European
Commission

A study of negligible creep criteria based on EN-10028 standard creep strength and yield properties

Contribution to CEN/TC 54/WG 59 CREEP
MaCoSyMA JRC project deliverable 20149

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November 2014

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Research
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Abstract

For simplified design of components operating at high temperatures it is recommended to design in the No Creep (NC) or Negligible creep (NEC) temperature regimes of the material. In nuclear design rules (such as RCC-MRx), it is possible to disregard creep as design criterion during normal service operation if the temperature, stress and time limits for NEC are respected. It is a challenge to define these limits reliably in the temperature range where creep behavior (time to strain and/or rupture) is traditionally not tested. In the non-nuclear field the European standard EN-13445 for the design of unfired pressure vessels intends to include NEC temperature curves (T_{NEC}) for a number of steels (austenitic, ferritic and ferritic-martensitic steels.). In this report the JRC contribution to the CEN/TC 54/WG CREEP activities are reported. A methodology originated from the FP7 MATTER project is here used for defining the T_{NEC} curves for X10CrMoVNb9-1 (Grade 91) and 10CrMo910 (Grade 22) steels with the limited data available in the material standard EN 10028. The T_{NEC} is successfully determined and validated by the MATTER results for X10CrMoVNb9-1 steel. The T_{NEC} curves are shown to be independent of product form (thickness of pipes). Also the curves are almost identical for both assessed steels. The change in yield and tensile strength seemingly compensates for the change in rupture strength. The approach can now be used for defining the NEC of other steels tabulated in the standards.

List of Acronyms

WE	*Wilshire model for creep rupture or strain*
NEC	*Negligible Creep*
T	*Temperature (°C)*
σ	*Stress (MPa)*
t	*Time (h)*
ε	*Strain (%)*
T_{NEC}	*Temperature-time curve for NEC*
T_{NC}	*Temperature limit for NO creep, 375°C for ferritic steels*
$R_{u/t/T}$	*Creep Rupture strength (MPa) to time t at temperature T*
$R_{p0.2}$, σ_{p02}	*Yield stress (MPa) at specified T*
R_m, σ_{UTS}	*Ultimate tensile strength (MPa) at specified T*
σ_{ref}	*Reference stress (MPa) usually as ($\sigma_{ref}=2/3\cdot R_{p0.2}$)*
t_r	*Time to rupture at specified σ and T*
$t_{\varepsilon 0.2\%}$	*Time to 0.2% strain at σ and T*
SCF	*Stress correction factor used on creep rupture strength*
RTF	*Rupture time factor; adjusting t_r to NEC criterion; $t_\varepsilon(\sigma, T)=t_r(\sigma, T)/RTF$*

Introduction

To avoid expensive implementation of surveillance programs and/or frequent inspections of components (monitoring creep damage) it is recommended to design components to operate in the No Creep (NC) or Negligible creep (NEC) temperature regimes. For nuclear components, it is possible to disregard creep as design criterion during normal service operation if the temperature, stress and time limits for NEC are respected. It is a challenge to define these limits reliably in the temperature range where creep behavior (time to strain and/or rupture) is traditionally not tested. If the designer can show that the component does not exceed the NEC criteria the design can be made without considering time dependent damage accumulation.

In the non-nuclear field the European standard EN-13445 [1] for the design of unfired pressure vessels intends to publish NEC temperature curves (T_{NEC}) for a number of steels (austenitic, ferritic and ferritic-martensitic steels). For this purpose JRC was invited to contribute to the CEN/TC 54/WG CREEP activities on negligible creep, with the final target to update of the draft amendment to Clause 19 of EN 13445-3 for proposing it for Public Enquiry in 2014.

Extensive assessments of the ferritic-martensitic steel X10CrMoVNb9-1 (Grade 91) has been done during 2012-2014 in the MATTER project (FP7) to introduce a T_{NEC} curve for use in the nuclear RCC-MRx design code [2]. The work done in MATTER has been invaluable for the verification of the proposed methodology to define T_{NEC} curves from very scarce data such as standard creep strength and tensile property data sheets (EN-10028 [3]).

Materials and methods

Negligible creep assessments have been performed on the standard creep strength and tensile property sheets of EN-10028 for X10CrMoVNb9-1 (Grade 91) and 10CrMo910 (Grade 22) steels. Background data, methodologies and assessment results from a comprehensive assessment on X10CrMoVNb9-1 steel is used for comparison and verification of the resulting T_{NEC} curves [4]. The extensive assessment was based on MATTER project data and data published by NIMS, Japan [5].

Objectives

The objectives of this work are:

1. Propose and evaluate suitable methods for acquiring the T_{NEC} from standard creep rupture and tensile property data tables (=insufficient data)
2. Verify method on extensive data set (X10CrMoVNb9-1) with sufficient data
3. Apply method on another steel (10CrMo910)
4. Prepare Excel template for T_{NEC} determination
5. Propose T_{NEC} curves and define the methodology for producing them for use in the EN-13445

Defining the T_{NEC} curve

Method 1

The present draft amendment of EN-13445-3 proposes a semi-graphical method for determining the T_{NEC} curve [6]. This method uses tabulated values of creep rupture strength at specified rupture times and temperatures as well as the corresponding yield stress for the definition of the T_{NEC} curve. The yield strength $R_{p0.2}$ and the creep rupture strengths $R_{u/t/T}$ of durations of 10 000, 100 000 and 200 000 h are divided by the same correction factor SCF of 1.5. The reference stress has been defined as $R_{p0.2}$ / 1.5 and the safety on creep rupture is induced by keeping the rupture time the same but lowering the stress by $R_{u/t/T}$ /1.5. The modified rupture and yield curves are plotted against temperature to localize the intersection points. The determination of intersection points are shown in Figure 1 and Figure 2 for X10CrMoVNb9-1 and 10CrMo910 respectively. Note the difference in extrapolations (dashed lines) for acquiring the intersection points.

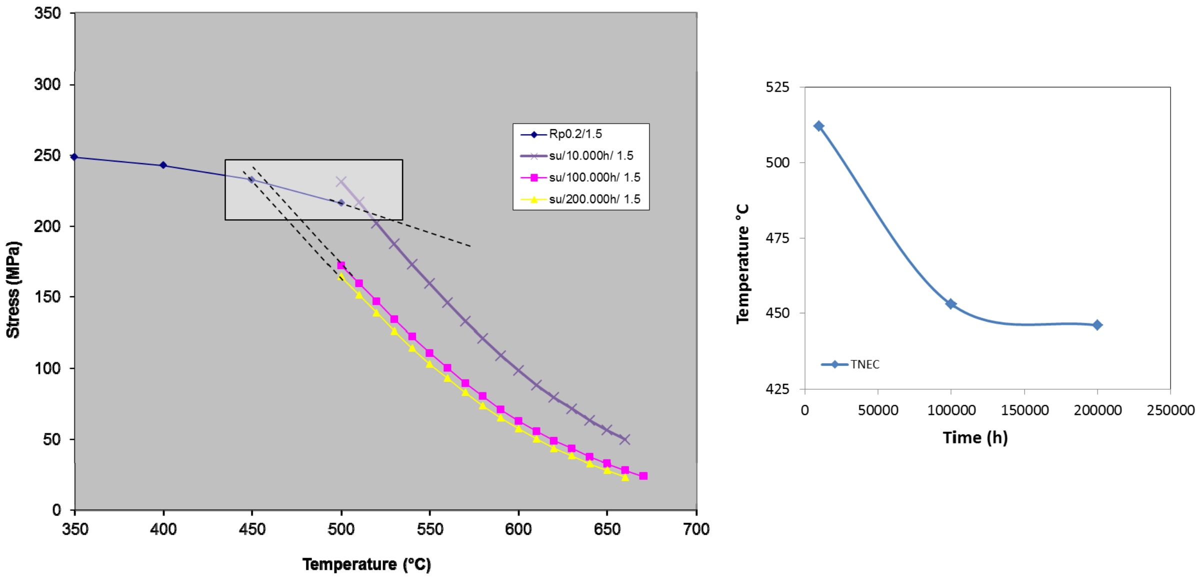

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Figure 1. A) EN-10028 creep rupture properties and yield strengths corrected by proposed reference and creep strength correction factors: Case X10CrMoVNb9-1. B) Proposed T_{NEC} curve.

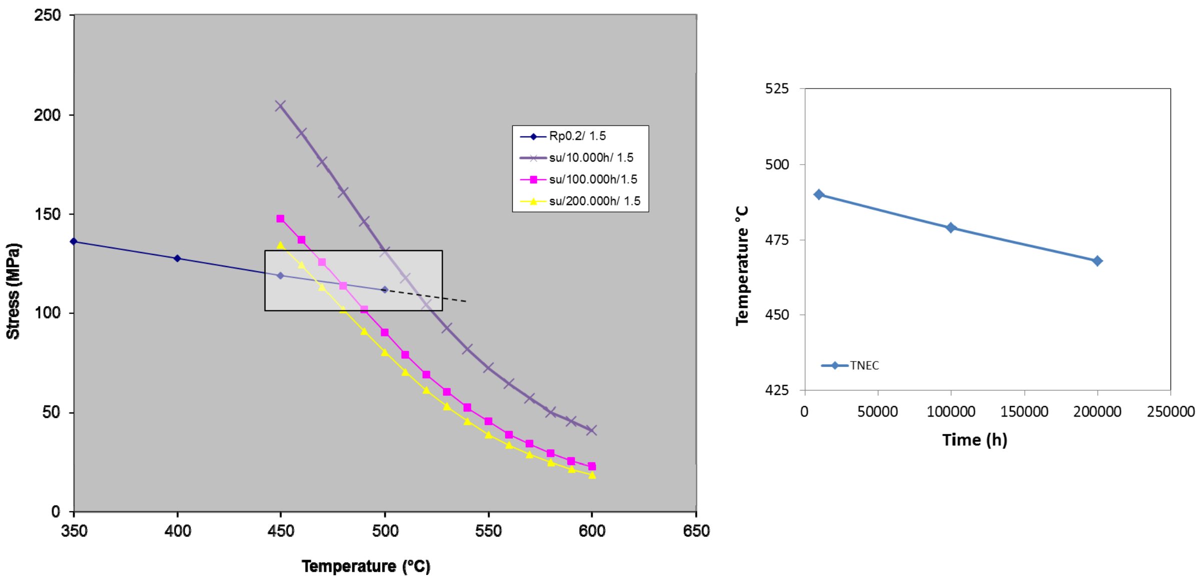

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Figure 2. EN-10028 creep rupture properties and yield strengths corrected by proposed reference and creep strength correction factors: Case 10CrMo910, B) Proposed T_{NEC} curve.

The main challenges of this method to overcome are:

1. Tensile and creep data do not always overlap.
2. Insufficient data causes extrapolations both in rupture strength and in tensile properties.
3. **For shorter durations (< 10 000h) creep rupture extrapolations both in time and temperature have to be made (CRITICAL).**
4. Safety against creep damage/rupture in the NEC temperature regime is brought by the stress correction factor SCF.
5. A rupture time safety factor (RTF) for the generated T_{NEC} is not defined by the method.

Method 2

An alternative methodology has been defined in the MATTER project based on the Wilshire equation (WE) for creep rupture [7]. The model uses stresses normalized either with a factor of yield (here the measured yield/tensile ratio has been used) or the tensile strength.

The WE for time to rupture t_r is:

$$t_r = \left[-\frac{1}{k} \ln\left(\frac{\sigma}{R_m}\right) \right]^{\frac{1}{u}} \cdot \exp\left(\frac{Q}{R \cdot T}\right) \qquad \text{Eq.1}$$

where σ is the test stress and R_m the ultimate tensile strength, i.e. σ/R_m.is the normalized stress, Q the activation energy, R the gas constant and T the absolute temperature.

The normalized stress σ/R_m can be expressed as:

$$\frac{\sigma}{R_m} = \exp\left[-k\left(t_r \cdot \exp\left(\frac{-Q}{R \cdot T}\right)\right)^u \right] \qquad \text{Eq.2}$$

The WE rupture model can then be used with a stress correction factor approach or with a rupture time safety factor (RTF) for defining $T_{NEC.}$ The same equations can be used for time to strain values, as was done in the MATTER project for the comprehensive NIMS data set of X10CrMoVNb9-1 as shown in Figure 3.

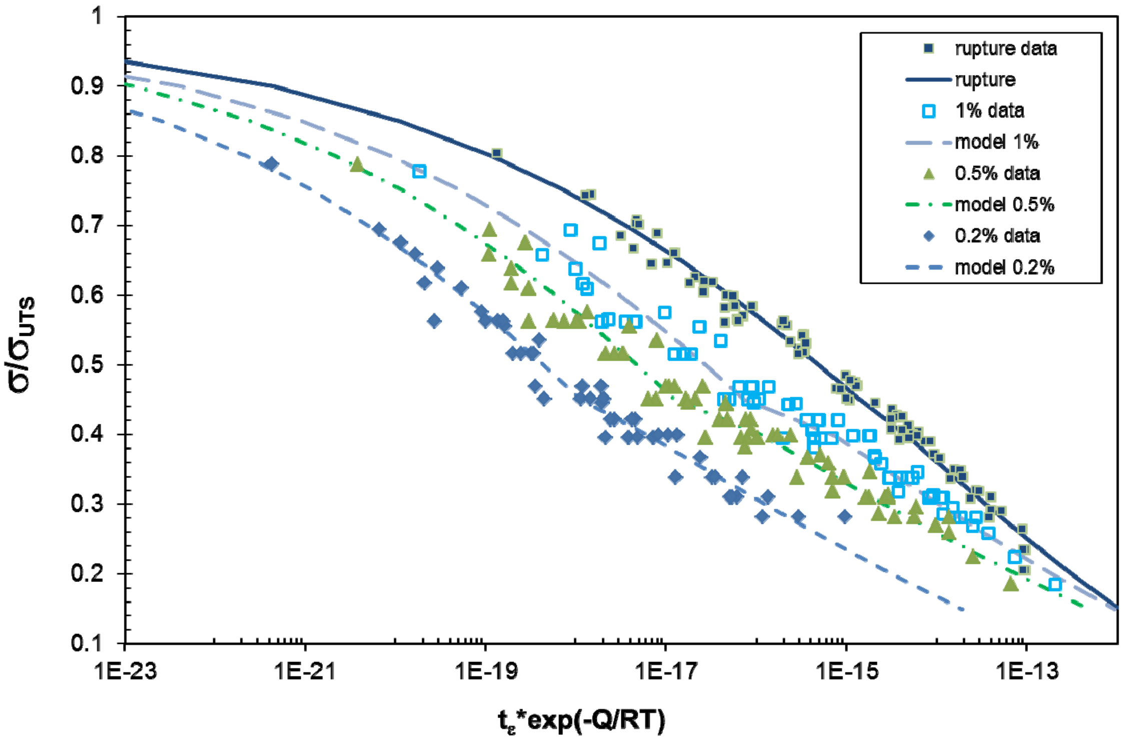

Figure 3. Full creep rupture and creep strain assessment on NIMS creep data

In MATTER the acquired time to strain models, with additional data produced in the temperature range 375-500°C, were used to determine T_{NEC} as illustrated in Figure 4. Note that the higher the reference stress the lower the T_{NEC}; thus if a "conservative" (low) yield stress is used for the reference stress T_{NEC} will be higher.

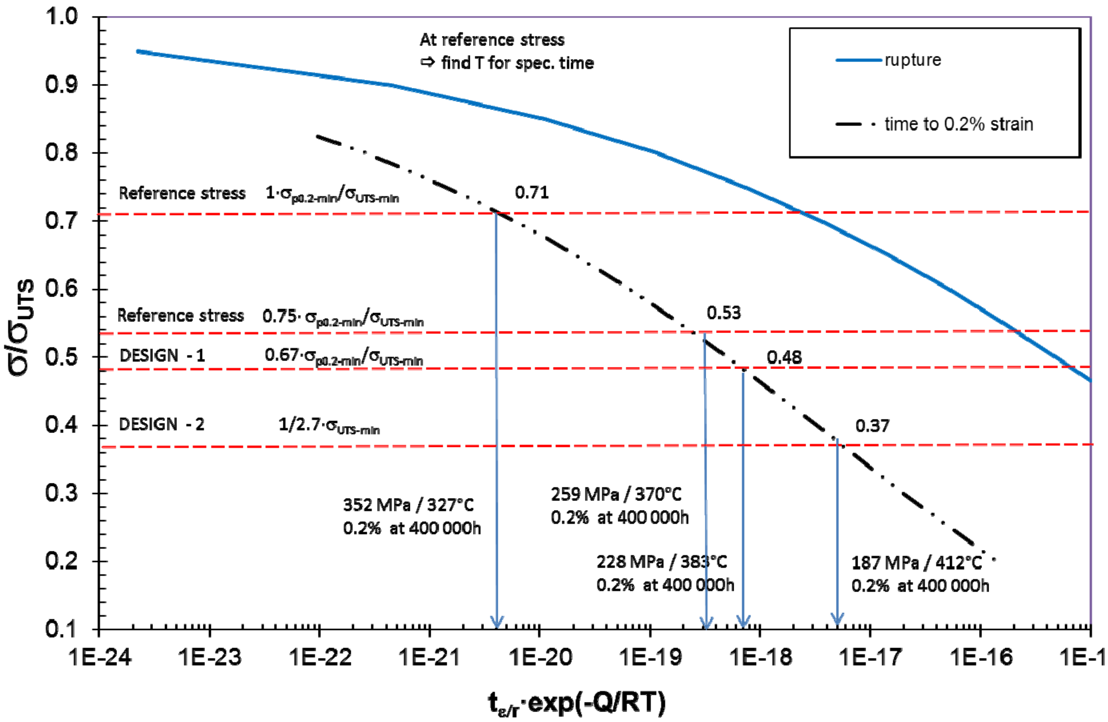

Figure 4. T_{NEC} predictions at different reference stresses using RCC-MRx minimum tensile strength and yield properties

The rupture time correction factor (RTF, see Eq.3) needed to overlap the creep rupture model with the time to 0.2% strain was also determined as shown in Figure 5.

$$t_{0.2\%} = \frac{t_r}{RTF} \qquad \text{Eq.3}$$

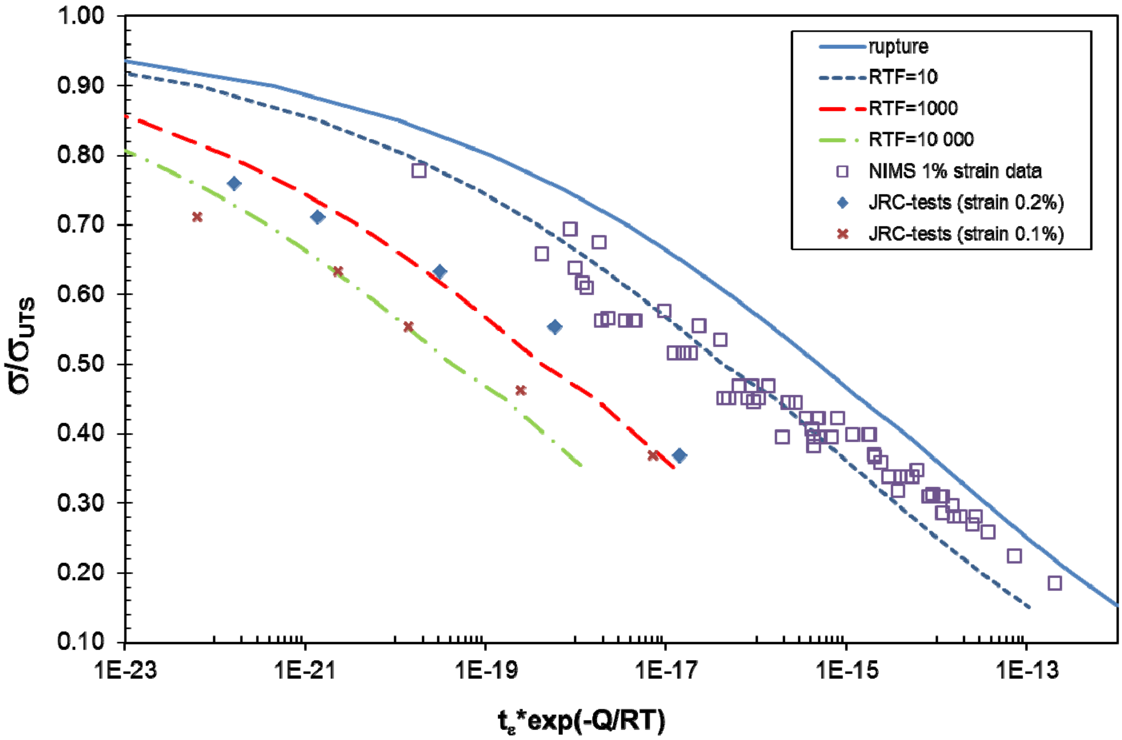

Figure 5. RTF factors for overlapping the creep strain data curve with the time to rupture curve

In the absence of creep strain data when applying to standard table values the same methodology is used on time to rupture data and with the corresponding RTF=1000 with the rupture model to mimic the 0.2% creep strain criteria.

For defining the T_{NEC} with this method the same reference stress has been adopted as for Method I, namely $R_{p02}/1.5$. Other reference stresses that were evaluated for the X10CrMoVNb9-1 steel in MATTER were $0.75 \cdot R_{p02}$ and $1 \cdot R_{p02}$. The nearer to yield the reference stress is the lower T_{NEC} temperatures result (Figure 6).

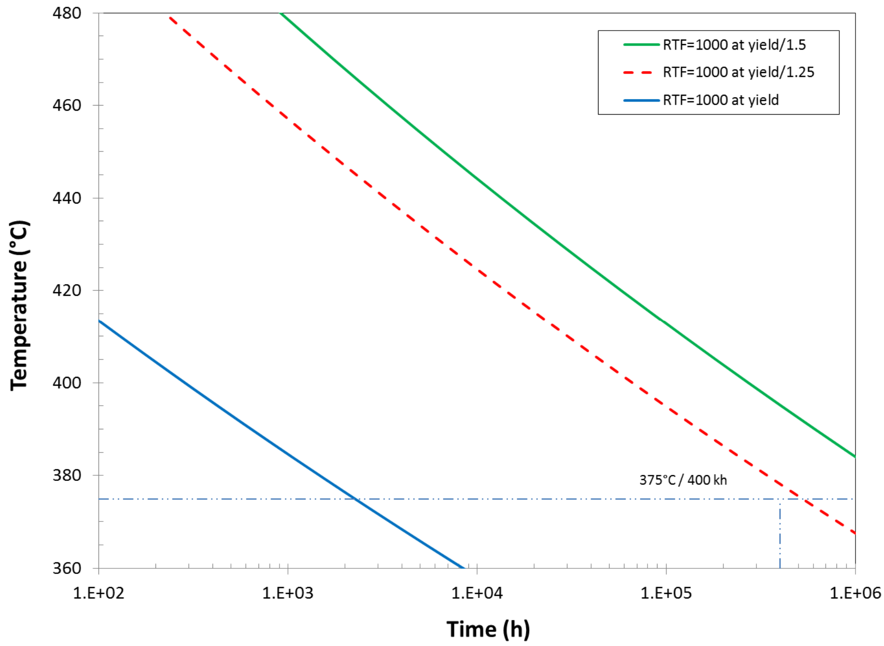

Figure 6. Effect of reference stress on the T_{NEC} curves. Here RCC-MRx minimum R_{p02} properties have been used and the RTF=1000 corresponds to 0.2% creep strain.

T_{NEC} based on EN-10028 material property table values

Applying the WE-method on the limited data available in standards shows some limitations due to insufficient data, but a promising feature is the nearly identical outcome of T_{NEC} curve for X10CrMoVNb9-1 for both methods. The lower temperature creep data relevant for the NEC temperature regime are given in Table 1 and Table 2. The row below the actual yield or creep strength is the strength divided by the SCF given in the second column, i.e. 1.5 in all cases.

Table 1. X10CrMoVNb9-1 tabulated R_{p02} and $R_{u/t/T}$ values for 10 000, 100 000 and 200 000 h.

T	[°C]	50	100	150	200	250	300	350	400	450	500
$R_{p0.2}$	MPa	423	406	392	383	376	371	365	356	341	316
/1.5		282	271	261	255	251	247	243	237	227	211
T	[°C]	500	510	520	530	540	550	560	570	580	590
$\sigma_{u/100\,000h}$	MPa	258	239	220	201	183	166	150	134	120	106
/1.5		172	159	147	134	122	111	100	89	80	71
$\sigma_{u/200\,000h}$	MPa	246	227	208	189	171	154	139	124	110	97
/1.5		197	182	166	151	137	123	111	99	88	78
$\sigma_{u/10\,000h}$	MPa	289	271	252	234	216	199	182	166	151	136
/1.5		193	181	168	156	144	133	121	111	101	91

Table 2. 10CrMo910 tabulated R_{p02} and $R_{u/t/T}$ values for 10 000, 100 000 and 200 000 h.

T	[°C]	50	100	150	200	250	300	350	400	450	500
$R_{p0.2}$	MPa	240	227	219	213	210	208	204	191	178	167
/1.5		160	151	146	142	140	139	136	127	119	111
T	[°C]	450	460	470	480	490	500	510	520	530	540
$\sigma_{u/100\,000h}$	MPa	221	205	188	170	152	135	118	103	90	78
/1.5		147	137	125	113	101	90	79	69	60	52
$\sigma_{u/200\,000h}$	MPa	201	186	169	152	136	120	105	91	79	68
/1.5		134	124	113	101	91	80	70	61	53	45
$\sigma_{u/10\,000h}$	MPa	306	286	264	241	219	196	176	156	138	122
$R_{p/10.000h}$		204	191	176	161	146	131	117	104	92	81

The main challenge in trying to find an optimal model for interpolation and extrapolation of standard table a value ("reverse engineering"), when there is no reference to the actual model used, is that the values can be mean values of different models by different assessors or even intentionally chosen to be conservative. It is also quite common that both the 100 000 h and the 200 000 h strength values are extrapolated for some (or all) of the tabulated temperatures. Thus it is not surprising that the isochronous rupture strengths do not always seem to fit classical model presentations. Figure 7 and Figure 8 show the "mismatch" between the 10 000 h values and the longer duration data when attempting to use the Larson-Miller model, PLM=[log(tr)+C]·T where C=20 and the temperature T is in Kelvin. Also the WE model clearly shows mismatch as a gap between the short and long duration creep strength values. In the case of the WE model the mismatch is mainly caused by the "mismatch" between the rupture strength and the given yield stress (or assumed tensile strength) at specified temperature. The actual model for X10CrMoVNb9-1 used in EN 10028 is the one from the ECCC data sheets [8]. The model is a 4th degree polynomial of the Manson-Haferd parameter as shown in Figure 9.

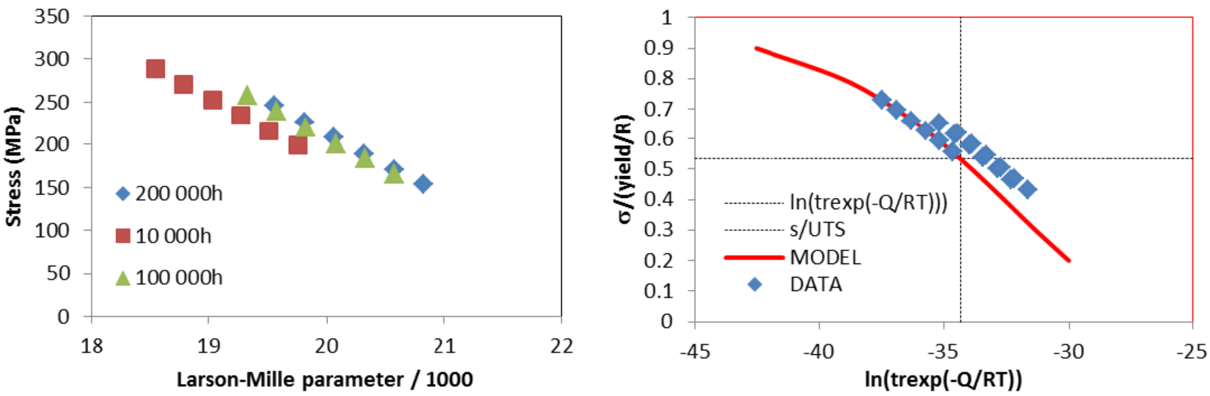

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Figure 7. EN10028 strength data for X10CrMoVNb9-1 plotted in A) Larson-Miller plot with C=20 and B) Wilshire plot with Q=300 000 J/mol and R= R_{p02}/R_m=1.25. In B) the target reference stress and corresponding constant value for T_{NEC} is shown in the crosshairs.

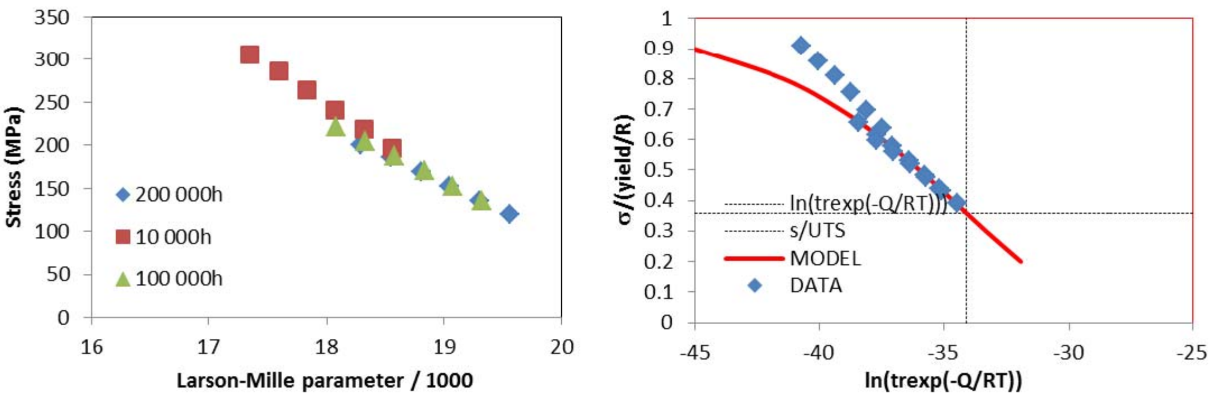

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Figure 8. EN10028 strength data for 10CrMo910 plotted in A) Larson-Miller plot with C=20 and B) Wilshire plot with Q=300 000 J/mol and R= R_{p02}/R_m=1.85. In B) the target reference stress and corresponding constant value for T_{NEC} is shown in the crosshairs.

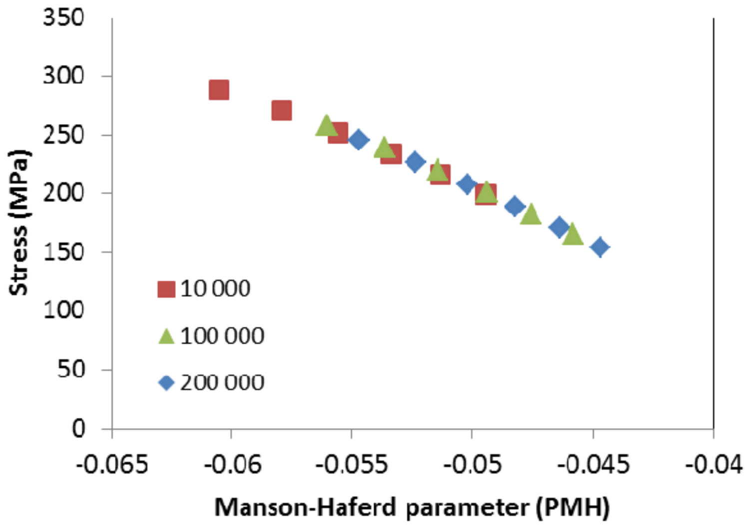

Figure 9. EN10028 Manson-Haferd model plot for X10CrMoVNb9-1, PMH=(log(t_r)-17.5)/(T-550) where T is in Kelvin and t_r in hours.

Note that for both materials a Larson-Miller extrapolation towards lower temperatures (left) results in overly optimistic stress values due to insignificant curvature of the available data. For the WE model the extrapolation will be conservative since the model limits the stress to values below the tensile strength (or factor of yield).

For the two steels it was decided to limit the calculated "tensile strength" to 1.1 times the largest $R_{u/t/T}$ over R_{p02} found in the data sheets, with a maximum of 50°C temperature extrapolation of the yield strength towards the creep temperatures. In creep strength no extrapolation was allowed. For the X10CrMoVNb9-1 the largest ratio was 0.91 for 60 to 250 mm thick pipes whereas in the case of 10CrMo910 it was 1.7 for the 150 to 250 mm thick pipes. Note that it seems that the yield stress has intentionally been set low for this steel. Creep data for ferritic and ferritic-martensitic steels are generally expected to have been generated below yield.

In the case of X10CrMoVNb9-1 the WE model used for the T_{NEC} curve was chosen to be the one for the 10 000 h creep strengths and for the 10CrMo910 steel the 100 000 h strengths, both models will produce conservative predictions of rupture in comparison to the other isochronous data. The comparison of the full negligible creep assessment in MATTER to the simplified assessment on EN10028 table values is shown in Figure 10. The actual rupture model predictions (Manson-Haferd) for the reference stress at temperatures 520-550°C are also presented to show that the WE model is conservative as claimed earlier. Note that the results for the T_{NEC} of the full and the standard table based assessments are almost identical.

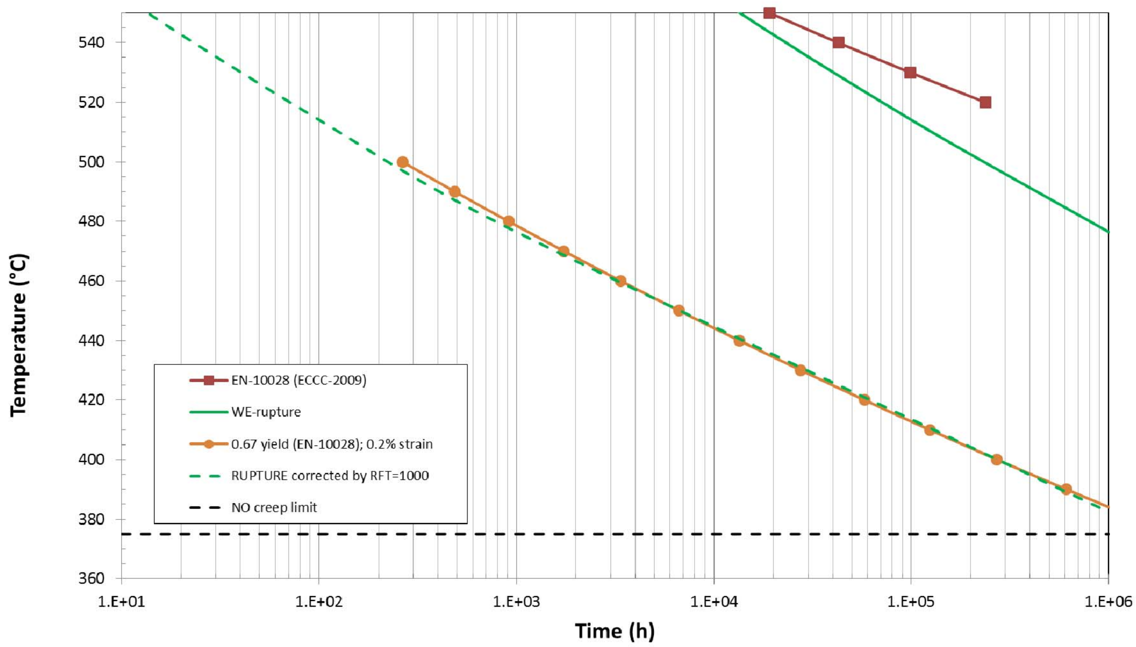

Figure 10. X10CrMoVNb9-1 steel Comparison of T_{NEC} for the full assessment (with strain data) to the simplified one using EN10028 data tables and a RTF of 1000. The time to rupture predictions at reference stress (520-550°C) calculated with the MH model (origin of EN-10028 values) are also compared with the conservatively defined WE model.

The T_{NEC} curves generated by Method II are shown in Figure 11 and Figure 12.

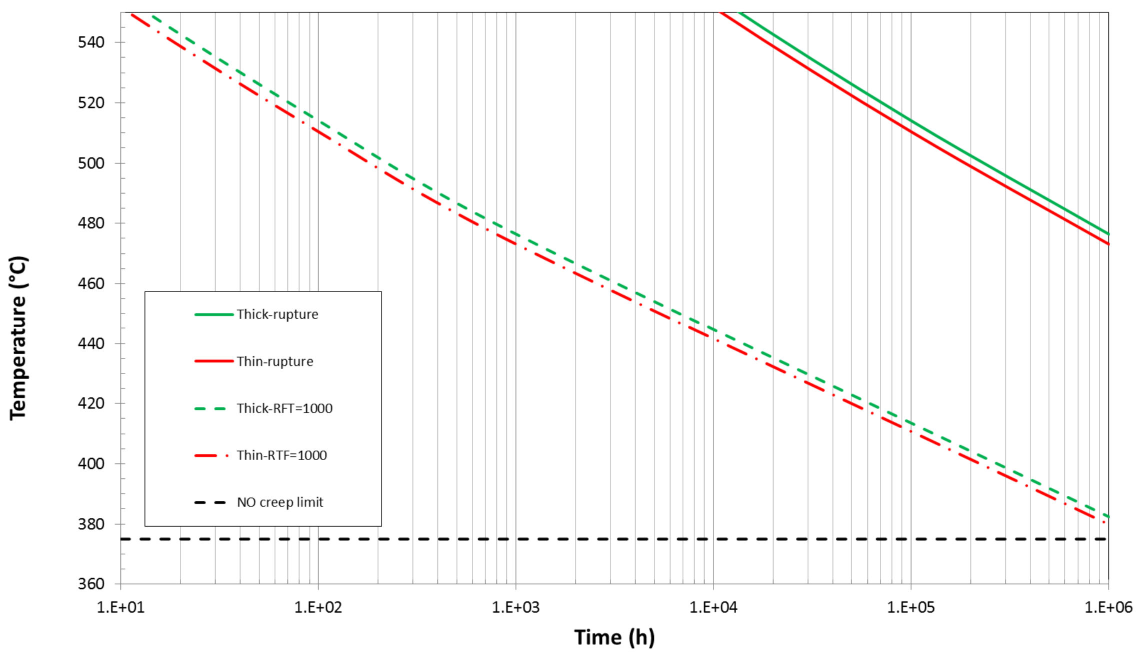

Figure 11. X10CrMoVNb9-1 rupture (upper right corner) and negligible creep temperature curves T_{NEC} for thick (60-250 mm) and thin (≤ 60 mm) pipes. The WE model parameters Q=300 000 J/mol, R=1.25 and RTF=1000.

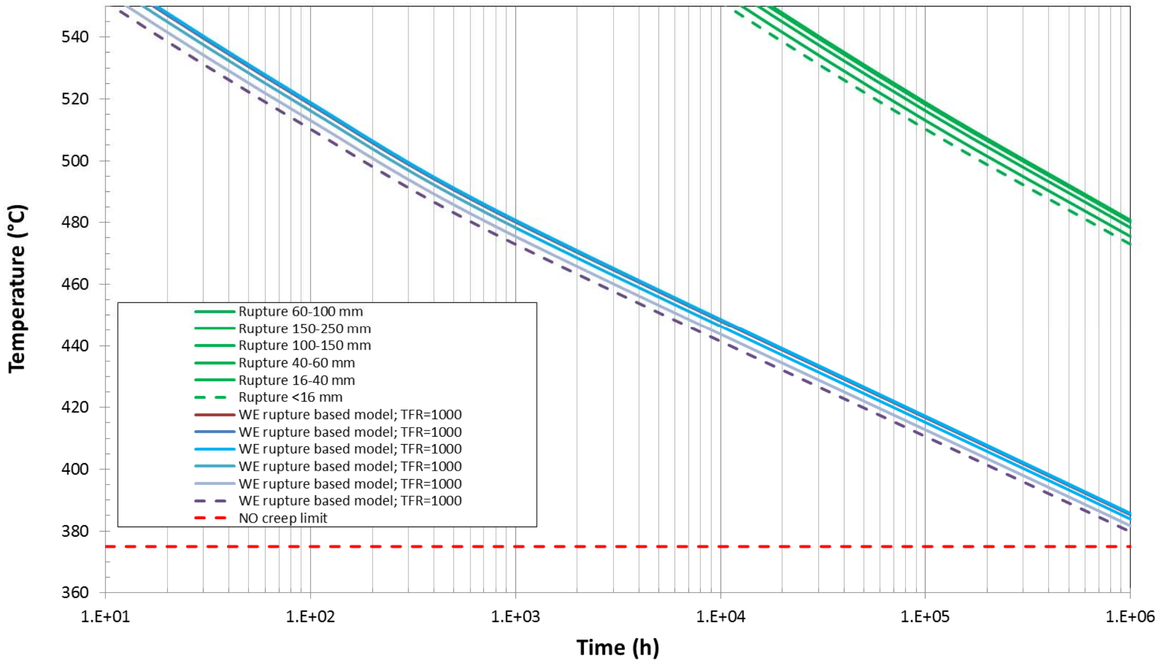

Figure 12. 10CrMo910 rupture (upper right corner) and negligible creep temperature curves T_{NEC} for thicknesses ≤16, 16-40, 40-60, 60-100, 100-150 and 150-250 mm. The WE model parameters Q=300 000 J/mol, R=1.9 and RTF=1000.

It can be seen from the figures that the T_{NEC} is not sensitive to the product form of the material (thin or thick) since the NEC reference stress adjusts to the material properties and thereby compensates for lower or higher creep strengths of that product form. It can also be seen that the T_{NEC} for X10CrMoVNb9-1 and 10CrMo910 are quite similar. This is also the effect of the interaction between allowable (reference) stress and creep strength. The T_{NEC} of X10CrMoVNb9-1 (60-250 mm thick) and 10CrMo910 (150-250 mm thick) are compared in Figure 13.

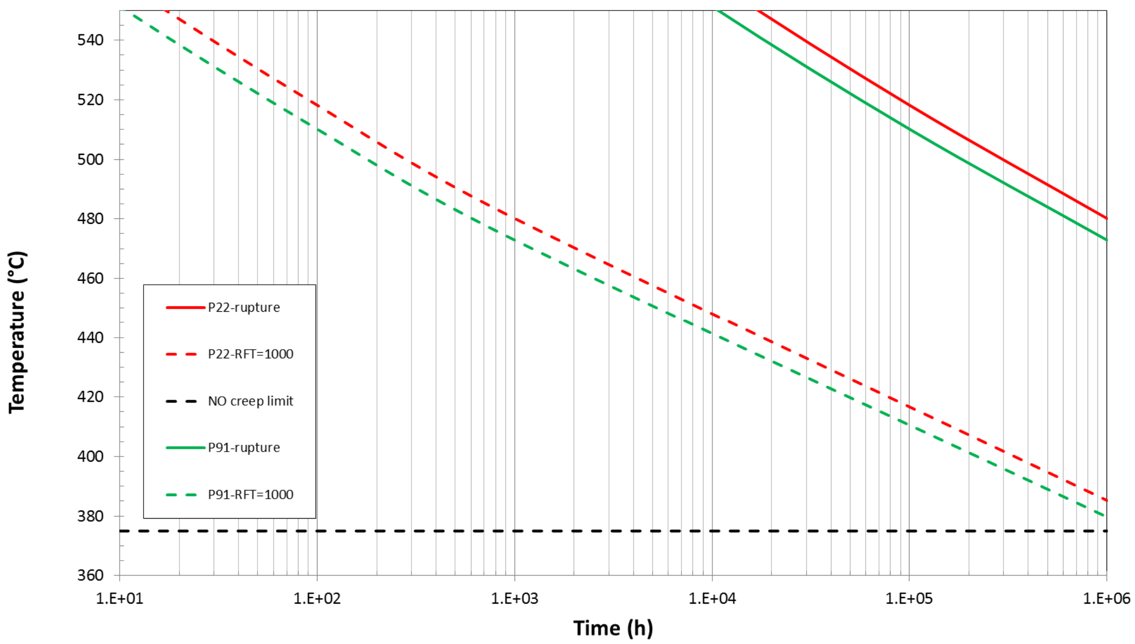

Figure 13. T_{NEC} curves for 10CrMo910 (P22, 150-250 mm thick) in red and X10CrMoVNb9-1 (P91, 60-250 mm thick) in green.

It is possible that also other ferritic/ferritic-martensitic steels follow the same T_{NEC} curve. This of course would be the optimal solution for generating negligible creep curves for the EN-13445 standard.

It is to be emphasized that the T_{NEC} curves rely on the applicability of the Wilshire equation at temperatures below the temperatures where the actual creep tests have been done, i.e. temperatures up to 125°C lower than the tabulated rupture strength data. It has been shown that the WE model can accurately predict low temperature (375-450°C) creep strain accumulation for X10CrMoV9-1. However, this has not yet been shown to be the case for any other material listed in EN-13445.

Comparing proposed T_{NEC} for X10CrMoVNb9-1 to 0.2% creep strain predictions by RCC-MRx

To check the proposed T_{NEC} curve against another comparable model, creep strain calculations were made using the nuclear design code RCC-MRx. The creep strain formulations and parameters for the temperatures 375, 400, 450 and 500°C were used to predict time to 0.2% creep strain. The same reference stress as the above methods ($2/3 \cdot R_{p02}$, EN 10028 values) was used. The predictions are depicted in Figure 14 together with the T_{NEC} curve proposed for X10CrMoVNb9-1.

It can be seen that the RCC-MRx predicted time to 0.2% strain coincides well with the T_{NEC} curve based on the EN-10028 strength tables with a RTF=1000. The proposed T_{NEC} is conservative compared to the RCC-MRx predictions for durations longer than 300h and temperatures below 500°C. The degree of conservatism increases for longer service durations.

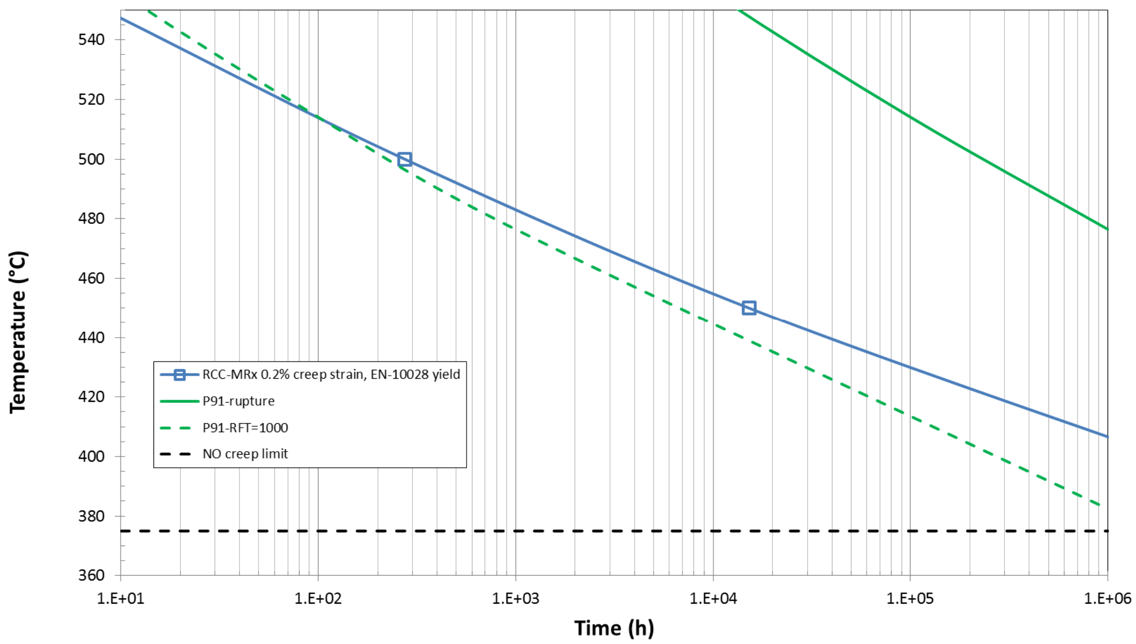

Figure 14. Comparison of 0.2% time to strain predictions at σ_{ref} for X10CrMoVNb9-1 using the RCC-MRx creep strain formulas with the proposed T_{NEC} curve.

Recommendations for EN13445

- If possible it is recommended to base the T_{NEC} curve on a combination of strain and rupture data. True data would of course be preferred, especially at low temperatures, but standard tables are an option with an extrapolation disclaimer in place (see below).
- The standard should include a disclaimer to emphasise the extended extrapolation in time for the T_{NEC} curves (up to 10^6 hours). For example, extrapolations beyond 3 times the longest tests are not allowed for creep rupture strength prediction. For T_{NEC} however the extended extrapolation range should be considered. Also, the amount of low temperature data available for verification of the material specific T_{NEC} curves should be declared.
- If Method II is chosen, the most conservative WE curve should be used if there is mismatch between rupture strengths over the time range (10, 100, 200 kh).
- Sufficiently conservative RTF on rupture should be selected to correspond to sought NEC criteria (such as strain). Here a RTF=1000 has been used corresponding to time to 0.2% strain for X10CrMoVNb9-1 steel.
- **The T_{NEC} curves should be verified by any additional data from literature or by additional time to strain creep tests at the temperature range 375 - 500°C**.
- TC54 should contact the convenors of the European Creep Collaborative Committee (ECCC) work groups 3a and 3b to request assistance on finding or generating data for the low temperature range. Also, contact to ECCC work group 1 should be established for assistance on model applicability for extrapolations in temperature and time beyond the range of data.
- More assessments with extensive data sets (both rupture and strain) should be conducted. Potential materials could be 10CrMo910 and an austenitic steel such as X2CrMoNiMo17-12-2 (316L).

Conclusions

- A Wilshire based creep model approach for determining the negligible creep curves based on creep strain and rupture has been used for an extensive assessment of X10CrMoVNb9-1.
- T_{NEC} curves on time to 0.2% creep strain have been defined in the MATTER project and compared to a time-based approach using rupture times as reference.
- The RTF=1000 corresponds to 0.2% strain for X10CrMoVNb9-1 steel.
- The same methodology to construct the T_{NEC} curves is proposed for use with standard tabulated creep rupture values.
- The T_{NEC} for X10CrMoVNb9-1 using standard strength tables is almost identical to the one calculated from the extensive data set assessment.
- The reference stress to be used in NEC design can be the same as used in time independent design, i.e. the allowable stress $1/2.7 \cdot R_m$ (RCC-MRx ferritic steel) or $2/3 \cdot R_{p02}$ (austenitic steel). Here the $2/3 \cdot R_{p02}$ has been used to allow comparison with the graphical method in the present draft amendment.
- Safety margin in NEC is accomplished by defining a rupture time factor (RTF) for "sufficient" conservatism.

- The RTF is a good criterion for NEC determination since for instance time to 0.2% strain could be un-conservative for creep brittle materials and overly conservative for creep ductile materials.
- It has been shown that the same T_{NEC} could be used for all pipe thicknesses described in EN-10028 (both for X10CrMoVNb9-1 and 10CrMo910).
- It has also been shown that the T_{NEC} for X10CrMoVNb9-1 and 10CrMo910 are very similar.
- There is a good chance that the same T_{NEC} could also be used for other ferritic-martensitic steels, but that needs to be confirmed.
- **More creep strain data at low temperatures and low stresses are needed for validation of the methodology for the other materials tabulated in EN-13445 and EN10028**
- Further work should be carried out to clarify the impact of material softening/hardening in cyclic service (creep-fatigue) for improved pin-pointing of best/acceptable RTF values.

Acknowledgments

The author wishes to acknowledge the support from the MATTER project under the umbrella of EERA Joint Program Nuclear Materials (Project no: 269706 – FP7-Fission-2010) and the JRC institutional project MaCoSyMA.

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