The role of small specimen creep testing within a life assessment framework for high temperature power plant

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ABSTRACT

The safe operation of ageing materials and structures operating at high temperature and pressure is challenging. This paper, for the first time, clearly addresses the role of small specimen creep testing methods within a practical life assessment framework, with a case study used to illustrate the main principles and applications. To enhance the current practice for assessing the condition of creep ageing components, more proactive use of small specimen testing methods is proposed for the in-service condition assessment of power plant materials, earlier in the plant lifecycle and within a holistic life assessment framework. The paper describes how small specimen creep testing methods and other complementary tools can be used together in a new structured approach to life management. There is a clear need to provide the plant owner with more reliable and effective life prediction tools, based on earlier and more rigorous assessment of in-service life consumption. A novel, holistic, life assessment methodology including the use of small specimen creep testing has been developed by the authors.

INTRODUCTION

Power stations are designed and maintained to operate for long periods safely and reliably in accordance with statutory requirements. In the UK, these statutory provisions are detailed in the pressure systems safety regulations (PSSR) [1], which are applicable to both conventional and civil nuclear generating plant. Further to the PSSR, UK civil nuclear advanced gas cooled reactor (AGR) generating plant is subject to licence conditions stipulated by the office for nuclear regulation [2]. The aim of these regulations is to prevent injury from the hazard posed by high stored energy systems because of a failure.

Subsequent pressure system inspections must be undertaken by competent persons and in accordance with written schemes of examination that identifies the systems or components requiring inspection. These written schemes take into account the relevant ageing mechanisms, asset condition including past inspection, assessment history and intended future
operation. The inspection periodicity between major statutory outages on UK conventional fossil-fired generating plant is every 4 years, with a short interim outage scheduled after 2 years. Typically, AGR generating plant is subject to a periodic pressure systems outage inspection every 3 years. Understanding residual life (and critically the mode of failure and rate of deterioration) is essential to maintain safety and to enable the utility to plan for any repair or replacement activities in a timely and cost-effective manner.

The operational duty of the high temperature and pressure steam circuits differ considerably between an AGR plant and a conventional fossil-fired plant. Large conventional fossil-fired plant are operated far more flexibly and at higher temperatures than AGR plant (design temperature of 568°C for conventional fossil fired plant vs. 540°C for AGR plant), but with similar maximum pressures of ~170 bar; this reflects process conditions as the steam exits the boiler.

There are other high temperature components aside from pressure systems in operation that could equally benefit from the use of small specimen creep testing, such as high pressure (170 bar) and intermediate pressure (40 bar) steam turbine rotors. The potential use of small specimen creep testing on these components is however considered more difficult due to limited access, since periodic overhauls typically occur every 12 years and with the turbines removed from berth. On these rotors access to the most relevant locations for material sampling is more restricted, for example the turbine disc steeples are of great interest, however these locations are precision machined and a sample could not be feasibly extracted without undertaking a costly repair to the disc head. Hence, the use of small specimen creep testing of material extracted from these components is more likely to be a practical choice on a rotor that has been retired from service, where the information obtained from the examination could be used to provide a more informed view on the condition of other in-service rotors.

The review published by Hyde et al. [3] in 2007 focussed on the use of small specimen testing methods to satisfy data requirements. This paper is applicable to both conventional and nuclear plant applications and also provides a review of the current state-of-the-art of small specimen creep testing, but focussed on plant application. Subsequently the work emphasises the following:

- Techniques currently used to assess the residual creep life of in-service plant,
- A proposal is presented that describes how the more proactive use of small specimen testing methods could improve the approach to creep life expiry and support subsequent run-repair-replace decisions.

Examples of in-service inspection data and a detailed case study based on high temperature and pressure pipework on conventional fossil-fired plant operation is used to illustrate the above points. Pipework systems are chosen for the case study because of the extensive amount of through life inspection data available as well as extensive research studies related to material creep behaviour and modes of failure.

Understanding the contribution of prior service duty to creep life consumption and a prediction of the future rate of ageing is essential if a utility is to optimise its generating output and return on investment, with respect to both maintenance and capital infrastructure costs.

Figure 1 shows historical operating data from two 2000 MW fossil fired conventional power stations presented as unit operating hours divided by unit starts; the data presented for each station has been averaged across all of the units on each site. This shows a dramatic variation in operating hours-to-starts ratio ranging from >500 during the early operational years, which reflects significant operation at constant (base) load to a dramatic change in the mid-1990s, to around 25 h-to-starts. This significant reduction in hours-to-starts ratio indicates a move to more flexible plant operation, which is driven by the demands of the commercial market. Figure 2 shows specific unit average operating hours and starts for station ‘A’. If all eight 500 MW units operating in stations ‘A’ and ‘B’ are considered the range of unit operating hours is from 250 to 280 khr and the range of unit operating starts is from 2500 to 4100. To put this operational data into context particular reference is made to a UK parliamentary study on UK energy policy [4], which describes the significant impact of the privatisation of the central electricity generating board (CEGB) in 1990 on these figures.

Both current and future operation is greatly influenced by legislation regarding environmental compliance. As a consequence of this legislation it is anticipated that stations ‘A’ and ‘B’ will from 2016 onwards revert to limited annual operational hours and unit starts (up to ~2000 h and 100–200 starts).

Figure 1. Unit average operating hours/starts ratio: for two 2000 MW fossil fired conventional power stations, from initial commissioning until end of 2014.
This illustrates the challenges associated with optimal deployment of small specimen testing methods (or any other monitoring or life assessment approach); the methods have to account for a wide range of operating duty throughout the station’s operational life.

In the UK, the approach to managing the integrity of the high pressure and temperature pipework systems and components on conventional fossil-fired plant is based primarily on an inspection-based assessment (IBA) approach. This IBA approach is practically implemented in line with the statutory outage inspection periodicity and consequently it has no specific requirement to provide longer-term predictions of component degradation rates.

For the utility, the goal of optimised life management would be realised with the following:

- Timely replacement of life expired components (maximising the useful service life), allowing the utility to budget and plan for cost-effective replacement;
- Continual optimisation of inspection plans during unit shutdowns; making the best use of all available condition monitoring and outage overhaul data;
- More timely use of on-load monitor data and outage inspection findings to update and manage the plant risk profile within acceptable levels;
- Avoidance of significant unplanned and costly outages.

In this context, the development and more proactive use of small specimen creep testing methods for the assessment of the integrity of high temperature and pressure systems provides a significant opportunity to reach this goal, but in conjunction with other complementary assessment tools that are outlined in this paper.

**Specialised small specimen creep testing**

In the last 20 years small specimen creep testing techniques (SSTT) have been increasingly developed to evaluate creep properties for materials relevant to components operating at high temperature in power plant applications, to assess their remaining life and avoidance of premature failures [5]. A way forward to establish this key material data is considered to be the use of standard size uniaxial creep tests, which are well-standardised mechanical test techniques, but requiring a large amount of material to be sampled from the operating components. Furthermore, it is often needed to perform analyses on critical locations on operating components, e.g. the heat-affected zone of welds, or to risk rank the most vulnerable operating components within a larger population. In order to avoid these particular difficulties, innovative non-invasive testing techniques, such as the small punch, impression, small two-bar and small ring creep tests, have been investigated by several authors, because of the relatively small volume of material they require. In practice, these techniques have been used to provide a ranking of material creep strength, thereby assigning a suitable inspection priority that has been adopted during a plant outage [6]. Furthermore, small punch creep testing has found applications in the nuclear field, especially for the characterisation of irradiated materials (see the section ‘Applications for irradiated materials’).

**Scoop sampling**

In order to manufacture miniature specimens from in-service components, scoop sampling techniques are currently used for industrial procedures [7,8]. Rolls-Royce produced the SSamTM-2 sampler for the extraction of material samples, shown in Figure 3; the machine has a length of 420 mm and presents a hemispherical shell cutter of 50 mm in diameter, which can remove a ‘button’ shaped sample of material, that is, typically, 25 mm in diameter and 4 mm thick [8]. Rolls-Royce has also designed two other smaller samplers, one able to fit within a 38 mm diameter tube bore and the second within a 30 mm annulus [8]. Scoop sampling techniques are such that the wall thickness of the component does not become smaller than the design wall thickness after some material has been removed [9]. Nevertheless, an increase of the creep strain rate in the sample area has been observed.

![Figure 2.](image-url) (a) Unit average operating starts for station A and (b) unit average operating hours for station A.
by finite element (FE) analyses of drum, steam pipes and turbine rotor bores. This is due to the increase in stress at the bottom of the excavation, which is up to 1.2–1.5 times greater than the stresses in the intact wall in the same depth from the external surface of the component [10,11]. In order to assess the creep damage due to this stress increment caused by the scoop sampling, Klevtsov and Dedov [11] carried out FE analyses of a steam pipe with an outer diameter, \( D_0 \), of 325 mm and a wall thickness, \( t_w \), of 30 mm, and creep cavity count on three bends steam pipes of 12Ch1MF and 15Ch1M1F. Two important conclusions can be deducted from their research; firstly, after 23–27 khr of service, the analysed components presented the same creep damage in the region under the scooping area and at a distance of 10 mm from that. Secondly, tensile properties of the materials remained the same during service and were independent of the excavation location and of the specimen typology [11].

Brett carried out 170 impression creep tests (ICTs), scoop sampled by using the SSamTM-2 on CrMoV main steam and hot reheat pipes, which had a wall thickness of 60–65 mm and 30–35 mm, respectively [12–15]. He found that the scoop technique can be considered to be ‘quasi-non-destructive’ since it does not require the repair stage as long as the maximum excavation depth does not exceed 10% of the wall thickness of the main steam pipe. For the hot reheat pipe a depth larger than 10% of the wall thickness is acceptable only over a restricted area in the centre of the excavation [15].

Rouse et al. [16] investigated the effects of scoop sampling on the creep response of straight pipe sections with different geometries, for a range of cut depths from 1 to 5 mm and for different load conditions, for the material 0.5Cr0.5Mo0.25 V at 640°C. They found that the presence of the excavation generates a localised stress around the base of the excavated notch. In the case of a static application of the load to the pipe, the condition is considered safe if the stress at the base of the excavation does not exceed the magnitude of the stress at the inner surface. This condition is achieved only when the depth of the excavation, \( h' \), is 1 mm for a pipe section with \( D_0 = 360 \text{ mm} \) and \( t_w = 60 \text{ mm} \). Rouse et al. [16] also propose a parametric equation which can estimate the scoop sample riser effect for a wide range of materials and pipe geometries, here given in Equation (1), where \( A, B, C, \ldots, I \) are fitting constants. Future study is needed on the effects of scoop sampling on the sampled component under the effects of cyclic load conditions.

\[
\frac{\sigma_{ss}}{\sigma_{MDH}} (\frac{D_0}{t_w}, h') = A \frac{D_0^4}{t_w} + B \frac{D_0^3}{t_w} + C \frac{D_0^2}{t_w} + DH^2 \\
+ E \left( \frac{D_0^2}{t_w} + h'^2 \right) + F \frac{D_0}{t_w} \\
+ GH + H \left( \frac{D_0}{t_w} + h' \right) + I
\]  

(1)

These studies on the effect of the scoop excavation suggest that a degree of prior assessment is required before a sampling exercise is undertaken to consider the excavation depth, component geometry, material type, material condition and the operational duty of the plant. The study by Rouse et al. [16] considers operating temperatures at 640°C, which is much higher than the typical plant operating temperatures (~570°C) that Brett’s study alludes to. This emphasises the need to measure on plant or estimate by analysis, the operating temperature related to a proposed sampling location.

For practical purposes a scoop sample location would be identified as a location on a future inspection schedule, noting that the additional cost and effort for the inspection of scoop sample locations typically is insignificant when compared to the full inspection scope during an outage. Ideally, all scoop sample locations would be accessible for repair should the need be foreseen.

**Reference stress method**

A major concern in the evaluation of test data of small specimen creep testing techniques is their correlation with uniaxial creep data. The approach currently used for data conversion is the reference stress method [17,18]. For materials obeying the Norton creep law, here reported in Equation (2), where \( A' \) and \( n \) are material constants, the reference stress method involves calculating two reference parameters, \( \eta \) and \( \beta \), such that a relationship between the equivalent uniaxial stress, \( \sigma_{ref} \), and the applied stress, \( \sigma \), and a relationship between the creep strain rate in the steady-state, \( \dot{e}_{ss}^{C} \), and the creep displacement rate obtained by SSTT, \( \dot{\Delta}_{ss}^{C} \), are established.

\[
\dot{e}_{ss}^{C} = A' \sigma^n
\]
\[
\dot{\Delta}_{ss}^{C} \text{ can be expressed as a function of the creep material}
\]
properties, the dimensions of the specimen and the nominal stress, $\sigma_{\text{nom}}$, as reported in Equation (3).

$$\Delta_{ss}^{c} = f_{1}(n)f_{s}(\text{dimensions})A'\sigma_{\text{nom}}^{n}$$

(3)

The reference parameter $\eta$ is defined as a material independent, non-dimensional constant such that the ratio $f_{1}(n)/\eta^n$ is also constant with $n$. Thus, the equivalent gauge length (EGL) of the structure can be defined as in Equation (4). It should be noted that the EGL does not vary with $n$ since none of the terms in Equation (4) does.

$$\text{EGL} = \frac{f_{1}(n)}{\eta^n}f_{s}(\text{dimensions})$$

(4)

If $s$ is a characteristic dimension of the sample, for example a length, the reference parameter $\beta$ can be expressed as in Equation (5) and again it should be noted that this constant is independent of $n$.

$$\beta = \frac{\text{EGL}}{s}$$

(5)

Finally, Equations (6) and (7) represent the sought relationships for $\Delta_{ss}^{c}$ and $\dot{\varepsilon}_{ss}^{c}$.

$$\Delta_{ss}^{c} = \text{EGL} A'\sigma^n = \beta s A'\sigma_{\text{nom}}^{n}$$

$$= \beta s \dot{\varepsilon}_{ss}^{c}(\sigma_{\text{ref}})$$

(6)

$$\dot{\varepsilon}_{ss}^{c}(\sigma_{\text{ref}}) = A'\sigma_{\text{ref}}^{n}, \quad \sigma_{\text{ref}} = \eta\sigma_{\text{nom}}$$

(7)

**Codes and standards for small specimen creep testing techniques**

Agreed standards for small specimen creep testing techniques still do not exist, but two codes of practice have been released for small punch creep test (SPCT) by the European committee for standardisation in 2006 [5] and by the standardisation administration of China in 2012 [19,20]. Efforts in developing a standard draft for the SPCT are also ongoing in Japan [21]. In the U.S.A, an ASTM standard test method for small punch testing of ultra-high molecular weight polyethylene used in surgical implants has been released, but does not concern creep testing [22].

The European CEN CWA 15627 [5], last updated in 2007, has been accepted as a first iteration for industrial applications all through the world, even if it is far away from being a recognised standard and certainly needs to be improved [23]. The CEN code of practice consists of two parts, Part A is related to specifications for the test rig, test procedure and interpretation of results for small punch test designed for material characterisation [5]. Part B is focused on the test rig, test procedure, test specimen preparation, interpretation of results and methods for deriving the yield strength, the ductile-to-brittle transition temperature (DBTT) and the fracture toughness [5,23]. Hurst and Matocha [23] published a critical review on the CEN CWA 15627 also suggesting some potential improvements of the code. One of their concerns is related to the shear punch test, which is not included in the code, even if it has been proven to be a reliable technique for the evaluation of tensile properties [23,24].

An open problem regarding small punch creep testing is the correlation between the load level applied to the small disc specimen and the stress induced in a conventional uniaxial creep test that exhibits the same time to rupture. Some equations for data interpretation have been proposed in the CEN CWA 15627 and are here reported in the section ‘Small punch creep test’, but the procedure is still not totally accepted for industrial applications and further investigation on the complex behaviour of the specimen during testing is ongoing [25].

**Currently used test methods**

Reliable bulk behaviour can be obtained if at least eight grains are contained through the specimen thickness [26]. Among the small specimens described in this section, the smallest dimension of the samples is the small punch disc thickness, equal to 0.5 mm. The materials generally used in power plant have at least 20 grains through such a thickness, allowing consistent results to be obtained.

**Impression creep test**

In the ICT a steady constant load, $P$, is applied to a flat-ended indenter in contact with the specimen at a fixed temperature. The test output is the variation of the indentation displacement with time, which is related to the creep properties of the small volume of material in the contact region between the specimen and the indenter. Figure 4 (a) shows the typical test geometry. If the indenter is rectangular, the reference stress approach can be used to establish the corresponding equivalent uniaxial stress, $\sigma_{\text{ref}}$, and the creep strain rate in the steady-state, $\dot{\varepsilon}_{ss}^{c}$, for materials obeying the Norton creep law [27]. Equations (8) and (9), where $d$ is the indenter width, express the relationships between them and the mean indenter pressure, $\bar{p}$, and creep displacement rate, $\Delta_{ss}^{c}$. The reference stress parameter, $\eta$ and $\beta$, do not depend on the impression depth, if the creep displacement $\Delta$ is relatively small compared to the specimen thickness.

$$\sigma_{\text{ref}} = \eta\bar{p}$$

(8)

**Figure 4.** (a) ICT specimen; (b) SPCT specimen; (c) small ring creep test specimen, adapted from Sun et al. [28].
\[
\dot{\epsilon}_{ss}^c = \frac{\Delta_{ss}^c}{\beta d}
\]

Once \(\Delta_{ss}^c\) is known, for example by FE analyses, for different values of \(n\), it is possible to calculate \(\beta\) through Equation (10), by using assumed values for the stress multiplier, \(\alpha\) [27]. The value of \(\alpha\) such that \(\beta\) does not vary with \(n\), is the reference stress parameter \(\eta\) [27].

\[
\beta = \frac{\dot{\Delta}_{ss}^c}{dA'(\alpha\sigma_{ref})^n}
\]

The \(\eta\) and \(\beta\) values for the recommended geometry \((w \times b \times h = 10 \times 10 \times 2.5\, \text{mm})\) are \(\eta = 0.43\) and \(\beta = 2.18\), for an indenter width of \(d = 1\, \text{mm}\) [27]. A typical set of deformation data obtained from such tests for a high temperature CMV \((0.5\%\text{Cr}0.5\%\text{Mo}0.25\%\text{V})\) steel is shown in Figure 5(a). The slight fluctuations in the data observed in Figure 5(a) are mainly caused by temperature variations within the furnace and laboratory. However, it can be seen that these variations are typically well within \(\pm 1\, \mu\text{m}\) [28]. A comparison of minimum creep strain rate data for CMV and 316 stainless steel is illustrated in Figure 5(b). The ICT data lies on the same straight line as uniaxial creep test data, confirming the reliability of the ICT.

**Small punch creep test**

The SPCT consists of the application of a constant load, \(P\), to a hemispherical indenter in contact with a disc specimen clamped between an upper and lower die containing the receiving hole. Figure 4(b) shows the sketch of typical specimen and punch, while a schematic cross section of the test rig is given in Figure 6(a).

The European committee for standardisation has released a code of practice which provides standard dimensions of both test rig and samples to be tested [5]. According to that, the disk diameter has to be between 3 and 10 mm, the specimen thickness, \(t_0\), between 0.2 and 0.5 mm, and the punch radius, \(R_p\), between 1 and 1.50 mm. Li and Sturm [29] found a third order polynomial based on Chakrabarty’s membrane theory [30] and valid for \(R_p = 1.25\, \text{mm}\) and \(a_p = 2\, \text{mm}\) (receiving hole diameter), which correlates the strain, \(\varepsilon\), at the contact boundary between the punch and the disc and the central displacement of the punch, \(\Delta\), as shown in Equation (11). An empirical relationship between the applied load and the membrane stress, \(\sigma_{mm}\), is also given in the CEN code of practice and is here reported in Equation (12) [5].

\[
\varepsilon = 0.17959\Delta + 0.09357\Delta^2 + 0.0044\Delta^3
\]

\[
P \sigma_{mm} = 1.72476\Delta + 0.05638\Delta^2 + 0.17668\Delta^3
\]

These relationships are only valid when bending deformation of the specimen is negligible and thus the deformation mode can be assumed to be governed by membrane stretching. This happens when large deformations are exhibited by the specimen during the test, that is, from an engineering estimation, when \(\Delta > 0.8\, \text{mm}\) [5]. However, according to many researchers, during SPCT the specimen deformation is caused by bending prior to membrane stretching [31–33] and a recent study, confirming this theory, suggests upper limits to \(\Delta\), depending on the specimen and the punch dimensions [34], as shown in Table 1.

Another empirical relationship, always derived by Chakrabarty’s membrane theory, is reported in an annex of the code of practice [5], and can be used to derive the load to be applied for the SPCT, here

![Figure 5](image-url)

**Figure 5.** (a) Impression deformations with time at 90 MPa and 600°C obtained from ex-service CMV steam pipe samples, from Sun et al. [28], and (b) minimum creep strain rate (MSR) data for 316 stainless steel at 600°C and 2-1/4Cr1Mo weld metal at 640°C, obtained from uniaxial and ICTs, from Sun et al. [28].
given in Equation (13), where $K_{SP}$ is a correction factor depending on the tested material.

$$\frac{P}{\sigma_m} = 3.33K_{SP}R_s^{-0.2} \alpha_p^{1.2}t_0$$  \hspace{1cm} (13)

In order to find $K_{SP}$, at least five SPCTs are necessary as well as a comparison with a conventional creep test [5,35]. This parameter generally ranges between 1 and 1.5 [36]. An additional difficulty in SPCT data interpretation is the notable variation of the reference parameters due to large deformations involved in the test [35] and, although it is still possible to define $\eta$, as in Equation (14), in virtue of Equation (11) a constant EGL, and thus a constant $\beta$, cannot be determined [37].

$$\eta = \frac{0.6\pi}{K_{SP}} \left( \frac{\alpha_p}{R_s} \right)^{0.2}$$  \hspace{1cm} (14)

**Figure 6(b)** shows typical SPCT data output, in terms of displacements versus time, for a P91 steel at 600$^\circ$C, while **Figure 6(c)** shows converted creep rupture data (using Equation (12), with $K_{SP} = 1.275$) obtained from a SPCT (SPT in the graph) on a P91 steel at 650$^\circ$C, compared with corresponding uniaxial data.

**SPCT data** are in good agreement with uniaxial data.

**Small ring creep test**

**Figure 4(c)** shows the typical specimen and loading system of the small ring creep test method that involves diametrically loading in tension a circular or elliptical ring. The test output is the deformation versus time curve, and similar to the ICT, this needs to be related to the data obtained from a standard uniaxial creep test, using the reference stress approach. An analytical solution for the load-line displacement rate of the elliptical ring in the secondary region of the creep curve has been developed at the University of Nottingham in 2009 by assuming as the main hypotheses the effects
of the shear stresses to be negligible, bending as the
governing deformation mode, and material obeying
Norton’s creep law [37]. The solution is given in
Equation (15), where $a'$ and $b'$ are the ellipse half-
axes and $b_0$ and $d'$ are the thicknesses in the radial
and axis directions, respectively, $P$ is the applied load,
while Int$_2$ is defined in Equation (16), where $\theta$ is the
angular coordinate of the small ring system, as shown
in Figure 7, and $\theta$ the value of $\theta$ for null bending
moment, $M$. If the ring is circular $a'=b'=R$, where $R$
is the radius of the ring.

\[ \dot{\Delta} = \left( \frac{2n+1}{n} \right)^n \text{Int}_2 \left( \frac{n}{b'} \right) \frac{4a'd'}{d} A' \left( \frac{Pd'}{b_0d'^2} \right)^2 \]  

\[ \text{Int}_2 \left( \frac{n}{b'} \right) = \]  

\[ -\theta \left[ (\cos \theta - \cos \theta')^n (1 - \cos \theta) \sqrt{\left( \frac{a'}{b} \right)^2 \sin^2 \theta + \cos^2 \theta} \right] \right] d\theta 
+ \theta \left[ (\cos \theta - \cos \theta')^n (1 - \cos \theta) \sqrt{\left( \frac{a'}{b} \right)^2 \sin^2 \theta + \cos^2 \theta} \right] \right] d\theta \]

Equation (15), where a curve still shows primary and secondary regions,
the moment, $M$ and axis directions, respectively,
while Int$_2$ is defined in Equation (16), where
the uniaxial creep stress and the equivalent uniaxial creep
By virtue of the reference stress method, the equivalent uniaxial creep stress and the equivalent uniaxial creep
strain rate for the load-line deformation rate, $\dot{\Delta}$, are
given in Equations (17) and (18) [37,38]. For the full
mathematical treatment, refer to Hyde and Sun [37].

\[ \sigma_{ref} = \eta \frac{Pd'}{b_0d'^2} \]  

\[ \dot{\varepsilon}(\sigma_{ref}) = \frac{d'}{4a'b'} \frac{\dot{\Delta}}{\beta} \]  

Large deformations involved during the test do not
significantly affect the conversion parameter $\eta$, the
thickness in the radial direction, $b_0$, and the thickness
axis direction, $d'$; while they affect $a'$, which decreases
during the test as well as $\sigma_{ref}$ the conversion parameter $\beta$ also varies with the ratio $a'/b'$ at each
instant of time [37,38]. As a consequence, the creep
curve still shows primary and secondary regions,
but the latter is characterised by a finite curvature
rather than a constant rate [38]. In other words,
with this test, a constant strain rate is not quite
achieved, but it is still possible to calculate the equivalent uniaxial data by using the method proposed by
Hyde et al., which involves calculating the instantaneous values of $a'/b'$, $\eta$, $\beta$, $\sigma_{ref}$ and $\dot{\varepsilon}$ at many intervals in the secondary region. The average of the calculated values of $\sigma_{ref}$ and $\dot{\varepsilon}$ can be then assumed to be the equivalent uniaxial data [38]. In order to obtain a better-defined steady-state, Hyde et al. [38] are
developing a software capable of varying the
load during the test according to Equation (17) as the specimen shape changes.

The test results for circular ($a'/b'=1$) and elliptical ($a'/b'=2$) rings, with $R/d'$ = 5, for a P91 steel at 650°C, with a range of equivalent uniaxial stresses, are shown in Figure 8(a) in terms of displacement, $\Delta$, versus time, and in terms of minimum creep strain rate
versus the applied stress in Figure 8(b). It can be observed that the method proposed by Hyde et al. [38] allows highly accurate secondary creep properties to be obtained, since the small ring data are on the same straight line as the uniaxial data.

**Small two-bar creep test**

Another small specimen experimental technique which has been recently developed at the University of Nottingham by Hyde et al. [39] is the two-bar specimen (TBS) test. Figure 9(a) shows the typical test rig, while Figure 9(b) shows the typical two-bar specimen, which consists of two relatively slim bars connected by supporting ends. The sample is creep tested by applying a constant load to the supporting ends through the use of two pins (Figure 9(a)). The specimen geometry consists of the initial bar length, $L_T$, which is the distance
between the centres of the loading pins, the
length of the loading pins supporting end, $k$, the specimen thickness, $d_T$, the diameter of the loading pins, $D_T$, and the bar width, $b_T$ [39]. Hyde et al. [39] recommended $L_T/b_T = 4.5$, $D_T/(2b_T) = 1.25$, $k/D_T = 1.3$ and a bar length, $L_T$, of 26 mm, which is larger than the diameter of the SPCT specimen recommended in the CEN code of practice [5], i.e. 8 mm, and of the ICT specimen recommended in Hyde and Sun [27]. The equivalent uniaxial creep stress and the equivalent uniaxial creep strain rate are again defined through the reference stress method and here given in Equations (19) and (20), where $\eta$ and $\beta$ are determined by FE analyses, as for ICT, and their values are 0.9866 and 1.456, respectively [39]. However, those values were obtained by the use of Norton’s law, thus the FE analyses could well predict the primary and secondary region of the creep curve, but not the tertiary region. Consequently, further investigation in determination of the reference

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**Figure 7. Reference frame of the small ring, adapted from Hyde and Sun [37].**
stress parameters is ongoing [40].

\[
\sigma_{\text{ref}} = \frac{p}{2\beta d_T} 
\]  

(19)

\[
\dot{\varepsilon}_{cs}^{c}(\sigma_{\text{ref}}) = \frac{\Delta T}{L_T \beta} 
\]  

(20)

During the test, the creep deformation of the specimen is essentially due to stretching under uniaxial stress, as well as the rupture of the bars. Bending occurs in the area of the contact between the sample and the pins, but it has been proven not to have a significant effect on the failure mode and on creep deformation [40]. This behaviour of the specimen is also observed by FE analysis results, as shown in the contour plot presented in Figure 10, where the specimen failure of P91 steel at 600°C and applied stress of 170 MPa is achieved when the damage variable, \( \omega \), approaches unity. Two-bars creep test output is very close to uniaxial creep test output because most of the uniform section is predominantly under a uniaxial state of stress. This is the reason why \( \eta \) is almost 1.

Typical small two-bar creep test data output and the corresponding correlation with uniaxial tests are shown in Figure 11. TBS data are in good agreement with uniaxial data, as their MSR trend is still on the same straight line of the uniaxial data, as well as for impression and small ring creep tests data.

**Evaluation of current test methods**

The selection of a small specimen creep test technique is dictated by factors such as, economics, the type of data required, e.g. creep rupture data or creep strain rate data, material to be tested and the test conditions [41].

![Figure 8](image1.png)  

Figure 8. (a) Deformation (\( \Delta R/R \)) versus time curves obtained from circular rings for a P91 steel at 650°C, and (b) minimum creep strain rate data for a P91 steel at 650°C obtained from uniaxial and ring tests, from Hyde and Sun [37].

![Figure 9](image2.png)  

Figure 9. (a) Two-bars experiment setup and loading application; (b) schematic representation of the two-bar specimen, adapted from Hyde et al. [40].
In practice, the ICT method is easy to perform and it gives accurate output in terms of minimum creep strain rate, particularly at relatively high stresses and in the heat-affected zones of welds. This technique appears to be useful in power plant component life assessment [6], and has been deployed in-service to support decisions to continue operation as opposed to undertaking immediate repairs. Despite these advantages, the test has some limitations, e.g. the indenter creep resistance needs to be two or three order higher in magnitude than that of the specimen. Also, tertiary creep behaviour cannot be obtained, because of the compressive stress field in the specimen which does not allow crack nucleation and propagation [26]. The deformations involved during the test are very small, of the order of μm, requiring very accurate data acquisition and temperature control systems. Furthermore, FE analyses of this test are complicated by the contact interaction between the indenter and the specimen. The same problem is observed in numerical simulations of SPCT, where the contact is also non-linear.

The SPCT potentially allows the entire characterisation of material behaviour up to failure, because the specimen is taken to rupture and it can also be used to perform focused analyses on critical locations of operating components. Despite these advantages the interaction of several non-linearities, such as large deformations, large strains, non-linear material behaviour and non-linear contact interactions between the specimen and the punch, induces a complex multi-axial stress field in the specimen which also evolves in time [42–45]. This affects the SPCT fracture mechanism and introduces several challenges for the identification of a robust correlation to convert SPCT data into respective standard uniaxial creep test data [35,46]. Another major concern is the non-repeatability of the testing method, since the experimental results depend on the set up geometry [5]. For this reason, a well-established and universally accepted method for data interpretation still does not exist.

Progresses in the understanding of the complex behaviour of the specimen have been made through FE analyses and microstructural studies. In particular, the implementation in a commercial FE code of the Liu and Murakami damage model [47], by the use of a subroutine, leads to good simulation of the crack propagation in the small punch specimen, as shown in Figure 12, where a comparison between SEM images of interrupted tests and FE results of P91 steel is illustrated. Figure 12 also confirms Chakrabarty and other researchers’ statement that the necking occurs at a certain distance from the specimen centre due to friction [30,32,34,48] and that the zone affected by the maximum damage spreads from the bottom of the specimen through the thickness in the necking area, as reported in the open literature [33,49,50]. The creep mechanism characterising the deformation of the specimen, that is represented by dislocation creep in the secondary creep regime and inter-granular cavitation when the tertiary creep stage is reached, is not affected by the different temperature values of the test, 600°C, and of that assumed for the material properties in the numerical simulations, 650°C [34,51]. Figure 13 shows the typical uniaxial creep test output in terms of strain versus time, and illustrates that the crack propagation starts in the tertiary region of the creep curve if the uniaxial creep test is carried out at constant stress. By comparing Figures 6(b), 12 and 13, the different behaviour of the small punch specimen with respect to the uniaxial specimen is evident. In fact, the crack propagation in the small punch disc starts in the secondary region of the creep curve instead of the tertiary region, as observed for the typical uniaxial specimen.

Difficulties in obtaining good agreement between FE analysis and small punch test time to failure are due to the effects of punch load misalignments, initial plasticity and approximation of the friction formulation between the specimen and the test machine components [34] used in the FE analyses. An increase of the failure life has been found to be up to 10 times.
when initial plastic deformation is included in the model [31]; the time to failure can also increase up to 8 times when the friction coefficient between the specimen and the punch varies from 0 to 0.5 [51–53]. Punch load misalignments can also increase the time to failure by up to 1.49 times, in the worst possible situations [54].

The small ring creep test method is able to provide accurate minimum creep strain rates, especially at relatively low equivalent uniaxial stresses with a unique application of this test type being for creep resistant materials. During the creep test, the small ring specimen is subjected to relatively large deformations, from which relatively small strains are obtained with a lower equivalent stress than that applied to other miniature specimens. As shown in Figure 8(b), the minimum creep strain rate data obtained from circular and elliptical ring creep test at stresses between 50 and 65 MPa lie on the same straight line as the uniaxial data obtained at higher stresses, between 70 and 100 MPa. The deviation of the elliptical ring data from the straight line is in the range of the typical scatter of creep tests, which is about of 8%. Future development involves the establishment of time-dependent geometric correction functions to compensate for the effects of geometry changes during the deformation process [37,38].

Figure 11. (a) Deformation versus time curves obtained from two-bar specimens for a P91 steel at 600°C, (b) Creep rupture data and minimum and (c) creep strain rate data obtained from two bar and uniaxial specimens for a P91 steel at 600°C, from Sun et al. [28]. (d) Fitted uniaxial and converted (by using Equation (20)) two-bar strain versus time curves for a P91 steel at 650°C, from Sun et al. [113].
The small two-bar creep test allows production of full uniaxial creep curves, but further experimental data and validation are necessary. With this technique, the pins must be made of a material characterised by higher creep strength than that of the specimen, therefore there is a limitation in the range of materials which can be potentially tested. In the case of testing high creep strength materials, e.g. nickel-based superalloys for turbine blades, using the two-bar specimen, careful consideration of the specimen design should be given. Relatively larger diameter pins and smaller cross-sectional areas of the test sections of the two-bar specimen should be adopted to reduce the mean contact stresses between the pins and the specimen. In such a case, the material for the pins can be chosen to have a similar creep strength as that of the tested material. The contact between the pins and the specimen induces a bending deformation in the extreme regions of the specimen, while the stress distribution in the bars is almost constant [40]. In view of this feature, the reference stress parameters for this specimen type are almost one, as the stress field in the effective section of the structure is considerably similar to that found in conventional uniaxial creep test specimen. Furthermore, the specimen is taken to failure, therefore, contrary to the impression creep and the small ring creep tests, the tertiary creep region of the material can be characterised and the failure behaviour identified.

In conclusion, good agreement between small specimen creep data and uniaxial creep data have been obtained with all of the techniques described so far, particularly with good correlation against minimum creep strain rates. Both small punch and small two-bar creep tests are able to predict the specimen failure life, but difficulties in data interpretation of small punch data have not been overcome yet, while, methods for data interpretation of the two-bar test are still under investigation, even though this test has already been validated for steel materials and a nickel-based super-alloy material. Impression and small ring creep tests are both suitable for the determination of the steady-state creep properties. The noise in the ICT output can be of the same order of the output itself, since very small deformation occurs during the test. An opposite problem has been observed for the small ring creep test, during which the specimen shape varies, causing the reference stress to change as well. As a final consideration, small specimen creep testing techniques look very promising for determining creep properties and providing information about failure, even though further experimental and numerical investigations are needed.

The current status of the techniques can be summarised as:

- Provide estimates of minimum creep strain rate that show good comparison to uniaxial data;
- Impression creep specimens have been used to support operational run-repair-replace decisions on components;
- The small two-bar creep test specimen is the only method considered to be capable of providing a full uniaxial creep curve;
- There is currently no agreed standard for the application of small specimen testing, although the definition of a SPCT standard is the most advanced;
Material is typically sampled from the surface of a component, which confers the following opportunities:
- correlation against current methods for assessing the condition of the bulk component, such as surface creep replicas, hardness tests,
- provide component specific in-service creep strain rates, which can be compared against the response from a representative structural model, thereby allowing a more objective assessment of component condition that accounts for the stress state,

Industry practice for condition monitoring and life management

A range of non-destructive inspection based assessment techniques and surveys are used during a statutory plant shutdown to support an evaluation of the condition of components operating at high temperature and pressure. These techniques do not provide a direct measure of accumulated creep damage (life consumption); however they support the subsequent residual life assessment by reference to similar components and systems on sister plant. The current assessment approach requires extensive data mining and review of large quantities of site metallurgical data, from a number of different power stations and at different times in their lifecycle.

The techniques routinely used to assess the condition of components during a plant outage include: surface replication, surface hardness, ultrasonic inspection, magnetic particle inspection and physical dimension measurements using callipers and micrometres. The selection and use of these techniques are influenced by a host of considerations such as cost, perceived risk, familiarity and confidence with the techniques, plant access, accuracy, reliability, regulator preference and tradition. In addition, on-load monitoring of pressure and temperature conditions can be used to provide a generally conservative estimate of the residual creep life. This involves using sampled operational steam or metal temperature data coupled with steam pressure data, with an appropriate creep rupture expression to determine the residual creep life, which is discussed further in the section ‘On-load: use of operational data’.

It is standard practice to use different approaches and diverse data sets, such as outage overhaul inspection data and on-load monitoring to evaluate component condition. This is necessary because of the intrinsic scatter in the material creep properties and uncertainty in some of the load components, such as fixed support loads and reaction loads from adjacent components and systems, which can also vary as the plant is cycled on and off-load. It should be noted that modern plant design can limit the ability to deploy some of these traditional techniques due to restricted access for inspection.

For example, heat recovery steam generators are designed so that it is not possible to use traditional diametral strain measurements on the steam headers. Hence, this provides a requirement to consider the use of the novel techniques to assess creep life consumption such as optical strain gauges [55], alternating current potential drop [56] and small specimen testing techniques such as impression creep, small punch and ring specimens [3,37].

With respect to the use of the non-destructive techniques: on-line strain rate measurement offers great potential to the utility, from the perspective of being able to use the information to proactively manage the integrity throughout the whole life cycle of the station and to prompt beneficial changes in operation, in good time. The ultimate aim is to use the strain rate data iteratively in pipework or component specific computational models, where the system or component model response would be calibrated against component-specific strain rate information, and compared against other relevant condition assessment data obtained during the plant outage. This would demonstrate a truly holistic approach and is considered to be the ultimate aim for optimal plant integrity management. Figure 14 shows a schematic of the current integrity management approach. Particular reference is made to the two following aspects: (1) miniature specimen testing, which could provide significant benefits to the utility with respect to maintaining safe operation, maximising availability and optimising operational and capital costs, and (2) more proactive use of on-load data assessment.

Inspection planning and reporting

The inspection planning process is driven by the need for the utility to demonstrate compliance with PSSR requirements [1] and is applicable to both conventional and nuclear AGR pressure systems. The inspection plans are developed by a ‘competent body’ that can demonstrate that its staff are suitably qualified and experienced.

It is common practice in the UK for large conventional fossil-fired stations to prepare a technical review document about three months before the statutory outage. This gives an overview of the previous operational history, maintenance, replacement, inspection and assessment history of all the pressure systems for the Unit. Operating AGR plants are subject to additional licence requirements [2], which for example define requirements for sites to produce periodic safety reviews in support of the stations risk management process.

There is a statutory requirement for the ‘competent person’ to compile a written report of the outage examination within 28 days of return to service, which is agreed with site representatives and the technical
inspection body. Subsequently, detailed component and system specific integrity assessment reports and safety cases follow after return to service.

Off-load: outage works

The following outage inspection techniques are applicable to both conventional and AGR high temperature and pressure systems. None of these techniques are used as systematic input into a predictive creep life assessment model of the piping system or other high temperature components.

Pipe movement. Pipe movement is obtained via hot and cold surveys of pipe work hanger positions, an example of one type of pipe hanger set-up is shown in Figure 15. In this arrangement there are two spring loaded pipe hanger supports either side of the main steam pipe, with connections to structural steelwork above and connections to the main steam pipe via a ring (trunnion) clamp below (out of the image). This arrangement is designed to ensure that a constant load is imposed on the pipe as it moves up or down with normal plant operational transients. The hot and cold surveys provide information on pipework operational loads (between cold condition and full load hot operation), which can be compared against the design basis and prompting readjustment of hangers as required.

Passive strain measurement. Bow gauge micrometres shown in Figure 16 are typically used for headers and pipework for diameters up to about 600 mm with a precision of 0.01 mm, especially when used with a more accurate locating method such as non-oxidising creep pips. It has been shown [57] that safe management of plant can be achieved with well controlled and managed diametral surveys, coupled with

**Figure 14.** High temperature plant condition assessment (dotted line represents aspects of data analysis/methods that are not fully utilised. Solid lines represent the current and well-established IBA approach).

**Figure 15.** Typical pipe hanger arrangement.
interrogation of other outage and operational plant data. However, a review of large datasets from periodic conventional fossil-fired plant diametral surveys show much greater than expected variability and emphasises the need for good procedural control on site if such methods are to be relied on.

More recent developments to improve the accuracy and reliability of passive strain measurement include the ARCMAC high temperature optical strain measurement system [58,59]. The ARCMAC system uses stud-welded optical targets attached to the component in a bi-axial arrangement, which is illuminated from a light source within a purpose designed camera system with a telecentric lens and beam splitter arrangement. The attachment of the stud-welded optical gauge is facilitated by the use of a purpose designed gauge carrier that allows consistent gauge installation, along with the installation of a suitable protective cover. The optical arrangement and illumination ensures that accurate measurements of strain can be captured even if the camera system is not located precisely normal to the target gauge. The strain measurement resolution is $\sim 60$ micro-strain with an error of $<10\%$. Gauge images captured during subsequent shutdown periods enables the creep strain rate to be deduced. The authors have un-published data from validation tests at 600°C and a period of that 20 khr operation, with test periodically interrupted to obtain gauge images and thereby simulate intended use on site, which shows strain resolution and repeatability that is in very good agreement with the laboratory creep test extensometer instrumentation. Further extensions to these optical strain measurement techniques have been developed using surface speckle coatings and digital image correlation techniques to provide a non-contact surface strain distribution (across a weldment), with reference images from an adjacent ARCMAC gauge to provide a calibrated strain reference [60,61].

Surface creep replicas. These are targeted at regions considered to be more prone to creep damage accumulation, such as weldments, pipe penetrations (fillet welds), attachment welds, pipe bends and pipe terminal positions. The requirement for creep replicas is dependent on the age of the plant and the perceived risk, which may be influenced for example by adverse readings from routine passive strain measurement campaigns or known periods of mal-operation evident from reviews of operational data. It is not unusual for several hundred replicas to be taken during an outage on a single unit.

The surface replica technique involves capturing the surface features on a film that can subsequently be examined under a microscope. This involves careful surface preparation by grinding the surface with progressively finer abrasive papers, with final polishing. This process should be undertaken with great care to avoid removing the creep damaged surface and also to ensure that any surface oxidation and decarburised layers are removed. The prepared surface for replica assessment typically covers a surface area of $25 \times 50$ mm is then etched with a dilute acid such as Nital to reveal the microstructure. A soft cellulose acetate strip is then pressed onto the surface and allowed to dry before spraying with a matt black paint. This provides a contrast under white light when the replica is removed and examined under the microscope. Carefully applied this process should reveal creep cavities that can subsequently be counted per mm$^2$ and classified, which is described in further detail in the section ‘Case study: ageing main steam pipework’. It should be noted that different types of steel may require a modified process to the above in order to obtain the best quality surface replica.

Figure 16 illustrates a surface replica of a CMV main steam line weld, taken after grinding to a depth of 5 mm from the outside surface. Two photomicrographs are shown, at $\times 200$ and $\times 500$ magnification, in this example a high creep cavity count was assessed at 842 cavities/mm$^2$. In this case, the material had been in operation on one of the EDF Energy’s conventional fossil-fired power stations for circa 260 khr before retirement and subsequent examination.

The repair or return to service decision is usually supplemented by experiential knowledge, as indicated in the current condition assessment route, Figure 14. The importance of experiential knowledge should not be underestimated in the decision making process due to the significant differences in creep degradation characteristics of power plant materials in widespread use such as CMV and modified 9%Cr steels (P91).

Surface hardness. These outage measurements are targeted at regions considered to be more prone to creep damage accumulation, with the key aspect being the change in surface hardness captured at successive
inspections. It is custom and practice to cross-check these results against periodic trends from surface creep replicas obtained from an adjacent location.

This is essentially a similar approach to surface creep replication and is frequently used during an outage to provide a large amount of data, with the key feature of the subsequent assessment being the change in surface hardness at a repeat location between periodic inspection intervals. It is custom and practice to cross-check with other site metallurgical techniques, such as surface creep replicas obtained from an adjacent location on the component.

There are a range of portable site hardness test tools available, either using ultrasonic contact impedance, direct measurement or dynamic rebound, such as the Equotip system, which uses the impact and rebound velocities to determine the surface hardness value. It is necessary to prepare the surface before testing (to remove hard scale), and these methods are frequently used on site during the outage. Various industrial studies associated with the performance (accuracy and repeatability) of these techniques have been undertaken. For the dynamic rebound systems, the characteristics are (assuming trained and competent operators and for specimens in the range 180–300 HB):

- low standard deviation,
- error typically ~5%,
- error is significantly influenced by the hardness of the specimen, with the error increasing with softer materials,
- results can be influenced by the angle of the probe.

Again, decisions on repair or return to service options that use hardness data is typically based on rate of change in hardness and experiential knowledge from hardness trends associated with other similar components, material, service age and duty. This information is not used in a predictive life assessment model.

**Material composition checks.** This standard practice confirms that the correct materials have been installed on plant. In some instances rogue materials have been identified, hence composition checks are recommended good practice. For on-site composition checks portable X-ray fluorescence analysers are typically used.

**On-load: use of operational data**

The station routinely records steam temperature and pressure data at selected key points in the process system. The decision on the sampling interval is influenced by the stability of operation; if the unit is prone to temperature instability then the sampling interval should be reduced. These techniques are applicable to both conventional and AGR high temperature pressure systems.

In addition, most stations will invariably have installed additional surface mounted or deep drilled thermocouples on key components or on components being monitored as part of a safety case. This data is stored in the plant historian and various data sampling frequencies can be defined. Typically if a plant transient is being monitored the thermocouple sampling interval may be as frequent as every 15–30 s. For longer-term creep temperature monitoring the sampling interval could be increased to several minutes. With respect to creep temperature monitoring, the decision on the sampling interval is influenced by the stability of operation; if the unit being monitored is prone to temperature instability then the sampling interval should be reduced. Hence, some judgement and experience is needed to define the required sampling interval prior to any computation being undertaken.

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**Figure 17.** Weld Type IV region of a main steam pipework weld, surface replica taken 5 mm below the outer surface at (a) ×200 magnification and (b) ×500 magnification.
Once this data is collected the station evaluates what is termed as the creep effective temperature (CET); defined as the average temperature at which all of the creep damage (over the monitored period) can be equated to. This approach typically uses the design pressure in the computation, although it is possible to use the measured operational pressure. However, for the purposes of the CET calculation, the design pressure is usually sufficient. For UK conventional plant designs 0.5%Cr0.5%Mo0.25%V (CMV) steels are typically used for main steam line construction.

The creep rupture life calculation, using CET, gives a value of creep rupture life, which is dependent upon stress and temperature. Equation (21) is used to estimate the creep rupture life of CMV material and is based on the Manson–Brown 4th degree polynomial formula, where $t_r$ is the predicted time to creep rupture in hours, $T$ is the temperature in Kelvin, $\sigma = 1.25\sigma_{eq}$ and $p_0, p_1, \ldots, p_7$ are constants, which values for the aforementioned 0.5%Cr0.5%Mo0.25%V (CMV) steels are expressed in Table 2.

$$\log t_r - p_5 = p_0 + p_1 \log \sigma + p_2 (\log \sigma)^2$$
$$+ p_3 (\log \sigma)^3 + p_4 (\log \sigma)^4 \quad (21)$$

For a main steam line the creep reference stress, $\sigma_{ref}$, is equivalent to the mean diameter hoop stress in Equation (22), where $p$ is the operating pressure, $D_0$ is the pipe outside diameter and $t_w$ is the wall thickness.

$$\text{Mean diameter hoop stress} = \frac{p(D_0 - t_w)}{2t_w} \quad (22)$$

Figure 18 shows the effect of changes in operating temperature from 568 to 578°C against the minimum creep rupture life, for two operating stress levels of 42 and 47 MPa of a typical main steam line based on nominal dimensions of 360 mm outside diameter, 60 mm wall thickness with an operating pressure of 168 bar. The subsequent mean diameter hoop stress is 42 MPa and it can be observed that an increase in operating temperature of ~5°C or an increase in stress of ~10% results in a reduction in creep rupture life of ~20 khr. Information presented later in this section provides examples of plant temperature data trends that show that abnormal operating temperatures are not uncommon; in addition practical experience during periodic plant overhauls regularly shows evidence of the biasing of observed creep damage around pipework sections due to in-service system loading effects.

The above example is significant for the following reasons:

(i) Relatively modest increases in operating conditions (temperature and stress) result in a significant reduction in creep rupture life;

(ii) The reduction in creep rupture life of ~20 khr, due to variation in temperature or stress is approximately equivalent to a typical 4-year operating period for a large conventional fossil-fired power station;

(iii) Stations would prefer to be able to plan future outage scope and replacement strategies with more certainty for budgetary purposes; the example presented shows the dilemma that stations face as unit operation nears the end of practical commercial life.

From the perspective of the station, the sensitivity to modest increases in operating conditions makes planning the scope of subsequent outages or replacement exercises fraught with uncertainty. This uncertainty triggers a natural response to conduct more sampling inspections at subsequent outages and may result in premature replacement of large sections of pipework or components.

Figure 19 shows an example of a typical steam temperature trace obtained at the final superheater outlet from a boiler on a 500 MW conventional unit, with temperatures plotted from two of the four outlet steam legs (A1 and B1) during a run-up to full load. In this example, steam temperature is sampled at 1-min intervals. Since there are four main steam lines exiting the boiler on a typical 500 MW unit it is not unusual to find each of the four steam outlet legs operating at different CET’s.

| $p_0$  | $p_1$  | $p_2$  | $p_3$  | $p_4$  | $p_5$  | $p_6$  | $p_7$  |
|--------|--------|--------|--------|--------|--------|--------|--------|
| -0.10086133 | 0.2521769 | -0.27441233 | 0.12751693 | -0.02218978 | 8.659 | 650 | 0.95 |
In this example, there are a number of temperature excursions that significantly exceed the 568°C design temperature. Hence, the primary use of the CET computation is to provide a systematic process to identify operational issues and to prompt a correction. In addition, historical CET computations on units and across steam systems and components are used to support the definition of the inspection scope prior to the next statutory outage.

It should be noted that on current UK conventional fossil-fired stations the steam outlet design conditions are nominally 568°C and 168 bar. However, from experience it is not unusual for steam temperatures to cycle beyond 600°C, which is the limit of the CMV creep rupture models, in Equation (5). In such cases, the use of the CET data is problematic and a consequence of such adverse operation is that more ‘inspection sampling’ during an outage is usually stipulated in order to determine if the operational instability has manifested itself as an unexpected accumulation of creep damage or the initiation of damage (metallurgical or physical macro-cracks) at weldments. Hence, unstable temperature excursions as illustrated in Figure 19 should be minimised. Unstable operation can also result in severe (rapid) thermal transients occurring on plant, which can result in the initiation of fatigue cracks in weldments and for high temperature systems subsequent propagation via creep crack growth through wall [62] under steady load conditions.

Figure 20 shows a typical stub header, with three rows of boiler tubes; Figure 21(a) shows the design of a large steam header, which is a significant class of high temperature thick-sectioned component installed in a boiler. These components are subject to very similar outage inspections and on-line CET assessments as described for main steam pipes, however, these are considered to be more complex to assess due to the numerous penetrations in the header shell and difference in stiffness between the relatively rigid header shell and the thin interconnecting boiler tubes. Steam headers ensure proper distribution of steam across the boiler space, with the boiler tubes providing the heat transfer surface within the furnace of a conventional fossil-fired boiler. There are many different designs of steam header (material and geometry) within a typical conventional fossil-fired boiler. With respect to the use of small specimen testing the critical areas on the header are usually the inter-ligament positions between the numerous header to boiler tube connections. The photograph in Figure 21(b) shows the limited access available associated at the inter-ligament positions on this particular design for material extraction. For this design the approach would be to take a reference small specimen material sample from the adjacent and accessible header shell. A computational model of the header, using on-line temperature and pressure measurements to determine the theoretical residual life at the inter-ligament

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**Figure 19.** Typical steam temperature trace for two boiler outlet steam legs (A1 and B1).
Holistic condition assessment

The main objective of the station is to maximise plant availability and profitability, whilst maintaining safety. In order to achieve this objective the station must be able to understand, with good certainty, the remaining life of the assets at any time during the operation of the asset so that it can cost-effectively plan future inspections, refurbishments and replacements as required.

This requirement to understand with certainty the remaining life becomes ever more acute in commercial electricity generation where the profitability may be marginal, whether caused by government or environmental policy, market prices, taxation or other factors. At the time of writing this paper these factors are all significantly influencing the profitability of large conventional fossil-fired stations in the UK. From a technical perspective, the current approach to define a ‘holistic’ view of the condition of the generating assets is achieved by the assimilation and deductive assessment of information gleaned from the activities described in the sections ‘Off-load: outage works’ and ‘On-load: use of operational data’. The process is strongly dependent on the experience of the assessment engineers, who ideally will also have conducted similar investigations on other generating plant (likely of different age and condition).

Hence, the current approach is considered to be ‘inspection based’ and usually results in an incremental increase to future inspection sample size to contain a perceived emerging threat. The current approach is captured in Figure 14.

However, the current ‘holistic’ condition assessment process does not:

- Provide a predictive life assessment beyond the next major statutory outage, which in the UK occurs every 4 years,
- Actively integrate the various disparate data sets obtained from the plant outage or on-load monitoring.

Figure 14 seeks to illustrate two significant missing activities, namely (1) miniature specimen testing and (2) on-load condition assessment, which could be exploited to embed a more predictive life assessment approach and thereby satisfy the main objectives of the plant owner outlined at the beginning of this section.

The following case study illustrates how creep life assessments and decisions are currently achieved.
Case study: ageing main steam pipework

The data presented in this case study is based on conventional plant operation and focused on information and techniques currently used to assess the remaining creep life and hence decide on replacement.

The through life integrity of main steam CMV butt welded pipework systems has been dominated by the condition of the weldments, which have typically been addressed by means of periodic inspection, weld repair or pipe spool replacement. Most of the integrity issues associated with the weldments have manifested as circumferentially distributed creep cavitation or subsequent circumferential cracking. This damage is affected by pipework system loads and it is not uncommon to find the observed weld damage biased (creep cavitation or depth of cracking) around the circumference of the pipe weld. Invariably at the latter stages of a station's life the location and condition of all the major welds has been established and procedures are in place to implement any needed repair and replacement activities.

However, the failure of parent material is more likely to occur due to the acting pipe hoop stress, which can potentially initiate longitudinal cracking. It is very difficult to comprehensively identify those

![Figure 21. 6th stage superheater outlet header (a) schematic component and (b) replacement component.](image)
parent material regions close to creep expiry, noting the large volume of parent material in typical steam pipe systems. As the pipe system enters the later stages of life, conducting piecemeal butt weld replacement by the insertion of new pipe spools becomes more difficult due to the aged condition of the cut faces of the original pipe section, which is typically assessed by on-site surface replication and hardness testing. This ‘test’ of the parent material condition, when conducting pipe spool replacements, is often used as an opportunistic indicator of parent material condition, due to the opportunity to undertake some metallurgical examination through thickness.

Firstly, some background related specifically to the case study pipework example. During the 2005 outage on a unit on Station ‘A’, Figure 2(Unit operating history): Data blocks of more or less equal spread are taken over installed stellite grade 6 creep pips, as reference measurement locations, on the outer diameter. For the case of the unit on Station ‘A’ the pipework creep pip locations were towards the boiler stop valve at the 160 ft level in the boiler, as well as at the 100 and 60 ft levels. Various diametral strain measurements had been taken over installed creep pips during successive outages dating back to 1993 (unit operation at 161 khr and 321 starts) and including the 2009 outage. Table 4 shows the pipe diametral measurements taken at the 160 ft level on legs B1 and B2 between 1993 and 2005 for comparison. Four diametral measurements are taken across the eight installed creep pips around the pipe circumference.

The pipe diametral measurements show a generally steady increase in pipe outside diameter, with only a small number of measurement anomalies evident. Hence, the average strain rate over the period 1993–2005 (60,000 h) is $\sim 4 \times 10^{-8}$ h$^{-1}$, which equates to a minimum operational creep life of $\sim 300,000$ h. The strain rate is determined by evaluating the diametral strain between periods and correcting for any micrometre zero (offset) errors recorded. Pipe diametral measurements can sometimes be taken directly across the pipe outer diameter, if this is the case additional corrections would be necessary.
be required to account for oxide film growth over the time period between successive measurements. The subsequent site diametral measurements are assessed using conservative residual life formulae, which are derived from strain measurements taken from a series of internally pressurized creep rupture tests undertaken by the UK’s former central electricity generating board.

When comparing the CET and diametral data for legs B1 and B2; leg B1 shows a lower average strain rate, but a higher CET trend when compared with leg B2. It might have been expected that the higher CET trend on leg B1 over the extended period of measurements would have led to a higher diametral strain rate. This shows the current difficulty interpreting such measurement data in isolation and the reason why other more invasive methods, such as surface replication, is used to assess material condition.

During the 2009 outage the original CMV straight pipe section, identified as SM14, was removed from leg B1 for further laboratory examination; based on observed ‘High Orientated’ creep replica results. The adjacent pipe section immediately upstream from this removed section was left in service, with only a ‘very isolated’ replica assessment level assigned to the parent material.

**Post-service laboratory examination**

Both surface creep cavity and through section creep cavity mapping was carried out to industry procedures described in GENSIP guidance [63]. GENSIP refers to the UK ‘Generators Safety and Integrity Programme’, which is a member self-funded utility collaboration tasked with ensuring best practice is shared across the industry. The creep cavity damage levels indicated are classified in accordance with the definitions in Table 5. These classifications are provided by the technical service provider and enable them to compare observed creep damage and hence recommend a suitable course of action. The surface creep cavity mapping was taken at various axial and circumferential positions on the examined specimen (SM14 from leg B1), and is illustrated in Table 6.

With reference to the pictorial representation and definitions in Figure 13, the technical service provider classification in Table 5 is more generally interpreted as follows: isolated (level 2–3), aligned (level 8–9), micro-cracking (level 10). In addition, Figure 17 shows a photomicrograph from a section of retired CMV pipework, with a creep cavity count of 842 cavities/mm², in this case the classification would be judged at level 5–6 mid-to-high orientated. This exhibits quite a high creep cavity count per unit area and would be expected to progress to grouped and aligned in the short term if left in service.

The German VGB guideline [64] provides a revision of the Neubauer–Wedel creep cavity classification [65] and is reproduced in Table 7.

ECCC recommendations [66] on residual life and microstructure references investigations undertaken to correlate the VGB damage classification [64] against residual life for low alloy steels in the heat-affected zone of a weld. In this particular investigation VGB damage level 3 correlates to an expended life fraction of 0.691.

With reference to the ex-service SM14 straight specimen surface replication (Table 6); three angular positions (135, 225 and 315 degrees) at distance 1500 mm along the pipe were selected for through section creep void mapping. Table 8 shows an example for the 315° position. Each of the through section samples was carefully aligned with the corresponding surface replica positions.

A series of replicas were taken at through section depth increments of approximately every 4 mm until the bore was reached. At each ‘depth’ position surface

**Table 4. Diametral measurements, main steam legs B1 and B2.**

| Leg | Boiler level | Axis | 1993 (161,643 h) | 1997 (187,116 h) | 1999 (196,583 h) | 2001 (203,010 h) | 2005 (221,799 h) |
|-----|--------------|------|-----------------|-----------------|-----------------|-----------------|-----------------|
| B1  | 160 ft       | N–S  | 364.31          | 364.62          | 364.77          | 364.82          | 364.98          |
|     |              | E–W  | 364.03          | 364.46          | 364.64          | 364.69          | 365.03          |
|     |              | NE–SW| 364.44          | 365.79          | 365.97          | 365.02          | 365.27          |
|     |              | SE–NW| 365.23          | 365.61          | 365.79          | 365.81          | 366.11          |
|     |              | Average| 364.50          | 364.87          | 365.04          | 365.09          | 365.35          |
| B2  | 160 ft       | N–S  | 368.27          | 368.58          | 368.71          | 368.73          | 368.89          |
|     |              | E–W  | 366.04          | 366.24          | 366.27          | 366.64          | 366.83          |
|     |              | NE–SW| 369.02          | 367.64          | 367.69          | 367.78          | 368.77          |
|     |              | SE–NW| 368.07          | 368.38          | 368.53          | 368.50          | 368.77          |
|     |              | Average| 367.26          | 367.75          | 367.78          | 367.80          | 368.28          |

**Table 5. Creep cavity damage level (technical service provider classification).**

| Level | Description | Abbreviation |
|-------|-------------|--------------|
| 0     | Clear       | C            |
| 1     | Isolated    | I            |
| 2     | Isolated/low orientated | I/LO         |
| 3     | Low orientated | LO          |
| 4     | Low orientated/mid orientated | LO/MO      |
| 5     | Mid orientated | MO          |
| 6     | High orientated | HO          |
| 7     | High orientated/grouped | HO/G        |
| 8     | Grouped     | G            |
| 9     | Aligned     | A            |
| 10    | Micro-cracking | MC        |
| 11    | Cracking    | Crack        |
replicas were taken horizontally across the width of the extracted through wall specimen, resulting in a sample of approximately 15 per 'depth' position. These replicas were commenced at a distance of 2 mm from the cut face to avoid any damage from specimen preparation. The results show a trend of reducing cavity count through the section, peaking at the outer surface position. It is possible to further summarise and compare the through wall cavity count distributions in Table 8 as follows, based on the classifications in Table 5 (technical service provider) and Table 7 (VGB):

- Outer 10% of the wall section
- Intermediate 60% of the wall section
- Inner 30% of the wall section

This illustrates the somewhat subjective nature of the cavity count classifications and the importance, of where possible, having a clear understanding of the origin of the cavity count classification used during an in-service inspection and the subsequent impact on residual life.

### Table 6. Creep cavity surface damage levels; CMV straight section SM14, leg B (technical service provider classification).

| Angle (°) | 0.5 | 0.75 | 0.8 | 0.85 | 0.9 | 0.95 | 1 | 1.4 | 1.5 | 1.6 | 2 |
|-----------|-----|-----|-----|-----|-----|-----|---|----|----|----|---|
| 0°        | 1   | 2   | 3   | 4   | 3   | 3   | 3 | 1  | 1  | 1  | 1 |
| 45°       | 3   | 3   | 3   | 3   | 3   | 3   | 3 | 1  | 1  | 1  | 1 |
| 90°       | 6   | 3   | 3   | 3   | 3   | 3   | 3 | 1  | 1  | 1  | 1 |
| 135°      | 3   | 3   | 3   | 3   | 3   | 3   | 3 | 1  | 1  | 1  | 1 |
| 180°      | 3   | 3   | 3   | 3   | 3   | 3   | 3 | 1  | 1  | 1  | 1 |
| 225°      | 3   | 3   | 3   | 3   | 3   | 3   | 3 | 1  | 1  | 1  | 1 |
| 270°      | 3   | 3   | 3   | 3   | 3   | 3   | 3 | 1  | 1  | 1  | 1 |
| 315°      | 3   | 3   | 3   | 3   | 3   | 3   | 3 | 1  | 1  | 1  | 1 |

### Table 7. VGB guideline classification [64].

| Assessment class | Structural and damage conditions |
|------------------|----------------------------------|
| 0                | As received, without thermal service load |
| 1                | Creep exposed, without cavities |
| 2a               | Advanced creep exposure, isolated cavities |
| 2b               | More advanced creep exposure, numerous cavities without preferred orientation |
| 3a               | Creep damage, numerous orientated cavities |
| 3b               | Advanced creep damage, chains of cavities and, or grain boundary separations |
| 4                | Advanced creep damage, micro-cracks |
| 5                | Large creep damage, macro-cracks |

### Table 8. Through section creep cavity count distribution (1500 mm and Circ/315° position) (technical service provider classification).

| % Through wall (from outside surface) | Cavity count (cavities/mm²) | Category | Classification number |
|--------------------------------------|-----------------------------|----------|-----------------------|
| 0.00                                 | G                           | 8        |
| 9.23                                 | 115                         | LO 5     |
| 18.46                                | 75                          | LO 3     |
| 27.69                                | 50                          | LO 3     |
| 36.92                                | 60                          | LO 3     |
| 46.15                                | 55                          | LO 3     |
| 55.38                                | 45                          | LO 3     |
| 64.62                                | 25                          | I 1      |
| 73.85                                | 13                          | I 1      |
| 83.08                                | 10                          | I 1      |
| 100.00                               | 0                           | C 0      |

**Comments**

The following points are evident considering the site inspection history and subsequent examination of the ex-service life expired CMV straight pipe section SM14:

- Leg B1 shows a lower average strain rate based on diametral measurements compared to leg B2, but operates at a higher temperature (CET),
- There are significant operational temperature differences between the main steam legs exiting a 500 MW conventional boiler,
- Through section creep cavity mapping on straight pipe section SM14 (Table 8) shows a wide range of damage levels, peaking at the outer surface, which infers a significant residual life for the bulk of the parent material.

These results emphasise why the current inspection and sentencing approach requires expert deduction and elicitation of various data sets in order to provide advice on future inspection plans, monitoring schemes and eventual repair and replacement options.

The case study illustrates some of the more subjective aspects of the current approach to life assessment of ageing components at high temperature. The importance of the experts view on the condition of the component under examination should not be underestimated, as well as the need for comparison against other similar components elsewhere (possibly older with respect to service duty) is evident. The case study shows that the current life assessment process would benefit from more synergistic use of the data routinely collected during an outage. In addition, life assessment would greatly benefit from the more proactive use of in-service monitoring data along with the use of more predictive models for assessing residual life, which would subsequently allow optimisation of future plant operation.

**The role and application of small specimen creep testing**

Small specimen creep testing techniques are currently applied for ranking the strength of power plant
components, in order to establish repair strategies and supporting life assessment. They are also used in nuclear applications and for fatigue life evaluation.

**Strength ranking**

Power plant materials age during high temperature service and periodic structural integrity assessments are needed to quantify their permissible service life. Implementing an inspection priority for welds that are subject to in-service creep damage and fatigue cracking is standard practice, with suitable inspection and repair methods being readily available to the utility.

However, identifying a suitable and cost-effective inspection priority for ageing parent material is of concern due to the extensive amount of material that may be affected, and the difficulty in identifying the optimum locations and inspection sampling regime required. Understanding system or component specific creep degradation rates will enable more quantitative life predictions to be made that truly reflect the ageing of the material (weld or parent) operating under service loads and ideally should enable timely changes to operation and hence optimise serviceable life. Figure 14 emphasises the importance of the need for timely feedback on factors affecting condition of the assets to the plant operator.

The use of small specimen testing is intended to provide information on component strength ranking and the rate of creep life consumption to improve targeting of subsequent outage inspections and operational improvements, resulting in a reduction in the rate of damage accumulation. If these methods are implemented on parent materials, as recommended in this paper, the expectation is that there will also be a commensurate reduction in the creep damage accumulation rate at welds. The greater use of on-line monitoring, highlighted in Figure 14, is an important complement to the use of small specimen testing.

The use of small specimen creep testing provides an alternative technique that has merit when compared to conventional creep testing, due to the less invasive procedures, which do not require a significant amount of material to be removed from in-service components and subsequent weld repair [67].

**Decisions on inspection, replacement and repair strategy**

In the open literature, many examples of plant component strength ranking have been considered in case studies [13–15]. In the 1990s, RWE npower carried out impression creep and small punch tests on scoop samples from two Grade 91 headers which were considered close to premature Type IV weld failures. As a reference material, a weak Grade 91 bar section was creep tested by using both small specimen and standard testing methods. By plotting the impression creep strain rates obtained from the headers samples against the strain rate of the reference material, it was found that the creep strength was similar for both materials, as shown in Figure 22. In the same plot were also reported the strain rates for a prematurely failed endplate and two other samples taken from plant items with no known problems. Cross-weld specimens were also creep tested from the reference material, specifically welded, in order to acquire Type IV data. The test results led to an early inspection of the headers, one of which was found to be widely cracked, while the other header cracked a few years later. Hence, deployment of the non-conventional small specimen creep testing methods avoided costly failure in service and associated unplanned outage time and allowed life extension of the headers [14,67].

Other tests were carried out by RWE npower by sampling main steam pipework components with the intention to identify the damage at an early stage, the results of which are plotted in Figure 23 that shows impression creep strength ranking for CMV. The ISO lower bound line intersects a sample which parallel conventional uniaxial testing has shown possesses a strength equivalent to the lower bound (mean-20%) ISO value for this material in the as-received condition [15,67]. By testing a significant number of ex-service CMV samples an empirical correction factor was found as well, in order to compare components of very different plant ages. The histogram in Figure 24, shows the CMV data corrected for operating hours at the time of sampling to reflect strength at the start of life, is helpful in placing any other CMV sample within the creep strength scatter band [67]. Although small specimen testing techniques have been proved to be extremely useful in the creep strength ranking, their standardisation is still required and the effects of the
scoop sampling on the creep response of components still needs to be investigated [67].

Small specimen creep data correlated with hardness data for life assessment

The research into the correlation between room temperature hardness data and time temperature parameters has been ongoing since 1943 [68,69], but no physical link nor any explicit relationship between them has been found. Many researchers have related creep life evaluation and hardness data through the Larson–Miller parameter, but this approach only allows a first assessment of the damage if the initial hardness, at a time of 0 h of creep, is known [70–77].

Unfortunately, it is very rare for a station to have record of this initial hardness data and as a consequence, the method is suitable only to provide an initial idea of the component damage. Currently, hardness data continues to be routinely collected during plant outages because of the simplicity of the test method and the potential to provide an indication of the condition of the material in contrast to the evaluation of the minimum creep strain rate, but more research is needed to evaluate the benefits.

Figure 26 provides an illustration of the correlation between hardness (HV) and creep replica assessment level obtained during an outage on 200,000 h old CMV parent material, and is taken from two main steam lines (legs A1 and A2) exiting the boiler on a conventional fossil-fired unit operating at a design temperature of 568°C and pressure of 170 bar. This sample comprises 79 assessment locations from leg A1 and 113 from leg A2, with a mean hardness of 123 on leg A1 and 126 on leg A2, which compares to a start of life mean hardness of 170 Hv. In this data sample, the creep replica is assessed at seven levels as defined in Table 9; these assessment level definitions are from the same source as those shown in Table 5. The data has been obtained from a range of locations on the main steam pipe system and from a mixture of pipe bends and straight sections, but predominantly straight sections, hence these locations will be exposed to a range of in-service stress levels and temperature histories, Figure 19.

Inspection of hardness data at creep replica assessment levels 2, 3 and 4 reveals very similar mean hardness values of between 123 and 125 for these datasets. The section ‘Off-load: outage works’ outlined that typical hardness measurement accuracy of ~5% can be expected but with an increasing error on softer material. Hence, it is evident from this sample of data collected from ageing CMV parent material that there is no definitive correlation between the surface replica assessment levels and hardness data. The data presented for leg A1 in Figure 26(a) could be interpreted as indicating a potential reduction in hardness with increasing creep cavity count, however this is not evident in the data presented for leg A2 in Figure 26(b).
Applications for irradiated materials

Understanding the effects of neutron irradiation on the performance of materials used in the construction of nuclear power stations is a challenge when considering the requirements for life extension of existing reactor designs and future advanced fusion reactor technologies. The use of small specimen testing to characterise materials behaviour has many advantages in this respect due to the small volumes of irradiated material required. The ASTM symposium [78] in 1983 provided an initial milestone for the development of these methods for irradiated specimens. This highlighted some of the important considerations that have influenced the development of the testing methods, such as limited space in hot test cells, the effect of neutron fluence gradients across the reactor components, personnel dose levels in post-irradiation testing and the development of materials suitable for use in high energy (≈14 MeV) nuclear fusion reactors.

The following sections review the more prevalent uses of small specimen testing on irradiated materials and related to fracture strength, material property evaluation, behaviour and condition monitoring of in-service reactors.

In-service condition monitoring

Currently the SP testing technique has gained an important role for monitoring nuclear power plant operation and critical areas, such as the heat affect zone of welds. In particular, the material state of all

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**Figure 25.** (a) Variations of minimum creep strain rates at 600°C and at a stress of 155 MPa, with room temperature hardness for Grade P91 steels (with different service histories) from Brett [12], and (b) variations of uniaxial rupture life, $t_f$, at 600°C and at a stress of 155 MPa, with room temperature hardness for Grade P91 steels (with different service histories), from Brett [12].

**Figure 26.** Main steam line parent CMV hardness vs. creep replica assessment level, at 200,000 h for (a) leg A1 and (b) leg A2.
Slovak reactor pressure vessels is monitored through SP testing (several thousand material samples) as part of the advanced surveillance specimen programmes, which aims to extend the reactor pressure vessels life in the WWER-440 pressurised light water reactors by at least 20 years [79,80], with typical operating conditions at 297°C and 123 bar [81]. The focus of this surveillance programme is to provide a through life assessment of the tensile strength and ductile–brittle transition temperature at various locations within the reactor, with material extracted using the Rolls-Royce SSamTM-2 device with comparison against reference material blocks. Sampling locations are defined with care so that there is no requirement for subsequent repair or monitoring.

Some of the small specimens have been irradiated in the Halden research reactor at a fluence of 4.02 × 10^{23} \text{n m}^{-2} [79], which showed an expected increase in the tensile and yield stress properties. Comparisons between the fracture appearance transition temperature values obtained from the SP tests and standard charpy tests provided good agreement between material in the initial state and the irradiated condition. This application of SP testing provides the Slovak regulatory authorities with contemporary information on the change in material properties due to in-service operation and irradiation levels.

This application of SP testing is similar to the use of impression creep testing applied to ageing conventional power plant materials subject to thermal creep by Brett et al. [12–15]. Importantly the examples provided by these investigators show practical examples of the techniques use to assess the condition of operating plant, driven by regulatory and safety requirements.

### Material properties

Hyde et al. [3] produced a comprehensive review of the use of miniature specimen testing for mechanical and creep material properties. This importantly concluded that viable test methods exist; however, there is no single specimen design that can cater for all data requirements. It is evident that commercial objectives have driven the development of some of these techniques, such as SP and impression creep and on specific materials of interest on operating plant, such as CMV and P91 steels on conventional stations.

Hyde’s [3] review provided a perspective on future requirements and emphasised the need for greater standardisation of experimental test methods, which is still the case as discussed in the section ‘Codes and standards for small specimen creep testing techniques’ in this current work.

Small specimen testing is perceived as a key approach for obtaining critical information on the mechanical properties, deformation and fracture behaviour of candidate materials in support of the ongoing design and development of fusion reactors. The challenges associated with the development of the international fusion materials irradiation facility (IFMIF) to test reactor materials at high fluxes of 14 MeV and temperatures in the range 250–550°C, is described by Knaster et al. [82]. This test facility is expected to be ready and available to use within 10 years from project approval and is constrained for test volumes of up to 500 cm³. A range of small specimens have been irradiated as part of the engineering validation and engineering design activities phase, with subsequent tests related to tensile data, fracture toughness, creep and fatigue crack growth, thereby demonstrating the practical set-up of the irradiation capsules. However, one of the major challenges cited by Knaster et al. to overcome is ensuring adequate validation of the derived irradiated properties to the regulatory bodies. This again emphasises the need for accepted standards and codes of practice for all the deployed small specimen test methods and in readiness for the high flux IFMIF facility once constructed. The further validation of these test methods on ageing materials on operational nuclear or conventional stations will certainly support this objective.

Lucas et al. [83] provides some examples of the developments required related to improve understanding of the fracture, fatigue and deformation behaviour. Fracture toughness tests on a range of specimen sizes on candidate reduced activation ferritic-martensitic EUROFER97 steel are described, with the use of correction factors derived with finite element simulations of crack tip stress fields to address specimen size effects. These tests show the requirement for close scrutiny of the mechanics of the testing process coupled to the observed material behaviour. Knaster et al. [82] emphasised the ultimate requirement for validation of material properties derived from small specimen tests in support of the design of fusion reactors. The challenge is to establish material behaviour models that use the measured parameters and observed behaviour of the materials tested; a mechanistic modelling approach. These material behaviour models must be demonstrably scalable to account for the size of the reactor components and expected in-service loading due to neutron fluence gradients, thermal gradients and environmental factors such as the presence of helium produced by the fusion process, which will
influence the fracture behaviour [83]. Examples of the potential to model SP tests with a finite element simulation is provided, with respect to the evaluation of the deformation behaviour obtained in conjunction with hardness testing, although the potential effects of thermal, environmental ageing or stress state effects are not explicitly captured.

Hardness data is routinely acquired during periodic inspections of ageing conventional plant and is usually interpreted in conjunction with metallurgical evaluation by creep replicas. There are some material models in use on conventional plant that couple surface hardness data with the Von Mises stress to evaluate time to creep rupture. These models typically are used to supplement safety case assessments on operating plant and hence are necessarily used in conjunction with several other methods described in the section ‘Industry practice for condition monitoring and life management’. Nonetheless, it is evident that such hardness models (possibly in conjunction with other measured parameters) may be able to be further developed to a position where a practical forward-looking lifting model can be routinely implemented on operational plant. Various options for modifying Liu and Murakami’s [47] constitutive creep models are currently being investigated by the authors of this paper for CMV and P91 steels that account for the change in surface hardness and the stress state. The hardness data used in this model development is based on experimental tests and examination of periodic hardness data collected over several inspection campaigns on operational plant.

The assessment framework in Figure 14 illustrates how small specimen testing should be used in conjunction with data acquired from existing inspection procedures along with material or component behaviour models that utilise in-service operational data. The authors of this paper and co-workers in the EPRSC sponsored Flex-E-Plant consortium are actively developing these integrated models for conventional plant applications and on materials such as P91 steel, which is similar in composition to materials being evaluated for fusion reactor applications.

Reduced activation ferritic-martensitic steels such as F82H are candidates for use in fusion reactors [84] and have been developed from modified 9Cr-1Mo steels (by replacing Mo and Nb with W and Ta), which are used extensively in modern conventional power stations. In 2014, Bruchhausen et al. [85] assessed the behaviour of ferritic-martensitic oxide dispersion steels by use of SP testing at 650°C complemented by uniaxial creep tests. Importantly the SP tests were conducted in accordance with the current CEN SPCT code of practice [5]. The SP failed specimens were extracted from a material block in the transverse and longitudinal directions and the micrographs of the failed specimens exhibited very different crack patterns, which are indicative of the anisotropic alloy microstructure.

The evident strong anisotropy is considered due to scatter in the steady-state creep response and influenced by the bi-axial stress field active in the SP test and variability in the alloy’s microstructure, which was also evident from other uniaxial creep tests on conventional specimens. These results illustrate again the requirement for comprehensive modelling-simulation studies of the SP and other small specimen tests in order to inform the relevant code of practice. It is important to adapt this integrated test-modelling approach to the situation of in-service components and the inevitable regulatory requirement to demonstrate fitness-for-service in a production reactor. The requirement for integrated small specimen experimental designs to provide fundamental material behaviour models is reiterated in Odette et al.’s review on innovations in small specimen testing [86].

One of the challenges of demonstrating the validity of selected materials used in a production fusion reactor is to account for the effects of the neutron fluence and thermal gradients in the structural components. Gilbert et al. [87] have reviewed some of the factors influencing material behaviour such as neutron flux gradients, component size and helium production on the design of a proposed demonstration fusion power plant. The study shows an expected spatial variation of the neutron flux across various structural components, which is also evident in other reactor designs associated with naval pressurised water reactors. For these naval reactor designs the through life effects on material behaviour due to the spatial variation in irradiation creep and swelling is accounted for by measuring the deformation of representative fuel coupons irradiated in research reactors, supplemented by measurements of end of life fuel deformation of spent reactor fuel modules. These experiences with the effects of spatial variation of neutron flux in naval reactors, coupled with the very high energy levels expected in production fusion reactors only further emphasise the need for standardised small specimen test codes of practice.

On conventional power plant an analogy can be made with the change to flexible operation in the 1990s (see Figure 2(a) and the significant increase in annual unit starts). This resulted in large periodic thermal stress gradients acting across thick-sectioned components, resulting in critical integrity problems [62]. The older conventional stations are still suffering from the effects of this type of operation, which coupled with the long running hours has driven the development and field application of small specimen testing methods described in this paper.
Fracture

Understanding the long-term fracture behaviour is critical to ensure the integrity of irradiated structures. The SP testing technique has undeniable advantages due to the small irradiated specimen volume and availability of a recognised code of practice [5]. Material properties of the heat-affected zone of welds, and the DBTT can be determined by the use of the SP testing technique [79,88].

SP testing technique was first used by Baik et al. in 1983, who evaluated the DBTT of a Ni-Cr steel and established a linear relationship between small punch and standard Charpy V-Notch test results in terms of DBTT [89,90]. Mao and Kameda [91], by observing SP test data, found that neutron irradiation significantly increases the DBTT in Fe based alloys doped with Cu, while Wakai et al. proved that the production of helium can cause the shift of DBTT in F82H steels [92].

According to Kasada et al. [93], the master curve (MC) methodology, developed by the American Society for Testing and Materials [94], has been successfully used by employing small specimens in the assessment of the drop in fracture toughness caused by neutron irradiation. More recently, Martínez-Pañeda et al. have proposed a novel methodology which involves a notched small punch specimen for the evaluation of the fracture toughness [95]. In particular, they determined a linear relationship between the notch mouth opening displacement and the vertical displacement of the SP, and a critical value of the notch mouth opening displacement of the SP, that can be compared with the corresponding parameter in conventional fracture tests [95].

Other applications

There are a variety of other applications to note such as, screening of materials, assessment of hydrogen embrittlement, supporting fatigue studies and investigating very high temperature performance of materials such as single crystal alloys used in gas turbine applications. These are all derivatives of the methods discussed previously and are discussed briefly in this section.

One of the other aspects to note in this work is that many of these small specimen tests require the development of novel measurement techniques due to factors such as specimen size and geometry, requirements for hot cells in nuclear applications or for testing in combustion atmospheres for conventional plant applications. These may present requirements for the use of full-field optical based non-contact measurement systems such as digital image correlation, infra-red thermography, laser extensometry etc.

In 2013, Methew et al. [96] demonstrated the benefits of using the SP techniques to rapidly investigate the creep performance of 316LN stainless steel with different nitrogen content levels, using the technique as a means of differentiating the creep rupture performance between alloy heats. Although the SP technique provides the ability to undertake multiple tests quickly the study emphasised the potential for shortfalls due to the short duration of the tests, typically <1000 h and the inability to assess effects due to longer-term thermal ageing and environmental factors. This is a common problem associated with small specimen tests and emphasises the opinion proposed in this paper that the application of small specimen testing in a life assessment framework requires periodic sampling as the material ages in-service.

Hydrogen embrittlement of steels is a particular concern for materials employed in hydrogen-powered vehicles and offshore platforms, as well as in power plant components [97,98]. Furthermore, hydrogen can be added to materials during the manufacturing process [99]. Therefore, investigating the effects of hydrogen embrittlement is of great interest. One of the latest studies on this matter has been conducted by García et al. [100], who investigated the effects of hydrogen embrittlement on the tensile properties of three different CMV steels (parent material, welding, and heat-treated welding) through small punch tests. They found that the yield strength of the steels can be assessed by the SP test yield load and that the technique is able to evaluate the degradation of the material tensile properties due to the hydrogen environment.

Fatigue studies are crucial in many engineering fields and especially in the design of nuclear reactors because of the temperature and neutron flux cycles they are subjected to [101,102].

Hirose et al. [101] and Nogami et al. [102] for example describe the development of small-scale fatigue specimens, with a specimen gauge diameter of 1.25 mm for testing reduced activation ferritic-martensitic steels in nuclear applications. These cyclic load test present challenges for test machine alignment, load control and measurement of extension, especially for applications to irradiated specimens in a hot cell. Validation of these small-scale fatigue tests for full-size components is a challenge, due regard to the potential in-service load cycles (strain range and hold periods) and operating environment is required as well as the impact of thermal or environmental ageing that might be expected to occur in an operating reactor. It is envisaged that such small-scale tests will be invaluable as a means of assessing for example the performance not only of the base material but also the welding fabrication process and therefore reducing the overall time and cost to develop a material that is fit for purpose. Therefore, the development of new testing methods using small specimens is of great interest in current research [101–104].
Roebuck et al. [105] have developed a novel miniature specimen testing facility use for assessing the high temperature properties of Ni-base superalloys such as CMSX-4 used in the manufacture of gas turbine hot gas path components. This facility operates at temperatures above 1000°C, includes water-cooled grips and has been used to investigate flow stress dependence on strain and temperature, resistivity measurements, oxidation, pyrometry measurements and recrystallisation kinetics. The test facility also comprises an environmental chamber and is equipped to apply high heating and cooling rates and variable thermo-mechanical loads. Single crystal superalloys such as CMSX-4 are subject to very arduous operating conditions in an operational gas turbine engine and often manufactured in relatively thin sections, hence the need for miniature specimens and suitable test facilities to determine properties and characterise their behaviour.

**Plant assessment model adopting small specimen creep testing in a condition-based monitoring framework**

The section ‘Industry practice for condition monitoring and life management’ and Figure 14 illustrate the current condition assessment process, which has reliably been used in the UK for many years. This approach results in an increasing inspection and assessment scope as the plant ages, until a point at which the economic life is reached and replacement is advised. The development of this staged approach to life management has been heavily influenced by the periodic inspection, condition assessment and remediation of defects and damage in welds, with the assessment of the condition of ‘parent’ material following later in life and primarily influenced by the utilities desire to manage their requirements for large capital spend on plant refurbishment. As an example, for high temperature CMV main steam pipes on conventional plant this staged approach is typically applied as follows:

- **Stage 1:** includes first weld inspections after 50 khr of operation;
- **Stage 2:** first parent material checks (bends) initiated at circa 130 khr;
- **Stage 3:** initiation of planned inspection of straight pipe sections at circa 190 khr, with first pass of bend inspections completed;
- **Stage 4:** economic replacement scheduled at around 260 khr.

The case study presented in the section ‘Case study: ageing main steam pipework’ shows that considerable effort from inspection bodies is required throughout the life of the plant to understand the rate at which the material deteriorates until component replacement is required.

This has shown the uncertainty that the plant owner is faced with, due to the lack of consistency in inspection data trends. In broad terms, the generating plant operates on a 3- to 4-year ahead operating ticket, whereas ideally the plant operator would prefer a longer-term 8–10 year forward prediction of the rate of life consumption to facilitate economic decisions related to capital investment and optimisation of periodic statutory inspections. In addition, a more predictive assessment of life consumption would provide the plant operator with the opportunity to optimise operation such that the economic lifetime of the assets can be safely and cost-effectively extended. The optimisation of life consumption (to minimise outage inspection scope and prolong asset life) is worth multi-million pounds over the life of a station.

Figure 14 illustrates the current IBA procedures, with the inclusion of small specimen testing and on-load condition assessment highlighted as areas that warrant further development and implementation. The development of on-load condition assessment methods is not the main subject of this particular paper; however, the authors are involved in other complementary research to develop these approaches for plant based applications [106]. In an example of this approach for the assessment of main steam bends [107,108], routine data assimilated during current plant monitoring and outage inspections is used seamlessly in computational models to rapidly assess current condition and predict remaining life. This methodology is being further explored and developed as practical ‘tools’ within the UK Flex-E-Plant research consortium related to the analysis of main steam pipe systems on conventional plant.

Small specimen creep testing provides the opportunity to remove some of the uncertainty associated with the site outage inspection and assessment processes currently used, illustrated by the comparison between surface hardness and creep replica assessments acquired from outage inspections in Figure 26. Based on the current maturity level of the testing techniques outlined in the section ‘The role and application of small specimen creep testing’, it is proposed that the most practical approach to consider at the moment is the further development and deployment of the impression creep method, particularly since it has been exploited on ageing plant by Brett [13–15,109] for purposes of component risk ranking and condition assessment. The extensive programme of sampling undertaken on Slovakian reactors [79,80,110] is also noteworthy and is another example of the proactive and systematic use of these small specimen testing techniques. It is worth noting that other methods such as the two-bar creep test specimen may provide additional benefits due to the potential to model the
tertiary phase of creep, however further work on miniaturisation is likely to be required.

The key point to note is that more precise information is required on the in-service rate of material ageing and any subsequent acceleration of the ageing rate that might indicate that repairs or replacements are required.

**Implementation of small specimen testing**

The intention is to provide more reliable and periodic measurements of material properties throughout the operating life of the asset. This approach can be applied to both conventional and nuclear generating assets and will allow the plant operator sufficient time to implement positive corrections to operation that maximise the useful life of the asset. Data obtained from these small specimen tests can be used to:

- Amend and update relevant pipeline system and component life prediction models,
- Advise plant operators on creep strain rates and changes in material behaviour, hence allow operating conditions to be optimised with respect to the plant owner’s requirements for economic asset life,
- Influence and optimise the inspection scope at subsequent statutory outages,
- Provide a more informed view on the loads acting on complex regions such as welds, complemented by expert review of outage findings from weld inspections and metallography, thereby improving the management of weld integrity,
- Enable some current non-productive site examination methods to be gradually phased out or improved.

In order to provide useful information to the plant operator, results from small specimen testing must be acquired at a suitable time in life to enable appropriate modifications to plant operation to be implemented.

Using the current CMV life management methodology summarised previously as a reference for current practice, the following modification to the current approach is proposed for high temperature pipework. This essentially provides an earlier baseline condition assessment from targeted sample locations, supplemented by interrogation of on-line monitoring data. Subsequent statutory inspections provide periodic updates on the condition of the in-service ageing materials. Importantly, this modified approach gives the operator more opportunity to optimise how they can effectively manage the plant. The proposed modified approach is as follows (weld inspections would start initially as per normal practice at 50 khr):

- **Stage 1:** Develop full pipeline model(s) of a lead system, which allows estimates of creep strain rate based on design values for material creep models, hanger survey data, plant temperature and pressure monitored data. Ideally, pipeline model(s) developed by ~75 khr and used to proactively support future outage inspection planning. This essentially provides the baseline or reference model(s) for the plant.
- **Stage 2:** Start to acquire small specimen samples from lead pipeline(s). Specimens should be obtained from straight pipe sections that are adjacent to bends proposed to be first inspected at ~100 khr and from positions that will not require subsequent repair or additional monitoring. Update pipeline model(s) accordingly and compare predictions against outage inspection findings. Review and update future periodic inspection plans (including weld inspection plans).
- **Stage 3:** Select additional targeted small specimen samples to further assess and optimise pipeline model(s), thereby supporting continued safe operation towards end of life. The selection of suitable locations for additional material sampling would be informed by assessment of previous inspection findings. Review and update periodic inspection plans.
- **Stage 4:** At an economic point, plan to implement replacements.

It is important to recognise that there is a cost to implement small specimen testing, however it is anticipated that this will be offset by cost reductions elsewhere, such as:

- Reduction in the use of diametral strain measurements,
- Optimisation of outage site creep replica and hardness sampling and analysis campaigns,
- Optimisation of outage weld inspections,

**Concluding remarks**

This paper has focussed on the application of small specimen testing methods with an emphasis on their place in a modified and practical life assessment framework that could be applied to both conventional and nuclear generating assets. Examples have been provided on current practice associated with invasive site inspections and material condition assessment towards the end of economic life on conventional plant pipework systems. A previous review [3] has described the use of small testing methods to satisfy specific material property and data requirements.

The exacting demands associated with the use of small specimen testing methods in nuclear plant applications strongly emphasises the importance of developing agreed codes of practice and standards. The successful development and validation of alloys under consideration for fusion reactors demands the
application of standardised small specimen test methods. Importantly, the experiences described in this paper on the successful application of both SP and impression creep techniques to support operational plant gives a clear indication of their potential use in the field.

There are of course still a number of challenges to overcome before their use can be more widespread to assist the plant operator. The case study example provided shows how the current methods for assessing the condition of materials via hardness and surface replica surveys have some scope for improvement, ideally towards a position where more mechanistic material behaviour models can be applied, which would be regularly and seamlessly updated with operational and inspection data. Information from the application of small specimen testing campaigns can support this objective, but only if applied in accordance with a timely and structured approach as described in this paper. The development of validated small specimen testing methods will also require complementary innovation of experimental measurement methods, facilities and data interpretation.

Developments to improve measurement methods applied in experimental tests may well result in useful applications on operating plant. The use of laser based measurement systems is now accepted and applied (for measuring component displacements) to assist plant investigations associated with premature failure of welds. High resolution and high temperature optical strain measurement systems have been taken out of the laboratory and engineered for site applications [55]. Features of these high temperature optical strain measurement systems have recently been used to assist the first site application of creep damage sensors [56]. There are also examples of the first trials of non-contact full-field strain measurement on high temperature plant using digital image correlation [60] and the site application of thermographic approaches for defect identification and residual stress measurement using infra-red camera systems [111].

The power industry is facing severe challenges as the economy transitions to a low carbon future. This puts much emphasis on conventional and nuclear AGR plant continuing to operate reliably, cost-effectively and with a focus on life extension.

This paper has presented the current practice for life management of high temperature and pressure systems and proposes that small specimen testing methods should ideally be used earlier in the plant lifecycle. The current inspection based approach for life management is unable to provide sufficiently rigorous future life predictions that allow the plant operator to efficiently optimise plant operation and reduce through life inspections costs.

It is recognised that developing rigorous predictive life assessment models is not trivial; however targeted use of small specimen testing methods described in this paper and within a new life assessment framework that also exploits the capabilities offered by modern computational techniques, provides an opportunity to achieve this objective. To support this aim there is a critical need to improve the exploitation of extensive plant data acquired during outages, along with online data routinely captured during operation.

These challenges are being addressed as part of the remit of the EPSRC funded Flex-E-Plant consortium and it should be acknowledged that some aspects of this challenge have been addressed in other recent research and plant trials; for example:

- Plant applications of impression creep testing for risk ranking components [35,38],
- The development of computational models for main steam pipe bends that use plant outage inspection data as model inputs to provide forward predictions of creep life consumption based on measured operational loads [42],
- Ongoing development and trials of creep damage sensors on operating plant [17].

Hence, it is the authors’ belief that the development and practical use of such predictive life assessment tools within the proposed new life assessment framework is now both cost-effective and achievable.

The ultimate aim is to develop ‘point of application’ material models that can seamlessly use in-service metallurgical, inspection and operational data and provide the station operator with a timely and predictive life assessment capability. These aims are applicable to both conventional and nuclear generating stations.

Moreover, the arduous operational duty experienced by conventional generating plant provides a useful source of both metallurgical and operational experience to assist the cost-effective life management of existing nuclear AGR plants and could support the approach to life management of materials used in next generation nuclear reactors.

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