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Creep-fatigue design for power plants

3rd Workshop on AUSC Power Plant
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Rome, Italy

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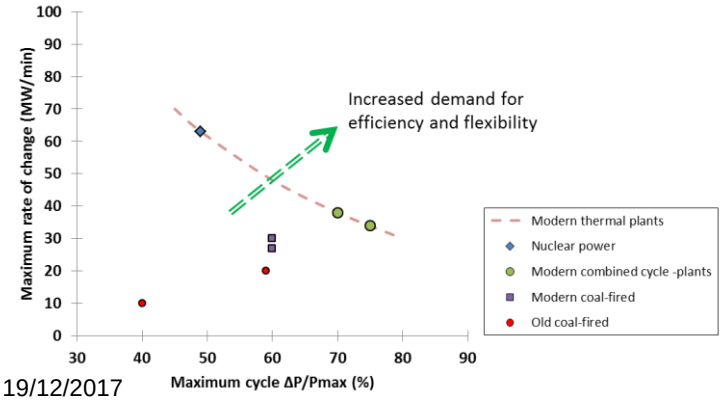
Background

- Many existing thermal power plants operating at high temperatures were designed mainly for demands set by creep load, the creep-fatigue interaction did not play significant role in design
- With the growing share of renewable (solar and wind) capacity, thermal power plants are forced to shift from relatively steady and predictable service to more fluctuating operation, to balance the variation between demand and supply.
  - ➢More cycling and ramping (thermal and stress cycles, also fast change)
  - ➢Reduced minimum loads where possible
  - ➢Creep turns more into creep-fatigue for number of components



[Timpf & Fuchs (2012), Jeschke, Henning & Schreier (2012)]

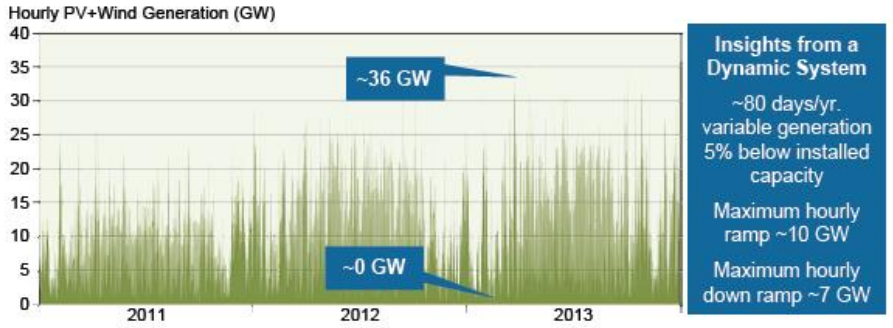


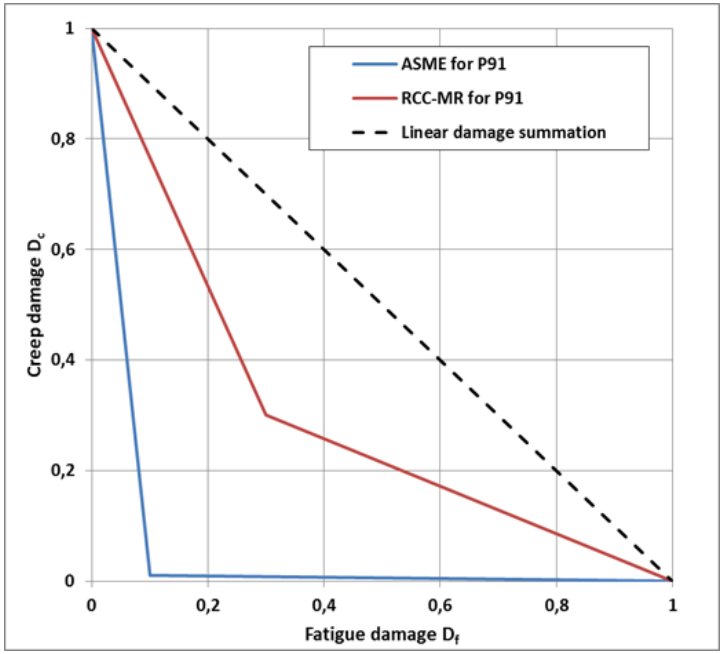
Figure 3. Hourly PV and wind generation over a three-year period in Germany shows the wide variability of the resource.
Source: Data from Klaus Kleinekorte, Amprion, German TSO.

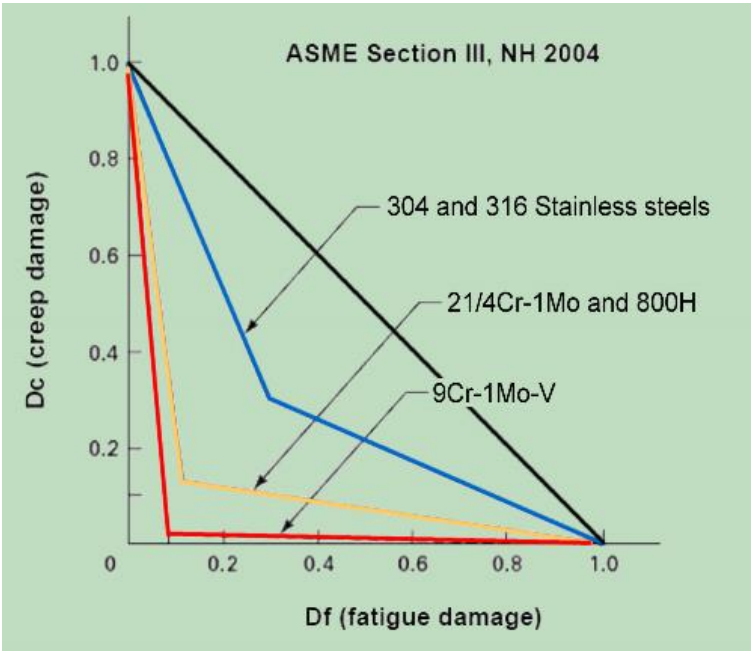
Creep-fatigue design for power plants

- Usually the design for power plant high temperature components (regarding the creep-fatigue interaction) is carried out by using the methods provided in the design codes and standards – Design by Codes approach
  - Codes for design: EN 12952-4, RCC-MRx, ASME III NH…
- Creep-fatigue assessment and prediction methods provided in design and life assessment codes usually require inputs for both creep damage and fatigue damage. Then these damage terms are combined using some form of interaction diagram to enable estimation of the creep-fatigue life.
- A consequence of these approaches is that uncertainties in creep calculations, uncertainties in fatigue calculations and uncertainties in the form of interaction all lead to significant uncertainties in the overall lifetime assessment.

Creep-fatigue in codes

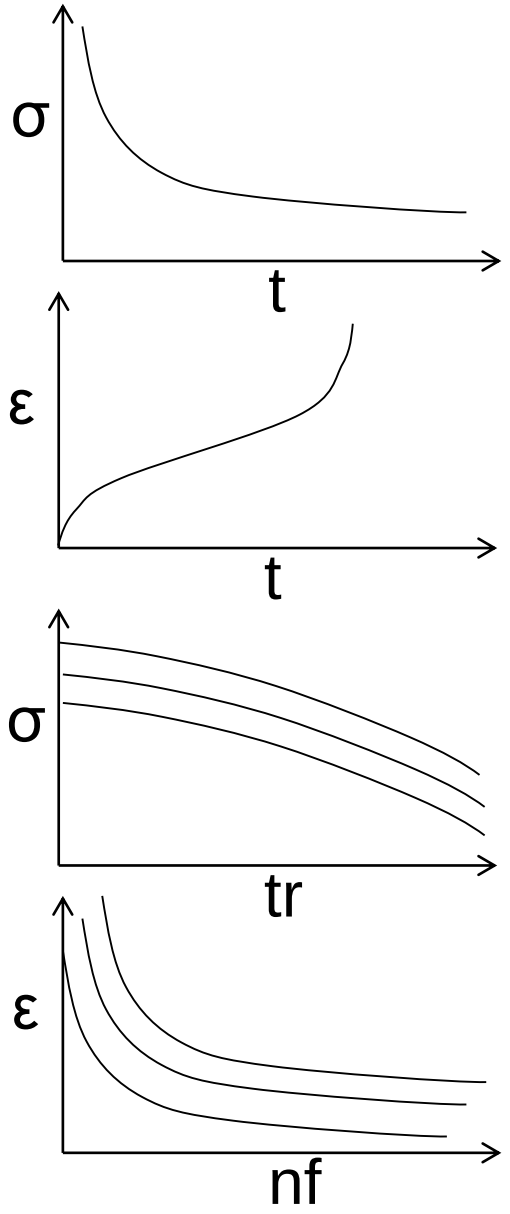
- Design and life assessment codes, such as RCC-MRx, ASME III NH and R5, provide interaction diagram based methods for creep-fatigue evaluation and prediction with different (bi-linear) interaction curves.
- Evaluation methods differ: R5 differs from RCC-MRx and ASME III NH in using a ductility exhaustion method rather than a time-fraction rule for creep damage.





Design codes: calculation procedures for creep, fatigue and relaxation

- Stress relaxation: σ = f(T,t)
- Creep strain: ε = f(σ,T,t)
- Creep to rupture: tr = f(σ,T)
- Fatigue (cycles to failure): nf = f(ε/σ,T)



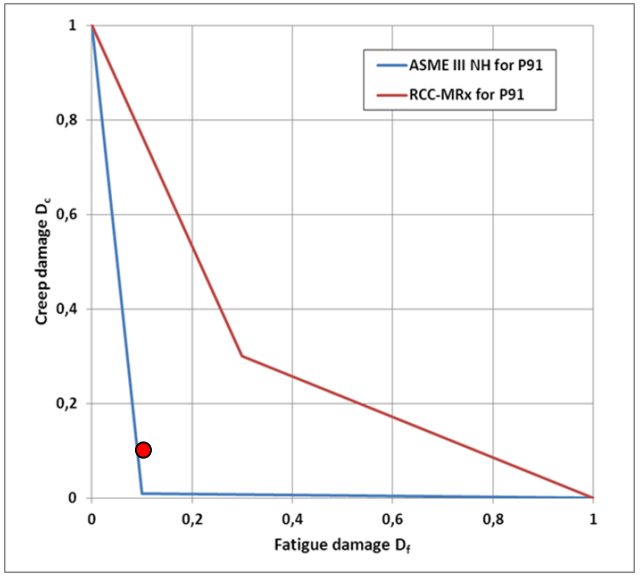
Example of design code assessment procedure

- Creep fatigue loading history:
  - Creep: σ=x1, T=y1, Creep period length 1000h, 100 creep periods (cycles)
  - Fatigue: ε=z1, T=w1(=y1) number of cycles: 100
- Creep fraction calculation
  - Code: creep to failure with σ=x1 and T=y1 is = 1000000h
  - Cumulated creep damage in our case is: Creep period length x Number of creep periods = 100000h

    -> Creep usage fraction Dc = 100000h/1000000h = 0.1
- Fatigue fraction calculation
  - Code: Allowed number of cycles with ε=z1 and T=y1 is = 1000
  - Cumulated fatigue damage in our case is: number of fatigue cycles (100)

    -> Fatigue usage fraction Df = 100/1000 = 0.1

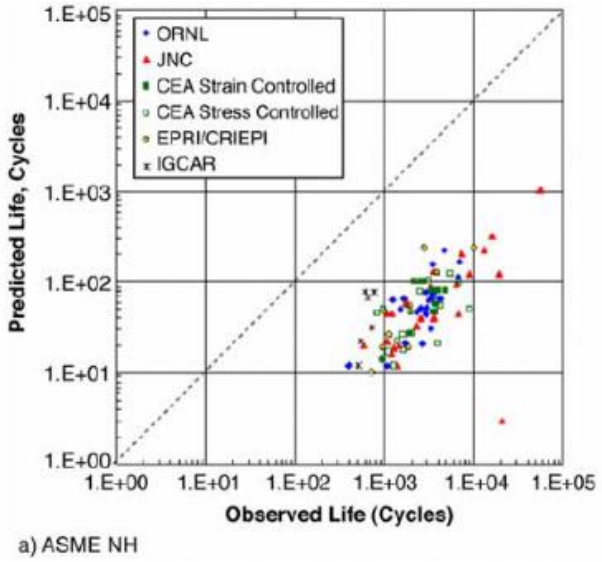
Dc , Df = 0.1 , 0.1 or,
Dc + Df = 0.2



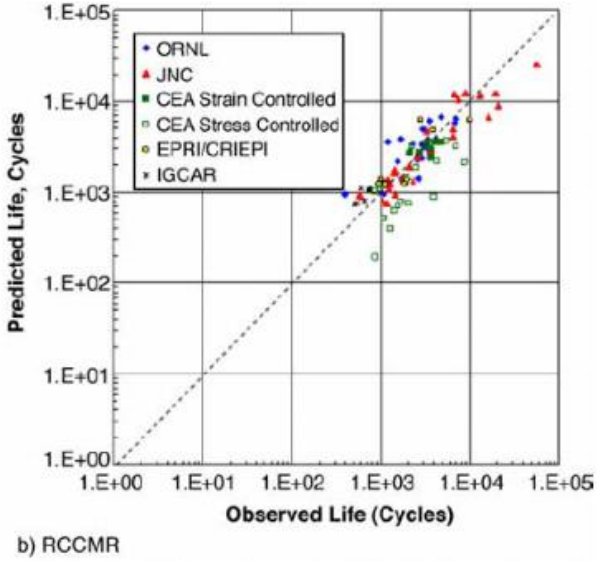
Creep-fatigue in codes

- The capability of codes to predict the creep-fatigue damage differs, depending on the method (code), material and type and parameters of loading.
  - ➢Usually codes give conservative predictions, where especially the conservatism regarding the creep fraction can be several orders of magnitude

P91 steel



a) ASME NH



b) RCCMR

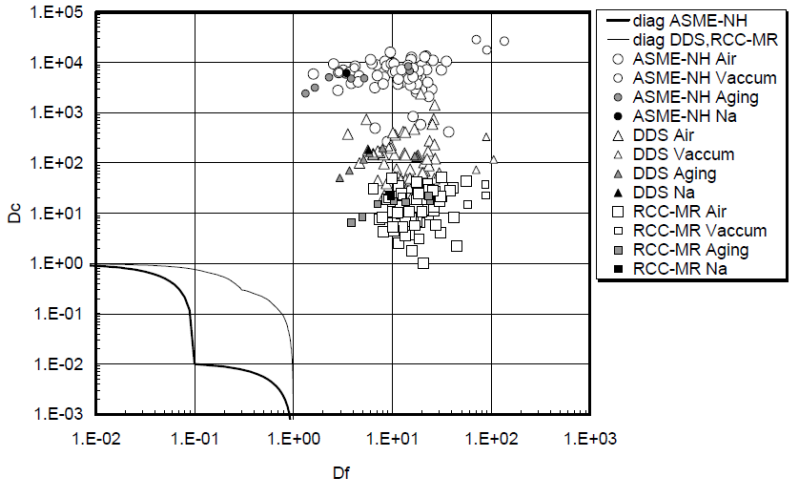


Fig. 2.4.5 Creep-fatigue evaluation of experimental data by code procedure

DOE/ASME Generation IV Materials Project

A report on Task 5 submitted to ASME ST-LLC
Revision 3 Final Report

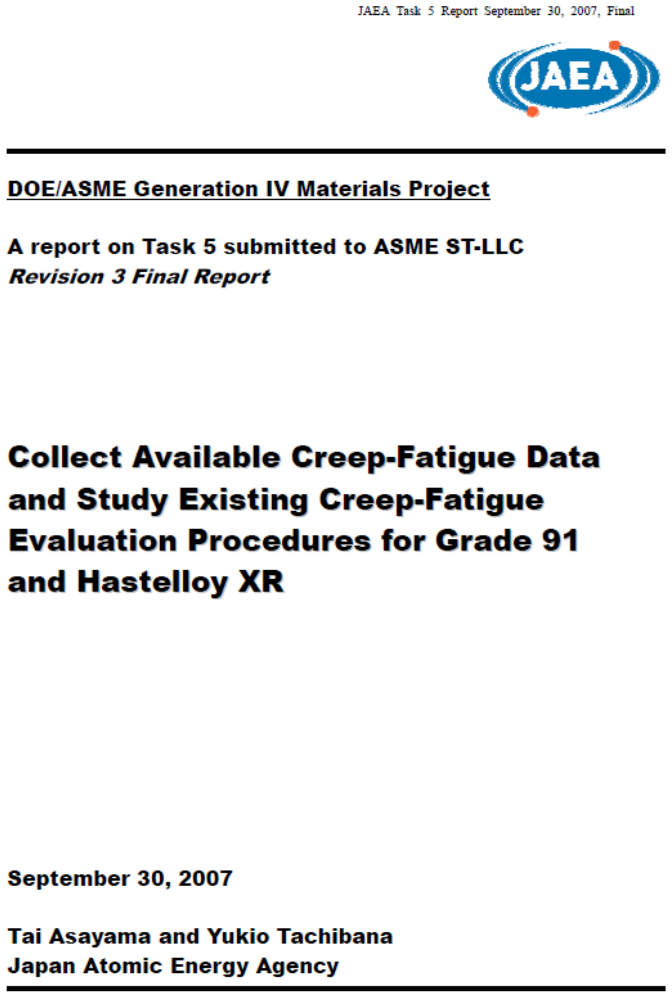
Jonathan Parker, EPRI creep–fatigue achievements in support of safe and reliable flexible operation of power plant components

Creep-fatigue design - Desing by Analysis

- More accurate and economical procedure for safe design of power plants may be achieved by Design by Analysis - approach
  - Less unnecessary safety margins
  - More efficient materials use
  - Choosing the most suitable materials for high temperature applications
- To explore the Design by Analysis option for creep-fatigue assessment the DP700 project has launched the creep-fatigue modelling round-robin in cooperation with ECCC
  - Round-robin is launched to challenge the assessment and prediction methods provided in the codes
  - Includes ~15 partners, physically based and simplified models and design code methods as a reference

First data set for the effort

- P91 data from JAEA – DOE/ASME report
  - Multi-heat data set, which includes 205 creep, 281 fatigue and 78 creep-fatigue test results



JAEA Task 5 Report September 30, 2007, Final

JAEA

DOE/ASME Generation IV Materials Project

A report on Task 5 submitted to ASME ST-LLC
Revision 3 Final Report

Collect Available Creep-Fatigue Data and Study Existing Creep-Fatigue Evaluation Procedures for Grade 91 and Hastelloy XR

September 30, 2007

Tai Asayama and Yukio Tachibana
Japan Atomic Energy Agency

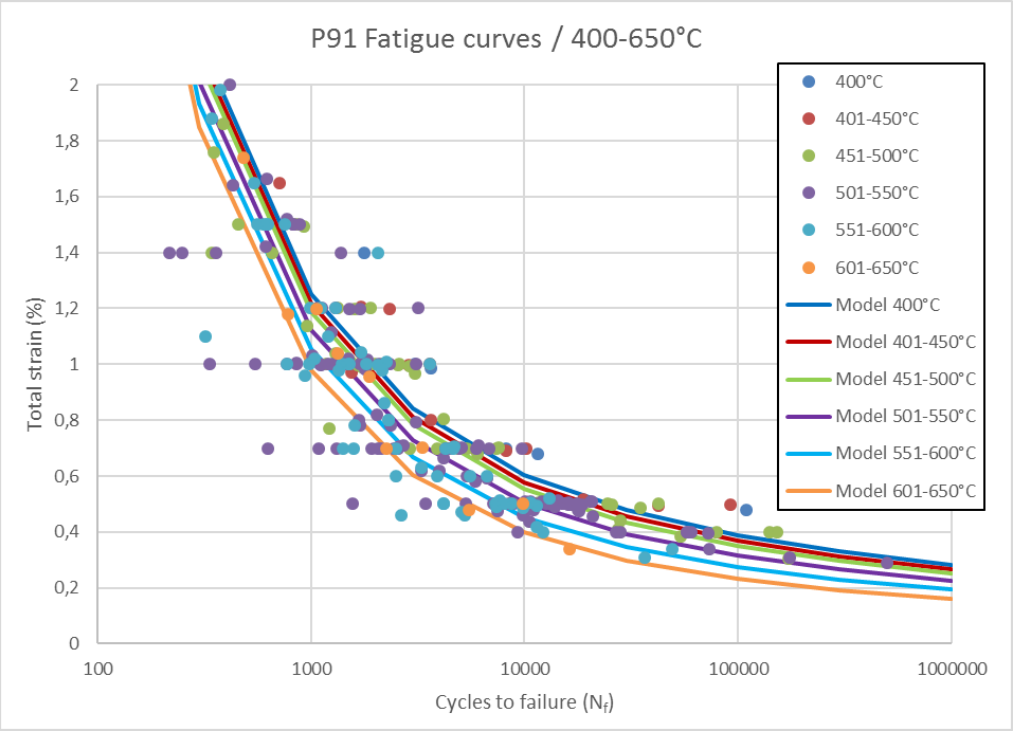
VTT's approach for round-robin

- Manson-Halford model for creep-fatigue: The main element of this model is the assumption that there exists a relationship between an "effective time" spent in (pure) creep and the amount of cycles that the material can withstand under the varying stress conditions during the cycling
- The model utilizes fatigue and creep models
  - The parameters A and m are derived from power law creep equations
  - The parameter b is obtained by extracting the elastic exponent of the Manson-Coffin equation
  - The parameter k is temperature dependent material constant which is also expected to be dependent on the type of control (strain or stress)

$$N_{CF} = \frac{N_f}{1 + \frac{k}{\frac{A}{t_h} \cdot (N_f)^{\frac{m-b}{m}}}}$$

Fatigue

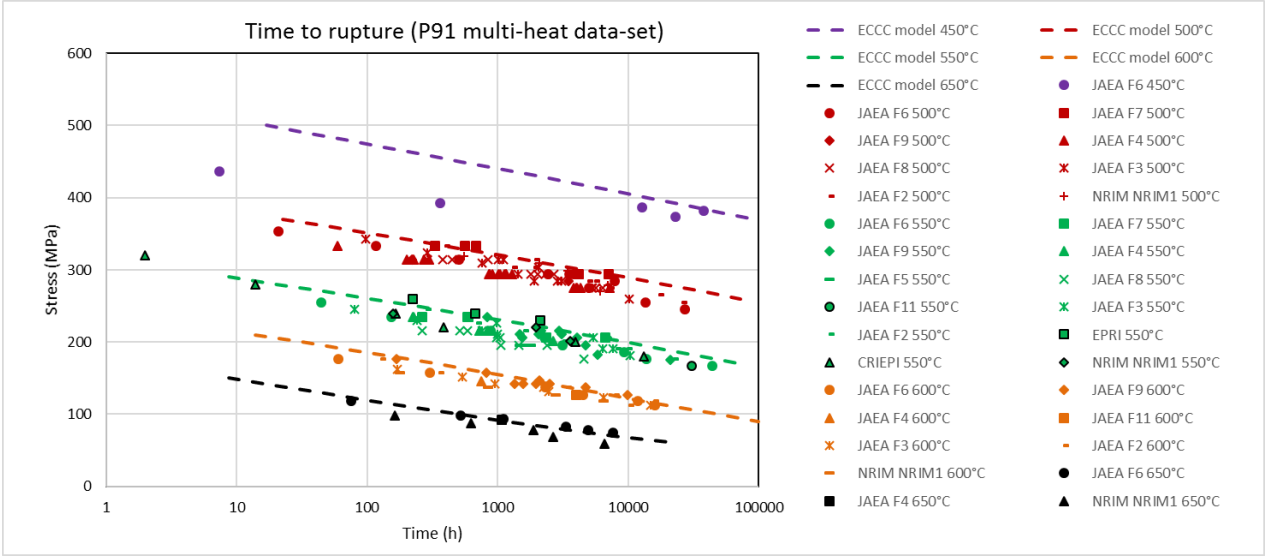
- Assessment of fatigue data to obtain fatigue model
- Fatigue model by Manson: $\Delta\varepsilon_t = \Delta\varepsilon_{el} + \Delta\varepsilon_p = S \cdot \frac{\sigma_{UTS}}{E} \cdot N_f^b + D^{-c} \cdot N_f^c$



Creep

- Assessment of creep data to obtain creep model
- Power-law dependence for creep has been calibrated to equal the Manson-Haferd model, (for which the parameters are provided in *ECCC, Annex R, Coefficients for creep-rupture model equations for extrapolation of creep-rupture strength*)

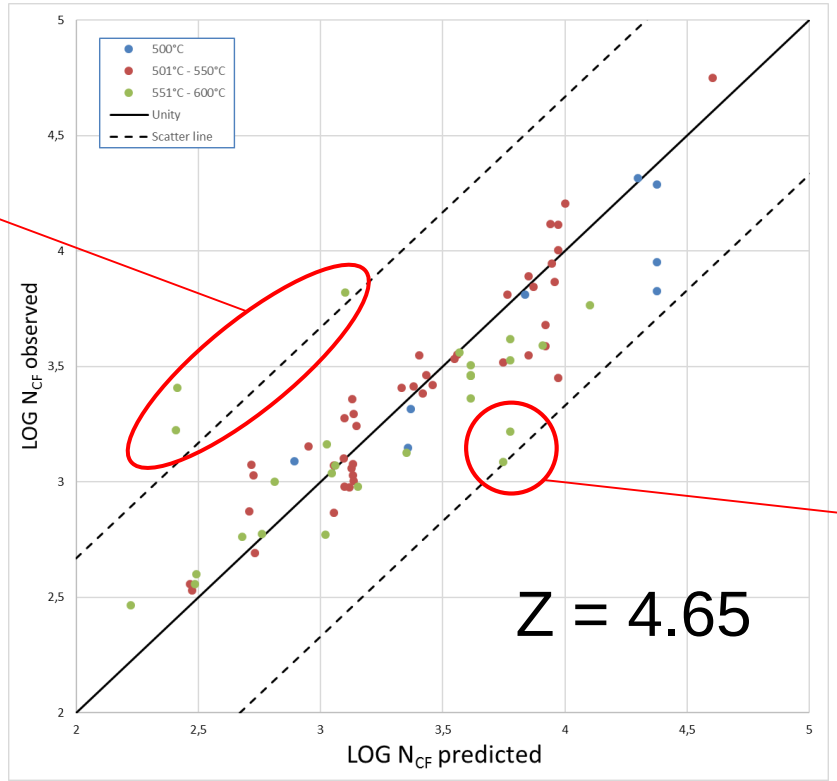
$$f(\sigma) = \beta_0 + \beta_1.\log(\sigma) + \beta_2.\log(\sigma)^2 + \beta_3.\log(\sigma)^3 + \beta_4.\log(\sigma)^4 \Rightarrow \log(t_u^*) = f(\sigma).(T - T_o) + \beta_5 = t_r = A \cdot \Phi^{1/m}$$



Creep-fatigue

- Number of cycles to failure (measured vs predicted, LOG values)
- Multiple heats, 78 results, T = 500-600°C, $\Delta\varepsilon$ = 0,345-2,02%, t_h = 0,017-10h
- The scatter factor Z indicates the value with which the result should be multiplied or divided by in order to lie inside the scatter bands (Standard deviation * 2.5) with 98.75% confidence.

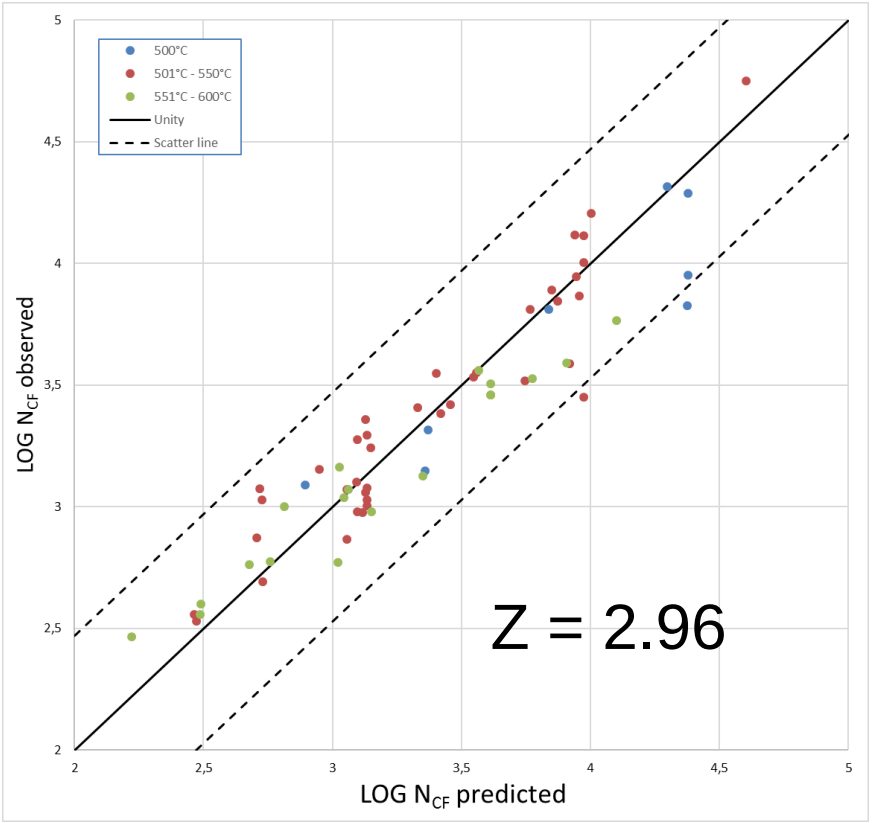
Specimens tested in vacuum



Aged specimens

Creep-fatigue

- The data set without aged specimens and those tested in vacuum

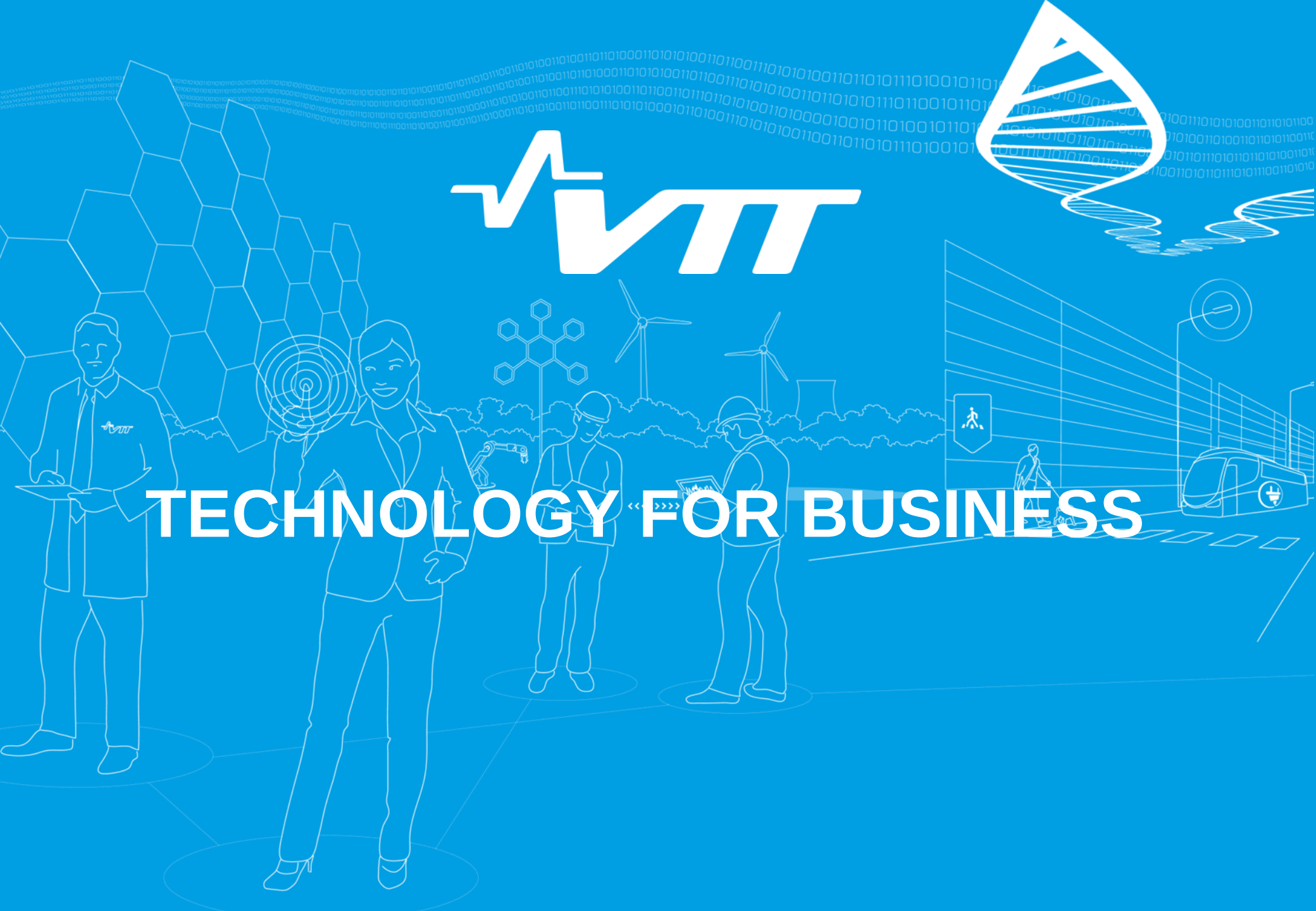


Observations

- The MH CF modelling approach does not take the microstructural or environmental effects into account
- The creep model seems to overestimate the creep to rupture performance of P91 in relation to this data set
- Large scatter was observed in the fatigue data. Mainly tests with slow strain rate exhibited short cyclic lifes.

Next steps

- Collecting modelling results from other partners and comparison of the model performance
- Extending the round-robin for austenitic steels and nickel alloys
- Challenging the most promising models with tailored tests, which simulate better the service-like conditions than “conventional” creep-fatigue tests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