# Practical Improvements in Power Plant Efficiency Through Materials Engineering

*Figure 1. A schematic of a MBEL-designed supercritical power plant*

## OBJECTIVES

- To develop welding materials for the new generation of high-strength steels.
- To develop joints between austenitic and ferritic components operating in the high-temperature regions of a boiler.
- To develop non-codified material properties that are required for advanced boiler design.
- To design, by analysis, the critical high-temperature components of a supercritical pulverised fuel (pf)-fired boiler employing the new generation of high-strength steels.
- To optimise the design, with regard to efficiency and plant flexibility.
- To develop the composition of E911 steel in order to maximise its high-temperature operational properties.

## SUMMARY


Recent work in the field of high-strength ferritic materials has demonstrated the ability of 9% chromium (Cr) tungsten bearing alloys to outperform existing steels. The creep resistance of this new steel, E911, is such that the possibility of producing boiler plant operating with main steam temperatures ~30-40°C above those presently used is close to realisation.

In this project, the practical implications of employing this new steel in pf-fired supercritical boiler plant were investigated. The mid-life and near end-life aspects of boiler plant were investigated by testing materials in various aged conditions. Data were generated covering material properties not normally directly considered in simple design philosophies. These included the effect of temperature down-shock, creep/fatigue interaction and creep/fatigue crack growth. The data produced indicated no significant concern regarding the use of E911 steel in future power plant. All the mechanical properties investigated were found to be adequate for the likely applications and comparable with those of the similar Japanese steel NF616. Although some deterioration in mechanical properties occurs with ageing, the effects are generally small and should not compromise plant performance.

Weld metal and weldment evaluations were also conducted on tungsten inert gas (TIG), manual metal arc (MMA) and submerged arc (SA) consumables with particular attention to examination of Type IV cracking. Type IV cracking takes place in many high-strength steels and is a natural consequence of the thermal history of the heat-affected zone created by welding. This effect was quantified. However, it was not possible to minimise the effect of the Type IV zone by the choice of welding consumable. Ultimately, the design of components will need to accommodate this phenomenon.

The use of high-strength ferritic materials in boiler design would also require the use of austenitic materials in superheaters that would operate at higher metal temperatures than the ferritic material could withstand. Model components were tested for such transition joints capable of operating at higher temperatures and results were compared with predictions using various models in order to assess the most appropriate for future designs.

Oxidation performance was assessed with the primary aim of correcting the creep rupture data. These data were assessed in relation to various existing models and revealed that, for long-term creep tests, a life extension of ~5% or less might be expected with the application of an oxidation correction.

Steel development is an evolving process; the standard E911 composition was optimised in order to give material properties appropriate for use under more demanding steam conditions. Optimisation of the E911 composition, by increasing Cr content to 11.5%, improved the creep properties at 600°C and 625°C and, most important, oxidation performance.

The project provided valuable experience and data that will allow the design, fabrication and operation of E911 boiler components to be optimised.


## POTENTIAL USERS OF THE TECHNOLOGY

Manufacturers and operators of supercritical steam power plant.

## COST

The total cost of the project was £821,900, with the Department of Trade and Industry contributing £295,884 and the industrial collaborators the balance.

## DURATION

43 months - June 1996 to December 1999

## CONTRACTOR


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FEBRUARY 2000

dti Department of Trade and Industry

# COLLABORATORS

PowerGen plc
British Steel plc

# BACKGROUND

The thermal efficiency of supercritical plant can be greatly increased by increasing the maximum temperature and pressure of operation of the plant. Presently, coal-fired power stations operate at ~565ºC/180 bar and have thermal efficiencies of ~39%. Increasing this to 620ºC/325 bar would allow an increase in efficiency to ~45%.

The problem that prevents the realisation of such advanced thermal cycles is the availability of a suitable material to cater for the high temperature and pressure. Under such conditions, the materials operate in the creep range and the design must cater for time-dependent deformation of the material. Austenitic stainless steels offer excellent creep resistance but have the disadvantage of relatively poor thermal conductivity and high expansion coefficient, in comparison with ferritic materials, and their use in thick-section components would severely limit a plant's operational flexibility. In particular, the plant start-up and shutdown rates would be limited, which in practice would restrict the plant to base load.

It was for these reasons that this project concentrated on the most advanced European martensitic steel, E911. The objective of the work was to provide valuable experience and data that would allow the design, fabrication and operation of E911 boiler components to be optimised. Assessment of the economic feasibility of utilising E911 in future supercritical plant was also planned.

# EXPERIMENTAL WORK, RESULTS AND DISCUSSION

## Weld Consumable Assessment

Various consumables have been developed for the welding of E911 by the major industrial processes of TIG, MMA and SA. Twelve available consumables were assessed for weldability, microstructure and temperability, in order to select the preferred consumable for each of the welding processes. The selected consumables possessed fabricating properties similar to consumables currently available for P91; therefore, there should be no joining problems.

Uniaxial all-weld strain-monitored creep tests were carried out on the selected weld metals in as-manufactured and simulated service-aged conditions, and the results analysed by comparison with parallel tests on parent E911 material. This work addressed the risk of failure by transverse cracking in low-ductility weld metal, a potential long-term threat to welds under pressure loading. The analysis developed in previous work on P91 shows that it is creep ductility, not uniaxial rupture strength, that governs how the weld metal performs in a real welded component. The results on E911 weld metals were broadly similar to those on P91. They indicate that, while low creep ductility is a concern, weld metal cracking will probably not occur until late in plant operating life. Development of improved weld metals with better creep ductility is recommended to minimise future risks. However, Type IV cracking in the weld heat affected zone (HAZ) is likely to be the greater problem in welds on plant that are subject to significant system loading.

## Weld Type IV Assessment

One of the major causes of premature failure of pressure part weldments at high temperature is the so-called Type IV failure where cracking occurs in the HAZ of the parent metal, a few mm from the weld fusion line (Figure 2).

The main feature of the results on unaged welds is that data from COST (Co-operation in Science and Technology) 501 and ACCT (Advanced Cycle Component Testing) projects, together with the current (PIPPE) project, using a variety of different weld metals, all fall within the same scatter band below that of the parent (Figure 3). This phenomenon is a reflection of the failure of these specimens consistently taking place in the Type IV position in the HAZ, and the properties of this position being largely independent of the weld metal used. The aged PIPPE welds also clearly show that there were no significant differences in the performance of the three different welds tested. However, all the results fall far below those of the unaged welds. The shortfall in life varies from a factor of >10 at the highest test stress of 135MPa, down to ~2 at the lower stress of 70MPa. It is known

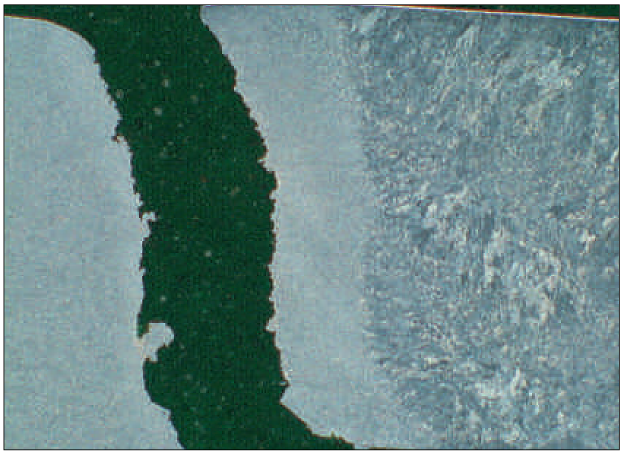


*Figure 2. Type IV failure*

that pre-aged and ex-service welds commonly perform particularly poorly in high-stress tests, probably because ageing reduces tensile properties. Extrapolation to longer life indicates that the unaged and pre-aged trend-lines intersect at the relatively low life of about 20,000h and stress of 60MPa. The linear extrapolation, and the potential inference that pre-ageing might even be beneficial in longer-term lower-stress operation, is not reliable. However, it does indicate that pre-ageing does not necessarily have any marked deleterious effect on welds at normal plant operating stresses and temperatures, for which the expected life will be much greater than 20,000h. Further longer-term test data and/or creep modelling is needed to determine whether the linear curve still applies at longer creep lives, and hence to reach any clear conclusion on the effects of pre-ageing.

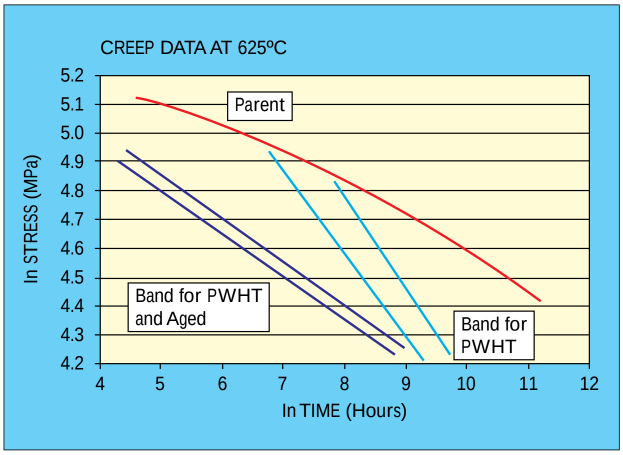



*Figure 3. Uniaxial creep data on similar welds*

The results indicate that weld Type IV performance should be considered at the design stage for high-alloy ferritic steel components. A conservative allowance may be appropriate for components likely to experience significant end loading. Furthermore it may be necessary to consider whether the degradation of weld HAZ performance at higher temperatures, rather than the parent material properties, should set the practical upper limit to materials operating temperature.

## Austenitic-Ferritic Joint Development

In order to maximise pf power plant temperature of operation, tubing with better properties than E911 will need to be used in the final superheater (but allowing the E911 to be used to its maximum potential for headers and steam pipework). The use of austenitic steel is therefore required, with a consequent need for austenitic-ferritic joints in the superheater tubes. Such joints are inherently a weak link in the boiler circuit.

## Uniaxial Testing

From the work carried out on E911 to Esshaete 1250 dissimilar welds, it is immediately apparent that all Inconel 182 welded joint results, and the lower-stress results with Inconel 625 welded joints, fail at the Type IV position in the E911 material, and the rupture durations fall close to the predicted values for similar welds (Figure 3). There is, therefore, no evidence that dissimilar welds in the uniaxial tests under-perform similar welds. However, there is evidence that Inconel 625 welds significantly outperform other weld types when tested at higher stresses (135-115Mpa).

The metallographic evidence of reduced creep strain due to the stronger weld metal confirms that this is a real effect. However, the benefit is greatest at the highest stress. It appears to be lost when lower stress testing at 80-70MPa is carried out, although the macroscopic ductility parameters in the dissimilar weld tests generally do remain rather lower than for similar welds. As all the test stresses employed are much higher than those which would be encountered in actual components, it does not seem likely from these results that Inconel 625 offers a significant real advantage.

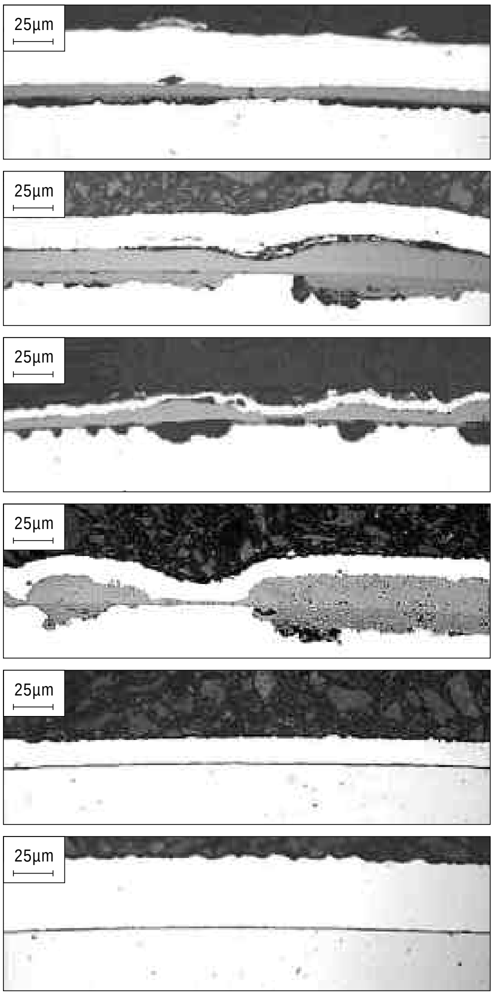
## Multiaxial Testing

In order to investigate the performance of the dissimilar welds under multiaxial conditions, internally pressurised tubular bottles with and without additional end loads were utilised. This work demonstrated that E911 Type IV cracking occurs (due to the strength reduction factor in this region) when the hoop/axial stress ratio is 1.0. Parent material failure occurs in the 0.5 stress ratio tests. Under this condition, weld cracking will not occur unless the strength reduction factor increases from the experimentally observed 20-30% in relatively short times.

The multiaxial test results show good correlation with uniaxial behaviour, indicating that factors such as dissimilar materials mismatch have no major harmful effects. However, the tests did not fully reproduce the cracking mechanisms identified in longer-term plant failures at boiler tube dissimilar welds.

## Oxidation

One of the idiosyncrasies of the manner in which design data are produced for creep-resistant steels is that thicker components tend to be penalised by the fact that the properties are determined using relatively small-dimension specimens. As oxidation of the specimens takes place during creep testing, the resulting ‘properties’ of bulk material can be underestimated. This results in components being made thicker than need be, with consequent penalties regarding weight and cost, but above all with implications for thermal shock resistance.




*Specimen No 6: 1150 hours, 580ºC*

*Specimen No 9: 16213 hours, 580ºC*

*Specimen No 15: 1150 hours, 610ºC*

*Specimen No 31: 16213 hours, 640ºC*

*Specimen No A2: 4496 hours, 640ºC*

*Specimen No A3: 7760 hours, 640ºC*

*Figure 4. Representative cross-sections of oxide films and pitting*

The assessment of air oxidation (Figure 4) has revealed that, for longer-term (>10,000h) creep tests, a life extension of ~5% could be expected with the application of an oxidation correction, with this factor increasing for longer test times. Such a factor would only be applicable for creep tests on small-diameter specimens that are used to predict lives of thick-sectioned components. The life extension is somewhat smaller than those calculated in other work for lower-alloyed materials, due to the lower oxidation rate of the higher Cr alloys. The oxidation mode (pitting) was also somewhat unexpected, leading to significant scatter in the results. Pitting can result in stress concentrations in the surface of the component. In creep ductile materials, this does not present a problem as the localised stresses can be dissipated by creep deformation. In creep brittle materials however, this can lead to creep crack growth. The susceptibility of E911 to creep crack growth is worth further investigation.

The life extension of 5% is a fairly low, but real, value. At the boiler design stage, it is unlikely that a designer would be able to take advantage of it, certainly not without more extensive testing, due in part to the scatter in the present results. However, at a mid-life analysis of any boiler, it should be possible to check any predictions against the actual metallurgical state of the components. If at this time an advantage can be confirmed, then it can be taken into account at this stage or during remaining-life activities.

Data from the higher (11.5%) Cr-optimised E911 steels indicate that any oxidation effect on these alloys will be much smaller than on the standard E911 material. Hence, when used for thick-section components, the creep strength of E911 will actually be closer to that of the 12%Cr materials than is apparent from normal creep tests.

## Property Database

Basic rupture data are available for E911 and such data are used in a code approach to the design of pressure parts. This approach alone does not allow the optimisation of the design, especially in the crucial balance between plant efficiency and plant integrity, which is directly affected by temperature ramp rates. In this work the crack growth behaviour of E911 was examined by creep fatigue of specimens (Figure 5) and down-shock testing of component-like cylinders. This has allowed the quantification of creep fatigue interactions that influence plant design and ultimate capabilities. Tests were performed on E911 material in the normal pre-service condition as well as on aged material to simulate changes occurring during service.

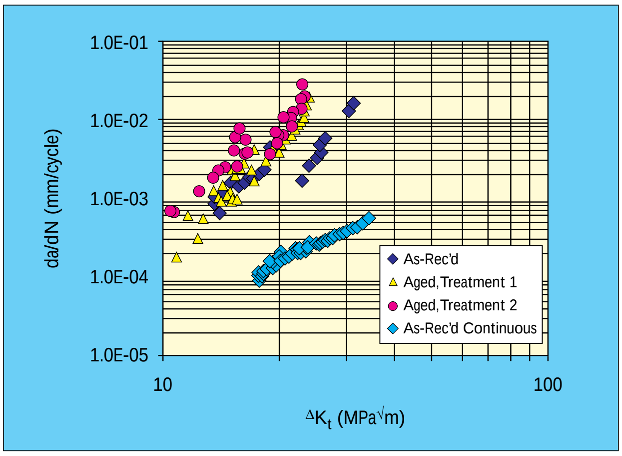



*Figure 5. Effect of ageing on creep-fatigue crack growth rates*

The data generated within this project indicate no significant concern for the use of E911 steel in future power plant. All the mechanical properties investigated were adequate for the likely applications and comparable with those of the similar Japanese steel NF616. Thus, although some deterioration in mechanical properties occurs with ageing, the effects are generally small and do not compromise plant performance.

The properties of the material in the two aged states investigated, representing those expected to exist early in plant life and after extended operation, differ only slightly. Hence, when carrying out integrity assessments of components, it will generally be appropriate to use materials' data relating to the fully-aged condition (Treatment 2), particularly when metal temperatures have been significantly higher than 600ºC.

### Design

Advanced numerical analysis techniques were employed to model the creep and creep-fatigue behaviour of the stub header (Figure 6) which is a critical component in cycled advanced power plant. The stub header collects superheated steam from a series of tubes and then transfers this to the main manifold. This is a critical component as individual tubes can be hotter than the mean temperature and this thick-walled component must be designed to cope.

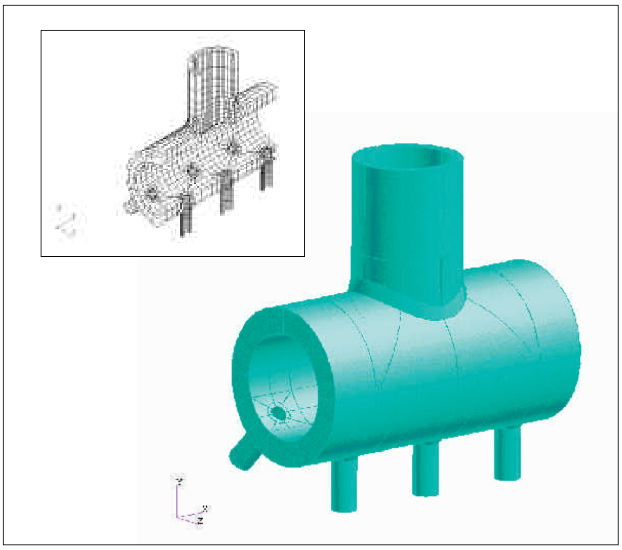


*Figure 6. Geometry of a typical stub header and selected nodes*

This work was performed using allowable stresses as given in BS1113 and also for the E911 data generated in this project. The improved creep strength of E911 over P91 leads to a reduction in header thickness of ~10% using a standard code design. The benefit of improved thermal fatigue performance due to this reduction in thickness during thermal transients is very dependent on the rate of the thermal transients. At slower plant start-up rates of around 4-5K/minute, the benefit is not particularly great, but as the rate rises to around 8-10K/min the thinner E911 structures begin to reap the benefit of a much improved fatigue life. When higher localised thermal shocks occur in the headers (eg when condensate carryover from the boiler tubes to the header occurs), which can be ~100K/min, the thermal fatigue performance of E911 is superior to that of P91. The obvious benefit of the thinner structures designed using E911 is either an improved creep-fatigue life or one that allows much more rapid start-up, with consequent savings and a more competitive response to power demands.

### Optimised E911

Steel development is an evolving process. The base E911 composition was developed to give material properties appropriate for use under more demanding steam conditions. Optimisation of the E911 composition improved the creep properties at 600ºC and 625ºC; however, the most important improvements are to oxidation performance. At temperatures above ~600ºC it is not the creep strength that limits the high temperature operation of 9%Cr materials such as E911, but the oxidation rate. Increasing the optimised E911 Cr content to 11.5% reduces the oxidation rate and thus allows the material to operate at temperatures >600ºC. The higher creep strength and significantly higher oxidation resistance has been achieved with a material that can still be produced using conventional steel-making equipment, and can be welded with conventional processes.

## CONCLUSIONS

Welding consumables with excellent weldability, temperability and suitable microstructures for the new generation of high-strength steels, that will also be suitable for existing and emerging 9-12%Cr high-strength martensitic steels, were successfully identified.

The different weld metals investigated were fairly similar in composition and, correspondingly, fairly similar in creep performance. The TIG weld metal showed poorer creep ductility and less improvement after pre-ageing than the MMA and SA weld metals. Weld metal transverse cracking is likely to be the predominant failure mechanism only in welds subject to low system loading.

The principal creep failure mechanism for both similar (like-to-like) and dissimilar welds would be 'Type IV' cracking in the fine-grained E911 HAZ. Data extrapolation to long-term plant-operating timescales suggests that the strength reduction factor could reach alarmingly high values, ie ~ 50%. Longer-term test data are required to clarify the position.

Generally, the selection of weld metal (whether a matching or non-matching ferritic, or a nickel-based consumable) and welding procedure had little or no effect on the Type IV creep life.

The performance of the dissimilar welds under multiaxial test conditions showed no significant shortfall by comparison with the performance of either similar (like-to-like) or dissimilar welds.

Thermal cycling did not appear to have a significant effect on multiaxial dissimilar weld performance.

Type IV cracking might be a major threat to the long-term performance of welded high-alloy ferritic steel components. Pending better long-term creep data, a conservative design allowance should be considered for components likely to experience significant end-loading. Furthermore, the degradation of weld HAZ performance at higher temperatures should be taken into account when determining the practical upper limits to plant operating temperatures with advanced high-alloy ferritic steels.

The oxidation mode of the E911 steel in air was not uniform, but took the form of pitting interspersed with regions of much lower and more regular oxidation. The results suggested that an improvement in life of ~3-4% at 580ºC, 4-6% at 610ºC, and 5-7% at 640ºC (creep test temperatures) could be expected if an oxidation correction is applied to creep tests lasting 30,000h.

The 11.5%Cr steels experienced uniform oxidation at a much lower rate than the E911 material. Hence any creep test corrections for oxidation would be much lower than for the E911.

All of the mechanical properties of E911 steel investigated were found to be adequate for its likely application in power generating plant operating at raised steam temperatures, being comparable with those of the similar Japanese steel NF616.

The properties of the material in conditions representing those expected to exist early in plant life and after extended operation differed only slightly.

It is seen from code design calculations that the E911 material is stronger than P91 and consequently, under the same design conditions, the minimum thicknesses of the E911 header are 10% thinner than those of the P91 header.

The finite element analyses showed that the thinner component sections, as a result of using E911 designs, gave lower levels of thermal fatigue damage that could be commercially exploited as either extended life or in more rapid start-up, with consequent savings and a more competitive response to power demands.

The optimised E911 steels showed improved tensile and creep properties, and acceptable charpy properties. Hot ductility properties established by direct/indirect test methods and assessment of delta ferrite levels indicated suitability of these optimised steels for pipe/tube-making through hot working manufacturing routes.

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