Advances in Materials Technology for Fossil Power Plants
Proceedings from the Eighth International Conference
October 11–14, 2016, Albufeira, Algarve, Portugal
https://doi.org/10.31399/asm.cp.am-epri-2016p0494

J. Parker, J. Shingledecker, J. Siefert, editors

INVESTIGATION AND POST SERVICE CREEP TESTING OF A MIS-HEAT TREATED SEAM WELDED GRADE 91 HOT REHEAT BEND

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INTRODUCTION

This paper reports the results of a collaborative investigation of an ex-service grade 91 bend carried out by the UK generating companies Centrica, SSE, Engie and RWE.

As part of the handover exercise for Centrica's Langage power station in 2009 a number of routine checks were carried out on the main steam and hot reheat grade 91 steam pipework. In some cases low hardness readings were found with subsequent metallurgical replication showing the presence of an aberrant non martensitic microstructure. This led to a more extensive inspection programme on the steam lines and the discovery of other areas of suspect material. A review of the operating capability of the plant, including detailed pipework stress analysis and a pipework peaking assessment, along with the assumption that lower strength grade 91 material was present, led to the steam lines being down rated and returning to service under these revised conditions.

At the first C inspection in December 2012, after the HRSG and associated pipework had operated for 18720 hours, a bend with a soft weld, along with a section of the straight pipe on either side, was removed from service. An investigation was undertaken to establish how long this component would have survived, had it been left in service, and to consider the implications for the future operation of the plant.

DESCRIPTION OF THE COMPONENT

The component removed from service comprised a 90° bend section with lengths of straight pipe at each end. The bend assembly, cut into two to facilitate handling in the workshop, is shown in Fig.1.

Fig.1. The bend, cut into two halves for ease of handling. The seam weld at the bend intrados and one of the circumferential welds can be seen.

The bend and pipe dimensions were 864mm outside diameter and 37mm wall thickness. The bend had been fabricated from two rolled plate sections by longitudinal seam welding at the extrados and the intrados, while each of the adjacent straight pipe sections had been made from plate rolled into a cylinder and welded with a single longitudinal seam weld. The straights had been welded to the bend by two circumferential butt welds. The assembly therefore contained four different parent materials (identified as A and D in the straights and B and C in the bend) and six different welds (identified as 1-6).

The bend assembly was then cut into a number of smaller sections to investigate the metallurgical condition of each of the component parts. This included a section across each of the six welds. The materials were found to be in a variety of metallurgical conditions, allowing a number of different parent materials (base metals) and cross weld arrangements to be tested. The details are summarised in Table 1 below.

Table 1.Materials in the Bend Assembly.

ID	Description	Microstructure	Hardness
Parent A	Straight section constructed from rolled plate with single seam weld	Normal martensitic structure	219-242HV
Weld 1	Longitudinal seam weld in Parent A	Normal martensitic structure	
Weld 2	Circumferential weld between Parent A and the bend (Parents B and C)	Normal martensitic structure	
Parent B	One of two rolled plate sections used to construct the bend using two seam welds	Normal martensitic structure away from Weld 4 Aberrant structure near Weld 4	188-226HV 142-145HV
Parent C	One of two rolled plate sections used to construct the bend using two seam welds	Normal martensitic structure away from Weld 4 Aberrant structure near Weld 4	191-203HV 145-168HV
Weld 3	Longitudinal seam weld in the bend between Parents B and C	Normal martensitic structure	
Weld 4	Longitudinal seam weld in the bend between Parents B and C	Aberrant structure	
Parent D	Straight section constructed from rolled plate with a single seam weld	Normal martensitic structure away from Weld 6. Aberrant structure near Weld 6 Aberrant structure in a band of parent away from Weld 6	192-216HV 148-161 HV 153-160HV
Weld 5	Circumferential weld between Parent D and the bend (Parents B and C)	Normal martensitic structure away from Weld 6 Aberrant structure near Weld 6	
Weld 6	Longitudinal seam weld in Parent D	Aberrant structure	

In general mis-heat treatment appears to have been associated with the welding operations. Welds 1,2,3 and most of Weld 5 were found to be normal, but Welds 4 and 6, and Weld 5 near the intersection with Weld 6, had aberrant non martensitic microstructure. Parent A, and Parents B and C away from Weld 4, were normal, but Parents B and C near Weld 4 had aberrant non martensitic microstructure. Parent D was generally normal but with two separate longitudinal bands of aberrant structure, one centred on the single seam weld (Weld 6) on this pipe and the other, approximately 600mm wide, in parent material on a separate part of the circumference. The most likely explanation is that the weld was mis-heat treated during a local post weld heat treatment and the other aberrant band arose during a subsequent heat treatment of the completed pipe. The hardness and microstructure of the two bands were similar.

Examples of normal and aberrant microstructures in the same parent are shown below. Fig. 2 shows the normal martensitic microstructure found in Parent B away from the mis-heat treated seam weld. The (prior Austenite) grain size is ~50μm, with an internal acicular lath structure clearly visible, and the average hardness of this material was >200HV.

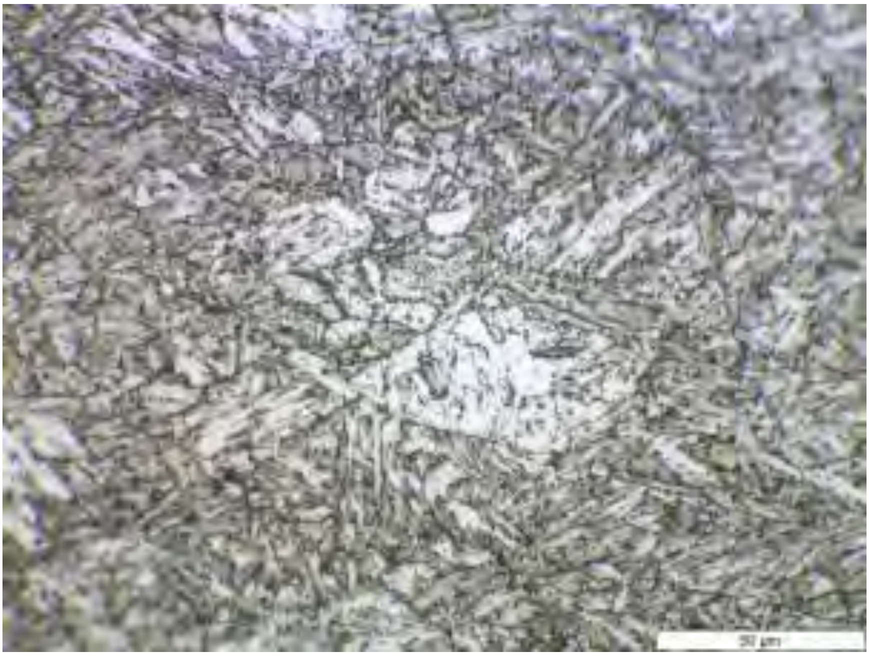

Fig.2. Normal martensitic microstructure found in Parent B away from Weld 4 (Image provided by AMEC FW).

Fig.3 shows the aberrant microstructure found in Parent B near the mis-heat treated seam weld. This microstructure appears to be 100% Ferrite. The grains are featureless, with no evidence of an internal lath structure, and the hardness is much lower (~143HV).

It has been demonstrated that a very similar microstructure can be reproduced artificially by a rapid temperature rise to 910ºC in the austenitic region followed by an air cool to 760ºC, with a hold at this temperature for 3 hours, before cooling [1]. It is therefore possible that in this case the microstructure was caused by an overshoot during post weld heat treatment of the seam weld before the temperature stabilised at the correct level.

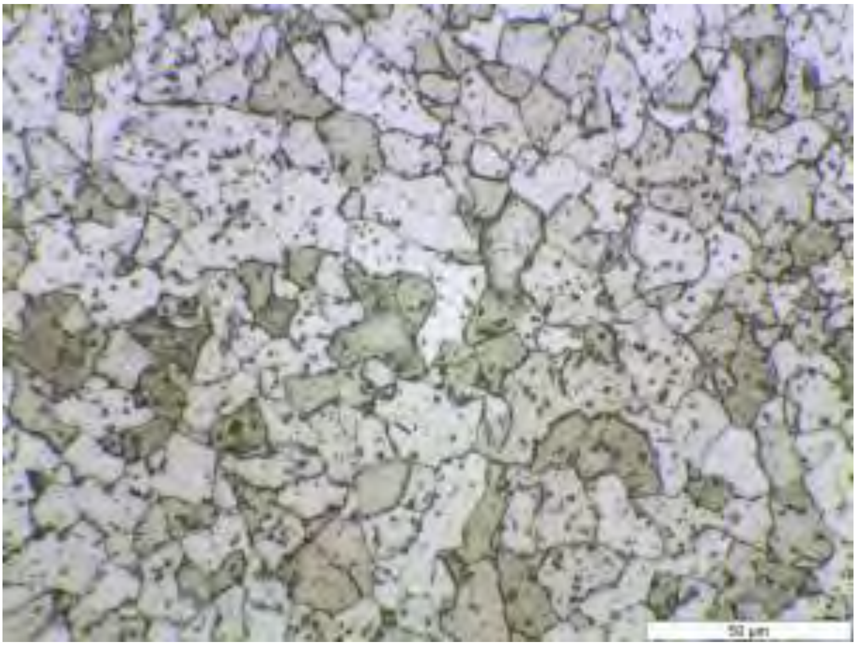

Fig.3. Aberrant non martensitic microstructure found in Parent B (Image provided by AMEC FW)

CREEP TESTING

A number of shorter term (<1000 hour) crossweld creep rupture tests were initially carried out at 90MPa and 630˚C. As shown in Fig.4, two distinct failure behaviours were observed. Where an aberrant non martensitic parent microstructure was present in the specimen, failure occurred in this material. Where no non martensitic parent microstructure was present, failure occurred instead in the Type IV location.

In the case of Parent D, with two areas of aberrant material, the parent band away from Weld 6 was sampled for creep testing, while Weld 6 itself was sampled for crossweld creep testing.

Each parent or crossweld failure time can be used to estimate creep strength with respect to the mean expected value. The stress for a given failure time can be divided by the stress required to produce the same failure time in material with mean properties. The Type IV lines shown in Fig.4 are derived from the mean prediction from the Bell equation [2] with a margin of +/-20% on stress. It can be seen that the Type IV failure times in three different parent materials all fall within this range. In contrast the failure times for the non martensitic parent are much shorter. The dashed line is derived from the mean Cipolla equation for Grade 91 parent [3] reduced by 44% on stress.

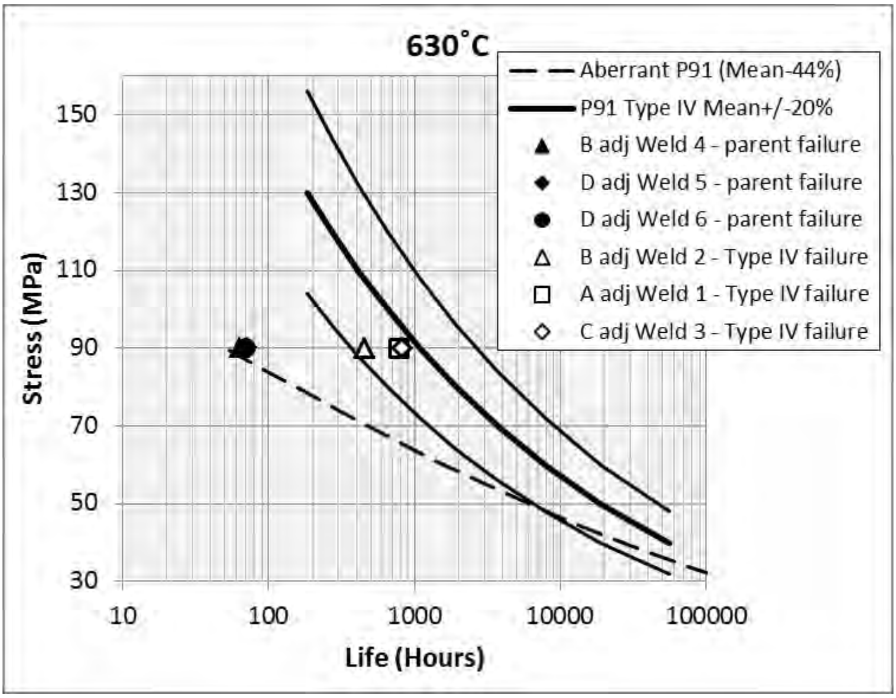

Fig.4. Crossweld rupture tests at 90MPA and 630˚C.

Two of the aberrant materials, B and D, were then tested in the range 60-87MPa at 600˚C as crossweld specimens to produce somewhat longer term failures. Parent D material from the aberrant band away from the seam weld was also tested in the range 75-95MPa at 600˚C as all parent creep and rupture specimens. The results are plotted in Fig.5. Parent B adjacent to Weld 4 and Parent D adjacent to Weld 6 failed in aberrant parent material. One Parent D adjacent to Weld 5 crossweld specimen survived longer than expected, but the post test metallography showed this to be a Type IV failure in martensitic microstructure. It appears that this specimen avoided that part of the bend in which Parent D had a non martensitic structure. As with the similar failures at 630˚C, the failure time falls within the expected Type IV range.

Parent D away from the seam weld has an average strength of Cipolla Mean-44.8%. Parent B adjacent to Weld 4 is slightly weaker, with an average strength of Cipolla Mean-47%. Parent D adjacent to Weld 6 has a strength similar to Parent B adjacent to Weld 4.

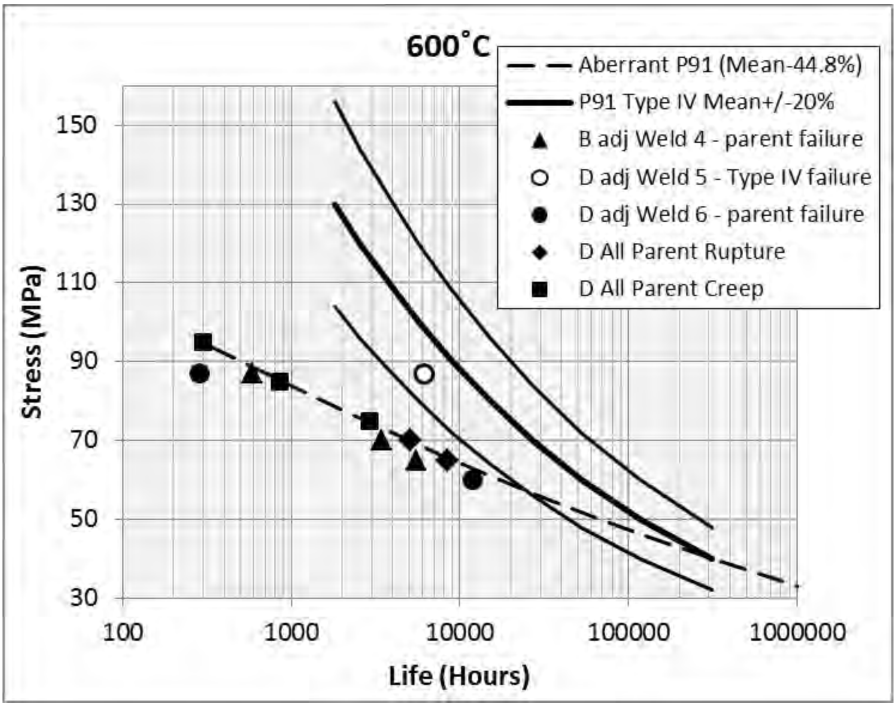

Fig.5. Crossweld rupture tests at 600˚C.

DISCUSSION

During the course of this project consideration has also been given as to whether the Type IV zone formed in aberrant non martensitic material is weaker than that formed in normal martensitic material. On the basis of the currently available evidence (see for example [4]), it appears that the Type IV zones formed in the two microstructures are equivalent. Renormalisation occurring in the heat affected zone restores the martensitic condition within the aberrant material. While a creep strength shortfall factor has to be applied to the normal grade 91 parent strength in order to arrive at either the aberrant non martensitic parent strength or the normal Type IV strength, these effects are not additive. Application of the normal Type IV shortfall will be sufficient and, in either case, life is best predicted using the Bell parametric [2].

The implication of these findings is that, while Type IV cracking is the most likely long term failure mode for welds in service, whether or not the heat affected zone is formed in normal martensitic material or in aberrant non martensitic material, it will be difficult to produce Type IV failures in accelerated test programmes where an aberrant non martensitic parent is present in the test specimen. Failure will tend to occur first in the aberrant material and any extrapolation to the longer term will overestimate life compared to Type IV life. For the strength of aberrant Parent D for example, even if Type IV strength is at Mean-20%, Fig.5 indicates that it will not be possible to produce Type IV failures at 600˚C in test durations less than ~30kHrs. If the Type IV strength is higher, as appears to be the case for the Type IV failure at 600˚C, correspondingly longer test durations will be required.

Type IV cracking may occur circumferentially at circumferential butt welds or longitudinally at seam welds. The alternative failure mode in aberrant parent, should this arise in a pipe section, is expected to occur as a longitudinally orientated split. Considering the behaviour of aberrant material shown in Fig.5, life is best predicted by applying a life reduction factor to the Cipolla 2005 equation [3].

PREDICTION OF LIFE IN SERVICE

The present work has placed the creep strength of aberrant Parent D away from the seam weld at Cipolla Mean-44.8%. More generally investigations of a number of aberrant materials have shown strength typically falling within the range Cipolla Mean-35% to Cipolla Mean-50%. It must be recognised therefore that the actual failure mode in service at 565˚C will be heavily dependent on the precise level of aberrant and Type IV strength present.

Table 2 below gives estimates of the earliest appearance of Type IV cracking at the down rated operating temperature of 565˚C for different levels of aberrant creep strength. At Cipolla Mean-40% aberrant failure will occur at 81.2MPa (corresponding to ~67kHrs) and above, while at Cipolla Mean-50% aberrant failure will persist down to 58.6MPa (corresponding to ~233kHrs).

Table 2.

Aberrant Strength (Cipolla 2005)	**Predicted earliest Type IV failure at 565˚C**	**Stress (MPa)**	**Notes**
Mean-40%	67kHrs	81.2	
Mean-45%	120kHrs	69.6	Average strength found for aberrant Parent D (away from Weld 6)
Mean-50%	233kHrs	58.6	Lowest strength values found for aberrant Parent D and aberrant Parent B

On the basis of the down rated operating conditions of 565˚C and 66MPa for the station concerned, Type IV failure will occur before failure in aberrant material of strength Mean-40%, provided the Type IV strength is in the lower half of the distribution. Failure may occur in aberrant material first if the Type IV strength is towards the top of the range. For aberrant material of strength Mean-45%, failure in aberrant material will occur earlier than Mean Type IV failure, but later than Mean-20% Type IV failure (ie lower bound Type IV). For the weakest aberrant material strength found in this project, Mean-50%, failure will occur in aberrant material before Type IV failure. This is summarised in Table 3 below, with Figs 6 & 7 showing this information graphically.

Table 3.

Aberrant Strength (Cipolla 2005)	**Predicted earliest Type IV failure at 565˚C & 66MPa**	**Mean Type IV failure predicted at 565˚C & 66MPa**	**Aberrant failure in the absence of Type IV**
Mean-35%	147kHrs	345kHrs	724kHrs
Mean-40%	147kHrs	345kHrs	387kHrs
Mean-45%	147kHrs	345kHrs	190kHrs
Mean-50%	147kHrs	345kHrs	84kHrs

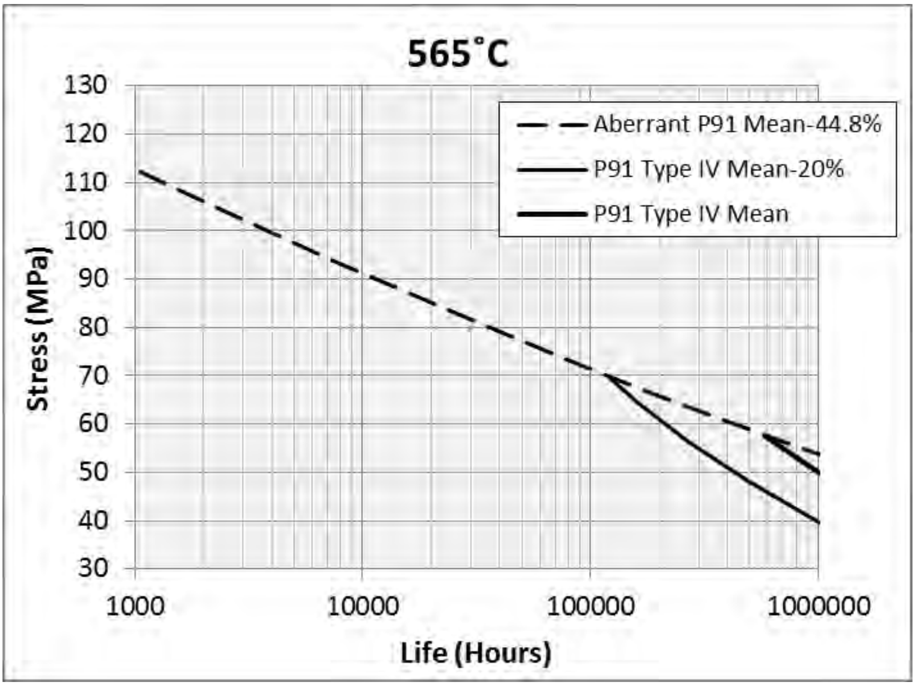

Fig.6. Estimated creep life for Parent D material at the down rated station operating temperature of 565˚C.

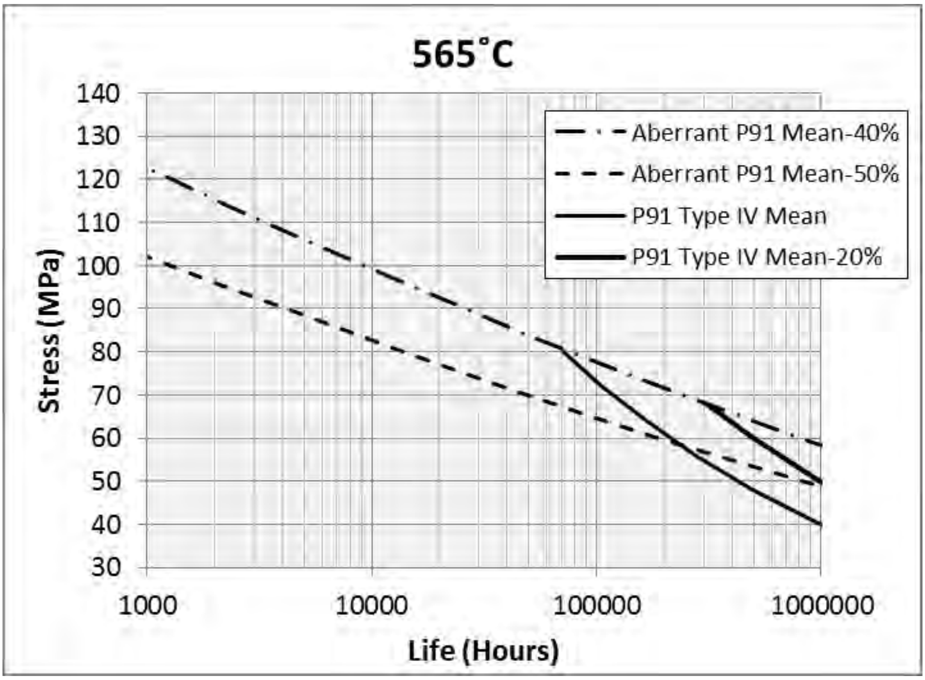

Fig.7. General estimate of creep life for aberrant material at the down rated station operating temperature of 565˚C.

The estimates of how long the bend assembly would have survived in service may be academic for this particular component, now that it has been removed from service, but have implications for bends and straights remaining in service. In order to apply the results of this test programme to these plant components the options are to assume the worst materials properties are present, or to obtain component specific material data from the plant.

As illustrated in Table 3, the wide range of aberrant material strength encountered results in a correspondingly large difference in predicted failure time in service. In some cases pipework replacement may be called for, while in other cases the aberrant material, although substandard, may be safely left in service until the end of plant life. In these circumstances obtaining an estimate of actual material creep strength becomes a key part of the decision making process.

One way of obtaining component specific data is by the use of small scale sampling and impression creep testing. The in-situ sampling is effectively non destructive, in that it can be carried out without the need for subsequent weld repair, and impression creep testing is a means of placing the material sampled in the creep strength scatter band. The project was extended to investigate this aspect and this work is reported in a companion paper [5].

SUMMARY

1. A mis-heat treated seam welded grade 91 hot reheat bend, along with adjacent sections of straight pipe, found to contain aberrant non martensitic material, has been taken out of service for investigation.

2. A programme of creep and creep rupture testing, including crossweld testing was carried out to compare the strength of the Type IV zone, where present, and the aberrant non-martensitic microstructure.

3. The aberrant non martensitic materials were found to have a creep strength equivalent to approximately Mean-45% (based on Cipolla 2005).

4. Crossweld tests on specimens incorporating aberrant material failed in this part of the specimen.

5. Type IV cracking was found in some crossweld cases, but only in specimens which did not incorporate aberrant material. In these cases only normal martensitic structure was present.

6. Where Type IV cracking did occur the timescale was within the range predicted by the Bell parametric equation.

7. At station down rated operating conditions of 66MPa and 565˚C, the aberrant material strength of Mean-45% (based on Cipolla 2005) found here implies a further life of >100kHrs.

ACKNOWLEDGEMENTS

The work reported here was carried out by the UK generating companies Centrica, SSE, Engie and RWE, and is published with their permission. The named authors would like to acknowledge the important contributions of other members of the project, in particular Toby Lant, Centrica, Richard Walton and James MacArthur, SSE, Dr. Birendra Nath, Engie, and Jeff Hulance, RWE. Creep testing and metallography was carried out by AMEC FW, Warrington, with additional metallography by TEI, Wakefield.

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