Joint Research Centre

the European Commission's in-house science service

Serving society
Stimulating innovation
Supporting legislation

Advances in high temperature property determination for Gen-IV materials

Stefan Holmström

November 2015

European Commission

Background

Commercially available steels (like 316L, 316L(N) and P91) have to be used for the near future ESNII GenIV reactors.

Challenge:

The service temperatures/loads for the ESNII Gen-IV test reactors are mainly in the low temperature and low stress regime where creep properties are rarely generated

- **Industrial main interest lies in the high temperature / high stress regime**

Objectives:

Design for creep can be avoided by service temperature / time below negligible creep temperature (T_{NEC}) …

Simpler methodologies to determine Creep-Fatigue life with and without the interaction diagram …

- **Improved methodologies for creep-fatigue interaction,**
- **Impact of softening on relaxation behaviour**
- **Relaxation extrapolation**

European Commission

Supporting Projects

EU project MATTER

- Properties for P91 steel, 3 heats (MATTER, DEMETRA, INTEGRITY)
- Defining low stress/low temperature creep strain rates
- Definition of T_{NEC} + new methodology (based on Wilshire Eq.)
  - Spin-off: curves for EN-13445 (unfired pressure vessels)
- Simplified CF models compared to SOTA models (Interaction Diagram)

EU project MATISSE

- models for cyclic-softening and impact on CF damage (P91)
- models for creep-fatigue crack propagation

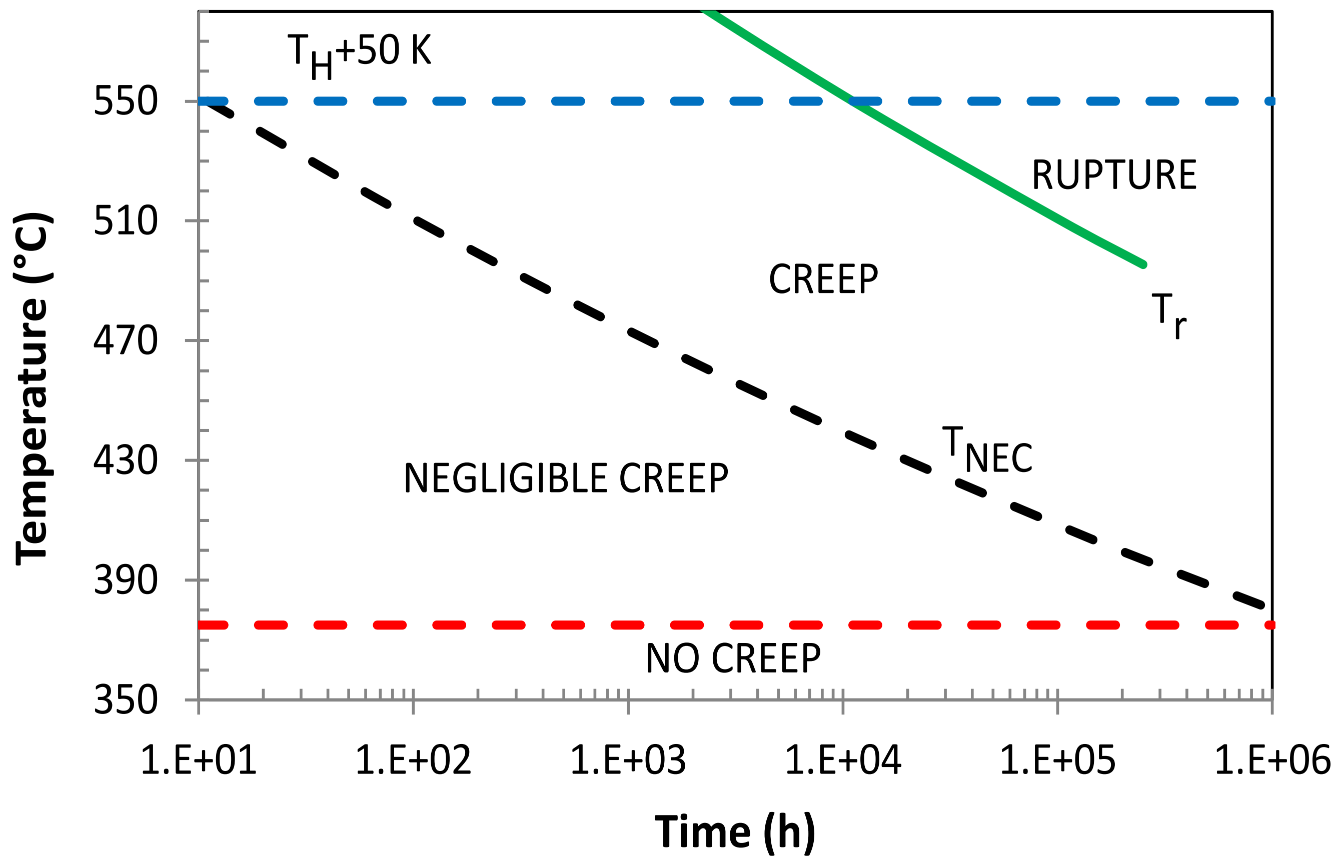
JRC internal projects MaCoSYMA & PreMaQ

- Standardization and support for CEN/TC54-WG59
- Development of a standard for Small Punch Testing

EERA-JPNM Pilot Project TASTE

- Test methods for determining material properties for thin walled tubes (fuel claddings)

T_{NEC} curve (definition for EN-13445 revision)



MATTER: Grade 91, RCC-MRx reference stress $0.56 \cdot R_m$ $(1.5 \cdot 1/2.7 \cdot R_m)$
EN-13445 revision, reference stress $2/3 \cdot R_{p02}$

European Commission

EN-13445:2 steels
(curves suggested to WG59 creep for review)

Steel name	T_{min} (°C)	T_{max} (°C)	σ_{min} (MPa)	σ_{max} (MPa)	t_{min} (kh)	t_{max} (kh)	1% data (Yes/No)
P235GH	380	480	33	229	10	250	Yes
P265GH	380	480	33	229	10	250	Yes
P295GH	380	500	30	291	10	250	Yes
P355GH	380	500	30	291	10	250	Yes
16Mo3	450	530	45	298	10	250	Yes
18MnMo4-5	425	525	69	421	10	100	Yes
20MnMoNi4-5	450	490	194	290	10	100	No
15NiCuMoNb5-6-4	400	500	69	385	10	100	Yes
13CrMo4-5	450	570	26	285	10	250	Yes
13CrMoSi5-5	450	570	31	313	100	100	No
10CrMo9-10	450	600	28	306	10	250	Yes
12CrMo9-10	400	520	107	355	10	100	No
X12CrMo5	475	600	27	147	10	10	Yes
13CrMoV9-10	400	550	108	430	10	100	No
12CrMoV12-10	400	550	108	414	10	100	No
X10CrMoVNb9-1	500	670	35	289	10	250	No

= PROPOSED Probationary Phase (SECT III, Tome 6)

= POTENTIAL Technical Appendix SECT III, Tome 1

European Commission

EN-13445:7 creep resistant steels ongoing assessment work for CEN/TC54-WG59

ECISS grade		Number	AISI	ECCC data	EN-	
X3CrNiMoBN17-13-3		1.4910	316LNB	yes	EN-10028-7	
X6CrNiTiB17-10		1.4941	321H	yes	EN-10028-7	
X6CrNi18-10		1.4948	304H	yes	EN-10028-7	
X6CrNi23-13		1.4950	Type 347	yes	EN-10028-7	
X6CrNi25-20		1.4951	Type 310S	No	EN-10028-7	
X6NiCrAlTi31-20 (+RA)		1.4958	Alloy 800	yes	EN-10028-7	
X8NiCrAlTi32-21		1.4959	Alloy 800H	yes	EN-10028-7	
X8CrNiNb16-3		1.4961	16-13Nb	yes	EN-10028-7	

Challenges remain in defining the appropriate reference stress / rupture time correction factor

RCC-MRx
T_{NEC} curves exists for: 316L and 316L(N)

Methodology using Wilshire equation

$$\frac{\sigma_{u/t/T}}{R_m} = \exp\left[-k\left(t_r \cdot \exp\left(\frac{-Q}{R \cdot T}\right)\right)^u\right] \quad \text{or} \quad \frac{\sigma_{u/t/T}}{A \cdot R_{p02}} = \exp\left[-k\left(t_r \cdot \exp\left(\frac{-Q}{R \cdot T}\right)\right)^u\right]$$

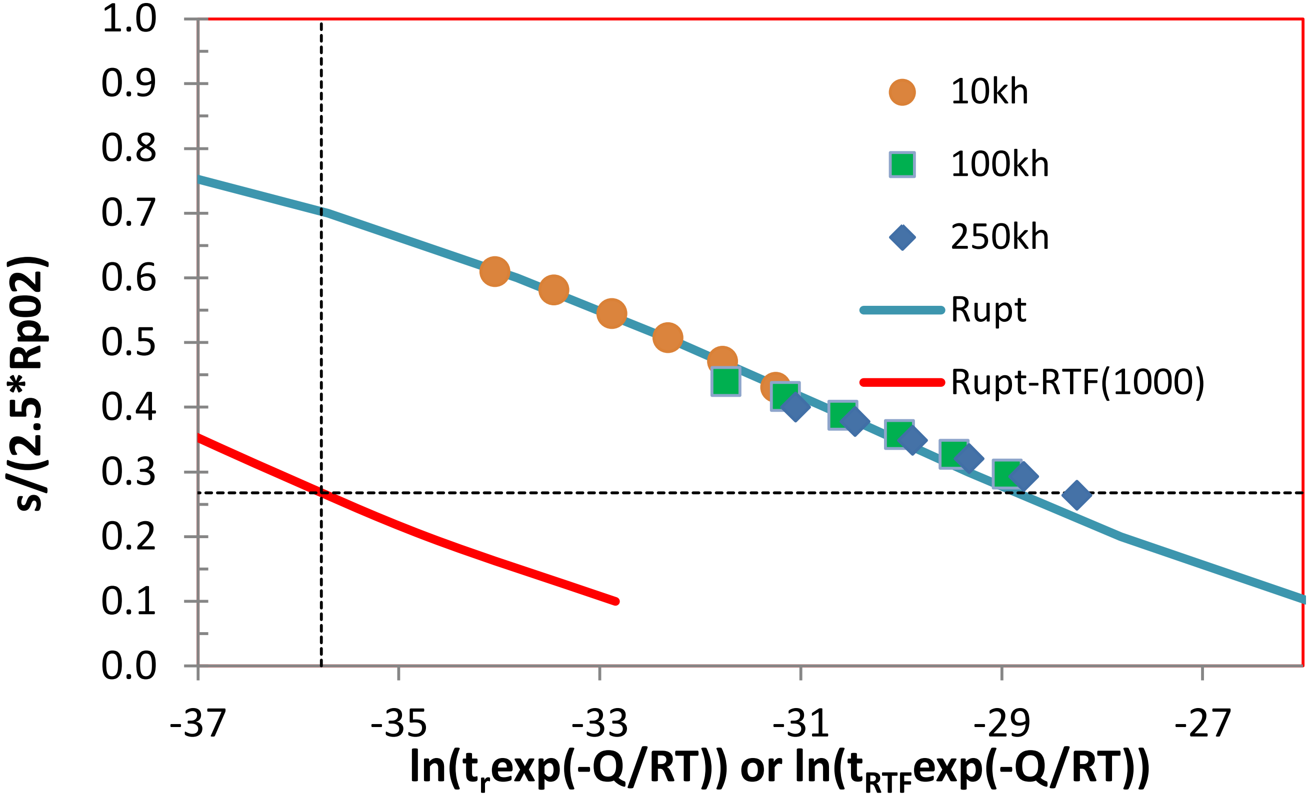
$$t_{NEC} = t_{\varepsilon\%} \quad \text{or} \quad t_{NEC} = \frac{t_r}{RTF}$$

$$T_{NEC} = \frac{Q}{R \cdot \ln\left(t_{NEC} \cdot \left[-\frac{1}{k}\ln\left(\frac{2}{3 \cdot A}\right)\right]^{-\frac{1}{u}}\right)}$$

In MATTER **t_{NEC} was based on time to 0.2% creep strain**

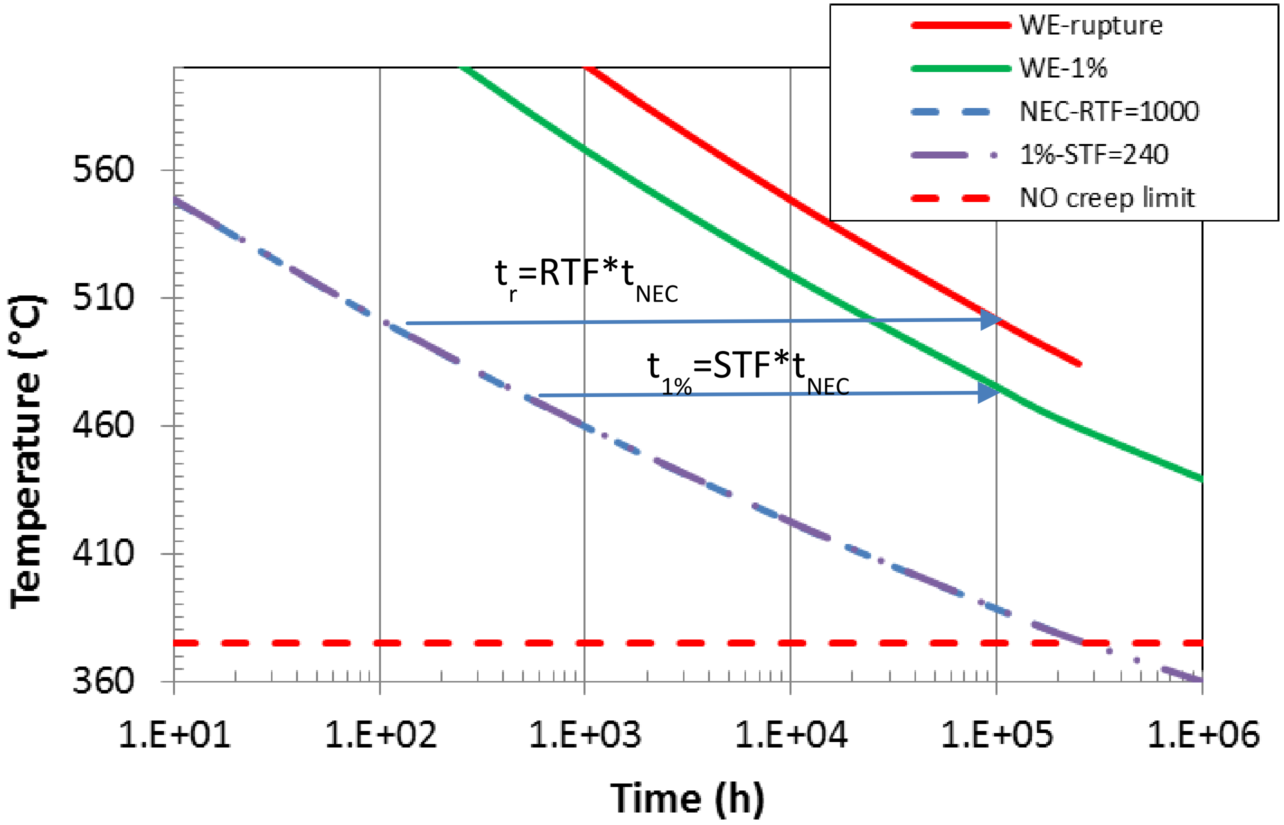
Creep strength tables EN10028:2,7 for $\sigma_{u/t/T}$

Example: 10CrMo910 (P22)



The reference stress (2/3 R_{p02}), equal to allowable stress, is the horizontal line at 0.27 normalized stress and the cross hairs on the RTF corrected rupture curve defines the location where the T_{NEC} curve is calculated

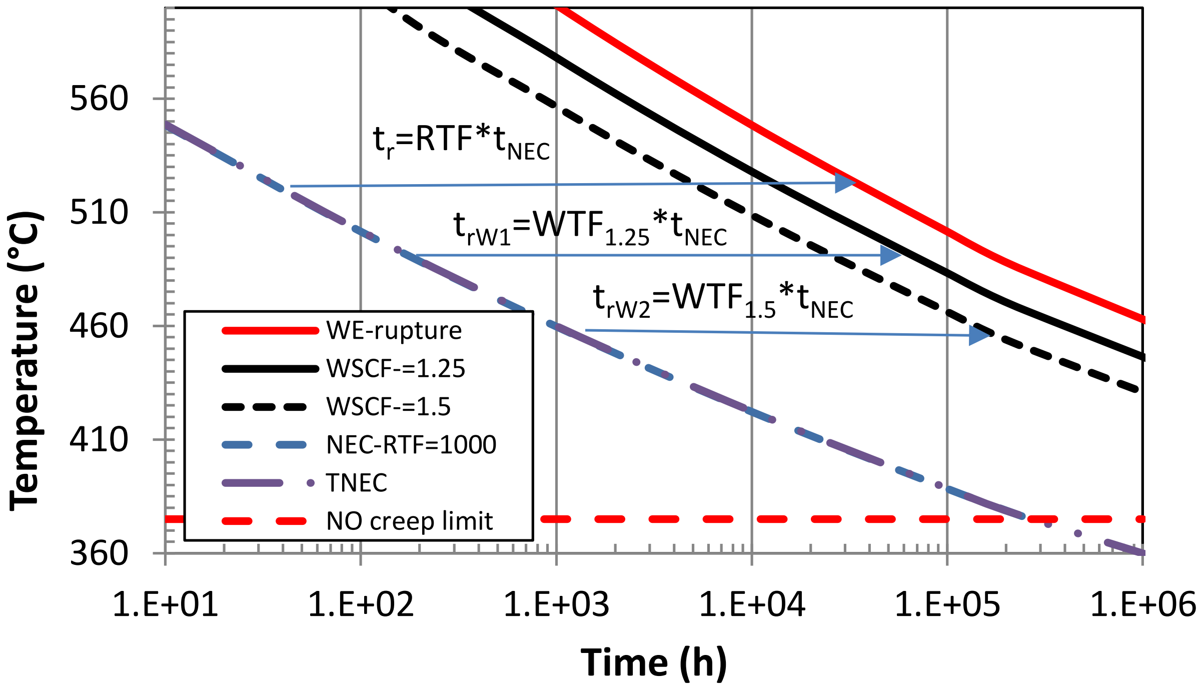
Time factors, Rupture and Strain (1%)



Assessing the safety margin between the t_{NEC} and the time to 1% creep strain $t_{1\%}$ for steel 10CrMo910.
*RTF=1000 and STF=240

***RTF=1000 from MATTER / time to reach 0.2% strain for P91 (T=375-550°C)**

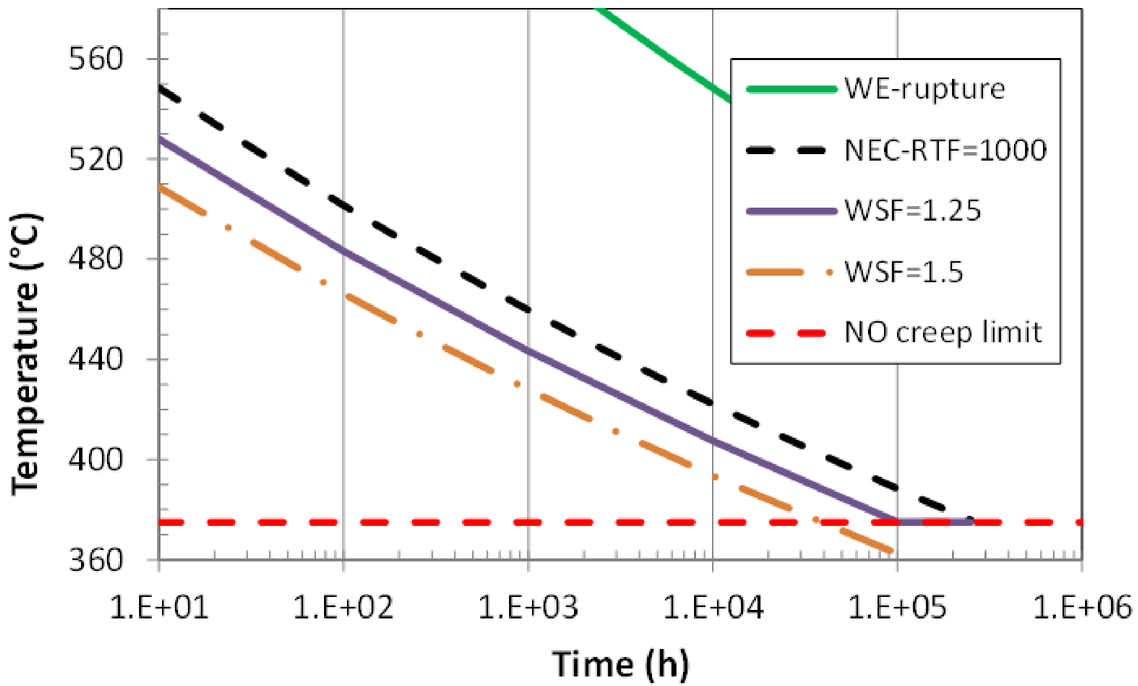
Time factors, weld strength reduction by 1.25 and 1.5



Assessing the safety margin between the T_{NEC} curve and the corrected reduced rupture times with WCSRF=1.25 and 1.5 for steel 10CrMo910 steel.

The $WTF_{1.25}$ = 377, $WTF_{1.5}$ = 143, RTF=1000

Inversely T_{NEC} curves for welds using strength reduction by 1.25 and 1.5



"The same procedure defined for base materials applies with the following modification: if the values of are different from those of the base materials, these values are to be multiplied by the relevant Weld Creep Strength Reduction Factor defined in 19.6."

European Commission

Pending work for NEC

T_{NEC} calculations for all creep resistant steels of EN10028-7 (for TC54/WG59)

- $\sigma_{ref}=2/3\cdot R_{p1\%}$ or $\sigma_{ref}=1/3\cdot R_m$ (1% proof or UTS)
- $T_{NC}=425°C$
- Additional curves for 316L and 316 L(N) using ECCC creep data sheets

EN-10028:7 steels

X3CrNiMoBN17-13-3 (316-LNB) and X6CrNi18-10 (304H)

can be compared to

RCC-MRx T_{NEC} curves for

X2CrNiMo17-12-2 (316L), X6CrNi18-10 (304H) and X2CrNiMo17-12-2(N) (316L(N))

Sect.III, Tome1, Z, Appendix A3-1S,2S and 3S

X3CrNiMoBN17-13-3
X6CrNiTiB18-10
X6CrNi18-10
X6CrNi23-13
X6CrNi25-20
X5NiCrAlTi31-20 (+RA)
X8NiCrAlTi32-21
X8CrNiNb16-13

European Commission

Predicting Creep-Fatigue life

In **MATTER** the P91 CF endurance (cycles to failure) was predicted by 3 methods

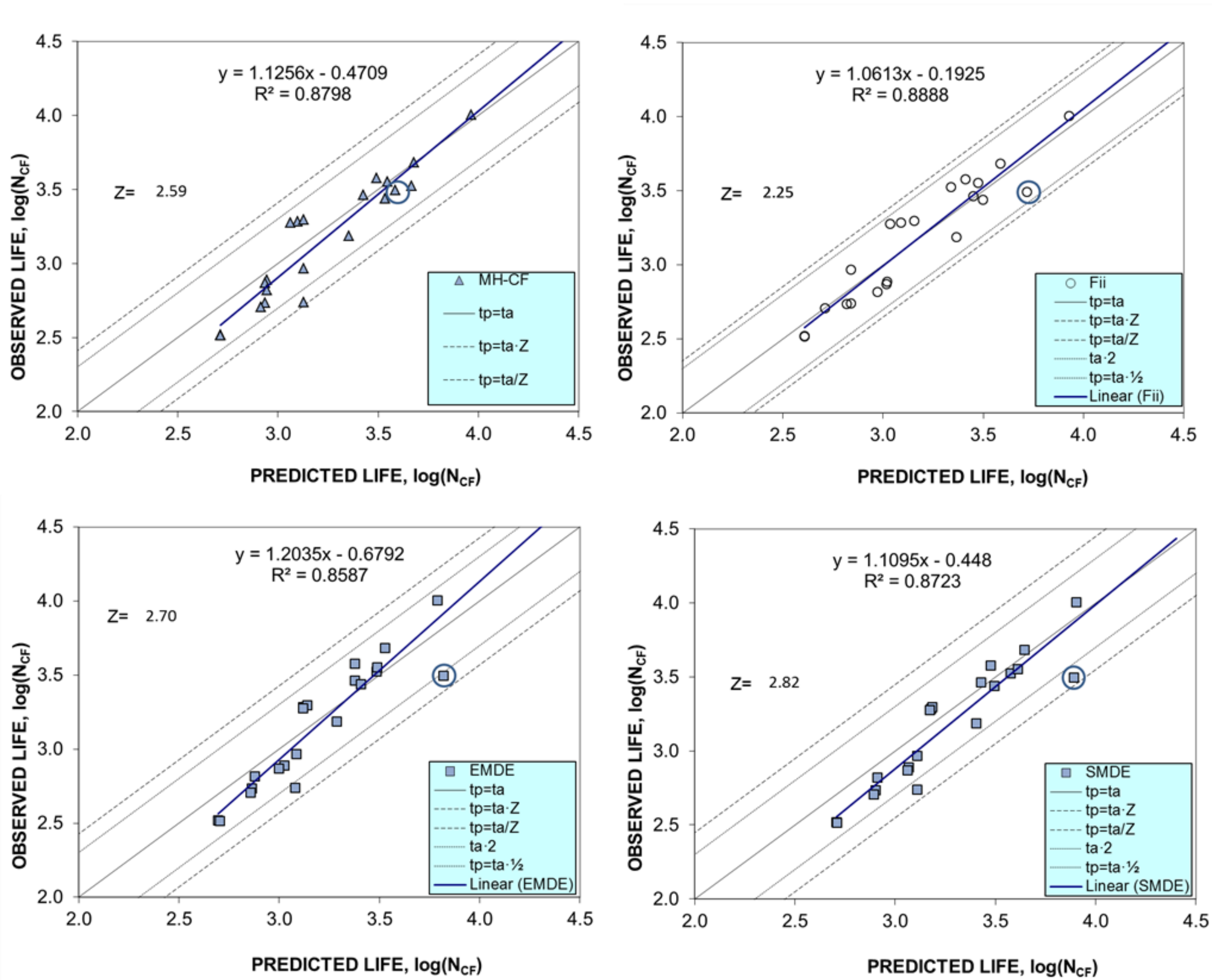
1. CF interaction diagram (RCC-MRx , R5 or ASME III-NH) with creep damage from the relaxation (life fraction or ductility exhaustion)
2. Simple LCF models with correction for creep strain accumulation, i.e increased total strain range $\Delta\varepsilon$ by relaxed strain or forward creep strain (at $N_{f/2}$)
3. Simplified models based on **reference stress** and hold time t_h, softening/hardening or strain range corrections not nesessary

- The simplified models were the most robust/accurate and showed potential for design rule application ...

Examples of model predictions (P91 CF data set)

Simplified CF models (Manson-Halford and Φ-model) vs EMDE and SMDE

(JRC, VTT, ANSTO paper*)



$$N_{CF} = \frac{t_{CF}(\Phi_{CF})}{t_h}$$

$$\Phi_{CF} = \exp\left\{-k\left[t_{CF}\cdot\exp\left(-\frac{Q_c^*}{RT}\right)\right]^u\right\}$$

$$\Phi_{CF}(\Delta\varepsilon, t_h, T) = A_1 + \frac{A_2}{\Delta\varepsilon} + A_3\cdot\log(t_h) + A_4\cdot T$$

$$N_{MH}(t_h) = \frac{N_{f0}}{1+\dfrac{k}{\dfrac{A}{t_h}\cdot\left(N_{f0}\right)^{\frac{m+b}{m}}}}$$

EMDE =Energy Modified Ductility Exhaustion
SMDE=Stress Mod. DE

The calculated Z values for the different models applied on the same data set (strain controlled tests and 550°C). The test with the longest hold time is encircled.

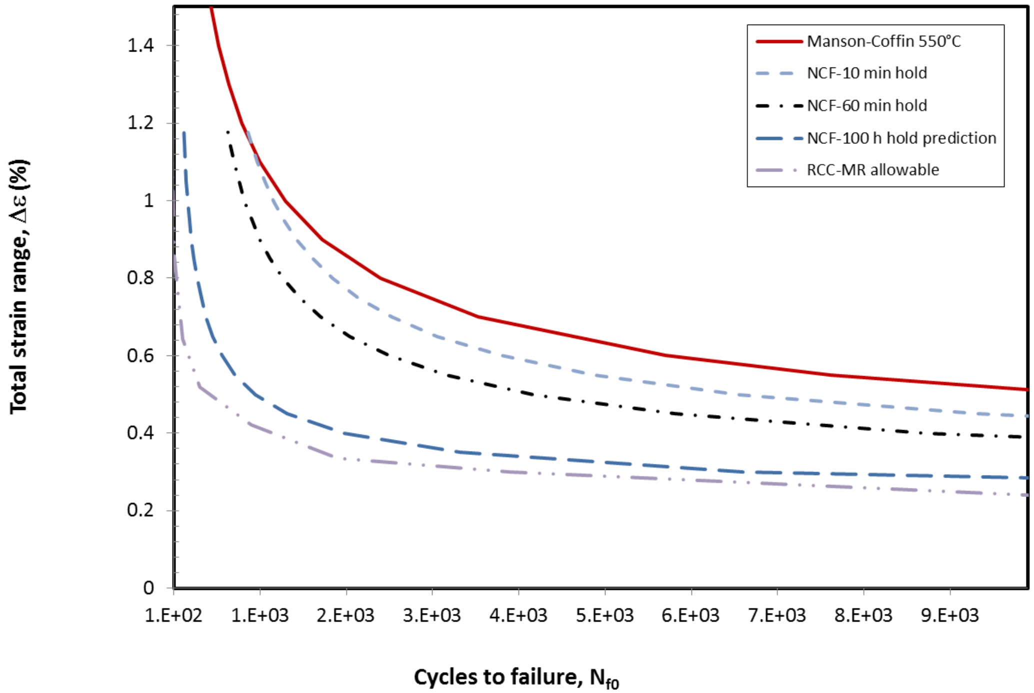
***Holmstrom S., Pohja R., Payten W., Creep-Fatigue Interaction Models for Grade 91 Steel ASTM, Materials Performance and Characterization, DOI: 10.1520/MPC20130054,**

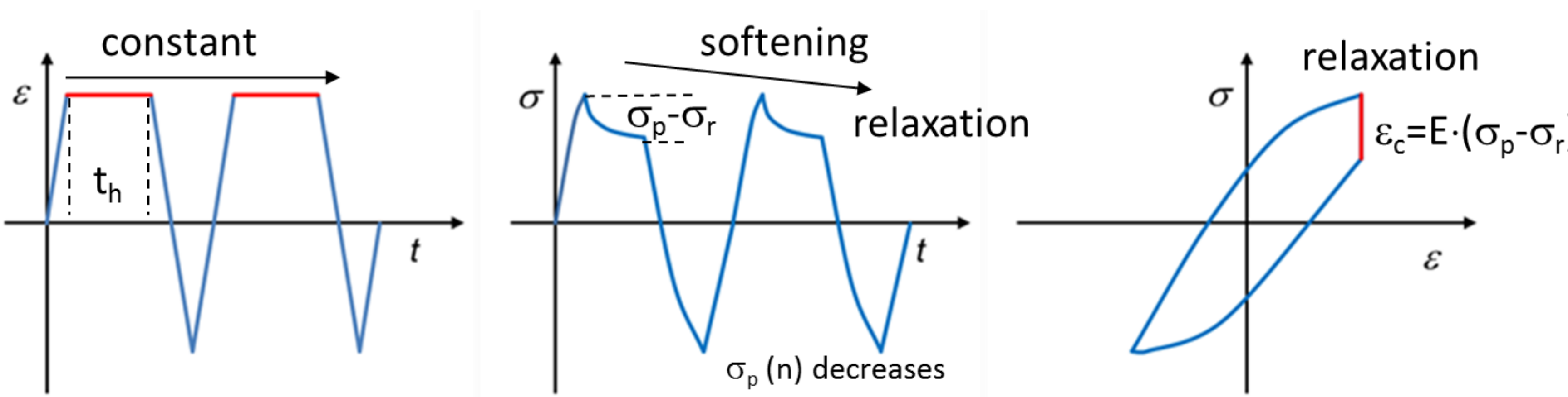
Benefits of using "Simplified" models

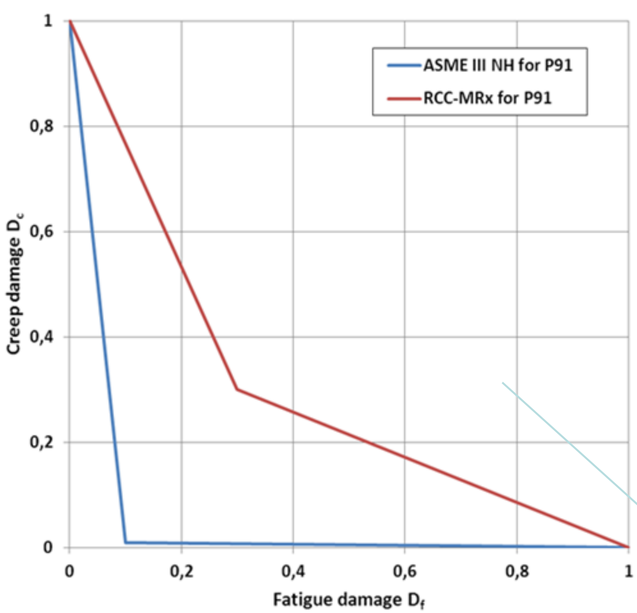
- few fitting parameters needed
  - **many of them are acquired from standard creep and tensile tests**
- For the Φ model no forced "anchoring" to LCF (N_{f0}), based on creep, fitted to CF
- For MH_{CF} there is the anchoring to LCF (N_{f0}), based on LCF, creep is a correction
- The interpolation and extrapolation with the simplified models have shown robustness and applicability over the whole range of available data

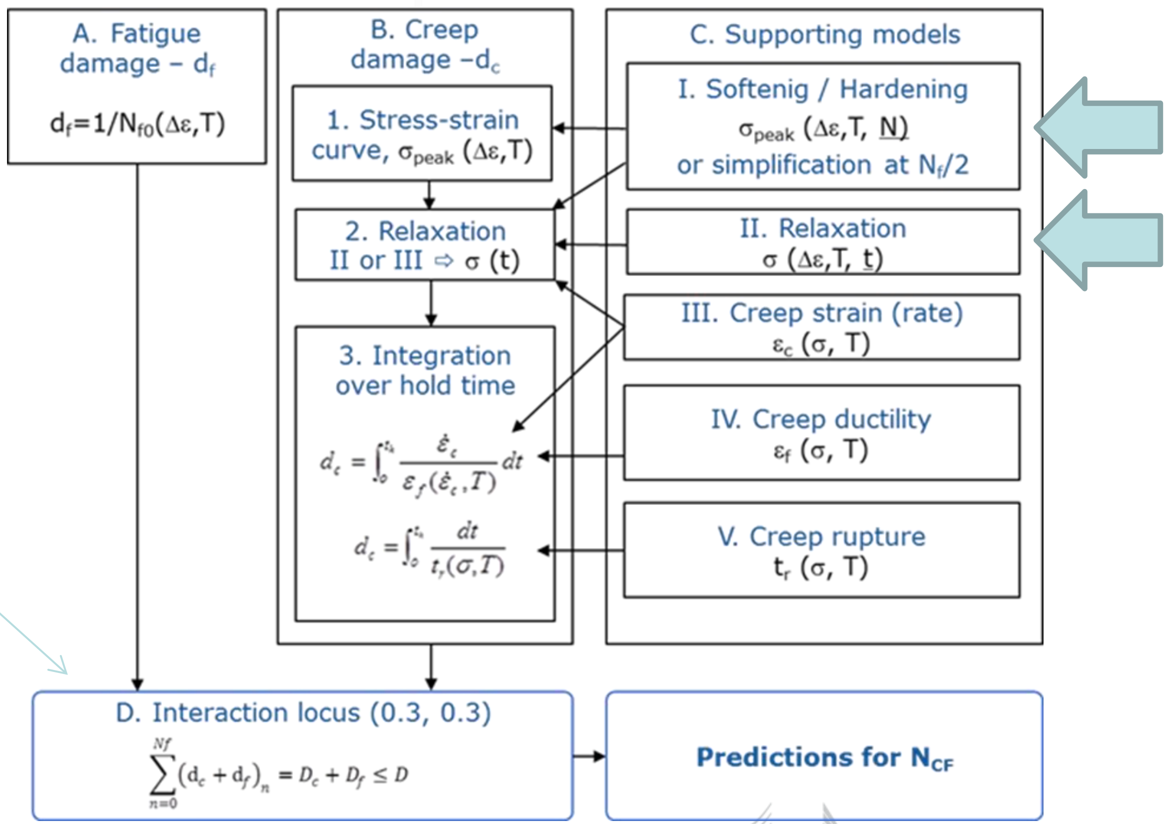
– SIMPLE

– ROBUST





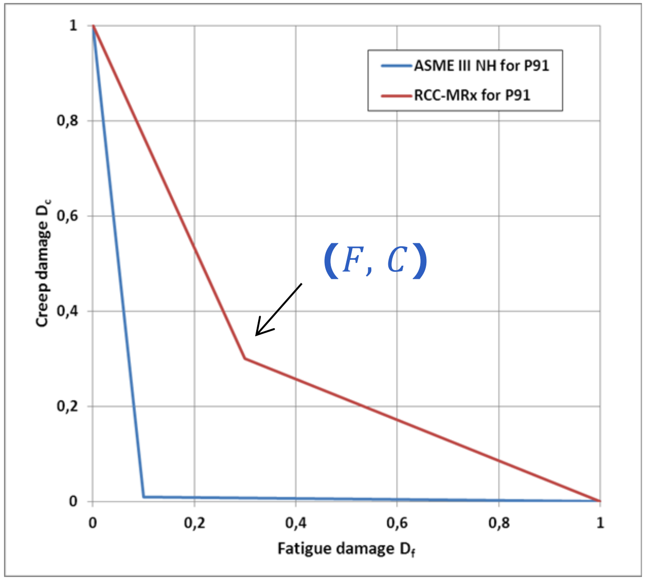




European Commission

The interaction diagram – time fraction approach (RCC-MRx and ASME III-NH)

- **Unity for creep fraction ($D_c=\Sigma t/t_r$) is the time to rupture at specified stress and temperature**
- **Unity for fatigue fraction ($D_f = \Sigma d_c$) is cycles to failure (LCF) at defined temperature and strain range.**
- **For design the allowable combined creep and fatigue damage for P91 steel is (0.3, 0.3) interaction locus.**
- **Allowable number of cycles (N_f) can be defined (for design) or number of cycles can be predicted (in test result evaluation) with following equations:**



$$N_{CF} = \frac{F}{(1-C)d_f + F d_c} \quad \text{if} \quad \frac{d_f}{d_c} < \frac{F}{C}$$

$$N_{CF} = \frac{C}{(1-F)d_c + C d_f} \quad \text{if} \quad \frac{d_f}{d_c} \geq \frac{F}{C}$$

where d_c is the creep component of a single cycle (in most cases represented by the $N_f/2$ cycle creep responce) and d_f is the fatigue component of a single cycle ($1/N_{f0}$).

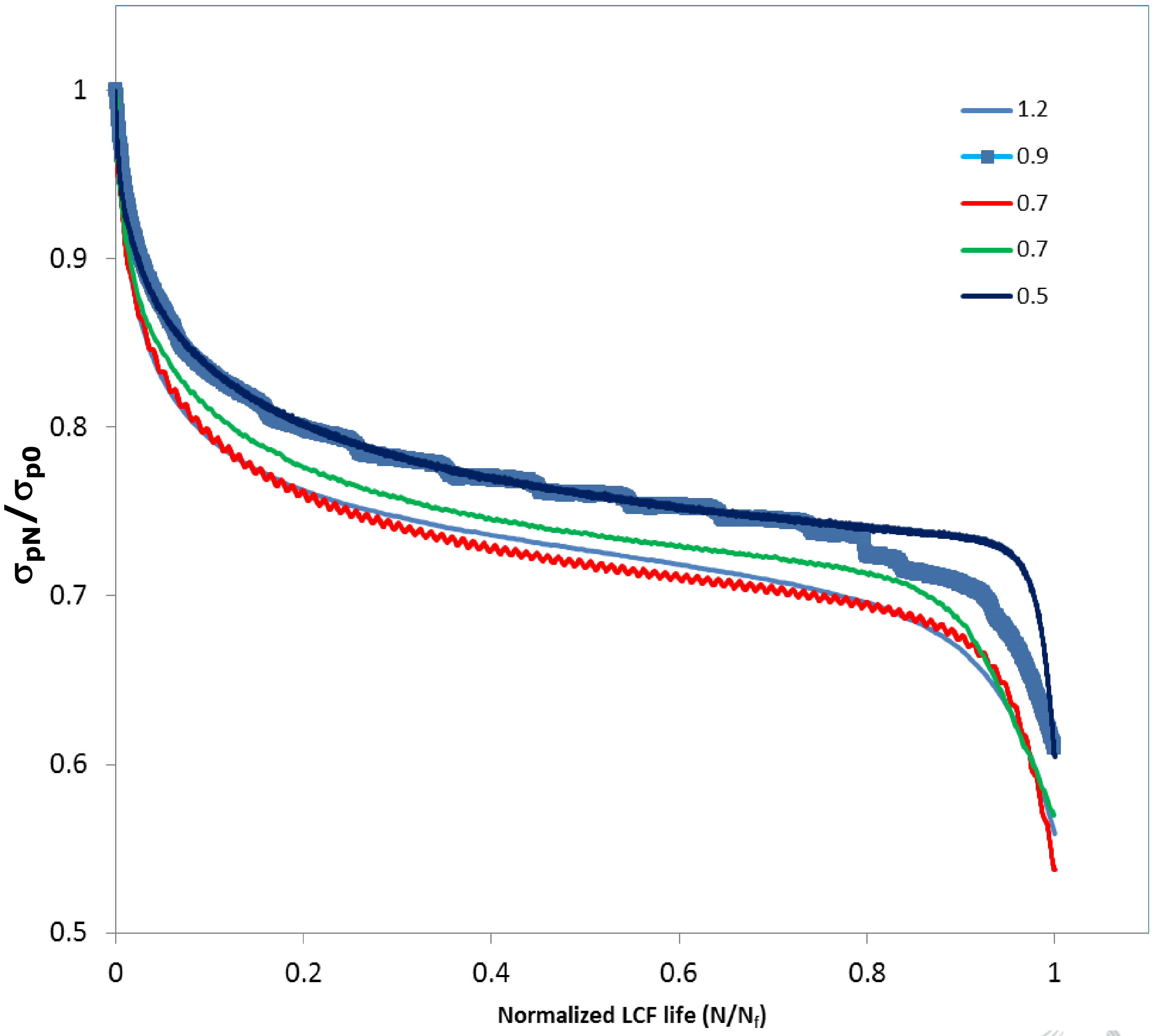
Initial (simple) softening model

- LCF softening curves as a function of normalized peak stress (σ_{pN}/σ_{p0}) and cycles to failure (N_f at 25% of drop in stress) are assessed:
- σ_{p0} is the tensile peak stress (virgin material) in the first cycle
- σ_{pN} is the tensile peak stress at cycle N

The normalized cyclic peak stress curves fall "nearly" on top of each other …

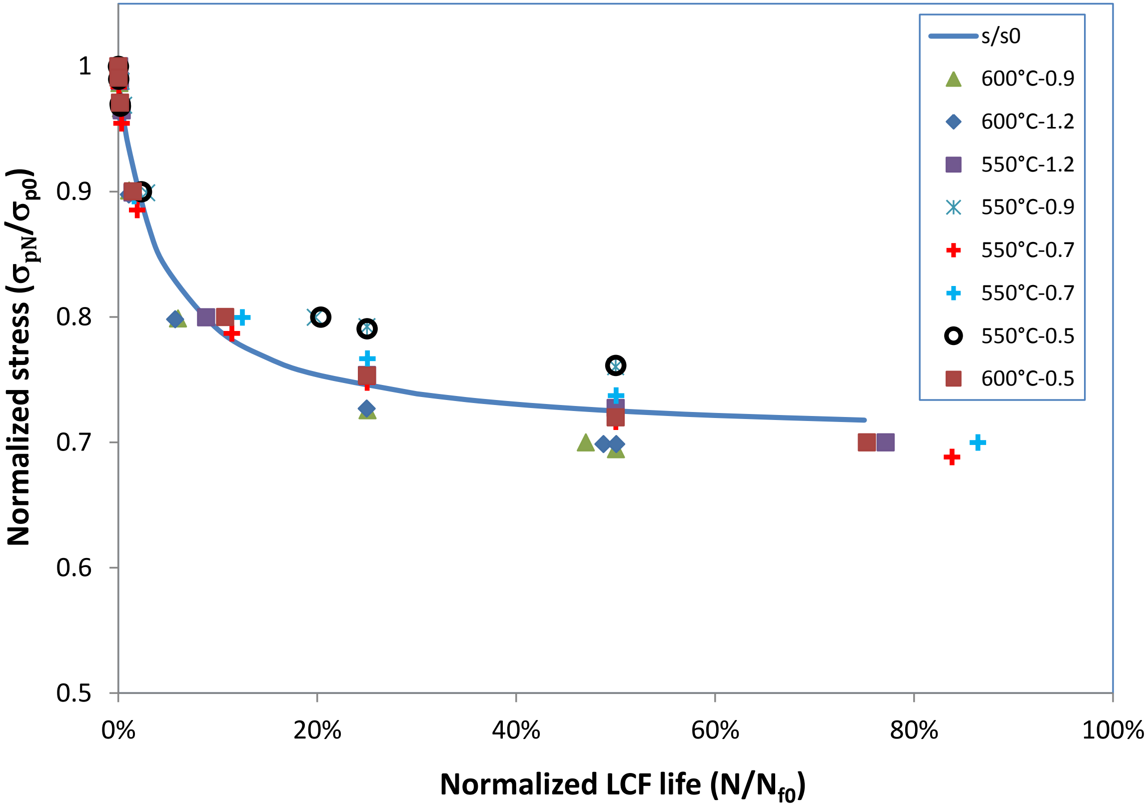
First modelling assumption … they do …

European Commission



European Commission

Softening model



$$\frac{\sigma_{pN}}{\sigma_{p0}} = A_1 + \frac{A_2}{A_3 + N/N_{f0}}$$

A_1	7.017E-01
A_2	1.276E-02
A_3	4.441E-02

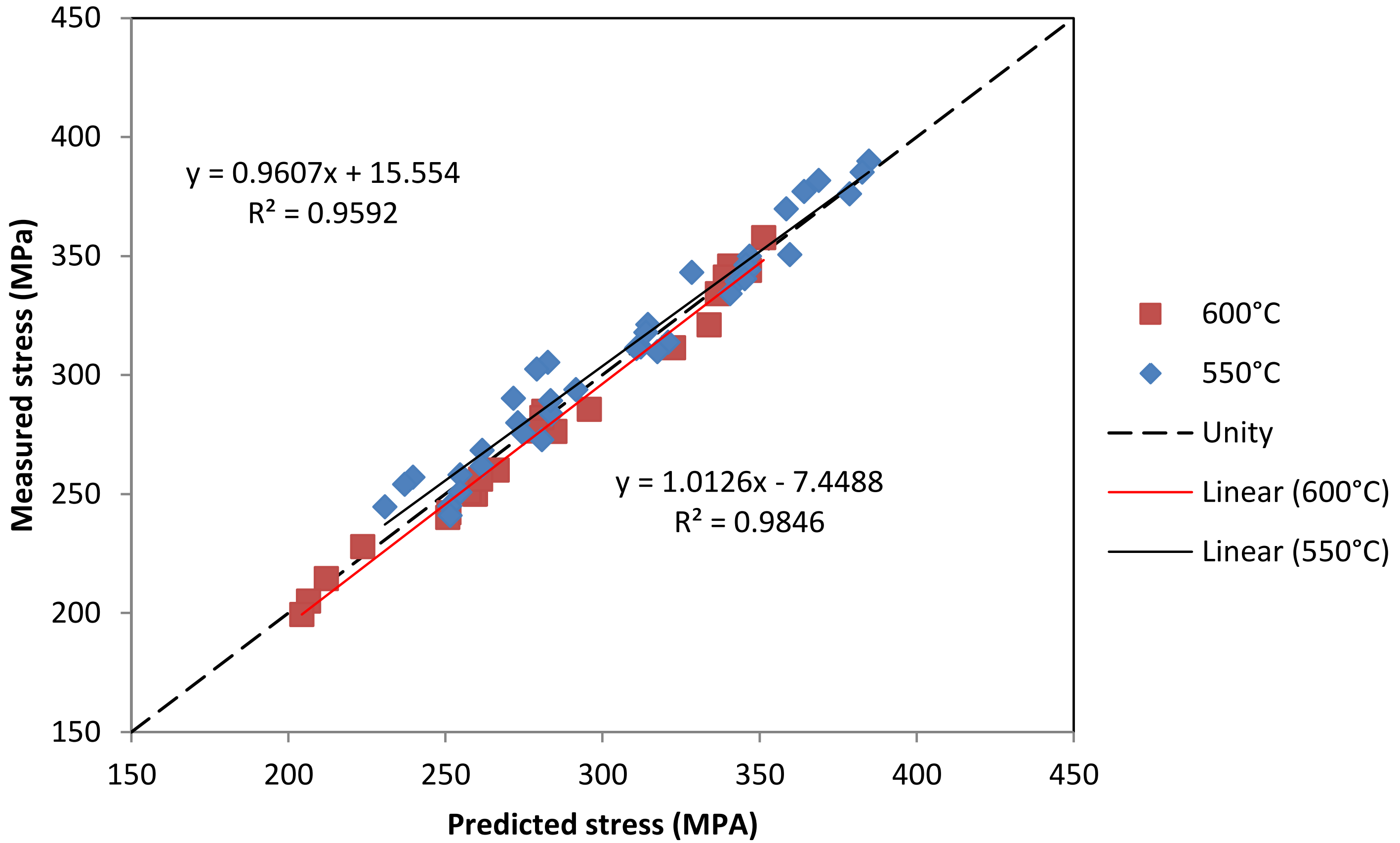
$$N_{f0} = \left(\frac{(\Delta\varepsilon - C_1)}{C_2}\right)^{\frac{1}{C_3}}$$

550°C	-------------------------	
	Δε	0.24
	C2	41.90976
	C3	-0.53821

Where A_1-A_3 are *f(R, t_h), here R=-1, t_h=0 for initial model*

Normalized N/N_f with N_f determined from Manson-Coffin model

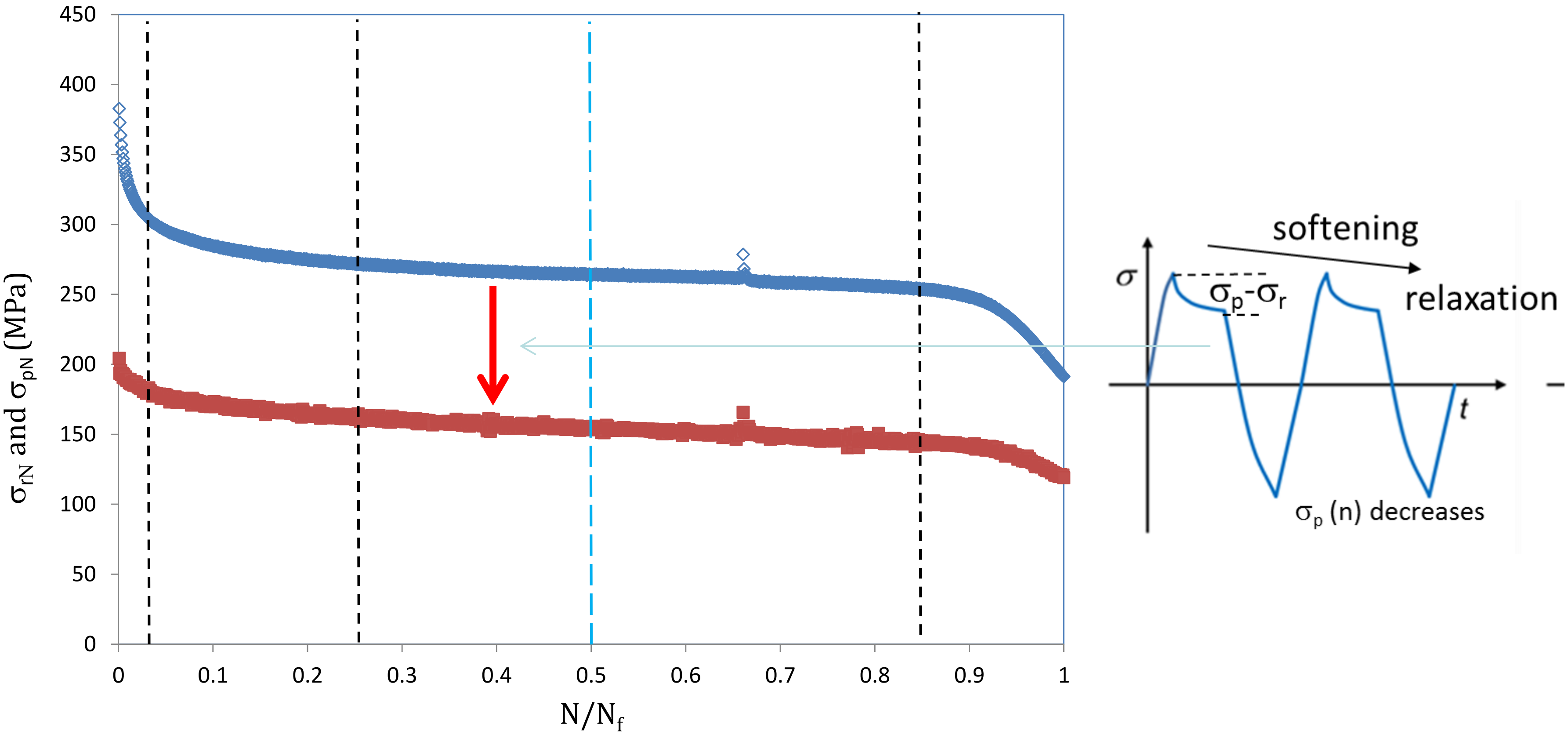
Predicted peak stress at cycle N_1-$N_{75\%f}$



Using modelled value for σ_{p0} and Manson-Coffin predicted N_f

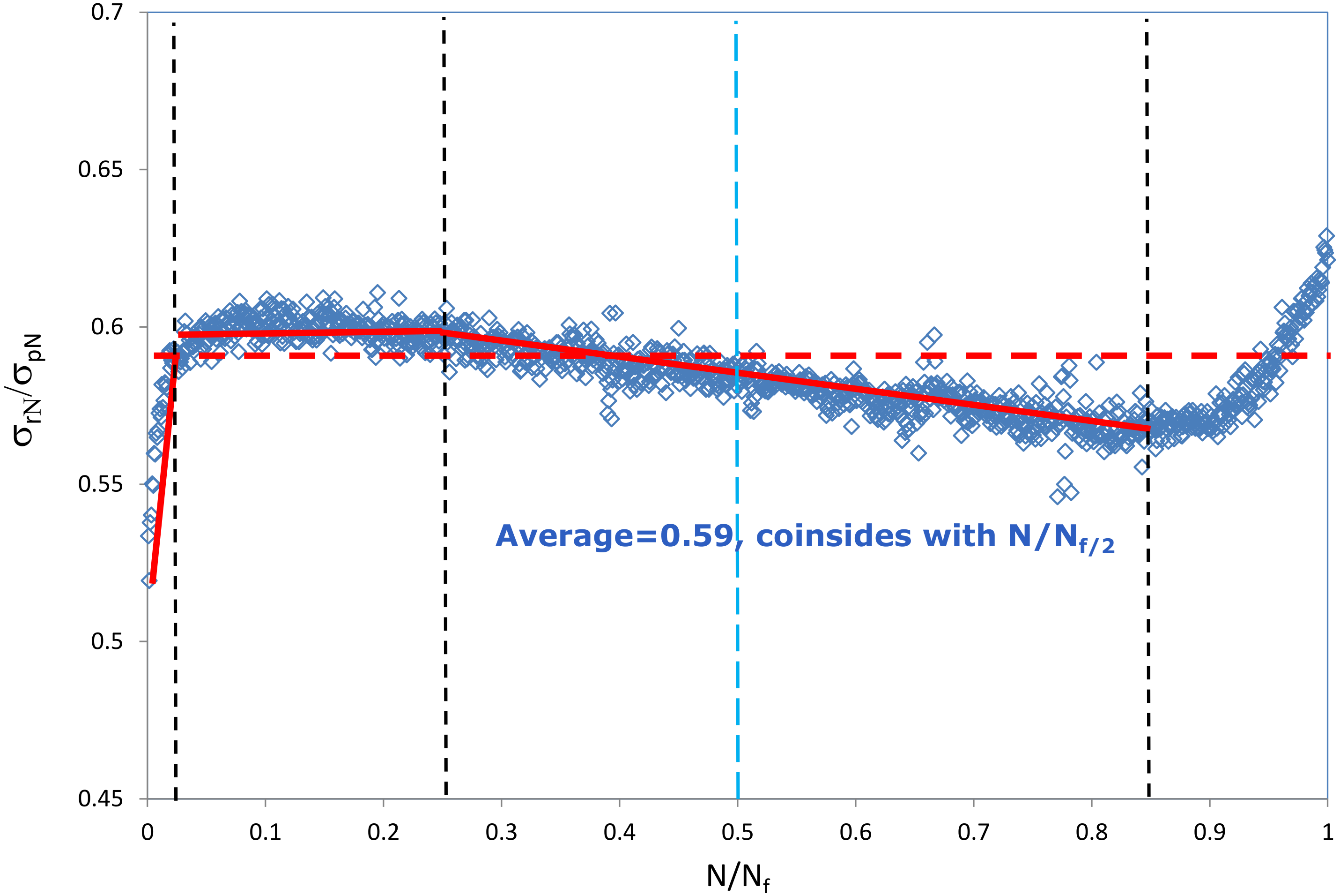
- 2.5·standard deviations, error ~8% in stress

Example: 600° C/$\Delta\varepsilon$=1.2%/t_h=1080s



N_f=1215, peak stress decreases, relaxed stress decreases, different rate of decrease …

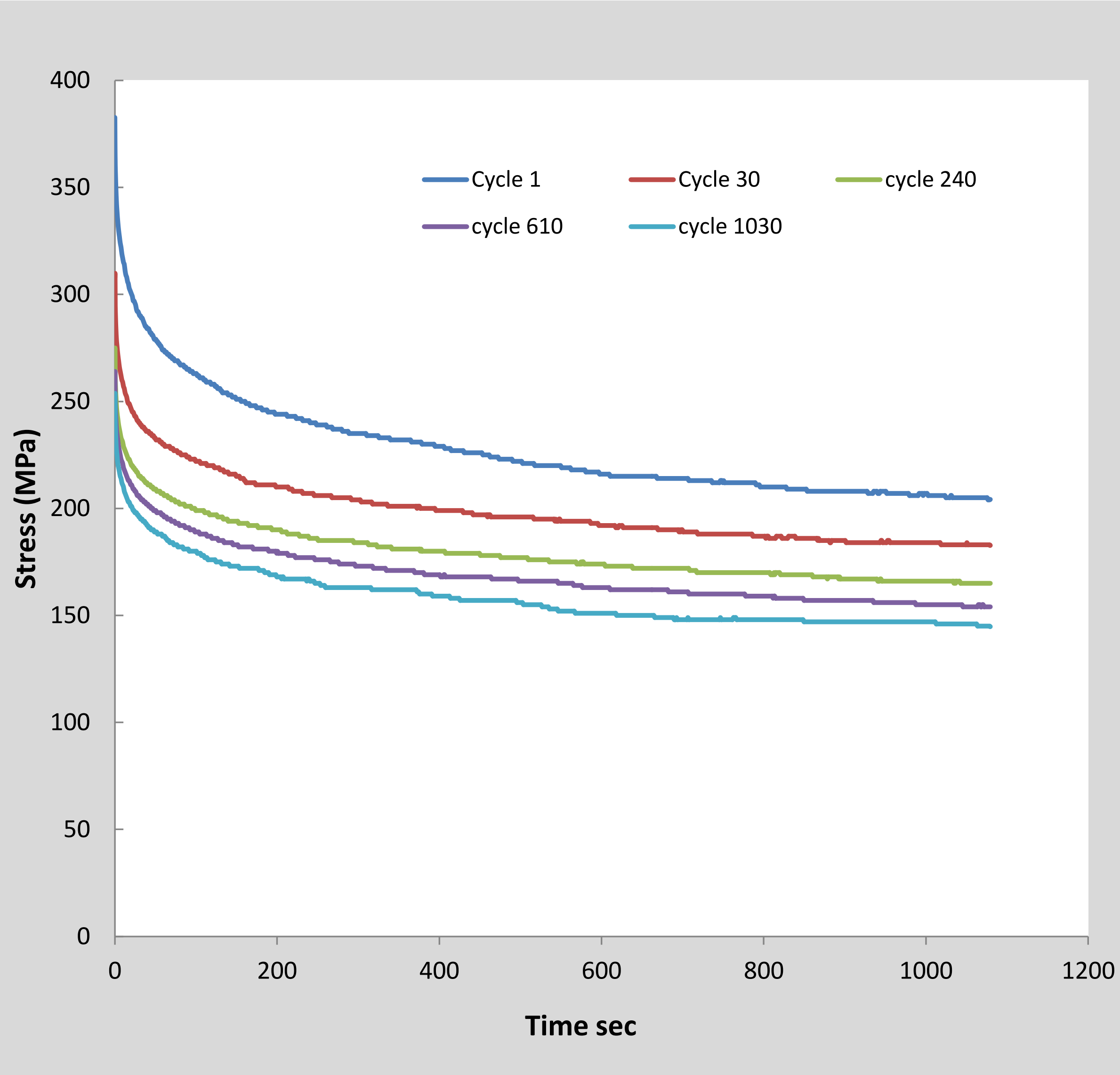
Example: 600° C/$\Delta\varepsilon$=1.2%/t_h=1080s



N_1 to N/N_f=0.025	increasing relaxation ratio
$0.025 \leq N/N_f \geq 0.25$	~ constant relaxation ratio
$0.25 \leq N/N_f \geq 0.85$	decreasing relaxation ratio

European Commission

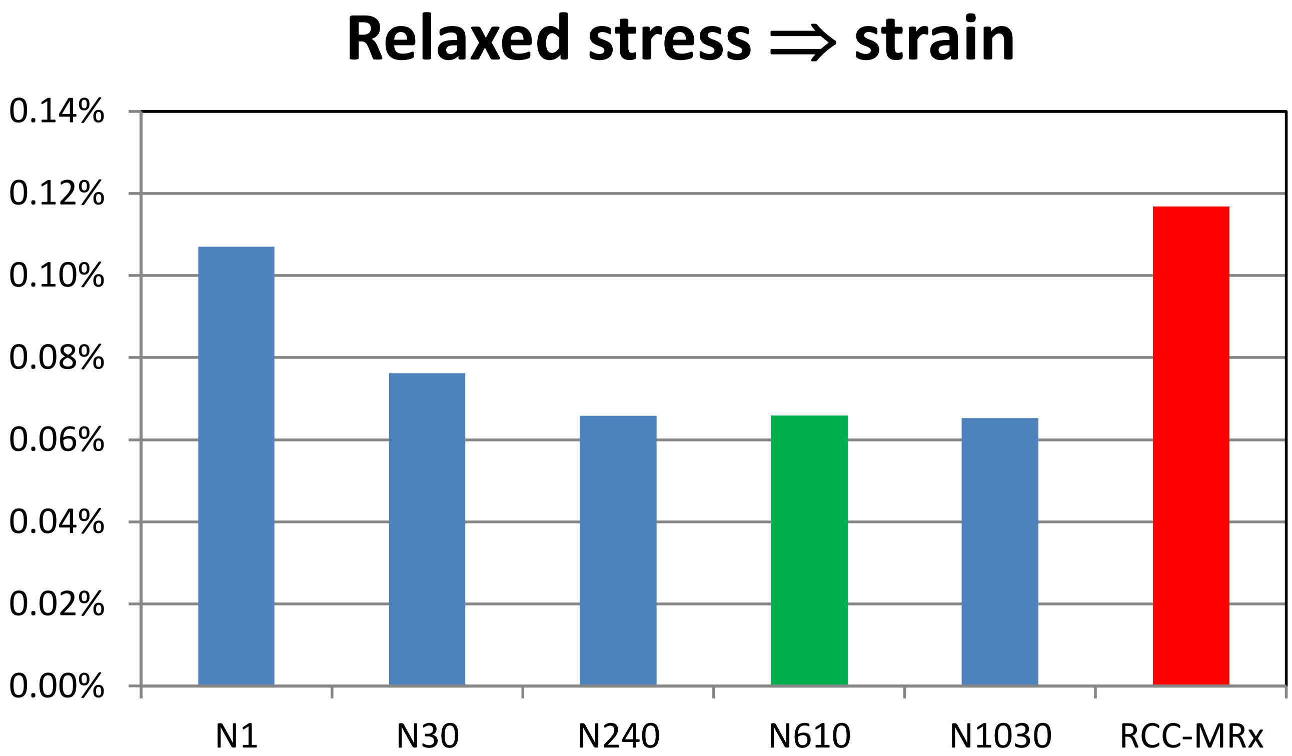
Example CF relaxation curves



Cycle 0 – virgin
Cycle 3 (N/Nf=0.25%)
Cycle 30 (N/Nf=2.5%)
Cycle 240 (N/Nf=20%)
Cycle 610 ($N_{f/2}$)
Cycle 1030 (N/Nf=85%)

As a function of N:
relaxed creep strain
Creep damage d_c

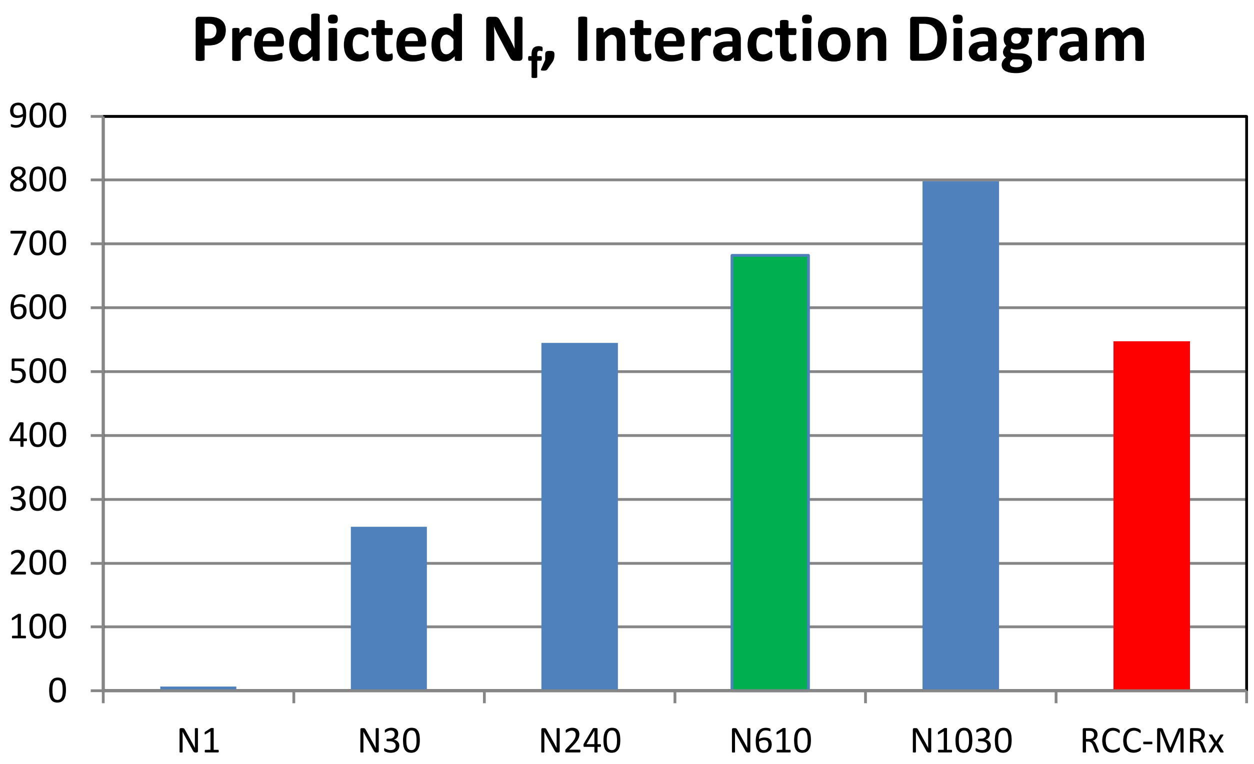
Relaxed strain / sample cycle



Virgin material **relaxed strain > half life relaxed strain**

European Commission

Predicting cycles to failure N_f using the relaxation of cycle N (for d_c)



The first cycle d_c >> half life d_c (life fraction)

Pending work for CF / relaxation / softening

The initial (engineering) softening model for peak stress seems to work well in the strain range 0.5-1.2% at 550 and 600° C

Extended to incorporate effect of hold times

$$\frac{\sigma_{pN-CF}}{\sigma_{p0}} = \mathrm{f}\left(\frac{\sigma_{pN}}{\sigma_{p0}},\ \mathrm{t}_h\right)$$

The relaxation model to be chosen for describing $\sigma(t)$

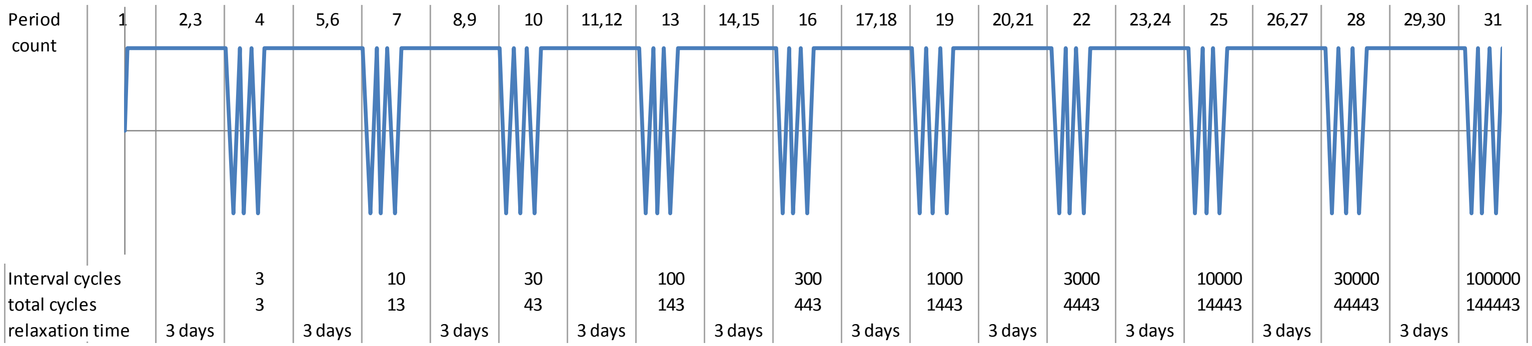
ECCC round-robin results as base

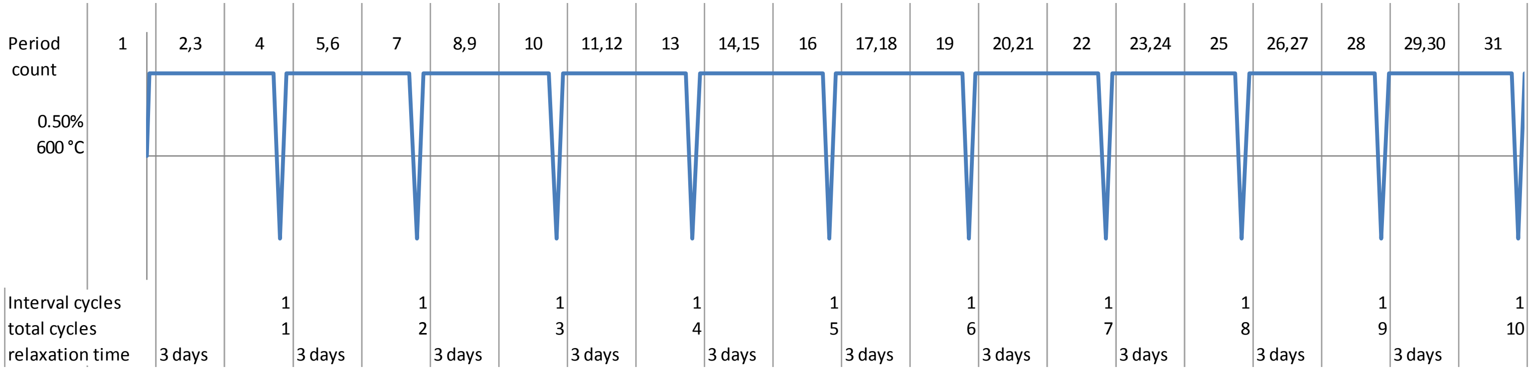
- Kohlrausch
- TTP models
- WE-R
- Feltham
- Norton
- Garofalo

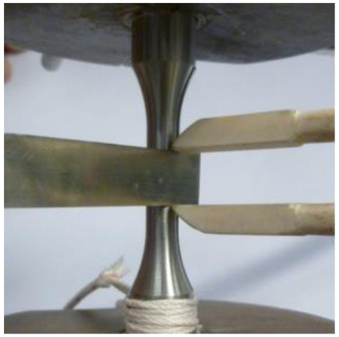
MaTISSE test for softening / relaxation modelling

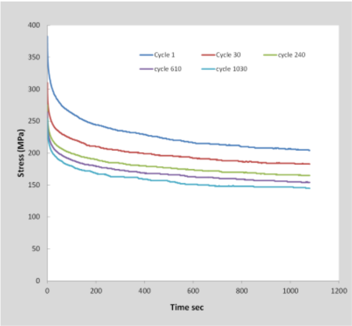
Relaxation and CF (monotonic, cyclic)

- Standard LCF and CF tests with hold times up to 3 h
- Relaxations in different locations of the softening curve
- Relaxations every cycle in the beginning of the curve









Conclusions

Creep and NEC

- New T_{NEC} curve suggested for RCC-MRx (proposed for P91)
- **New methodology for EN-13445:9 for a number of other steels**

Creep-Fatigue

- New (/old ☺) models for CF life determination (standards)
- Engineering model for softening and relaxation (⇒interaction diagram)
- Verification in MATISSE …

European Commission