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Impression creep testing for evaluation of grade 22 ex-service hot reheat piping seam weld

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Abstract: U.S. electric power production is significantly dependent on the operation of coal-fired steam generation units and a large majority of these units are reaching ages over 50+ years with concerns for operating component integrity and remaining life. This paper discusses a small sample testing technique (impression creep) that was used to estimate the remaining life of a hot reheat seam welded piping system that saw about 322,000 hours of operation at nominally 4170 kPa (605psig) and 538°C (1000°F) steam conditions. Two different life assessments using experimental impression creep data are discussed and findings compared to a previous preliminary study of the same piping system using operational data, reported measured piping thickness values (from UT measurements), and published creep rupture data. Impression creep tests were conducted in unaffected base metal, weld metal and the heat-affected zone. Impression creep rates of the various zones showed no creep mismatch. Minimal creep mismatch, proper design, fabrication and operation, combined with proper metallurgy have successfully demonstrated that even low-alloy seam welds can operate 300,000+ hours and still exhibit useful remaining life.

Keywords: Impression creep; seam weld; small sample testing; CrMo steels; remaining life assessment

1. Introduction

The world's first commercial supercritical coal fired power plant was commissioned in 1957 in Philo, Ohio. This engineering accomplishment resulted in a significant increase in thermal efficiency in power generation [1]. From the 1960's to 1980's, supercritical units were constructed throughout the world with steam conditions of 538 to 565°C (1000 to 1050°F) and >221 bar (3205 psig).

Today, U.S. electric power production remains significantly dependent on the operation of a number of these steam generation units, including coal-fired ones that are now exceeding 300,000 hours of operation. In 2017, about 30% of the United States electricity was generated from coal sources [2,3]. With many of these aging units continuing to operate, there is a need for improved component integrity and life management strategies, including review of prior assessments in high energy piping and other critical components. The general movement to cleaner energy sources has further complicated life management strategies as these aging assets are now expected to cycle and operate outside their intended baseload operation.

Typically, the life management of high energy piping systems is inspection-based using a variety of non-destructive evaluation (NDE) techniques, such as phased array ultrasonics during planned outages, but this information does not, on its own, give a measure of remaining useful life. The accumulation of damage by creep remains a key area of concern in seam-welded high energy piping [4]. The factors affecting performance of a structure can be broadly grouped into design, operation, fabrication and metallurgy. Creep is a time-dependent mechanism that is affected by temperature, global stresses due to pressure and system loads, local stresses affected by geometry (weld cross section, out-of-roundness including peaking) and the aggravating effect of local mismatch in creep resistance between weldment zones. Metallurgical risk factors, including weld metal chemistry and cleanliness, and fabrication related issues further exasperate creep (e.g., [5-8]).

In the U.S., low alloy chromium molybdenum (CrMo) steels, Grades 11 (1.25Cr-0.5Mo) and 22 (2.25Cr-1Mo), have been the commonly used materials for main steam (MS) and hot-reheat (HRH) piping systems of older generating units. These materials have been used for boiler piping as HRH long seam-welded piping fabricated to ASTM A155: Electric-Fusion-Welded Steel Pipe for High-Temperature Service, beginning in 1952, and replaced circa 1975 with the use of ASTM A691: Specification for Carbon and Alloy Steel Pipe, Electric-Fusion-Welded for High-Pressure Service at High Temperatures. While the A691 standard specifically identifies three optional heat treatments for the welds - subcritical post-weld heat treatment (temperature below the lower critical Ac1), normalizing, and normalize + temper (N&T), the older A155 standard only specified a minimum heat treat temperature of 593°C (1100°F), i.e., normalizing or N&T treatments were not a specific part of the standard, although not prohibited. The extent of weld metal-adjacent base metal or heat-affected zone mismatch in creep rate that affects creep life can, at least for an extended period immediately following installation, be significantly large in case of subcritically heat treated welds, far less so with N&T'd welds. In all cases of Grades 11 and 22, long seam-welded piping is fabricated from plate product specified by ASTM A387: Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum.

Impression creep testing has been used as a qualitative assessment tool in the evaluation of CrMoV and Grade 91 piping systems (e.g., [9,10]). In this work, the usefulness of impression creep testing was assessed in the evaluation of a seam-welded Grade 22 hot reheat piping system. The principle focus of the work was to compare a global assessment based on steam conditions, service life, and component dimensions with targeted metallurgical studies and findings from impression creep testing performed on material removed from service. The impact on creep of mismatch between the base metal and weld metal including the analysis of the measured impression creep-rates will be discussed.

2. Materials and Methods

The impression creep test has been used for several decades and was first applied to the power industry in the UK in 1997. With the increasing age of coal-fired power plants, major components, such as the piping systems, need continuous evaluation to help ensure reliable, continued service. The results of uniaxial creep rupture tests are typically used to characterize material, predict long-term performance in high-temperature service, and develop rules for the use of these materials in design. This conventional approach to testing and performance evaluation is unfortunately not easily applied to operating equipment since the significant amount of material required for such testing is, at best, difficult to extract from the equipment. Additionally, rupture testing times limit the ability to derive useful information from such testing within a practical time frame. The impression creep test method uses a relatively small volume of material that may be obtained in a 'non-invasive' manner, such as by surface scoop sampling of the component. Figure 1 shows the amount of material that is typically removed for machining both uni-axial and impression creep test specimens. Since the test uses a strain rate based approach to estimate life, test durations can be short enough to produce useful information in a timely manner.

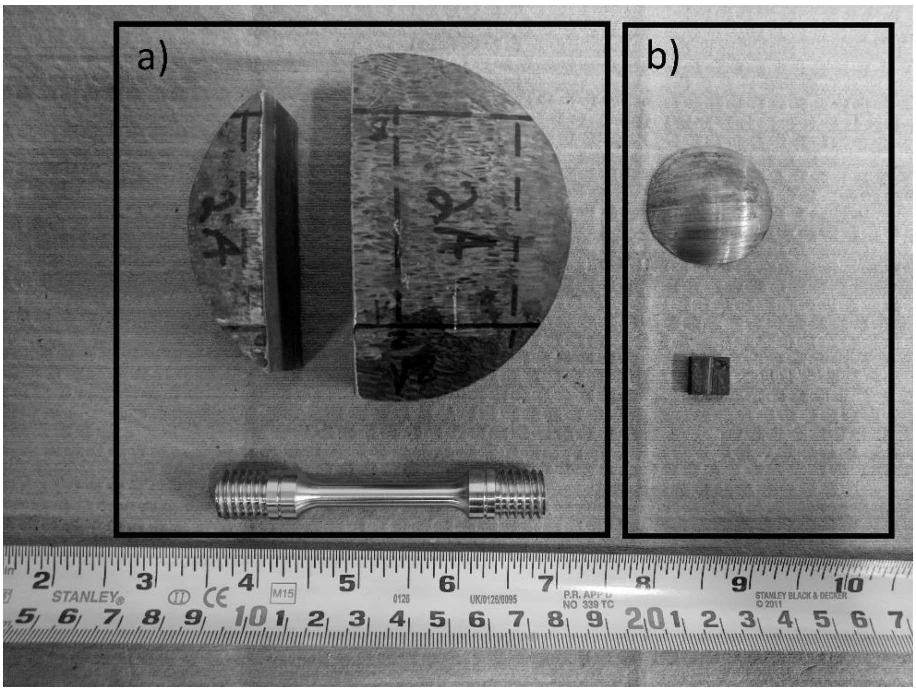

Figure 1. The uni-axial creep specimen is machined from a 'plug' sample (a) and the impression creep specimen is machined for a 'scoop' sample (b).

The material of interest in this study was removed from a Grade 22 HRH long seam-welded piping system of a coal-fired supercritical unit that experienced about 322,000 hours of operation since its original installation in 1969. The reported nominal HRH steam conditions were 4170 kPa (605psig) and 538°C (1000°F). In 1986 the utility reviewed the future prospective for the unit and elected to implement a condition assessment and replacement program with an objective to operate the plant through the year 2010 [11]. Many major components were evaluated and either repaired, replaced or determined to be in acceptable condition for continued operation. The HRH long seam-welded piping was inspected by visual examination, surface wet fluorescent magnetic particle testing, surface replication, ultrasonic testing (UT) for wall thickness, and volumetric inspection for damage by straight beam and shear wave UT. The inspections found no indications of damage or near-term failure risk. Lifetime calculations made at the time based on measurements of pipe dimensions and assumed creep rupture strength also did not indicate a significant concern for near-term failure.

In 2015, an EPRI-led review of the HRH piping system highlighted a need to adopt a risk-based approach to future prioritization of locations for NDE because the system had not been routinely and fully evaluated since the mid-1980s and since development of advanced UT methods suited for long seam welds. The EPRI assessment based on reported operating conditions, the results of prior inspections, and the plant-reported patterns of personnel traffic (for qualitatively considering exposure to personnel) provided a list of locations with a ranking of prioritization for inspection and testing [12]. Following the assessment, the utility removed a set of plug samples from several seam weld locations for laboratory testing and evaluation. These plug samples serve as the source of evaluated material for research that is summarized in this manuscript.

Six plug samples, as shown in Figure 1 a), were extracted by the plant at several straight segment long seam-weld locations in the HRH piping system at varying EPRI-estimated priority rank (risk) levels. The plug samples were ~80 mm (3.1 inch) in diameter with the seam weld nominally in the center of the sample. A portion of each sample was removed and polished using standard metallographic techniques. Hardness testing (0.5 kgf, 0.50mm spacing in weld metal, 0.25mm spacing in base metal) and assessment for the presence of creep damage was conducted on the as-polished samples using an automated Vickers microhardness tester (LECO AMH43) and a confocal laser microscope (Keyence VK-X105), respectively. Etching of the samples was performed for light optical microscopy using a 2% Nital solution (2 mL HNO_3 with 100mL of ethanol) following ASTM E407 [13].

Impression creep specimens were removed from two of the six plug samples using electric discharge machining (EDM) to a size of 10 x 10 x 2.6 mm. Specimens were sectioned from the base metal (BM), weld metal (WM) and heat-effected zone (HAZ) as shown for one of the samples (low risk, plug 1B) in Figure 2.

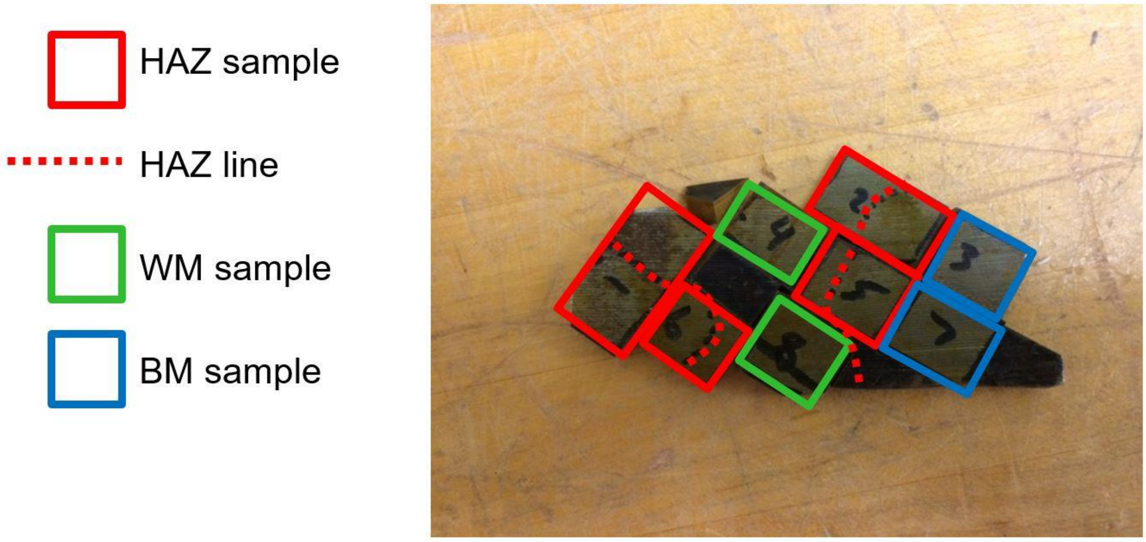

Figure 2. Extraction of impression creep specimens (BM, WM, HAZ) from low risk plug 1B using electric discharge machining (EDM) to cut specimens to ~ 10 x 10 x 2.5 mm in size.

The specimens were ground to a final thickness of 2.50 ± 0.02 mm using 240, 300 and 600 grit sandpaper. Impression creep test conditions were varied to include single stressed, multi-stressed and iso-stress (stepped temperature) testing to the ECCC guidelines for impression creep in reference [14]. The tests were conducted using a twin-screw servo-mechanical loading frame with a high temperature ceramic shell furnace using kanthal windings.

A software program was used for controlling the static load and type K thermocouples were used to control temperature to ± 1°C of the set point. The impression creep indenter was constructed of a high strength Waspaloy nickel based superalloy with creep strength more than 3 orders of magnitude that of the test material. Twin water cooled linear variable differential transformers (LVDT's) were used to measure displacement during the testing period. Impression creep tests were run for a minimum of 300 hours and the last 100 hours were used for determining the minimum creep rate.

Post-test evaluations were performed on all specimens after testing. This consisted of hardness mapping, measurement of indentation depth using a confocal laser microscope (Keyence VK-105) and evaluation of the microstructure.

3. Results

3.1. HRH Piping and Pipe Samples – Preliminary Study of Stresses and Lifetime

The 419MW unit had reported nominal 4170 kPa (605 psig), 538°C (1000°F) pressure-temperature HRH system steam conditions. The impression creep test material was from samples removed from a portion of the HRH system with nominal dimensions of 560mm (22 inch) OD and 28.6mm (1.125 inch) wall thickness. The current ASME B31.1 Power Piping Code material allowable stress at 538°C (1000°F), including with weld strength reduction factor of 0.82, is 44.1 MPa (6.4 ksi) [15]. The operational data for pressure and temperature and actual pipe wall thicknesses (by ultrasonic wall thickness measurements) showed that these straight sections operated well below the current B31.1 allowable stress limit. Table 1, adapted from Ref. [12], shows the estimated consumed life fraction for two sections analyzed (L2, L10) using the nominal steam conditions, pipe dimensions as shown, an ASME B31.1-calculated hoop stress, and an expectedly conservative, minimum rupture strength curve developed by EPRI from Grade 22 cross-weld stress rupture data.

Table 1. Findings from Preliminary Study of Two Straight Sections in the Hot Reheat Piping System [12].

Segment	D (in.)	t (in.)	T* (°R)	ASME B31.1-Calculated Hoop Stress, S MPa (psi)	Consumed Life Fraction (1968-2015)
L2 (straight)	22.0	1.005	1460	38.76 (5622)	0.582
L10 (straight)	22.0	1.040	1460	41.20 (5976)	0.478

The results from the preliminary study detailed in Ref. [12] indicated that there was an extensive amount of predicted remaining life at the two straight segments in the hot reheat piping system (≈231 kh, 351 kh). The ASME B31.1-calculated hoop stresses for the pipe sections of the two samples used for impression creep testing are shown in Table 2. These sections experienced similar temperature and pressure conditions to the straight section segments used in the preliminary study shown in Table 1, although lifetime calculations for these specific sampled sections were not performed as part of the preliminary study.

Table 2. Hoop Stresses for Two Plug Samples from Straight Sections in the Hot Reheat Piping System.

Sample	D (in.)	t (in.)	T* (°R)	ASME B31.1-Calculated Hoop Stress, S MPa (psi)
Plug 1B (low-risk)	22.0	1.068	1460	34.23 (5807)
Plug 3A (high-risk)	22.0	1.044	1460	41.02 (5950)

3.2 Metallographic Results

Etched macrographs of plug 1B and 3A are displayed in Figure 3. The seam welds were fabricated using a multi-pass weld with a double-vee. In this seam weld configuration, the highest susceptibility to the formation of damage is typically found at the cusp region of the weld and near the ID weld toes, based on previously summarized failures (e.g., [16]). No damage was observed in the low-risk (1B) sample and very little, low density, random, homogenous cavitation damage was observed in the high-risk (3A) sample. The observed damage (as-polished samples) was captured using stitched images from the confocal laser microscope as shown in Figure 4.

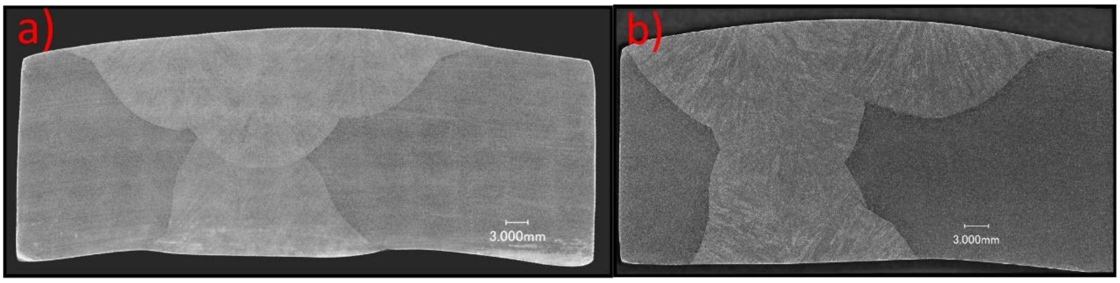

Figure 3. Etched macro image of low-risk plug 1B (a) and high-risk plug 3A (b).

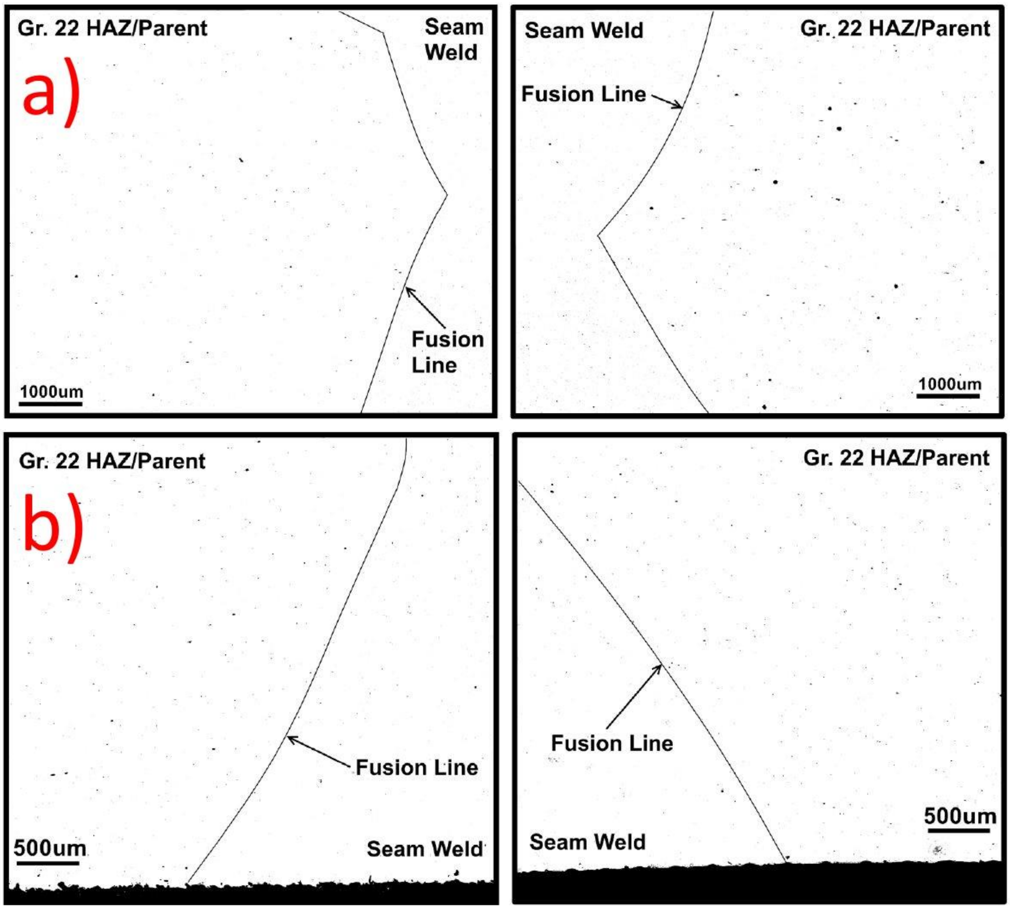

Figure 4. Observed damage/inclusions in high-risk plug 3A. Cusp region is shown at (a) and ID toe weld region is shown at (b).

Hardness testing was conducted across the welds with results shown in Figure 4-5 for sample 3A. The top hardness trace was from the left side parent material to the centerline of the weld in the lower portion of the macro of Figure 3B and the bottom hardness trace was from the centerline of the weld to the right side parent material in the upper portion of the macro. Results indicated similar hardness values in the weld metal and base metal with a moderate increase in the weld metal for the high-risk sample 3A. Hardness tests conducted on two other samples not included in this paper showed similar results.

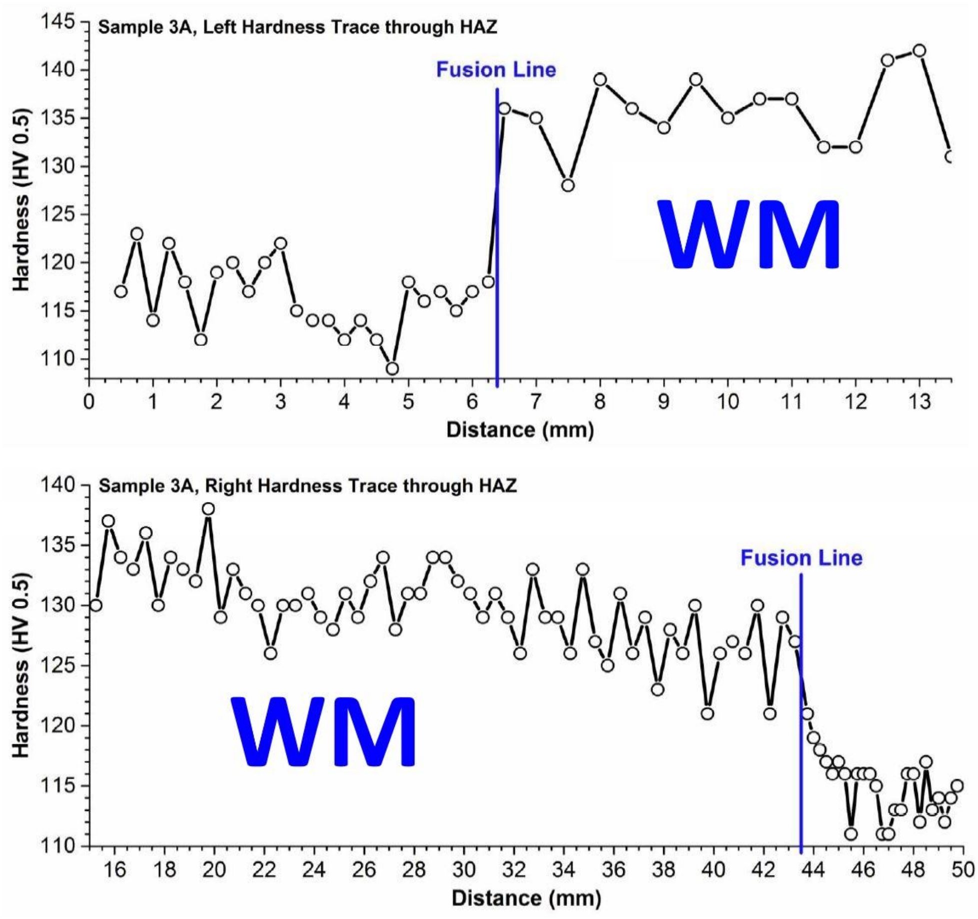

Figure 5. Hardness testing for sample 3A at both the left and right sides show no signs of low strength in the weld (spacing of 0.50mm in weld, 0.25mm in HAZ/parent, 0.5 kg load).

3.3 Impression Creep

Impression creep testing consisted of single load tests (single temperature), stepped loading (constant temperature) and iso-stress (stepped temperature) testing. Hyde et al. (e.g., [9]) have shown that the measured minimum creep rates (MCRs) in multi-step load tests agree well with minimum creep rates obtained in single load tests for low alloy CrMoV steels. The testing summarized in this manuscript assumes that each step can be represented by a single minimum creep rate (MCR) and corresponding representative rupture time. The impression creep test results for the evaluated plug samples are reported in Table 3. The (uniaxial) stress and MCR have been calculated from the indenter pressure and minimum displacement rate using the conversion factors and method of Hyde et al. (e.g., [9]). The rupture time is estimated from a Monkman-Grant, MCR-Rupture Time relationship as discussed below.

Table 3. Impression Creep Results for Service Exposed Grade 22 Hot Reheat Seam Weld

Sample	Zone	Temperature (°C)	Stress (MPa)	MCR (1/hr)	Rupture Time (hrs)*
Plug 1B (low-risk)[1]	BM	570	70	1.17E-5	2621
Plug 1B (low-risk)	BM	570	80	2.56E-5	1257
Plug 1B (low-risk)[1]	BM	570	90	3.05E-5	1067
Plug 1B (low-risk)	WM	570	80	3.07E-5	1060
Plug 1B (low-risk)	HAZ	570	80	3.50E-5	938
Plug 3A (high-risk)[2]	WM	570	80	3.61E-5	911
Plug 3A (high-risk)[2]	WM	580	80	4.08E-5	812
Plug 3A (high-risk)[2]	WM	590	80	4.52E-5	738
Plug 3A (high-risk)[2]	WM	600	80	6.14E-5	553
Plug 3A (high-risk)[2]	WM	620	45	2.07E-5	1535

Plug 3A (high-risk)[2]	WM	640	45	4.54E-5	735
Plug 3A (high-risk)[2]	WM	660	45	1.43E-4	250
Plug 3A (high-risk)	BM	570	80	4.32E-5	770

[1] Minimum Creep Rate from Stepped Loading Test (same temperature)

[2] Minimum Creep Rate from Stepped Temperature Test (same load)

*From a Monkman-Grant, MCR-Rupture Time relationship (see text)

One limitation of impression creep test is the lack of rupture time. The rupture times stated in Table 4 are estimated rupture times derived from a Monkman-Grant (MG) approach. The MG approach has been traditionally adopted for extrapolation of experimental creep rate data to assess remaining life (e.g., [17,18]). In this study, the MG relationship was used to relate the impression creep MCR to a rupture time. A key assumption in this approach is the applicability of the assumed MCR-Rupture Life MG relationship assumed. Published MCR data for 2.25CrMo steel is limited, with most coming from the 1971 ASTM dataset [19]. Not only are data limited, but MCR data for 'properly heat treated' versions of steel are even more limited. A MG relationship of all datasets was shown to have a wide scatterband possibly due to the wide range of heat treatments and temperatures used. The MG relationship used here was determined using uni-axial data from ASTM in material quenched between 927 to 954°C (1725F) and tempered at 621°C (1150°F) [19]. Equation (1) and Figure 6 show the calculated relationship using uni-axial data from ASTM plate material. It is important to note that application of an MG relationship based on relatively homogenous and ductile base metal or weld metal data can be considered non-conservative. As weldments are susceptible to localized damage and low ductility.

$$t_f = 0.062 \cdot MCR^{-0.938} \tag{1}$$

where t_f in (hours) and MCR in $(1/hr)$

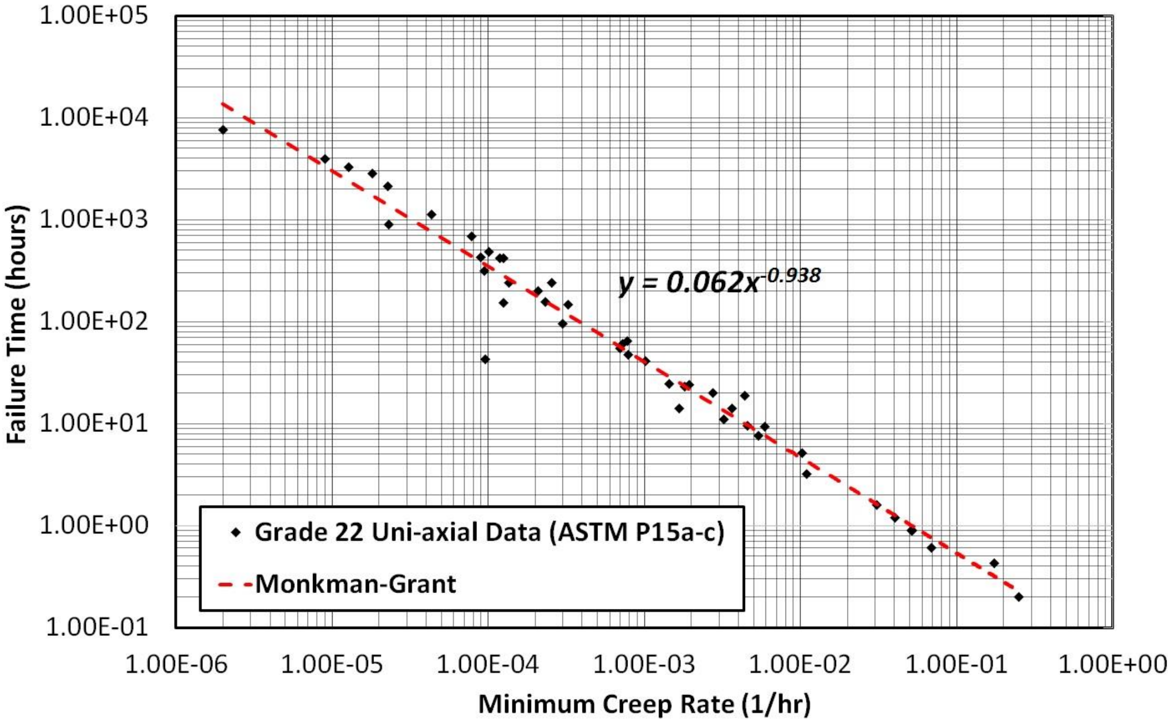

Figure 6. Monkman-Grant relationship using Grade 22 uni-axial creep data from Ref. [19].

4. Discussion

The impression creep test results were used in conjunction with uni-axial creep data to estimate the remaining useful life via two different methods. Previous literature was also reviewed to highlight the importance of creep mis-match, design, operation, fabrication and metallurgy of low alloy (CrMo) seam welds exposed to high temperatures and pressure. This discussion will review the following:

1. The useful remaining life of high-risk plug (3A) from iso-stress impression creep results for operating conditions of 45MPa (hoop stress) and 538°C (1000°F)
2. Assessment of experimental impression creep data using a Larson-Miller approach and use of published tools (EPRI, ECCC and API-579)
3. The effects of creep mis-match between zones (BM, WM, HAZ), design, operation, fabrication and metallurgy on long term performance of low alloy seam welds.

4.1. Calculation of remaining life for high-risk plug using iso-stress experimental impression creep data

The impression creep (IC)-derived strain rates for the iso-stress tests at applied loads for an equivalent uniaxial stress of 45 MPa (6.525 ksi) were plotted on a natural log of strain rate vs. the inverse of temperature, shown in Figure 7. The operating condition of 538°C (1000°F, 811°K) was then used as the input for Equation (2). The remaining life calculation is then made from the MG equation (1).

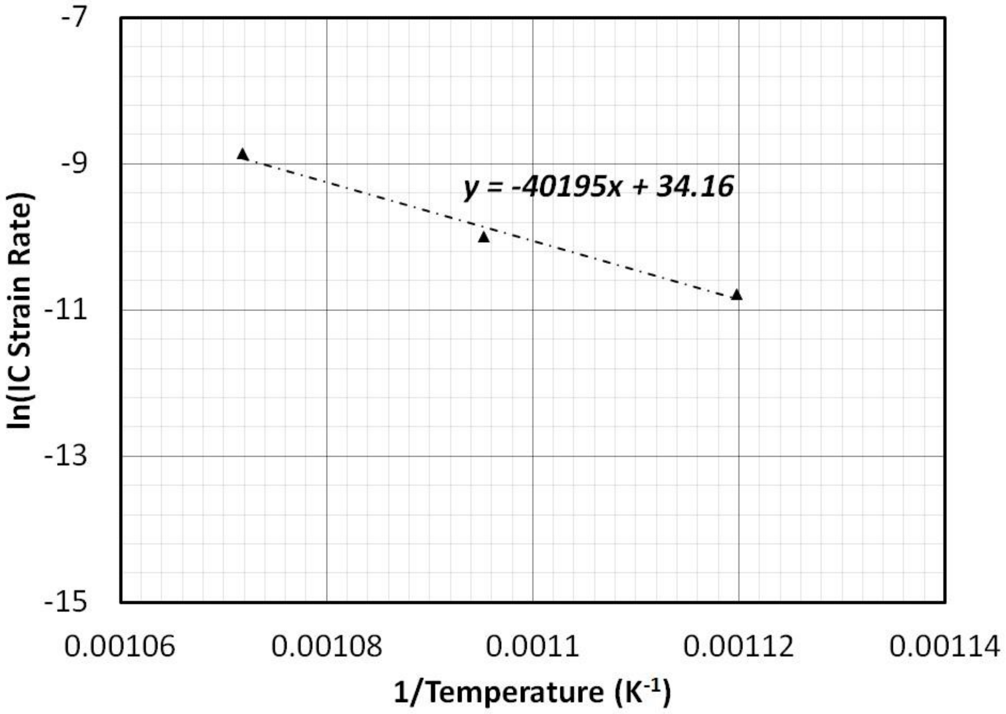

Figure 7. Natural log of Impression Creep (IC) Strain Rate vs. Inverse Temperature for iso-stress impression creep tests of weld metal at 45MPa on high-risk plug (3A).

$$\ln(IC\ strain_{rate}) = -40195\left(\frac{1}{T}\right) + 34.16 \tag{2}$$

The various impression creep strain rates at different testing temperatures under the same loading conditions show the temperature dependence for creep. This is typically expressed as the activation energy and can be found using the slope from equation (3) multiplied by the universal gas constant (8.314 J/mol-k). Experimental results of the impression creep testing show that activation energy is very consistent between the testing temperature of 620 to 660°C (1148 to 1220°F). Assuming the activation energy is consistent at operating conditions of 538°C (1000°F) at a given stress of 45 MPa (6.53 ksi), the fit can be used to predict the minimum creep rate. It is important to note that the range of extrapolation from data at 660 to 620°C, down to 538°C, is significantly large. Thus, this may explain why life estimates were lower using this method compared to the Larson-Miller method shown in section 4.2. These experimental findings and calculations are shown in Table 4.

Table 4. Estimated Remaining Life using Iso-stress Data and MG Relationship.

Sample	Zone	Temperature (°C)	Stress (MPa)	MCR (1/hr)	MG Rupture Time (hrs)*
Plug 3A (high-risk)[1]	WM	620	45	2.07E-5	1535
Plug 3A (high-risk)[1]	WM	640	45	4.54E-5	735
Plug 3A (high-risk)[1]	WM	660	45	1.43E-4	250
Estimated Remaining Life	-	***538***	***45***	***2.05E-7****	***116404***

[1] Minimum Creep Rate from Stepped Temperature Test (same load)

*Estimated using MG Relationship in Equation (2)

For the test stress and corresponding pressure (if applied in future operation), the estimated remaining life of the high-risk plug (3A) was found to be over 116,000 hours, which is almost 20 years of operation at a 70% availability factor. The estimated remaining life appears lower than that in the preliminary EPRI study (≈231,000 h, 351,000 h, see Table 1 and related text) that used nominal conditions with a lower applied stress, albeit a more conservative rupture curve. Based on continued operation at nominal conditions (538°C, 4.17 MPa pressure), it appears reasonable that this segment of the HRH piping system could operate more than 20 years (at 60 to 80% availability factor) based upon impression creep estimates of life and supporting metallurgical results showing minimal damage at the cusp and weld toes. It should be noted that such estimates of remaining life do not include time expended in the progression of the cracking forms of damage, particularly relevant where creep damage occurs locally. In this regard, such estimates are conservative. On the other hand, estimates made based on tests of relatively homogenous material do not capture the effect of local weak and/or creep brittle zones and the effect of varying creep rates in adjacent zones of the weldment seen in an operating component, and may therefore not be conservative (see discussion later).

4.2. Assessment of experimental impression creep data using a Larson-Miller approach

The impression creep-derived rupture time results may also be presented and analyzed using the Larson-Miller time-temperature parameter. The approach allows for a comparison of data with established rupture strength curves representing the behavior of base metal. In recent years, several organizations have determined statistical data fits for Grade 22 uni-axial creep rupture data. These fits can be used for extrapolation of service-like conditions to estimate life of high temperature components in the creep regime. The Electric Power Research Institute (EPRI) [20], European Creep Collaborative Committee (ECCC) [21] and American Society of Mechanical Engineers (ASME) [22] statistical data fits are the basis for the assessment in this section. The Larson-Miller (LMP) temperature-time dependent parameter is used in conjunction with stress to represent a single curve for all creep rupture data. The representative rupture times for the experimental impression creep data were used to determine the corresponding LMP values. The results are shown in Figure 8.

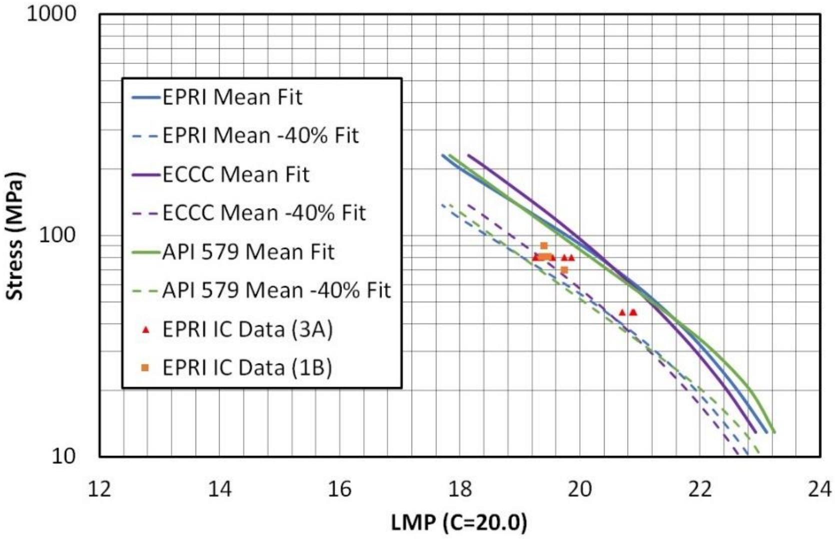

Figure 8. Larson-Miller vs Stress for Grade 22 Uni-axial and Impression Creep Data.

It is important to note that impression creep data at the base metal, heat-affected zone and weld metal are compared to average base metal curves, as shown in Figure 8. The impression creep-derived data suggest a qualitative difference between the predictions made for the low risk and the high-risk plug material, supporting the use of the test method in discriminating between materials with varying levels of creep strength. The experimental impression creep data fall below the average creep strength of base metal. The impression creep data points also appear to be just above the -40% of the mean strength for the three rupture strength curves (EPRI, ECCC and API-579). A calculation of remaining life using the -40% mean fit gave results summarized in Table 5. The LMP-based extrapolation of remaining life appears greater than that made with the MCR-MG method. A more rigorous comparison of impression creep test data and the MCR-MG relation with uniaxial data and the corresponding MG relationship is needed to better understand the potential reasons for the difference.

Again, lifetime estimates made from results on a weldment zone alone do not reflect the complex effect of mismatch, localized properties, concentration of damage, etc. that can produce reductions in lifetime from what is simply predicted from tests on a single zone of homogenous material.

Table 5. Estimated Remaining Life based on a 40% Reduction of Rupture Strength from Average Expected Behavior for Both Plug Samples using the LMP.

Fit Method	Temperature (°C)	Stress (MPa)	Remaining Life (hrs)
ECCC	538	45	174372
API 579	538	45	165542
EPRI	538	45	189984

4.3. The effects of creep mis-match between zones (BM, WM, HAZ), design, operation, fabrication and metallurgy on long term performance of low alloy seam welds

Creep mis-match, design, operation, fabrication and metallurgy have all been shown to have significant impacts on service life in high temperature structures and all influence the quality of welds. Creep mis-match over time leads to stress concentrations and can be exacerbated by weld geometries, such as weld width, weld preparation angle and the state of loading [5-8].

Unlike traditional uni-axial creep testing, the impression creep test can be used to test the individual zones (BM, WM, HAZ) of a weldment. Limited studies have shown that the impression creep minimum creep rates are directly relatable to uni-axial minimum creep rates when proper reference stresses are used [23,24]. Individual single stressed impression creep tests were performed at the BM, WM and HAZ (as shown in Figure 2 from methods section) for the low-risk plug sample using the same test conditions. Results are shown in Table 6 with the rupture time calculated using the same MCR-MG method applied to the high risk plug sample material test specimen data.

Table 6. Impression Creep Results for Low-risk Plug (1B) at BM, WM and HAZ.

Sample	Zone	Temperature (°C)	Stress (MPa)	MCR (1/hr)	MG Rupture Time (hrs)*
Plug 1B (low-risk)	BM	570	80	2.56E-5	1257
Plug 1B (low-risk)	WM	570	80	3.07E-5	1060
Plug 1B (low-risk)	HAZ	570	80	3.50E-5	938

*Estimated using MG Relationship in Equation (1)

The minimum creep rate in the different zones showed to be very similar, with minimal creep mis-match. The as-constructed weldment post-weld heat treat condition is not known. If the weldments were subcritically heat treated, as in the typical case for older seam-welded low alloy steel straight section piping (see Introduction), the effect of tempering due to extended elevated temperature service exposure (e.g., [25]) would be expected to significantly reduce the mismatch with exposure time. If the weldments were initially normalized and tempered, the starting mismatch would be lower than for the subcritical condition and there would be far less of an effect of service exposure on changes in mismatch during service.

The Holloman-Jaffee time-temperature parameter (a Larson-Miller representation) is often used to describe the effect of a heat treatment at a temperature for a specific time on the time-independent strength characterized by hardness [26]. To be clear, the time-independent strength or hardness does not represent the elevated temperature time-dependent creep strength/resistance. Changes in hardness are nevertheless a measure of the extent of tempering which does affect the change in creep resistance and the mis-match in creep rates between various weldment zones. There is almost always a variation in hardness between the weld metal, heat-affected zone and base metal and the heat treatment following welding largely controls the initial hardness and its variation across a given weldment. Hardness results from the plug samples as presented in Figure 5 show that the heat-affected zone adjacent to weld metal exhibits a hardness level even lower than weld metal (15-20% difference), not generally seen in as-constructed weldments. The observation indicates that the weldment has been substantially tempered as would be expected from the extended elevated temperature operation. The hardness data are plotted on tempering curves for Grade 22 [25]. The LMP value is calculated for the operating period at 538°C (1000°F) without an equivalent time correction for any initial post-weld heat treatment (this is very small relative to the extended operating period LMP value). The apparent tempering effect of service is expected to reduce the weld metal-heat-affected zone creep rate mismatch (from the initial as-constructed) condition, and the impression creep results, albeit on material not immediately adjacent to the weld fusion line, are consistent with the expectation.

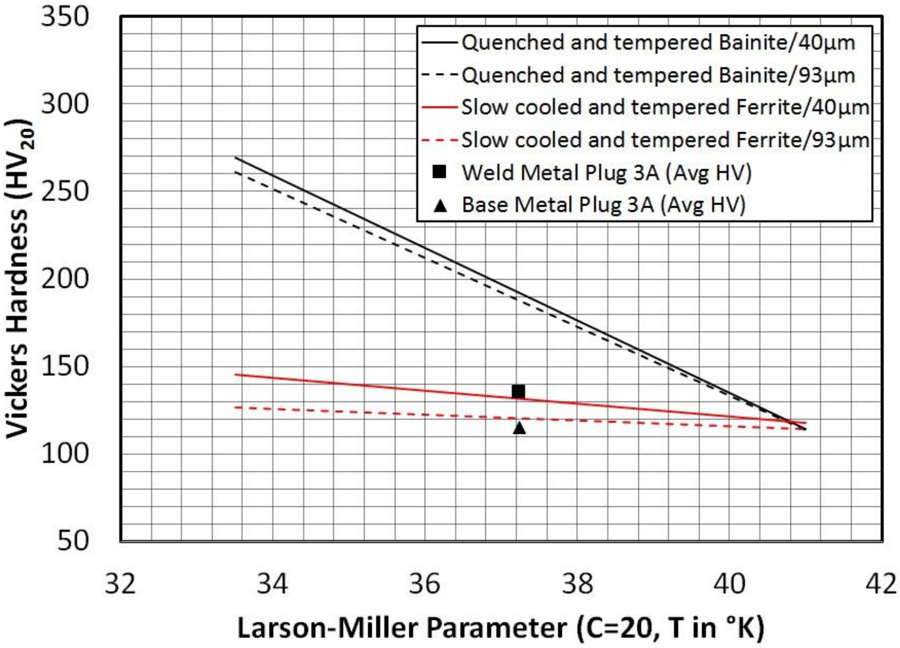

Figure 9. Reductions in Hardness as a Function of Time and Temperature for CrMo steels [25] with measured data on plug 3A material superimposed

It should be noted that in case the as-constructed weldments had been given a normalizing and tempering post-weld treatment, the creep rate mismatch would be expected to be low even before service exposure; i.e., the effect of in-service exposure would not be as significant. Regardless, for estimating the remaining life, what is of interest is the current condition, and the impression creep tests provide an indication of the creep mismatch going forward. Since the impression creep tests, although conducted on specific weldment zones, do not adequately characterize local, near-fusion line material properties that can be key to weldment lifetime, this limitation is recognized.

Impression creep testing provides valuable weldment zone-specific information that cannot be obtained from standard uniaxial test methods, in addition to allowing for the testing of in-service component material. In addition, as has been demonstrated for Grade 91 and CrMoV, the test is a tool that can discriminate between material of varying creep strength levels. With more research, the impression creep test could prove to be an asset when characterizing creep mismatch of service exposed welds, in addition to its application for remaining life estimation. Additional testing should be conducted on similar material of known behavior to compare findings. This will help in further exploring and validating the impression creep test method. It is also suggested that selected seam-welds be given a normalize and temper heat treatment, then re-evaluated by impression creep testing between the BM, WM and HAZ to assess mismatch conditions more representative of an as-constructed N&T condition. Uniaxial testing will also help validate suggested 'representative failure times' produced from impression creep test results.

5. Conclusions

Impression creep testing performed on service exposed seam welded hot-reheat piping material has been effective in discriminating between two material cases with expectedly different creep strength levels. The tests were also useful in indicating that the piping system material evaluated had useful remaining creep life. These findings are consistent with a previous preliminary study of the same service exposed system material. Two different evaluation methods of impression creep data were discussed, an LMP-based approach and MCR-MG method. The remaining life from extrapolation of the LMP-based approach showed slightly higher life predictions than that the MCR-MG method. Impression creep testing was also performed at various zones of the seam weld to show that there was nearly no creep mismatch between the base metal, weld metal and heat-affected zone. It is likely that observed minimal creep mismatch, proper design, operation and fabrication, combined with proper metallurgy are reasons this low-alloy seam-weld piping system has successfully seen over 300,000 hours of operation and still shows significant useful remaining life. It is recommended that additional impression creep be done on a reheat-treated (normalized and tempered) version of the same material in addition to uniaxial creep testing to examine the mismatch question and the most suitable means of test data interpretation for remaining lifetime estimation. Further metallurgical evaluation, including weld chemistry and oxygen content are planned to fully characterize the materials variables that can affect local damage rates.

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References

1. "Philo 6 Steam-Electric Generating Unit." ASME.org. Accessed March 23, 2018.
2. Your Guide To Understanding Energy – Energy Information Administration. Accessed March 23, 2018. https://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states.
3. "Coal & Electricity." World Coal Association. Accessed March 23, 2018. https://www.worldcoal.org/coal/uses-coal/coal-electricity.
4. *30-Plus Years of Long-seam Weld Failures in the Power Generation Industry –Perspective and Continuing Challenges with Life Management.* EPRI, Palo Alto, CA: 2017. 3002011587.
5. Samuelson, L.A.; Tu, S.-T.; Storesund, J., Life Reduction in High Temperature Structures Due to Mis-Match of Weld and Parent Material Creep Properties, Mis-Matching of Welds, ESIS 17, Edited by K.-H. Schwalbe and M. Kocak, Mechanical Engineering Publications, London, (1994) 845-860.
6. Segle, P.;. Tu, S.-T.; Storesund, J.; Samuelson, L.Å. Some issues in life assessment of longitudinal seam welds based on creep tests with cross-weld specimens, International Journal of Pressure Vessels and Piping, Volume 66, Issues 1–3, 1996, Pages 199-222
7. Storesund, J. Tu, S.-T.; Geometrical effect on creep in cross weld specimens, International Journal of Pressure Vessels and Piping, Volume 62, Issue 2, 1995, Pages 179-193
8. Segle, P. (2002). Numerical simulation of weldment creep response (PhD dissertation). Materialvetenskap, Stockholm.
9. Hyde, T. H.; Sun, W. (2001). Multi-step Load Impression Creep Tests for a 1/2Cr1/2Mo1/4V Steel at 565°C. Strain, 37(3), 99-103.
10. Brennan, K.; Brett, S.J.; Eaton-Mckay, J. Impression Creep Testing of Aberrant Grade 91 Material Removed from Piping in Service; 4th International ECCC Conference, 2017.
11. Barry, J.E.; Guilfoyle, C.J.; Rupinskas. R.L. "Sibley Station Life Extension Program." Life Extension and Assessment: Nuclear and Fossil Power-Plant Components 138 (June 19, 1988): 165-69.
12. Method for the Preliminary Assessment of a Seam-Welded Hot Reheat Piping System: Damage Estimation and Prioritization of Sections for Evaluation at Kansas City Power and Light Sibley Unit 3. EPRI, Palo Alto, CA: 2017. 3002011588.
13. ASTM E407-07(2015)e1, Standard Practice for Microetching Metals and Alloys, ASTM International, West Conshohocken, PA, 2015
14. ECCC Guidelines for Impression Creep Testing; Discussion at 3th International ECCC Conference, 2014.
15. ASME Code for Pressure Piping, B31, Power Piping B31.1-2016, ASME, New York, NY, 2016.

16. Foulds, J. R.; Viswanathan, R. (1995). Guidelines for Assessment of Seam-Welded High Energy Piping (III ed., Vol. 57). Chicago, IL: Proceedings of the American Power Conference.
17. Evans, M. (2006). A generalised Monkman-Grant relation for creep life prediction: An application to 1CrMoV rotor steel. Journal of Materials Science, 41(12), 3907-3915.
18. Povolo, F. (1985). Comments on the Monkman-Grant and the modified Monkman-Grant relationships. Journal of Materials Science, 20(6), 2005-2010.
19. ASTM Data series DS 6S2, “Supplemental report on the Elevated-Temperature Properties of Chromium-Molybdenum Steels (An evaluation of 2-1/4Cr 1Mo Steel),” ASTM, West Conshohocken, PA, 1971.
20. Recommendations for Weld Strength Reduction Factors. EPRI, Palo Alto, CA: 2010. 1019791.
21. Engineers, A. S. (2016). *API 579-1/ASME FFS-1 Fitness-For-Service*. American Society of Mechanical Engineers
22. ECCC Data Sheets 2005, European Creep Collaborative Committee, 2005.
23. Hyde, T.H.; Yehia, K.A.;. Becker, A.A Interpretation of impression creep data using a reference stress approach, International Journal of Mechanical Sciences, Volume 35, Issue 6, 1993, Pages 451-462.
24. Hyde, T.H.; Sun, W.; Becker, A.A. Analysis of the impression creep test method using a rectangular indenter for determining the creep properties in welds, International Journal of Mechanical Sciences, Volume 38, Issue 10, 1996, Pages 1089-1102.
25. Grade 22 Low Alloy Steel Handbook: 2-1/4Cr-1Mo, 10CrMo9 10, 622, STPA24. EPRI, Palo Alto, CA: 2005. 1012840.
26. Hollomon J.H.; Jaffe, L.D. “Time-Temperature Relations in Tempering Steel,” Transactions, American Institute of Mining, Metallurgical Engineers, Volume 162, 1945, p. 223–249.