

JRC VALIDATED METHODS, REFERENCE METHODS AND MEASUREMENTS REPORT

Recommendation for the negligible creep domain for P91

*MATerials TEsting and Rules
MATTER Deliverable 5.3*

Stefan Holmström (JRC-IET)
Jia-Chao Chen (PSI)

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Joint Research Centre

Institute for Energy and Transport

Contact information

Stefan Holmström

Address: Joint Research Centre, Westerduinweg 3, NL-1755 LE Petten, the Netherlands

E-mail: Stefan.holmstrom@ec.europa.eu

Tel.: +31 224 565069

JRC Science Hub

<https://ec.europa.eu/jrc>

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Authors: Stefan Holmström, Chen Jia-Chao

Contributors: JRC, PSI

Approval:



MATTER project

EC Scientific Officer: Mykola Džubinský

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Summary

The report is a recommendation on the methodology for determining the negligible creep (NEC) domain for P91 steel. The objective to define the actual T_{NEC} curve for P91 was fully reached and time safety factors involved in the recommended curve was calculated and found to be conservative. The curve can be recommended for use in the nuclear design codes. The report also contains the new data collated in the negligible creep domain (375-450°C).

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Name	Organisation	Comments
Dzubinsky, Mykola	EC	Scientific Officer
Agostini, Pietro	ENEA	Project Coordinator
Uti, Marco	ENEA	Scientific Responsible Domain Leader – 4 Workpackage Leader – 15
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Angelika Bohnstedt	KIT	Domain Leader – 3 Workpackage Leader – 8
Gelineau, Odile	AREVA	Workpackage Leader – 1
Chen Jia-Chao	PSI	Workpackage Leader – 2
Davide Bernardi	ENEA	Workpackage Leader – 7
Ancelet, Olivier	CEA	Workpackage Leader – 4
Aktaa, Jarir	KIT	Workpackage Leader – 5
Rami Pohja	VTT	
Nilsson, Karl-Fredrik	JRC	Workpackage Leader – 9
Hyeong-Yeon Lee	KAERI	
Stéphan Marie	CEA	
Malerba, Lorenzo	SCK•CEN	EERA JPNM coordinator
Martine Blat	EDF	
Pertti Auerkari	VTT	
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Sophie Dubiez-Legoff	AREVA	
Sylvain Pillot	Industeel	
Nathalia Luziginova	NRG	
Warwick Payten	ANSTO	
Wolfgang Hoffelner	retired	
Colombarini, Mara	ENEA	Assistant for the Project Organization

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List of Acronyms

WE	<i>Wilshire model for creep rupture or strain</i>
NEC	<i>Negligible Creep</i>
T	<i>Temperature (°C)</i>
T_{Rupt}	<i>Temperature-time curve for creep rupture at reference stress</i>
T_{NEC}	<i>Temperature-time curve for NEC at reference stress</i>
T_{NC}	<i>Temperature limit for NO creep, 375°C for ferritic steels</i>
σ	<i>Stress (MPa)</i>
t	<i>Time (h)</i>
ε	<i>Strain (%)</i>
$R_{u/t/T}$	<i>Rupture strength (MPa) for time to rupture t at temperature T</i>
$R_{f\varepsilon/t/T}$	<i>Strength (MPa) to reach specified creep strain ε at temperature T and time t</i>
$R_{p0.2}$	<i>Yield stress (MPa) at specified temperature T</i>
R_m	<i>Ultimate tensile strength (MPa) at specified temperature T</i>
S_m	<i>Allowable stress (MPa), Austenitics $S_m=2/3 \cdot R_{p0.2}$, P91 (RCC-MRx) $S_m=1/2.7 \cdot R_m$</i>
σ_{ref}	<i>Reference stress (MPa), $\sigma_{ref}=1.5 S_m$</i>
t_r	<i>Time to rupture (h) at specified stress σ and temperature T</i>
$t_{\varepsilon 0.2\%}$	<i>Time to 0.2% strain (h) at stress σ and temperature T</i>
SCF	<i>Stress correction factor used on creep rupture strength</i>
RTF	<i>Rupture time factor; adjusting t_r to NEC criterion; $t_\varepsilon(\sigma, T)=t_r(\sigma, T)/RTF$</i>

Scope

This report is the final deliverable in Task 5.2. The report is a recommendation on the methodology for determining the negligible creep (NEC) domain for P91 steel. The objective to define the actual T_{NEC} curve for P91 has been reached and the safety factors in time against creep rupture and strain have been calculated for the recommended curve. The curve is proposed for use in the nuclear design code RCC-MRx [1]. This report contains both data collected from literature [2] [3] [4] [5] and the new data produced in the MATTER project for the negligible creep domain, i.e. temperatures below 450°C. It is to be noted that in the latest version of the RCC-MRx (2012) the material properties for P91 steel (tensile strain curves, creep, and fatigue) have been moved to "probationary phase rules" in section III-Tome 6.

The negligible creep has different interpretations depending on which damage mechanisms potentially affected by creep are considered. For instance the impact of cyclic softening on and the interaction between creep and fatigue, creep and fatigue crack growth as well as ratcheting. In this work the main effort is laid in defining the limits for pure creep to a small strain that can be considered to be negligible. In earlier work the softening is found to have a beneficial effect on the localized damage rate induced by cyclic loading, i.e. slower damage rate is lowering the NEC temperature [5]. For a cyclic hardening material the effect is reversed. It is to be noted that this conclusion was made assuming strain controlled cyclic loads.

In the MATTER consortium the negligible creep criteria to be investigated was consensually defined as the time to 0.2% strain at a specified reference stress. The negligible temperature curve (T_{NEC}) is defined as the temperature that causes 0.2% of creep strain in a specified time at the specified reference stress. Thus, the negligible creep domain is the limiting temperature / time within which designers do not need to consider creep, i.e. if the service time is below the negligible creep curve. In this work the reference stress used in T_{NEC} calculations are either based on yield stress, as is suggested in the non-nuclear standard for unfired pressure vessels (EN-13445 [7]) or on tensile strength as is defined in the RCC-MRx for P91 steel

The different design regions in temperature-time at specified (reference) stress is shown in Figure 1.

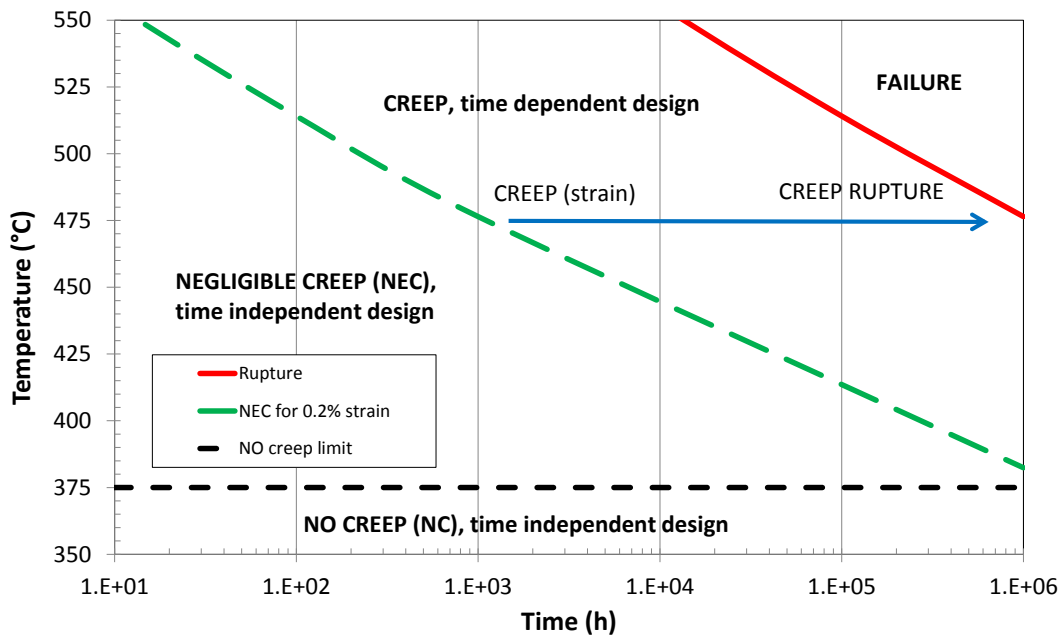


Figure 1. Time-temperature regions for specified reference stress. The Negligible Creep temperature curve T_{NEC} (long dash) separates the regions where time dependent and time independent design has to be applied. The creep rupture temperature curve beyond which creep failure occurs (T_{Rupt} continuous line) and the No Creep limit (T_{NC} small dash) at 375°C are also given.

The negligible creep curves are sensitive to the chosen reference stresses, i.e. low yield or tensile strength properties given for a material move the T_{NEC} curve towards longer times. This means that a more conservative curve is acquired by using mean value tensile properties instead of minimum values for the NEC evaluation. The T_{NEC} is of course also sensitive to the creep strain model chosen for the predictions. In [8] strain models from the codes ASME-NH [9], RCC-MRx and R5 [10] were compared for both 316FR and P91 steel for a range of different reference stresses. It is clear that the T_{NEC} curves from different codes cannot be compared against each other if the NEC strain limit is ranging from 0.01% to 0.2% and the reference stresses are defined differently ($0.95-1.25 \cdot R_{p02}$). However, the most conservative result for P91 was acquired by the RCC-MRx code using a reference stress of $0.95 \cdot R_{p02}$ and a strain limit of 0.01%. As will be explained later in this report the very low strain limit will have an overly conservative safety factor against creep

damage. The allowable NEC service times for the high reference stress and low allowable strain was only about 4 hours at 425°C and 1000 h at the NC limit of 375°C, which would be useless for design purposes.

Reference stress and strain limits for NEC

Negligible creep (NEC) is an important design parameter since it gives a temperature / time range below which creep damage does not need to be considered in the design analysis. The RCC-MRx design code does not provide the negligible creep curve for ferritic/martensitic steels, such as the T/P91 steel as it does for the austenitic steel 316L(N). It is however given that for ferritic steels the "no creep" (NC) temperature limit is 375°C regardless of stress (\leq allowable stress). The temperature limit is consistent with the ASME design code.

The P91 material yield stresses given in RCC-MRx and ASME are listed as a function of temperature in Table 1. for the NEC temperature range 350-500°C. The RCC-MRx minimum yield values (designation $R_{p02-min}$) are in average 5% lower than the ASME yield strength values (designation S_y). The ASME S_y stress is also defined to represents the lower bound of material property.

Table 1. Minimum yield strength of P91 steel as given in ASME and minimum and average yield strength as given in RCC-MRx for the NEC temperature range

Temperature (°C)	ASME S_y (MPa)	RCC-MRx -min $R_{p02-min}$ (MPa)	RCC-MRx -average $R_{p02-ave}$ (MPa)
300	377	355	426
325	375	-	-
350	371	349	416
375	366	-	-
400	358	338	403
425	348	-	-
450	337	320	385
475	322	-	-
500	306	292	361

In this work the modelling and plots are given in terms of normalized stress ($X_m = \sigma / R_m$), i.e. the stresses are normalized by the ultimate tensile strength R_m at the specified temperatures. The specific test stress can then be extracted as $\sigma_{ref} = X_m \cdot \sigma_m$ when the normalized value and the tensile strength are known. The same can be done using yield as normalizing factor ($\sigma_{ref} = X_p \cdot R_{p02}$). However, the normalization by the ultimate tensile strength is more convenient in creep modelling since the Wilshire model [9] uses this form. Also, in RCC-MRx the allowable design stress for P91 is calculated as the tensile strength divided by a factor of 2.7 ($\sigma_{ref} / R_m = 1/2.7$), i.e. $X_m = 0.37$.

In the NEC temperature range the RCC-MRx minimum yield stress over minimum tensile strength ratio is at a level of $R_{p02}/R_m = 0.72$ and the corresponding ratio for average yield stress over average tensile strength is at the level of $R=0.8$. Thus if the normalized stress level in a creep test is 0.8 it corresponds to a test stress at or very close to average yield stress.

Note also the substantial difference between the minimum and the average ratio values. The measured yield over tensile strength for the MATTER test material is 0.81 (as reported later in Figure 3) and complies well with the RCC-MRx average values.

The negligible creep definitions in the current nuclear design codes as well as the corresponding reference stresses are defined in Table 2 for austenitic stainless steel [4]. These definitions are formulated taking into account steels that exhibit cycling hardening. For austenitic steels such as 316L(N) component design can be done assuming NEC as long as the time fraction, i.e. time in service divided by the rupture time (t/t_r), is below 0.1 for a reference stress of $1.5 \cdot S_y$ and the accumulated creep strain is below 0.2% at a reference stress of $1.25 \cdot S_y$ (at specified temperature). It should be noted that the factors 1.5 and 1.25 are claimed to take into account creep fatigue hardening and ratcheting phenomena.

Table 2. Nuclear design code NEC definitions for austenitic stainless steels:

Based on:	Code	Reference stress	NEC criterion
Time fraction	ASME NH	$1.5 \cdot S_y^*$ (R=0.67)	$t_u/t_r \leq 0.1$
Creep strain	ASME NH	$1.25 \cdot S_y$ (R=0.8)	$\leq 0.2 \%$
Time fraction (App. RB3216)	RCC-MRx	-	$\Sigma t_i/T_i \leq 1$
Creep strain	RCC-MRx	$1.25 \cdot S_y$ (R=0.8) $1 \cdot S_m^{**}$	$\leq 0.03\%$ $\leq 0.01\%$
Relaxation	RCC-MRx	$3 \cdot S_y/E^{***}$ $1.5 \cdot S_m$	$1 - \sigma_0/\sigma_{rel} = 10\%$ $1 - \sigma_0/\sigma_{rel} = 20\%$
Creep strain	Japanese design (Fast reactor)	$1.5 \cdot S_m$	$\leq 0.03\%$
Strain Relaxation	R5	$1.5 \cdot S_y$ $1.35 \cdot S_y$	0.03% $1 - \sigma_0/\sigma_{rel} = 20\%$

* S_y is the yield (0.2%) stress, ** S_m is the allowable stress defined by the design code at specified temperature, Note that $S_m \neq R_m$ (R_m being ultimate tensile strength) and $S_m \neq R_{T/t}$ ($R_{T/t}$ being the rupture strength for given temperature and rupture time, i.e. 100 kh or 200 kh in standards).*** determined as the stress to produce a total strain of $3S_y/E$ on the average monotonic curve.

To solve the difference in reference stresses between the austenitic stainless steel and the ferritic-martensitic steels the following rationalizing based on the R5 procedure [10] could be done:

For the austenitic steel the traditional design limit was set at $0.5 \cdot R_m$ (half minimum tensile strength) or $1.35 \cdot R_{p02}$. The factors included a safety factor 1.5 based on engineering judgement. This means that the allowable stress S_m is set at $1/3 \cdot R_m$ (one third tensile strength) or $0.9 \cdot R_{p02}$. The criterion for negligible creep was set to 20% relaxation of the initial (reference) peak stress. By using the same logic for P91 the ultimate tensile strength is a suitable base instead of yield due to the strongly differing yield to tensile strength ratios of the materials.

The allowable stress in RCC-MRx for P91 steel is defined as $1/2.7$ times the tensile strength, i.e. $0.37 R_m$. The reference stress is then 1.5 times the allowable stress or $3/2 \cdot 1/2.7 R_m = 0.56 R_m$. Alternatively the traditional design limit (for austenitic steel) of $0.5 R_m$ could be used. The

justification of using the same factor of 1.5 for the reference stress is gained from the safety factor calculations later in this report.

The definition for reference stress in the draft amendment of the non-nuclear European standard EN-13445 for design of unfired pressure vessels is $2/3 \cdot R_{p0.2}$, corresponding to $0.48 \cdot R_m$ or $0.54 \cdot R_m$ depending on if minimum or average yield stress values are used for the conversion.

As a consequence the potential candidates for reference stress of P91 steel are between 0.48 and $0.56 R_m$. In this work the **$0.56 R_m$** is chosen to fulfil the objective of the MATTER project to define the T_{NEC} curve for the RCC-MRx design code.

In Table 3 the allowable stresses (0.33 and $0.37 R_m$) and the reference stresses (0.5 and $0.56 R_m$) are presented as actual stress values for 400°C as given in RCC-MRx. The average strength of the reported NIMS heats and the measured material properties of plate 20057 are also given. Note that the lowest stress (RCC-MRx-min) is about 82% of the highest (NIMS). This difference in the tensile properties clearly indicates the importance of anchoring the reference stress at a specific set of tensile strength values and not allowing to use the true material properties. The main reason for this when considering negligible creep is that if higher tensile strengths are used as base for the T_{NEC} curve, such as the NIMS [12], the allowable times at the corresponding σ_{ref}/R_m will be shorter.

Table 3. Reference stresses in MPa for the proposed factors of tensile strength for RCC-MRx, NIMS and plate 20057 at 400°C . The ASME allowable stress $2/3 R_{p02} = 239 \text{ MPa}$ corresponds rather well to the $0.5 \cdot R_m$ (min) values.

Code –min/ave	$0.33 R_m$	$0.37 R_m$	$0.50 R_m$	$0.56 R_m$
RCC-MRx - min	155	174	236	262
RCC-MRx-ave	169	190	257	285
Plate 20057	176	198	267	297
NIMS - ave	191	213	287	321

The reference stress definition and the selected NEC criterion will of course have a direct impact on the calculated NEC temperature creep curve. In Table 1 there were also NEC limits based on very small strains (0.03-0.01%). It is most likely that the small creep strains are in fact calculated from relaxation data, and do not as such represent values acquired from constant load creep testing.

In terms of measuring accuracies and testing machine limitations for conventional creep testing a strain of 0.01% is a highly impractical limit and will be prone to errors larger than the targeted measurement value. Standard dead weight creep test rigs cannot accurately record the precise time and/or the precise strain when full load is reached. Therefore the initial strain and the following rapid primary creep strain extracted from the recorded data at quite low sampling rate are susceptible to considerable scatter. In the loading phase it is therefore almost impossible to distinguish between instantaneous plastic deformation and time dependent creep deformation.

The data available in the open literature for determining low creep strains at low temperatures are not sufficient for a thorough assessment of the NEC. The majority of existing data are targeting creep rupture or high strains. Tests programs are also usually designed to assess creep rupture during service lives and therefore low stress creep tests at low temperatures are limited or totally lacking. In the rare cases where such data exists, the data owners are unfortunately not publishing it or the full creep curves are not shown in the open literature.

To satisfactorily define the negligible creep domain for P91 steel to be used in design codes is therefore a challenging task. In the MATTER project the target has been set to accurately predict the time to 0.1-0.2% of strain in a temperature range below 450 °C at a stress range relevant to creep strain assessment at the reference stress. Initially it was assumed that the reference stress would be around the yield strength.

In this work different time to strain models are used for predicting NEC temperature curves. Also, the life fraction approach is tested (based on rupture life) to equal the results of the strain models. It should be noted that the life fraction route or an equivalent method based on creep rupture properties is convenient to use in the design codes since it allows relating the NEC limits to creep strength and service time limits available in material standards such as EN-10028 [13]. Work is currently being carried out by the CEN TC/54 WG 59 (CREEP) work group to include negligible creep limits (NEC curves) for all steels tabulated in EN 13445. In the work of the WG59 one of the suggested definitions of negligible creep temperature curves is based on linear extrapolation of 10 000, 100 000 and 200 000 hours creep strength values corrected by a safety factor towards the lower temperature to find the insertion point with the corresponding yield stress curve (also corrected by the same safety factor).

Materials and methods

Negligible creep tests, i.e. tests below 450°C have been performed with two heats of P91 material. The main negligible creep test material used at JRC is the 60 mm thick plate (heat nr. 20057) from ArcelorMittal [14]. The plate was tested in "as received" product state and has undergone the following heat treatment: 1060°C – 4Hrs + Water Quenching + 760°C – 3hrs and 20min – Air Cooling. This plate was produced in full accordance with RCC-MR requirements (STR RM 2432).

The other P91 heat tested at PSI for NEC is a 30 mm plate (heat nr. 25240002) delivered by CEA. The steel has undergone a heat treatment consisting of austenitization at 1323K during 30 min followed by quenching and tempering at 1053K for 1 h.

The chemical compositions of the above materials are given in Table 4.

The JRC creep tests have been performed with the 60 mm thick plate. The test specimens used were 8 mm in diameter with a gauge length of 50 mm and a diameter of 8 mm as shown in Figure 2.

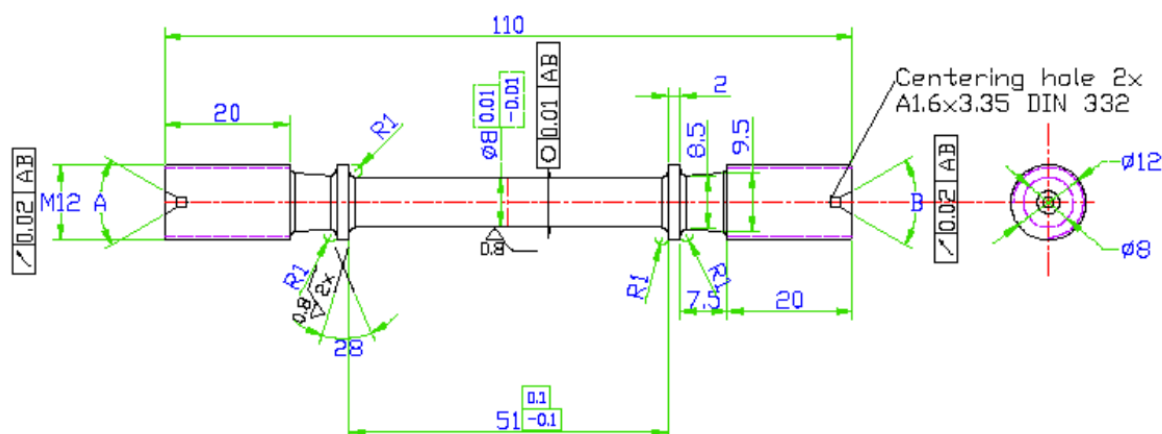


Figure 2. Creep specimen for negligible creep tests with the JRC test material.

Table 4. Chemical compositions in % of the P91 steels tested and assessed in MATTER.
#N/A=information not available.

Elements	Min/Max	Plate 20057	Plate 25240002
C	0.08/0.12	0.12	0.086
Mn	0.30/0.60	0.41	0.363
Si	0.20/0.50	0.24	0.324
Ni	≤ 0.20	0.1	0.149
Cr	8.00/9.50	8.32	8.91
Mo	0.85/1.05	1.02	0.917
Cu	≤ 0.10	0.05	0.068
Al	≤ 0.040	0.006	0.018
S	≤ 0.0050	0.001	0.001
P	≤ 0.0200	0.0091	0.017
V	0.180/0.250	0.235	0.198
Nb	0.060/0.100	0.084	0.080
N	0.030/0.070	0.041	0.0411

For the assessment of time to rupture and time to strain in the creep range, where the designers do need to take creep into consideration, the main source of data was acquired NIMS Japan. In the negligible creep temperature range some additional low temperature data were obtained from the public domain [14].

The tensile properties for the assessed materials are given in Table 5. The ratios for yield stress normalized by ultimate tensile strength are shown in Figure 3 as a function of temperature.

The low temperature creep data used in the assessment is not optimal for low temperature predictions. The JRC low temperature tests are the only available tests with test temperatures as low as 375°C. In the temperature range ≤ 450 °C there are only 3 data points in the NIMS data, at or just above yield stress for the selected time to 0.2% creep strain criteria. There are 4 data points

for 0.1% strain at 450°C and 2 points at 427°C in [14]. No additional public data below 427 °C was found.

Table 5. Tensile properties of the 60 mm thick P91 plate. The M1 yield stress is ~28% higher than the RCC-MRx minimum yield in the NEC temperature range.

Identif.	Temp	R _{p02}	R _m	ε _f (%)	R _{p02} /R _m	R _{p02} /R _{0p0m-RCC}
AA003	22	510	680	38.7	0.75	1.28
AA004	375	436	542	38.9	0.80	1.27
AA005	375	436	541	40	0.81	1.27
AA006	375	433	544	40	0.80	1.26
AA007	400	430	534	39.1	0.81	1.27
AA008	425	425	524	39.4	0.81	1.29
AA009	425	433	533	37.7	0.81	1.31
AA010	425	425	526	41.2	0.81	1.29
AA011	450	410	502	41.9	0.82	1.28
AA012	500	395	475	38.4	0.83	1.35
AA013	550	340	404	49.2	0.84	1.34
AA014	600	260	322	54.7	0.81	1.28

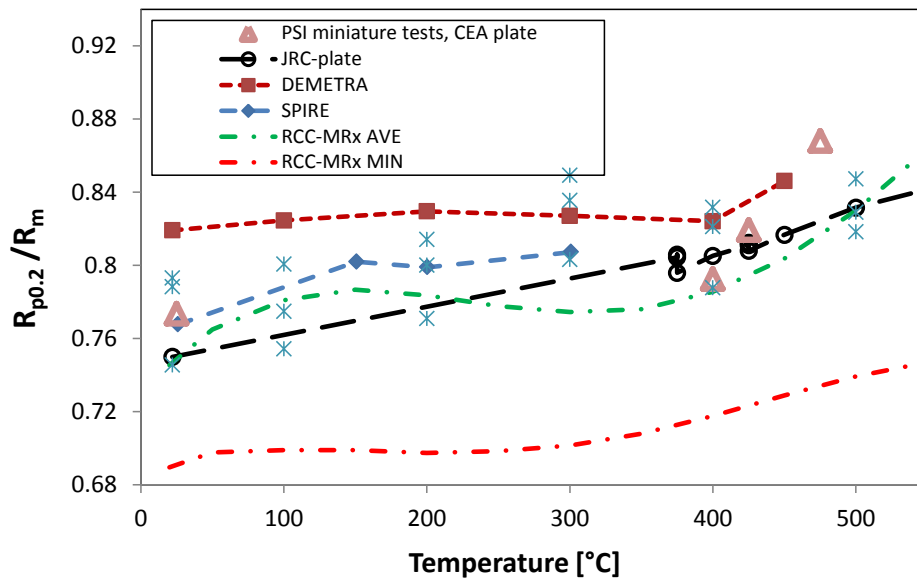


Figure 3. Yield over ultimate tensile stress for MATTER test materials and the 3 heats tested by NIMS. Corresponding values for the RCC-MRx are calculated on average and minimum $\sigma_{0.2}$ and σ_{UTS} values given in the code. The temperature range of interest for NEC is between 350 and 500°C. The expected variations in the ratio are between 0.76 and 0.86 in this range.

For the existing tests conducted to failure (at high stresses) at temperatures close to the NEC temperature range it was found that minimum strain rate is reached (for ferritic-martensitic

steels) at strains of at least 1%. It is to be remembered that for the targeted temperature range (375-450°C) the required loads for short to medium test durations are very high in comparison to expected service stresses (see RCC-MRx allowable stress), especially if tests to 1% strain or rupture are targeted. It is also to be noted that tests designed for relatively high strains or to rupture are not always helpful for determining the NEC temperature curve. These tests have seldom the recorded information at the very short durations to reach 0.1 or 0.2% in strain and the stresses are very close or above yield whereas the allowable stress range with $S_m \sim 1/3 R_m$ are only tested at high temperatures far from the NEC temperatures.

Testing to support the definition of negligible creep for P91

The test matrices of JRC and PSI for Task 7.1 (Test in support to the definition of the negligible creep domain) are presented in Table 6 and Table 7, respectively. The creep tests are performed according to the ISO 204:2009 standard, which defines the standard test method for creep testing in tension. The uniaxial tensile tests at elevated temperatures were performed according to ISO 6892-2:2011.

Table 6. The JRC tensile and creep test matrix:

Heat	Test type	Temp. (°C)	Nr of test	Target	Note
20057	Tensile	RT	(1)?	Reference $R_{p02} / R_m = 0.76$	$\sigma_{0.2} = 518, 522 \text{ MPa}$ [[1]] $\sigma_{UTS} = 680, 684 \text{ MPa}$
20057	Tensile	375	3	R_{p02} / R_m	for normalization
20057	Tensile	400	1	R_{p02} / R_m	for normalization
20057	Tensile	425	3	R_{p02} / R_m	for normalization
20057	Tensile	450	1	R_{p02} / R_m	for normalization
20057	Tensile	500	1	R_{p02} / R_m	for normalization
20057	Tensile	550	1	Reference $R_{p02} / R_m = 0.86$	$\sigma_{0.2} = 387, 389 \text{ MPa}$ [[1]] $\sigma_{UTS} = 453 \text{ MPa}$
20057	Uniaxial Creep	500	1	$\epsilon_c = 0.2\%$ in 5000 h	171 MPa
20057	Uniaxial Creep	450	1	$\epsilon_c = 0.2\%$ in 5000 h	280 MPa
20057	Uniaxial Creep	425	1	$\epsilon_c = 0.2\%$ in 5000 h	330 MPa
20057	Uniaxial Creep	400	1	$\epsilon_c = 0.2\%$ in 5000 h	380 MPa
20057	Uniaxial Creep	375	1	$\epsilon_c = 0.2\%$ in 5000 h	415 MPa ₂

Table 7. The PSI test matrix for NEC with miniature specimen (0.1 mm thick, 2 mm wide dogbone specimen).

Heat	Test type	Temp. (°C)	Nr of test	Target	Note
25240002	Uniaxial Creep	475	1	Time to strain and rupture	460 MPa
25240002	Uniaxial Creep	475	1	Time to strain and rupture	430 MPa
25240002	Uniaxial Creep	475	1	Time to strain and rupture	400 MPa
25240002	Uniaxial Creep	475	1	Time to strain and rupture	370 MPa
25240002	Uniaxial Creep	475	1	Time to strain and rupture	350 MPa
25240002	Uniaxial Creep	425	1	Time to strain and rupture	510 MPa
25240002	Uniaxial Creep	400	1	Time to strain and rupture	510 MPa

The times to specified strain and rupture targeted in the test program are rather short (≥ 5000 h) and the required extrapolations for the targeted service times are large. However, the test matrix provides data that does not exist in the public domain, especially for intermediate stress levels at low temperature.

Tensile test results (JRC)

The tensile test results for the 60 mm thick P91 plate (heat 20057) are presented in Figure 4, the raw data can be retrieved from the ODIN data base at <https://odin.jrc.ec.europa.eu/> [23].

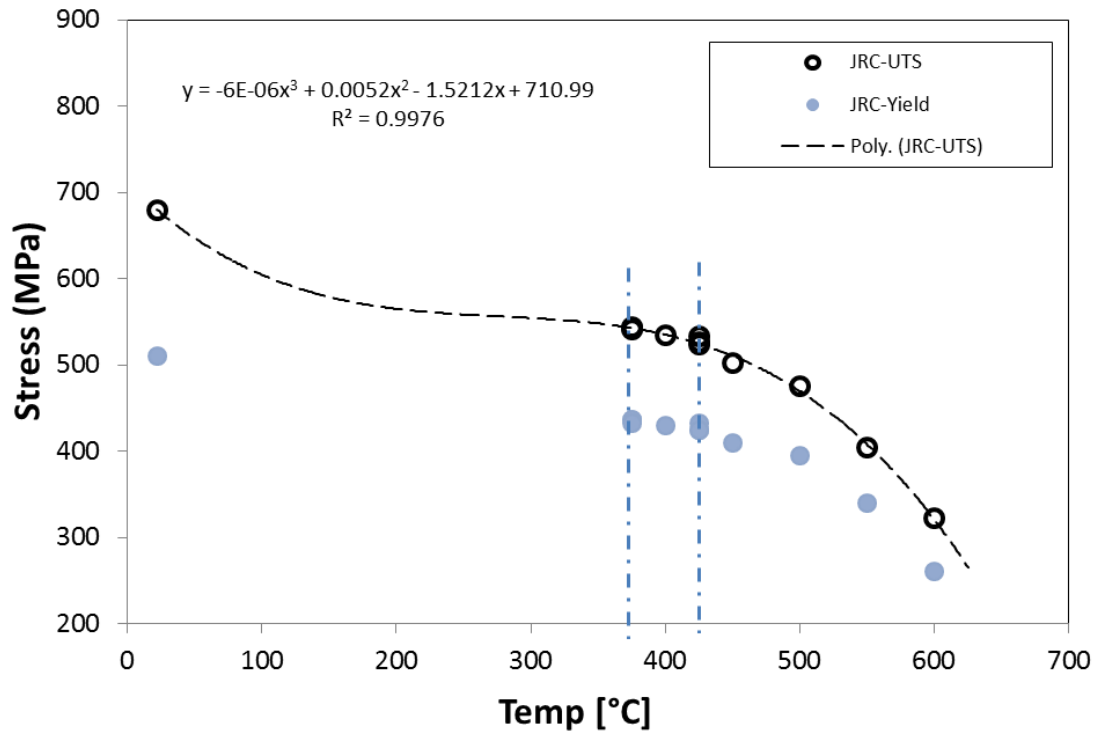


Figure 4. Tensile test results, ultimate tensile strength and yield. The temperature field relevant for NC testing is marked with dash-dotted lines.

Polynomials were fitted to tensile strength and yield stress test data and to the RCC-MRx values for easier use in modelling as :

$$\sigma(T) = A_1 + A_2 T + A_3 T^2 + A_4 T^3 + A_5 T^4 + A_6 T^5 \quad (1)$$

Where σ is the yield stress or the ultimate tensile strength in MPa, T the temperature in Celsius and the A_i are fitting constants given in Table 8.

Table 8. Fitting parameters for ultimate tensile strength and yield stress as a function of temperature. Note that for RCC-MRx the fit is to minimum (lower bound) values.

Parameter	M1 (JRC) σ_{UTS} -average 3 rd degree	M1 (JRC) $\sigma_{0.2}$ - average 3 rd degree	NIMS σ_{UTS} - average 2 nd -degree	NIMS $\sigma_{0.2}$ - average 3 rd degree	RCC-MR σ_{UTS} - min 5 th -degree	RCC-MR $\sigma_{0.2}$ - min 5 th degree
A_1	6.997E+02	3.736E+02	3.879E+02	5.574E+02	5.979E+02	4.089E+02
A_2	-9.733E-01	-2.740E-01	1.455E+00	-7.026E-01	-9.824E-01	-4.542E-01
A_3	2.993E-03	2.838E-03	-2.518E-03	2.685E-03	4.538E-03	1.243E-03
A_4	-3.969E-06	-4.467E-06	0	-3.726E-06	-8.792E-06	1.729E-07
A_5	0	0	0	0	3.848E-09	-5.170E-09
A_6	0	0	0	0	4.005E-13	3.238E-12

For the tensile tests the stress-strain response was also modelled to compare the initial strains recorded at loading for the creep tests.

In RCC-MRx the stress-strain curve is the standard Ramberg-Osgood relation that allows to separate elastic and plastic contribution. It is defined as:

$$\varepsilon_i (\%) = 100 \cdot \sigma / (E \cdot 1000) + (\sigma / (c_0 \cdot \sigma_{0.2}))^{(1/n)} \cdot 1/100 \quad (2)$$

Where σ and $\sigma_{0.2}$ are in MPa, E in GPa and the parameters c_0 and n are temperature dependent as shown in Figure 5. Note that for this model the temperature dependences of E and $\sigma_{0.2}$ also have to be taken into consideration. We assume that between 300-450°C the c_0 , n , E and $\sigma_{0.2}$ depend linearly on temperature.

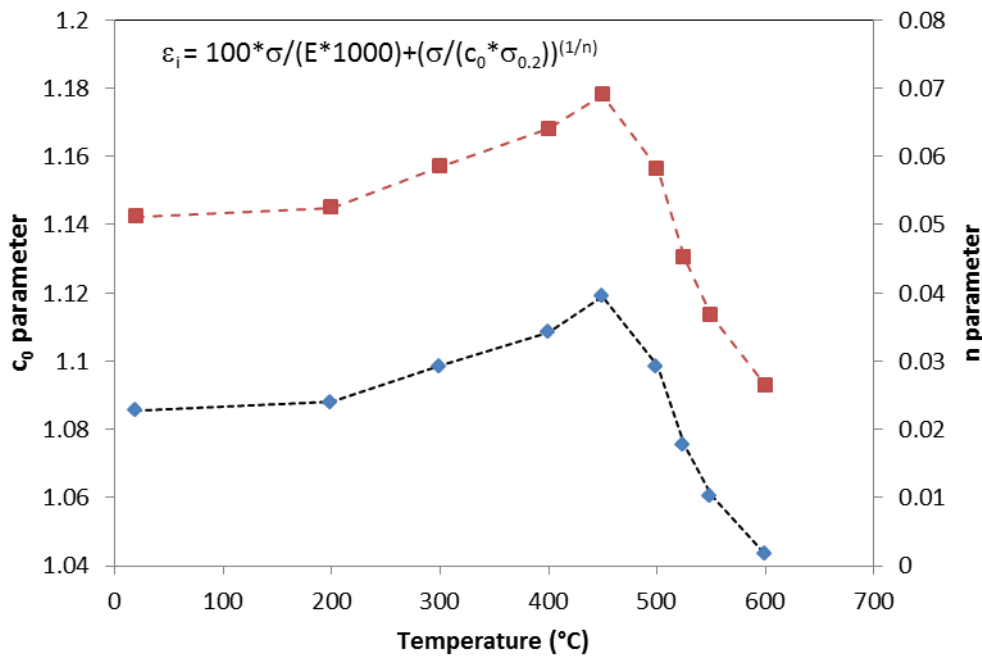


Figure 5. Parameters c_0 and n for describing the stress-strain curve for P91 as given in RCC-MRx (version 2010).

Using the RCC-MR formula to predict initial strains at loading (for creep tests) the strains are higher than the ones measured in the MATTER project. The main reason being lower "average" yield stress values in the code. To simplify the calculation of initial strain for the whole temperature range and to accurately represent the MATTER materials the initial creep strain as a function of normalized stress was solved for both NIMS and MATTER data representing a more average material property range.

The engineering stress-strain curve below 0.8% in strain can be described by:

$$\varepsilon_i (\%) = 0.18 \cdot R / (72.5 - 83.8^R) \cdot 100 \quad (3)$$

Where $R = (\sigma / \sigma_{UTS})$ is the normalized stress, the temperature dependence of ε_i is handled by the temperature dependence of σ_{UTS} . Note that the model should not be used for strains above 0.8%

and outside the 375-500°C temperature range. The simplified model reduces the fitting parameters to 3 temperature independent constants. Together with the parameters needed for a linear relationship for tensile strength (in the NEC temperature range) there are all in all only 5 material constants needed for the full stress-strain curve definition. The stress-strain model predictions are presented in Figure 6 and Figure 7 with initial strain measurements from both NIMS and MATTER creep tests. A comparison to the RCC-MRx predictions is given for 450°C test data in Figure 8. In Figure 9 the RCC-MRx equations are used with the measured yield values showing a substantial improvement in the predicted initial strains, which of course is expected since the calculated yield values are intended to represent average material properties.

The normalized stress method is inherently simple and optimal for determining material stress-strain curves from initial (instant) strain obtained in creep testing. It can of course also be optimized on full strain curves increasing the applicable strain range. It also has potential for use in design codes.

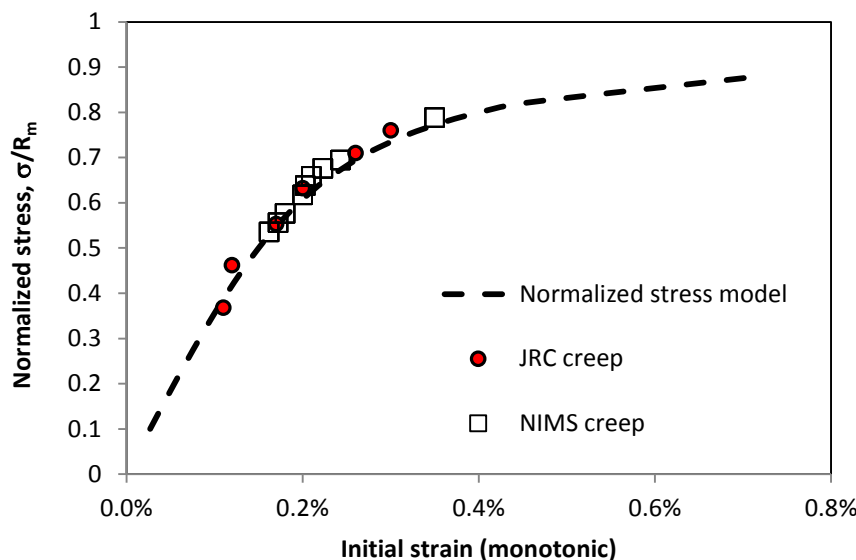


Figure 6. The normalized stress approach (Eq. 3) for P91 with JRC initial strain data from 375-600°C tests and NIMS initial strain data from creep tests at 450 and 500°C.

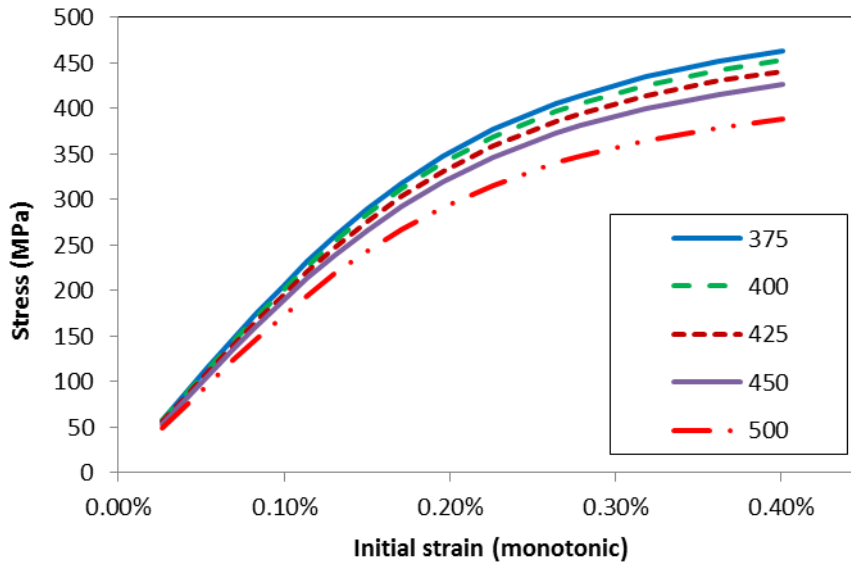


Figure 7. Modelled stress-strain curves for using the normalized stress approach (Eq. 3) for P91.

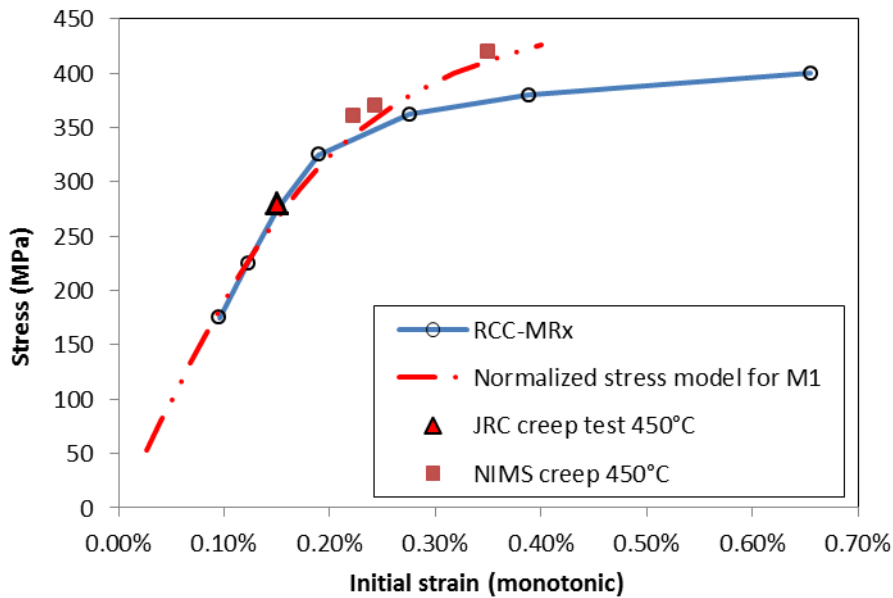


Figure 8. Comparing the RCC-MRx stress-strain response with the normalized stress model and measured initial stress data from 450°C tests (JRC and NIMS data).

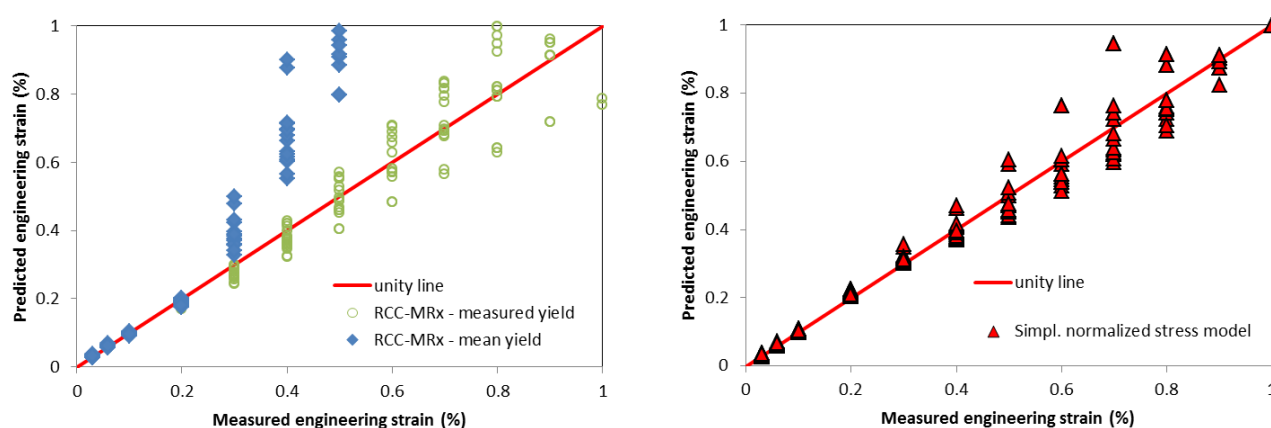


Figure 9. Measured versus predicted stress-strain from tensile tests for the temperature range 375°C – 450°C predicted with a) RCC-MRx model using both mean yield stress of the code and the measured yield stress values, and b) simplified normalized model. Note the increased scatter between tests at higher strain levels.

Ensuring the sufficient quality of the creep data in the NEC range

At JRC the test programme was launched in mid-2013 restricting the available testing time to up to 10 000 hours to the end of the MATTER project. To give room for inaccuracies in the initial predictions the target times were set to 5000 h. To reach the target of defining small creep deformations in the specified time range requires high accuracy in determining the instant (elastic-plastic) strain at loading. Normally in creep rupture testing where the target is reaching minimum strain rate or rupture the initial strain is usually neglected or determined from tensile tests. The tests performed at JRC is targeting creep strains considerably lower than 1% meaning that the tests will be entirely within the primary creep region. The strains at minimum strain rate for ferritic-martensitic (ductile) steels are usually around 1%. For the targeted temperature range (375-450°C) the required loads for short to medium term test durations are high, especially if 1% or rupture is targeted. For supporting design rules again only stress ranges close to or below material yield are relevant. Extrapolation from the "power law break-down" region at stresses close to maximum tensile strength towards lower stresses are likely to be more challenging than extrapolations in temperature at moderate stresses. To define the stress range applied in terms of proximity to yield and ultimate tensile strength and to have the possibility of using the Wilshire approach for modelling rupture and time to strain the ultimate tensile strengths as a function of temperature described earlier are used. As mentioned before, the initial strain and time when the load is fully applied is crucial for determining the time to the targeted small strains. To acquire as good results as possible using standard dead-weight creep machines without load measurement capacity, a methodology for starting the tests has been developed. For the standard creep machine the applied dead weight is usually amplified by a lever ratio depending on the machine manufacturer (at JRC 1:10 or 1:15). Loading is normally done manually with little or no control of the loading rate of the specimen. This of course makes accurate determination of the time and strain when full load is applied difficult, thus making the time to specified low strain also uncertain. The new method described in APPENDIX 1 for improving the measured primary creep and especially the initial strain at loading has been applied at JRC.

Creep test results

The time to specified creep strains for the MATTER tests (by JRC) are given in Table 9 and are available in the MatDB data base [22]. The full strain curves of the tests are given in APPENDIX 2. Note that in these plots "CORR" refers to curves in which the initial strain ε_i have been removed.

Table 9. The results of the JRC creep test program for determining creep and NEC properties. Designations; t_r =time to rupture, t_ε =time to strain, ε_f =fracture strain, ε_t =strain at time.

Ident.	Temp. (°C)	Stress σ (MPa)	Norm. Ratio σ/R_m	Time t (h)	Strain ε (%)	Note:
MC06	600	155	0.46	$t_r=666$	$\varepsilon_f=38.4$	Ruptured
MC08a	550	280/330/380 3 x 415	0-0.76	-	-	Interrupted ¹⁾
MC08b	550	230	0.56	$t_r=417$	$\varepsilon_f=36.5$	Ruptured ²⁾
MC01	500	171	0.37	$t_\varepsilon=7050$	$\varepsilon_t=0.180$	Interrupted
MC02	450	280	0.55	$t_\varepsilon=+7970$	$\varepsilon_t=+0.191$	Interrupted
MC03	425	330	0.63	$t_\varepsilon=+7800$	$\varepsilon_t=+0.215$	Interrupted
MC05	400	380	0.71	$t_\varepsilon=+7950$	$\varepsilon_t=+0.247$	Interrupted
MC07	375	415	0.76	$t_\varepsilon=817$	$\varepsilon_t=+0.23$	Interrupted
MC04	375-450°C	415	0.76	$t_\varepsilon=+11660$	$\varepsilon_t=+1.65$	Running ³⁾

1) load cycling test with stress ratio $R=0$, i.e. unload between loading

2) creep test with pre-strain from load cycling continued test from above (0.4 creep strain at start)

3) temperature cycling test cycling between 375-450°C at 415MPa

As given in the above table the creep strain of 0.2% has been reached for some of the tests and for some it has nearly been reached. The result indicates that the primary creep rates at temperatures as low as 375°C might be higher than what would be expected from extrapolation towards lower temperature with classical time-temperature parameter approaches.

The two tests where changes in stress or temperature have been made are presented in Figure 10 and Figure 11. The tests were done to support modelling of transients. The decreasing primary creep strain rates measured in the step wise increased loading tests clearly shows the increased strain hardening imposed on the material. For the temperature cycling test the strain rate change can be used for verification of creep models and calculating the activation energy.

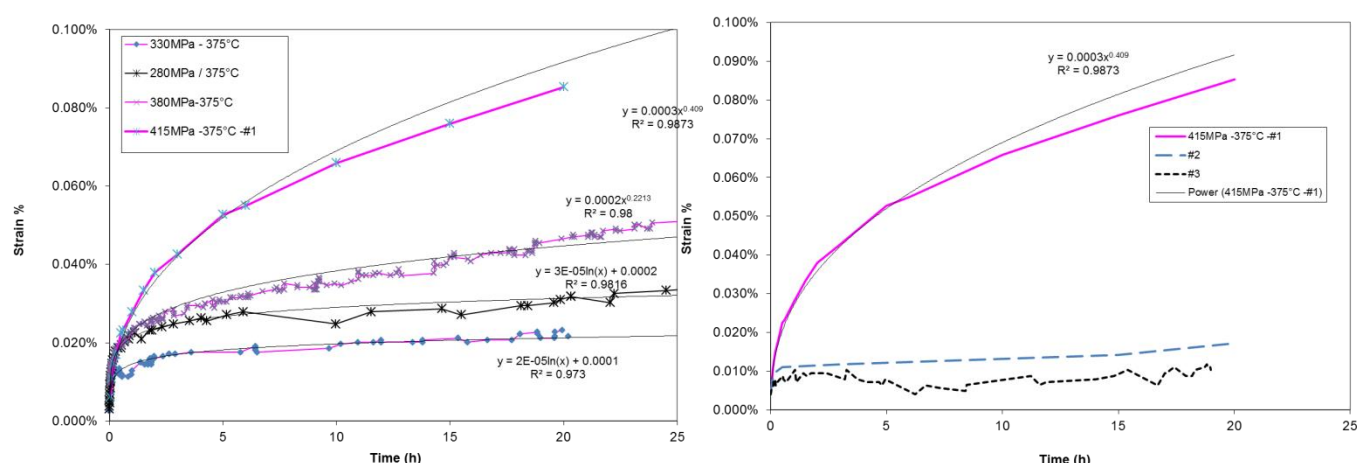


Figure 10. Stress cycling test (MC08a) with increasing stress, i.e. 280, 330, 380 and 415MPa at 375°. There was 3 cycles at 415 MPa. Note that the specimen was unloaded between stresses levels.

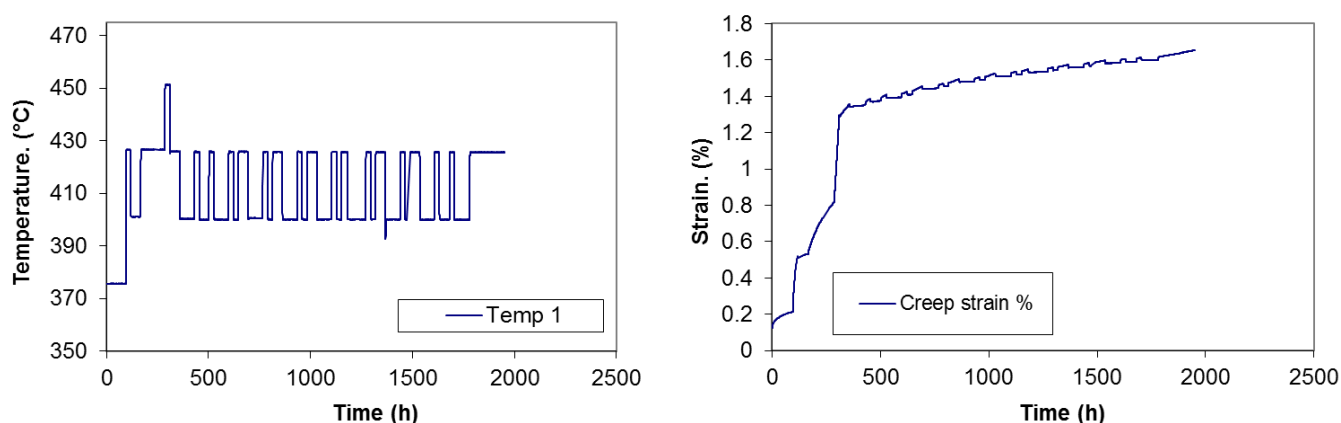


Figure 11. Temperature cycling at 415MPa at the border of yield (MC04).

The measured creep strain curves and strain rate plots of the miniature tests performed by PSI can be found in APPENDIX 3.

Defining the negligible creep curve

Initial predictions for time to creep strain limit

Extrapolations towards lower temperatures have been performed for all test data below 450°C by using both classical models [16] such as Manson-Haferd (MH), Manson-Brown (MB) or the minimum commitment (MC) method and by the Wilshire equations (WE) [11] together with the LCSP strain model [17] as shown in Figure 12.

The DESA [18] software was used for the classical creep models predicting stress required to gain 0.2% strain at a given time mainly using the NIMS P91 data set [12]. These predicted (extrapolated) stress values to gain 0.2% strain in 5000 h were used to set-up the MATTER (JRC) test matrix given earlier in this report (see Table 10 and compare to Table 6). The models represented are of course more reliable in extrapolation towards higher temperatures but the initial predictions give information on the potential "challenges" of temperature extrapolation towards NEC conditions.

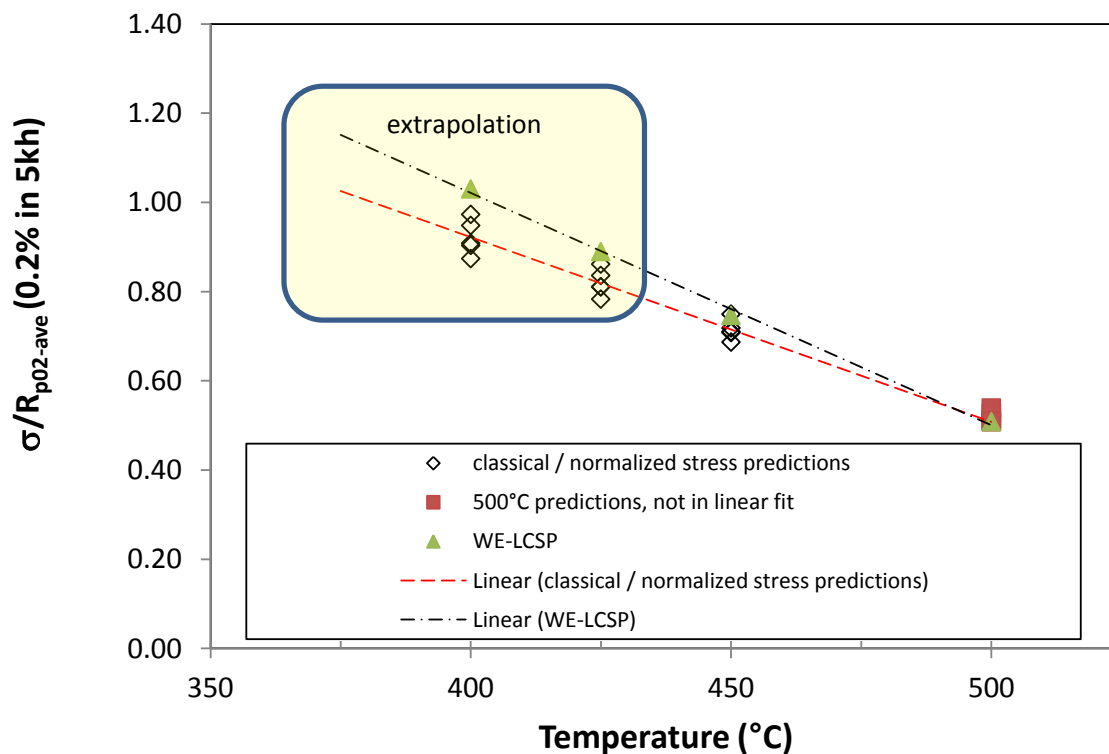


Figure 12. Initial determination of stress to give 0.2% creep strain in 5000h as given Table 10. The two methods used are; classical parametrical extrapolations ($t_{0.2\%}$) and using the LCSP creep strain model with temperature and stress dependent shape functions. Note that the normalization is by yield stress.

Table 10. Predicted stress to cause given strain in 5000 h (for MATTER test matrix) using direct fitting of time to specified strain with classical creep models. The stress ratio: predicted test stress over yield stress (S_y as in RCC-MR, mean value) and ultimate tensile strength is also given.

Temp	Creep model*	Creep strain (%) in 5000 h	Predicted stress (MPa)	Pred. stress / Yield Stress	Note:
------	--------------	----------------------------	------------------------	-----------------------------	-------

500	LM MH MC MB WE-0.2 LCSP (WE)	0.2%	191 186 195 184 180 184	0.519±0.012	Data available 6 pts 0.2% Max. $t_{0.2}$ ~70h at 260 MPa
450	LM MH MC MB WE-0.2 LCSP (WE)	0.2%	287 263 272 271 275 286	0.713±0.023	Data available: 3 pts 0.2%, (NIMS) 2 pts 0.1% [14]
425	LM MH MC MB WE-0.2 LCSP (WE)	0.2%	339 308 319 319 329 350	0.816±0.028	Data available: 2 pts 0.1% [14] Inconsistent results (higher stress longer $t_{0.2\%}$)
400	LM MH MC MB WE-0.2 LCSP (WE)	0.2%	393 353 365 367 383 (416 > $R_{p0.22}$)	0.914±0.035	No data available Temperature extrapolation -25°C
375	WE-0.2	0.2%	415 (457 > $R_{p0.2}$)	1	Temperature extrapolation -50°C

*LM=Larson-Miller, MH=Manson-Haferd, MB=Manson-Brown, MC=Minimum Commitment, WE=Wilshire Equation, LCSP=Logistic creep strain prediction

Creep strain model based on the Wilshire equations

The classical models used for the initial predictions were compared to the Wilshire type strain model (WE) optimised on the MATTER and NIMS data. This type of strain model was selected due to the robust nature of the model. The main WE model advantages for defining the NEC limit temperatures and stresses are:

- Few fitting parameters (u, k)
- the activation energy Q for time to strain seems to be constant also at NEC temperatures

- easy to express time to specified strain $t_\varepsilon(\sigma)$ as a function of stress and stress required to cause a specified strain as a function of time $\sigma(t_\varepsilon)$ (see below Eq. 1 and 2)
- easy to relate to rupture properties (same models used with differing u and k)
- robust in extrapolation limited by tensile strength (normalized value between 0 and 1)

The WE equation for time to strain t_ε is:

$$t_\varepsilon = \left[-\frac{1}{k} \ln\left(\frac{\sigma}{\sigma_{UTS}}\right) \right]^{\frac{1}{u}} \cdot \exp\left(\frac{Q}{R \cdot T}\right) \quad (1)$$

where σ is the test stress and σ_{UTS} the ultimate tensile strength, i.e. σ/σ_{UTS} is the normalized stress, Q the activation energy, R the gas constant and T the temperature in K.

The WE equation for normalized stress σ/σ_{UTS} is:

$$\frac{\sigma}{\sigma_{UTS}} = \exp \left[-k \left(t_\varepsilon \cdot \exp\left(\frac{-Q}{R \cdot T}\right) \right)^u \right] \quad (2)$$

and the sought temperature T at specified stress σ and time to strain or rupture as:

$$T = \frac{Q}{R \cdot \ln \left(t_\varepsilon \cdot \left[-\frac{1}{k} \ln\left(\frac{\sigma}{\sigma_{UTS}}\right) \right]^{\frac{1}{u}} \right)} \quad (3)$$

The WE model fits for rupture, 1%, 0.5%, 0.2% strain (NIMS data only) are shown in Figure 13 and the corresponding model parameters derived from the plot are shown in Figure 14 and Table 11. Note that the data close to yield (at about $\sigma/R_m \sim 0.8$) seems to be in quite good agreement with the model predictions. The activation energy Q used is 300 000 J/mol in the temperature range 450°C-650°C. The predicted against measured logarithmic time to strain (or rupture) are given in Figure 15.

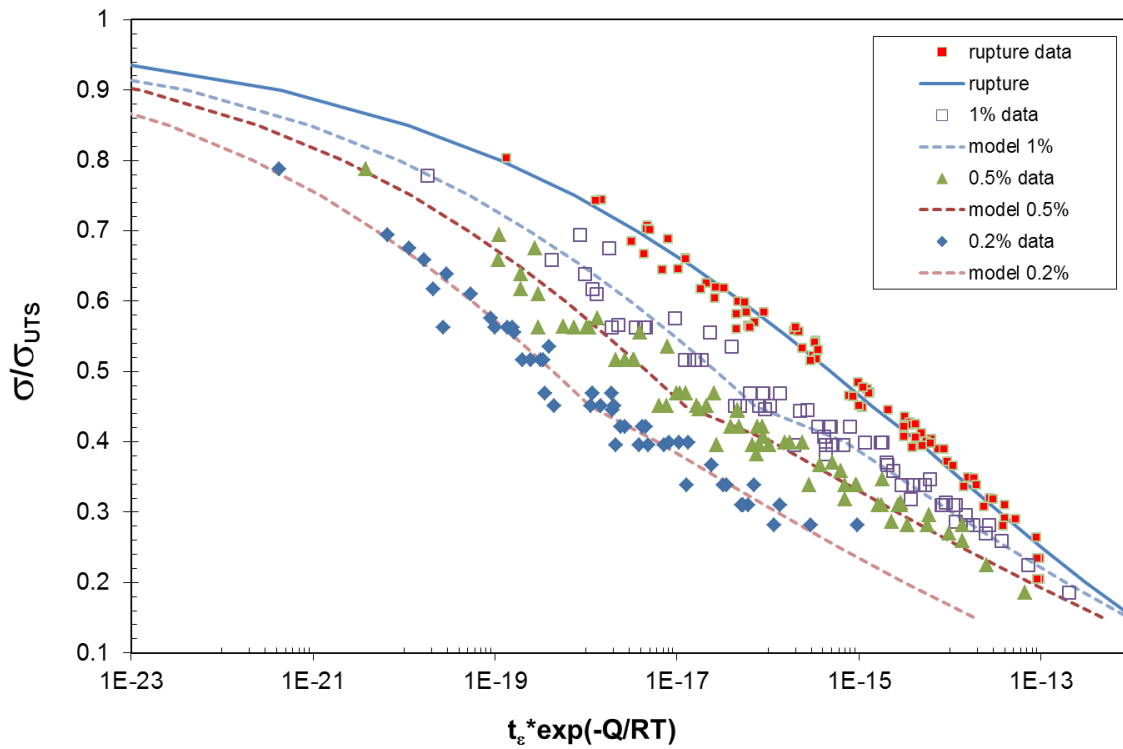


Figure 13. NIMS strain data and WE model predictions for rupture, 1%, 0.5% and 0.2% strain.

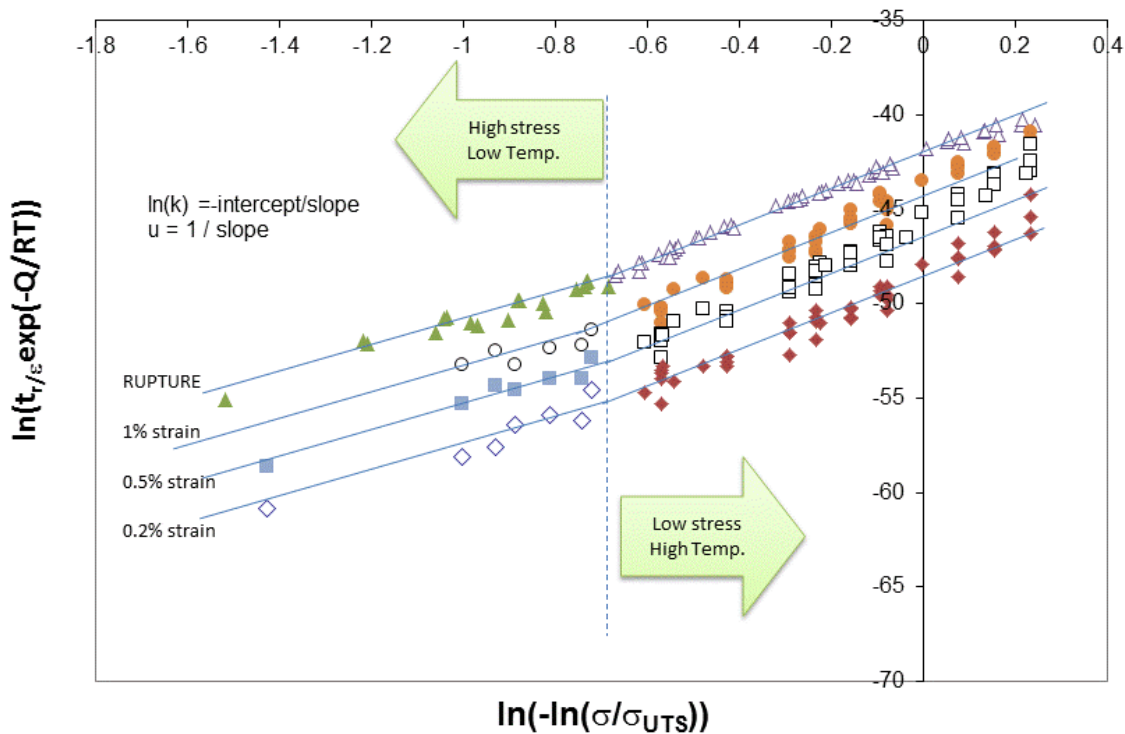


Figure 14. Determination of fitting parameters u and k for the strain data.

Table 11. Wilshire creep strain and rupture model parameters for P91 steel (NIMS data). Note that time ($t_{r/\varepsilon}$) is in hours, and the total strain range in %. Note also that there is a change in parameters at the stress ratio of 0.45. The activation energy Q is 300 000 J/mol in all cases (see Eq. 2-4).

Model type	$\sigma/R_m > 0.45$		$\sigma/R_m \leq 0.45$	
	k	u	k	u
rupture	82.769102	0.135627	75.618032	0.133624
1.0% strain	150.827655	0.141074	31.330443	0.101257
0.5% strain	246.987398	0.147260	22.206093	0.086804
0.2% strain	382.358129	0.149313	33.303955	0.090673

The full master strain model for stresses above $0.45 \cdot R_m$ and strains in the range of 0.2-1% is defined by using Eq. 1-2 with k and u as functions of strain. The functions for k and u are given in Table 12.

It is to be noted that predicted time to 1% strain is closing in on the rupture curve as the extrapolation time increase, showing a tendency of creep ductility decrease at long extrapolation times.

Table 12. Wilshire creep strain parameters k and u for full master strain model ($\varepsilon_c \leq 1\%$, $T=375-600^\circ\text{C}$ and $\sigma/R_m > 0.45$). Note that ε is not to be given in %.

$\sigma/R_m > 0.45$ predicted		
Strain range % (0.2-1%)	$k = -331.71 \cdot \log(\varepsilon)$	$u = -1.051 \cdot \varepsilon + 0.1518$

The new creep strain test results from MATTER and the NIMS data are plotted in Figure 16 for time to 0.2%. The PSI test data obtained with miniature specimen at 475°C are plotted in Figure 17. The results of the miniature specimens give comparable results to the classical creep specimen. There were inconsistencies in some high stress range tests.

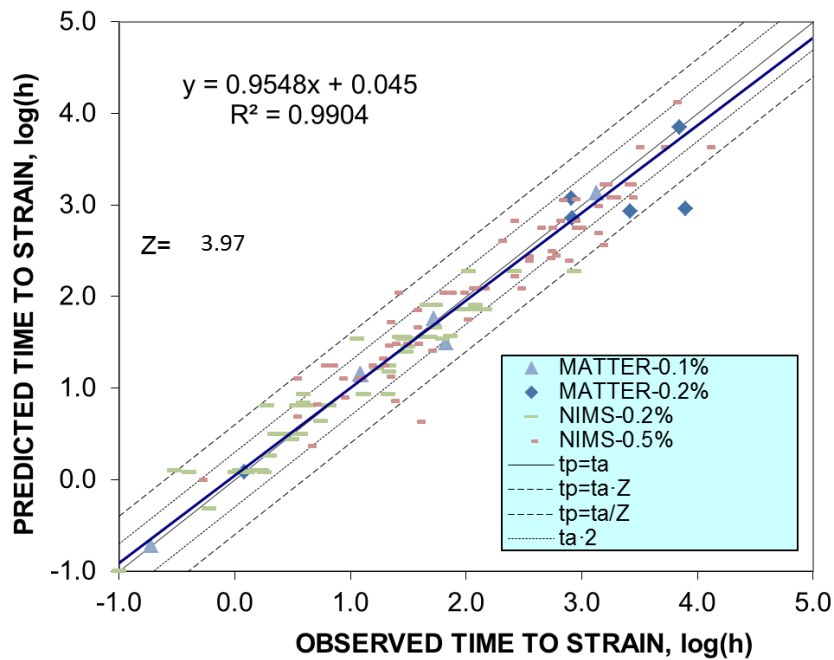


Figure 15. Measured against predicted time to strain for 0.1-0.5% strain using the WE model and WE model parameters optimized to the data.

Note that extrapolation towards the "power law break-down" region at stresses approaching the ultimate tensile strength are likely to be more challenging than extrapolations in temperature at moderate stresses due to the curvature of the Wilshire equation. The reference stress is however still in the stress region where creep test results (at higher temperatures) are available and the effect of the proximity to the power law breakdown region is sufficient.

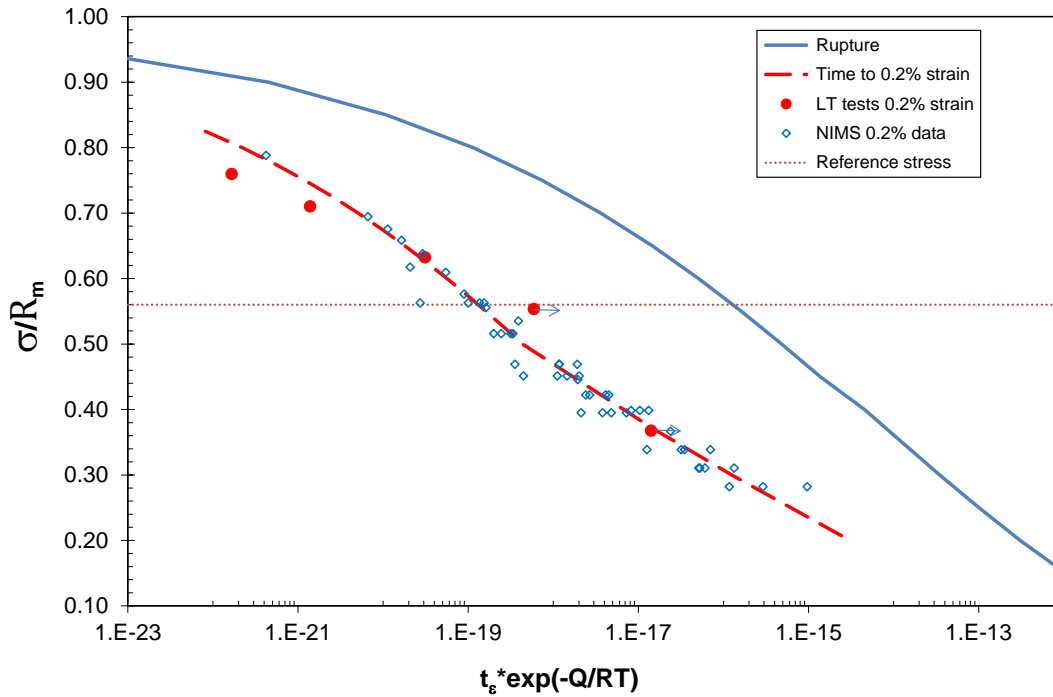


Figure 16. Normalized stress plot for JRC test results for time to 0.2% creep strain. The selected reference stress of 0.56 R_m is marked by a dotted line.

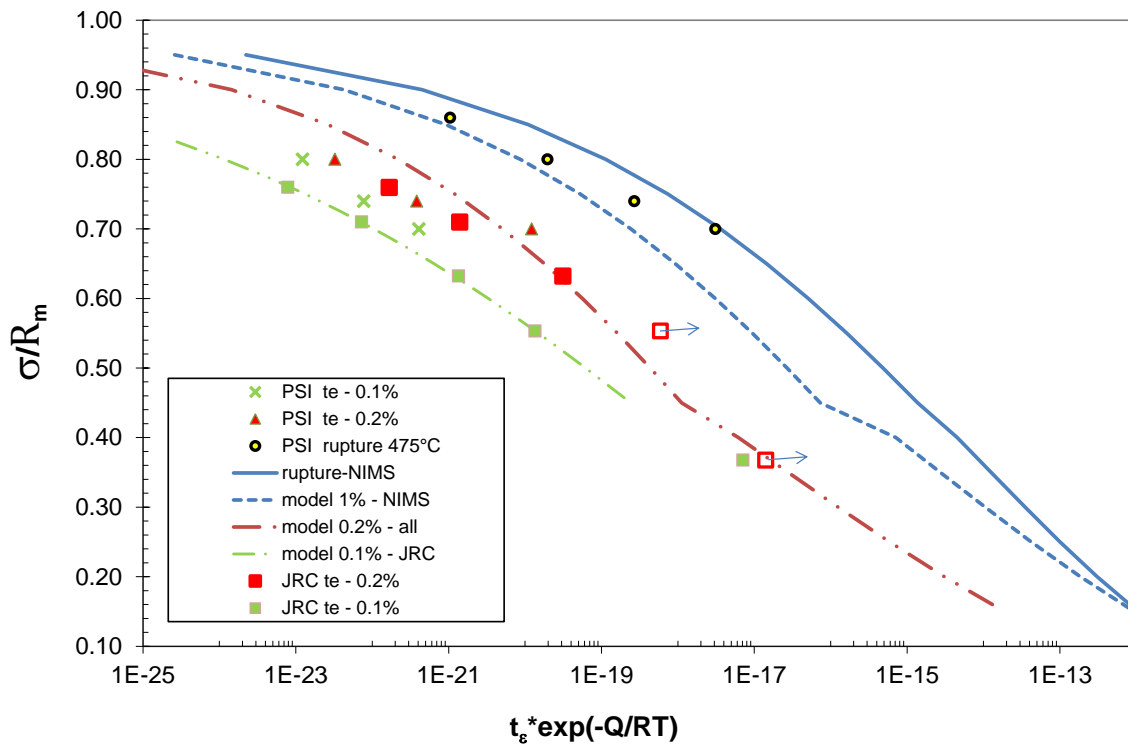


Figure 17. Normalized stress plot for PSI miniature tests (475 °C) specimen results for time to 0.2% creep strain.

With both the creep strain model and the rupture model in place it is now possible to calculate rupture time safety factors (RFT) corresponding to different strain limits by overlapping the strain and rupture models using Eq. 2 by finding the optimal RFT that satisfies $t_{\varepsilon} = t_r / \text{RFT}$. For P91 it can be shown that $\text{RFT} \sim 10$ corresponds to time to 1% strain, $\text{RFT} \sim 100$ to 0.5% strain and $\text{RFT} \sim 1000$ to 0.2% strain as shown in Figure 18.

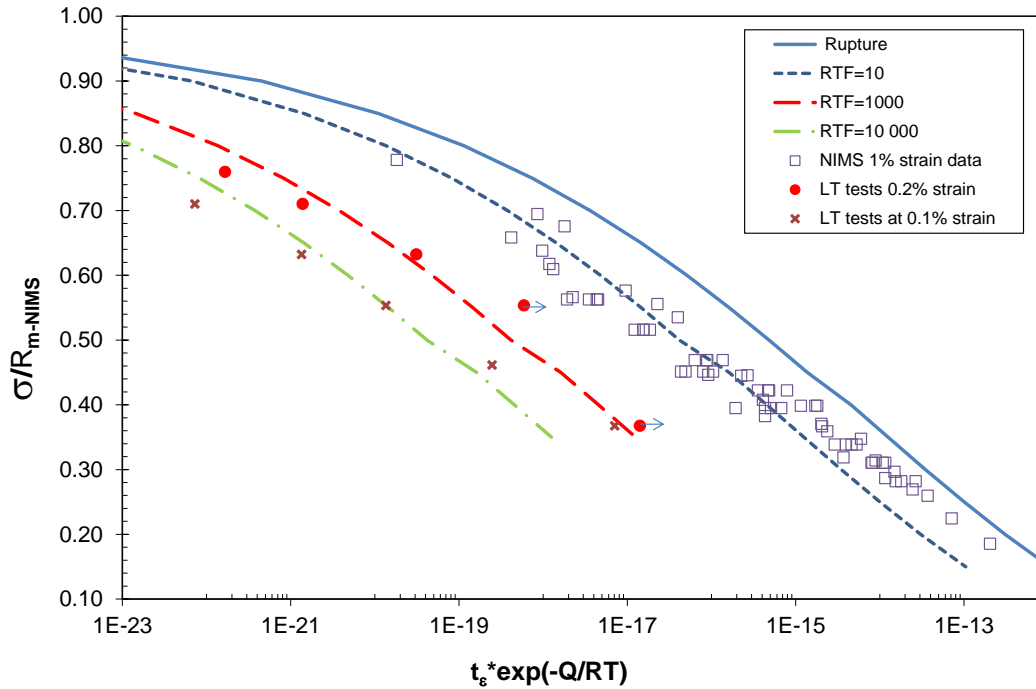


Figure 18. Normalized stress plot for JRC test results with RTF corrected time to strain estimates.

The negligible creep (NEC) curve for P91 steel

In Figure 19 the proposed NEC temperature curve is presented using the time to 0.2% strain criteria and a reference stress of $0.56 R_{m-ave}$ as generated by Eq. 4.

To further verify the proposed T_{NEC} curve against another comparable model, creep strain calculations were made using the RCC-MRx creep strain formulations and parameters for the temperatures 400, 450 and 500°C to predict time to 0.2% creep strain. The same reference stress and R_m values were used. The predictions are depicted in Figure 20 together with the 0.2% strain T_{NEC} curve and a curve calculated on the T_{Rupt} curve corrected with a RTF of 1000.

It can be seen that the RCC-MRx predicted time to 0.2% strain coincides well with the T_{NEC} curve based on the MATTER assessment. The proposed T_{NEC} predicts marginally longer time to 0.2% than the RCC-MRx creep strain model.

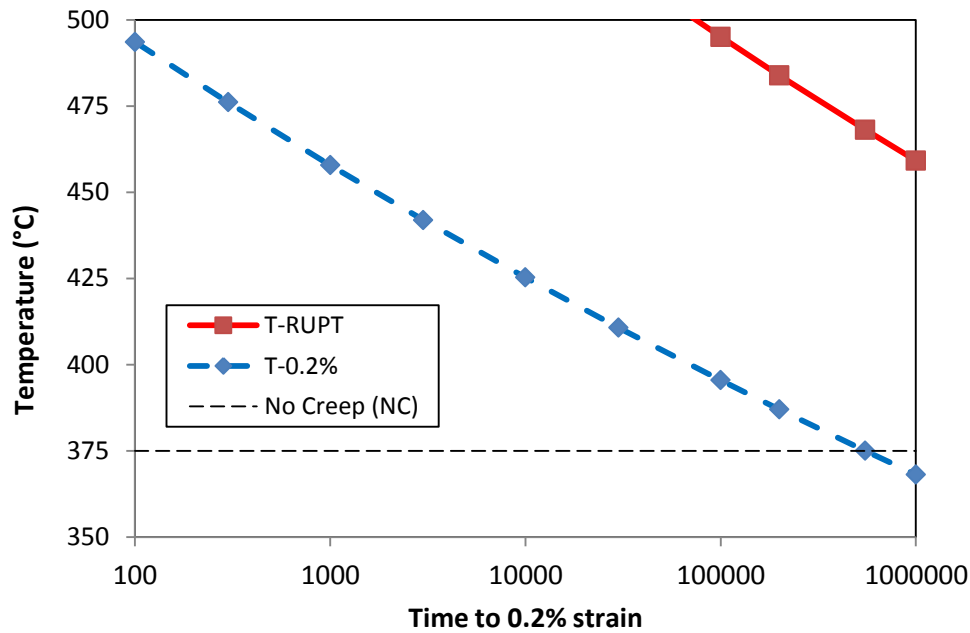


Figure 19. Proposed negligible creep temperature curve for the 0.2% creep strain criterion with reference stresses of $0.56 \cdot R_m$ with correction for RCC-MRx average rupture strength. Note that the curve is intersecting the NC temperature (375°C) at approximately 500 000 h.

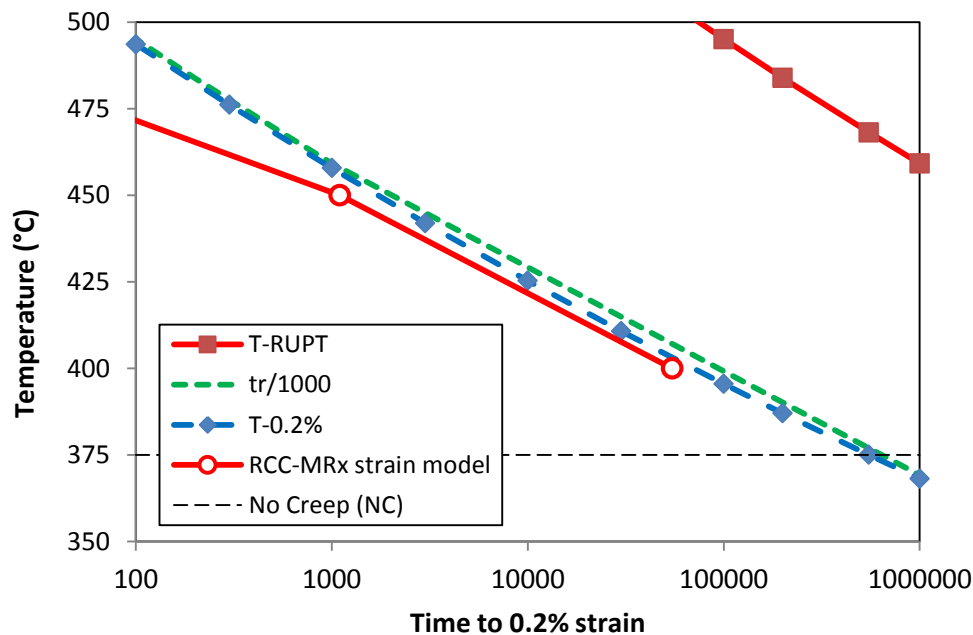


Figure 20. Negligible creep temperature curves using time fractions of time to rupture (all available rupture data) The NEC curve for RTF life fraction of 1/1000 corresponds well with the above given 0.2% creep strain criteria.

Conclusions and recommendations

The negligible creep temperature curve (T_{NEC}) has been constructed for P91. A reference stress of 0.56 times the ultimate tensile strength has been recommended in compliance with the RCC-MRx allowable stresses for this steel. The T_{NEC} curve has been defined using the Wilshire equations for rupture and strain with data from public domain and the recent MATTER project. The generated data is a set of low temperature tests with test stresses close to the proposed reference stress ranging from 0.37 to 0.76· R_m . The NEC criteria proposed for the RCC-MRx design code are tabulated in Table 13.

It is to be remembered that there is extensive extrapolation involved in defining the T_{NEC} curve and the corresponding time factors. If the extrapolation range would be limited to a factor of 3 as recommended when defining the creep rupture properties, the curve could not be defined.

Table 13. P91 negligible creep definition to be proposed for RCC-MRx with $S_m=R_m/2.7$

Based on:	Reference stress	NEC criterion
Creep strain $\varepsilon_c \leq 0.2\%$	$1.5 \cdot S_m$ ($0.56 \cdot R_m$)	$\sum_{i=1}^n \left(\frac{t_i}{t_{i-\max}} \right) \leq 1$
Time factor $t \leq t_r/1000$	$1.5 \cdot S_m$ ($0.56 \cdot R_m$)	$\sum_{i=1}^n \left(\frac{t_i}{t_{i-\max}} \right) \leq 1$

The conservativeness of the generated T_{NEC} curve, based on time to 0.2% creep strain, is large compared to rupture. Rupture times are ~1000 times higher than the time to 0.2% strain. The predicted rupture times at reference stress and allowable stress were compared and an additional safety factor of >100 in time is imposed by the stress ratio between reference stress and allowable stress (time factor $t_{\text{allowable}}/t_{\text{ref}}=115$ for 0.2% strain and 400 for rupture).

With the proposed curve the total design safety factor against creep rupture (in time) is > 100 000, i.e. 100 times 1000. The corresponding factor against 0.5% strain is 1000 (100 times 10).

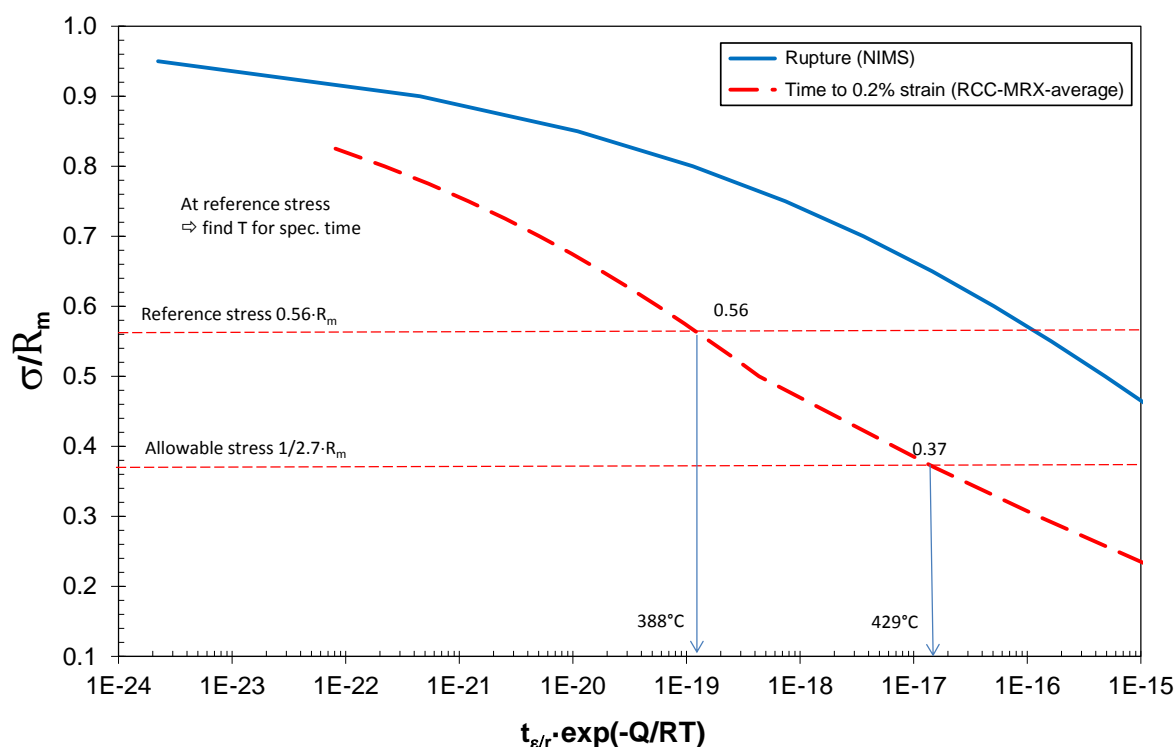


Figure 21. Normalized stress plot for NEC criterion time to 0.2% creep strain and temperature predictions for 200 000 h service at reference or allowable stresses.

It is concluded that a "sufficient" safety margin is in place for the proposed T_{NEC} and that it can be recommended for use in the nuclear design codes such as RCC-MRx.

It is also to be noted that additional creep tests are highly recommended to verify the results with a closer range of test stresses around the reference stress and an increased amount of test temperatures in the 375 to 500°C range.

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<http://dx.doi.org/10.5290/2500076>, <http://dx.doi.org/10.5290/2500002>,
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APPENDIX 1, Methodology for creep test loading to acquire accurate initial strain and time at zero creep strain.

The tests for NEC determination have all been started by a new technique ensuring equal loading rate and better initial strain measurement. The method is using the automatic lever correction feature of the creep machines. It means that the load is applied to the specimen by the electrical motor that corrects the lever when the specimen creeps. The measured loading rate for the loading bar movement when correction is activated is approximately 0.02mm/s. The assessed data for initial strain (for plate 20057) is show in Figure 22.

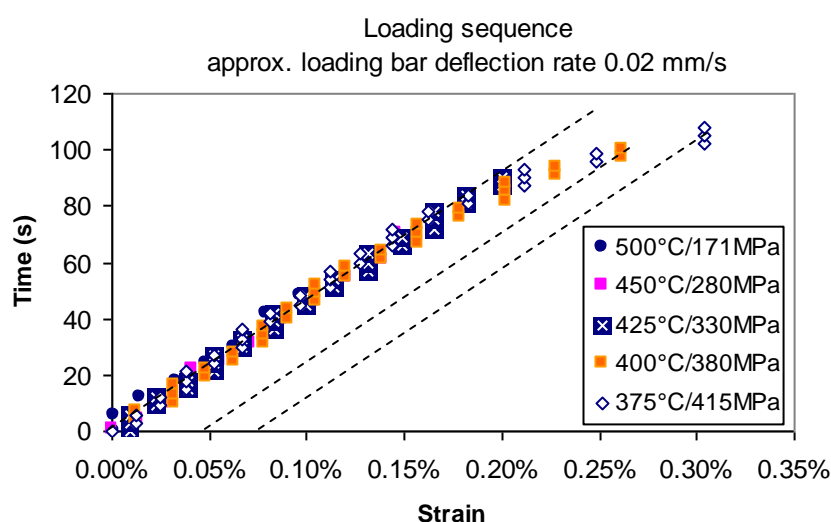


Figure 22. Strain development during loading with electrical lever correction motor.

It can be seen that only the tests at the two highest stresses yield. The yielding is though less than 0.1% thus not over the defined standard yield point referring to 0.2% plastic deformation.

Method for acquiring equal loading conditions sequences in creep testing with dead-weight lever machines

The standard dead weight creep machines have in most cases an inbuilt automatic lever correction function. The lever correction, working by an electric motor, keeps the lever ratio constant and the load lines vertical, automatically levelling the lever by retracting the loading bars when creep strain is accumulated. This feature can be used to load the specimen at a repeatable rate.

The procedure for creep tests for NEC included the following steps;

- The LVDTs are zeroed at level lever position (lever correction is ON)
- The automatic lever correction is switched OFF and the load train is lowered below the lever correction limit to the supporting tray

- The full load is applied on the machine supported by the tray, i.e. the force on the specimen is negligible
- The automatic lever correction is switched ON and the lever correction function lifts the weights to a level lever position
- The time from switching ON the lever correction to the instant the load is free from the support tray is measured
- The data is assessed with the time and measured strain data as shown in Figure 23.
- The initial strain at loading is recorded and the actual creep strain accumulation and time starts from this point.

The above procedure enhances the quality of the initial and primary creep strain data.

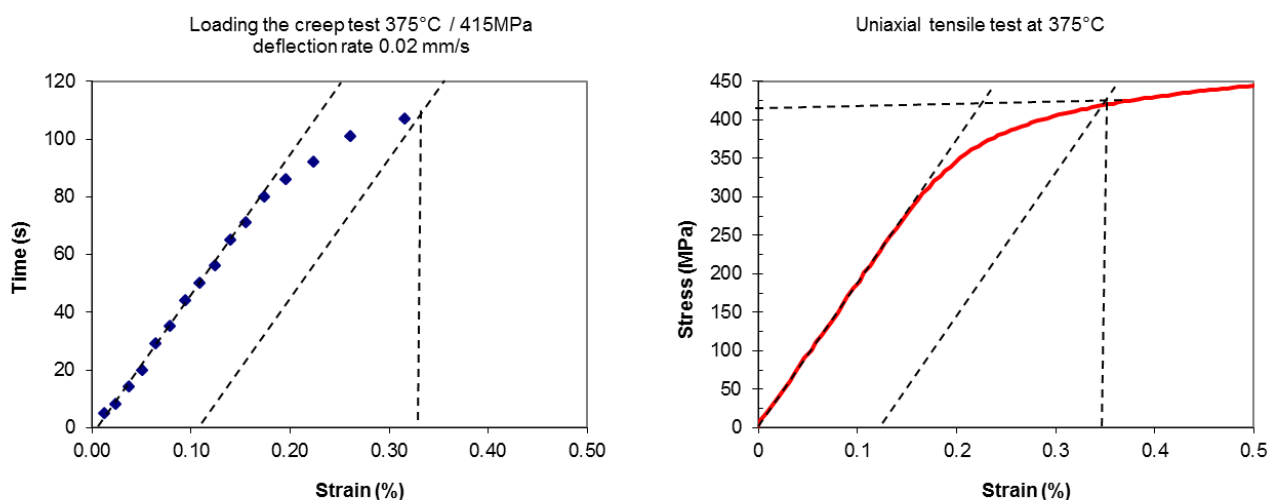


Figure 23. a) Loading of a creep test at 375°C to 415 MPa with lever leveling function b) uniaxial tensile test at the same temperature. Note that the initial strain at full load (creep) is corresponding very well with the expected strain at 415 MPa in the tensile test.

APPENDIX 2; Uniaxial creep tests

Uniaxial creep test at 500°C / 171 MPa

Note that the LVDT1 has an initial problem, only LVDT1 is used for creep strain only after the signal drop at 20h if creep.

Result table for MC01 tested at 500°C / 171 MPa, initial strain ε_0 (elastic-plastic) was 0.11 %

Creep strain (%)	0.01	0.03	0.1	0.2	0.202 % (test max)
Strain rate (1/h)	6.6E-5	6.8E-5	2.9e-7	1.5E-7	1.3E-7
Time (h)	0.75	12	936	6845	7050

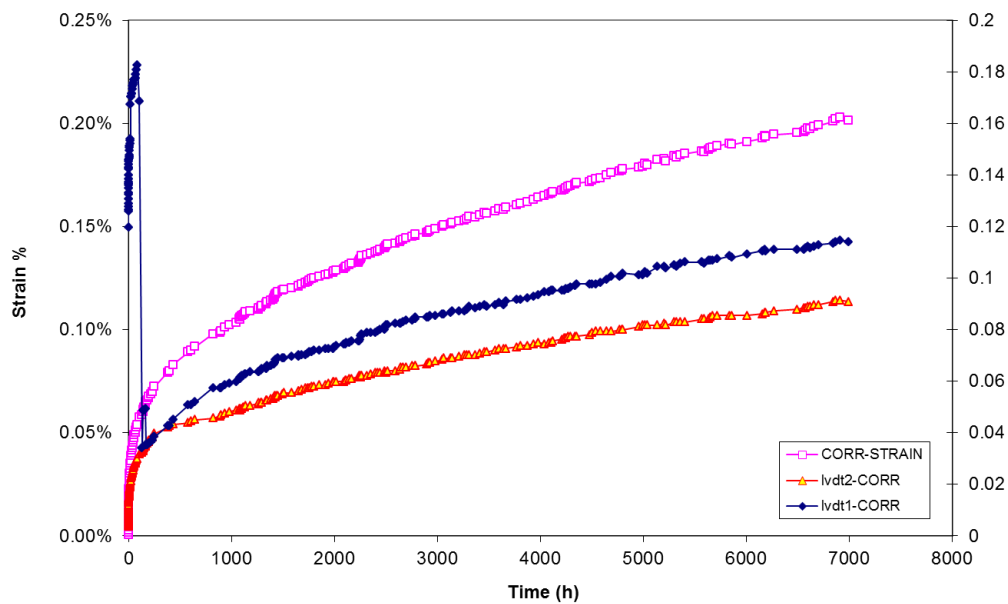
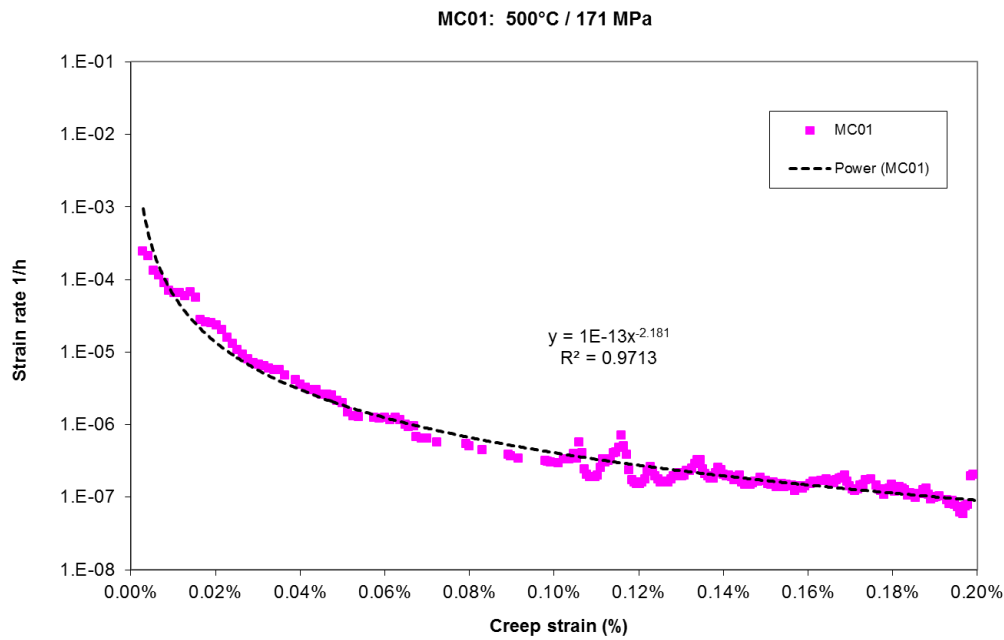
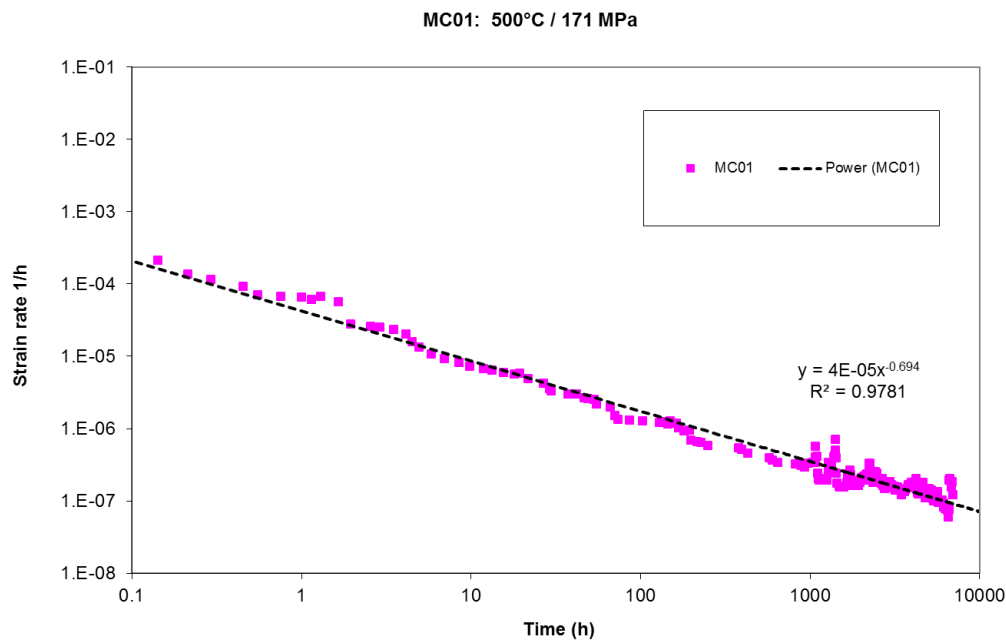


Fig. X Time to deflection (right y-axis) and engineering strain (left y-axis). CORR means that the initial strain has been removed.



Strain rate (1/f) as a function of creep strain.



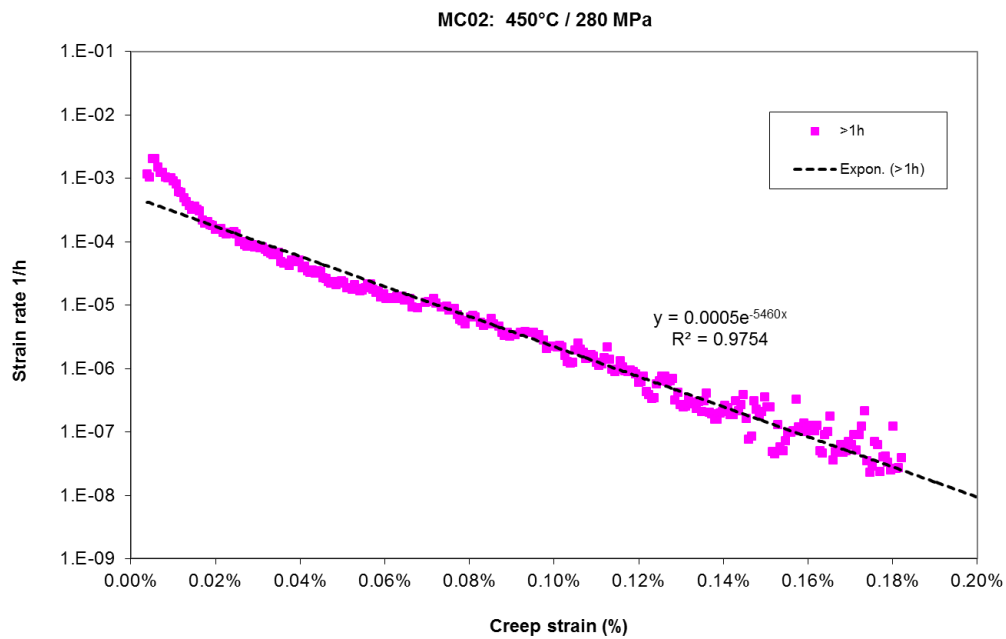
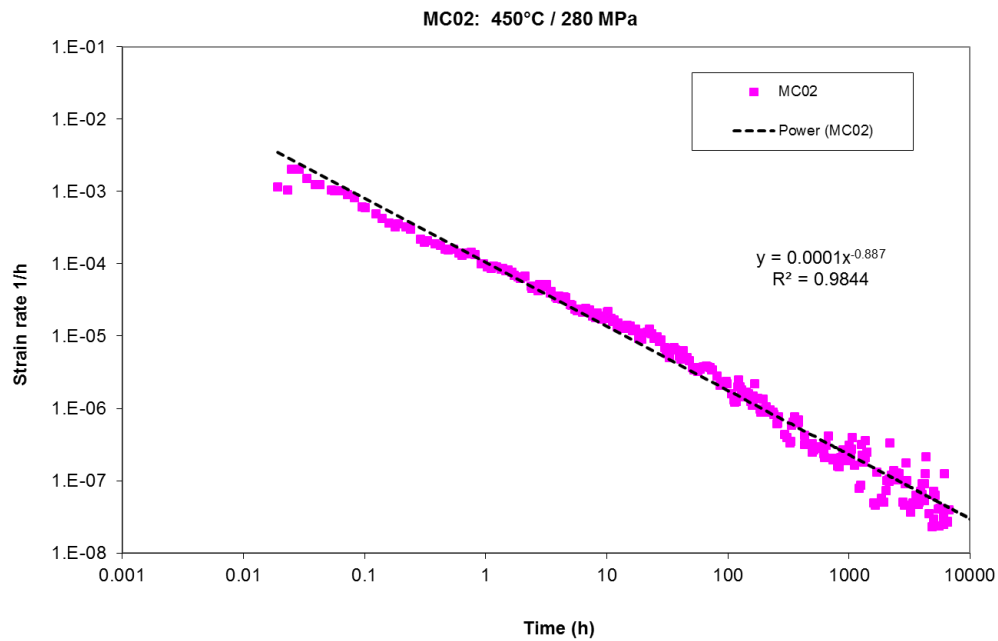
Strain rate (1/f) as a function of time (h).

Uniaxial creep test at 450°C / 280 MPa

Result table for MC02 tested at 450°C / 280 MPa, initial strain ε_0 (elastic-plastic) was 0.17 %

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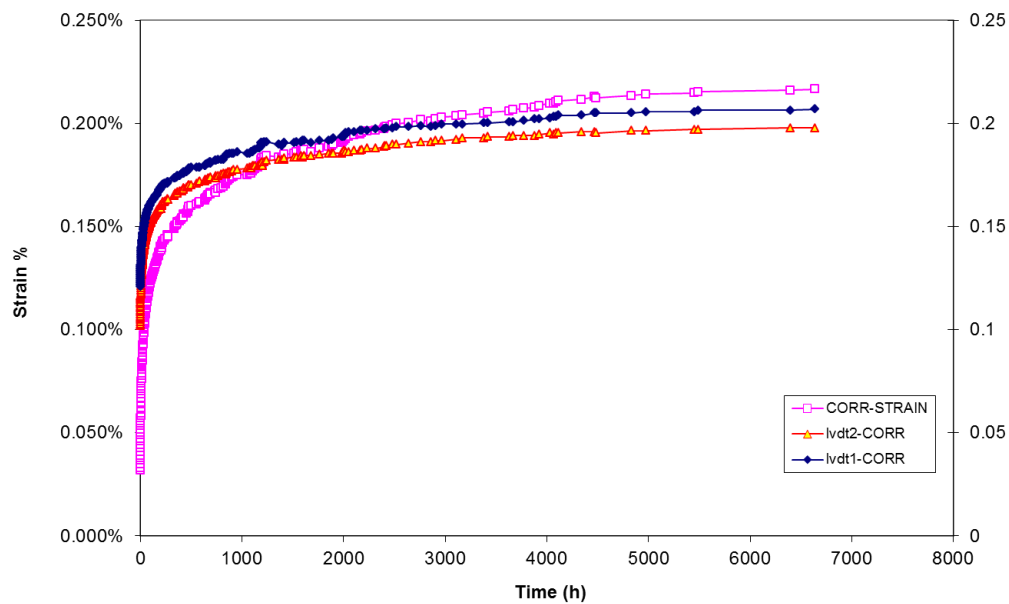
Strain (%)	0.01	0.03	0.1	0.2	0.19% (test max)
Strain rate (1/h)	2E-3	1.4E-4	3.7E-6	-	3E-8
Time (h)	0.06	1.39	89	-	7053

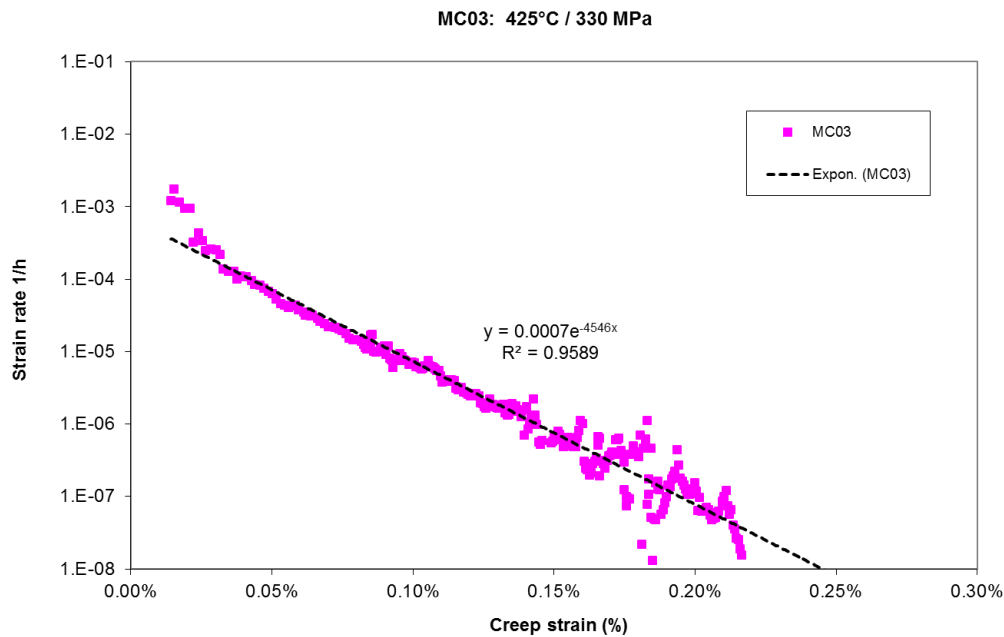
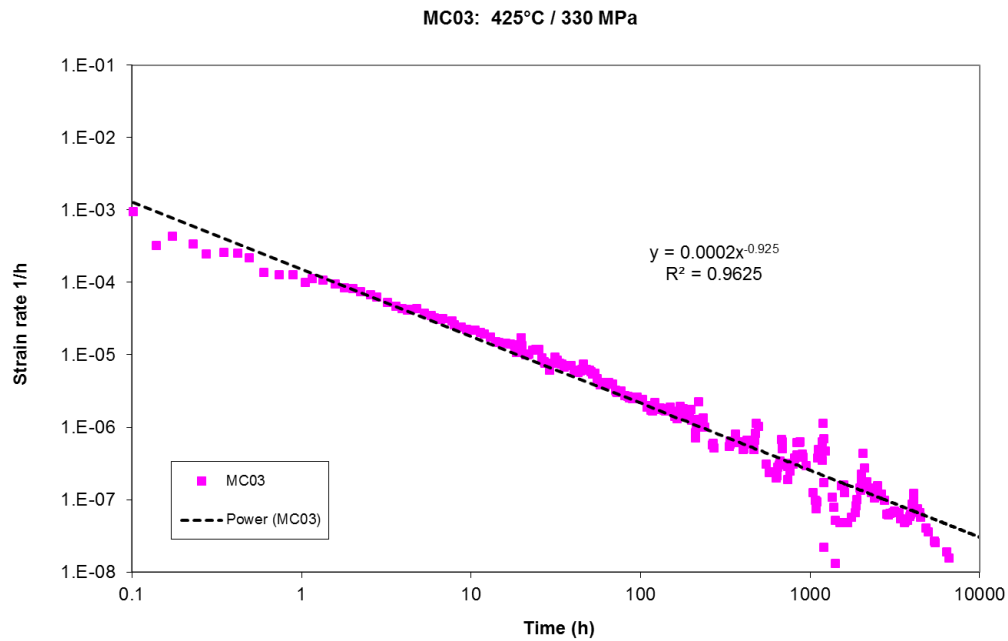


Uniaxial creep test at 425°C / 330 MPa

Result table for MC03 tested at 425°C / 330 MPa, initial strain ε_0 (elastic-plastic) was 0.20 %

Strain (%)	0.01	0.03	0.1	0.2	0.22% (test max)
Strain rate (1/h)	1.2E-2	2.5E-4	7.1E-6	1.5E-7	1.5E-8
Time (h)	0.01	0.42	38	2522	6882





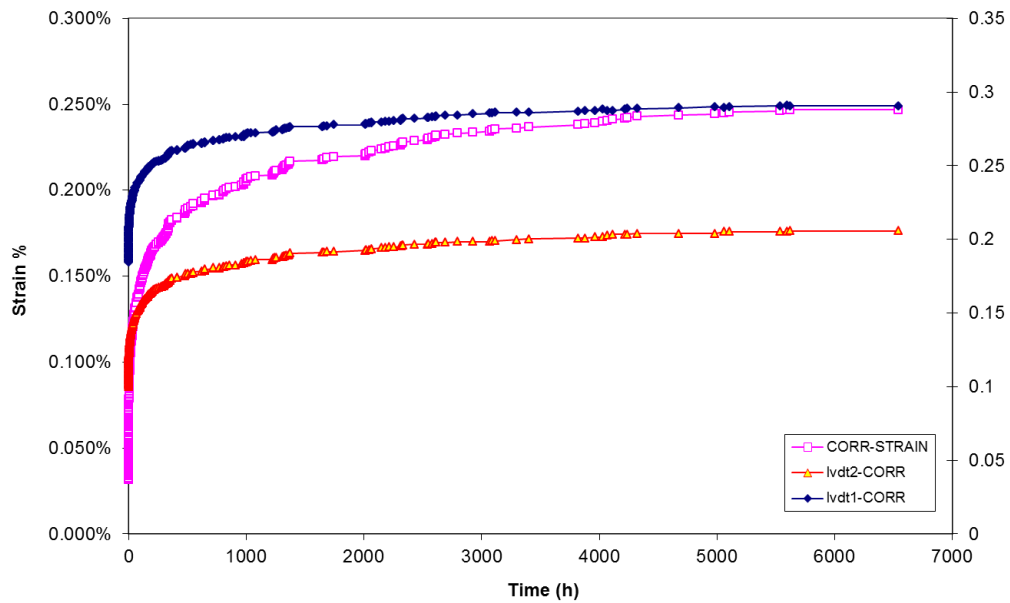
Uniaxial creep test at 400°C / 380 MPa

Result table for MC05 tested at 400°C / 380 MPa, initial strain ε_0 (elastic-plastic) was 0.26 %

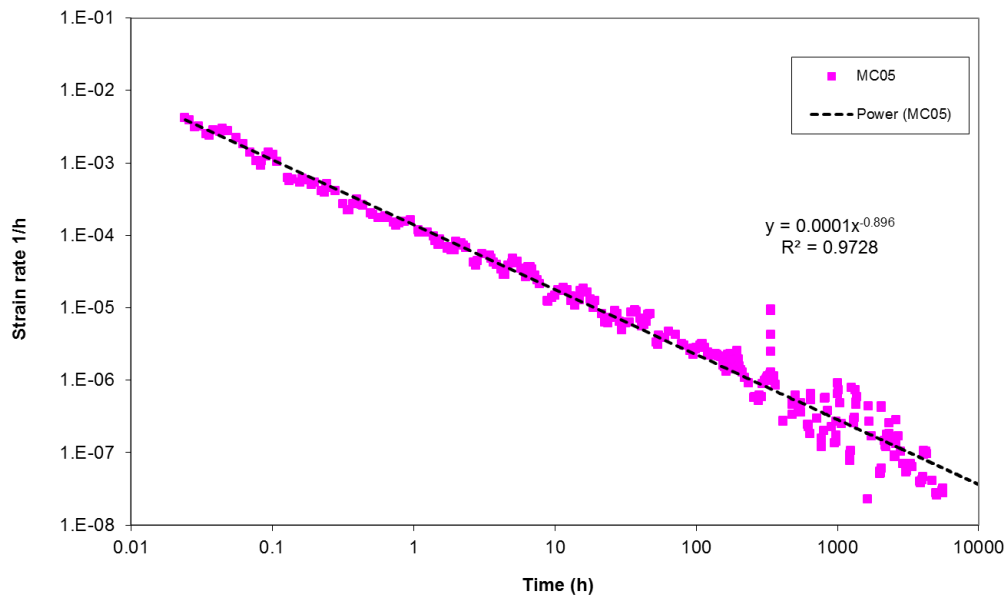
Strain (%)	0.01	0.03	0.1	0.2	0.24%
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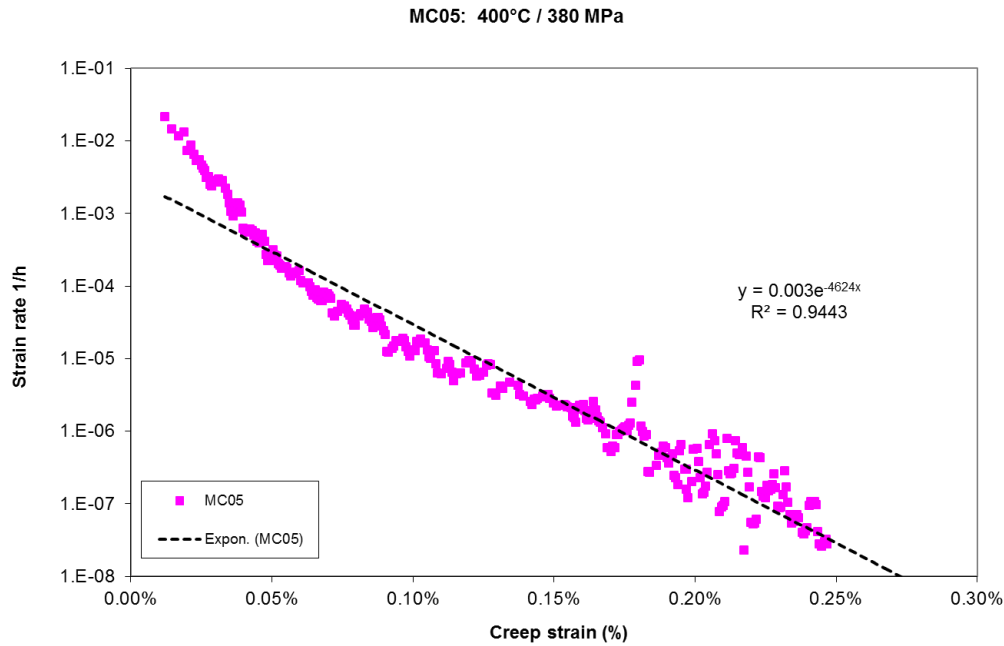
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					(test max)
Strain rate (1/h)	2.9E-3	2.8E-3	1.3E-5	5.6E-7	2.8E-8
Time (h)	0.005	0.04	14.2	812	7026



MC05: 400°C / 380 MPa



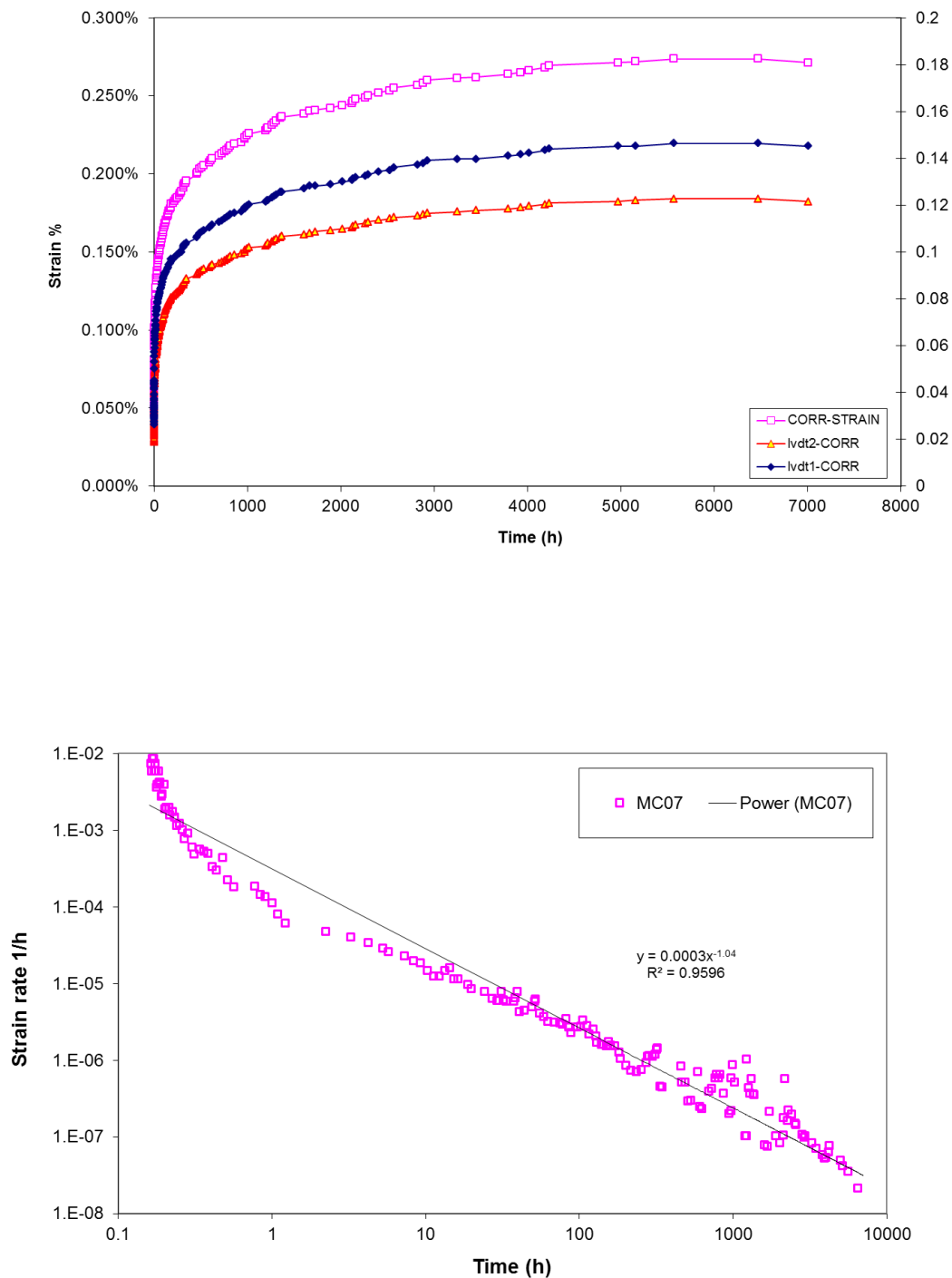


Uniaxial creep test at 375°C / 415 MPa

Result table for MC07 tested at 375°C / 415 MPa, initial strain ε_0 (elastic-plastic) was 0.32 %

Strain (%)	0.01	0.03	0.1	0.2	0.27% (test max)
Strain rate (1/h)	1.2E-2	3.6E-3	1.2E-5	8.3E-7	5E-8
Time (h)	0.002	0.02	5.1	458	7005

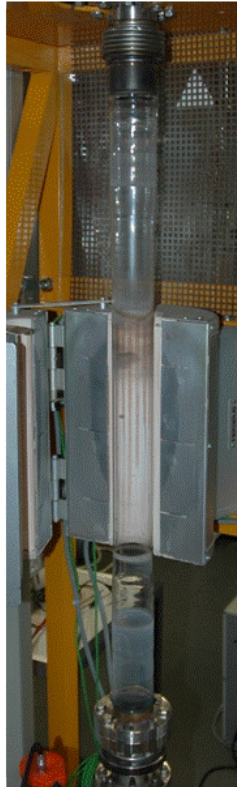
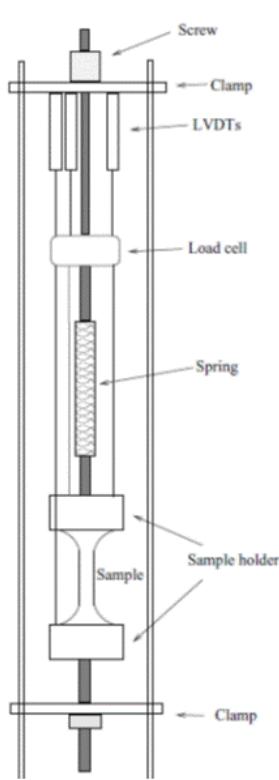
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Initial strain rates compared against the predictions made for the test matrix;

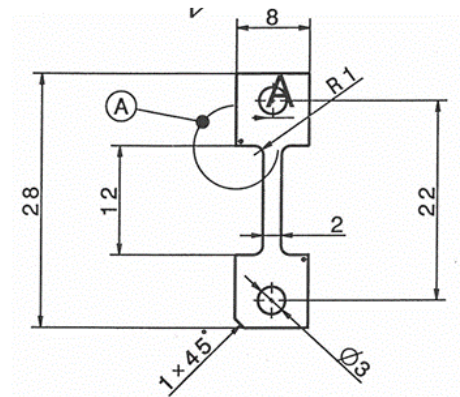
APPENDIX 3; PSI miniature test results

Miniature test rig



Main parameters

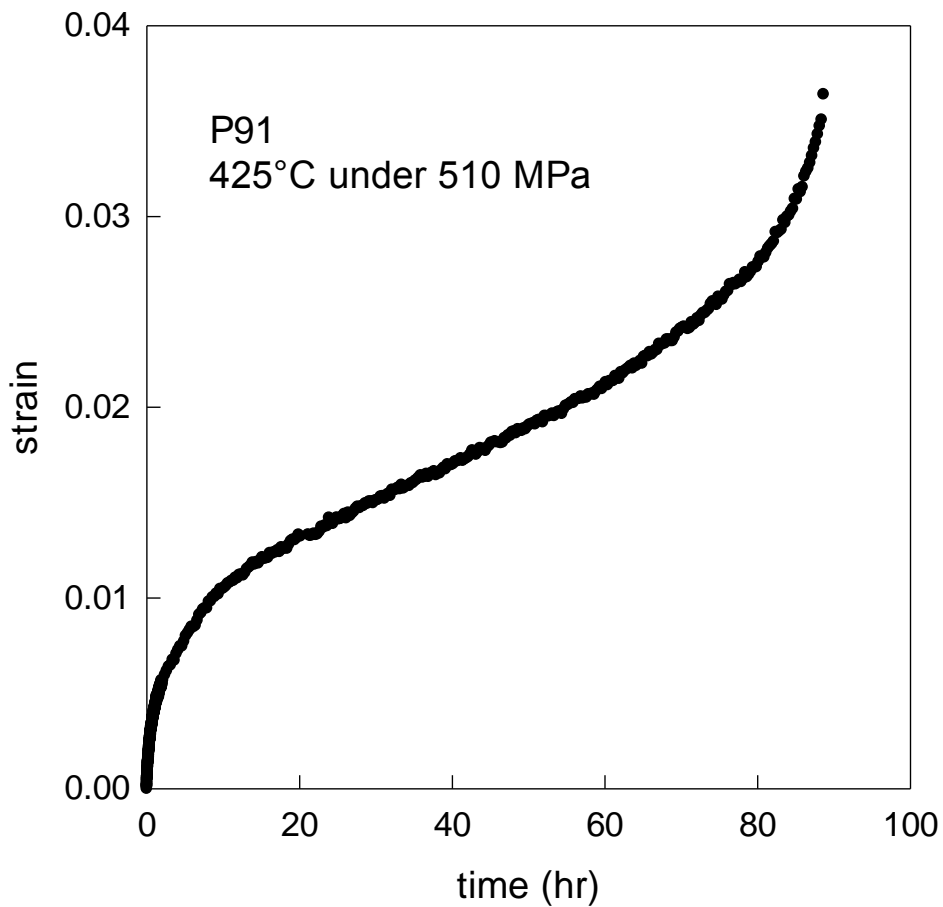
- Temperature: RT-1000°C
- Environment: Vacuum
- Miniaturized plate dog-bone specimen
- Strain resolution: $\sim 10^{-4}$



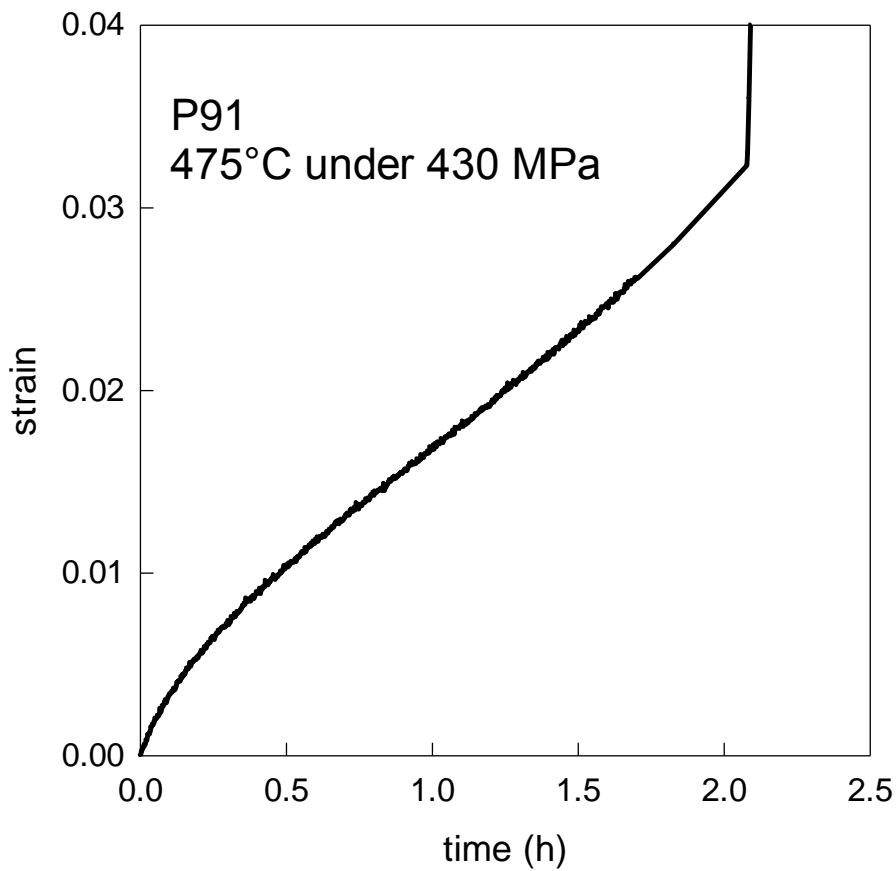
Tensile test results

Sample_ID	Temperature[°C]	$\sigma_{0.2}$ [MPa]	Strength[MPa]
7	475	434	500
9	425	431	526
17	400	428	540
8	25	526	680

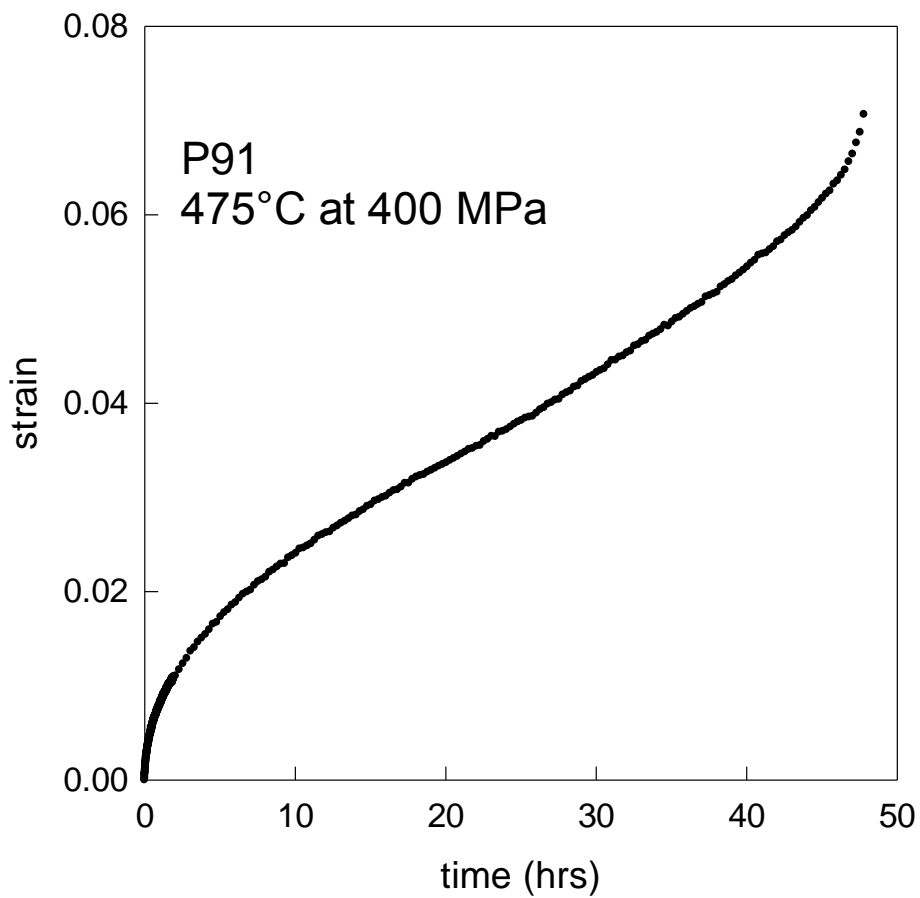
Creep results with miniaturized samples from PSI



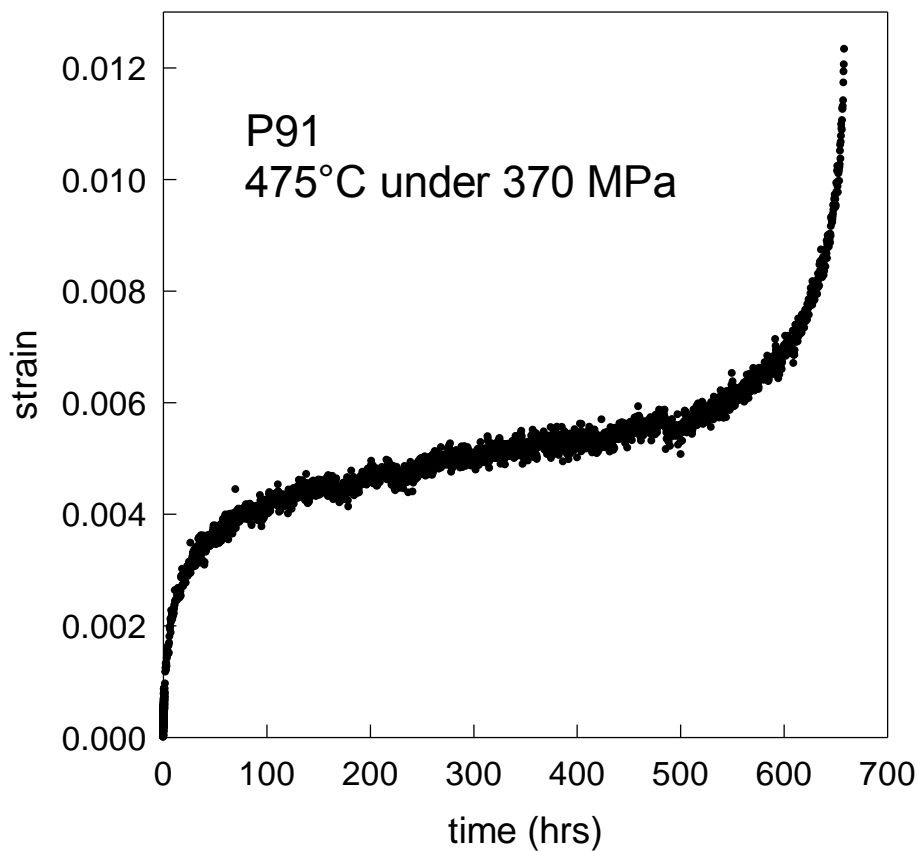
Time to 0.1% strain: 0.10 h
Time to 0.2% strain: 0.27 h
Time to failure: 88.6 h



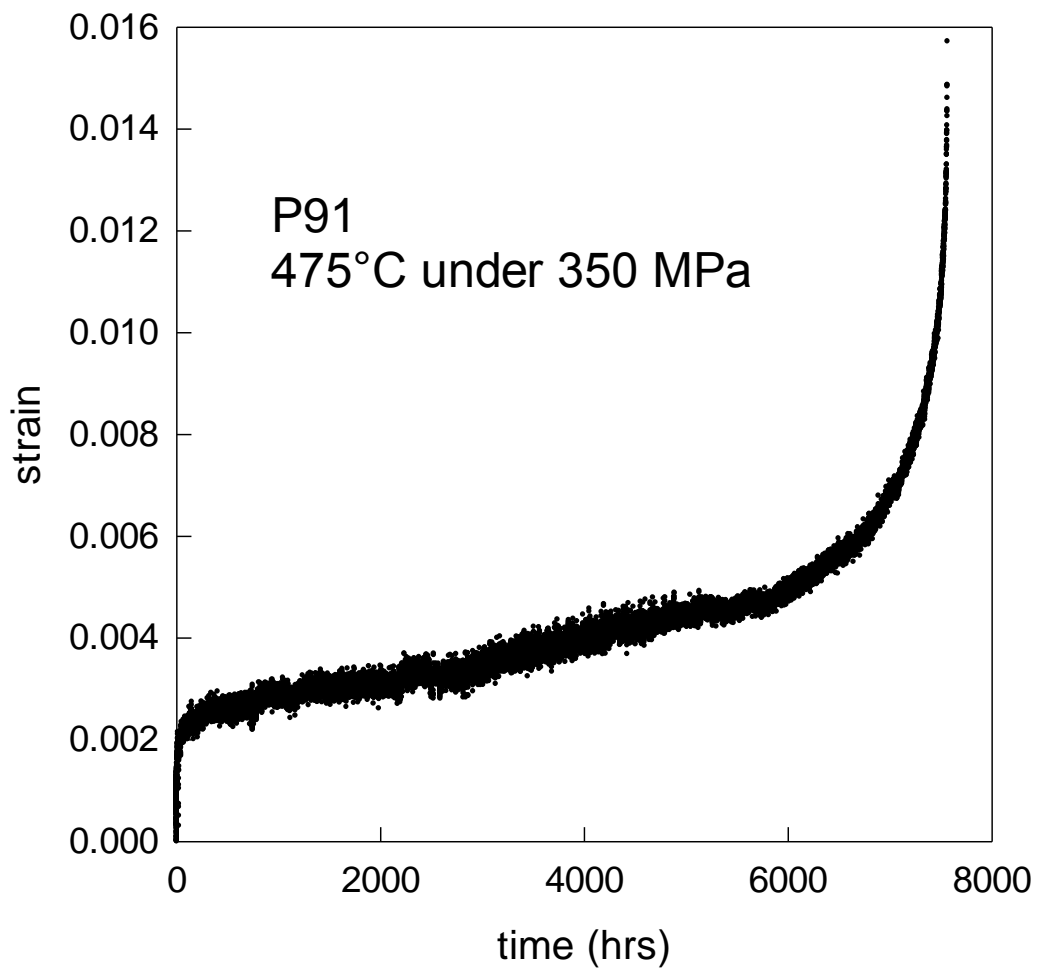
Time to 0.1% strain: -
Time to 0.2% strain: -
Time to failure: 2.37 h



Time to 0.1% strain: 0.03 h
Time to 0.2% strain: 0.08 h
Time to failure: 47.8 h



Time to 0.1% strain: 0.19 h
Time to 0.2% strain: 0.94 h
Time to failure: 659 h



Time to 0.1% strain: 1.0 h

Time to 0.2% strain: 30 h

Time to failure: 7564 h

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