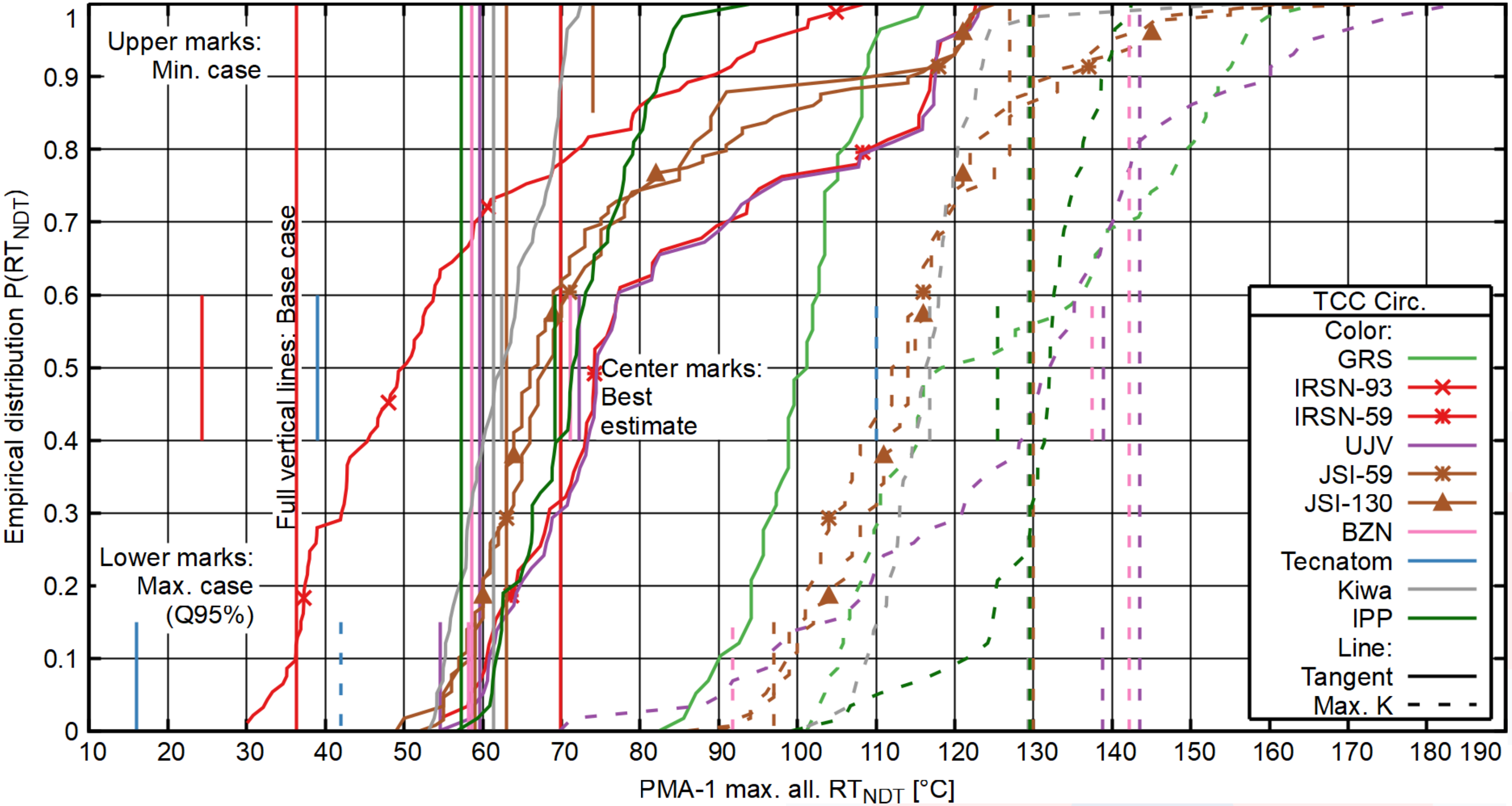
Thermal-hydraulic uncertainties and probabilistics

- Probabilistic Analysis of full Wilks set
  - First of a kind in APAL
  - Demanding (59-130 transients)!
- Apply margin to full set
  - Max. all. ref. temperature
  - Lifetime margin
- Derive cumulative distribution function (CDF) for margin



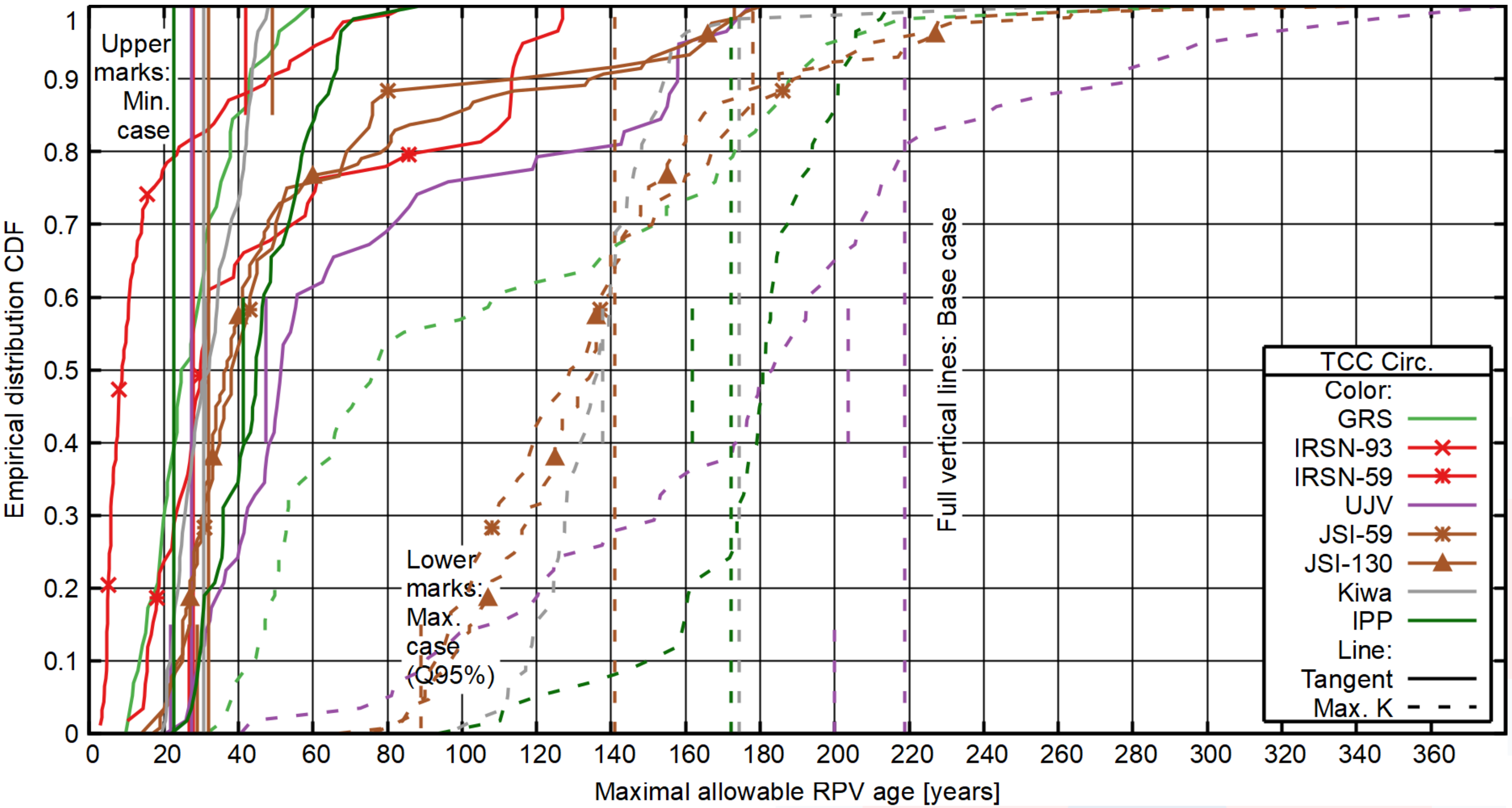
Max. all. ref. Temperature: Full Wilks Set

- Different TH codes / data sets
- Consideration of 59-130 transients
- Empirical distribution function for margin RT_{NDT}
  - 30-80 °C scatter
- Criterion:
  - Tangent
  - Max. K WPS



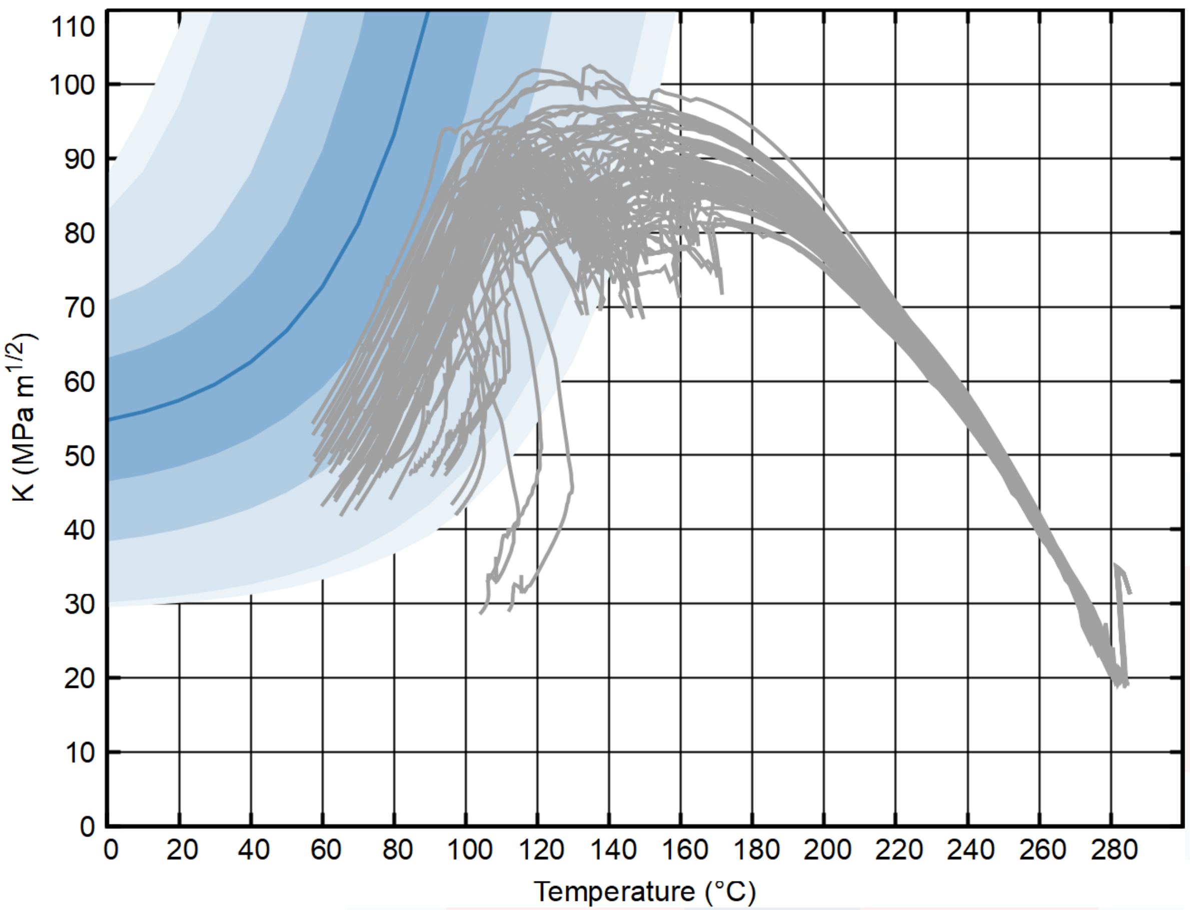
Max. all. lifetime: Full Wilks set

- Different TH codes / data sets
- Consideration of 59-130 transients
- Empirical distribution function for margin
- Tangent
  - ~50-140 years scatter
- Max. K WPS
  - ~240-320 years scatter

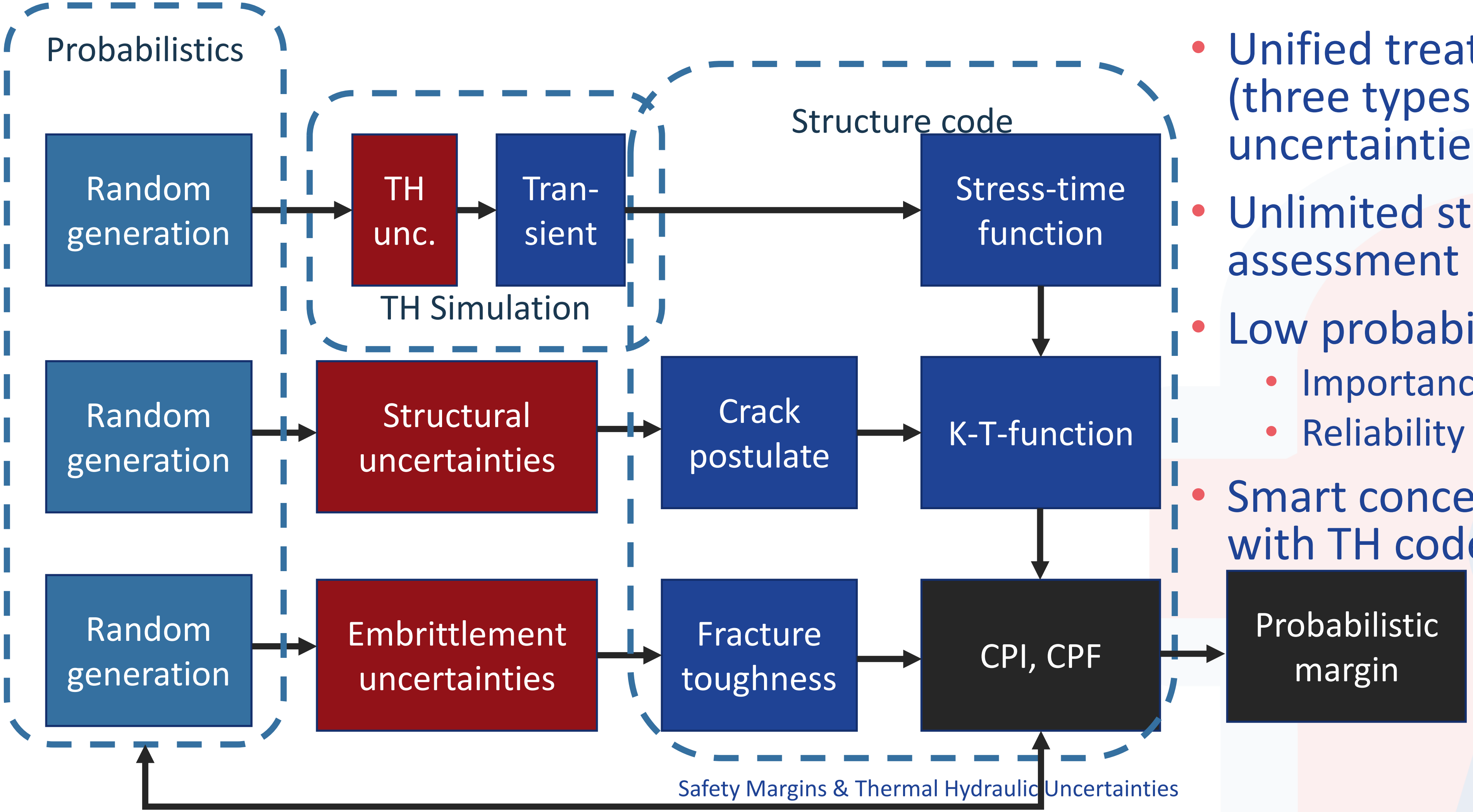


The challenge

- Why not „integrating“ THU?
- Sketch: Simplistic Monte Carlo
  - Random sampling of „structural“ parameters
  - Random selection of transient from set
  - Monte Carlo summation
- Problem:
  - The sample size N of the TH transients is limited (N between 59 and 130)
  - The targe CPI is usually much smaller than 1/N



Vision: Integrated probabilistic approach



- Unified treatment of all (three types of) uncertainties
- Unlimited strict probabilistic assessment
- Low probability:
  - Importance sampling
  - Reliability toolbox (CPI)
- Smart concepts for coupling with TH code required!

Final Summary

- Margin quantification
  1. Assessment based on maximal allowable adjusted reference temperature
  2. Assessment based on lifetime
  3. Assessment based on reliability theory
- Thermal-Hydraulic Uncertainties
  - THU propagate to broad CDF for the margins
  - This shows the need for systematic consideration of THU in PTS assessment
  - Motivation for integrated probabilistic assessment
    - „Vision“ of integration of THU
    - Requires advanced sampling / reliability techniques for low target probability