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SINGLE PHASE AND TWO PHASE EROSION CORROSION IN BOILERS OF GAS-COOLED REACTORS

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Abstract

Erosion-corrosion is a phenomenon causing metal wastage in a variety of locations in water and water-steam circuits throughout the power generation industry. Erosion-corrosion can occur in a number of regions of the once-through boiler designs used in the later Magnox and AGR type of gas cooled nuclear reactor.

This paper will consider two cases of erosion-corrosion damage (single and two phase) in once through boilers of gas cooled reactors and will describe the solutions that have been developed.

The single phase problem is associated with erosion-corrosion damage of mild steel downstream of a boiler inlet flow control orifice. With metal loss rates of up to 1mm/year at 150°C and pH in the range 9.0-9.4 it was found that 5μg/kg oxygen was sufficient to reduce erosion-corrosion rates to less than 0.02mm/year. A combined oxygen-ammonia-hydrazine feedwater regime was developed and validated to eliminate oxygen carryover and hence give protection from stress corrosion in the austenitic section of the AGR once through boiler whilst still providing erosion-corrosion control.

Two phase erosion-corrosion tube failures have occurred in the evaporator of the mild steel once through boilers of the later Magnox reactors operating at pressures in the range 35-40 bar. Rig studies have shown that amines dosed in the feedwater can provide a significant reduction in metal loss rates and a tube lifetime assessment technique has been developed to predict potential tube failure profiles in a fully operational boiler.

The solutions identified for both problems have been successfully implemented and the experience obtained following implementation including any problems or other benefits arising from the introduction of the new regimes will be presented. Methods for monitoring and evaluating the efficiency of the solutions have been developed and the results from these exercises will also be discussed. Consideration will also be given to the similarities in the metal loss mechanisms and possible methods of solution that both problems exhibit.

Finally the adaption of the new regimes described in the paper to problems in other areas of the power generation industry will be reviewed.

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1. INTRODUCTION

Erosion-corrosion is a phenomenon causing metal wastage in a variety of locations in water and water-steam circuits throughout the power generation industry. It can in principle occur whenever high velocity single phase water or two phase steam-water comes into contact with mild steel. In practice it is confined to temperatures below about 275°C and thus in power plant it can occur in feed heaters, boiler tubes, steam lines and separators etc. In particular it can and does occur in the once through boiler designs used in the later Magnox and AGR type of gas cooled nuclear reactors.

This paper will consider two cases of erosion-corrosion (single and two phase) that have occurred in once-through boilers of the CEGB's nuclear reactors. The solutions that have been developed will be presented and the role that the CEGB's full scale single tube boiler facility has played will be discussed. Experience obtained following implementation including any problems or other benefits arising from the introduction of the new regimes will be presented. Methods for monitoring and evaluating the efficacy of the solutions have been developed and the results from these exercises will be discussed.

2. TWO-PHASE EROSION CORROSION

Two-phase erosion-corrosion has been identified as the mechanism of several boiler tube failures at the CEGB Magnox type nuclear reactor at Wylfa. These failures have been associated with localised areas where enhanced gas flows have resulted in the boiling boundary being depressed into the smallest diameter (18mm) section of the serpentine boiler tube (Figure 1). Under normal operating conditions evaporation takes place in the 30mm diameter section. Hydrodynamic changes were made in an attempt to

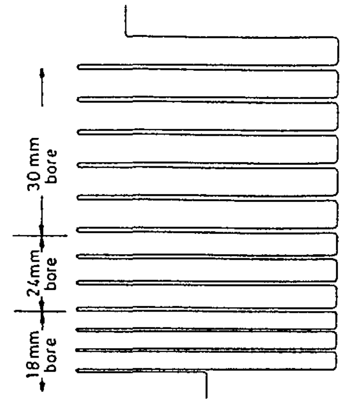

Fig 1 Serpentine Boiler Tube

return the boiling boundary to the 30mm section and the feedwater pH was increased from 9.0 to 9.6. Boiler tube failures continued but at a reduced rate. Further consideration of the two-phase erosion-corrosion problem indicated that the boilers more generally may be susceptible to metal loss from this mechanism and that a method of assessment was required to identify the likely loss rates.

During normal boiler operation mild steel surfaces quickly become covered with a thin, compact, impervious corrosion film of magnetite (Fe_3O_4) which grows with parabolic kinetics and effectively protects the underlying metal from further attack. Under conditions of high fluid turbulence enhanced localised dissolution of magnetite occurs, the corrosion film becomes thinner and the metal loss rate increases. Affected surfaces are usually shiny black in appearance, overlayed with a thin (<1 μm) magnetite oxide. Surrounding areas are frequently reddish (Fe_2O_3) oxide. A scalloped, 'orange peel' appearance is visible which is produced by the overlapping of horse-shoe shaped pits. No evidence has been seen of work hardening of the parent metal surface at the corrosion site. These features are consistent with a dissolution rather than an erosion process. Erosion-corrosion is therefore perhaps a misnomer for this phenomenon which has been more correctly termed 'flow assisted corrosion'.

Two important sequential steps are believed to control the metal loss rate, i.e. oxide dissolution at the oxide-solution interface and mass transfer of this dissolved material into the bulk fluid. The rate of metal loss in two-phase erosion-corrosion can be described by the diffusion equation:-

$$\text{Rate} = w(C_s - C_b) \quad (1)$$

Examination of the individual terms on the right hand side of the equation (1) gives an indication of the complexities of the overall process. The mass transfer coefficient, W, in two-phase flow in a bend is not defined at present and will depend on many parameters including mass flow rate, thermodynamic quality tube bore and bend diameter, whilst the concentration of soluble iron at the oxide - solution interface, C_s is even less predictable. The final term in the rate equation, C_b is the bulk concentration of soluble iron. This parameter is unknown in all once-through boilers in nuclear plant, since the concentration in the evaporator bears little relationship to feedwater levels and local sampling is obviously impossible.

2.1 Factors Affecting Erosion-Corrosion

The two main factors which affect two-phase erosion-corrosion are the mass transfer coefficient and the solubility of ferrous ions at the metal surface. To alleviate the erosion-corrosion problem a reduction in either or both of these parameters is required. In practice a reduction in mass transfer coefficient would involve the drastic step of a significant reduction in boiler load and consequential loss in generation. One of the main parameters controlling the solubility of iron at the erosion-corrosion site is the high temperature pH in the aqueous phase at the oxide-solution interface, referred to as pH(T). Over the practical range covered with volatile alkalis an increase in pH(T) leads to a reduction in iron solubility. The calculated values of pH(T) for pure water and a solution of ammonia decrease markedly with temperature. It will be seen later that steam generation and the presence of acidic anions changes the pH(T) further. Clearly, the pH(T) values used in this paper were not measured directly but were calculated by the solution of several non-linear simultaneous equations involving mass balance, charge balance, dissociation constant for water, base dissociation constants and partition coefficients of the relevant alkalising agents and anions.

Like most once-through boilers, Wylfa was designed for operation with pH control with ammonia. It also has 100% condensate polishing which, since it is a sea water cooled station, is considered essential to limit chloride ingress. The maximum pH is in practice limited by the capacity of the polishing plant and the rate at which it can be regenerated. This means that the highest practicable ammonia concentration in feed water is 1.5-2 ppm. Although both direct conductivity and pH at 25°C are used for station control purposes the relevant parameter for two-phase erosion-corrosion is the pH at saturation temperature at the erosion-corrosion site denoted by pH(T). Using this criterion ammonia does not perform well and several other amines provide a higher two phase pH(T) for the same equivalent concentration. The use of morpholine in erosion-corrosion control has been reported and two other potentially applicable amines have been identified: piperidine and 2-amino-2-methyl-propanal-1-ol, subsequently referred to as AMP.

2.2 Boiler Rig Studies

The calculation of two-phase erosion-corrosion metal loss rates on a purely theoretical basis at power station operating conditions is at present impossible. Therefore such analyses are confined to the use of plant data and failure statistics from stations which have exhibited two-phase erosion-corrosion problems together with a direct experimental simulation of a serpentine boiler tube, such as that reported here.

A full scale replica of a serpentine boiler tube was installed on the CEGB Boiler Rig Facility at the Operational Engineering Division Laboratories at Wythenshawe as part of the study of the two phase erosion corrosion problem at Wylfa Power Station. The test section is electrically heated by passing a low voltage three phase alternating current through the boiler tube wall. The boiler tube is supplied with feed water at the appropriate flow rate, temperature, pressure and chemical purity. Steam produced within the boiler tube is condensed at high pressure cooled and returned via a circulating pump and full flow condensate polishing plant to the boiler inlet. The electrical heating system is designed to provide a heat flux profile matched to that obtained in the gas heated boiler.

Full hydrothermal and chemical control and monitoring is carried out with ammonia concentration and any contaminants such as chloride, oxygen, acetate etc. being controlled by the use of small high pressure dosing pumps. Chemical sampling via stainless steel capillary tubing is carried out at polishing plant outlet, test section inlet and at a number of positions in the evaporator section. Typical operating conditions for the two-phase erosion-corrosion studies described here are presented in Table 1.

TABLE 1 - OPERATING CONDITIONS

Mass flowrate	0.21 kgs^{-1}
Test Section Inlet Temperature	105°C
Test Section Outlet Temperature	330°C
Saturation Pressure	35 bar
Total Heat Input	550 KW
Chemical Parameters (at Boiler Inlet)	
Ammonia controllable	0-10 ppm
After cation conductivity	<0.06 μS/cm
Sodium	<1 ppb
Chloride (before dosing of additional Cℓ)	<1 ppb
Sulphate	<1 ppb
Oxygen	<1 ppb
Iron	<2 ppb

Metal loss is monitored continuously on load using a thin layer activation technique (T.L.A.). In addition to this a wall thickness survey of the whole extrados of the bend, along the centre line, is carried out before and after each run using a pulse echo ultrasonic probe. This is a much less sensitive technique than TLA having a standard deviation of about 3 μm compared with a resolution of better than 0.2 μm with TLA. However the use of the two techniques is complementary allowing both metal loss and total loss profiles to be observed.

2.2.1 Amine Studies and Development of a pH(T) Dependence

A series of experiments was conducted at typical Wylfa flowrates over a range of thermodynamic qualities between 50% and 90% with 0.4 ppm ammonia and 15 ppb chloride. These conditions were chosen because they were considered typical of early Wylfa operation and the metal loss rates obtained could be compared with that obtained from the time to first failure on the plant. Results obtained at the high steam quality with 15 ppb chloride showed good agreement with plant data. The presence of chloride is significant in producing a marked reduction in the aqueous phase pH(T) at the high quality condition, Figure 2, which was therefore associated with the highest erosion-corrosion rate of approximately 1.4 mm yr^{-1} observed. In the absence of chloride the maximum erosion-corrosion rates occurred at lower thermodynamic quality conditions (70%) probably linked with the peak in mass transfer profile with quality.

A multifactorial analysis of the limited data obtained on achieving realistic metal loss rates, indicates that the relationship between erosion-corrosion rate and pH(T) can be represented by

$$\log(\text{rate}) = 0.92\ \text{pH(T)} \qquad (2)$$

with the uncertainty in the slope being ±0.2.

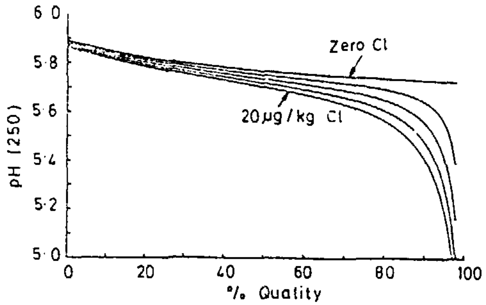

Fig 2 High Temperature pH versus quality

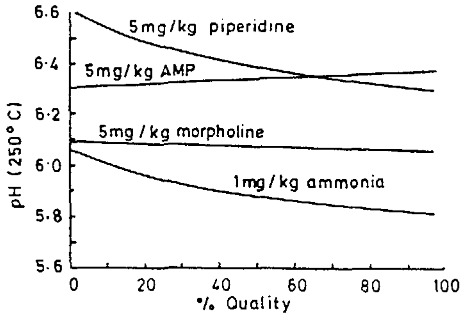

Fig 3 High Temperature pH versus quality for equivalent amine concentrations

The initial phase of the experimental work on the Boiler Rig did not provide absolute rate data. However it did give information on the relative performance of a number of amines (ammonia, morpholine, AMP and piperidine) over a range of concentrations and at thermodynamic qualities between 40% and 60%. The results of some forty tests, whilst showing more scatter, gave a similar relationship to that described above in equation (2) of

$$\log(\text{rate}) = -0.95\ \text{pH(T)}. \qquad (3)$$

There was no indication of any chemical factor other than pH(T) influencing the performance of these amines; i.e. there is no evidence of any surface or complexing effect peculiar to any amine. On this basis the selection of an amine for erosion-corrosion control with equal CPP loading, can be made simply by consideration of pH(T) variation with quality. This is illustrated in Figure 3 where the performance of ammonia, piperdine, morpholine and AMP are compared at equivalent concentrations. At qualitities above 60%, where Rig studies have demonstated the highest metal loss rates occur, AMP provides the greatest benefit and of the amines considered AMP provides the best palliative of erosion-corrosion control in once-through boilers in this pressure range. Further studies on the Boiler Rig, have been carried out to study thermal decomposition of AMP. These tests demonstrated that no significant decomposition of AMP (<2%) could be detected either as a loss of AMP across the boiler or as an increase in after cation conductivity at normal boiler operating conditions.

2.2.2 Mass Transfer Dependence

The dependence of erosion-corrosion on mass transfer coefficient has not been studied at the temperature and pH existing in the modern magnox power station boilers. It has been argued theoretically by Bignold et al (1) that because of electrochemical effects the erosion-corrosion rate should vary with the cube of the mass transfer coefficient and metal loss rates observed on both plant and experimental rigs operating under single phase flow conditions tend to support this theory with the power dependence generally lying between 2 and 3. However experimental studies indicate that the metal loss rate dependence on mass transfer coefficient is a function of both temperature and pH and the range covered in these studies is outside that which applies to the two-phase conditions under consideration here. Therefore it is not possible to use these relationships to predict the dependence of two-phase erosion-corrosion on mass transfer coefficient.

A series of experiments have been carried out on the Boiler Rig test section to investigate the effect of mass flow rate changes on erosion-corrosion rate. Assuming that the erosion-corrosion rate was proportional to the mass flow rate raised to some power, n, then the mass flow rate change be expressed as

$$\log_{10}\left\{\frac{\text{erosion-corrosion rate 1}}{\text{erosion-corrosion rate 2}}\right\} = n \log_{10}\left\{\frac{\text{mass flow rate 1}}{\text{mass flow rate 2}}\right\} \qquad (4)$$

The rig data, plotted in this form, with a linear regression line gives a value for n of $1.97 \pm .74$ to 95% confidence limits. Thus despite the large degree of scatter on the data the lower mass flow dependence indicated is of the order of 1.2 which implies a dependence of (mass transfer coefficient)^2 whilst the regression implies (mass transfer coefficient)^3.

2.2.3 Tube Failure Predictions

In order to make predictions of future tube failures, a method of extrapolating from a small number of leaks to the performance of the whole population at risk is required. One method that may be used, once an initial failure history has been estalished, makes use of the Weibull distribution which has the form:-

159 $$F(t) = 1 - e^{\left(\frac{t-t_o}{\zeta}\right)^{\beta}} \qquad (5)$$

By taking the time for the start of the failure process, t_o, to be zero, equation (5) may be rearranged such that:

$$\ln \ln \frac{1}{1-F(t)} = \beta \ln t - \beta \ln$$

where 1-F(t) is the reliability R and

$$R = 1 - \frac{\text{number of failed items}}{\text{total number at risk}} \qquad (6)$$

Plotting the left-hand side of equation (6) against the logarithm of time, t, should produce a straight line from which the shape factor, β and characteristic life, ζ, may be determined. The Weibull distribution can represent a wide variety of probability profiles by varying the value of β and so has the advantage of not fixing the data to fit some predetermined shape.

Once a predicted failure distribution has been established for a known operating regime the effect of proposed chemical or hydrodynamic changes may be examined using the pH(T) and mass transfer dependencies developed earlier. The change in metal loss rate produced may be calculated and applied to the Weibull distribution to give an indication of the scale of the reduction in future failures. The ratio of the metal loss rate before a change to that after it has been termed the "benefit factor". A demonstration of this method for tube lifetime assessment is presented in Figure 4 where the effect of benefit factors between 2 and 5 have been imposed on a hypothetical failure distribtution after thirty six years.

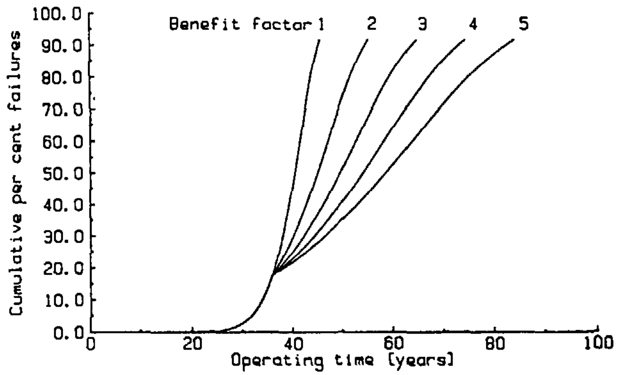

Fig 4 Effect of rate change on failure predictions

2.3 Choice of an Amine for Wylfa

The experimental work on the boiler rig has demonstrated the importance in achieving maximum pH(T) to control erosion-corrosion and that of the amines considered AMP could provide the highest pH(T) for the steam qualities where the greatest metal loss had occurred.

AMP was also reasonably cheap compared with other oranic amines, is readily available and presents no significant handling difficulties. It is of relatively low toxicity and can be discharged into the sea after regeneration of the CPP resins. Preliminary laboratory tests indicated that no adverse effect on the CPP resins was expected.

On this basis AMP was selected for use at Wylfa and dosed to give 5 mg/kg from September 1983. Following application of the tube lifetime calculation in March 1984 the dose rate was increased to 10 mg/kg to give a very high degree of confidence in achieving the desired boiler lifetime.

2.4 Experience of Operation with AMP at Wylfa

Tube failures attributable to two-phase erosion-corrosion have been reduced significantly for both reactors for the period September 1983 - Jan 1987 compared with the number expected with continuation of ammonia dosing at 2 mg/kg.

Performance of the condensate polishing plant is unchanged except that the burden is rather less than with ammonia dosing to the same equivalent concentration at boiler inlet since the low volatility AMP concentrates in the steam separator drain and about 20% of the amount at the boiler inlet has been recycled unpolished. Both capacity and water quality produced by the CPP appear unaffected even with 10 mg/kg AMP.

Iron concentrations around the water-steam circuit are less than with ammonia dosing. Not only does this reflect lower corrosion in the feed system and lower erosion-corrosion in wet steam but it also results in lower iron transport into the boilers. Copper levels at CPP inlet have increased since AMP dosing but the polishing plant prevents any increased transport of copper to the boiler.

Dosing of AMP has been received favourably by the operators. It has a mild and not unpleasant smell compared with the pungency of ammonia. For this reason it can be dosed undiluted and hence faults due to incorrect dilution avoided.

AMP shows little thermal decomposition under the steady load conditions but boiler transients do give rise to breakdown. Nevertheless, even under the worst incidents, the higher basicity and low volatility of AMP compared with ammonia still result in improved protection of all mild steel surfaces.

3. SINGLE PHASE EROSION-CORROSION

A number of cases of single phase erosion-corrosion damage have been observed within the CEGB on both AGR and Magnox boilers. These have occurred whenever high velocity single phase water comes into contact with mild steel surfaces and have been a severe problem in the area immediately downstream of boiler flow control ferrules where high velocity jets impact on the surface. Two such cases have occurred at Wylfa and Heysham 1. At Wylfa the single phase erosion-corrosion damage was restricted to immediately downstream of the boiler inlet control ferrules. Erosion-corrosion is effectively restricted to mild steel and Huijbregts (Reference 2) has demonstrated that chromium, molybdenum and copper has a beneficial effect. A solution for Wylfa was then engineered which ensured that the emerging jet from the boiler control orifice impacted on stainless steel which is resistent to erosion-corrosion. A new ferrule was therefore designed with a downstream shroud of stainless steel. This ferrule was internally welded into the restrictor tube and has proved successful in operation over seven years. Test rigs which included groups of four ferrules were mounted in the feed system of the Wylfa boilers and load followed at identical conditions to the installed ferrules. Examination of these ferrules in the test rigs were carried out at periodic intervals and have demonstrated satisfactory performance.

A similar but more extensive problem occurred at the AGR stations of Hartlepool and Heysham 1. The boiler inlet ferrules were originally designed as shown in Figure 5 and downstream of the ferrules was a length of restrictor tube (7.6 mm diameter) followed by a number of small radius right angle bends. Throughout the CEGB a series of investigations were carried out on both laboratory and station based facilities to evaluate the erosion-corrosion risk. These are reported in detail by Bates et al (Reference 3). The tests demonstrated that in the area downstream of the ferrule metal losses in the range 1.5 mm/year to 2.4 mm/year at a pH of 9.05 temperature of 148°C and flow rate of 0.201 kg/s could be obtained. Finite erosion-corrosion rates were observed in the restrictor tube and feed tail bends which were in excess of those which would guarantee full station life. The need for a palliative which would protect both downstream of the ferrules and also the restrictor tube and feed tail bends was thus demonstrated.

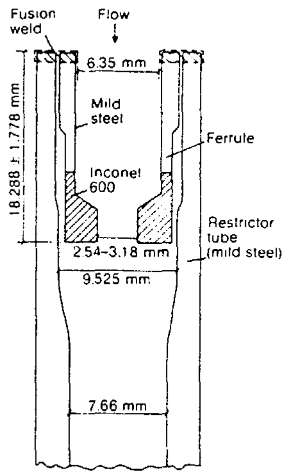

Fig 5 Original production Heysham 1 ferrule

The replacement of all the ferrules with an erosion-corrosion resistant design was obviously a very expensive opltion and therefore it was prudent to consider the possibility of an alternative palliative. Initial investigations demonstrated the dependence of erosion-corrosion on pH and that the damage could be limited by increasing pH. However with the limitation of condensate polishing plant it was not considered possible to achieve boiler lifetime in the components that had high metal loss rates.

The search was widened further to consider the role of small quantities of oxygen on erosion-corrosion. It was considered that oxygen dosing had one major disadvantage with this particular boiler design in that it was thought to be incompatible with an austenitic superheater section of which some parts could be sensitised with high stress levels. Although the austenitic section is designed to operate dry with adequate superheat the possibility of some tubes being wetted could not be discounted and hence there was the risk of oxygen induced stress corrosion cracking. However it was considered that an excess of hydrazine could be added which would consume all the oxygen before it reached the austenitic section but not before the areas prone to erosion corrosion. This also required that hydrazine did not prevent oxygen from inhibiting erosion corrosion. This paper will now concentrate on the role that the CEGB's single tube boiler facility has played in the development of the oxygen-hydrazine-ammonia regime for controlling single phase erosion-corrosion.

3.1 Boiler Rig Studies

The rig has briefly been described earlier in this paper and for these studies a medium diameter Heysham 1 helical coil was installed on the facility. The typical operating conditions are described below in Table 2.

TABLE 2

Feed flow rate	0.16 kg s^{-1}
Feed temperature	148°C
Steam temperature	512°C
Feed pressure	180 bar
Feedwater pH	9.1-9.4
Conductivity after cation	0.06 µS/cm
Na^+, Cl^-, SO_4^{2-}	<1 µg/kg
Fe	1-12 µg/kg
O_2 (unless dosed)	<1 µg/kg

Three metal loss techniques were employed for measurement post ferrule and on feed tail bends. These include the on load technique of Thin Layer Activation and two off load techniques of bore mensuration (Diatest) and ultrasonics wall thickness measurement.

In the post ferrule situation, in the absence of oxygen dosing, a steady reproducible and linear rate of metal loss was readily established and maintained, if necessary for several hundred hours.

The effect of oxygen dosing on the erosion-corrosion rate is illustrated by Figure 6 which shows results from the first of several such experiments.

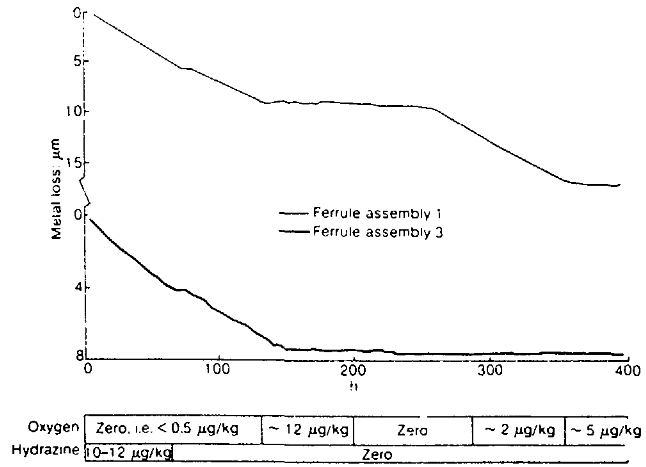

Fig 6 TLA results and the equivalent metal losses on two ferrules with oxygen dosing

Metal loss on ferrule assembly 1 stopped within an hour of starting oxygen dosing to give 12 µg/kg, whereas there was a delay of a few hours on ferrule assembly 3 due to the time for oxygen to penetrate through the feed system as confirmed by local oxygen sampling. In both instances the metal loss rate during oxygen dosing was less than 20 µm/year. When oxygen dosing was discontinued, the first specimen showed a very slight rate increase for about 50 h before resuming metal loss at about 500 µm/year which is very close to the rate before oxygen injection. Ferrule assembly 3 did not restart metal loss during that test despite 90 h operation with no oxygen. Subsequent oxygen injection at about 2 µg/kg had no apparent effect but 5 µg/kg did stop metal loss on ferrule assembly 1 with an efficacy equal to that in the 12 µg/kg test. In all cases when oxygen was dosed into the feedwater the result was either, at oxygen levels below about 5 µg/kg, no effect on erosion-corrosion or, more usually, complete arrest of metal loss. There was never any instance of metal loss being merely slowed down, which led to the concept of an oxygen threshold concentration for stopping erosion-corrosion.

The other useful property of oxygen initially observed at this stage was the reduction in feedwater iron concentrations.

3.2 Oxygen-hydrazine reaction

The oxygen-hydrazine reaction was not a straight-forward experiment since oxide surfaces which have been grown under reducing conditions have a considerable capacity for oxygen so that in short-term tests, even in the absence of hydrazine, oxygen would not reach the austenitic section. Thus to achieve a meaningful result within the time-scale of one run (500-700 h) it was necessary to equilibrate the test section to oxygen alone before assessing the effect of hydrazine addition. The criterion for 'equilibrium' (in a system which cannot achieve a true thermodynamic equilibrium) was taken as being that oxygen profiles throughout the test section should return to their previous values following a period when the oxygen dosing had been increased fourfold.

Oxygen conditioning of the test section was initially carried out under subcooled conditions (320°C at the outlet) with a flow rate of 0.095 kg/s.

The oxygen-hydrazine reaction at 80% load conditions was then studied. The main feature of these results is that an inlet oxygen concentration of 30 µg/kg was consumed by 50 µg/kg hydrazine before reaching the inlet to the 9Cr section of the boiler, well upstream of the austenitic section. Subsequent tests at the same flow with 15 µg/kg oxygen and 30 µg/kg hydrazine at the inlet produced a similar result except that about 2 µg/kg oxygen was detected at the inlet to the 9Cr section. There was still less than 1 µg/kg oxygen at the evaporator inlet. Another important feature of these results is that sufficient oxygen survives beyond the ferrule and as far as the coil inlet to control any erosion-corrosion in these areas.

3.3 Operational Considerations

The first important feature of this work is the demonstration that oxygen does provide a palliative. Although the use of oxygenaed feedwater systems to control iron pick-up in general and erosion-corrosion in particular is not new, this particular combination of the relatively high pH of 9.4 and the relatively low range of oxygen concentrations used here is believed to be a new approach.

The most novel feature is the simultaneous use of oxygen and hydrazine to control single-phase erosion-corrosion and yet to consume all the oxygen well before it could reach the austenitic section of the boiler. The appropriate parameters that have been validated on the full-scale boiler rig and recommended for use by the stations are 15 µg/kg oxygen, 30 µg/kg hydrazine and ammonia to give pH 9.4 (i.e. 1.05 mg/kg ammonia). The oxygen value of 15 µg/kg is at least three times the value that was found to be necessary to stop erosion-corrosion and thus makes a generous allowance for the possibility of some sites having a higher erosion-corrosion rate (in the absence of oxygen) than replicated on the rig. The pH of 9.4 is also a conservative estimate when it is recalled that only 5 µg/kg oxygen was necessary to stop erosion-corrosion at pH 9.2. The reservations about allowing a reduced pH arose from concern about iron pick-up in the feed system before dosing rather than any doubts about the efficacy of erosion-corrosion control. Any lowering of pH, which would be of appreciable benefit in reducing the burden on the condensate polishing plant, will need to be decided on the actual performance of the stations' feed systems and the boilers sensitivity to iron level.

The new feedwater regime offers much reduced iron pick-up in oxygenated feedwater which should lead to significantly less iron transport to the boilers. Also, since oxygen persists to mid-economizer level, potential erosion-corrosion sites after the orifice, which would be unaffected by a redesign of the orifice, are given protection. The new feedwater chemistry has been shown to be tolerant to a loss of oxygen dosing, a loss of hydrazine dosing and, as far as the feed system, orifice and restrictor tube are concerned, to at least 20 µg/kg chloride.

The dosing procedure adopted has been to inject oxygen gas immediaely downstream of the deaerator. Hydrazine is also dosed at this stage while ammonia is added downstream of the CPP in the normal way. Oxygen dosing is controlled to give 15 ± 3 µg/kg at the boiler inlet, recognizing that a loss of oxygen can occur along the feed system. Control is via a two-stage system in which the flow of oxygen gas rapidly responds to feed flow changes with a slower 'trim' based on a measured oxygen concentration. The system is orificed to prevent gross overdosing of oxygen in the event of instrument malfunction.

Following other boiler problems relating to the maldistribution of individual tube feed flows some of the boilers at Heysham 1 and Hartlepool have now been referruled with erosion-corrosion resistant upstand ferrules. The oxygen-hydrazine-ammonia feedwater regime is maintained in all cases to provide erosion-corrosion protection throughout the single phase regime.

3.4 Monitoring Programme

There is a high level of confidence that the single phase erosion-corrosion palliatives developed for Heysham 1 and Hartlepool will guarantee station life. However a continued monitoring process has been installed to ensure that the application of the palliatives remain successful. Monitoring of the ferrule performance is carried out using load following rigs installed on the respective stations and including a number of the boiler control ferrules. These are removed and inspected at periodic intervals. An ultrasonic wall thickness measuring technique has been developed for monitoring a number of accessible restrictor and feed tail bends.

4. EROSION-CORROSION PALLIATIVES

The two cases of erosion-corrosion that have been considered in this paper are typical of a number that have occurred in the boilers of the CEGB's nuclear stations. The nature of single phase and two phase erosion-corrosion are essentially the same and it may be considered that identified palliatives could be applied to either type of damage. The use of alloy steels to prevent erosion-corrosion damage protects both in the single phase and two phase regimes. The design of boiler control ferrules with 316 stainless steel shrouds has proved very successful and there is no evidence of two phase damage in AGR boilers where all the evaporation takes place in 9% Cr boiler tube.

The control of erosion-corrosion by the increasing of pH of the water phas has again been demonstrated and is the basis of the method of two phase erosion-corrosion control by such amines as AMP and morpholine. This palliative does not result in a cessation of damage but offers a significant reduction in metal loss rate and the increase of pH has to be assessed to give confidence in providing a guarantee of boiler lifetime. In the case of post ferrule metal loss at Hartlepool and Heysham 1 this confidence could not be achieved with the limit of condensate polishing plant loadings.

The oxygen-hydrazine-ammonia feedwater regime applied at Heysham 1 and Hartlepool provided a method of stopping erosion-corrosion metal loss even in high metal loss areas and in the case described was needed because erosion-corrosion sites existed at unaccessible sites in the boiler. The use of oxygen was considered as a palliative for two phase erosion-corrosion at Wylfa. Initial results appeared encouraging with 100 ppb oxygen producing a response. However subsequent tests should that 100 ppb was not always effective in preventing metal loss and more importantly, in the presence of mildly acidic solutions oxygen dosing resulted in an increase in metal loss rate. Thus despite the initial promise the use of oxygen to combat two phase erosion-corrosion was rejected.

Erosion-corrosion has been extensively research within the CEGB and palliatives identified to combat particular problems. Care has been taken to continue monitoring following implementation of the palliatives using either plant data or power station based facilities. All the evidence available to date is that the problems associated with erosion-corrosion are well under control.

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PLUGGING OF FEED INLET TUBE UPSTANDS WITH Ni/Ti SHAPE MEMORY ALLOY PLUGS — HEYSHAM 1 POWER STATION

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Abstract

The paper contains a description of a new approach for plugging feed inlet tubes of Gas-Cooled Reactors. Instead of utilizing the original explosive method plugging by fitting a shape memory alloy plug into the upstand is being described.

1. INTRODUCTION

The fitting of upstands to the feed inlet tubeplates has made plugging by the original explosive method protracted and difficult. Certain leaks, i.e. those from the bore of the boiler tube/upstand to the gas space could be plugged by fitting a shape memory alloy plug into the upstand.

The upstands consist of a bimetallic 1Cr ½Mo/Inconel 600 tube bore welded to a buttered spigot on the face of the tubesheet. As shown in Figure 1 the high impedance flow restrictor is screwed into the upstand and this proposal deals with sealing the upstand once the flow restrictor has been removed.

The plug location is shown in Figure 2 and details of the relevant properties and similar applications are appended (Appendix I and II).

2. INSTALLATION PROCEDURE

Once the leaking tubes have been identified and the reactor depressurised the plugging procedure would follow this sequence:-

2.1 Remove the anti-rotation straps from the ferrule and unscrew the ferrule from the upstand.

2.2 Fit a removable plug at the tube plate level in order to prevent debris entering the tube.

2.3 Clean the bore of the Inconel 600 portion of the upstand using a stainless steel wire brush mounted on a flexible drive. The intention is to merely remove any loosely adherent oxide, etc.