New Material Assessment Procedures for Plant Life Extension

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ABSTRACT

The advantages of the new θ Projection Concept compared with traditional approaches to creep are discussed in relation to the important problem of safe life extension of high temperature components and structures in power stations and chemical plants.

INTRODUCTION

For components and structures in power stations and chemical plants which must operate for prolonged periods under stress at high temperatures, designs are generally based on the criterion that creep failure must not occur within the planned operational life. With design lives of up to 250,000 hours (over 30 years), expensive multi-laboratory test programmes are then carried out to generate the required long-term stress rupture properties, Figure 1.

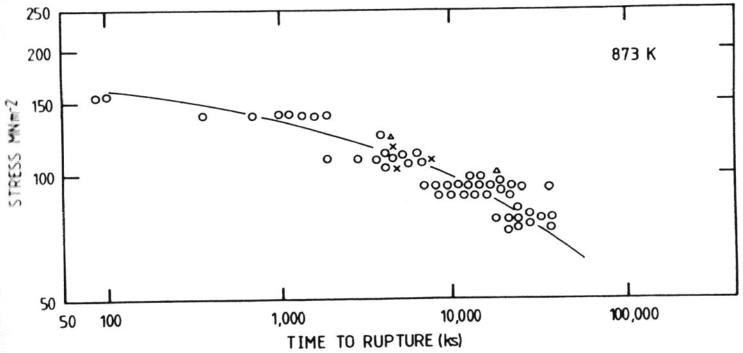

Fig.1. Stress rupture data for $\frac{1}{2}Cr\frac{1}{2}Mo\frac{1}{4}V$ steel at 873K showing
(a) the curvature of $\log(\sigma)/\log(t_r)$ plots and
(b) the scatter in conventional multilaboratory test results (1)

The data for $\frac{1}{2}Cr\frac{1}{2}Mo\frac{1}{4}V$ ferritic steel in Figure 1 illustrate

(a) the curvatures of log (σ)/log(t_r) plots which limit extrapolation by conventional parametric techniques to three times the longest reliable test data available and

(b) the large scatter in properties which is usually +20% in stress, equivalent to about an order of magnitude in rupture life.

Since the lower limit of the scatter band is commonly used for design purposes, and a safety factor is introduced in addition to the assumption of minimum materials properties, the design codes adopted are conservative. Indeed, operating experience has established that service lives significantly greater than design expectations are achieved in practice. In view of the major economic advantages now gained by extending the operational lives of existing plants, considerable emphasis is therefore being placed on safe life extension programmes. For this reason, the present work aims to illustrate the benefits derived by extending traditional remanent life assessment methods to include those based on a new approach to creep data analysis, termed the θ Projection Concept (2,3).

TRADITIONAL APPROACHES TO PLANT LIFE EXTENSION

To demonstrate that high temperature components and structures have an adequate margin against creep failure during planned periods of future service, a three-stage procedure has been recommended (4). Stage I involves a reassessment of the original design methods, using any new long-term stress rupture data which may have become available since the plant was commissioned, i.e. from the original design calculations and plant operating records, it may be possible to estimate the approximate life fraction exhausted. However, plant operating records are rarely comprehensive. Moreover, this reassessment procedure does not compensate for original design conservatism or for the assumption of minimum property values from the scatter band in the stress-rupture data, Figure 1. In consequence, greater reliance tends to be placed on Stage II procedures, involving in-situ inspection of components, e.g. determination of material composition, dimensional checks, visual and non-destructive examination, metal temperature monitoring, surface hardness determination, surface metallography and replication to assess surface cracking, carbide coarsening, etc. Yet, since Stage II in-situ procedures are not necessarily representative of the bulk properties of the material, Stage III involves taking samples from components for laboratory microstructural examination and for post-exposure stress-rupture testing. However, the accelerated procedure for remanent life estimation, illustrated in Figure 2, assumes that the high temperature test conditions imposed in post-exposure tests do not substantially modify the dislocation configurations, the carbide types and distributions, and other microstructural features typically developed in steels during long-term plant service.

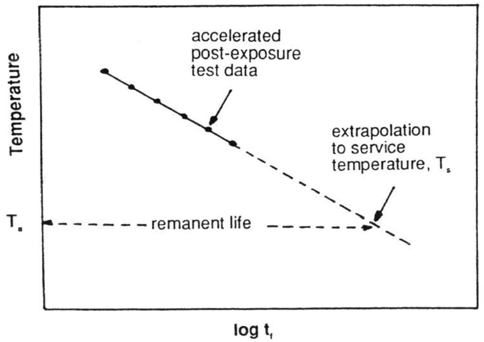

Fig.2. With traditional post-exposure stress-rupture procedures, accelerated tests are usually carried out at the service stress but at increased temperatures. Extrapolation of the data obtained to the service temperature, T_s, then gives an estimate of the remaining life.

THE Θ PROJECTION CONCEPT

For many decades, most theoretical and practical approaches to creep and creep fracture have relied on measurements of only a few parameters, such as the secondary creep rate, the rupture life and the creep ductility. Unfortunately, this traditional simplistic representation of creep behaviour ignores the fact that the creep curve shape varies with test conditions, Figure 3. Moreover, detailed examination of high-precision constant-stress creep curves indicates that a secondary or steady-state condition is not achieved and all that can be defined is a minimum rate as the decay in creep rate during the primary stage is offset by the acceleration due to tertiary processes. For this reason, the new θ Projection Concept describes the full creep strain (ε)/time (t) curve as

$$\varepsilon = \theta_1\left(1 - e^{-\theta_2 t}\right) + \theta_3\left(e^{\theta_4 t} - 1\right) \tag{1}$$

where θ_1 and θ_3 define the extent of primary and tertiary creep with respect to strain, while θ_2 and θ_4 are rate parameters which govern the curvatures of the primary and tertiary stages respectively (3). For many materials, equation 1 has been shown to accurately describe the shape of individual creep curves. Furthermore, the systematic variations of the θ parameters with stress and temperature (Figure 4) quantify the dependence of curve shape on test conditions (Figure 3). While the exact form of equation 1 and the observed variation of the θ parameters with stress and temperature have been justified by detailed micro-modelling of the processes determining primary and tertiary creep characteristics (3), it is also important to note that the linearity of the θ relationships in Figure 4 should allow not only interpolation but also reasonable extrapolation of creep properties, i.e. once the θ values are calculated for a given stress and temperature, a full creep curve can be constructed. From the resulting creep curve, the rupture life can then be defined as the time to reach the limiting creep ductility. Since full creep curves can be constructed, any creep or creep rupture parameter can be predicted. The accuracy with which the θ Projection Concept allows extrapolation of creep properties can be seen from Figure 5 (2). Thus, data for test conditions giving lives well in excess of 100,000 hours has been predicted from high-precision constant-stress creep curves having a maximum duration of little more than 1000 hours.

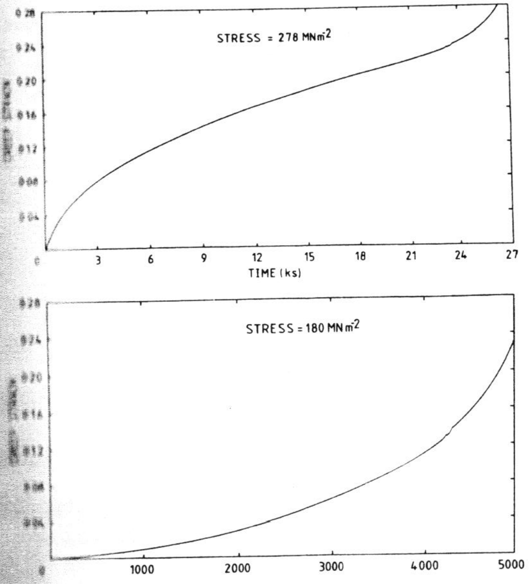

Fig.3. Creep curves recorded in constant stress tests for $\frac{1}{2}Cr\frac{1}{2}Mo\frac{1}{4}V$ steel at 838K.

Table 1 Values of the $\log_{10}\theta_i$ and fracture strain parameters according to equations 2 and 3. Units are seconds, degrees K, MNm^{-2}

Parameter	a	b	c	d	Standard Error
θ_1	-0.8736×10^{1}	-0.4489×10^{-1}	0.4604×10^{-2}	0.6814×10^{-4}	0.102
θ_2	-0.2346×10^{-2}	0.2195×10^{-1}	0.2225×10^{-1}	-0.1951×10^{-4}	0.062
θ_3	-0.1869×10^{-1}	-0.5497×10^{-1}	-0.2034×10^{-2}	0.7990×10^{-4}	0.088
θ_4	-0.1643×10^{2}	-0.4723×10^{-1}	0.9149×10^{-2}	0.7139×10^{-4}	0.084
ε_f	-0.1123×10^{1}	0.5473×10^{-3}	0.1517×10^{-2}	-0.4721×10^{-6}	0.010

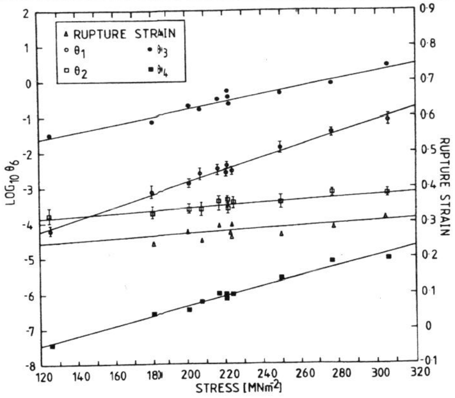

Fig.4. Stress dependence of θ parameters and ε_f for $\frac{1}{2}Cr\frac{1}{2}Mo\frac{1}{4}V$ steel at 878K.

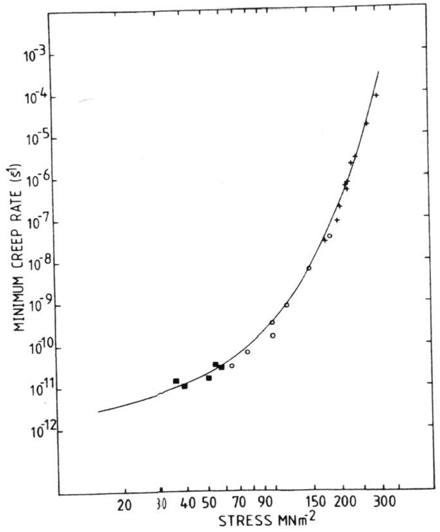

Fig. 5 The solid curve shows the variation of the minimum creep rate with stress predicted using the θ data derived from short-term tests (+) compared with long-term experimental results (o,o)

NEW DESIGN REASSESSMENT PROCEDURES

Although presentation of the stress and temperature dependencies of the θ parameters in the form shown in Figure 4 is ideally suited to theoretical studies concerned with identification of the processes governing primary and tertiary creep, an alternative computer-efficient procedure has been developed for practical analyses of creep data (5). Essentially, the variation of each θ parameter with stress (σ) and temperature (T) can be expressed as

$$\log \theta_i = a_i + b_i\sigma + c_iT + d_i\sigma T \tag{2}$$

where a_i, b_i, c_i and d_i are constants (with i = 1, 2, 3, 4). Furthermore, the creep ductility (ε_f) can also be represented as

$$\varepsilon_f = a + b\sigma + cT + d\sigma T \tag{3}$$

where a, b, c and d are constants. Once the values of the 20 coefficients associated with equations 2 and 3 are evaluated by analysis of short-term high-precision constant-stress creep data, as illustsrated for $\frac{1}{2}Cr\frac{1}{2}Mo\frac{1}{4}V$ steel in Table I, the θ Projection Concept allows almost instantaneous computation of any creep or creep rupture data needed with conventional design codes. However, the computer-efficient form of the θ relationships also makes this new approach ideal for use with modern engineering approaches to high temperature design. For example, advanced finite element methods require a knowledge of the creep strain rate as a function of strain, stress and temperature, so that analysis can be completed for components of complex shape operating under conditions resulting in thermal gradients and non-uniform loading. While the θ relationships easily provide this information, a full materials constitutive relationship must also allow design calculations to be performed for non-steady stress and temperature conditions. Clearly, if the imposed conditions change from σ_1T_1 to σ_2T_2, there is no difficulty in calculating the new θ values and therefore the new creep curve, but it is not clear how the new creep rate is to be determined from the new curve. The problem is illustrated in Figure 6a, showing two schematic curves corresponding to σ_1T_1 and σ_2T_2. It is possible to proceed from the first to the second curve along many paths, the extreme cases being for time hardening (Path A) and strain hardening (Path B). Experimental evidence has been obtained to show that the strain hardening path is very nearly correct and a simple constitutive relationship can be constructed on this basis. Once the values of the θ coefficients for the relevant materials are determined (e.g. Table 1), the θ Projection Concept therefore offers a new approach both to initial design studies and to Stage I design reassessment in the case of plant life extension programmes.

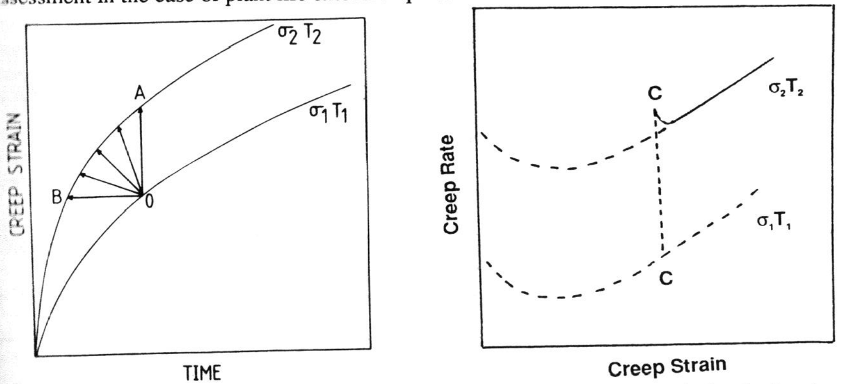

Fig.6(a) Schematic representation of time hardening (path A) and strain hardening (path B), rules on changing from σ_1T_1, to σ_2T_2 and (b) schematic curves for service conditions, σ_1T_1, and accelerated conditions σ_2T_2 plotted as creep rate against creep strain. The post-exposure test, presented as the solid line identifies the position reached under service conditions (position C), allowing the remanent life to be determined.

A NEW APPROACH TO POST-EXPOSURE TESTING

When Stage I design reassessment and/or the results of Stage II in-situ inspection procedures suggest that Stage III appraisal should be undertaken, estimates of the remaining safe life of high temperature components and structures are normally obtained by post-exposure stress-rupture testing of specimens machined from samples taken from the plant under investigation, e.g. Figure 2. However, just as traditional approaches ignore a considerable amount of information contained in the full creep strain/time curve by recording only a few parameters, substantially more information on materials condition can be derived from post-exposure tests by using accurate creep machines rather than stress-rupture methods.

Post-exposure measurements are equivalent to tests in which the average service conditions (σ_1T_1) are changed to accelerated test conditions (σ_2T_2), as illustrated in Figure 6(a). Thus, the θ Projection Concept can be used to derive remanent life estimates in the case of materials for which the coefficients in equations 2 and 3 have been evaluated (e.g. Table I). The procedures involved can be demonstrated by reference to Figure 6(b) which shows two schematic curves at σ_1T_1 and σ_2T_2 respectively, plotted as creep strain rate against creep strain. On changing from σ_1T_1 to σ_2T_2, detailed inspection of the subsequent behaviour pattern reveals that the creep rate immediately after the change is greater than expected for the new conditions but rapidly returns to the curve anticipated for σ_2T_2, i.e. a post-exposure creep test gives a curve represented by the solid line in Figure 6b. From a knowledge of the full curves expected for tests on virgin material under conditions σ_1T_1 and σ_2T_2 (derived from the θ data), together with the curve recorded in the post-exposure test at σ_2T_2, the remaining creep life can be derived in a straight-forward manner, i.e. data of the form shown in Figure 6b allows point C to be identified for the curve at σ_1T_1, so that the remaining life can be determined from the creep strain/time plot for these conditions.

It should be recognized that remanent life estimation using the θ relationships are based on strain-hardening rules whereas conventional stress-rupture procedures assume the less-realistic time-hardening behaviour, Figure 6(a). However, unlike traditional stress-rupture methods, accurate creep machines are needed in order to take advantage of the new procedures. Even so, the greater equipment costs are offset by the fact that

(a) while traditional methods and the θ relationships have been found to give similar estimates of remanent life, the scatter in the estimates from the θ analyses are far lower than with standard post-exposure stress-rupture tests,

(b) fewer tests are needed to estimate remanent life using the θ relationships and

(c) the θ Projection Concept allows stress/temperature contours to be defined to show the conditions which must be maintained in order to ensure a specified further safe period of plant operation so that, even for components approaching the end of their useful life, component replacement can be scheduled economically.

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