Review of Type IV Cracking in Piping Welds

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Prepared by
Tordonato Energy Consultants, Inc.
4156 South Creek Road
Chattanooga, TN 37406

Principal Investigator
F. V. Ellis

Prepared for
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
R. Viswanathan

Applied Science and Technology
Strategic Research and Development

ORGANIZATION(S) THAT PREPARED THIS REPORT

TORDONATO ENERGY CONSULTANTS, INC.

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REPORT SUMMARY

Several failures of seam welded main steam pipes have recently occurred by cracks forming and propagating in the fine grained heat affected zone adjoining the base metal. This form of cracking, termed Type IV cracking, is believed to lead to failures without forewarning. Consequently, utilities need guidance regarding inspection as well as disposition of piping that contains this form of damage.

Background

Type IV damage in girth welds of high temperature piping systems has been a matter of great concern in Europe for many years. In the U.S., this damage was not of much concern either because of the use of different steels and at lower temperatures, or because of lack of adequate documentation of failures. This situation changed in the past few years with several near-catastrophic failures of seam welded high-energy piping attributed to Type IV cracking. Since the evolution of these failures is believed to involve rapid cracking by link-up of creep cavities, conventional inspection-based approaches have often been deemed inadequate.

Objective

- To review, analyze, and consolidate all the available information pertaining to Type IV cracking, and in the process, provide new insights into the causes and evolution of cracking, life reduction due to cracking, and the disposition of cracked piping.

Approach

The authors reviewed the literature relating to laboratory studies, as well as field failure experience. This review encompassed the fundamental causes for the cracking, characteristic features of the cracking, models for damage evolution, methods of inspection/damage detection, and relevant service experience.

Results

Based on the results of the review, several conclusions regarding Type IV cracking were reached:

- Cracking occurs in the fine grained heat affected zone (FGHAZ), as well as in the intercritical region of the HAZ. Since these zones are present only in sub-critically

heat treated welds, normalized and tempered welds are immune to this form of cracking.

- Only creep cavitation damage is present until late in life, i.e., nearly 0.7 to 0.8 of the creep life fraction. This is followed by rapid, crack growth. Hence fracture mechanics crack growth based approaches for remaining life prediction are not applicable.
- Currently available NDE techniques are inadequate to detect TYPE IV damage. in some instances of girth welds, the damage could be detected by surface replication, although in most instances initiation of damage is believed to occur sub-surface. Removal of core plug samples remains the most unambiguous way for detecting early damage.
- Type IV cracking can reduce the life of piping systems, compared to the design life by as much as a factor of five.

EPRI Perspective

Non-destructive techniques (NDE) that can detect and identify Type IV cracking and improved (quantitative) models of damage evolution are critically needed for more accurate serviceability evaluations. Pending these developments, the only option available to the plant owner seems to be repair/replacement in the near term. The life assessment damage models available are useful only to estimate the interval by which remedial action can be deferred. The observation that the design life can be reduced by as much as a factor of 5, also calls for re-evaluation of the design basis for high-energy piping systems. On the positive side, it may be added that Type IV cracking is a "late in life" failure mechanism and pipes that have failed have done so after prolonged service (>150,000 hr).

It is also necessary to distinguish between girth welds and seam welds. Failure in girth welds is induced by out-of-design axial loads and the damage generally starts at the near OD, sub-surface region. This scenario lends itself to detection of creep cavitation by surface replication, and the ultimate consequence of cracking is only a pipe leak. Conversely, failure of seam welded pipes is caused by hoop stresses and can initiate deep inside the pipe. Failure can also be catastrophic and has more serious safety implications.

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Interest Categories

Applied science & technology
Fossil steam plant O&M cost reduction

Keywords

Welds
Cracking
Creep
Rupture
Pipes
Inspection

ABSTRACT

A comprehensive literature review for Type IV cracking and failure was performed. The review encompassed the fundamental causes for the cracking, characteristic features of the cracking, models for damage evolution, methods of inspection/damage detection and relevant service experience. Based on the results of the review, conclusions regarding Type IV cracking, recommendations for improvements in the EPRI guidelines and recommendations for additional studies were developed.

Type IV cracking is the result of a microstructural zone of material that has low creep strength surrounded by materials that are stronger in creep. Type IV cracking has been found in the fine-grained HAZ associated with exposure to temperatures around the A_{C3} temperature and in the intercritical region of the HAZ. Type IV cracking is caused by thermal softening of the HAZ due to the welding thermal cycle that produces a microstructure with a fine grain size and a coarse carbide distribution (minimizes particle strengthening contributions). The local failure strain for the Type IV mechanism is relatively large, i.e., greater than 10%, consistent with the physical interpretation of strain localization in a narrow zone.

In Type IV cracking, only cavitation damage is present until late in life - i.e., life fractions greater than 0.7 to 0.8. This is followed by rapid crack growth in highly creep damaged material. Qualitative cavitation assessments use three levels of isolated cavitation . They are extremely isolated, isolated and dense. Because the current quantitative cavity density model under-estimates the cavitation damage and the lack of data for CrMo steels, there is a need for both improved models and additional testing/cavitation measurements.

For girth welds, Type IV cracking is associated with applied piping system axial stresses. The degree of damage is greater for the portions of the fusion interface that are closer to radial in orientation. Grinding of the temper bead pass has been used to detect subsurface initiation of damage in girth welds. Because the failures for girth welds occur by typically leak before break, the frequency of repair determines the approach to weldment life management.

For the longitudinal seam welds, the hoop stress due to internal pressure acts directly across the weld/HAZ. Although Type IV failures have only been found in thick-walled piping with the either the J groove or single V joint geometry, there appears to be no reason to believe that thin-walled piping with longitudinal seam welds post weld heat treated sub critically will be immune to Type IV failure. Because failures of longitudinal seam welded piping can be catastrophic, consideration of safety determines the approach to weldment life management.

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INTRODUCTION

One of the first steps in performing a failure analysis is to identify the failure location. In many cases, there is a relation between the failure location and the failure mechanism. For the failure analysis of circumferential weldments, the classification scheme developed by Schuller, Hagn, and Wotischeck (1974) for damage types/crack position is commonly used worldwide. In this scheme, the damage type is denoted by a Roman numeral - values I to IV as shown in Figure 1-1. Type I damage is oriented either longitudinal or transverse, located in the weld metal and remains within the weld metal. Type II damage is similar to Type I, but grows out of the weld metal into the adjacent HAZ and base material. Type III damage is located in the coarse-grained region of the HAZ. Type IV damage is located in the fine-grained/intercritical region of the HAZ.

The system was initially used for girth welds in 1/2Cr-1/2Mo-1/4V piping made with 2-1/4Cr-1Mo weld metal. For the CrMoV weldment, there were short term welding process related problems including solidification cracks in the weld metal classified as Type I and stress relief cracks in the coarse grained region of the Heat-Affected-Zone (HAZ) classified as Type III. Although the classification scheme has several deficiencies including no type for the fusion interface damage, it has also been used for longitudinal seam weldments. The focus of the current review is the Type IV crack located in the fine grained/intercritical region of the HAZ shown in Figure 1-2. Because Type IV cracking occurs in service, it is often termed mid-life cracking

Recent fine grained/intercritical Heat-Affected-Zone (HAZ) failures for seam welded main steamline link piping has raised fundamental questions regarding the creep strength of the HAZ sub-structures and practical questions regarding both the inspection interval and technique. In order to allow utilities to deal effectively with the Type IV cracking problem, a comprehensive review of the literature for Type IV failure mechanism was performed. The objective of the current review was to develop a basis for improved guidelines for the assessment of girth and seam-welded components in the sub-critical stress relieved condition, i.e. , post weld heat treated (PWHT) below the lower critical temperature.

Type IV cracking has several features that make it worthy of in-depth review. First, the re-inspection interval may be short for the “worst case” failure scenario. In this scenario, Type IV has only cavitation damage present until late in life indicating potential problems in damage detection. Also, crack growth is expected to be rapid because of the advanced creep damage in the material ahead of the crack tip. Second, both laboratory creep test results and service experience indicates that the cracking initiates subsurface. Third, Type IV cracking is a generic problem in elevated temperature piping subjected to sub critical PWHT. Cracking has been found in both the girth welds and longitudinal seam welds. The cracking for girth welds is often associated with applied piping system stresses. For the longitudinal seam welds, the hoop stress due to internal pressure acts directly across the weld/HAZ. Lastly, most of the commonly used ferritic and martensitic steels are susceptible to Type IV cracking.

An outline of the review topics and relevant issues addressed is given below:

- Cause(s) of Type IV cracking
- Creep rupture and interrupted creep on cross welds and simulated HAZ results, effect of sample size, heat treatment and stress state
- Models of damage evolution versus life fraction
- Stress analysis
- Industry experience, occurrence of cracking and service conditions
- Methods of damage/crack detection
- Significance of cracking for girth and longitudinal seam-welded component

For convenience, the report has five sections. Section One is an introduction and gives a short description of the report organization. Section Two discusses the causes of the Type IV cracking, cross weld test results, damage detection methods and damage evolution. Section Three is an overview of the service experience for girth welds and longitudinal seam welds. Section Four gives the conclusions and recommendations for improvements in the assessment guidelines and further studies. The references are in Section Five.

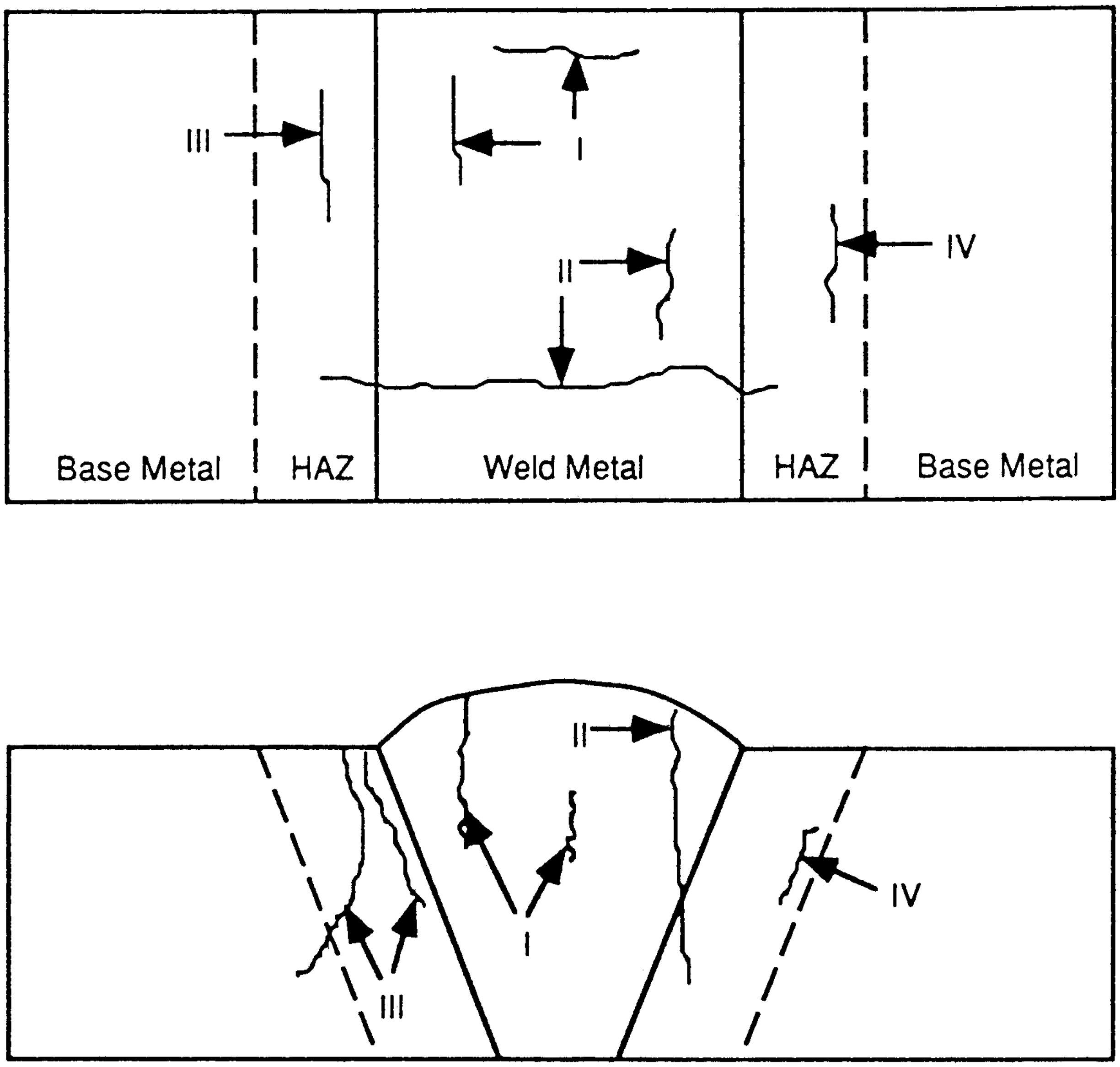

Figure 1-1
Classification Scheme for Damage Types in Weldments (Chan, McQueen, Prince and Sidey, 1991)

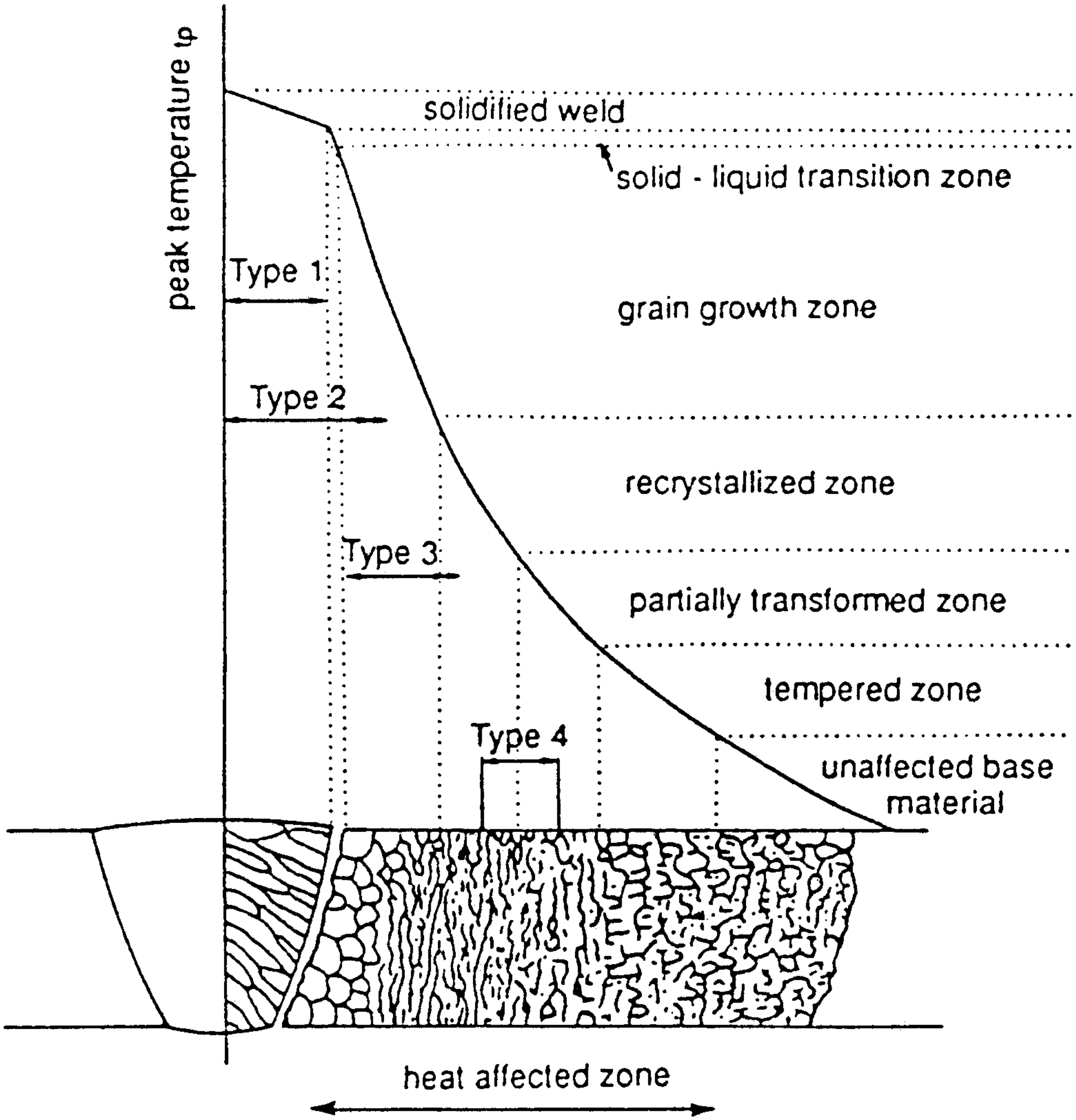

Figure 1-2
Relation of Single Pass Weldment Microstructure Zones and Four Damage Types (Chan, McQueen, Prince and Sidey, 1991)

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CAUSES OF TYPE IV CRACKING AND FUNDAMENTAL STUDIES

Introduction

Williams (1982) has reviewed the failure analysis of weldments at elevated temperature. Weldments are inhomogeneous. Their creep behavior is complex because of the various microstructural zones present. In a single pass weld, there are five distinct materials; the weld metal, the base material and HAZ zones of coarse-grained, fine-grained and intercritical. The failure location and mechanism depends on many factors including the creep strength, ductility and zone sizes of the various materials in the joint. Other important factors that affect weldment life are the following: the geometry of the weld; the applied service conditions of temperature, temperature gradients, thermal cycling, internal pressure induced stresses and applied system stresses.

Kimmins, Coleman and Smith (1993) have discussed the root cause of Type IV failure, characteristic features and important variables affecting life. Type IV damage/cracking is the result of a microstructural zone of material that is weak in creep surrounded by materials (base material, weld metal and other HAZ zones) that are stronger in creep. Because examples of Type IV cracking have been found in both the fine grained region associated with exposure around the upper critical temperature, A_{C3} , and in the intercritical region, the Type IV zone is loosely defined microstructurally. The low creep strength is the result of the short term welding thermal cycle that produces a microstructure with a fine grain size and a coarse carbide distribution (minimizes particle strengthening contributions).

Important features of the Type IV failure mechanism (Kimmins, Coleman and Smith, 1993) are the following: (1) The failure time is less than that for the wrought base material. Type IV failure is often termed mid-life cracking because of its characteristic failure time. Typically, the loss in creep strength can be described as either a stress reduction factor or a life reduction factor with respect to the base material. (2) The fracture has a macroscopic appearance typical of a low ductility failure but, significant creep deformations are measured in the narrow HAZ region indicating strain localization. (3) The susceptibility to Type IV damage is related to the ductility of the parent material. (4) The rupture life depends on the stress state and the applied loading direction, e.g., girth weld versus longitudinal seam weld. (5) Agreement between the theoretical predictions and experimental measurements for the effect of constraint and specimen size/component section size on the rupture life depend strongly on the material properties and multiaxial stress rupture criteria used in the analysis. Thus, further study is needed.

This section reviews stress and life reduction factors, the results of creep tests on cross weld and simulated HAZ specimens, specimen size effects and constraint, metallurgical examinations of creep damaged weldments, models for damage evolution and stress analysis contributions.

Stress And Life Reduction Factors

The significance of the measured weldment rupture life on service performance depends on the position of the rupture data with regard to the base material scatterband. If the weldment rupture time is within the scatterband, the service life of the welded component would be expected to be the same as the wrought component. For weldment rupture times below the minimum value for the base material, premature failure may result depending on the magnitude of the life reduction and the applied service conditions. To compare the base and weldment rupture properties, stress reduction and life factors have been used.

Corum (1990) has discussed the stress reduction factor for design applications. Both the weld metal and weldment rupture properties are used to develop the factor. Failures by the Type IV mechanism would be included in the weldment rupture data base. The stress reduction factor, R_F, is defined as the ratio of the average weldment creep-rupture strength to the average base material creep-rupture strength. The stress reduction factor is a function of time and temperature. Grade 22 (2-1/4Cr-1Mo) weldments have a stress reduction factor of 0.96 at 1000°F (538°C) and 100,000 hours. For Code applications, it was assumed that the ratio of minimum strength properties is the same as that for mean.

The life reduction factor, R_t, is useful for failure analysis/life assessment applications and is a function of temperature and stress. Isothermal stress rupture results are usually plotted on a log stress versus log rupture time graph. For a linear relationship, two general behaviors can be found for the base and weldment data. If the curves are parallel but have different intercepts, a heat-centered rupture life equation can be written as follows;

$$\log t_r = C_h - m \log F$$

where t_r is the rupture time, C_h is the heat constant with different values for the base material and the weldment, m is the slope of the log-log curve and F is the stress. The life reduction factor is independent of stress and can be calculated from the appropriate heat constants. In the second case, the slope of the weld metal is less than that of the base material (Kimmins, Coleman and Smith, 1993). The stress and life reduction factors increase as stress decreases.

Creep Deformation And Rupture

The creep deformation and rupture behavior of weldments have been studied using both cross weld samples and simulated HAZ samples. The cross weld samples are oriented transverse to the welding direction and the gage length contains weld metal, heat-affect zone and base material. The gage length for the simulated HAZ samples are a homogeneous material that was obtained by heat treating to produce a material with a microstructure and hardness value typical of the desired HAZ zone - either coarse grained, fine grained or intercritical.

The majority of the tests reported in the literature have been uniaxial but some multiaxial tests have also been performed. In addition, limited tests have been done to study the effect of sample size and post weld heat treatments on rupture life. In some instances, this low creep strength material can be found as a "soft zone" in a hardness traverse of the HAZ. Interrupted creep test have been performed to develop an understanding of the damage evolution as a function of life fraction.

Creep and/or creep-rupture tests have been performed for most of the commonly used ferritic and martensitic steels including 1/2Cr-1/2Mo-1/4V, 1Cr-1Mo-1/4V, 1-1/4Cr-1/2Mo, 2-1/4Cr-1Mo, Modified 9Cr-1Mo, and 12Cr-1Mo-1/4V (X20) that are susceptible to Type IV cracking. Results are reviewed for each below.

1/2Cr-1/2Mo-1/4V

Gooch and Kimmins (1987) performed creep rupture tests on 1/2Cr-1/2Mo-1/4V weldments and on simulated fine-grained HAZ material. The weldment rupture life was from one third at 11.6 KSI (80 MPa) to one fifth at 5.8 KSI (40 MPa) of that for the parent or base material as shown in Figure 2-1. The simulated HAZ rupture properties depend on the austenitizing temperature. For specimens at austenitizing temperatures of 1517°F (825°C) to 1652°F (900°C), failure was in about one third of the life of the tempered base material sample. Based on the dc potential drop measurements on the weldment rupture specimens, surface breaking cracks do not appear until late in life.

Metallurgical examination of the specimens revealed creep cavitation and cracking that was centered on the boundary between the completely re-transformed, fine-grained banitic zone and the partially re-transformed intercritical zone of the HAZ, i. e., the A3 boundary. In their study, the cavity size rather than cavity density was the major difference between the samples at failure and approximately one-half life.

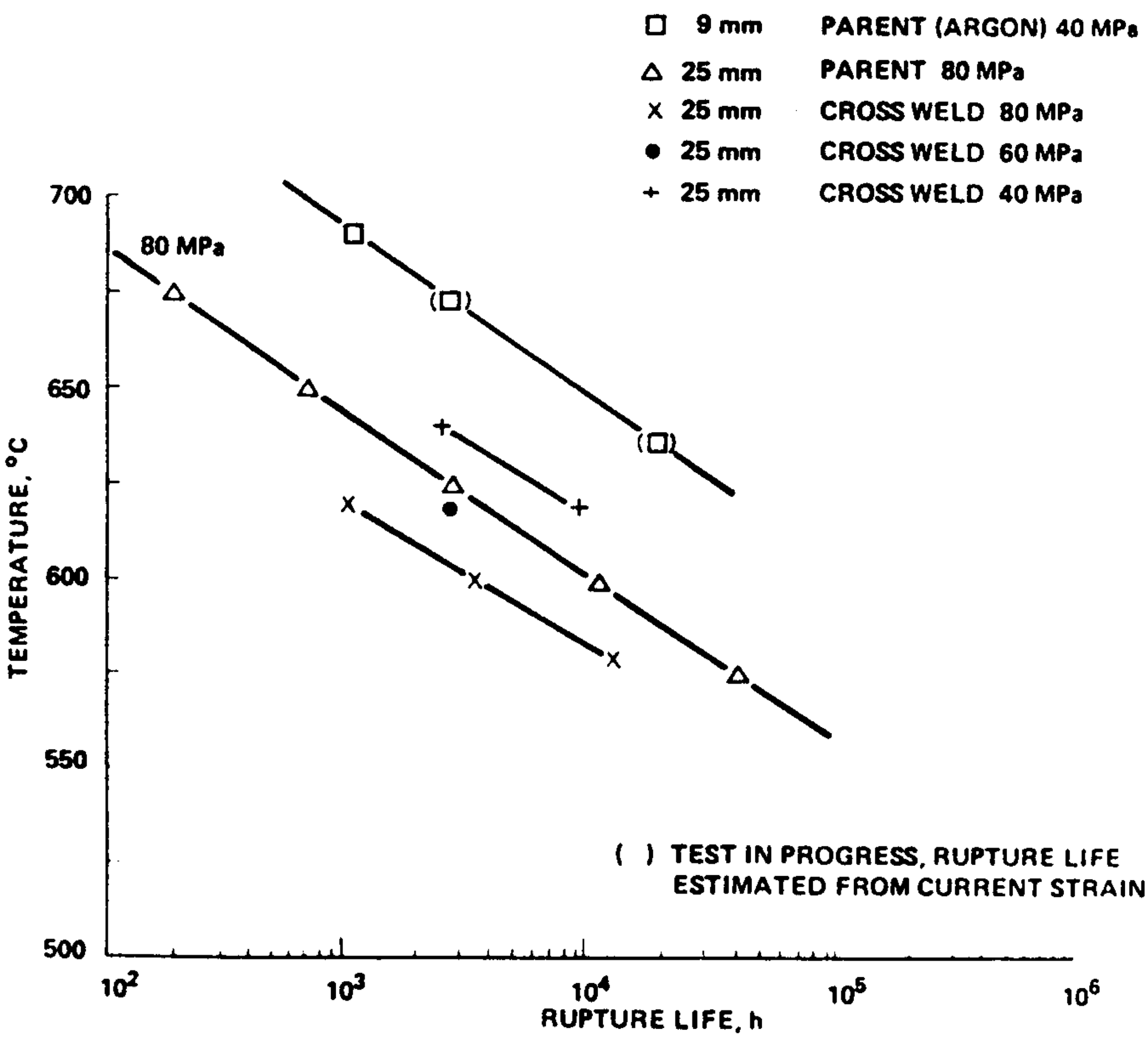

Figure 2-1
Cross Weld Rupture Properties for 1/2Cr-1/2Mo-1/4V (Gooch and Kimmins, 1987)

Gooch and Kimmins (1987) also performed creep crack growth tests on unexposed and pre-crept 1/2Cr-1/2Mo-1/4V weldments. The crack growth specimens failed by crack initiation and growth. Crack growth began upon loading for the creep damaged, pre-crept sample. For the unexposed weldments, crack initiation occurred at approximately 70% of the total life. Crack growth rates for the virgin weldment were typical of simulated fine grained material while the pre-crept weldment crack growth rate was about five times faster than that for the undamaged.

Reductions in creep life associated with Type IV failures and a tendency for subsurface cracking have also been reported by Parker and Parsons (1994) for a service exposed CrMoV weldment. Their studies emphasized the role of HAZ strain localization, base material creep ductility and inclusion distribution on Type IV fracture. The weldment had two base materials with different compositions but the welding procedure had produced comparable HAZ microstructures in each. The creep elongations at failure were low for the weldments based on the total gage length. However, using the gage length appropriate for the deforming HAZ zone, it was shown that strain accumulation localized in the HAZ. The maximum strain values were approximately 20% on the failed side of the joint as shown in Figure 2-2 (Parker and Parsons, 1996). Similar strain localization results have been found for 2-1/4Cr-1Mo by Laha, Rao and Mannan (1990).

Creep damage and Type IV cracking was found only in the base material that had the lower creep ductility and higher inclusion content of the two (Parker and Parsons, 1996). Based on these results, they concluded that the tendency for creep cavitation and Type IV cracking is related to local strain and inclusions at grain boundaries acting as cavity nucleation sites.

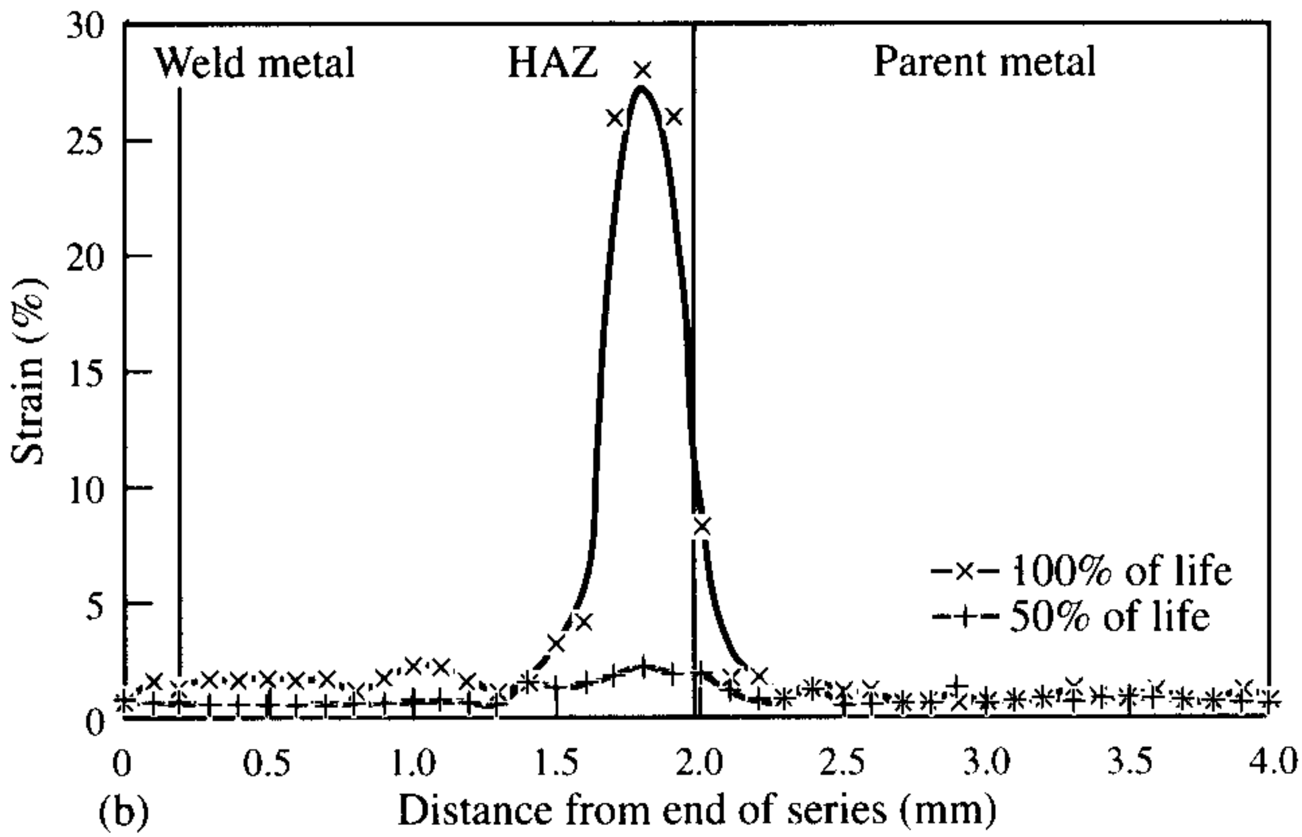

Figure 2-2
Strain Distribution on Failed Side of CrMoV Rupture Sample Showing Peak at Intercritical Region of HAZ (Parker and Parsons, 1996)

Walker, Kimmins and Smith (1996) performed interrupted rupture tests on virgin CrMoV cross welds made with a matching CrMoV welding consumable. The objective of the testing was to determine the evolution of creep damage measured by cavity density as a function of life fraction. These results are discussed in a subsequent section. The rupture lives for the weldments were approximately one third of that for the CrMoV base material.

1Cr-1Mo-1/4V

Weld repairs have been made on 1Cr-1Mo-1/4V turbine rotors to extend the service life. Stress analysis, metallurgical examination, and mechanical property measurements including tensile, Charpy and creep rupture tests were used to evaluate one repair (Bain, 1994). The GTAW welds were made using Modified 9Cr-1Mo weld metal with a controlled deposition sequence having many overlapping weld beads. The ASTM grain size was 5 for the base material, 9 in the coarse grained HAZ and 14 in the fine-grained HAZ. After PWHT, the hardness traverse showed the highest value of ~280 DPH in the weld and a linear gradient through the HAZ to ~220 DPH in the unaffected base. The rupture strength for the base material was near the top of the scatterband for unexposed base material, but the cross weld creep rupture tests failed at times significantly below that for minimum strength unexposed rotor base material. The failure location was the fine grained HAZ for the rotor repair weldments.

1-1/4Cr-1/2Mo

Following a failure in a main steamline girth weld by a Type IV failure mechanism, Ontario Hydro Technologies performed a failure analysis (Westwood, Clark and Sidey, 1990) and developed a life management strategy for high temperature steamline girth butt welds (Chan et al., 1991). In addition, they collaborated with University of Wales, Swansea on several fundamental experimental studies of Type IV cracking in 1-1/4Cr-1/2Mo steel discussed below.

Westwood (1995) compared the rupture lives of a virgin steampipe material and a service exposed material (75,000 hours at 1005°F (540°C)) in the form of base metal and in the form of welds. Both new and old welds had been sub critically stress relieved at 1337°F (725°C). Specimens one inch (25 mm) square in cross section were tested in the range of 1112°F to 1202°F (600°C to 650°C) at stress levels of 5.8 KSI to 11.6 KSI (40 to 80 MPa), and the results were extrapolated to estimate the remaining lives of the various materials under design conditions of 1005°F (540°C) and 5.8 KSI (40 MPa). These results shown in Table 2-1 lead to the conclusions that both new welds and welds to service exposed material are intrinsically inferior to the respective base metal conditions by nearly a factor of 5 (i.e., 20%) in terms of remaining lives, presumably due to Type IV cracking. Using the log stress versus Larson-Miller parameter curves for mean and minimum strength material given in the guidelines (Foulds et al., 1996), all of the weldment ruptures would be within the base material scatterband.

Table 2-1
Rupture Lives and LRF Values at 5.8 KSI (40 MPa) and 1005°F (540°C) for 1-1/4Cr-1/2Mo (Westwood, 1995)

Material	Time, h X 10^6	L.R.F.
New Parent	6.8	5.23
New Weld	1.3	
Old Parent	2.9	5.27
Old Weld	0.55	
New Weld	1.3	2.36
Old Weld	0.55	

Microstructural examination of the rupture samples revealed creep cavitation/cracking damage throughout the HAZ - CGHAZ, FGHAZ and ICHAZ - but no evidence of weld metal damage. Although microcracking was found in the coarse-grained HAZ, the failure location was the fine-grained HAZ for all samples. Westwood (1995) states that this dispersed HAZ damage morphology has been found in many service damaged weldments and, thus, the uniaxial cross weld samples achieved the desired goal of producing service-realistic creep damage. Examination of the interrupted samples indicated that surface examination can be misleading in the sense that significant damage could only be detected at the surface late in life (life fraction ~80% or greater) and damage tends to be at higher levels in the subsurface regions than at the surface.

Ellis, Borden and Schulte (1988) performed creep rupture and creep crack growth tests on service exposed 1-1/4Cr-1/2Mo longitudinal seam weldments. One sample had isolated creep cavitation damage in the fine grained HAZ and the second sample was undamaged. The rupture lives compared to unexposed minimum strength base material were approximately one half for the creep damaged weldment and equal for the undamaged weldment. The failure location for the damaged weldment was the fine-grained HAZ. The failure location for the undamaged weldment was the weld metal but creep cavitation damage was found throughout the HAZ. Significant crack growth was measured only at life fraction greater than approximately 60% for both damaged and undamaged weldments. For the crack growth specimen, creep damage and cracking was found in the weld metal at the fusion interface for creep damaged weldment.

To simulate the applied, axial piping system loading of a girth weld, an end loaded internally pressurized tube geometry was used by Parker, Stratford and Westwood (1992, 1993, 1994). Care was taken in the welding to produce model welds that had weld dimensional similitude and correctly modeled the microstructural characteristics found in the service welds. There were two welds per tube - weld A with a 1292°F (700°C) PWHT and weld B with a 1382°F (750°C) PWHT. The hardness traverse had no soft zone for either weld and the hardness values for weld A were similar to those for the service exposed welds. The tests were conducted in the temperature range of 1112°F (600°C) to 1193°F (645°C) at a hoop stress of 6.5 KSI (45 MPa) and axial stresses of twice, one and one half and one times the hoop stress. Because steam was used to produce the internal pressure and the horizontal orientation of the tube, the temperature at the top of the tube was approximately 36°F (20°C) greater than that at the bottom. Figure 2-3 compares the rupture properties for the uniaxial base metal tests and the end loaded, internally pressurized tube tests. The axial stress was used for the tube tests. Because the tube tests lasted substantially longer than the uniaxial base metal tests using this comparison, they concluded that a better method of describing multiaxial behavior — i.e., multiaxial stress rupture criteria, is required.

Because Type IV cracking was found for weld A at certain stress/temperature combinations but not for weld B, they concluded that Type IV cracking is related to factors affecting creep ductility such as PWHT, stress and temperature. Based on these tests, susceptibility to Type IV damage can be reduced in 1-1/4Cr-1/2Mo by maintaining a minimum PWHT of 1337°F (725°C).

To further study the effects of PWHT on creep fracture in 1-1/4Cr-1/2Mo welds, Parker and Stratford (1995a), Parker and Stratford (1995b) and Parker, Stratford, and Westwood (1996) reported results of creep tests on base material and weldments in four different heat treatment conditions - as-welded, PWHT for two hours at 1292°F, 1337°F and 1382°F (700°C, 725°C and 750°C). The fabrication procedure used to manufacture these weldments was discussed in an earlier paper by Parker and Stratford (1995a).

Temperature measurements during welding show that the thermal cycling is complex with up to seven excursion above 1472°F (800°C) recorded for the base adjacent to the weld fusion interface (Parker and Stratford, 1995a). Because a weaved welding technique was used, a high degree of refinement was attained in both the weld metal and HAZ microstructure. Creep tests on cross welds in the as-welded condition were performed at 1076°F (580°C) and 1112°F (600°C) at stresses of 19.6 KSI, 21.8 KSI and 23.5 KSI (135 MPa, 150 MPa and 162 MPa). All of the as-welded cross weld samples failed at the edge of the HAZ in the intercritically transformed region typical of "classical Type IV failures" at low uniform elongations. The HAZ failure is the result of strain localization in a creep weak zone. The low creep strength is believed to be the result of tempering or coarsening of the precipitates and the fine grain size. Metalographic examination of a cross weld sample after 375 hours at 1076°F (580°C) and 19.6 KSI (135 MPa)(life fraction of approximately 0.75) revealed significant cavitation and microcracking subsurface in the intercritical region of the HAZ but no damage at the outside surface of the specimen. The damage accumulation within the specimen interior is associated with the constraint on deformation by the stronger weld metal and base material.

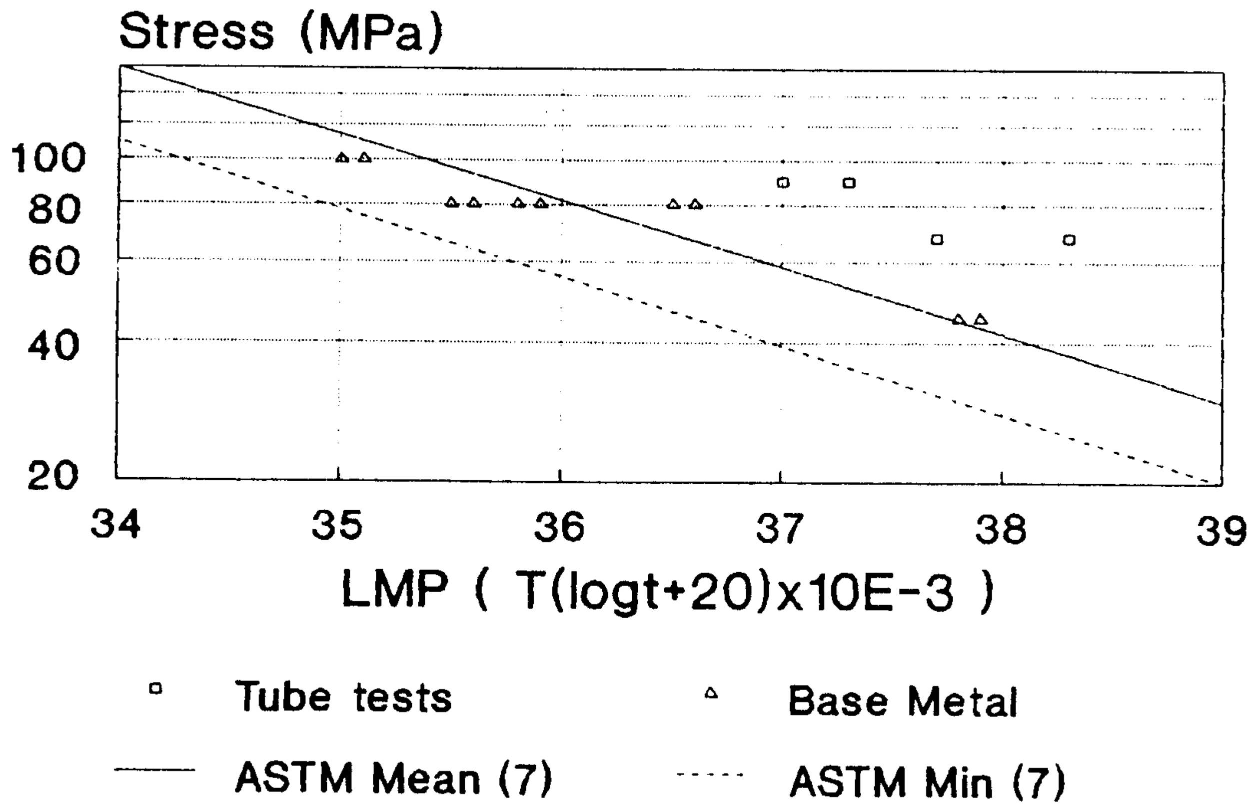

Figure 2-3
Comparison of Rupture Properties for 1-1/4Cr-1/2Mo Steel Uniaxial and End-Loaded, Internally Pressurized Tube Test (Parker, Stratford, and Westwood, 1993)

The weldment rupture lives increased with decreasing PWHT temperature (Parker and Stratford, 1995b). At 1076°F (580°C) and 11.6 KSI (80 MPa), the rupture lives as a function of PWHT were 2342 hours for 1292°F (700°C), 1812 hours for 1337°F (725°C) and 604 hours for 1382°F (750°C). Even at the highest degree of temper, the rupture strength of the base material was slightly above minimum compared to the ASTM data compilation. The failure location for the 1292°F (700°C) PWHT samples depended on stress, temperature and sample size with lower ductility Type IV failures found at longer rupture lives. All of the 1337°F (725°C) and 1382°F (750°C) PWHT samples failed in the base material. Because high tempering is believed to "homogenize the weldment microstructure and the creep strength", these tests indicate the importance of strength mismatch and creep ductility in Type IV cracking (Parker, Stratford and Westwood, 1996).

Parker and Stratford (1996) have studied the strain localization in several of the 1-1/4Cr-1/2Mo creep rupture samples discussed above. They used grain shape measurements for both the base material and weldments. The longitudinal strain, $\in_G$, was calculated using the equation developed by Rachinger:

$$\in_G = (N_L / N_T)^{2/3} - 1$$

where N_L is the number of grains/mm in the longitudinal direction relative to the specimen's axis and N_T is the number of grains/mm in the transverse direction relative to the specimen's axis. Results for the base material indicate that the grain elongation values are in reasonable agreement with diametrial strain based measurements and can reliably differentiate strains of ~10% or more. Because of the difficulty of grain definition for fine grained bainite microstructures, the strains were measured in the predominantly ferrite microstructure of the intercritical region of the HAZ for the weldment samples. Results for the weldments showed elongations from 14% to 22% for the HAZ and base metal strains from 1% to 4%. Although the creep tests were at much higher stress than typical of service, they concluded that outside surface strain monitoring should be an acceptable means of in-service damage detection and assessment.

Lundin, Kahn, Zhou and Liu (1995) have studied repair welding using low carbon content 1-1/4Cr-1/2Mo filler metal and controlled deposition welding procedures applicable to non-PWHT weld repairs. Repair welds were made in two 1-1/4Cr-1/2Mo longitudinal seam welded pipes. The rupture specimens were full wall thickness by one inch (25 mm) wide with the weld reinforcement left intact. Rupture test were conducted at 1125°F (607°C) and 10 KSI (69 MPa) on the service exposed weldments, as-weld repaired weldment and PWHT (1350°F (732°C) for one hour) weldments. Results are given in Table 2-2. Compared to the ASTM data for tests on small diameter base material specimens, all of the large cross section weldments were above minimum strength base material. The failure location for the repair welds was the outer boundary of the refined HAZ either in the original weld metal for the ½ inch (12.7 mm) thick weldments or in the service exposed base metal for the one inch (25 mm) thick weldments. Because both the service exposed and repair weldments with PWHT at 1350°F (732°C) failed by the Type IV mechanism, it is plausible that service failures in thin walled piping longitudinal seam welds could also fail by Type IV cracking as long as the PWHT is sub critical (not N&T).

Table 2-2
Weldment Rupture Properties for 1-1/4Cr-1/2Mo at 1125°F (607°C) and 10 KSI (69 MPa) (Lundin, Kahn, Zhou and Liu, 1995)

Condition	Rupture Life - Hours	Failure Location
½ Inch (12.7 mm) Thick		
Service Exposed Weldment	1429.7	Base metal remote
Repaired Weldment As-Welded (Controlled Deposition)	913.1	Repair weld refined HAZ in original weld metal
Repaired Weldment PWHT 1350°F (732°C), 1 hour (Controlled Deposition)	1423.1	Repair weld refined HAZ in original weld metal
One Inch (25 mm) Thick		
Service Exposed Weldment	924.5	Outer edge of fine grained HAZ in base
Repaired Weldment As-Welded (Controlled Deposition)	1494.9	Repair weld, outer fine grained HAZ in base
Repaired Weldment PWHT 1350°F (732°C), 1 hour (Controlled Deposition)	1021.1	Repair weld, outer fine grained HAZ in base

2-1/4Cr-1Mo

As a part of a study of austenitic-ferritic dissimilar metal welds (DMW), creep and creep rupture testing was performed on simulated HAZ material (Chilton, Price, and Wilshire, 1984; Evans and Wilshire, 1985). Short term thermal cycles were used to produce the coarse-grained, fine grained and intercritical HAZ materials. Test temperatures were 1050°F (565°C) and 1112°F (600°C). The measured creep rupture properties at 1050°F (565°C) for the normalized and tempered 2-1/4Cr-1Mo steel and the simulated HAZ structures are compared in Figure 2-4. The slopes of the stress rupture curves were nominally parallel for the simulated HAZ materials but steeper than that for the N&T base material. The strengths of the fine-grained and coarse-grained HAZ were approximately equal and slightly lower than that for the base material. The rupture lives of the intercritical HAZ material were significantly less than that of the base.

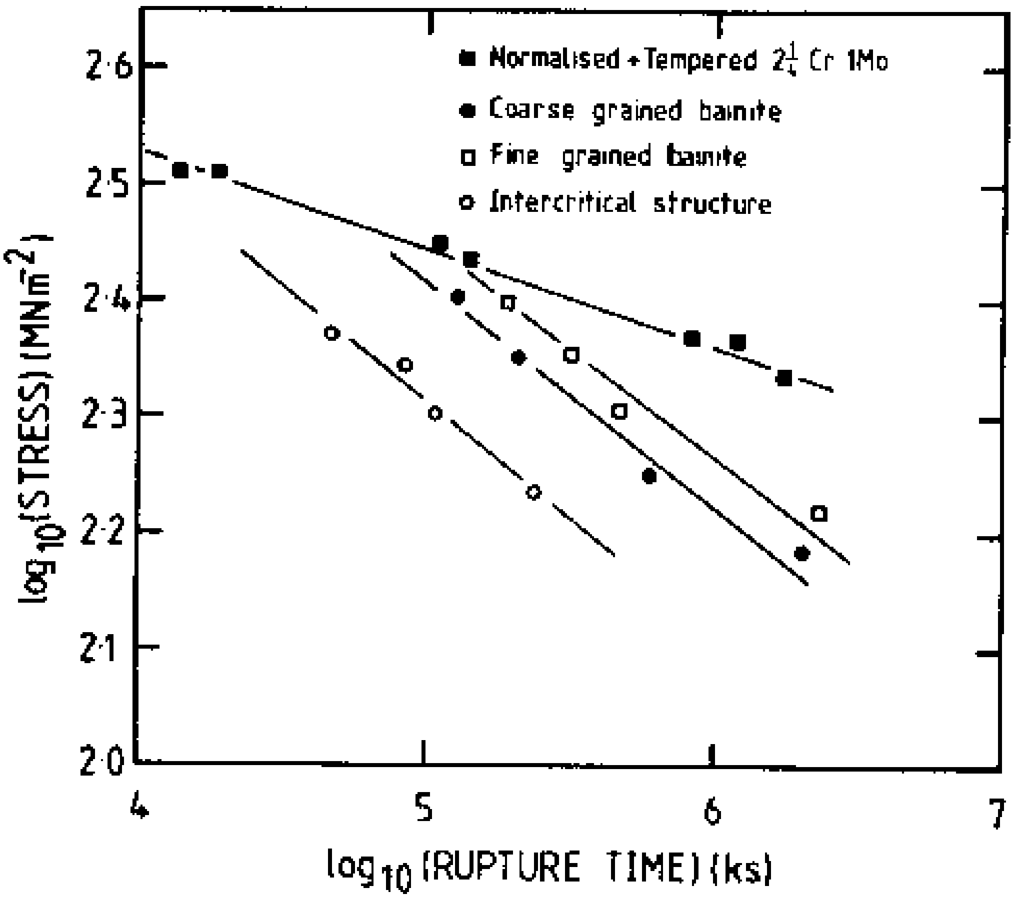

Figure 2-4
Comparison of Rupture Properties for N&T Base Material and Simulated HAZ for 2-1/4Cr-1Mo Steel at 1050°F (565°C) (Evans and Wilshire, 1985)

Because stress analysis was used to estimate the stresses and strains for the DMW joint, the minimum creep rate was also measured. Figure 2-5 shows that the slopes of the log minimum creep rate - log stress curves are the same for all materials at low stresses. The creep rate for the intercritical was the largest of all at low stresses. The average rupture ductilities were not strongly stress dependent at 1050°F (565°C) with values of 4% for the coarse-grained, 14% for the fine-grained and 16% for the intercritical.

The effects of PWHT on creep and creep rupture behavior of 2-1/4Cr-1Mo base material, weld metal and weldments was studied by Laha, Rao and Mannan (1990, 1992). The welds were made using SMAW process with basic coated electrodes and a single V joint geometry. The PWHTs were one hour at 1292°F (700°C) and 1472°F (800°C). The rupture strengths were lowest for the composite or weldment and were lower for the higher tempering condition of the 1472°F (800°C) PWHT. Metallography revealed transgranular fracture in the intercritical region for the composite specimens. The lower rupture strength for the intercritical region is associated with the virtual absence of Mo_2C carbides and the loss of particle strengthening (Roy and Lauritzen, 1986). The hardness traverse for the weldments showed the expected effect of PWHT and is played apparent soft zone at the edge of the HAZ in the intercritical region for the 1472°F (800°C)PWHT condition.

Isostress rupture tests at 6 KSI (41.4 Mpa) were performed on a service exposed longitudinal seam weldment and a girth butt weldment (Ellis, Steakley and Roberts, 1995). The rupture strengths of the two weldments were nominally equal and the fracture path was the same for both - the fine-grained region of the HAZ. Compared to the data in the NRIM data compilation, the rupture lives of the girth and long seam weldments were approximately 2/3 of that for unexposed minimum strength base material.

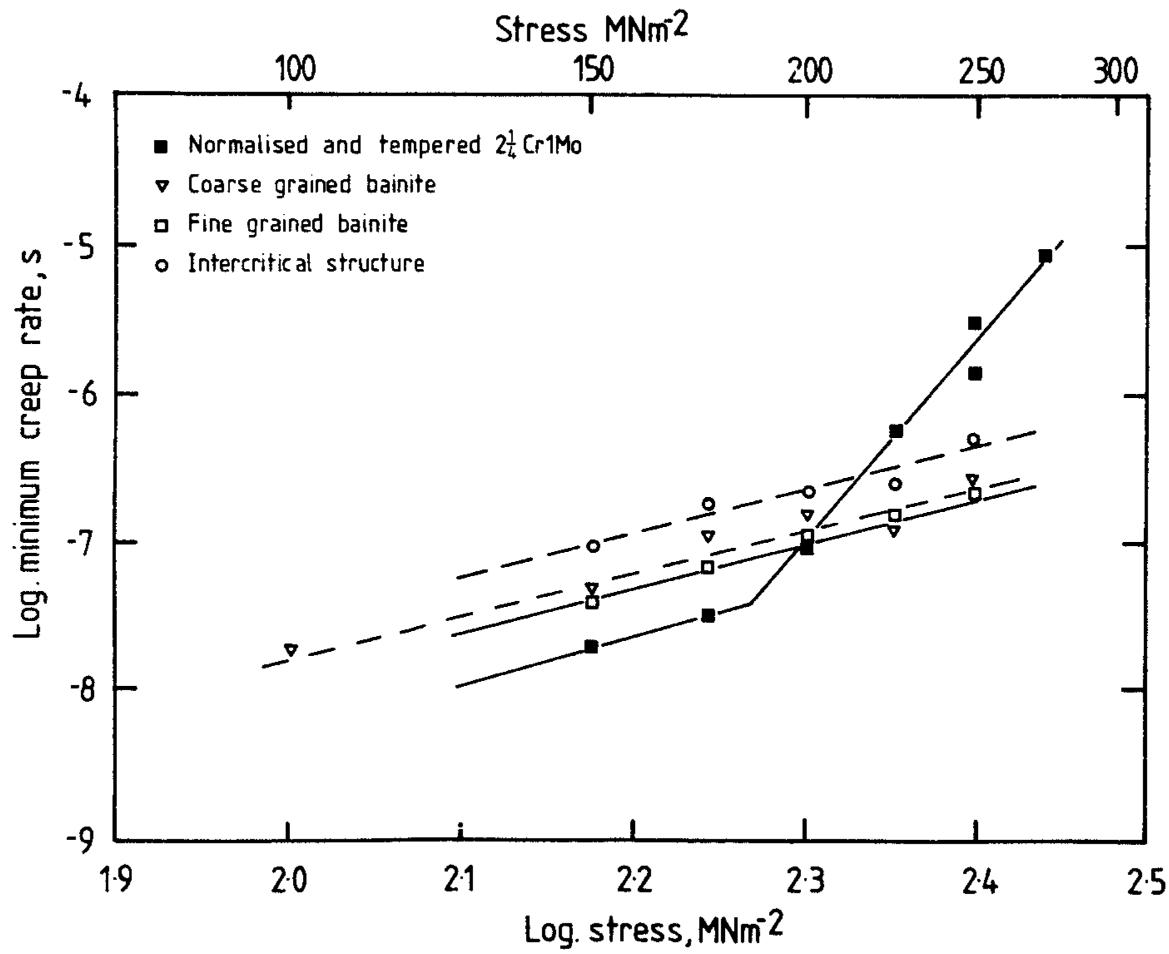

Figure 2-5
Comparison of Minimum Creep Rate Properties for N&T Base Material and Simulated HAZ for 2-1/4Cr-1Mo Steel at 1050°F (565°C) (Evans and Wilshire, 1985)

Blum and Hald (1994) reported results of piping system inspections and limited, short term creep rupture tests on service exposed base material and cross welds. The 2-1/4Cr-1Mo piping was tested after 170,000 hours at a nominal operating temperature of 1005°F (540°C). Isostress tests at 8.7 KSI (60 Mpa) and 36°F (20°C) increments for temperatures from 1184°F (640°C) to 1328°F (720°C) were used in the evaluation. The cross welds had an approximate life reduction of 30% compared to the base material.

Ripley and Snowden (1993) used miniature specimen tests to evaluate the remaining creep life of a service exposed superheater outlet header material. The creep and rupture properties were measured for the header base material, the longitudinal seam weld metal and HAZ. The rupture strength of the HAZ was near mean based on comparison with ISO data.

Several studies of unexposed cross welds have been performed. Boulisset et al. (1984) have performed cross weld tests at low temperatures and high stresses. They reported failure in the HAZ approximately 1/8 inch (3 mm) from the fusion interface but no significant life reduction for the weldments compared to the base material. Klueh and Canonico (1976) conducted a series of cross weld tests to study the effect of weld metal carbon content on rupture life. For the weld with 0.11% carbon, a slightly premature failure was found at the lowest stress condition. Again, this rupture time would be within the scatterband of properties for wrought base material.

Additional studies that have been performed on 2-1/4Cr-1Mo weldments (Henry and Ellis, 1990; Prager, 1992; Iwadate, Prager and Humphries, 1994) are discussed in the section on sample size effects.

Modified 9Cr-1Mo

Modified 9Cr-1Mo or Grade 91 steel is a high strength martensitic 9Cr steel that combines the advantages of high creep strength similar to Type 304 austenitic stainless steel with the high thermal conductivity and low thermal expansion typical of ferritic steels. When welded using conventional methods, the alloy is susceptible to Type IV cracking in the intercritical region or soft zone at the edge of the HAZ.

Three techniques to obtain satisfactory service performance using Modified 9Cr -1Mo steel have been discussed by Ellis, Henry and Roberts (1990) and by Roberts, Hackett and Canonico (1992). The techniques are the following: (1) limit applied axial loads for girth welds, (2) apply safety factors in design and (3) use a partial temper heat treatment following welding. The first recommendation would be applicable for girth butt welds in any Type IV cracking susceptible material. By limiting the applied axial stress or bending moment across the weld joint, the life of the welded joint is determined by the base material properties. For the case of girth welds of tubular Modified 9Cr-1Mo components, loaded by internal pressure only, Iseda et al. (1988) have shown that rupture occurs in the base material, and that there is no reduction in creep life for the welded component. Similar results for CrMoV tubular rupture tests have been reported by Williamson and Branch (1970) and Parker (1995a). Theoretically, the girth weld under internal pressure can be modeled as a parallel loading case and the hoop stress offloads to the stronger materials in the joint.

In creep-rupture test of Grade 91 cross weld specimens given the standard stress relief at temperatures of 1350°F (732°C) to 1400°F (760°C), the failures are localized in the soft zone at stress levels approaching 20-25 percent below those of the base material. Thus, a second method to insure good service performance is to use stress reduction factors for welded components (Corum, 1990). The stress reduction factors are the ratio of the average weldment strength to the average parent metal strength. Analysis of the weldment rupture data was performed and the values were submitted to ASME for possible inclusion in ASME Code Case N-47. The stress reduction factor are a function of time and temperature. At a typical operating temperature of 1100°F (593°C), the weldment/base material strength ratio varied from 0.91 at 100 hours to 0.84 at 300,000 hours. Modified 9Cr-1Mo is not the only material that has weldment stress reduction factors in Code Case N-47. For example, Grade 22 (2-1/4Cr-1Mo) welds have a stress reduction factor of 0.96 at 1000°F (538°C) and 100,000 hours.

Because the heat treatment condition of the base material and the welding sequence determine the final microstructures in the welded component, a modified fabrication sequence has been used for Grade 91 to minimize the soft zone at the edge of the HAZ. The standard PWHT uses one hour per inch (25 mm) at 1350°F (732°C) to 1400°F (760°C). In this partial temper approach, the material to be welded is normalized at the usual temperature, partially tempered at 1125°F (607°C) to 1292°F (700°C), welded, and final PWHT at 1350°F (732°C) to 1400°F (760°C). Limited testing at 1000°F (538°C) and 1100°F (593°C) have shown improvements in the stress rupture strength for the partial temper welding procedure (Brinkman et al., 1987).

Allen (1994) has studied the effect of base material heat treatment, welding procedure, and PWHT variables on the formation of the soft zone in Grade 91. Statistical analysis of the hardness drop (defined as difference between soft zone and base material hardness) was used as a basis for evaluation of the variables. The partial temper or half temper method showed a substantial reduction in hardness drop. Addition documentation of improvement in creep strength for partial temper weldments were also provided by the results of Coussement and De Witte (1988). Reduced weld heat input also developed reductions in the hardness drop and creep tests showed a small improvement in weldment rupture strength.

An initial assessment of the potential for Type IV failure in piping girth welds made with Grade 91 and X20CrMoV121 was undertaken by Middleton (1990). Strength reduction factors of 20% and 40% were used in the analysis and it was assumed that Type IV failure depended only on the maximum principal stress, i.e., stress state effects were considered small and ignored. Results indicate piping systems fabricated from either material would not have problems at temperatures of 1005°F (540°C) and 1050°F (565°C), but may require limits on applied system stresses at 1112°F (600°C).

Isostress testing was performed on Grade 91 cross welds of various cross section sizes and simulated HAZ material (Middleton and Metcalfe, 1990). Comparison of extrapolation of the isostress the test results for the cross welds with the ORNL data for average strength base material indicated a loss in rupture strength at 1058°F (570°C) of 23% at 19.6 KSI (135 Mpa) and 35% at 13.8 KSI (95 Mpa). To study the effect of austenitization temperature on rupture life, specimens were heated for 5 minutes at temperatures from 1472°F (800°C) to 1922°F (1050°C), then tempered one hour at 1350°F (732°C), typical of a stress relief. The rupture lives as a function of austenitizing temperature showed a broad minimum from 1562°F (850°C) to 1742°F (950°C) with lowest values at 1562°F (850°C). Sample size effects are discussed later in the report.

The effect of cold bending and welding on the creep life of T91/P91 material was studied using isostress tests at 14.5 KSI (100 MPa)(Arav et al., 1992). As expected, failure for the weldments was in the HAZ and the 10^5 hour stress reduction factor at 1112°F (600°C) was 15% compared to actual base material and ~20%-25% compared to the ASME base material values. Based on metallographic examination of the base material and the fine-grained HAZ, it was believed that the loss in creep strength could be explained by the change in the lath martensite with a high dislocation density typical for the unaffected base material into equiaxed cells for the HAZ.

12Cr-1Mo-1/4V (X20)

The creep behavior of 12% CrMoV steel weldments was studied by Kussmaul, Maile and Theofel (1987). Both cross welds and simulated HAZ specimens were used. Although the rupture strength of the weldments were below average at longer test times (approaching 100,000 hours at 1022°F (550°C)), they remained within the scatterband for the base material (±20% on stress) at 1022°F (550°C) and 1112°F (600°C). There were three different weld heat inputs used in the study. The rupture times were nominally the same for the different heat input welds, but there were slight differences in the width of the cavitation damage in the HAZ. Metallographic examination of rupture samples revealed a change in fracture location from base material to coarse-grained HAZ to fine-grained HAZ with increasing rupture time at 1022°F (550°C). A weldment specimen interrupted at 50,000 hours (expected rupture life of 120,000 hours) and 0.35% creep strain was found to have creep cavities in the HAZ. The simulated HAZ creep properties were used in a stress analysis. Analysis predicted an off loading of the stress to the higher strength regions of the HAZ. The rupture location was predicted at the edge of the HAZ in agreement with experiments.

Hald (1990) has studied the structure-property relation for 12 CrMoV weldments. The creep weak zone is the intercritical HAZ (IC-HAZ) that experienced peak temperatures of 1517°F (825°C) to 1832°F (1000°C). The microstructure of the IC-HAZ had larger subgrains, a lower dislocation density and larger, more spherical carbides compared to the base material. Although the IC-HAZ width was wider for higher interpass temperature, there was no apparent difference in the IC-HAZ microstructure as a function of interpass temperature. Repair welds are expected to have lower creep strength than original welds because secondary hardening will be less for repair welds.

The failure mechanism map for 12CrMov has three regions; (1) transgranular base material failures at high stress-low temperature, (2) transgranular HAZ fracture at low stress-high temperature and (3) intergranular HAZ fracture at low stress-low temperature (Hald, 1990). The fracture position is associated with changes in the constraint in the weak IC-HAZ as a function of the stress exponent in the minimum creep rate relation (Nicol and Williams, 1983). The intergranular IC-HAZ fracture is the result of the triaxial stress state that favors creep cavity nucleation. Because the strength mismatch is greater between the fine-grained HAZ and the IC-HAZ than between the base material and the IC-HAZ, the fracture position is expected to be close to the IC-HAZ to fine-grained HAZ interface.

Effect Of Sample Size On Rupture Life

Viswanathan and Foulds (1997) have reviewed accelerated stress rupture testing for life prediction including the effect of specimen size on rupture life and weldment behavior. For homogeneous specimens, the effect is a result of sample oxidation, with longer lives for larger diameter samples compared to smaller diameter samples.   They have developed an oxidation correction factor for accelerated rupture test data in order to improve the life prediction of operating components. For inhomogeneous weldments, the focus was the application of weldment isostress rupture data to a uniaxially loaded weldment. Included in the discussion were sample size effects, the inherent weakness of weldments, weld geometry effects and strain concentration. With regard to sample size, both the failure location and failure mechanism (stress controlled for small samples versus strain controlled for large samples) can change with specimen size. Because the sensitivity to sample size will vary with the specimen geometry, test conditions of applied stress and temperature, and creep strength/ductilities of the various zones, quantitative correlations between the rupture lives of small and large specimens cannot be established. Therefore, they recommend that accelerated tests on weldments should use large samples which simulate the weld geometry and microstructure. Additional results for the sub critical annealed weldments susceptible to Type IV cracking are discussed below.

Parker (1995) has discussed sample size effects including gage length and gage diameter for creep testing of homogenous materials and weldments. For homogeneous materials, gage lengths less than three diameters were shown to increase rupture life due to end restraints. Bending moments developed by non-axiality in the load application also reduces rupture lives. The effect of non-axiality is a function of specimen diameter and decreases as specimen diameter increases.

For creep testing of cross weld tests, Parker (1995) suggests a specimen geometry with a gage length, L, as follows;

$$L = 5\,d + W$$

where d is the specimen diameter and W is the length of the weld metal. Based on USA standards, a gage length of 4 d + W would be acceptable. Using the available data for CrMo weldments that fail by the Type IV mechanism, Parker (1995) concluded that the rupture life increases as specimen size or diameter increases.

Prager (1992) performed creep rupture test on specimens with a range of gage diameters for both N&T and sub critical PWHT 2-1/4Cr-1Mo weldments. Results were plotted on a log rupture time versus log specimen area basis for the tests at high stress/low temperature test conditions and at low stress/high temperature test conditions. Based on the test conditions selected, it was believed that oxidation effects on rupture life were small. In these tests, the rupture lives increased by a factor of two to four. Similar increases in life as a function of sample size for renormalized and tempered weld metal have been found by Ellis and Brosche (1993) and Henry and Ellis (1990). Using the rupture data of Henry and Ellis (1990), the slope of the log rupture time versus log specimen cross section area plot was calculated as 0.21 (Ellis, 1994).

An explanation for the increase in life with increase in sample dimension was given by Iwadate et al. (1990). They propose that the behavior of the weldment with a narrow, soft HAZ region is analogous to a braze joint. The stronger base material and weld metal adjacent to the HAZ results in triaxial stresses in the HAZ that constrains the deformation of the weaker HAZ zone. For a fixed HAZ width, as the size of the specimen is increased, the restraint to deformation and necking increases and results in an increase in rupture life.

Kussmaul et al. (1987) performed creep rupture tests on dissimilar metal weldments of 1%CrMoV and 12%CrMoV. Both conventional size specimens of ½ inch (12 mm) diameter and large scale specimens with cross sections of 1.2 inch X 3.5 inch (30 mm X 90 mm) were tested. The tests were conducted at 1022°F (550°C). For the conventional size specimens, failure at high stresses was in the coarse-grained HAZ of the 1%CrMoV at time comparable to those of the base material. At lower stresses, premature failures compared to the base material were found. At 12.3 KSI (85 Mpa), the fractures were in all HAZ zones - coarse-grained, fine-grained (~A_{C3}) and intercritical (~A_{C1}). The large transverse specimens had a rupture life approximately twice that for the conventional size specimens.

In contradiction to the above results, a minimal effect of sample size on life was found for 1-1/4Cr-1/2Mo as shown in Figure 2-6 (Parker, Stratford and Westwood, 1996) and no effect was found for Grade 91 (Middleton and Metcalfe, 1990). Results for Grade 91 are given in Table 2-3. The sample size effect saturated at 0.236 inch (6 mm) and the 0.118 inch (3 mm) diameter sample is representative of the unconstrained strength of the Type IV zone. It is believed that a slight or nonexistent sample size effect on rupture life is associated with the several features of the creep cavitation mechanism typical of Type IV deformation. It is hypothesized that numerous inclusions act as cavity nucleation sites and cavity growth occurs throughout life accompanied by an increase in the size of the deforming zone (Middleton and Metcalf, 1990).

Table 2-3
Effects of Sample Size on P91 Weldment Rupture Lives at 13.8 KSI (995 MPa) and 1202°F (650°C) (Midleton and Metcalfe, 1990)

Section Size - inches (mm)	Life - hour
2.36x1.57 (60x40)	300
1.57x.0.79 (40x20)	240
1x0.47 (25x12)	380
ϕ 0.353 (9)	281
ϕ 0.236 (6)	260
ϕ 0.118 (3)	88

Both sets of results and explanations for sample size effect capture vital elements of the Type IV cracking phenomenon. Any comprehensive model of Type IV cavitation/life would have to explain the apparent divergent rupture life behavior. A common element in both explanations is high hydrostatic stresses or triaxial stress state. The magnitude of the triaxial stress or hydrostatic stress state would depend on the specimen diameter, zone sizes and strength mismatch in a simple five material model - weld, CGHAZ, FGHAZ, ICHAZ and base. The difference in the two observed behaviors would appear to be the difference in the ease of cavity nucleation associated with the presence of suitable inclusions. For creep brittle materials having suitable inclusion distributions and strengths, the hydrostatic stress is sufficiently high to cause cavity nucleation and there is essentially no sample size effect on rupture life. For the creep ductile Type IV zone with improved inclusion distributions and/or higher inclusion/matrix interface strengths, some deformation of the surrounding material is required to accomplish cavity nucleation. This is an obvious analogous situation to that for the interface cracking found in longitudinal seam weldments.

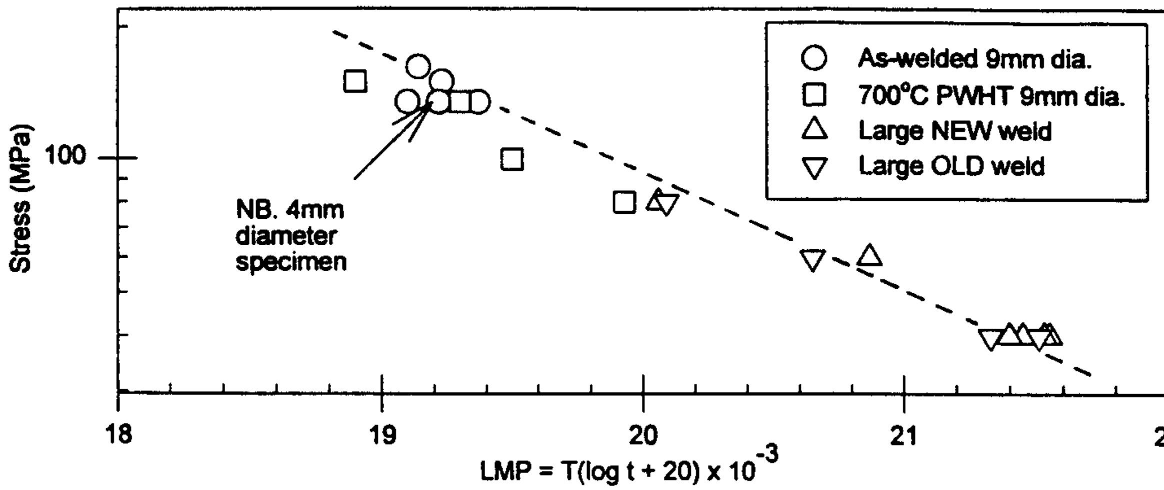

Figure 2-6
Effect of Specimen Size on Rupture Lives for Low Ductility Failures of CrMo Weldments (Parker, Stratford and Westwood, 1996)

Creep Damage Evolution

Gooch et al. (1990) have discussed the role of field replication in creep cavitation life assessments of high temperature components. They also concluded that "A" parameter measurements were not practical for Type IV cavitation because of the difficulty of accurately defining the grain boundaries in the fine grained microstructure. They indicated that outside surface based inspections using cavity density would be expected to be useful to determine time to crack initiation in some cases. Quantitative assessment is expected to be used for those cases where the stress distribution through the wall thickness was known such as longitudinal seam welds. For the girth welds in piping systems with known sub-surface initiation and complex stress distributions, it was believed that qualitative approaches would continue to be used in the future.

For life assessment, the damage mechanism and evolution of damage as a function of life fraction are important considerations. The damage mechanism for the Type IV zone is creep cavitation. Because advanced Type IV damage is characterized by profuse intergranular cavitation, it is readily conceded that the traditional approaches for damage characterization such as Neubauer's damage classification scheme or the "A" parameter are inappropriate (Foulds et al., 1996). Alternate life assessment methods for Type IV cavitation discussed below include a modification of the qualitative damage classification scheme and a cavity density based model.

Clark et al. (1993) have discussed a qualitative approach to cavitation assessment for Type IV damage in piping girth welds. It became apparent based on the results of extensive inspections of girth welds that a wide range of damage was being detected in the damage classification of level A - isolated cavities. In order to deal effectively with dispensation of piping, it was decided to subdivide the level A damage class into three sublevels: extremely isolated, isolated and dense. Definition of the sublevels are based in part on cavity density with dense corresponding to greater than 1000 cavities/mm^2.

Bissell, Cane and De Long (1988) have studied the cavitation damage in longitudinal seam welded hot reheat piping after approximately 170,000 hours of service. Eight through thickness core samples were removed from two different diameter steamlines. The weld geometry was variable but all welds had received a sub critical PWHT. Cavity density, cavity size and the A parameter were measured. The highest level of damage was found in the doubly refined HAZ at the cusp of the weld. Post exposure rupture test were conducted at 5.1 KSI (35 MPa) for specimens at three different through wall positions. Consistent with the observed damage levels, the creep rupture strengths of the cusp weldments were the lowest. The higher damage at this position in the weldment was believed to be due to the hydrostatic stress associated with the weld geometry and a creep strength mismatch between the base material (weak/soft) and the weld metal (hard/strong) indicated by hardness measurements. Their data showed an inverse relationship between the cavitation rate (cavity density divided by service time) and the maximum hardness difference ratio defined as the peak hardness ratio between the constituents of the microstructure - in this case the base metal hardness divided by the weld metal hardness.

Based on a cavitation rate - strain rate relationship and continuum damage mechanics, a life prediction model was derived relating life fraction, LF, to cavity density:

$$LF = t/t_r = (1 - (1-N/N_r)^{\lambda})$$

where t is time, t_r is the rupture time, N is the cavity density at time t, N_r is the cavity density at rupture and λ is the ratio of the rupture ductility to the Monkman-Grant constant (Bissell, Cane and De Long, 1988). They used a value for λ of 10 which is typical for a creep ductile material. Examination of the rupture specimens from the cusp region of the weld indicated that cavity density at rupture in the doubly refined region of the HAZ was in the range of 9000 to 12,000 cavities/$mm^{2.}$ The model is not extremely sensitive to N_r, but the value is expected to vary from application to application.

Using the life fraction value calculated above, the remaining life, t_{rem}, can be calculated from the following:

$$t_{rem} = t_s * (1 - LF) / LF$$

where t_s is the time in service. For life assessments based on smooth bar rupture properties such as the cavity density approach, the assessed remaining life usually corresponds to time to crack initiation for the component, not failure.

Because the Type IV cracking has been found in the HAZ of longitudinal seam weld metal, life assessment and damage evolution techniques are also required for the weld metal. Ellis et al. (1989) performed a failure analysis for a 2-1/4Cr-1Mo longitudinal seam weld that had developed a 60 percent through wall crack. For the weld metal near the inside diameter surface, the cavitation damage was advanced and characterized by a high cavity density and large average cavity diameters. Because of the fine-grained character of the weld microstructure, the cavities did not have the distinct oriented cavitation appearance. They concluded that the A parameter characterization was inappropriate and used the cavity density method described above. Based on the results of creep tests on SA weld metals, the measured value for λ was from approximately 3 to 7, with the lower value typical at the lower test temperature typical of service (Henry, Ellis and Lundin, 1990). For the I. D. weld bead of the service exposed weld, the average cavity density remote from the cracking was approximately 3900 cavities/mm^2. The cavity density at rupture was approximately 9500 cavities/$mm^{2.}$ Using these cavity density values and λ of 5, the life fraction consumed was calculated as 0.92 in good agreement with the observed life fraction found by rupture testing.

Walker, Kimmins and Smith (1996) have studied the evolution of creep damage in 1/2Cr-1/2Mo-1/4V weldments. The test welds used a matching composition filler metal and were given a PWHT at 1292°F (700°C). The specimens design was the same as that used by Gooch and Kimmins (1987) with a one inch (25 mm) square cross section. The cavity density was measured on the cross welds at selected interruption times using surface plastic replication. Unfortunately, the results were normalized with respect to cavity density at 8.7 KSI (60 MPa) instead of actual cavity density. At 8.7 KSI (60 MPa), result were consistent at the three test temperature of 1112°F, 1148°F and 1184°F (600°C, 620°C and 640°C) with the expected upward curvature for cavity density versus life fraction as shown in Figure 2-7. Comparison of the cavity density versus life fraction data in Figure 2-7 with predictions of the model discussed above indicates an underprediction if a value of λ equal to 10 is used. The agreement of calculated and observed is improved if a value of λ from 2.5 to 3 is used. Lower values of λ are usually associated with creep brittle materials.

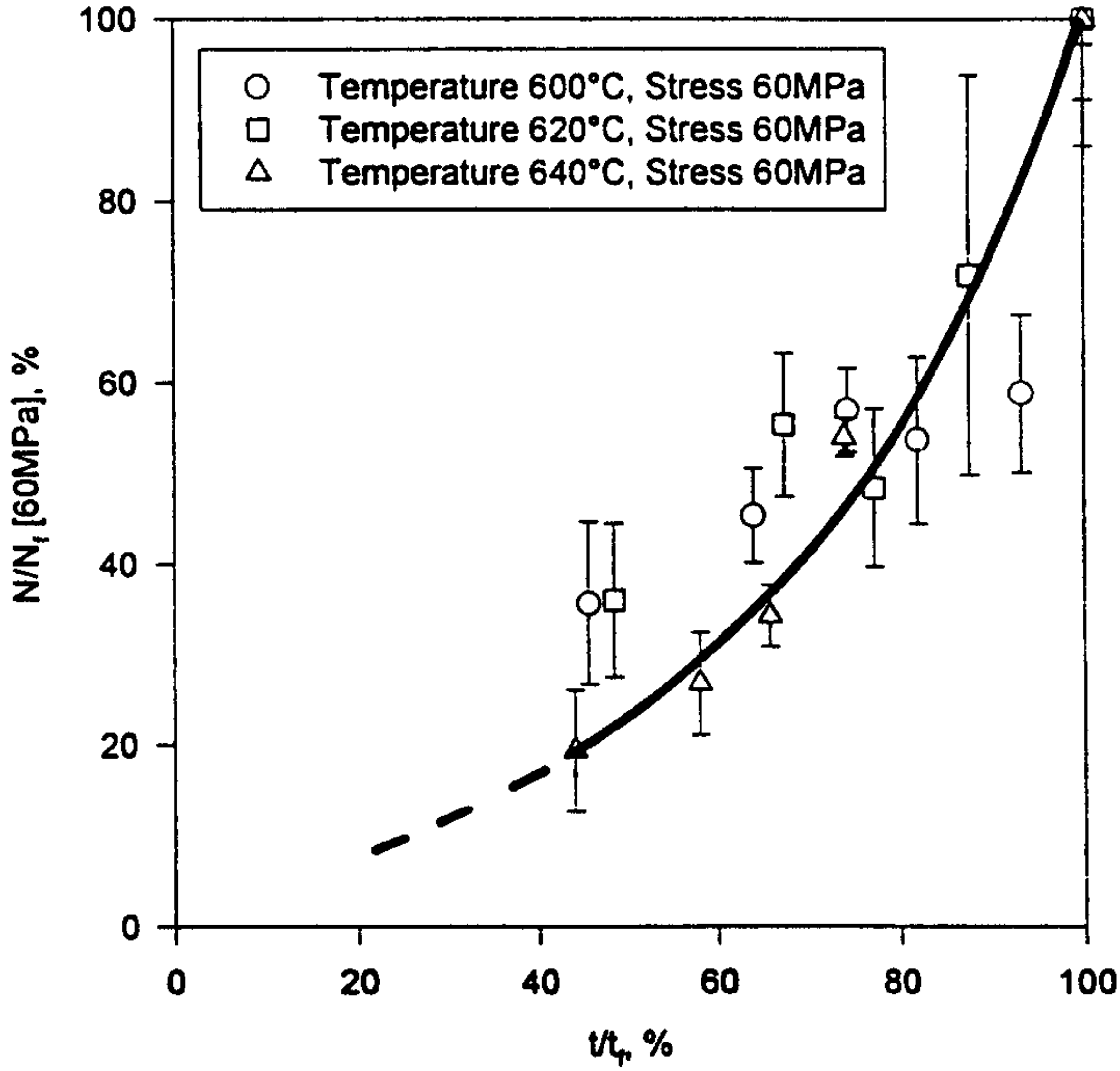

Figure 2-7
Normalized Type IV Cavity Density Versus Life Fraction for CrMo V Weldments at 8.7 KSI (60 MPa). N_r is the Cavity Density at Failure. (Walker, Kimmins and Smith, 1996)

Stress Analysis

Three stress analysis results are discussed. Nicol and Williams (1982) performed a steady state creep analysis for the cross weld geometry with two materials. For a creep weak zone such as the Type IV region, the calculated axial strain rate at the center of the zone was a function of the length of the zone, z, divided by the specimen thickness, h, as shown in Figure 2-8. For sufficiently thick zones, ~z/h = 2, the strain rate at the center of the zone equals that for the unconstrained material. They also studied the effect of the material properties on the deformation. A schematic illustration of the strong effect of the Norton stress exponent in the minimum creep rate equation on the creep rate distribution is shown in Figure 2-9 (Hald, 1990). Basically, at low values typical of service condition, the constraint on deformation of the soft material by the surrounding harder material is greatly reduced.

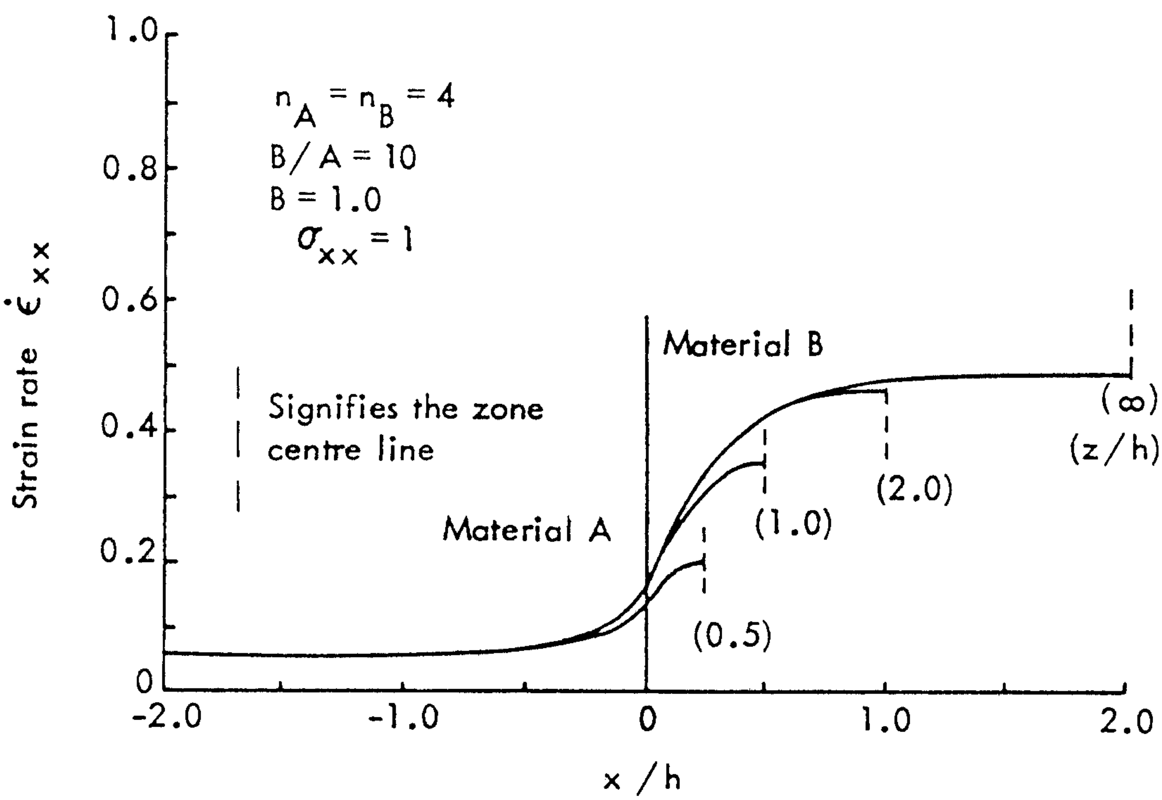

Figure 2-8
Axial Strain Rate Distribution as a Function of Soft Zone Size (Nicol and Williams, 1982)

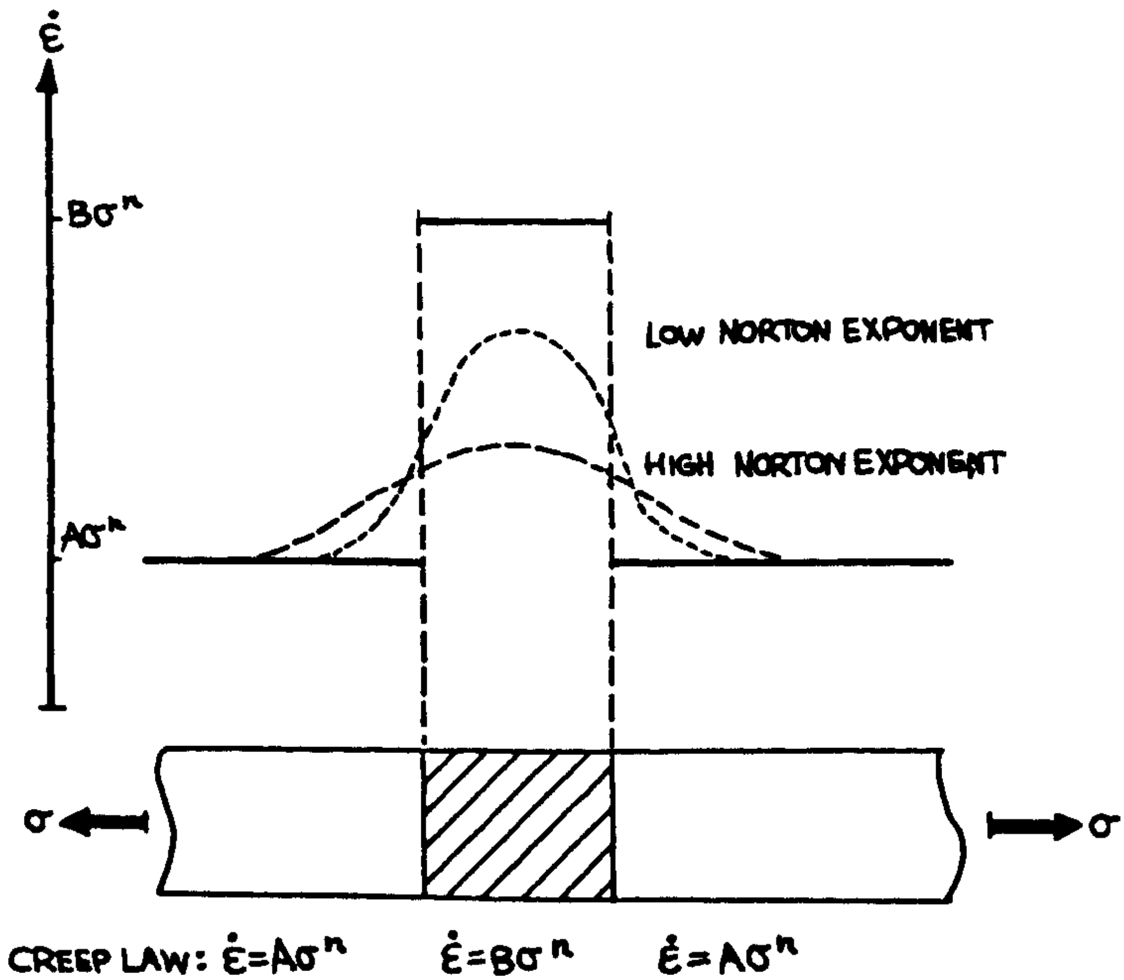

Figure 2-9
Schematic Illustration Showing Effect of Stress Exponent Strain Rate Distribution in a Cross Weld Specimen (Hald, 1990)

To study the complex stresses in the cross weld, two stress state parameters were used; (1) effective stress divided by maximum principal stress and (2) triaxility factor of hydrostatic stress divided by effective stress (Nicol and Williams, 1982). The triaxility factor is inversely related to rupture ductility and increased sharply in the soft material as the interface was approached. Several techniques were used to estimate the failure time and location, but are not discussed here.

Storesund, Tu and Wu (1992) have performed finite element stress analysis for a cross weld having three materials - weld, HAZ and base. The minimum creep rates for the base and weld were approximately equal and the HAZ rate was approximately five times the base/weld rate. Figure 2-10 shows the results of the analysis for the effective stress and multiaxial stress rupture criteria stress distributions. Within the HAZ, it is significant that the rupture stress is greater subsurface than at the outside surface. This analysis suggests that subsurface cracking observed in uniaxial cross welds is the consequence of higher rupture stresses subsurface generated by the creep rate mismatch.

Hayhurst and Perrin (1995) have performed a finite element stress analysis for a girth butt welded pipe loaded by combined internal pressure and applied axial loads. The narrow Type IV region was modeled. The constitutive equations had two state variables in order to describe damage accumulation due to both carbide coarsening and creep cavitation. For the internal pressure loading alone case, failure was predicted at 50,000 hours by macrocracking at the fusion interface. Failure of an all base material pipe would be expected in 60,000 hours. The second case had internal pressure and axial load. The ratio of the axial stress to the mean diameter hoop stress in an unwelded pipe was unity for this case. The failure time was 27,000 hours and the failure path was the Type IV region.

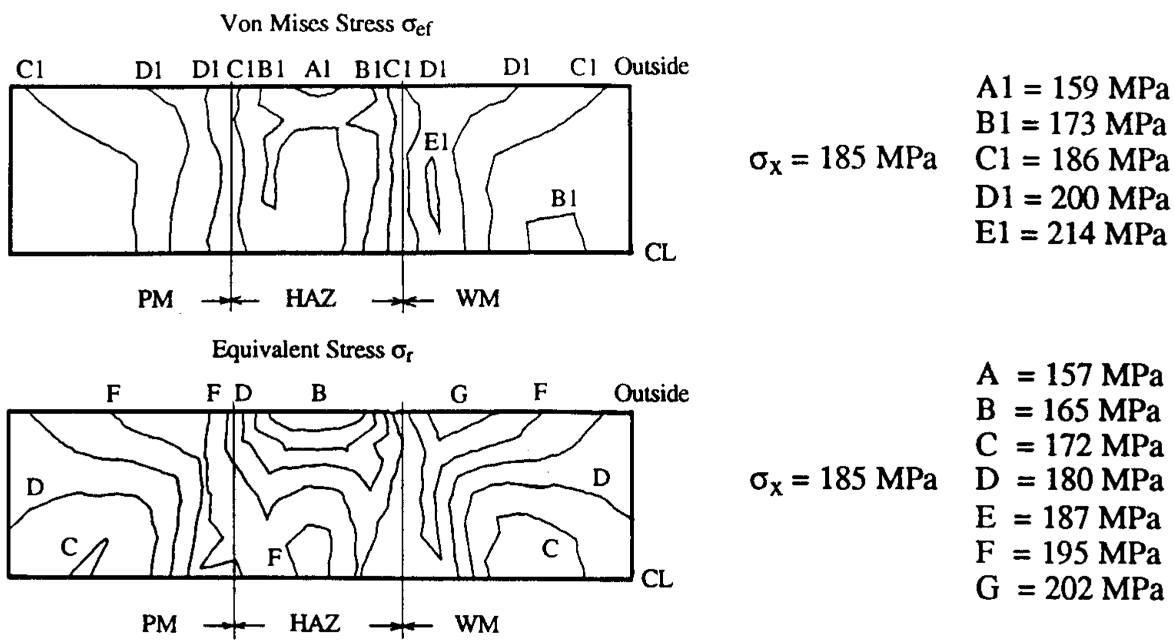

Figure 2-10
Stress at Steady State Creep for a Cross Weld Specimen (Storesund, Tu and Wu, 1992)

3

SERVICE EXPERIENCE

Introduction

This section reviews the service experience with Type IV damage in both girth welded and longitudinal seam welded piping. Included in the discussion are details regarding the Type IV damage/failure mechanism, known problem areas, and examination techniques that have been found useful for the detection of Type IV damage.

In assessing the potential for failure of a welded component, it is convenient to consider the variables that affect life in three categories - operational, geometry and material. So far in this review, the effect of material variables of heat treatment, zone strengths, composition, stress state, and inclusion content on creep ductility have been discussed. Important operational variables are time, temperature, internal pressure, applied piping system loads as well as any cyclic or transient conditions. Geometry variables include pipe dimensions, straight versus bent pipe, weld orientation - circumferential or longitudinal, joint geometry - double V, J or U groove, zone widths, cusp angle for double V, and roof angle for longitudinal seam welded pipe (Buchheim et al., 1994).

There are several important differences between girth and longitudinal seam weldments. First, most girth welds have been given sub critical PWHT whereas the longitudinal seam welds have been given either the sub critical (common in main steam link piping) or re-normalized and tempered (usual for HRH piping) heat treatment following welding. A second, major difference between girth and longitudinal seam welds is the direction of the hoop stress loading and the orientation of the creep weak Type IV zone for the pipe geometry under internal pressure loading. Kimmins, Coleman and Smith (1993) have discussed the theoretical difference in the creep behavior of the weld joints using a parallel model for the girth weld and a series model for the longitudinal weld. Based on the analysis results for a weak weld metal loaded in parallel, they conclude that the narrow Type IV zone would also be constrained by the surrounding stronger material and not deform in the hoop direction. For the series loading of the Type IV zone in a longitudinal seam weld, constrained deformation is predicted. The predicted creep life depends on the multiaxial stress rupture criteria used in the analysis.

Girth Welds

Based on service experience with 1/2Cr-1/2Mo-1/4V pipe girth welds, the potential for premature failure by the Type IV damage mechanism was recognized early on - mid 70's to early 80's. The damage classification scheme for weldments currently in use was developed specifically in response to the type of cracking typical found in CrMoV piping girth welds (Schuller, Hagn, and Woitscheck, 1974). Because there were different failure modes, it was expected that there would also be characteristic failure time associated with each cracking type — I to IV. Figure 3-1 shows a schematic representation of the failure/repair probability statistics for a weld having four failure/damage mechanisms (Williams, 1982). Curve A is the expected lifetime for the homogeneous component, i.e., the pipe base material. Premature weldment cracking mechanism lives are represented by curves B, C, and D. Curve B is for stress relief cracking in the HAZ, a Type III mechanism. Curve C is the transverse weld metal cracking of either Type I or II. Curve D is for the Type IV failure mechanism and is often termed mid-life cracking because of its characteristic failure/repair time.

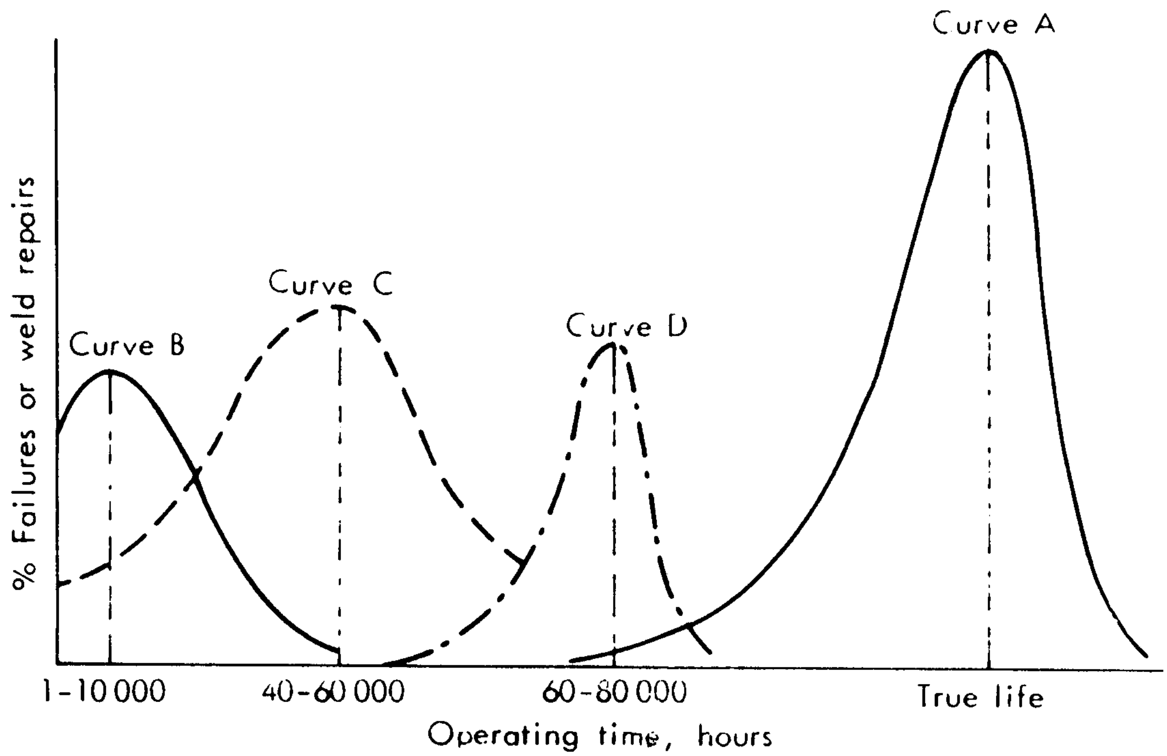

Figure 3-1
Schematic Representation of Failure/Repair Statistics for Weld Failure Type (Williams, 1982)

Type IV cracking is considered the major “end of life” failure mechanism for CrMoV weldments based on the incidence of cracking in UK piping girth welds (Townsend, 1987). Cracking in girth welds is the result of the applied bending/axial system stresses acting on the creep weak zone. The problem is especially acute at terminal joints in the piping system because of the geometry changes at these sites. Also, axial stress increases as low as 3 KSI (20 MPa) have been reported to trigger the damage. The National Power (formerly CEGB) assessment approach uses analysis of piping supports to identify high stress joints and traditional weld inspection techniques of magnetic particle, replication and ultrasonic examination. Because experience indicates that cracks can initiate and propagate to near failure before reinspection, repair is usually performed if Type IV damage is detected.

Brett (1994) has reviewed the recent girth weld Type IV cracking experience at National Power. In addition to the traditional Type IV cracking at the edge of the HAZ, inspections have revealed a variation in the HAZ approximately one grain from the fusion interface, termed Type IIIa, that has the same microstructural fine-grained cavitation characteristics as Type IV. Although Type IV cracking in girth welds is associated with bending stresses that are higher at the pipe outside surface, crack initiation is believed to be subsurface at the first bead below the surface weld bead. Reasons for subsurface initiation are twofold; (1) the temperbead at the outside surface and (2) the tendency for cavitation to occur for portions of the weld interface that are oriented more nearly radial, similar to the observations for coarse grained HAZ cracking in dissimilar metal welds. Subsurface cracking has been found in 20% of the Type IV cracks and in 75% of the Type IIIa cracks.

The fact that Type IV damage initiates subsurface and can remain so for substantial operating periods has important ramifications for inspection. First, ultrasonic examination is needed in addition to surface inspection techniques. Second, National Power locally grinds below the surface weld bead for replica inspections in order to insure that cracking is detected at the earliest stage of development and the damage level is representative (Brett, 1994).

For Type IV cracking, there were 90 total cases and six through wall cracks. To understand the cracking statistics, plots of cumulative girth weld repairs as a function of time were made. Using these plots, the Type IV/Type IIIa crack experience was analyzed for trends with regard to branch welds, butt welds, hot reheat versus main steam piping welds, terminal versus non-terminal welds and HP versus IP loop piping (Brett, 1994). The data was gathered over approximately 15 years of operation for about 15,000 total girth welds. Results of National Power cracking experience can be summarized as follows:

- Approximately 15% of all cracks are Type IIIa.

- Hot reheat piping is more susceptible to Type IV damage than main steam piping. Possibly because of early on stress relief cracking repairs that were performed on the more susceptible main steam piping having thicker wall.

- Hot reheat terminal welds are the major contribution to the higher cracking rate.

- Accumulated crack totals are similar for HP and IP loop pipe welds.

Following a Type IV creep failure, Ontario Hydro performed a failure analysis and developed a life management methodology for the high temperature piping systems in order to insure integrity (Clark et al., 1993). A multi-level approach was used with an emphasis on the behavior of welds. The selection of welds for inspection was based on actual behavior of piping supports and a ranking system for susceptibility to damage.

Corrective action for the weldment depended on the type and level of damage detected. Because the crack growth rate for Type IV damage was believed to be rapid, a cautious refurbishment approach was taken. In cases where Type IV damage was found in the girth welds, a full circumferential butt weld replacement was recommended. If creep damage was detected by replication at the weld root, then the root pass was also removed. It was recognized that improvements in the understanding of Type IV damage would dictate revision of the life management methodology.

As a part of the on-going effort at Ontario Hydro to assess high temperature piping welds, non-destructive inspections and metallurgical examinations have been conducted on a number of piping systems (Clark et al., 1993). Because stress analysis was not considered sufficiently reliable, a phased inspection plan was used that relied on an inspection priority to select the most damage prone welds for initial assessment. Based on an understanding of the crack/repair statistics and trends discussed above as well as in-house experience, a weld category scheme was developed to focus the inspections (Clark et al., 1993). In essence, the highest priority is given to terminal welds and welds at a change in section while girth welds in straight pipe sections have the lowest priority.

The inspections at Ontario Hydro used magnetic particle, replication and ultrasonic methods (Clark et al., 1993). Results were obtained for the high energy piping welds, P11 and P22 material, and for the turbine loop piping welds, almost exclusively CrMoV base material. In their experience, Type III damage was the most prevalent but most damage was shallow in depth. In agreement with their results, many instances of Type III damage were found in the review of USA and UK service experience with elevated temperature headers and steam lines (Ellis et al., 1988). The turbine loop CrMoV welds were the most damage prone, P11 material was intermediate and P22 the least susceptible with damage occurring at longer service times. The damage by categories for the hot reheat and main steam welds show good agreement with the weld category scheme and indicate the viability of their method.

Cane (1990) has reviewed the factors related to life extension of power plants including inspection strategies, life assessment techniques and stress analysis for evaluation of high temperature piping welds. Because the failures for girth welds are typically leak before break, the frequency of repair determines the approach to weldment life management. In the inspection schedule, the emphasis on terminal welds, inclusion of bends (possibly seam welded) and only selective inspection of straight pie to pipe girth welds is similar to the Ontario Hydro approach. The NDE inspection techniques are UT, MPI and replication. In order to select piping systems requiring inspection, it is suggested that piping systems with excessive primary system stresses (deadweight loading) tend to sink with time and should be inspected.

Stress analysis was performed for the case of Type IV cracking found on a Y-piece pipe weldment (Annis, Shirandami and Cane, 1990). Detailed creep analysis revealed twisting of the Y-piece and high bending stresses caused by creep relaxation. The position of the stress increase predicted by the analysis corresponded to the observed crack site.

The diversity in Type IV cracking is illustrated by a review of several failure analyses. Leakage occurred after approximately 75,000 hours of service for a high pressure steam inlet pipe girth weld consistent with the mid-life failure scenario (Ellis et al., 1982). The CrMoV pipe was welded with 2-1/4Cr-1Mo weld metal using a welding procedure that created an almost fully refined HAZ grain structure. Metallographic examination revealed intergranular cracking that had propagated in a narrow zone of material at the intersection of the fine grained HAZ and the base material - Type IV cracking. Because the failure path conformed to the contour of the HAZ through more than half of the wall thickness, the fracture surface had a superficial resemblance to a failure by lack of fusion.

Mann and Muddle (1995) studied the HAZ microstructure and creep cavitation in two cracked CrMoV weldments. The first crack was found after 89,250 hours of operation at 1000°F (538°C) in the HAZ of a cast bifurcation after a steam leak. Following repair of the bifurcation, strain gage measurements indicated large cyclic strains during operational transients. The second crack was detected by MPI in a main steam manifold after 130,000 hours of service at a design temperature of 1050°F (565°C). The Type IV crack in the manifold was ahead of a reheat crack. The emphasis was on features of the precipitate distribution within the Type IV region that could explain the development of cracking. The base material microstructure was ferrite-pearlite for both steels and contained "H-type" carbides (center vanadium-rich precipitate with M_2C wings at each end) in the ferrite grains. In the microcracked Type IV region of the bifurcation, coarse $M_{23}C$, M_6C,and M_7C_3 carbides were found. CrMoV is carbide particle strengthened material. Fine, spherical carbides were found in the HAZ, but it was not known if the interparticle spacing was such as to impart significant creep resistance.

Westwood, Clark and Sidey (1990) performed a failure analysis following leak detection at a girth weld in the main steamline. The leak was in a horizontal section of piping that joined the run of a tee to the boiler stop valve. The leak occurred after approximately 88,000 hours of service. The crack was through wall and extended approximately 200° around the circumference. Metallographic examination revealed probable subsurface crack initiation and identified the damage mechanism as Type IV cracking in the HAZ of the 1-1/4Cr-1/2Mo casting. The metal temperature was estimated as the nominal operating of 1000°F (538°C) based on steamside oxide scale thickness measurements. Although there was stress concentration associated with the change of section at the stop valve weld, the probable root cause of failure was higher than expected system stresses associated with piping system support abnormalities. Similar Type IV damage at earlier stage was found in three other steamlines having the same piping system layout as the leaked pipe.

The failure analysis included hardness testing, chemical analysis and creep rupture testing (Westwood, Clark and Sidey, 1990). The hardness traverse showed highest values in the weld metal, a gradual decrease through the HAZ (no soft zone) and lowest values in the base material for the stop valve casting and the forged tee. The maximum hardness differential was ~0.6. Comparison of the chemical analyses results for the casting and forging materials showed several systematic differences. Because of the lower molybdenum content for the casting material, the creep strength is expected to be lower than that of the forging. With regard to creep ductility, the higher arsenic and tin content for the casting can result in creep brittleness, especially if the higher chromium promotes segregation of these elements.

Quantitative microstructural characterization techniques were used to study the HAZ in a 1-1/4Cr-1/2Mo forging and casting following failure at a girth weld by Type IV creep damage (Westwood, 1993). Because of a grain size effect, hardness was not considered to be a good indicator of creep strength but the hardness differential was lower for the casting, 0.76, than the forging, 0.86, consistent with the failure side of the weld. Both the particle morphology and size were used as indicators of the potential creep strengths of the various HAZ zones. The carbide morphology for the forging was blocks and needles for the base material and all three HAZ zones. For the casting, the carbide morphology for the intercritical and fine-grained regions of the HAZ was rounded indicating a higher degree of tempering. The particle size measurements showed higher values for the intercritical and fine-grained regions of the HAZ, especially for the casing. Based on particle strengthening models of creep deformation, an increase in creep rate is predicted for an increase in particle spacing/size. In the grain shape analysis, values for the grain aspect defined as the ratio of maximum diameter to minimum diameter and the orientation of the long axis were measured for the tension and compression sides of the failed weldment. The grain aspect ratio and orientation can possibly be interpreted as indicators of deformation. Results indicate all had significant aspect ratios and there was a tendency for the grain orientation to be parallel to the pipe axis on the tension side of the bend.

Because the systematic differences in composition between casting and forgings suggest a potential higher damage susceptibility for the casting, Ontario Hydro has begun a program to study Type IV damage in casting grades of 1-1/4Cr-1/2Mo. In addition, studies of 2-1/4Cr-1Mo steel are planned because their experience suggests that instances of Type IV damage/cracking are expected but at longer service times compared to CrMoV and 1-1/4Cr-1/2Mo welds.

Two major, circumferentially oriented cracks were detected after approximately 33 years of service (French, 1993). The cracks were in the weld metal near the centerline of the girth weld. The 2-1/4Cr-1Mo main steam line operates at 1050°F (565°C) and the cracking was in a vertical section of piping below a rigid pipe support. The cracked weld was actually two welds, an original SA weld and a SMA repair weld. The crack path was at the edge of the HAZ of the repair weld in the original weld metal. Because of the advanced creep damage, it was not possible to definitively determine the specific region of the HAZ that was cracked. Stress rupture testing was performed on the piping base material, both weld metals and the original weld metal in three simulated HAZ conditions. At low stresses, the rupture strength of the original weld metal in all conditions was well below that for minimum strength base material with the intercritical and fine-grained HAZ simulation materials nominally equal and having the shortest rupture life. Based on these results, it was concluded that the failure was primarily caused by poor creep strength and not higher than expected piping system stresses.

Longitudinal Seam Welds

The service experience is reviewed separately for the steamlines and the headers. One last topic of discussion is the importance of operation conditions on expected failure potential for longitudinal seam welds.

Steamlines

A recent EPRI guideline (Foulds et al., 1996) and several papers by Viswanathan and Foulds (1995a; 1995b) have given an overview of the accumulated plant experience with seam welded high-energy piping. In their study, there were seventeen total cases consisting of three ruptures, five leaks and nine major cracking incidents in seam-welded pipes. In addition to these seventeen, a minimum of five leaks and eight cracking cases were reported for clamshell welded elbows. Based on the results of their study, the primary crack/damage locations in seam-welded piping weldments is shown in Figure 3-2.

Because of the many interacting factors that affect damage accumulation and life, it has proven difficult to develop screening criteria to identify seam welded piping at risk of failure. However, for the case of failure by major fusion line cracking, it was concluded that the integrity of seam-welded hot reheat (HRH) piping can be managed by appropriate inspection and evaluation. This conclusion was based on an understanding of the in-service damage process for this failure mode and benchmarking of the inspection and quantitative life prediction methods in the guideline against service experience. The situation for Type IV cracking and fine-grain weld centerline cracking is more complex and is discussed in more detail below.

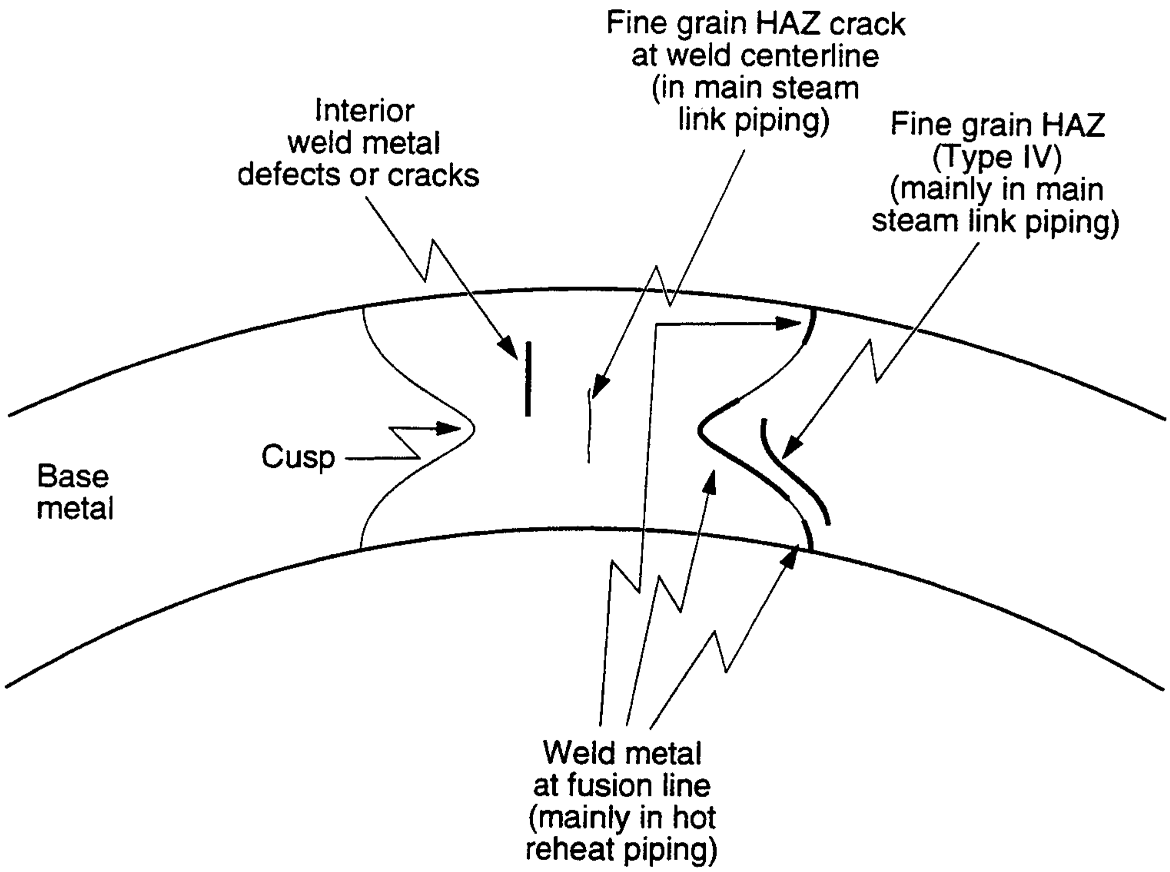

Figure 3-2
Schematic Illustration of Primary Cracking/Damage Locations Found in High Energy Piping Longitudinal Seam Weldments (Foulds et al., 1996)

Of interest in the current review are seven cases where the weldments had been given a sub critical heat treatment, plants G2, B, C, MS1, MS2, MS3, and G1 (Foulds et al., 1996). For hot reheat piping (HRH), the cracking was always in weld metal at the fusion interface for plants G1, B, and C. Plant C also had fine grained HAZ cracking. For the thicker wall, main steam line link piping welds, cracking was at the fine grain HAZ at the weld centerline for plants MS1 and MS2 and in the base material at the edge of the HAZ in the fine grained/intercritical region - Type IV cracking for plants MS3 and G1. Based on these observations, it was concluded that the non-fusion interface cracking may be related to the combination of the U-groove weld geometry and the sub critical PWHT common to all these case.

Because failures of longitudinal seam welded piping can be catastrophic, consideration of safety determines the approach to weldment life management. For the fine-grain HAZ damage in the weld centerline or Type IV damage in the base material , early stage damage is considered as only identifiable by metallographic examination of the cross-section of a sample removed from the pipe weldment. Service experience to date indicates that these forms of damage have been primarily found in thick-section, main steam line link piping welds. In recognition of this, the EPRI guidelines (Foulds et al., 1996) recommend that for all main steam line link piping, core plug samples be removed for the case of UT indications reliably located in the weld interior and UT indication not reliably located in the weld metal interior. If the metallographic examination finds macrocracking associated with cavitation damage, immediate replacement of the spool piece is recommended. In the absence of macrocracking, a cavity classification/density approach is recommended to evaluate this form of damage.

Bissel et al. (1988) have shown a relation between the hardness differential between the various microconstituents in a PWHT weldment and the creep cavitation rate in the cusp region. To assess the potential use of hardness as a nondestructive screening tool, the hardness data for plants S1, S2, M1, M2, G2, J, G1 and MS3 were reviewed (Foulds et al., 1995). For the HRH weldments heat treated above the critical temperature, relatively uniform hardness values were found indicating that the hardness measurements are not useful. For the sub critical PWHT weldments, only MS3 showed a soft zone at the approximate position of the Type IV cracking. Therefore, at present, there is insufficient information to support definitive conclusions regarding the applicability of hardness measurements to piping assessments.

Several features of interest for the plants in the EPRI study and a recent steamline failure are discussed below.

Ludden and Shelton (1994) have discussed three sequential failures at Virginia Power's Mt. Storm Unit 1. Although the failure location and material was different for the third failure than that found in the first two failures, all failures were by a creep rupture mechanism. Thus, one point these failures demonstrated is the cumulative failure nature for creep failures - i.e., if there is one failure, then a second, third, etc. should be expected based on the same nominal operating conditions, base material/weld metal compositions and fabrication procedures used in producing the welds. Several studies illustrate the cumulative failure scenario for creep rupture failures. First, prior to the straight pipe seam weld failure at Mohave, multiple clamshell welded elbow failures by a creep rupture mechanism had occurred (Foulds et al., 1996). Second, Monroe experienced significant interface cracking at second longitudinal seam welded pipe location after addition service time following the initial failure. Third, inspection of a main steamline found evidence of widespread creep damage where a piping base material creep failure (swelling) had initiated the investigation (Ellis et al., 1992).

At Mt. Storm, the third failure was classical Type IV in the base material at the edge of the HAZ (Ludden and Shelton, 1994). Of particular interest is the variation in damage through the wall. The weld has the temperbead cap pass, as did all failed welds. There was only a slight crack at the outside surface in contrast to the wide, numerous cracks found subsurface in the bead immediately below the cap pass.

Results of the failure investigation following a fourth longitudinal seam weld failure at Mt. Storm Unit 1 were discussed by Rinaca (1996). Unit 1 of Mt. Storm is a base-loaded, coal-fired plant. The failure was in a horizontal section of the main steam line. The specified pipe dimensions were 20 inch (0.5 m) OD x 3-3/8 inch (86 mm) nominal wall thickness. The pipe was longitudinal seam welded and given a sub critical PWHT. The piping base material was specified as SA387 Grade B, 1-1/4Cr-1/2 Mo plate material. The design conditions for the superheater were 2,650 psi (18.2 MPa) and 1000°F (538°C). The hoop stress is calculated as 6.5 KSI (44.8 MPa) using the mean diameter formula. The failure occurred on June 25, 1996 after 203,000 hours of operation (Rinaca, 1996). The Larson-Miller parameter value is 36,950 (English units). As expected, the rupture strength of the failed pipe weldment is below that for minimum strength 1-1/4Cr-1/2Mo base material (Foulds et al., 1996).

The fracture was a fishmouth opening approximately 8 inches (200 mm) wide at its maximum with a length of 8 feet (2.5 m). It was reported that approximately one to two minutes elapsed between the initial detection of a steam leak to the final rupture. Although the unit suffered significant structural damage as a result of the failure, no injuries were reported. The failed weld was at the 12:00 O'clock position in the "B" steam line. Because of the location of the weld seam and hanger problems in the early 80's, system stresses were cited as a possible contributing factor in the failure. The fracture path was through the fine-grained/intercritical region of the HAZ. A macroview near the center of the fracture is shown in Figure 3-3.

The review of unit history reported UT testing of all 20 inch (0.5 m) OD main steam line piping in 1993 and again in 1995. The 1995 inspection (contractor ABBAMData) was reported to have been performed using conventional UT using the EPRI recommended guidelines with EPRI calibration blocks, although no independent verification of this claim has been made. In several previous instances of HRH pipe Guidelines where the utilities believed the inspection to have been performed to EPRI standards, subsequent review of the records had shown significant deviations from the recommended practice in many aspects (Foulds et al., 1996). Results of the 1995 inspection were: "No relevant indications reported on seam that failed in 1996" (Rinaca, 1996). The creep life fraction consumed at the time of the 1995 inspection at Mt. Storm Unit 1 is estimated as 0.96. Based on experience, it would be expected that detectable cracking would exist at such a high life fraction.

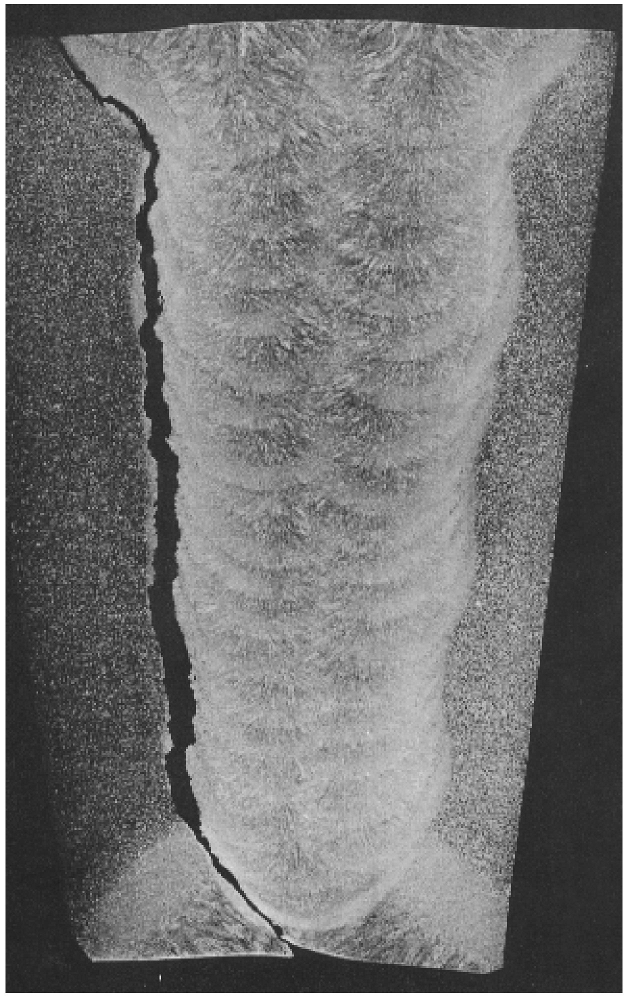

Figure 3-3
Cross Section of 1-1/4Cr-1/2Mo Main Steam Line Longitudinal Seam Weld Failure Showing Type IV Failure Mechanism After 203,000 hours (Rinaca, 1996)

Henry, Randolph and Richards (1994) performed metallographic examination and laboratory ultrasonic testing on a failed 2-1/4Cr-1Mo high pressure steam lead. The UT examination used two sensitivity levels. The areas of advanced microcracking in the fine grained HAZ were not detected using the normal sensitivity and recording levels, but could be detected using higher sensitivity techniques under laboratory conditions. However, the interpretation of the indications as microcracking was not reliable and advanced creep cavitation could not be detected.

Chemical analysis of the base plate material and the weld metal was performed (Henry, Randolph and Richards, 1994). Of interest to the investigators were the levels of residual elements in the base plate material that are known to affect creep strength and ductility. The level of carbide formers such as titanium, columbium, and vanadium were relatively low compared to expected, while the levels of impurities such as tin, arsenic and copper were higher than typical. Interpretation of these chemical measurements on the potential for failure are speculative but are consistent with an evolving at risk failure scenario. The low carbide formers in the base plate indicate possible lower bound creep strength and thus, a large creep strength mismatch for the base/weld metal. The high impurity levels indicate possible lower creep ductility for the HAZ. Combining these two elements of high triaxial stresses in the HAZ and a low ductility creep cavitation susceptible material results in the premature failure for the seam welded pipe.

One final element of importance in seam weld failure susceptibility is the U groove stressed by Foulds et al. (1996). As noted by Brett (1994) for the girth welds, the damage was greater the steeper the weld interface or more normal to the applied axial stresses. The same consideration may to the longitudinal seam weld with the hoop stress. In order to explore the effect of joint geometry on life, finite element stress analysis is recommended.

Both thin-walled and thick-walled pipes should be used in the analysis. The two joint geometries of interest are the J or single U groove and the double vee. One other feature that could be studied in the analysis is the strength of the Type IV zone. For thin-walled pipe, only a few large weld passes are used. The doubly refined HAZ is generally located at the cusp of the double vee and would be expected to have inferior properties to the singly refined HAZ. For thick-walled pipes that have failed, it appears that many small weld beads were used in the joining process. Because of the overlap, the HAZ is almost completely refined. At present, it is reasonable to conclude that thin-walled CrMo piping with longitudinal seam welds are susceptible to Type IV failure.

Results of a comprehensive inspection and life assessment project conducted on a seam welded hot reheat piping system after approximately 148,000 hours of service was reported by Middleton (1995). The nominal service temperature was 1050°F (565°C) and the piping material was 2-1/4Cr-1Mo. The welds had a single V geometry and had been given a sub critical PWHT. The on-site inspections included magnetic particle, ultrasonic, replication and hardness testing. In addition, full wall thickness samples were removed from 15 selected spool pieces from the approximately 50 in the steamline for metallographic examination and post exposure creep rupture testing.

All replicas from the straight pipe welds had cavitation in the fine grained/intercritical zone but almost no damage in the coarse grained HAZ (Middleton, 1995). The cavitation was slight in 37 of the 45 and less than 600 cavities/ mm^2 for even the most highly damaged. An automated image analysis system was used to measure cavitation parameters of cavity density and area fraction for the Type IV zone. No correlation of damage parameter and hardness were found based on plots of cavity density or area fraction (mean and maximum) versus hardness ratio. For these thin wall piping welds, the cavitation results showed that the damage was randomly distributed throughout the wall thickness and could be highly variable even in closely separated axial locations.

Three post exposure creep tests using full wall size specimens were performed at 1157°F (625°C) and the estimated service stress. Two of the specimens had no appreciable service induced damage but the third specimen, L21, had microcracking towards the pipe inside surface. The test times were correlated to obtain equivalent operating times at the service temperature of 1050°F (565°C) using time-temperature parameter methods. For the extrapolation, it was assumed that the slope of the rupture time versus temperature curve was the same for the weldment as that for base material — i.e., parallel isostress rupture behavior (Middleton, 1995). Figure 3-4 shows the maximum area fraction cavities versus equivalent time at 1050°F (565°C) for post exposure test specimen I21 containing a microcrack. In essence, very low damage was found after ~ 148,000 hours of service at 1050°F (565°C) but the damage accumulation rate increased greatly after approximately 70-80% of life. The macrocracking occurs at ~5% area fraction cavities of 8000 to 10,000 cavities/mm^2. This data suggests that, even for a highly cavitated weldment, remaining lives of order of magnitude from 10,000 hours to 20,000 hours would be obtained indicating some forewarning of failure.

Based on limited, ancillary, small specimen tests experience, the cavitation behavior may be material dependent (Middleton, 1995). A similar damage versus life fraction relationship was found for another heat of 2-1/4Cr-1Mo steel using conventional size weldment specimens, ~ 0.4 inch (10 mm) in diameter. In these tests, the cavitation rate was low in secondary creep for the first 70-80% of life followed by rapid damage accumulation in tertiary creep. Results for 1-1/4Cr-1/2Mo showed initial cavitation at approximately 30% of life and had a uniform rate of increase during secondary creep. Based on an expected creep strain-cavitation damage correlation and the typical primary, steady state and tertiary life fractions found for creep curves in service exposed Cr-Mo steels, the behavior of the 2-1/4Cr-1Mo cited above is not typical, but the behavior of the 1-1/4Cr-1/2Mo is typical of the USA experience. Because the actual behavior and optimal cavitation damage-life relationship is uncertain, further experimental studies are recommended.

Capacitance strain gages were used to measure the strains in the Type IV zone for the post exposure creep test specimens (Middleton, 1995). Based on the results of the tests, it was concluded that: (1) the gages have adequate sensitivity, (2) strain gages can detect the onset of tertiary which occurs before micro and macrocracking and (3) surface strains are representative of subsurface behavior.

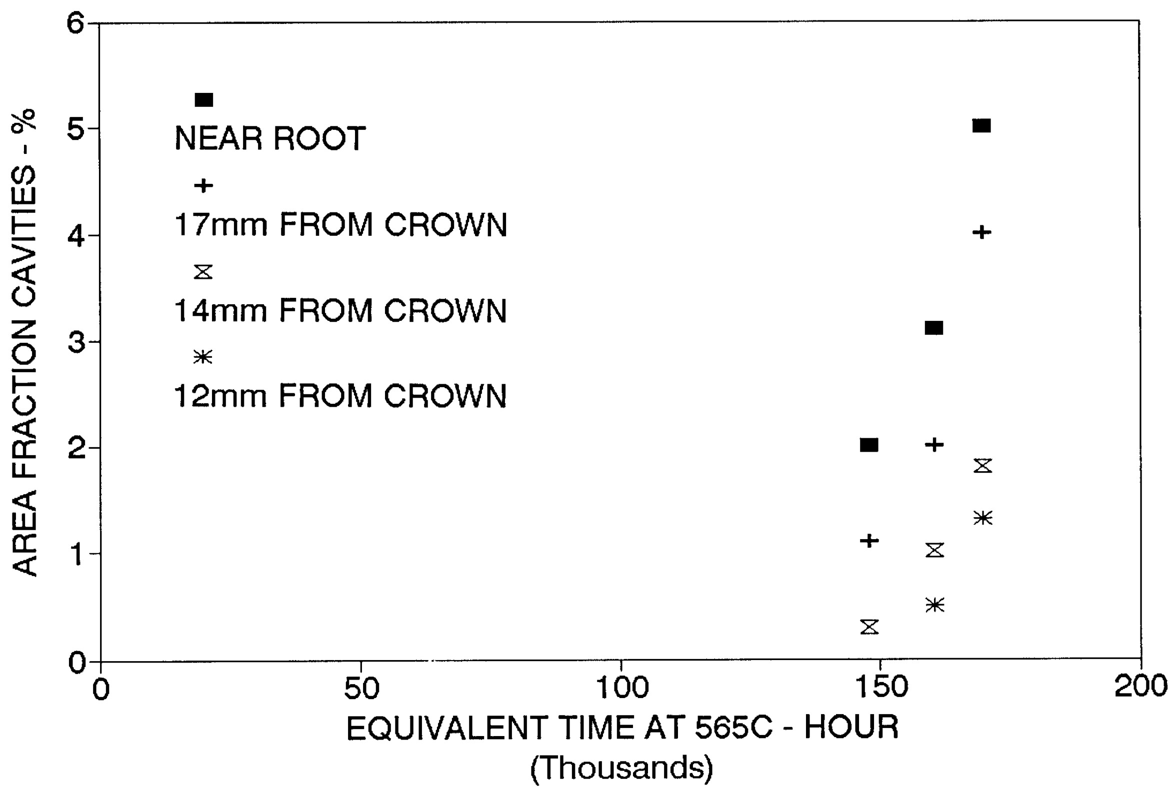

Figure 3-4
Maximum Area Fraction of Cavities as a Function of Service Time at 1050°F (565°C) for Specimen 121 Based on Interrupted Creep Tests at 1157°F (625°C) (Middleton, 1995)

Other potential surface strain measurement techniques are the replica grid technique discussed by Eggeler, Millward and Cane (1988) and an optical deformation measurement technique using the "speckle image" discussed by Etienne et al. (1992). Although the optical system has sufficient resolution for local strain measured required in Type IV damage assessment, addition development efforts are needed prior to practical field applications.

Headers

Henry et al. (1986) have conducted a failure analysis for a longitudinal seam welded header in the sub-critical heat treatment condition. A leak was detected after approximately 187,000 hours of service. The header was fabricated from 2-1/4Cr-1Mo plate material was designed for an outlet temperature of 1050°F (565°C). Cracking initiated subsurface just below the outside surface, broke through to the outside surface at a relatively early stage in the crack development, and then propagated through the wall to the inside surface. Cracking was found in the columnar grain boundaries of the weld metal near the seam weld centerline. The failure mechanism was creep rupture and the degree of creep damage in the weld metal ranged from isolated cavitation to macrocracking. In order to continue operation while a replacement header was fabricated, the failed weld and all macrocracked welds were removed and the header was weld repaired. Creep rupture tests predicted that the header would perform satisfactorily until replacement. Appropriate inspections were recommended during subsequent limited service to insure integrity. A similar failure has occurred at another plant in the midwest region of the USA.

Metallographic examination of a sample removed from a failed longitudinal seam welded header was performed by Cocubinsky (1983). The header was fabricated from SA 387 Grade C plate material, 1-1/4Cr-1/2Mo. The header dimensions were specified as 15 inch OD X 2.5 inch MWT (380 mm OD X 63.5 mm MWT). The nominal operating conditions were an internal pressure of 2,150 psi (14.7 MPa) and 1005°F (540°C). The unit went into service in 1960 and had accumulated approximately 164,000 hour of service at the time of the failure.

The mean diameter hoop stress is 5.3 KSI (36.6 MPa). Assuming a temperature imbalance of ~ 30°F (17°C), the Larson-Miller parameter is 37,700 (English units). Thus, the rupture strength of the failed header material is below that for minimum strength material based on comparison with unexposed base material (Foulds et al., 1996).

The crack was approximately 7 inches (180 mm) long on the outside surface of the header, axially oriented, and penetrated through the full wall thickness. In addition to the major crack, numerous circumferentially oriented cracks were found at the header stub tube welds. The header material conformed to the 1-1/4Cr-1/2Mo material specified based on chemical analysis. The crack was located in the fine-grained region of the HAZ for the longitudinal seam weld. Microstructural examination revealed the cracking was intergranular and discontinuous, typical of creep rupture.

Effect Of Operating Conditions On Failure Potential Of Long Seam Welds

Component failure is the result of a susceptible material, geometry and the applied loading conditions. It is believed that the majority of the seam welded hot reheat piping do not have the Type IV microstructure because they have been given either a re-normalizing or re-annealing heat treatment following welding. For those seam welded components with the Type IV microstructure, the basic question is the following; If the creep strength of the Type IV zone is inferior, then why haven't more failures been reported? Is it because; (1) failures are widespread but unreported or (2) the typical weldment strength is significantly greater than that of the failed materials or (3) the operating conditions for the general piping population are less severe than those found in the failed cases? Based on rupture test results, it is believed that a range of rupture strengths exist within the seam welded piping population. The role of applied loading is also important in understanding failure potential and is discussed in more detail below.

Even for the case of a creep weak material loaded in series, it is possible for the welded component to have adequate service life. The reason is that the creep life of seam welded piping is a strong function of operating temperature and operating stress. For many welded pipes in service, the operating stress is significantly below the design value because: (1) the actual wall thickness is significantly higher than minimum and the minimum wall thickness is based on design pressure and temperature conditions and (2) the operating pressure is significantly below the design pressure. In many instances, the operating temperature is also below the design temperature.

The results of Ellis and Brosche (1993) illustrate the favorable effect of operating stress on expected service life. The maximum calculated operating stress was 5 .1 KSI (35 MPa) for the seam welded hot reheat piping. This value is well below the ASME Code allowable stress for Grade 22, Class 2 material of 7.1 KSI (48.7 MPa) at 1015°F (546°C). The low operating stress compared to code allowable stress implies that this piping has an implicit safety factor on life. Although the measured rupture life for the longitudinal seam weld metal was near or slightly below minimum for base materials in the ASTM data base, the service life of the hot reheat piping was conservatively estimated as greater than 500,000 hours.

Using measured wall thickness values, actual pressure and temperature histograms (when possible), the life fraction consumption of twenty-nine longitudinal seam welded hot reheat piping systems was performed. For the calculation, a minimum strength material was used for both common CrMo piping materials. One interesting feature of the analysis is that these strength values are believed to be consistent with those used in developing the ASME Allowable stresses. Based on operating stress and temperature estimates, only four systems were identified with significant life usage.

4

CONCLUSIONS AND RECOMMENDATIONS

A comprehensive literature review for Type IV cracking and failure was performed. The review encompassed the fundamental causes for the cracking, characteristic features of the cracking, models for damage evolution, methods of inspection/damage detection and relevant service experience. The objective was to develop a basis for improved guidelines for the assessment of girth and seam-welded components in the sub critical stress relieved condition. This section provides conclusions regarding Type IV cracking, recommendations for improvements in the EPRI guidelines and recommendations for additional studies based on the results of the review.

Conclusions

The fundamental cause of Type IV cracking and features of the cracking can be summarized as follows:

- Type IV cracking is the result of a microstructural zone of material that has low creep strength surrounded by materials that are stronger in creep. Type IV cracking has been found in the fine-grained HAZ associated with exposure to temperatures around the A_{C3} temperature and in the intercritical region of the HAZ. Because cracking occurs in service, it is often termed mid-life cracking.

- Type IV cracking is caused by thermal softening of the HAZ due to the welding thermal cycle. For CrMo steel, creep strength is a function of grain size, substructure, solid solution and particle strengthening. For the fine-grained and intercritical regions of the HAZ, metallographic examination reveals changes in the dislocation substructure from high density laths to equiaxed subgrains and larger carbide size/interparticle spacing that is expected to result in lower creep strength of the material.

- Creep rupture tests on cross welds and simulated HAZ samples indicate premature failure as compared to base material for samples that fail by the Type IV mechanism. The degree of creep strength reduction can be expressed either as a life reduction factor or a stress reduction factor. For Cr-Mo steels, the weldment lives vary from approximately equal to values of 1/5 of that for minimum strength base material. Hence, failures in service may be expected at life fractions as low as 0.2, consistent with service experience.

- For the low alloy ferritic steels, the susceptibility to Type IV cracking and the degree of life reduction appears to depend on the specific alloy, and based on Ontario Hydro experience with girth welds increases in the following order; 2-1/4Cr-1Mo to 1-1/4Cr-1/2Mo to CrMoV.

- Factors that affect creep ductility such as multiaxial stresses, PWHT and inclusion content/matrix strength for the parent or base material may be important in determining susceptibility to Type IV cracking. In addition, the content of residual carbide formers - Cb, Ti, V that affect the creep strength of the base material may also play an important role in determining susceptibility to Type IV cracking and the degree of life reduction.

- The local failure strain for the Type IV mechanism is relatively large, i.e., greater than 10%, consistent with the physical interpretation of strain localization in a narrow, creep-ductile, low creep strength zone. Thus, damage detection and life assessment using capacitance strain gages, grids, or optical deformation measurements may be useful.

- For CrMo weldments that fail by the Type IV mechanism, the rupture life increases as the specimen size increases. However, the effect of specimen size and the use of the data in component life assessment should be studied in more detail.

The observations and conclusions regarding damage evolution are:

- Type IV has only cavitation damage present until late in life — i.e., life fractions greater than 0.7 to 0.8. Based on limited testing and service experience, it is believed that remaining service lives of 10,000 to 20,000 hours may be obtained for weldments with advanced cavitation damage. Crack growth is rapid in highly creep damaged materials.

- Qualitative and quantitative cavitation models of damage evolution are useful. Qualitative cavitation assessments use three levels of isolated cavitation. They are extremely isolated, isolated and dense. Quantitative cavitation models currently use cavity density versus life fraction. Area fraction models are being developed. Because the current quantitative cavity density model under-estimates the CrMoV cavitation damage at various life fractions, and, also because of the lack of data for CrMo steels, there is a need for both improved models and additional testing/cavitation measurements.

The observations and conclusions regarding inspection methods are:

- Traditional methods of damage/crack detection are replication, wet fluorescent magnetic particle testing and ultrasonic testing. For replication, grinding of the temper bead pass has been used to detect subsurface initiation of damage in girth welds.

- Because of the large strains in the Type IV zone, and the increasing damage accumulation rates associated with tertiary creep, strain based approaches using capacitance strain gages, grids, or optical deformation measurements may also be appropriate.

- For girth welds, Type IV cracking is associated with applied piping system axial stresses. The problem is especially acute at terminal joints in the piping system because of the geometry changes at these sites. Formulas which correlate the damage using the maximum principal axial stress are overly conservative, i.e., the observed failure times are longer than that based on simple summation of the applied axial and internal pressure induced axial stress. Evidence indicates subsurface initiation of damage in many instances. The degree of damage is greater for those portions of the fusion interface that are closer to radial in orientation.

- Because the failures for girth welds occur typically by leak before break, the frequency of repair determines the approach to weldment life management. The inspections can be prioritized using weld category schemes. The highest priority is given to terminal welds and welds at a change in section while girth welds in straight pipe sections have the lowest priority.

- For the longitudinal seam welds, the hoop stress due to internal pressure acts directly across the weld/HAZ. Service experience indicates subsurface initiation of damage in many instances.

- To date, service experience for longitudinal seam welded piping has found Type IV failures only in thick-walled, main steam line link piping with the either the J groove or single V joint geometry.

- Based on the results of the review, there appears to be no reason to believe that thin-walled piping with longitudinal seam welds post weld heat treated sub critically will be immune to Type IV failure.

- Because failures of longitudinal seam welded piping can be catastrophic, consideration of safety determines the approach to weldment life management. In recognition of this, the EPRI guidelines recommends that for all main steam line link piping, core plug samples be removed for the case of UT indications reliably located in the weld interior and UT indications not reliably located in the weld interior. If metallographic examination finds macrocracking associated with cavitation damage, immediate repair/replacement of the spool piece is recommended.

Recommendations For Improvements In Guidelines

Based on the results of the current review, several specific recommendations for improvements in the guidelines are:

- Equations should be given for the Larson-Miller parameter curves in the guidelines.
- For replica evaluations of longitudinal seam welds, the advantages/disadvantages of grinding of the temper bead pass to detect subsurface initiation of Type IV damage should be evaluated.
- The application of strain based approaches using capacitance strain gages, grids, or optical deformation measurements for detection/evaluation of Type IV cracking should be investigated.
- Methods to detect susceptible piping based on inclusion content of the base material should be investigated.

Recommendations For Future Work

- A review and verification of the inspection procedure and results at Mt. Storm should be performed.
- For the unfailed 20 inch (0.5 m) O.D. main steamline piping at Mt. Storm that is to be removed from service, a comprehensive ultrasonic examination using EPRI and advanced inspection procedures should be performed. Metallurgical examination of the weldments and creep rupture testing should be performed.
- Stress analysis should be performed for a longitudinal seam welded pipe. The analysis should use appropriate creep/failure properties for the HAZ zones to determine the potential for Type IV damage/failure. Both thin walled and thick walled pipes should be evaluated. The joint geometries of interest are the double V and the single U groove. One important feature that could be studied in the analysis is the strength of the Type IV zone. For thin-walled pipe, only a few large weld passes are used. The double refined HAZ is generally located at the cusp of the double vee and would be expected to have inferior properties to the single refined HAZ. For thick-walled pipes that have failed, it appears that many small weld beads were used in the joining process. Because of the overlap, the HAZ is almost completely refined.
- Interrupted creep rupture tests on cross welds and simulated HAZ samples should be performed for both 1-1/4Cr-1/2Mo and 2-1/4Cr-1Mo steels. Cavity density and area fraction measurements should be made. The measured damage level versus

life fraction values should be used to develop appropriate remaining life prediction models for both mean and minimum remaining life.

- The effect of sample size on the measured rupture life of weldments which have been subjected to sub critical heat treatment, and the use of the data in component life assessment should be studied in more detail.

- A high-quality, creep-rupture database for Type IV failures in 1-1/4Cr-1/2Mo and 2-1/4Cr-1Mo steel should be assembled and verified. Analysis should be performed to determine the suitability for establishing definitive life/stress reduction factors for both mean strength HAZ material and for minimum strength HAZ material corresponding to time of first failure values associated with initial service experience.

- Multiaxial stress rupture criteria should be developed for life prediction of piping girth welds with axial system stresses and a Type IV failure mechanism.

5

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