JRC CONTRIBUTIONS TO STANDARDS

Negligible creep temperature curves for EN-13445

JRC Contribution to CEN/TC 54/WG 59

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Foreword

This report is the JRC contribution to the revision of the European standard EN13445 on design for unfired pressure vessels. The work was conducted on the request of CEN TC 54 WG 59 / CREEP.

Acknowledgements

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Author

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Abstract

The simplified methodology proposed by JRC (in CEN TC 54 WG CREEP) for defining negligible creep temperature curves (T_{NEC}) has here been applied to define the negligible creep (T_{NEC}) curves and the no creep temperature (T_{NC}) for a service life of 200 000 hours for all the ferritic / ferritic-martensitic (F/M) steels in EN-10028-2 and the creep resistant austenitic steels in EN 10028-7. The curves are intended to be used in the revision of the European standard EN-13445. The work flow and methods used for the negligible creep temperature curves, based on the creep strength and tensile properties obtained from the standard tables, are described in detail and the T_{NEC} curves are presented together with comments on encountered challenges for each steel. Note that the methodology uses data from the material standards only and that the calculated temperatures are dependent on the combination of the tensile properties and the creep rupture strength tables.

Introduction

The objectives of this work are:

1. To present the background assumptions and method to determine the T_{NEC} curves applicable to different materials.
2. To define the TNEC curves for the steels in EN10028-2 and EN10028-7 based on the same rupture time factor against creep rupture with the aim of including them in the EN-13445 annex V.
3. Discuss the open issues on related to the T_{NEC} curves for the specific material or material class.

In earlier CEN/TC 54/WG 59 reports on the topic of negligible creep (NEC) [1][2], a simplified methodology, based on the Wilshire equations (WE) [3], to determine negligible creep (T_{NEC}) curves was presented and applied to selected steels. The methodology was selected to define negligible creep temperature curves (T_{NEC}) for the revision of the European standard EN-13445 [4]. In this report the negligible creep curves for the F/M steels in EN10028-2 [5] and the austenitic steels in EN10028-7 [6] are determined by limiting the allowable time (t_{NEC}) in creep to 1/1000 of the corresponding time to rupture (t_r) at the EN-13445 defined time independent reference stresses.

It is to be emphasized that the methodology is time based and does not take into consideration that different material types are likely to have different time factors for time to 0.2% creep strain than the X10CrMoVNb9-1 (P91) steel used as base. However, it was agreed in the WG that the rupture time factor RTF=1000 (as in Eq.1) is adequate to define negligible creep. The WE for rupture corrected with the chosen RTF=1000 was shown to be conservative for time to 0.2% creep strain for both 10CrMo9-10 (P22) and X2CrMoNiMo17-12-2 (316L) steels.

The assessment using the same RTF for all materials equally will not only give conservative estimates for the negligible and no-creep temperatures but also give an insight in material selection for applications operating near or within the negligible creep temperature range.

The assessed steels with creep rupture temperature and strength ranges are given in Table 1 and Table 2 for F/M and austenitic steel respectively.

The four main temperature curves defined and presented in this report are shown in Figure 1. The upper limit in temperature T_H+50K (if needed) depends on the highest temperature where yield properties are given (T_H) and the used maximum extrapolation range in temperature (here + 50K). The creep rupture temperature curve (T_r) is the base line defined with the tensile and creep rupture strength values available in the material standards.

The T_{NEC} curve is defined from T_r by transforming it by the rupture time factor RTF. At a material specific temperature the T_{NEC} curve reaches a duration of 200 000 h. This is temperature is defined as the "no-creep" temperature T_{NC}, i.e. the temperature limit below which time independent design can be done. It is to be noted that for longer service lives, such as 60 years design life the T_{NC} will be lower.

For materials where different tensile properties are given for different product thicknesses, only one T_{NEC} curve is needed. The thinnest product form is chosen to represent the materials since it holds the maximum yield (proof) stresses. As a consequence for the thicker components the actual design stress will be lower than the one used for the computed T_{NEC}, which results in additional conservatism.

Table 1. F/M Steels covered in EN10028-2 in the order given in the standard. The maximum temperature for which R_{p02} values are given (T_H), the available creep temperature range (T_{min} and T_{max}), stress range (σ_{min} and σ_{max}) and the time minimum and maximum times of the creep rupture data ($R_{m/t/T}$) (t_{min}, t_{max}) is given as well as the availability of time to 1% creep strength data ($R_{p1/t/T}$).

Steel name	$T_{H\text{-}nc}$ (°C)	T_{min} (°C)	T_{max} (°C)	σ_{min} (MPa)	σ_{max} (MPa)	t_{min} (kh)	t_{max} (kh)	1% data Yes/No
P235GH	400	380	480	33	229	10	200	Yes
P265GH	400	380	480	33	229	10	200	Yes
P295GH	400	380	500	30	291	10	200	Yes
P355GH	400	380	500	30	291	10	200	Yes
16Mo3	500	450	530	45	298	10	200	Yes
18MnMo4-5	450	425	525	69	421	10	100	Yes
20MnMoNi4-5	400	450	490	194	290	10	100	No
15NiCuMoNb5-6-4	450	400	500	69	385	10	100	Yes
13CrMo4-5	500	450	570	26	285	10	200	Yes
13CrMoSi5-5	450	450	570	31	313	100	100	No
10CrMo9-10	500	450	600	28	306	10	200	Yes
12CrMo9-10	500	400	520	107	355	10	100	No
X12CrMo5	500	475	600	27	147	10	10	Yes
13CrMoV9-10	450	400	550	108	430	10	100	No
12CrMoV12-10	450	400	550	108	414	10	100	No
X10CrMoVNb9-1	500	500	670	35	289	10	200	No

Table 2. Creep resistant austenitic steels covered in EN10028-7 in the order given in the standard. The maximum temperature for which R_{p1} values are given (T_H), the available creep temperature range (T_{min} and T_{max}), stress range (σ_{min} and σ_{max}) and the time minimum and maximum times of the creep rupture data (t_{min}, t_{max}) is given as well as the availability of time to 1% creep strength data.

Steel name	$T_{H\text{-}nc}$ (°C)	T_{min} (°C)	T_{max} (°C)	σ_{min} (MPa)	σ_{max} (MPa)	t_{min} (kh)	t_{max} (kh)	1% data Yes/No
X3CrNiMoBN17-13-3	600	550	800	27	164	10	100	No
X6CrNiTiB18-10	600	550	700	29	290	10	200	No
X6CrNi18-10	600	500	700	22	250	10	200	Yes
X6CrNi23-13	600	550	800	7.5	160	10	100	Yes
X6CrNi25-20	600	600	910	9	137	10	250	No
X5NiCrAlTi31-20	600	500	700	38	290	10	200	Yes
X5NiCrAlTi31-20 (+RA)	600	500	700	26	315	10	200	Yes
X8NiCrAlTi32-21	600	700	1000	2.8	73	10	200	Yes
X8CrNiNb16-13	600	580	750	15	182	10	200	Yes

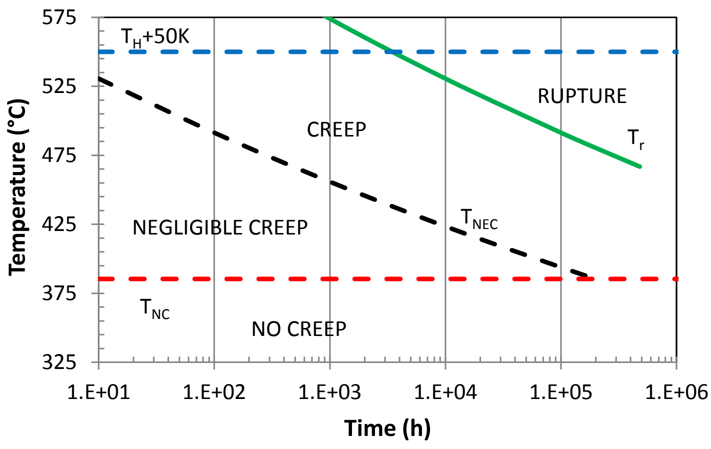

Figure 1. Example of a Negligible Creep temperature curve T_{NEC} (blue long dash) defined from the creep rupture temperature curve T_r (continuous green line) by dividing predicted rupture time with RTF=1000 at the reference stress. The T_{NC} (red horizontal long dash) equals the T_{NEC} at a duration of 200 000h.

Models and methods

The T_{NEC} temperature curves in this report are based on the Wilshire equation (WE) [3] for creep rupture. T_{NEC} is calculated using the tensile properties and the creep rupture strength of each specific material. T_{NEC} is defined at the reference stress $\sigma_{ref.}$

For non-alloyed and alloyed ferritic-martensitic steels (F/M steels) the reference stress used is the is the minimum 0.2% yield (proof) strength at calculation temperature divided by a 1.5 as given in EN 13445-3; 6.2.1.

For austenitic steels it is more complicated to choose a suitable reference stress. The French nuclear design code RCC-MRx [7] uses a reference stress of $0.9 \cdot R_{p02}$ for time to 0.01% strain whereas in the British R5 assessment code uses $1.35 \cdot R_{p0.2}$ [8][9] with a time criteria of 20% stress relaxation.

However, since the reference stress should comply with the rest of the standard the reference stress is defined from the (minimum) yield 1% (proof) strength at the calculation temperature divided by a factor 1.2, as given in EN 13445-3 6.5.1 for ductile (≥35% fracture strain) austenitic steels. The definition chosen for reference stress is more conservative than the same yield strength divided by a factor of 1.5, which would be used for less ductile (30-35% fracture strain) austenitic steels (6.4.1).

The T_{NEC} curve is described at the reference stresses defined above by four material specific parameters and the maximum time of negligible creep t_{NEC} (see Equations 1-3).

$$T_{NEC} = \frac{C_1}{\ln\left(t_{NEC} \cdot RTF \cdot \left[C_2 \ln(C_3)\right]^{C_4}\right)} \qquad (1)$$

$$t_{NEC} = \frac{t_r}{RTF} \qquad (2)$$

$$\frac{\sigma_{u/t/T}}{A \cdot R_p} = \exp\left[-k(t_r \cdot \exp(\frac{-Q}{R \cdot T}))^u\right] \qquad (3)$$

The parameters *Q*, *k* and *u* are fitting parameters, *R* the gas constant and *A* a material specific normalization parameter scaling yield stress R_p (R_{p02} for F/M steels and R_{p1} for austenitic) to mimic the tensile strength, i.e. $A \cdot R_p \approx R_m$. T is the absolute temperature and $\sigma_{u/t/T}$ the creep rupture strength taken from the standard tables for specified rupture times (t_r). The WE model predictions are un-sensitive to the choice of the A parameter.

Equation 3 turns into Equation 1 at the reference stress by; $C_1=Q/R$, $C_2=-1/k$, $C_3=1/A/F$ (normalized reference stress) and $C_4=-1/u$. The parameter F in C_3 is the design stress factor F=1/1.5 for F/M steels and F=1/1.2 for austenitic steels.

The material specific WE model parameters (Equation 3) for time to rupture are determined by fitting the creep strength data $\sigma_{u/t/T}$, i.e. the stress to cause rupture in 10000h (10kh), 100000h (100kh) and in some cases 200 000h (200kh) at specified temperatures (see Table 1 and 2).

For each steel the activation energy Q is determined by minimizing the data mismatch between the isotherms with isochronous data. For most steels a typical value of Q=300 kJ/mol fits the data adequately. For some steels Q had to be altered to avoid large differences between the isochronous rupture strengths. Generally the Q values should not differ largely between different types of steels such as F/M steels, non- or low alloyed steels and austenitic stainless steels. The difference in the calculated T_{NEC} and T_{NC} temperatures for a rather large difference in activation energy ΔQ=50 kJ/mol, i.e. Q=350 and Q=350 kJ/mol is shown in Figure 2 for the steel 15NiCuMoNb5-6-4. The difference in T_{NC} (at 200 000 h) is 14°C. The uncertainty of determining and choosing the activation Q is not likely to be this large but could be in the order of ΔQ=20 kJ/mol, this translates to a T_{NC} temperature difference of about 4°C.

It is to be noted that the WE will not give perfect fits to the standard data tables since the material specific tables have been generated with a multitude of creep models with different assessors and different methods for pinpointing the final standard strengths, i.e. single models, averages of several models, different amounts of extrapolations, etc.

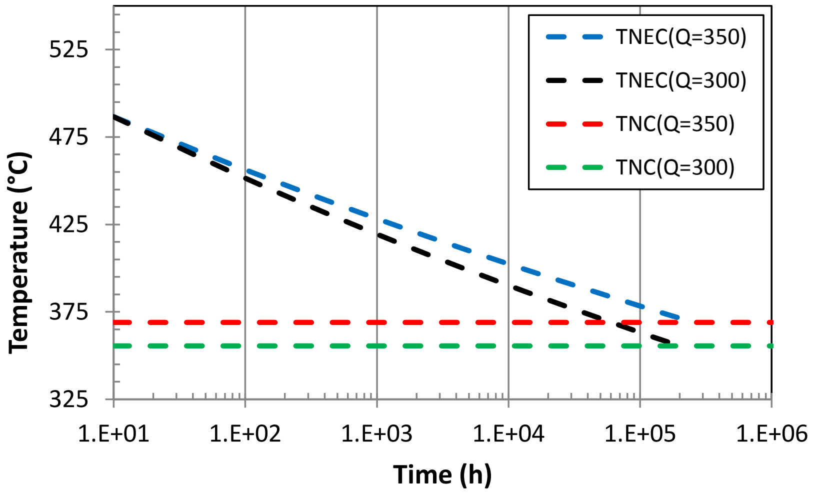

Figure 2. T_{NEC} plot of steel 15NiCuMoNb5-6-4 with Q=350 and Q=300 kJ/mol at reference stress.

The yield (proof) stress at specified temperature needed for the normalization in Equation 3 are acquired from 3rd degree polynomial fits of the $R_{p02}(T)$ or $R_{p1}(T)$ values in the standard as ;

$$R_p = D_0 + D_1 \cdot T_c + D_2 \cdot T_c^{\,2} + D_3 \cdot T_c^{\,3}, \qquad (4)$$

where D_0-D_3 are fitting parameters.

For some materials the yield strength has to be extrapolated in temperature by up to 50K to overlap the creep data range and to define the upper limit of T_{NEC} prediction (T_H+50K).

With these models in place, the creep strength data and the fitted WE model can be plotted with the normalized stress as the ordinate and the ln($t_r$exp(-Q/RT)) as the abscissa (see Figure 3).

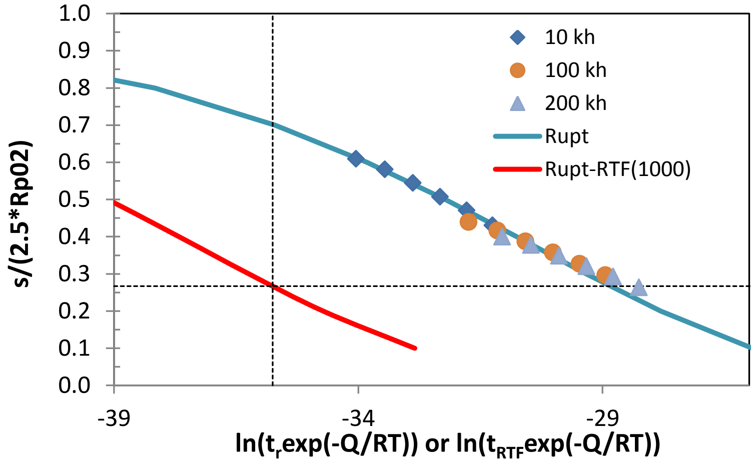

Figure 3. EN10028-2 creep strength data for 10CrMo9-10. The WE plot is calculated with Q=260 kJ/mol and normalized with 2.5 R_{p02}. The target reference stress (2/3 R_{p02}) is the horizontal line at 0.27 normalized stress and the cross hairs (dashed lines) on the RTF corrected rupture curve defines the location where the T_{NEC} curve is retrieved.

To acquire the T_{NEC} curve from the WE model Eq.1 is used at the normalized reference stress of C_3=1/A/F and with the selected rupture time factor RTF=1000.

In the case of steel 16Mo3 (Figure 4) there is a clear mismatch between the 10kh creep rupture strength data and the longer 100 and 200kh data. In this case where the long term data is to the right of the short term data it is an indication of that a better match between isochrones could be expected if the chosen activation energy Q would be increased. However, for some materials the optimized Q would become unrealistically high for the material type in question. In this case to ensure the conservatism of the predicted NEC curve, a lower Q was used and the WE fitting parameters are based on the sub-set of the available isochronous data (10kh, 100kh and 200kh) giving the most conservative T_{NEC} results. In the case of 16Mo3 it meant using 10kh data only. For other steels it could mean choosing a different set of isochrones. For many of the F/M steels the single set of 10kh data give the most conservative rupture (T_r) curve and thereby the most conservative T_{NEC} curve.

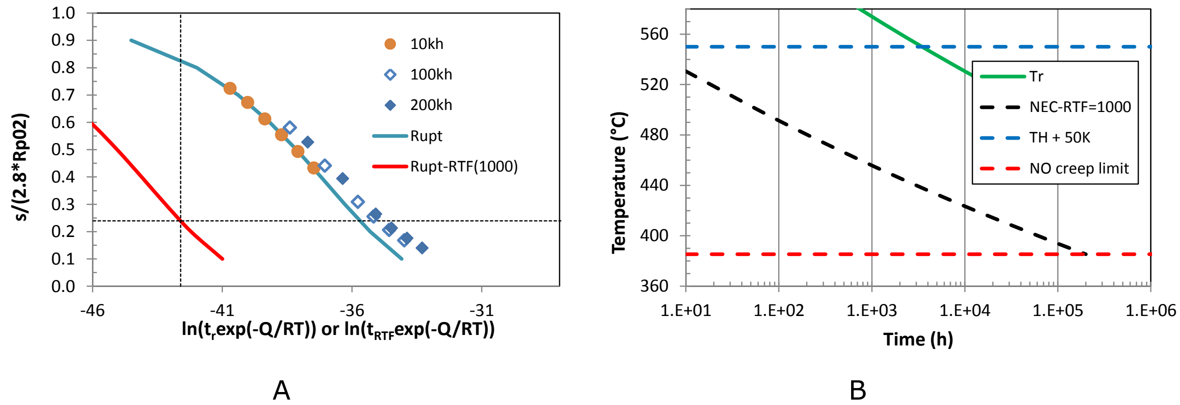

Figure 4. A) WE model fit and temperature curves and B) temperature-time plots (T_r, T_{NEC} and T_{NC}) for 16Mo3 steel using 10kh data for fitting. The calculated T_{NC} will increase above 385°C if the long term data is used in the WE fit.

To further test the conservatism of the acquired T_{NEC} curves, WE modelling was also performed on the 1% creep strength data (for the F/M steels only in this report). The 1% creep strain WE model is fitted using the same activation energy as for the corresponding rupture assessment. Strain time factors (STF) are calculated from the time difference between the T_{NEC} curve and the time to 1% creep strain curve as:

t_{NEC} (σ, T) = $t_{1\%}$ (σ, T)/STF at the reference stress, as shown in Figure 5 for 10CrMo9-10 steel.

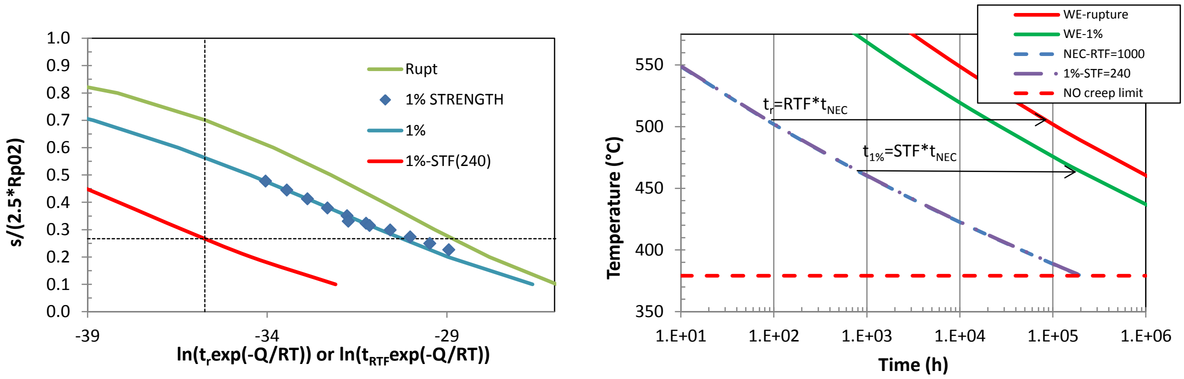

Figure 5. Assessing the STF (safety margin in time) between the t_{NEC} and the time to 1% creep strain $t_{1\%}$ for steel 10CrMo9-10, STF=240 for 1% creep strain equals RTF=1000 for rupture.

Weldments

The procedure defined for base materials can also be applied for the welds. Equation 3 is applied with the base material material specific parameters and the reference stress is further adjusted by the relevant Weld (Creep) Strength Factor WSF= $1/z_c$ as given in Equation 5 to account for potential creep damage (weld creep strength factor z_c). The WSF values are defined in clause 19.6 of EN13445 for significant creep.

$$T_{NEC-W} = \frac{C_1}{\ln\left(t_{NEC} \cdot RFT \cdot \left[C_2 \ln\left(\frac{C_3}{z \cdot z_c}\right)\right]^{C_4}\right)} \quad (5)$$

The T_{NEC} curve for the base material and for weldment corrected X10CrMoVNb9-1 steel is shown in Figure 6. The weld T_{NEC-W} curve has been calculated for the case z_c=0.8 (WSF=1.25). Note that the rationale for using the weld creep strength factor z_c at negligible creep temperatures is still under debate in the Work Group TC45/WG 59. The general experience from creep testing of cross welds at "low" creep temperatures is that there is no further reduction of creep life in relation to base material or weld material tests.

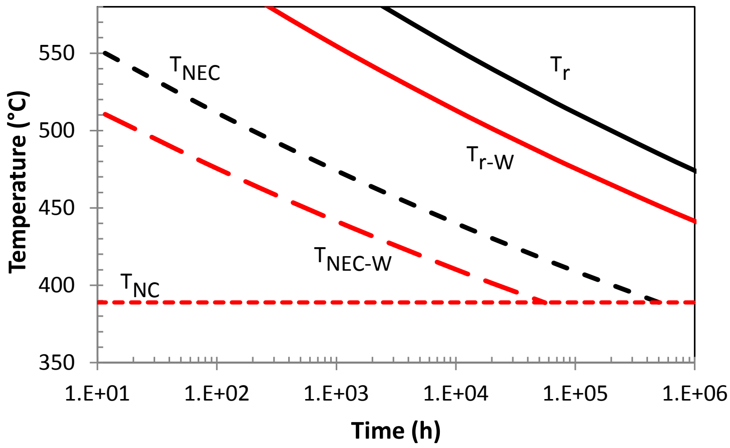

Figure 6. T_{NEC} **curves for X10CrMoVNb9-1 base material and welds with WSF=1.25. The temperature difference at 100 000 h is 27°C. The time ratio** $t_{NEC}/t_{NEC\text{-}W} \approx 9$**.**

FERRITIC-MARTENSITIC STEELS:

Steels P235GH and P265GH

The steels P235GH and P265GH are presented together since their creep rupture data in the EN10028-2 standard are the same. The differences in the T_{NEC} curves are due to their different yield behaviour leading to different reference stress. The WE models and the T_{NEC} curves are shown in Figure 7. The 1% creep strain strength assessment is presented in Figure 8.

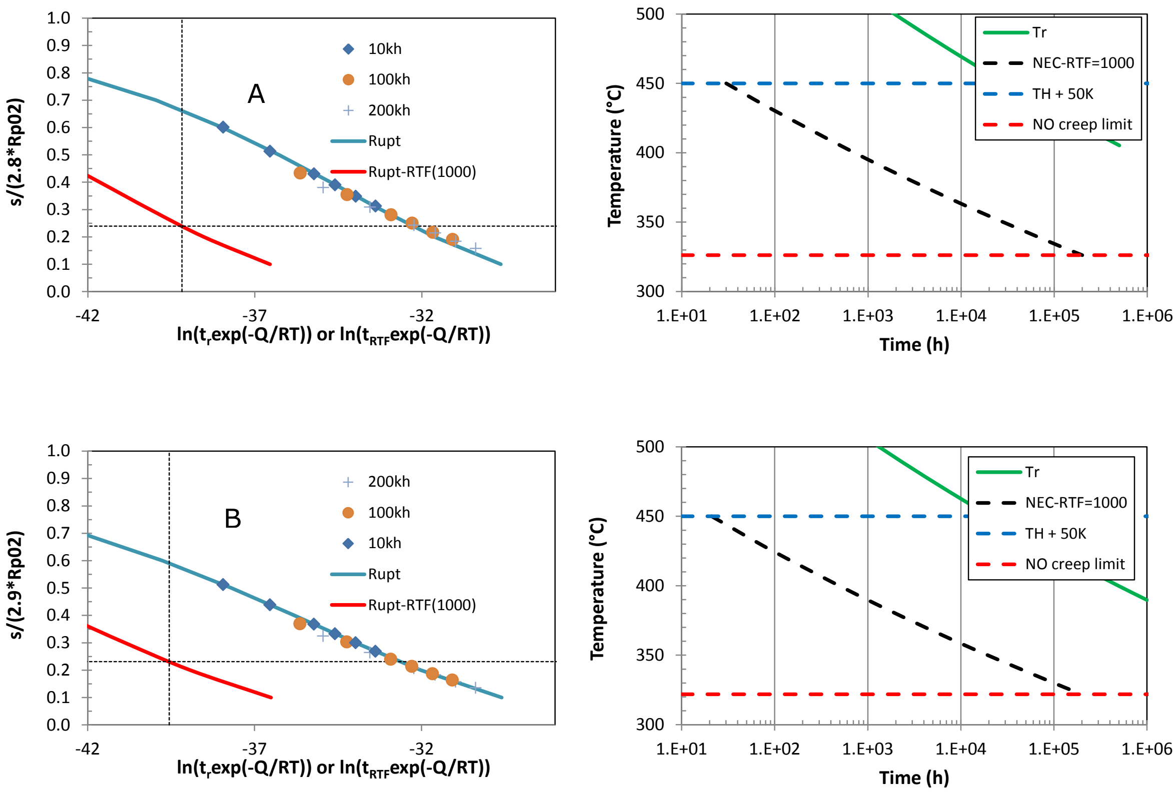

Figure 7. WE model and T_{NEC} curves for A) P235GH and B) P265GH steels. The calculated T_{NC} temperatures are 326°C and 322°C respectively. Note that RTF=1000 for these steels might be conservative for time to 0.2% creep strain.

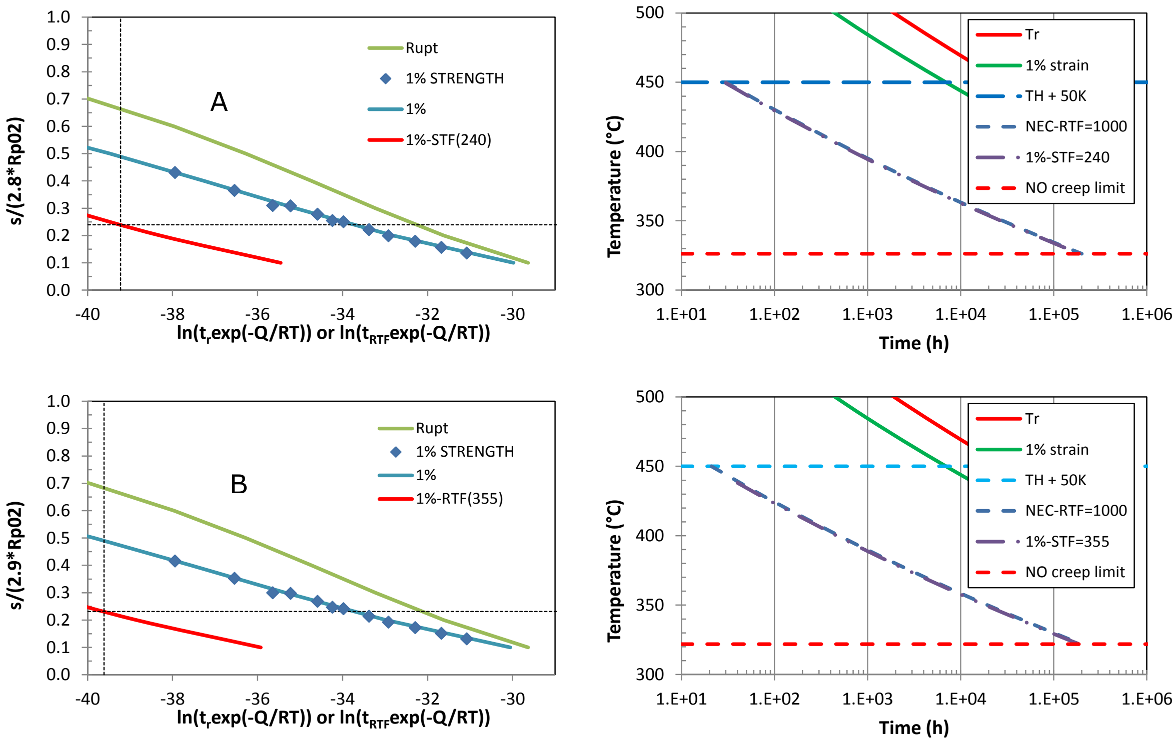

Figure 8. Time to 1% creep strain WE models for A) P235GH and B) P265GH steels.

Steels P295GH and P355GH

The steels P295GH and P355GH are also presented together since their creep rupture data of the EN10028-2 standard are the same. The differences in the T_{NEC} curves are due to their different yield behaviour leading to different reference stress. The WE models and the T_{NEC} curves are shown in Figure 9. The 1% creep strain strength assessment is presented in Figure 10.

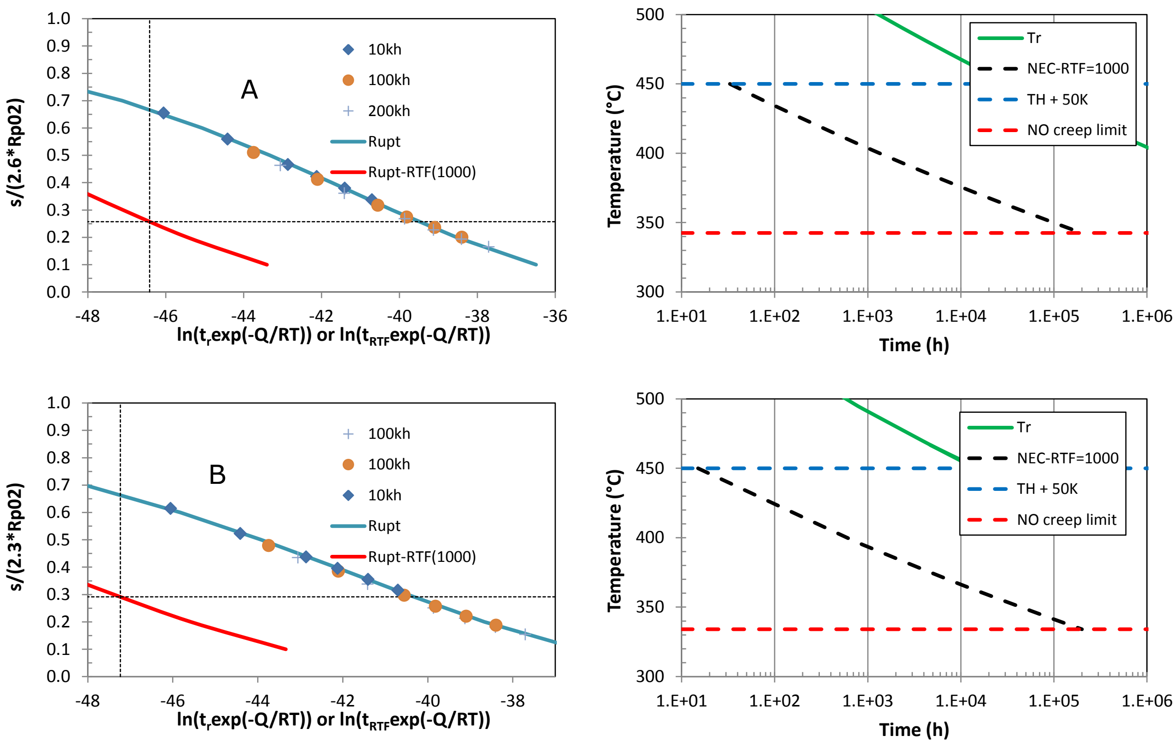

Figure 9. WE model and T_{NEC} curves for A) P295GH and B) P355GH steels. The T_{NC} temperatures are 343°C and 334°C respectively. Note that RTF=1000 for these steels might be conservative for time to 0.2% creep strain.

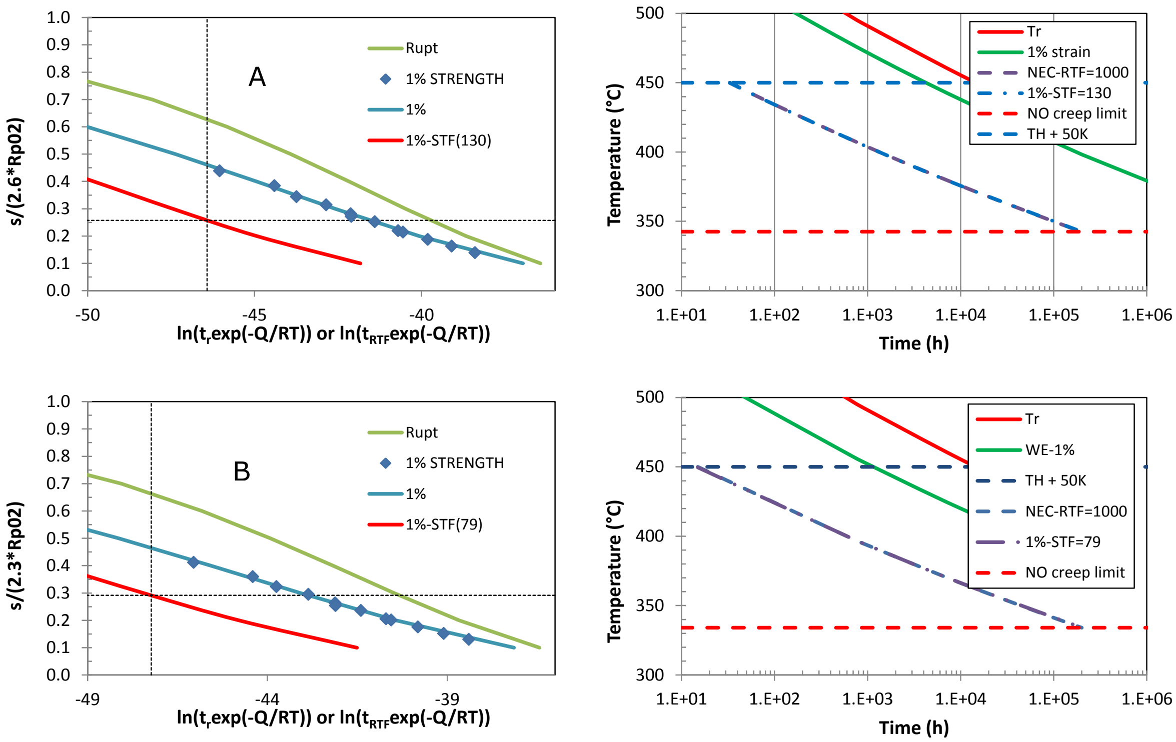

Figure 10. Time to 1% creep strain WE models for A) P295GH and B) P355GH steels.

16Mo3

The steel 16Mo3 WE model and the T_{NEC} curve are shown in Figure 11. Note that the chosen activation energy Q results in overlapping the 100 000 and 200 000 isochrones well, but not the 10 000 h one.

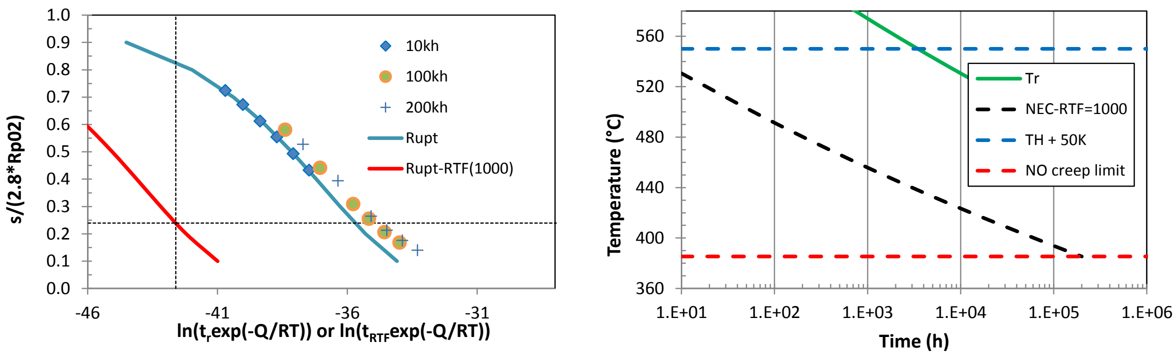

Figure 11. WE model and T_{NEC} curve for 16Mo3 steel. The calculated T_{NC} temperature is 385°C.

The 1% creep strain strength assessment is presented in Figure 12.

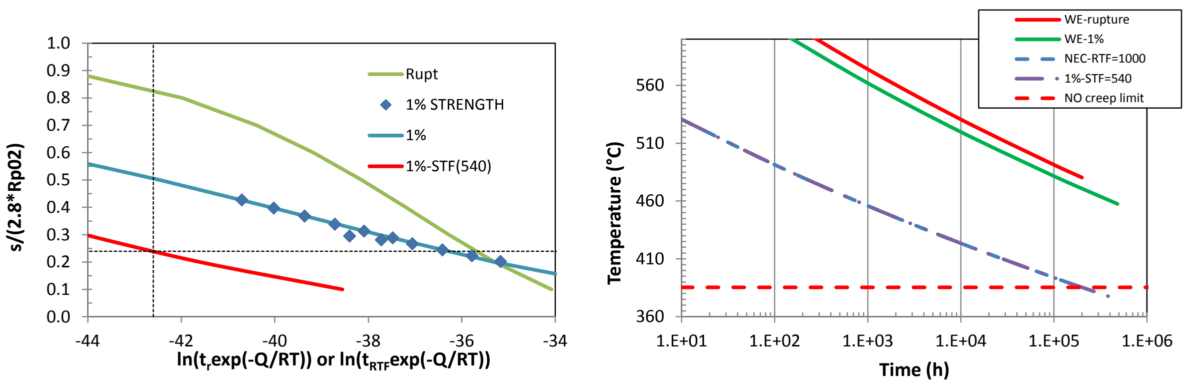

Figure 12. Time to 1% creep strain WE model for 16Mo3 steel.

18MnMo4-5

The steel 18MnMo4-5 WE model and the T_{NEC} curve is shown in Figure 13.

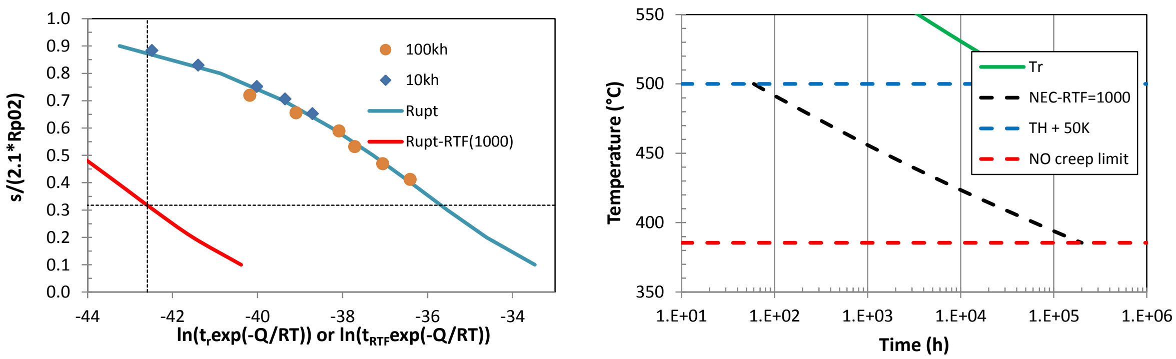

Figure 13. WE model and T_{NEC} curve for 18MnMo4-5 steel. The calculated T_{NC} temperature is 385°C.

The 1% creep strain strength assessment is presented in Figure 14.

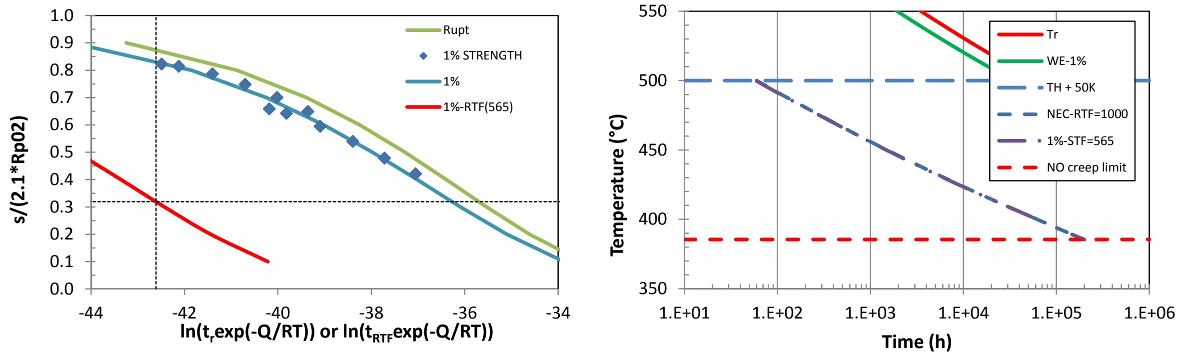

Figure 14. Time to 1% creep strain WE model for 18MnMo4-5 steel.

20MnMoNi4-5

The steel 20MnNiMo4-5 model and the T_{NEC} curve are shown in Figure 15. Note that for this material, there is very little creep strength data, i.e. only 5 points for the 10 00 h isochrone and two points for 100 000 h. The reference stress is in the middle of the available data range. Also note that the optimized activation energy Q (330 kJ/mol) is quite high for overlapping the 10 000 and 100 000h isochrones.

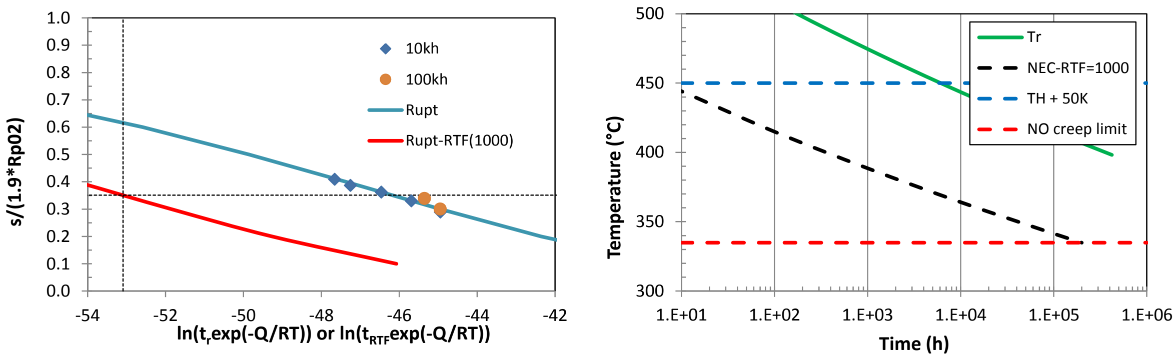

Figure 15. WE model and T_{NEC} curve for 20MnNiMo4-5 steel. The calculated T_{NC} temperature is 336°C. Note that the reference stress due to high yield strength is high (271 MPa). Note also that RTF=1000 for this steel might be conservative for time to 0.2% creep strain.

There are no time to 1% creep strain strength values for this material.

It is advisable to find more rupture data or standard strength values before introducing T_{NEC} and T_{NC} temperatures for this material in the EN-13445.

15NiCuMoNb5-6-4

The steel 15NiCuMoNb5-6-4 WE model and the T_{NEC} curve are shown in Figure 16 . Note that the optimized activation energy Q (350 kJ/mol) is the highest for the F/M steels. Note also that the A parameter is set low in comparison to other F/M steels to comply with the curvature of the data.

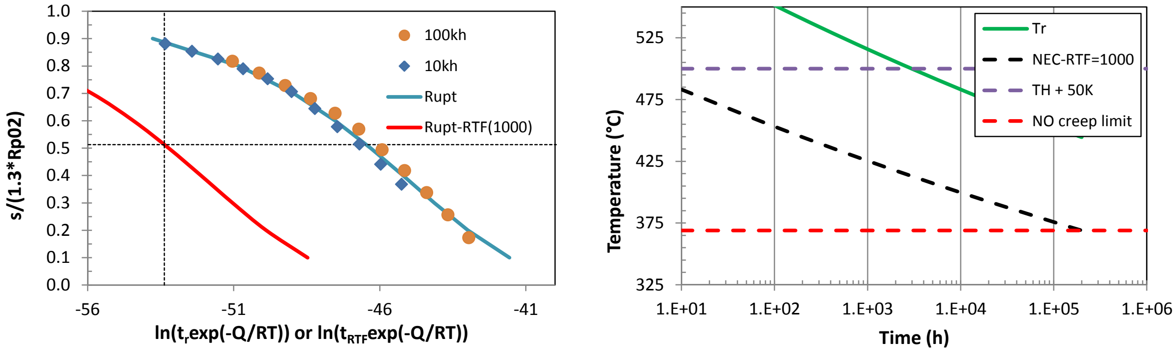

Figure 16. WE model and T_{NEC} curve for 15NiCuMoNb5-6-4 steel. The calculated T_{NC} temperature is 369°C. Note that RTF=1000 for this steel might be conservative for time to 0.2% creep strain.

The 1% creep strain strength assessment is presented in Figure. There seems to be a difference in the optimal Q for rupture and 1% creep strength.

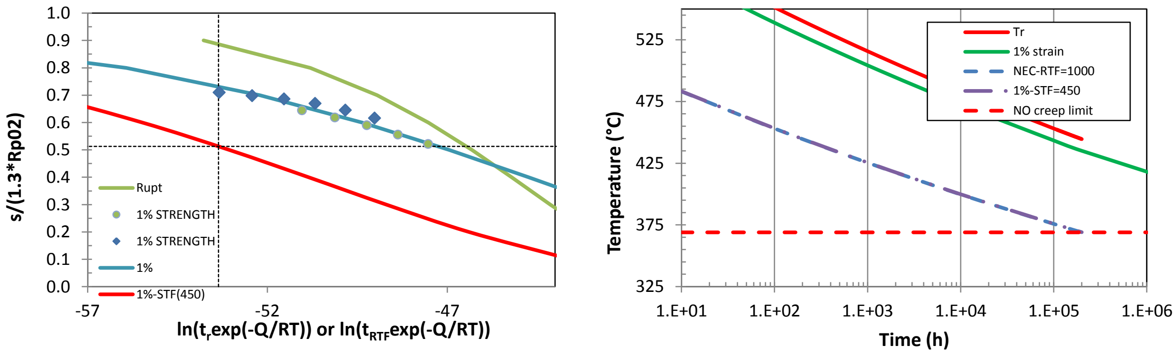

Figure. Time to 1% creep strain WE model for 15NiCuMoNb5-6-4 steel. The ratio $t_r/t_{1\%}$ is about 1.7

13CrMo4-5

The steel 13CrMo4-5 WE model and the T_{NEC} curve are shown in Figure 17.

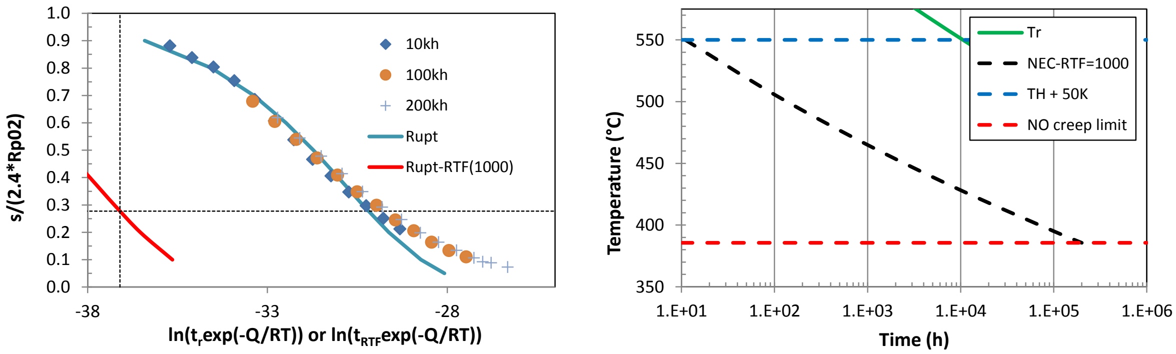

Figure 17. WE model and T_{NEC} curve for 13CrMo4-5 steel. The calculated T_{NC} temperature is 386°C.

The 1% creep strain strength assessment is presented in Figure 18. Note that the conservative choice of isochrone (10 kh) for the WE fit leads to crossing of the rupture and 1% creep strain models at low stress values.

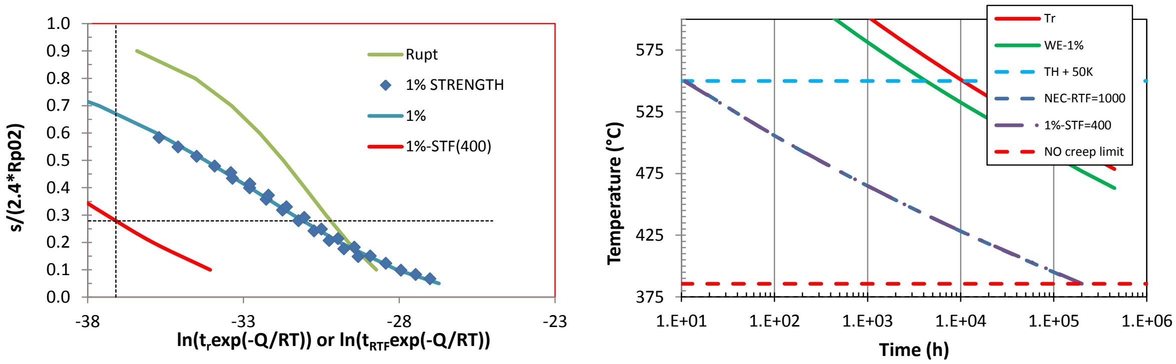

Figure 18. Time to 1% creep strain WE model for 13CrMo4-5 steel. The ratio $t_r/t_{1\%}$ is about 1.7

13CrMoSi5-5

The steel 13CrMoSi5-5 WE model and the T_{NEC} curve are shown in Figure 19.

Note that there are only 100 000 h creep strength and 1% strength values for this steel. The optimization (determination) of the activation energy Q is therefore not possible for this steel.

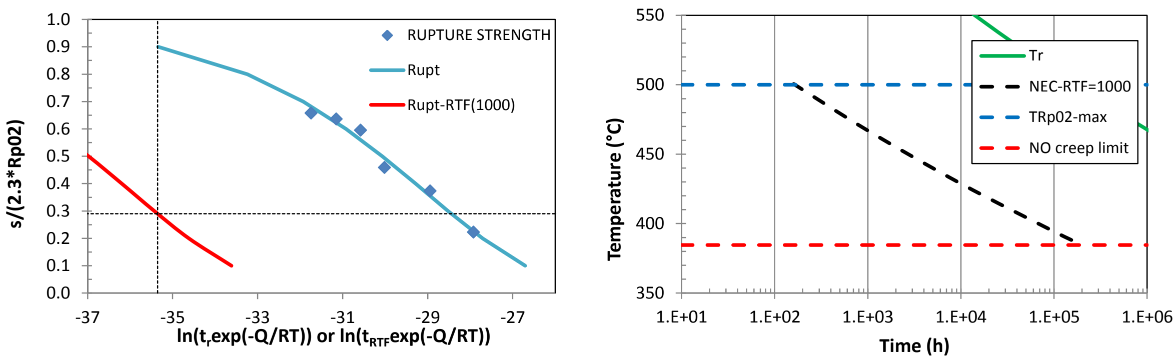

Figure 19. WE model and T_{NEC} curve for 13CrMoSi5-5 steel. The calculated T_{NC} temperature is 385°C.

The 1% creep strain strength assessment is presented in Figure 20.

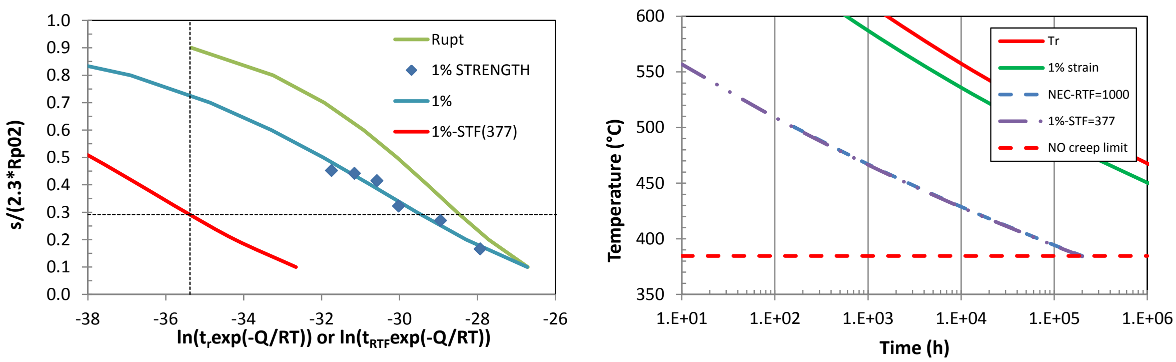

Figure 20. Time to 1% creep strain WE model for 13CrMoSi5-5 steel. The ratio $t_r/t_{1\%}$ is about 2.7

It is advisable to find more rupture data or standard strength values before introducing T_{NEC} and T_{NC} temperatures for this material in the EN-13445.

10CrMo9-10

The steel 10CrMo9-10 WE model and the T_{NEC} curve are shown in Figure 21. Note that this steel was extensively assessed with creep strain data and passed conservatively the time to 0.2% creep strain data available [2]. The material specific RFT complying with time to 0.2% creep strain is RTF=~30.

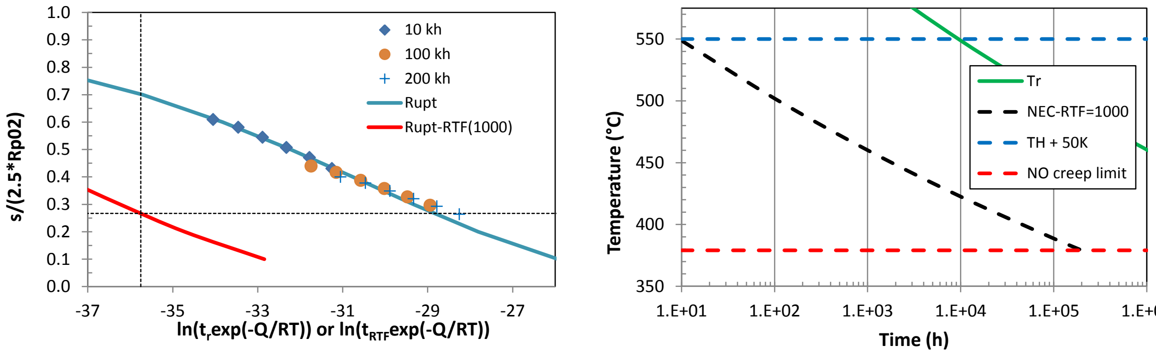

Figure 21. WE model and T_{NEC} curve for 10CrMo9-10 steel. The calculated T_{NC} temperature is 379°C.

The 1% creep strain strength assessment is presented in Figure 22.

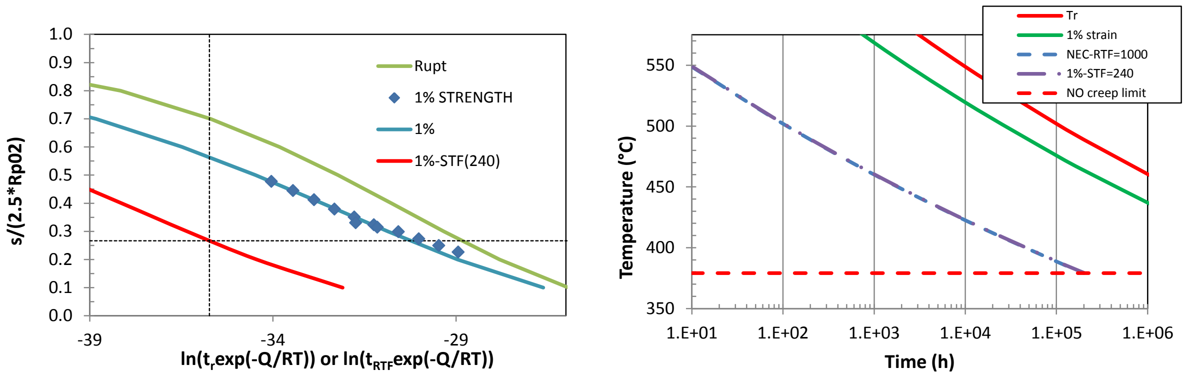

Figure 22. Time to 1% creep strain WE model for 10CrMo9-10. The ratio $t_r/t_{1\%}$ is about 4.2

12CrMo9-10

The steel 12CrMo9-10 WE model and the T_{NEC} curve are shown in Figure 23.

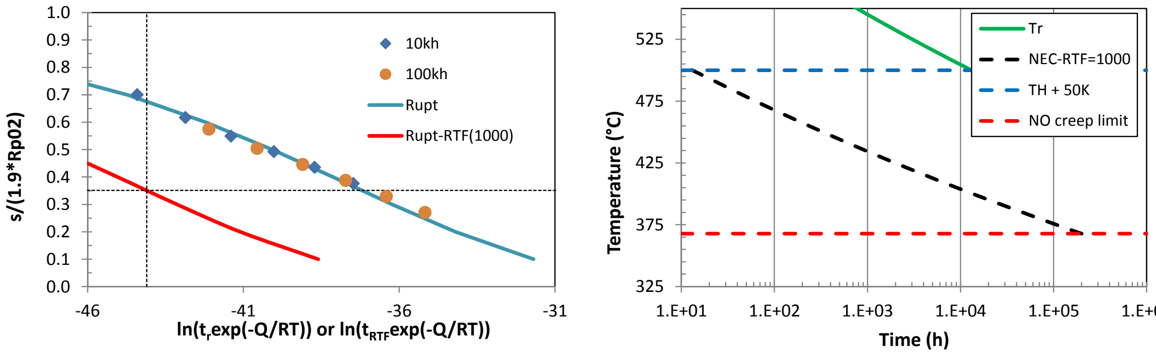

Figure 23. WE model and T_{NEC} curve for 12CrMo9-10 steel. The calculated T_{NC} temperature is 368°C. Note that RTF=1000 for this steel might be conservative for time to 0.2% creep strain.

For this steel there is no 1% creep strength data.

X12CrMo5

The steel X12CrMo5 WE model and the T_{NEC} curve are shown in Figure 24. Note that there are only 10kh data (both rupture and 1% strain) and that the reference stress is above the available creep data indicating unfavourable combination of high tensile properties and low creep properties. The determination of the activation energy Q is also not possible for this steel.

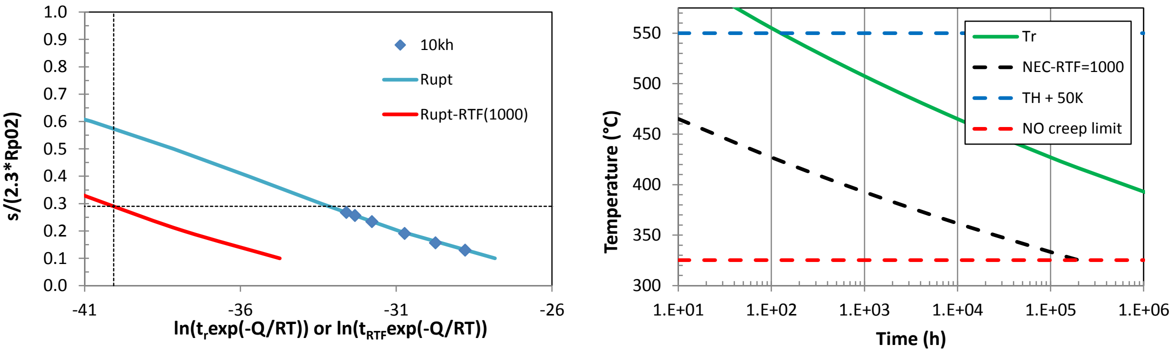

Figure 24. WE model and T_{NEC} curve for X12CrMo5 steel. The calculated T_{NC} temperature is 325°C. Note that RTF=1000 for this steel might be conservative for time to 0.2% creep strain.

The 1% creep strain strength assessment is presented in Figure 25.

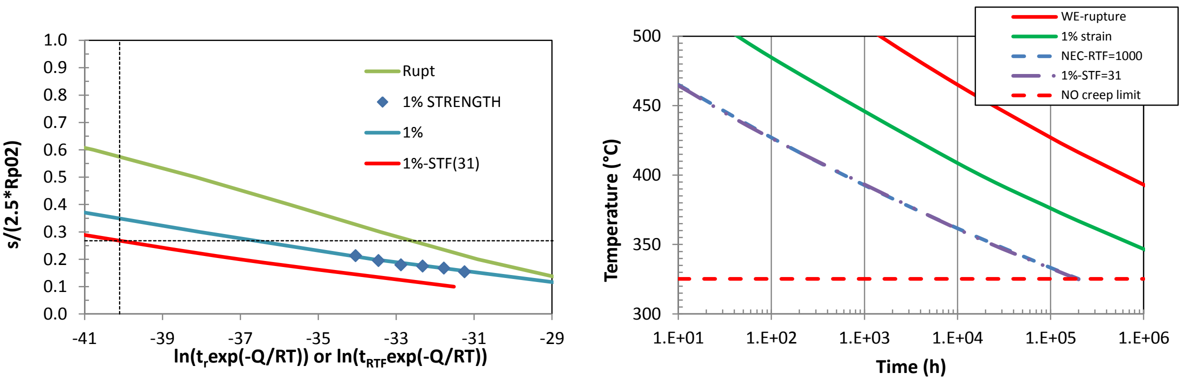

Figure 25. Time to 1% creep strain WE model for X12CrMo5 steel.

It is not advisable to introduce T_{NEC} and T_{NC} temperatures for this material in the EN-13445.

13CrMoV9-10

The steel 13CrMoV9-10 WE model and the T_{NEC} curve are shown in Figure 26. Note that the tensile properties are the same as for 12CrMoV12-10. For this steel there is no 1% creep strength data.

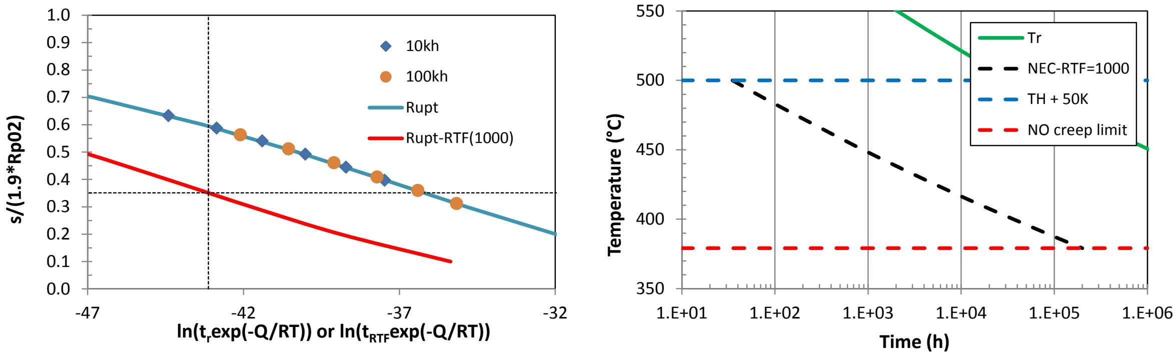

Figure 26. WE model and T_{NEC} curve for 13CrMoV9-10 steel. The calculated T_{NC} temperature is 379°C.

For this steel there is no 1% creep strength data.

12CrMoV12-10

The steel 12CrMoV12-10 WE model and the T_{NEC} curve are shown in Figure 27. Note that the tensile properties are the same as for 13CrMoV9-10.

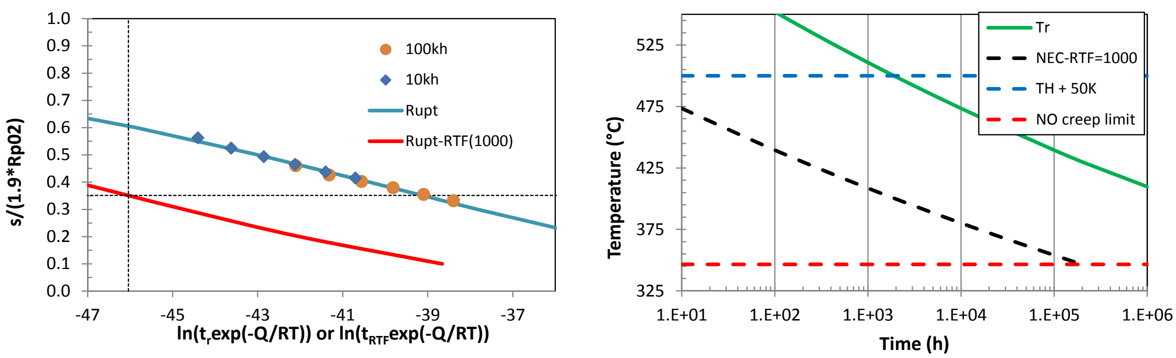

Figure 27. WE model and T_{NEC} curve for 12CrMoV12-10 steel. The calculated T_{NC} temperature is 347°C. Note that RTF=1000 for this steel might be conservative for time to 0.2% creep strain.

For this steel there is no 1% creep strength data.

X10CrMoVNb9-1

The steel X10CrMoVNb9-1 WE model and the T_{NEC} curve are shown in Figure 28. Note that this steel was used for the development of the NEC curve determination method [1][2]. The RTF of 1000 used in Eq.2 corrects the rupture time to achieve overlap with 0.2% creep strain data.

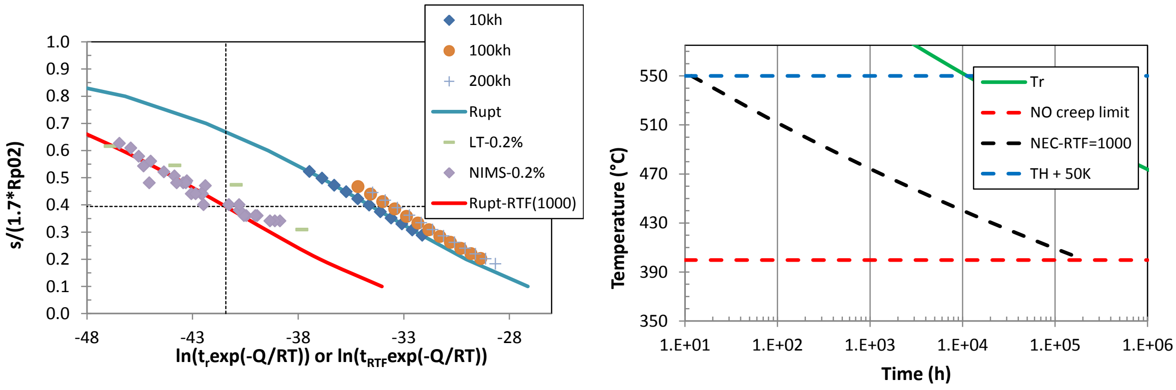

Figure 28. WE model and T_{NEC} curve for steel X10CrMoVNb9-1. The calculated T_{NC} temperature is 400°C. The NIMS and JRC data given in the WE plot are measured time to 0.2% creep strain data.

For this steel there is no 1% creep strength data in EN10028-2.

AUSTENITIC STEELS:

X3CrNiMoBN17-13-3 (1.4910, AISI 316LNB)

The steel X3CrNiMoBN17-13-3 WE model and the T_{NEC} curve are shown in Figure 29. The reference stress is in the mid-range of the 100kh creep data.

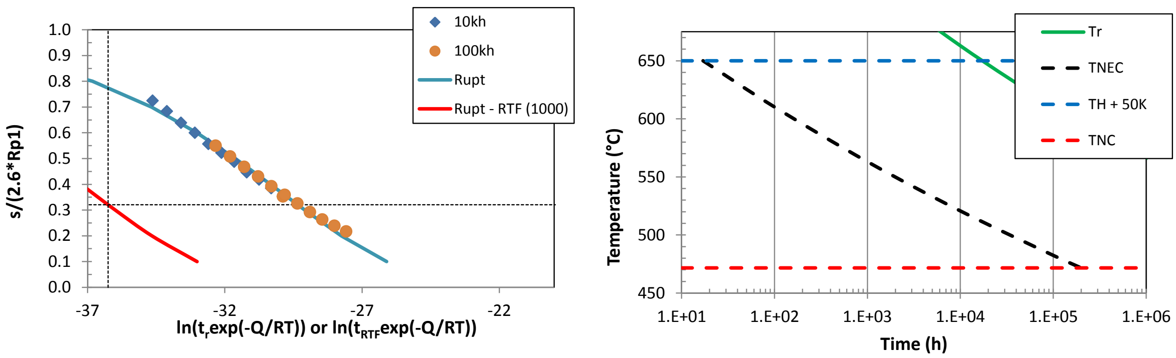

Figure 29. WE model and T_{NEC} curve for X3CrNiMoBN17-13-3 steel. The calculated T_{NC} temperature is 472°C.

For this steel there is no 1% creep strength data in EN10028-7.

X6CrNiTiB18-10 (1.4948, AISI 321H)

The steel X6CrNiTiB18-10 WE model and the T_{NEC} curve are shown in Figure 30. The reference stress is close to the centre of the available creep data range.

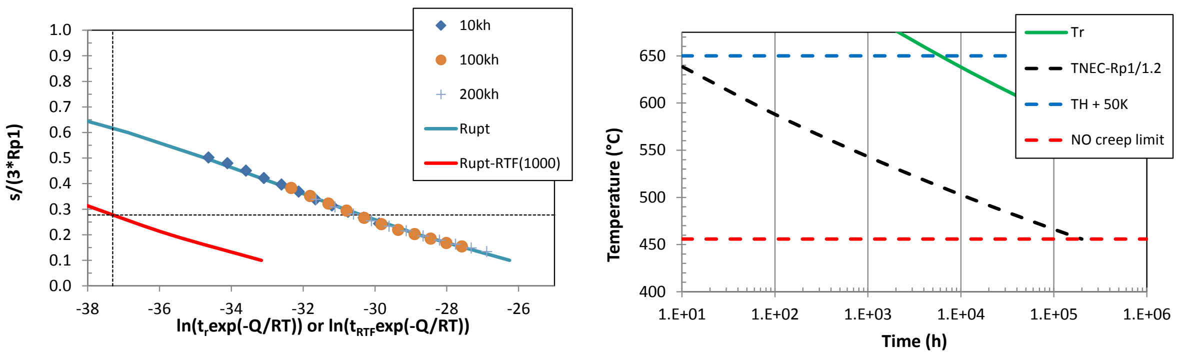

Figure 30. WE model and T_{NEC} curve for X6CrNiTiB18-10 steel. The calculated T_{NC} temperature is 456°C.

For this steel there is no 1% creep strength data in EN10028-7.

X6CrNi18-10 (1.4948, AISI 304H)

The steel X6CrNi18-10 WE model and the T_{NEC} curve are shown in Figure 31. The reference stress is in the lower range of the 100 000h creep strength data. Note that the chosen Q=250kJ/mol is the lowest of the austenitic steels. An even lower Q value would have further improved the overlap of the isochrones.

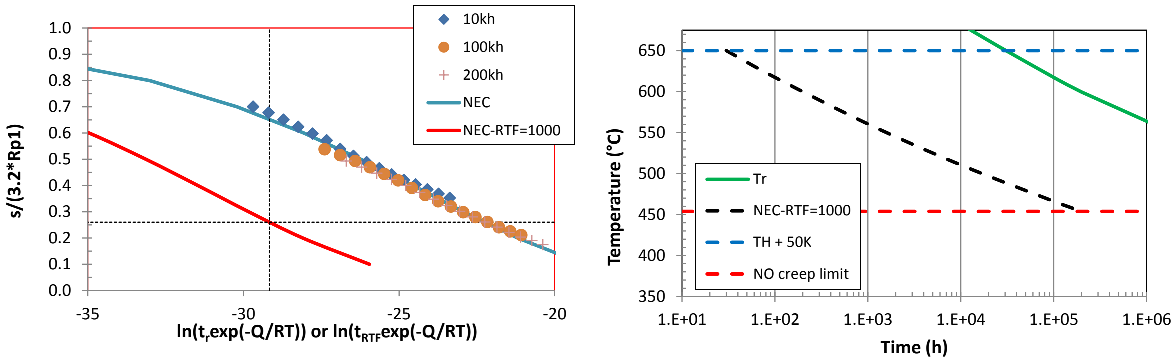

Figure 31. WE model and T_{NEC} curve for X6CrNi18-10 steel. The calculated T_{NC} temperature is 454°C.

The material would still reach the lower classical temperature limit of 425°C with a 40kJ/mol lower activation energy.

X6CrNi23-13 (AISI 309S)

The steel X6CrNi23-13 WE model and the T_{NEC} curve are shown in Figure 32. The reference stress is in the mid-range of the very scares creep rupture data. Note that the small amount of creep rupture data makes the optimization of Q difficult. The activation energy Q=300 kJ/mol was chosen to comply with the similar steel X6CrNi25-20 (below) even though a clearly lower value was more optimal for overlapping the isochronous curves. Also, if the 10 000 h data is used instead of the more conservative fit for 100 000h rupture strength, the T_{NEC} and T_{NC} temperatures increases above 425°C.

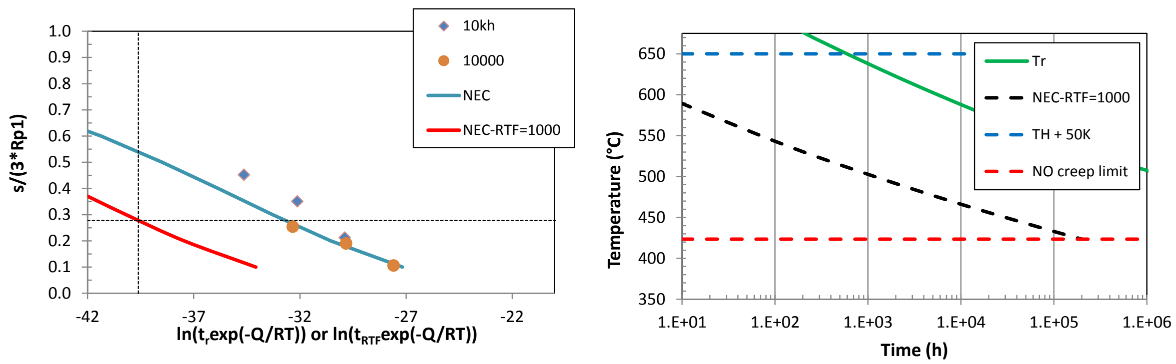

Figure 32. WE model and T_{NEC} curve for X6CrNi23-13 steel. Note that the calculated T_{NC} temperature is 423°C.

There is clearly too little data for robust calculation of Q, and thus the T_{NEC} and T_{NC} are less reliable. It is not recommended that the curve is included in EN-13445.

X6CrNi25-20 (AISI 310S)

The steel X6CrNi25-20 WE model and the T_{NEC} curve are shown in Figure 33. The reference stress is in the lower range of the 10kh creep data.

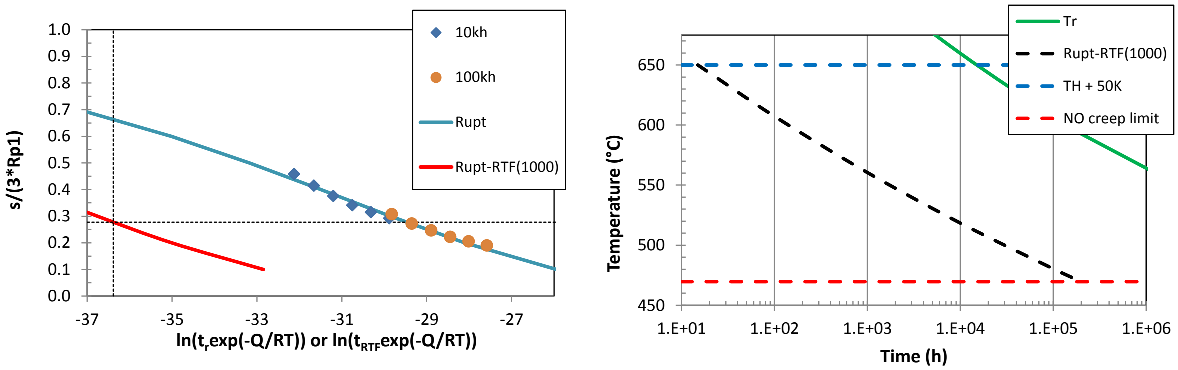

Figure 33. WE model and T_{NEC} curve for X6CrNi25-20 steel. The calculated T_{NC} temperature is 470°C.

X5NiCrAlTi31-20 and X5NiCrAlTi31-20+RA (Alloy-800)

The WE models for steel X6NiCrAlTi31-20 and X6NiCrAlTi31-20 (+RA) and the T_{NEC} curve are shown in Figure 34. The reference stress is in the lower region of the available creep data for the solution annealed steel (Figure 34-A) and in the higher for the crystallizing annealed version +RA (Figure 34-B). Note that the +RA version has a higher reference stress and inferior creep strength.

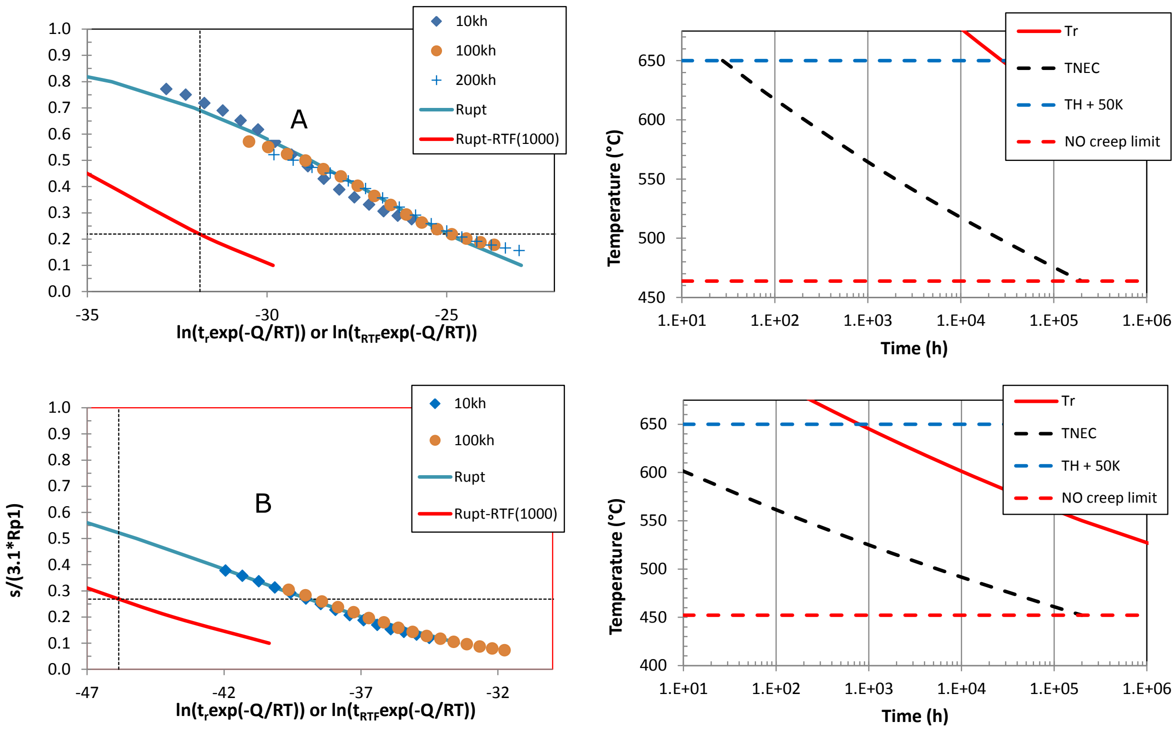

Figure 34. WE model and T_{NEC} curve for A) solution annealed X5NiCrAlTi31-20 and B) re-crystallizing annealed version (+RA). The calculated T_{NC} temperatures are 464°C and 452°C respectively.

X8NiCrAlTi32-21 (Alloy 800H)

The steel X8NiCrAlTi32-21 WE model and the T_{NEC} curve are shown in Figure 35. Note that the reference stress is above the available creep data stress range and the lowest temperature with creep data in the standard is 700°C making the extrapolation range in temperature extensive.

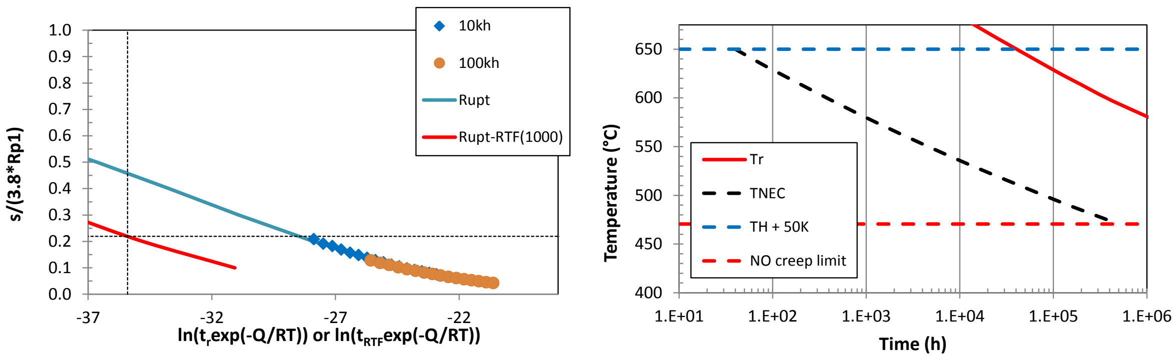

Figure 35. WE model and T_{NEC} curve for X8NiCrAlTi32-21 steel. The calculated T_{NC} temperature is 485°C.

X8CrNiNb16-13 (347H)

The steel X8CrNiNb16-13 WE model and the T_{NEC} curve are shown in Figure 36. The reference stress is in mid-range of the available creep data. The lowest temperature for which creep strength data is available is 580°C.

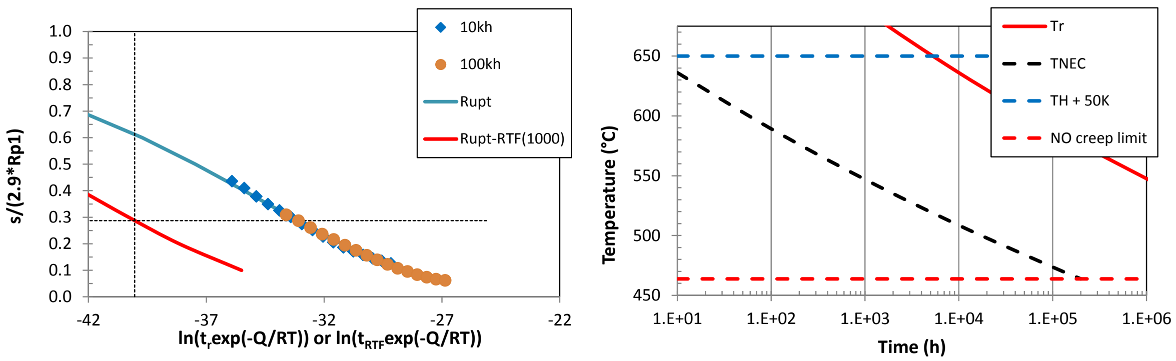

Figure 36. WE model and T_{NEC} curve for X8CrNiNb16-13 steel. The calculated T_{NC} temperature is 464°C.

Tabulated assessment results

The results of the assessments using steel properties of EN10028-2 and EN10028-7 are presented for the individual steels together with the resulting T_{NEC} curves. The material specific WE fitting factors are given in Table 3-4 and the simplified parameters to be used in the revision of the standard are given in Table 5-6 and the calculated T_{NEC} temperatures and reference stresses at t_{NEC} = 10, 100, 1000, 10 000 and 100 000 and 200 000 h are given in Table 7-8.

Table 3. Fitted parameters Q, k, u (Eq.3) of the time to rupture WE model for non-alloy and alloy steels (EN10028-2) and the pre-defined A parameter.

Steel name	Q (J/mol)	k	u	A
P235GH	256000	4.8893E+02	1.8079E-01	2.8
P265GH	256000	1.8548E+02	1.4828E-01	2.9
P295GH	300000	1.4012E+03	1.7567E-01	2.6
P355GH	300000	7.9397E+02	1.6038E-01	2.3
16Mo3	300000	5.5279E+04	2.9591E-01	2.8
18MnMo4-5	300000	4.6763E+04	2.9279E-01	2.1
20MnMoNi4-5	330000	1.8662E+02	1.1222E-01	1.9
15NiCuMoNb5-6-4	350000	8.3250E+04	2.5253E-01	1.3
13CrMo4-5	270000	2.3630E+05	4.0158E-01	2.4
13CrMoSi5-5	260000	3.3423E+04	3.5847E-01	2.3
10CrMo9-10	260000	3.2559E+02	1.9091E-01	2.5
12CrMo9-10	300000	2.1438E+02	1.4306E-01	1.9
X12CrMo5	260000	5.8653E+01	1.1634E-01	2.3
13CrMoV9-10	300000	4.1302E+01	1.0146E-01	1.9
12CrMoV12-10	300000	6.8283E+01	1.0676E-01	1.9
X10CrMoVNb9-1	300000	6.5557E+01	1.2321E-01	1.7

Table 4. Fitted parameters Q, k, u (Eq.3) of the time to rupture WE model for austenitic steels (EN10028-7) and the pre-defined A parameter. Note the seemingly low Q for X6CrNi23-13 steel.

Steel name	Q (J/mol)	k	u	A
X3CrNiMoBN17-13-3	300000	6.7652E+02	2.1770E-01	2.6
X6CrNiTiB18-10	300000	9.4978E+01	1.4168E-01	3.0
X6CrNi18-10	250000	5.5439E+01	1.6706E-01	3.2
X6CrNi23-13	300000	4.1070E+01	1.0605E-01	3.0
X6CrNi25-20	300000	1.7005E+02	1.6584E-01	3.0
X5NiCrAlTi31-20	300000	3.7009E+02	1.8935E-01	3.8
X5NiCrAlTi31-20 (+RA)	350000	7.0224E+01	1.0219E-01	3.1
X8NiCrAlTi32-21	300000	2.3526E+01	9.6186E-02	3.8
X8CrNiNb16-13	320000	1.1037E+02	1.3533E-01	2.9

Table 5. Simplified model parameters for defining T_{NEC} temperature (Eq-1 and Eq-5) as a function of time (t_{NEC}) for non-alloy and alloy steels. Note that the temperature calculated with these values is in K.

Steel name	C_1	C_2	C_3	C_4
P235GH	30791	-2.04500E-03	0.23929	-5.5314
P265GH	30791	-5.39100E-03	0.23103	-6.7441
P295GH	36084	-7.14000E-04	0.25769	-5.6923
P355GH	36084	-1.25900E-03	0.29130	-6.2353
16Mo3	36084	-1.80000E-05	0.23929	-3.3794
18MnMo4-5	36084	-1.10000E-05	0.31905	-3.1669
20MnMoNi4-5	39692	-5.35900E-03	0.35088	-8.9111
15NiCuMoNb5-6-4	42098	-1.20000E-05	0.51282	-3.9599
13CrMo4-5	32475	-4.23190E-06	0.27778	-2.4901
13CrMoSi5-5	31273	-2.99196E-05	0.291300	-2.7896
10CrMo9-10	31273	-3.07131E-03	0.26800	-5.2380
12CrMo9-10	36084	-4.66457E-03	0.35263	-6.9899

Steel name	C_1	C_2	C_3	C_4
X12CrMo5	31273	-1.70494E-02	0.29130	-8.5955
13CrMoV9-10	36084	-2.42116E-02	0.35263	-9.8558
12CrMoV12-10	36084	-1.46449E-02	0.35263	-9.3672
X10CrMoVNb9-1	36084	-1.52540E-02	0.39412	-8.1163

*Note that the yield properties of steels 13CrMoV9-10 and 12CrMoV12-10 are the same in standard 10028-2.

Table 6. Simplified parameters for defining T_{NEC} temperature (Eq-1 and Eq-5) as a function of time (t_{NEC}) for austenitic steels. Note that the temperature calculated with these values is in K.

Steel name	C_1	C_2	C_3	C_4
X3CrNiMoBN17-13-3	36084	-0.001478151	0.32051	-4.5935
X6CrNiTiB18-10	36084	-0.010528759	0.27778	-7.0583
X6CrNi18-10	30070	-0.018037971	0.26042	-6.0434
X6CrNi23-13	36084	-0.02434847	0.27778	-9.4294
X6CrNi25-20	36084	-0.005880624	0.27778	-6.0299
X5NiCrAlTi31-20	32475	-0.003974411	0.2193	-4.8841
X5NiCrAlTi31-20 (+RA)	42098	-0.01424023	0.26882	-9.7858
X8NiCrAlTi32-21	36084	-0.042505277	0.2193	-10.3965
X8CrNiNb16-13	38489	-0.009060362	0.28736	-7.3892

Table 7. Maximum temperature of negligible creep T_{NEC} (°C) and the reference stress σ_{ref}(MPa) at specified times t_{NEC} (h) . Note that T_{NEC} for 200kh = T_{NC}. and if $T_{NEC} \geq T_H$+50K then $T_{NEC}=T_H$+50K.

Steel name / t_{NEC}		10 h	100 h	10^3 h	10^4 h	10^5 h	$2 \cdot 10^5$ h (T_{NC})
P235GH	T_{NEC}	450	430	395	363	334	326
	σ_{ref}	87	87	90	93	97	98
P265GH	T_{NEC}	450	424	390	358	330	322
	σ_{ref}	97	99	102	106	110	112
P295GH	T_{NEC}	450	434	404	376	350	343
	σ_{ref}	109	109	112	115	119	120

Steel name / t_{NEC}		10 h	100 h	10^3 h	10^4 h	10^5 h	$2\cdot10^5$ h (T_{NC})
P355GH	T_{NEC}	450	423	393	366	341	334
	σ_{ref}	132	133	136	140	145	147
16Mo3	T_{NEC}	533	493	458	425	395	385
	σ_{ref}	94	95	98	102	108	109
18MnMo4-5	T_{NEC}	500	492	456	424	394	385
	σ_{ref}	119	123	139	152	163	165
20MnMoNi4-5	T_{NEC}	447	416	387	360	335	328
	σ_{ref}	241	251	260	266	271	272
15NiCuMoNb5-6-4	T_{NEC}	487	451	419	390	363	356
	σ_{ref}	209	220	229	236	242	243
13CrMo4-5	T_{NEC}	550	506	465	428	395	386
	σ_{ref}	102	109	114	120	125	127
13CrMoSi5-5	T_{NEC}	500	501	467	429	394	385
	σ_{ref}	132	131	136	140	144	146
10CrMo9-10	T_{NEC}	548	502	460	423	389	379
	σ_{ref}	106	121	132	139	145	146
12CrMo9-10	T_{NEC}	500	468	434	404	376	368
	σ_{ref}	178	184	188	191	193	194
X12CrMo5	T_{NEC}	465	427	393	362	333	325
	σ_{ref}	163	176	184	189	192	192
13CrMoV9-10	T_{NEC}	500	483	448	416	387	379
	σ_{ref}	226	229	234	237	240	240
12CrMoV12-10	T_{NEC}	473	440	409	380	354	347
	σ_{ref}	231	235	238	240	242	242
X10CrMoVNb9-1	T_{NEC}	550	512	474	440	417	400
	σ_{ref}	196	212	225	234	239	242

Table 8. Maximum temperature of negligible creep T_{NEC} (°C) and reference stress σ_{ref}(MPa) at specified times t_{NEC} (h). Note that T_{NEC} for 200 000h = $T_{NC.}$ and if $T_{NEC} \geq T_H$+50K then $T_{NEC}=T_H$+50K.

Steel name / t_{NEC}		**10 h**	**100 h**	**10^3 h**	**10^4 h**	**10^5 h**	**$2 \cdot 10^5$ h (T_{NC})**
X3CrNioBN17-13-3	T_{NEC}	650	610	563	521	482	472
	σ_{ref}	123	125	128	130	132	132
X6CrNiTiB18-10	T_{NEC}	650	588	543	503	466	456
	σ_{ref}	112	119	124	127	130	131
X6CrNi18-10	T_{NEC}	650	617	561	511	466	454
	σ_{ref}	83	88	94	98	101	102
X6CrNi23-13	T_{NEC}	588	543	503	466	433	423
	σ_{ref}	96	98	100	102	104	105
X6CrNi25-20	T_{NEC}	650	607	560	518	480	470
	σ_{ref}	91	95	97	100	102	102
X5NiCrAlTi31-20	T_{NEC}	650	617	564	518	476	464
	σ_{ref}	78	79	80	81	83	84
X5NiCrAlTi31-20 (+RA)	T_{NEC}	602	561	525	492	461	452
	σ_{ref}	112	116	119	122	124	125
X8NiCrAlTi32-21	T_{NEC}	650	629	580	536	496	485
	σ_{ref}	78	78	79	81	82	83
X8CrNiNb16-13	T_{NEC}	636	589	547	509	474	464
	σ_{ref}	118	119	121	123	125	126

Discussion

The new methodology for determining negligible creep and no-creep temperatures has been applied with the same criteria (RTF=1000) for a number of steels enabling direct comparison of the resulting temperatures. The benefits/capabilities of the materials can now be assessed for selection purposes. In Figure 37 and Figure 38 the reference stresses $\sigma_{ref}(T_{NC})$ and the T_{NC} temperatures are given for the ferritic and the austenitic steels.

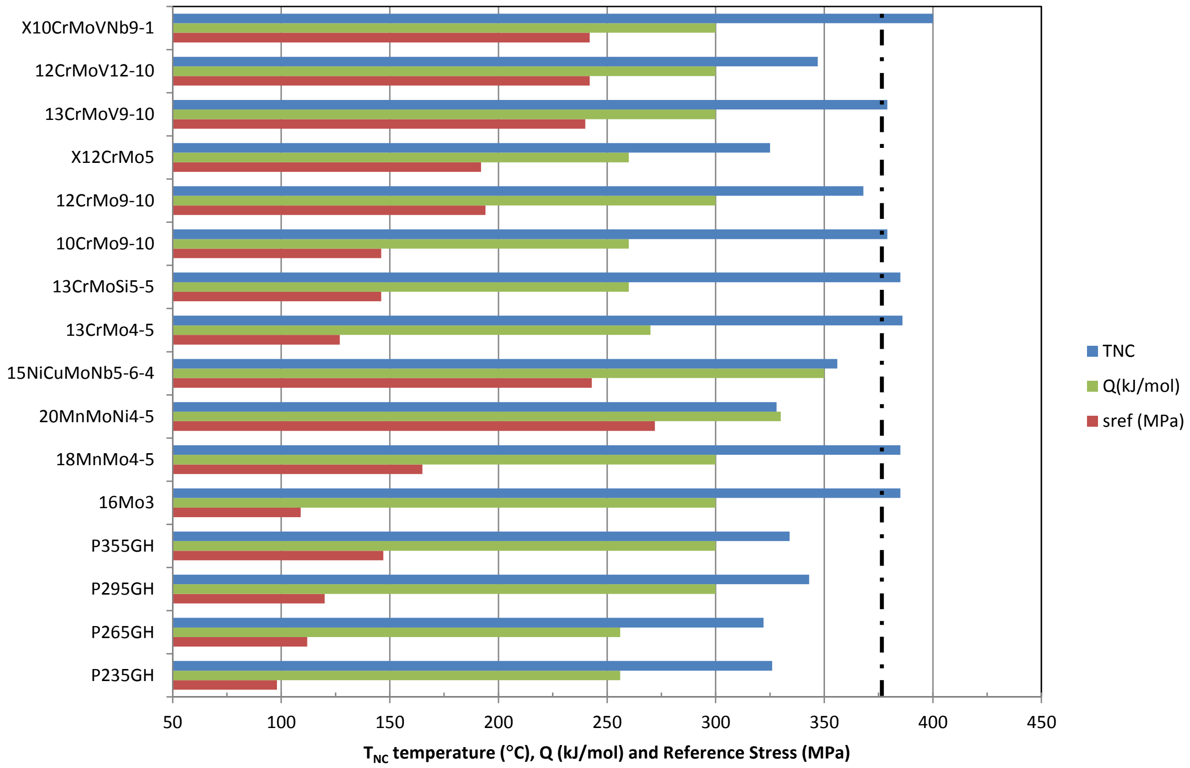

Figure 37. T_{NC}, σ_{ref} and chosen Q for the F/M steels from EN10028-2 in the order given in the standard. The classical temperature limit of 375°C is given as a dash-dot line.

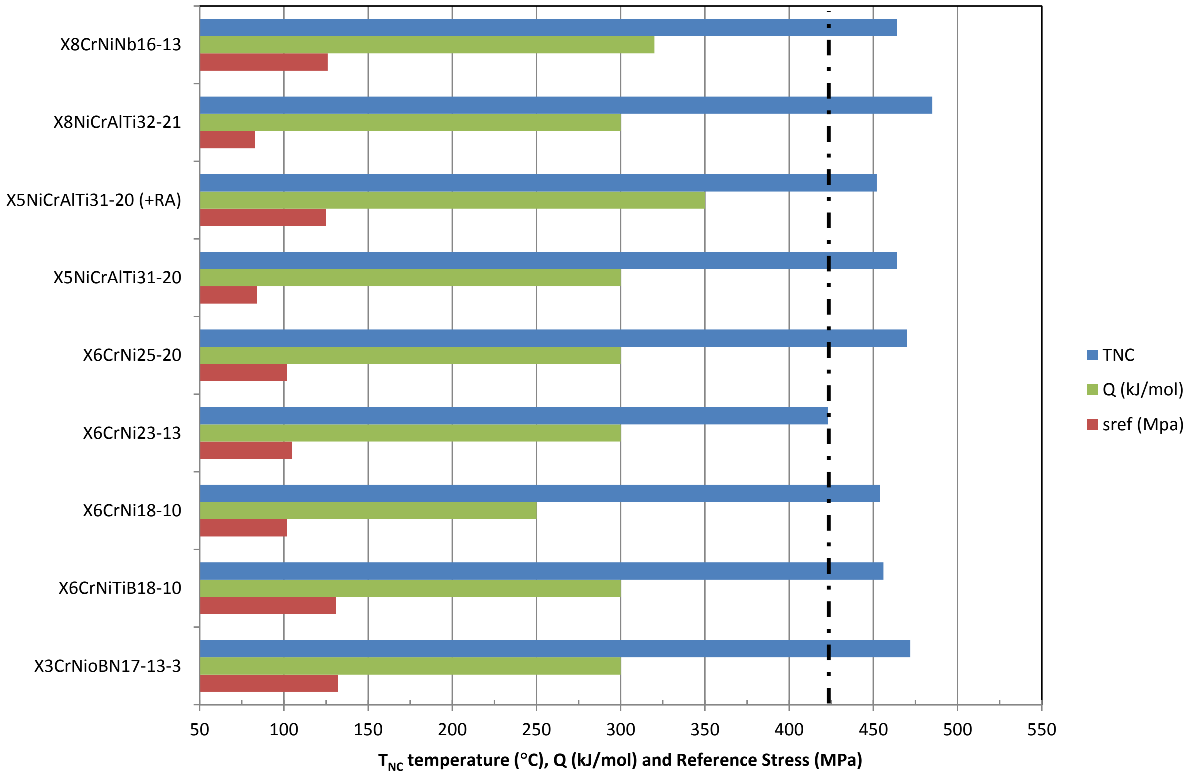

Figure 38. T_{NC}, σ_{ref} and chosen Q for austenitic steels from EN10028-7 in the order given in the standard. The classical temperature limit of 425°C is given as a dash-dot line.

As can be seen the assessment of the austenitic steels generally give T_{NC} temperatures above the classical limit of no creep.

In the assessments the largest uncertainty for the extrapolated T_{NEC} and T_{NC} temperatures is the activation energy Q. The optimization by overlapping isochronous creep rupture data did not always seem to result in similar Q values for steel types where the same creep response was expected. Roughly, a difference of 50 kJ/mol in activation energy changes the T_{NC} with 15°C. A change in RTF of a factor of 4 changes the T_{NC} at the reference stress about the same amount.

In the case of Ferritic-Martensitic steels the creep resistant steels reached the classical T_{NC} temperatures easily. For carbon-manganese steels and low alloy steels this was not the case. However, applying time to 0.2% creep strain data found in the literature to calibrate (the much lower) RTF values, give T_{NC} temperatures approaching the classical value. For instance the old British data on C-Mn steels [10] indicate that RTF values could be as low as 35. Clearly the worst combination for low T_{NC} temperatures is high yield strength in combination with low creep strength and isochrones overlapping at low activation energy values.

The strain specific RTF for low alloyed and carbon-manganese steels will be studied in the WG59 in the near future.

Furthermore, the conservatism of the proposed T_{NEC} temperatures should be cross checked with any available low temperature low stress tests data to show that the targeted maximum of 0.2% creep strain is not reached at the t_{NEC}. Also, the need of weld strength reduction factors for creep at T_{NEC} temperatures should be investigated more closely. For the time being no weld correction is suggested for the T_{NEC} calculation.

For the revision of EN13445 the following is recommended:

1. For materials clearly satisfying the classical limits of no-creep temperatures and has optimized activation energies in the expected range the T_{NEC} and T_{NC} curves could be published in the informative Annex V.
2. For materials not satisfying the above criteria the following could be recommended;
    a. base the T_{NEC} on WE assessment on time to 0.2% creep strain data, i.e. no time factors required. This option needs a sufficient amount of 0.2% data
    b. base the T_{NEC} on WE rupture assessment but define a material specific RTF value based on available time to 0.2% creep strain (less data needed)
    c. base the T_{NEC} on 1% creep strain and define a conservative STF value
3. It is also recommended that a further design stress limit would be introduced in EN-13445 limiting the design stress below 1/3 R_m. For some low alloy steels this would decrease the allowable design stress to a level where the T_{NC} approaches the classical values.

Conclusions

- The WE model has been used to define T_{NEC} and T_{NC} temperatures for all the steels in EN10028-2 and -7
- Each steel has a calculated (single) T_{NEC} curve based on the individual standard tensile and creep strength properties
- The T_{NEC} curves for welds can be attained from the base material ones by using the weld strength factors defined in EN13445, but the rationale in using a z_c at negligible creep temperatures is still under debate.
- The strain-time factor for 1% strain (STF) can be used for increasing the confidence in the conservatism of the chosen rupture time factor (RTF) or used as base for T_{NEC} calculation. This needs a defined conservative STF.
- The calculated T_{NEC} and T_{NC} temperatures can be used for material selection for specific stress-strain ranges.

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List of abbreviations and definitions

Miscellaneous:

NEC Negligible Creep

NC No-Creep

WE Wilshire model for creep rupture or strain

Strain and Stress:

ε Strain (%)

$f_{nc}(T)$ Time independent nominal design stress at temperature (MPa)

σ, s Stress (MPa)

σ_{ref} Reference stress (MPa), $\sigma_{ref} = 1/1.5 \cdot R_{p0.2}$ or $1/1.2 \cdot R_{p1}$ (i.e. definition for f_{nc})

R_m Ultimate tensile strength (MPa) at specified T

R_{p02} Yield stress 0.2% (MPa) at specified T

R_{p1} Yield stress 1% (MPa) at specified T

$R_{u/t/T}$ Creep rupture strength (MPa) to time t at temperature T

$R_{p1/t/T}$ Creep stress (MPa) for reaching 1% strain in *t* and specified *T*

S_m Allowable stress / design stress (MPa) of specific design rules

Temperature:

T Absolute Temperature (K)

T_H Maximum temperature (°C) where yield stresses are given in the standard

T_r Temperature-time curve for rupture (°C)

T_{NEC} Temperature-time curve for NEC (°C)

T_{NC} Material specific temperature limit for NC (°C)

Time:

t Time (h)

$t_{1\%}$ Time to 1% creep strain (h) at specified σ and T

t_r Time to rupture (h) at specified σ and T

t_{rW} Time to rupture (h) for welds at specified $\sigma \cdot$WSF and T

t_{NEC} NEC time limit (h) at σ_{ref} and T, $t_{NEC}=t_r/RTF$ (or $t_{NEC}=t_{1\%}/STF$, $t_{NEC}=t_{rW}/WTF$)

t_{RTF} RTF corrected rupture time (h), $t_{RTF}=t_r/RTF$ at arbitrary σ,T

RTF Rupture Time Factor; adjusting t_r to NEC criterion (see t_{NEC} or t_{RTF})

STF Stain Time Factor, as the RFT but for time to 1% creep strain

Welds:

WSF Weld Creep Strength Factor $WSF=1/z_c = 1.25$

WTF Weld Rupture Time Factor, stress reduction by WSF

z_c Weld Creep Strength Reduction Factor, 0.8 as in EN13445 cl. 19.6

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