OVERVIEW

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Advances in the assessment of creep data during the past 100 years

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Abstract

Many of the classical models representing the creep and rupture behaviour of metals were developed prior to and during the 1950s and 1960s. Nevertheless their subsequent exploitation, in particular for the assessment of large creep property datasets, was initially limited by the capability of the analytical tools available at the time.

Following an apparent decline in activity during the 1970s and 1980s, there has been a resurgence during the last two decades. Advances made in the assessment of creep data during the past 100 years are reviewed and factors contributing to the developments achieved are examined.

1. Background and introduction

At elevated temperatures, metallic structures deform with time under the influence of applied stress. Ultimately, the accumulation of such deformation leads to fracture by a creep rupture mechanism (Fig. 1a). The consideration of these deformation and damage processes is a key part of the design assessment of critical components for high temperature applications, with the necessary engineering calculations requiring a knowledge of the creep-rupture properties of the material from which the structure is manufactured.

Creep-rupture properties are determined from the results of a number of creep tests performed for a range of constant temperature and constant stress (usually constant load, i.e. constant σ_o) conditions, Fig. 2. In such tests, the creep strain may be monitored (but not always) either continuously by means of an extensometer attached to the gauge length of the testpiece, or by an optical measurement during planned test interruptions [1]. The data may have been determined from a matrix of $t_u(T,\sigma_o)$ tests for which T and σ_o are *i)* relatively homogeneously distributed for one or more casts, or *ii)* inhomogeneously distributed for the majority of casts of the alloy for which observations are available. Case *i)* is the ideal situation and generally arises within R&D projects or well co-ordinated data generation activities. Case *ii)* is more typical of large multi-national datasets, comprising information from many casts, gathered to produce alloy representative creep strength values for standards [2]. A list of symbols and terminology are given in the Nomenclature.

The rupture ductility (A_u in Fig. 2) can vary with stress (time) and temperature in a relatively complex way (e.g. Fig. 3a). The various ductiliy regimes are associated with distinct rupture mechanisms. For example, in ferritic steels, Regime-I involves ductile rupture resulting from the formation of voids typically as a consequence of particle/matrix decohesion. Regime-II is a transition regime in which the

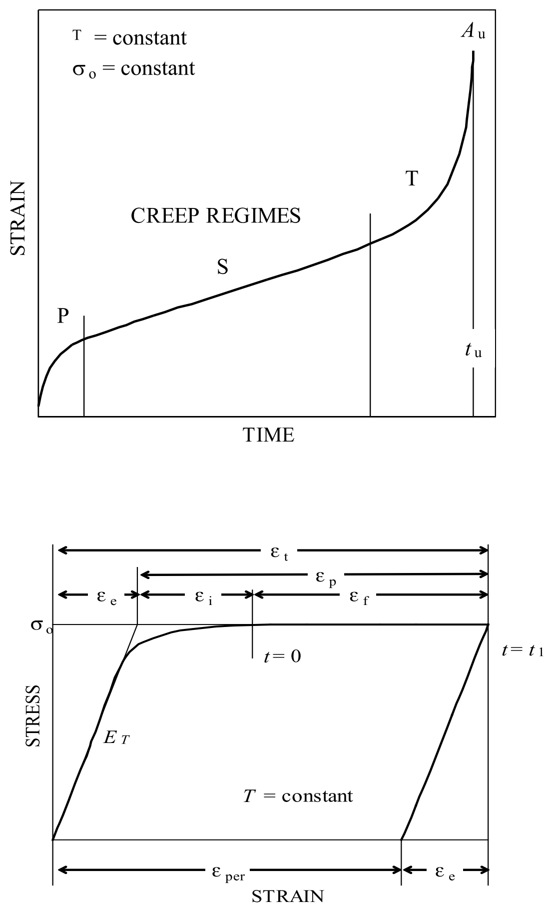

Fig. 1 : Schematic representations of: (a) a creep-rupture curve showing primary, P, secondary, S, and tertiary, T, deformation regimes, and (b) strains generated during a creep test

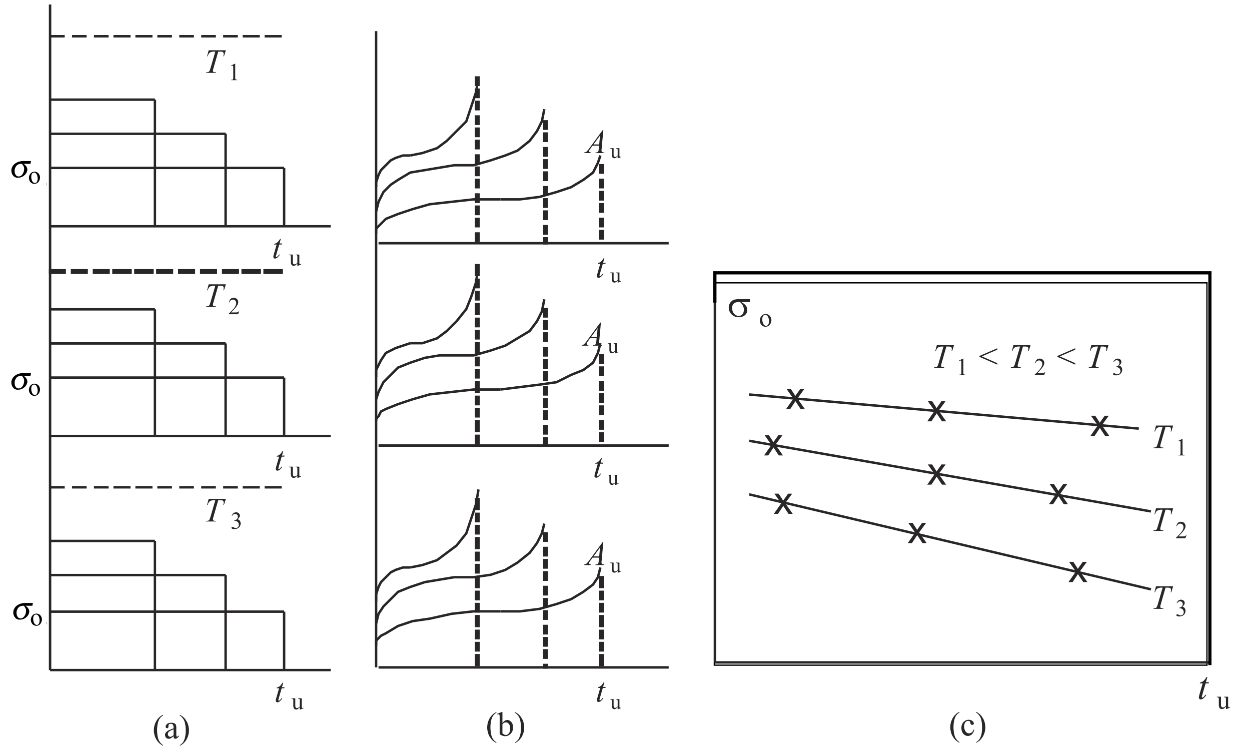

Fig. 2 : Schematic representation of (a) the T,σ_o dependent variable conditions for 3 creep-rupture tests each at 3 temperatures, (b) the corresponding $\varepsilon(t)$ response variable test records at each temperature, and (c) the resulting $t_u(T,\sigma_o)$ data points

ductility drops due to the increasing incidence of grain boundary cavitation, but still accompanied by relatively high levels of matrix deformation. In Regime-III, rupture is by the nucleation and subsequent diffusive growth of grain boundary cavities. In Regime-IV, over-ageing of the microstructure lowers the rate of cavitation nucleation and/ or growth leading to a progressive recovery of ductility. The mechanisms associated with the identified ductility regimes can differ for different alloy systems.

Many of the classical models representing the creep and rupture behaviour of metals were developed prior to and during the1950s and 1960s. Nevertheless their subsequent exploitation, in particular for the assessment of large creep property datasets, was limited by the capability of the analytical tools available at the time.

The following paper reviews advances made in the assessment of creep data during the past 100 years and examines factors contributing to the developments achieved.

2 European creep collaborative committee

In the early 1990s, the drive to greater integration in Europe led to the specification of unified (rather than independent National) Product and Design Standards. The European Creep Collaborative Committee (ECCC) was founded in 1992 to provide the means for European Industry to have a greater influence over the creep strength values incorporated into these Standards [3]. The original brief of ECCC's technical working group, WG1, was to devise common rules for the material specialist WG3x working groups to follow. The outcome was a series of ECCC Recommendation Volumes covering common terminology and guidance for the generation, collation and assessment of creep data [4]. While the Recommendation Volumes were originally produced for use by ECCC working groups, they were made freely available in the public domain and are now employed by a world wide user base.

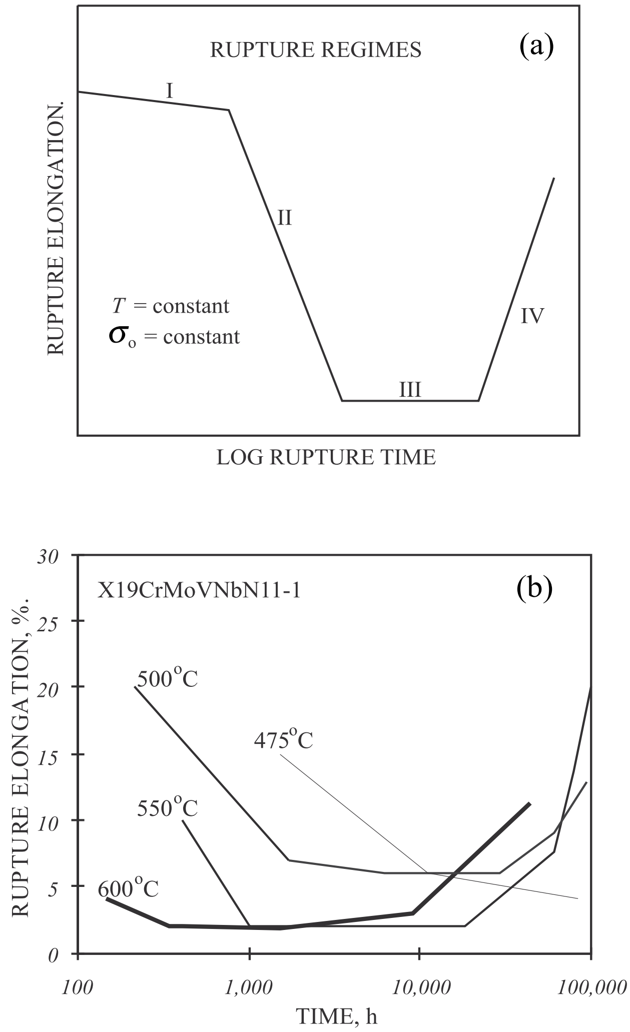

Fig. 3 : Rupture elongation profiles: (a) schematic representation, and (b) minimum $A_u(T)$ profiles for metallurgical complex steel

In ideal circumstances, creep rupture strength values for design purposes are determined from an assessment of the results of sufficient tests on a variety of casts of the specified material to ensure that its true property variance has been fully characterised for an appropriate range of stresses and temperatures (e.g. [2]). Such full-size datasets for traditional materials may comprise up to ~1,000 observations for ~100 casts covering several temperatures with test durations up to >100kh.

Originally, the focus for ECCC was on the assessment of such full-size (Case *ii)* type) datasets. Initially, ready access to low cost, powerful desktop computer processing was in its infancy, and the reliable numerical model representation of full-size datasets typically involved manually implemented graphical procedures, either for the full analysis (e.g. [5]) or at the very least in a pre-assessment (data reduction) phase (e.g. [6]). Subjective interpretations were almost inevitable with such manual intervention, and ECCC-WG1 devised the post assessment tests (PATs) to independently check: *a)* the physical realism, *b)* the within-data-range goodness-of-fit, and *c)* the extrapolation repeatability/stability of a model determined by any procedure [4e,7].

The original PATs were developed to independently check the credibility of rupture strength predictions irrespective of the applied assessment procedure [8]. Subsequently they were adopted for checking the credibility of creep strength and relaxed strength predictions [4e,9]. More recently, ECCC-WG1 developed the concept of the *Z* parameter to provide a measure of model fitting effectiveness to families of creep strain curves in specific creep strain regimes for both Case *i)* and Case *ii)* type datasets [10].

During the 1990s, many WG1 members were also involved in National developments in creep rupture data assessment procedures which were exploiting the growing availability of low cost powerful desktop computing and user friendly software platforms. The emergence of the PD6605 [11] and DESA [12] creep rupture data assessment procedures provided a significant step forward, which was ultimately complemented by automation of the PATs [13].

The first ECCC assessment recommendations published in 1996 undoubtedly provided a catalyst for others to exploit the availability of low cost, powerful desktop computers to develop rigorous methodologies for the physically realistic analysis of uniaxial and multi-axial data for the reliable and accurate characterisation of rupture strength and ductility, and creep strain properties. These more recent advances in creep data assessment methodologies are also acknowledged in the following paper.

3 Creep strain model equations

3.1 Overview

Creep strain curves are determined from the results of continuous-measurement or interrupted tests involving the application of a constant load (or stress) to an axial testpiece held at constant temperature (Fig. 1a). In continuous measurement tests, the creep strain, ε_f, is monitored without interruption by means of an extensometer attached to the gauge length of the testpiece [1]. In interrupted tests, the total plastic strain, ε_p, is determined from optical measurements of ε_{per} at room temperature during planned interruptions (where $\varepsilon_{per} = \varepsilon_p - \varepsilon_k$, i.e. $\varepsilon_{per} = \varepsilon_i + \varepsilon_f - \varepsilon_k$, Fig. 1b, and $\varepsilon_p = \varepsilon_{per}$ when $\varepsilon_k \approx 0$). The creep curve data collected in this way may then be modelled with a constitutive equation.

There are a large number of constitutive equations which can be used to represent the creep deformation characteristics of a material ranging from simple phenomenological to complex physically based (some of which are reviewed in [14]). No single constitutive equation effectively represents the creep deformation characteristics of all materials over their entire temperature application range. The effectiveness of a constitutive equation to model primary, secondary and/or tertiary creep deformation for specific applications can vary with material characteristics and source data distribution. In particular, not all model equations and fitting procedures are suitable for the prediction of alloy-mean long-time creep strength behaviour. As a generality, specific model equations are better suited to representing creep strain accumulation characteristics for a given material in either the primary/secondary or the secondary/tertiary regimes, although some models can be suitable for both [14]. The *Z* parameter (referred to in Sect.2) was developed to aid the selection of the most appropriate constitutive equation for a given material and deformation regime [14].

3.2 Classical representations

A wide range of creep model equations are in use today to represent the high temperature time dependent deformation behaviour of engineering materials, many of which comprise components originating from a small number of classical representations of primary, secondary and/or tertiary creep deformation (e.g. [15-24]), i.e.

Primary Creep

Logarithmic [15]: $\varepsilon_f = a.\log(1+b.t)$ (1)

Power [16]: $\varepsilon_f = a.t^b$ (2)

Exponential [17]: $\varepsilon_f = a.(1-\exp(-b.t))$ (3)

Sinh [18]: $\varepsilon_f = a.\sinh(b.t^c)$ (4)

Secondary Creep

Power [19]: $\varepsilon_{f.min} = d.\sigma^n$ (5)

Exponential: $\varepsilon_{f.min} = d.\exp(e.\sigma)$ (6)

Sinh [20]: $\varepsilon_{f.min} = d.\sinh(e.\sigma)$ (7)

Tertiary Creep

Power [16]: $\varepsilon_f = f.t^g$ (8)

Exponential [21]: $\varepsilon_f = f.(\exp(-g.t)-1)$ (9)

Damage [22,23]: $\dot{\varepsilon}_f = \dfrac{a.\sigma^n}{(1-\omega)^q}$ where $\dot{\omega} = \dfrac{c.\sigma^k}{(1-\omega)^r}$ (10)

Omega [24]: $\dot{\varepsilon}_f = \dot{\varepsilon}_o.\exp(\Omega.\varepsilon)$ (11)

where *a*, *b*, *c*, *d*, *e* and *f* are fitting constants.

As a generality, logarithmic creep only occurs at lower temperatures (i.e. below $0.3.T_m$). At higher temperatures, primary creep is more typically represented by power, exponential or sinh functions of time. Similarly, secondary creep rate can be represented by power, exponential or sinh functions of stress. For secondary creep rate, a sinh formulation reduces to a power law at low stresses and an exponential law at high stresses. Tertiary creep or creep rate is typically modelled by power or exponential representations, with or without a damage accumulation function, e.g. [22]. Typically, the effect of temperature is acknowledged by incorporating an Arhenius $A.\exp(Q_C/RT)$ function into the model equation.

In strongly physically based implementations of constitutive creep equations, it is now common practice to replace σ by $(\sigma - \sigma_i)$ to acknowledge the existence of a friction stress, in particular for precipitation strengthened alloys, e.g. [25].

3.3 Rupture property based models

With the growing interest in modelling alloy creep deformation characteristics from observations collated for a number of casts (e.g. in a Case *ii)* type dataset), newer formulations based largely on a knowledge of rupture properties have been developed. The forerunner of these were the expressions adopted to determine creep strength directly from rupture strength [26], e.g..

$$R_{u/t/T} = (a_1+b_1/\varepsilon-c_1.\varepsilon^2)R_{\varepsilon/t/T}+d_1+e_1/\varepsilon+f_1/\varepsilon^2-g_1.\varepsilon^2 \quad (12)$$

An extremely effective variant of this type of expression is the characteristic strain model [27], i.e.

$$\varepsilon_f(\sigma) = \varepsilon.(R_{u/t/T}/R_{\varepsilon/t/T}-1)/(R_{u/t/T}/\sigma-1) \quad (13)$$

In contrast to using creep and rupture strength values, the logistic creep strain prediction (LCSP) model relies on a knowledge of times to specific creep and rupture strains [28], i.e.

$$\log[t_u^*] = (\log[\alpha.t_u]+\beta)/(1+\{\log[\varepsilon]/x_o\}^p)-\beta \quad (14)$$

where x_o, p and β are fitting constants defining creep curve shape.

4. Creep-rupture model equations

4.1 Rupture time

4.1.1 Single model representations

Model equations for predicting creep rupture time generally fall into two categories, namely those which are based on time-temperature parameters (TTP) and those which are based on algebraic equations. By far the best known TTP formulation is that of Larson-Miller [29], i.e.

$$t_u^* = \exp[\{\Sigma_{k=0}^n \beta_k.(\log[\sigma_o])^k\}/T+\beta_5] \quad (15)$$

The development of eq. (15) was closely followed during the 1950s by a series of TTP based models [29-34], some of which derived from the same master equation [30], i.e.

$$t_u^* = \exp[\{\Sigma_{k=0}^n \beta_k.(\log[\sigma_o])^k\}/(T-T_o)^r/(\sigma_o)^{-q}+\beta_5] \quad (16)$$

In eq. (16), the Larson-Miller model (eq. (15)) is obtained if $q = 0$ and $r = -1$ [29], the Manson-Haferd model is obtained if $q = 0$ and $r = 1$ [31], the Manson-Brown model is obtained if $q = 0$ [32] and a stress modified model proposed by Murry is obtained if $q = 1$ and $r = 1$ [33]. An additional TTP model is that proposed by Orr-Sherby-Dorn [34]:

$$t_u^* = \exp[\{\Sigma_{k=0}^n \beta_k.(\log[\sigma_o])^k\}/Q_C/RT] \quad (17)$$

where temperature is represented by the Arhenius term in eq. (17), with Q_C being the activation energy for creep. During the 1970s, the focus was more on the development of algebraic models which were less flexible within-the-range of the observed $t_u(T,\sigma_o)$ data, but were more stable in extrapolation, e.g.

$$t_u^* = \exp[\beta_0+\beta_1\log[T]+\beta_2\log[\sigma_o]+\beta_3/T+\beta_4.\sigma_o/T] \quad (18)$$

$$t_u^* = \exp[\beta_0+\beta_1\log[\sigma_o]+\beta_2.\sigma_o+\beta_3\sigma_o^2+\beta_4.T+\beta_5/T] \quad (19)$$

Of these, eq. (18) is an example of one of the so-called Soviet models [35] and eq.(19) is the simplest form of the minimum commitment model [36].

As a generality, the preference of creep rupture data modellers has traditionally been to establish a single continuous representation of the observed $t_u(T,\sigma_o)$ data throughout the entire application ranges of temperature and stress. However, as the metallurgical complexity of engineering alloys has increased, the adoption of a single function to adequately represent rupture behaviour throughout the full application range has become increasingly challenging.

4.1.2 Multi-regime modelling

During recent years, there has been a tendency to increasingly adopt a multi-regime modelling approach for metallurgically complex alloys. This concept was not new and had been explored during the development of the minimum commitment models [36] and in Germany during the 1970s [37], but the profile of such an approach was raised by Kimura [38]. To date, Kimura has concentrated on fitting a Larson-Miller model (eq. (15)) to $t_u(T,\sigma_o)$ observations in two mechanism (stress) regimes. His main focus was P122 steel, and for this alloy the regime splitting stress was $0.5.Rp_{0.2}(T)$ (coincident with the limit of proportionality for this steel). Maruyama adopted a similar approach, but preferred to use the OSD model (eq. (17)) so that regime splitting could be done on the basis of activation energy [39]. Using a power function (eq. (20)), Spindler modelled the complex rupture behaviour of Esshete 1250 in three regimes by non linear regression [40], i.e.

$$t_u^* = A_i.\exp[Q_{Ci}/RT]\sigma_o^{B_iT+C_i} \quad (20)$$

where i was the regime number. The new Wilshire equation provided the analytical means to ensure that rupture strength at short times was sensibly constrained by the tensile strength of the material [41], i.e.

$$t_u^* = \exp[1/u_i.\ln[1/k_i]+1/u_i.\ln(-\ln[\sigma_o/Rm])+Q_c/RT] \quad (21)$$

This formulation was ideally suited for multi-regime modelling. In its original form, Wilshire set Q_C to that for diffusion creep (i.e. 300kJ/mole), irrespective of regime. Subsequently, Spindler demonstrated that eq. (21) could also be effectively implemented using piecewise non-linear regression to determine the u_i, k_i and Q_{Ci} parameters for each regime [40], i.e. with different Q_C for each regime (in a similar way to that adopted by Maruyama [39]).

4.2 Rupture ductility

Proven procedures for the assessment of rupture ductility, in particular for large multi-source, multi-cast, multi-temperature datasets are still under development. Such datasets can be highly complex with individual casts exhibiting the characteristics shown in Fig. 3a but displaced to shorter or longer times respectively with increasing or decreasing temperatures (e.g. Fig. 3b), the complexity being typically compounded by significant cast-to-cast variations in the rupture ductility properties for a given alloy [42]. There are model representations which can handle such complexity (e.g. [42]), with the most successful to date being that of Spindler [43], i.e.

$$\ln[A_u] = \mathrm{MIN}|\{\ln[A_1]+Q_c/RT+n_1.\ln[\dot{\varepsilon}_{av}]+m_1.\ln[\sigma_o]\},\ln[A] \qquad (22)$$

5. Assessment procedures

While significant advances in creep rupture property modelling have been made in the last two decades, the most notable progress has been made in the development of formal, well-defined, state-of-the-art assessment procedures which implement the available model equations with a high level of automation (e.g. [11,12]). For example, the PD6605 procedure involves rigorously defined pre-assessment, model selection and post assessment testing stages.

The basis of PD6605 [11] is a set of creep rupture models comprising six TTP expressions (based on eq. (16), eq. (17)) and three algebraic equations (based on eq. (18), eq. (19)). In addition, the user may define other models out of preference or when none of the given selection provided adequately represents the $t_u(T,\sigma_o)$ data (e.g. [40]). The software accompanying PD6605 provides the user with the opportunity to adopt either Weibull or log-logisitic error distributions depending on which best represents the random component of the creep data. However, the most notable feature of this assessment procedure is the use of maximum likelihood statistics to simultaneously estimate the parameters for the systematic and random components of the model using all available creep rupture data. The likelihood function for the model has the important characteristic that it comprises probability density functions covering the rupture times for failed testpieces and the survival time for unfailed testpieces. The routine consideration of unfailed tests is a main feature of the PD6605 analysis. Confidence intervals for the estimated time to rupture are obtained directly from the survival function.

The software forming the basis of the DESA procedure [12] similarly provides the user with the opportunity to check the effectiveness of a range of model equations. DESA does not yet employ maximum likelihood statistics and thereby does not routinely consider unfailed tests or offer a choice of error distributions but unlike PD6605, this procedure is still evolving with the latest version offering simultaneous assessments of creep strength and rupture strength [13].

6. Factors influencing advances in creep data assessment

The chronological trend of the level of creep data assessment development activity during the past 100 years is summarised in Fig. 4. The first peak of activity occurred during the 1950s and 1960s, and was initially driven by a requirement for accurate material creep property descriptions for the design of reliable critical high temperature components primarily for aerospace but also increasingly for power generation applications. The level of assessment development activity revealed in the public domain appeared to diminish during the 1970s and 1980s, but strongly increased during

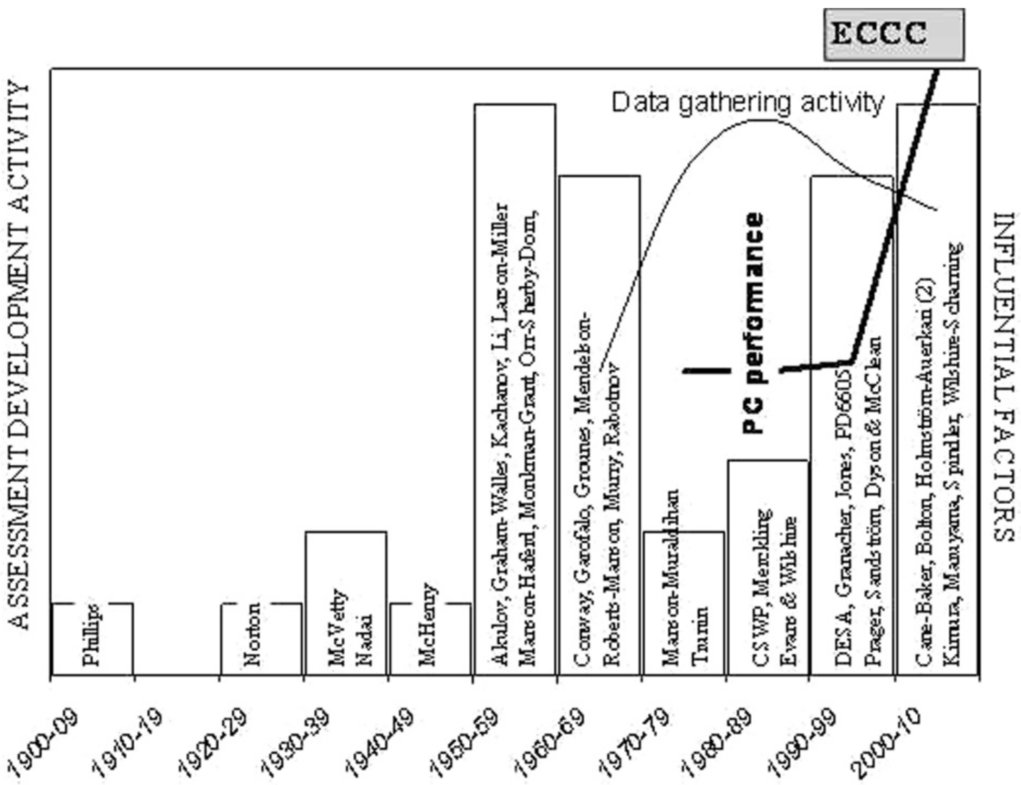

Fig. 4 : Chronological trend in the level of creep data assessment development activity and the impact of influential factors (refer to Sect.8 and [14] for source references)

the 1990s and the first decade of the 21st century. There were a number of factors responsible for this chronological activity trend.

As a direct consequence of the creep data assessment and modelling activities in the 1950s and 1960s, it became increasingly obvious that the level of uncertainty associated with predicted long time strength values significantly increased in relation to the extent of extrapolation required to bridge the gap between maximum observed creep rupture time in the available dataset and specified design life. By this time, design life requirements for power plant applications were already ≥100,000kh. Moreover, the importance of sufficiently characterising the property variability of the specified material, by gathering data for a significant number of representative casts, was also becoming increasingly clear. Worldwide, but in particular in Europe and Japan, large test programmes were initiated during the 1960s and subsequently to establish long time creep properties on strategic materials (for several casts of the same material and at a number of temperatures in the material's application range) [44-46]. This meant that towards the end of the 1970s and throughout the 1980s, large quantities of long term creep data were being accumulated (Fig. 4). Financial constraints led to the rate of long time creep data generation being significantly reduced during the 1990s and 2000s, but collaborative activities continued to establish the properties of strategic alloys (e.g. [47]), in particular those used for power plant components for which end users were by then requiring design lives of ≥250,000h. Initially, the large quantities of creep data were causing the analysts problems. A significant number of material models were available from the development activities of the 1950s and 1960s, but their effective implementation to large datasets was being constrained by the performance of readily accessible computer resources.

The situation concerning the availability of powerful desktop computing at reasonable cost started to change towards the end of the 1970s and during the 1980s, with the first 32-bit Intel processor being introduced in 1981. Since then, computer performance has increased by approximately two orders of magnitude per decade with reducing (rather than increasing) cost. This meant that by the mid 1990s, it was feasible to assess large international multi-cast, multi-temperature creep-rupture datasets using state-of-the-art statistical software packages on desktop PCs (e.g. using PD6605 [11], Sect.5). The resurgence in creep assessment development activity apparently coincides with the dramatic evolution of computer performance (Fig. 4), but this is not the only influential factor.

It has already been mentioned that ECCC began to exploit the availability of the large creep property datasets during the 1990s to form the basis of the long time creep rupture strength values required for new European Product and Design Standards (Sect.2). The associated assessment procedure development activity (e.g. [4e]) undoubtedly acted as a catalyst for further research both inside and outside of ECCC working groups.

By the middle of the 1990s, the intensity of large scale data generation had diminished significantly, with respect to its peak in the 1980s (Fig. 4), but there was still a requirement for long term creep rupture testing even at a relatively low level. In the power generation industry, there was an increasing requirement for higher efficiency plant at lower capital cost. This meant the development of new alloys to withstand higher operating temperatures, with the tendency being to focus on advanced steels because of their lower cost relative to for example nickel base alloys. As a generality the new advanced steels were metallurgically complex, exhibiting multi-regime creep rupture behaviour and requiring new analytical approaches to provide acceptable modelling.

The improvements in desktop computer performance and associated analytical software packages has also led to high temperature component design and assessment becoming more routinely the result of advanced finite element analysis (FEA) based procedures. Such procedures require accurate creep property model representations.

There are therefore a number of complementary factors which have been responsible for the most recent resurgence in creep data assessment development activity.

7. Concluding remarks

Advances made in the assessment of creep data during the past 100 years have been reviewed, and factors contributing to the developments achieved have been examined.

The first peak of creep data assessment development activity occurred at a time when major technical advances were first being made in the designs of high temperature components primarily for aerospace, but also for power generation applications. A resurgence in activity coincided with:

- the availability of large international industrial datasets,
- the need for their exploitation to underpin the long time creep rupture strength values for European Design and Product Standards
- the catalytic effect of the associated ECCC creep data assessment procedure developments
- the dramatic improvements in low cost desktop PC computing performance,
- the requirement for more effective modelling of the creep behaviour of new advanced metallurgically complex alloys, and
- the requirement for accurate creep property model representations for implementation in FEA based high temperature component design and assessment analyses.

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NOMENCLATURE

A, A_u	Tensile elongation at fracture, creep elongation at rupture
ECCC	European Creep Collaborative Committee
n	stress exponent
Q_C	Activation energy for creep
R	Universal gas constant
$R_{p\varepsilon/t/T}$, $R_{u/t/T}$	Creep strength and rupture strength for a given time and temperature
$Rp_{0.2}$, Rm	0.2% proof strength, tensile strength
t	time
t_u, $t_{u,max}$, t_u^*	Observed time to rupture, maximum observed time to rupture, predicted time to rupture
$t_{p\varepsilon/\sigma/T}$, $t^*{}_{p\varepsilon/\sigma/T}$	Observed and predicted times to given plastic strain
$t_{ef}(T,\sigma)$	Time to a specific creep strain as a function of temperature and stress
T, T_m	Temperature, melting temperature of material
Z	Parameter quantifying effectiveness of master creep equation to predict times to specific strains
ε, ε_e, ε_i	Strain, elastic strain, instantaneous plastic strain
ε_f, ε_p, ε_k, ε_{per}	Creep strain, plastic strain, anelastic strain, permanent strain
$\dot{\varepsilon}$, $\dot{\varepsilon}_{f,min}$, $\dot{\varepsilon}_{ave}$	Strain rate, minimum creep strain rate, average strain rate
σ, σ_o	Stress, initial stress
σ_i	Friction stress
ω, $\dot{\omega}$	Damage, rate of damage accumulation

ECCC terms and terminology recommendations are given in ECCC Volume 2 [4b]