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Juha Sarkki (juha.sarkki@fwfin.fwc.com)  
Foster Wheeler OY  
Finland  
Fionn Griffin (fionn.griffin@esb.ie)  
Stephen Scully (stephen.scully@esb.ie)  
Trevor Flynn (trevor.flynn@esb.ie)  
ESB, Ireland

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## CFB TECHNOLOGY IN ESB PEAT BURNING POWER STATIONS

JUHA SARKKI\* FIONN GRIFFIN\*\* STEPHEN SCULLY\*\*\*TREVOR FLYNN\*\*\*\*

*\*FOSTER WHEELER OY, FINLAND, JUHA.SARKKI@FWFIN.FWC.COM*

*\*\*ESB, IRELAND, FIONN.GRIFFIN@ESB.IE*

*\*\*\*ESB, IRELAND, STEPHEN.SCULLY@ESB.IE*

*\*\*\*\*ESB, IRELAND, TREVOR.FLYNN@ESB.IE*

**Abstract** Ireland's Electricity Supply Board (ESB) has owned and operated peat fired power plants since 1949. Due to a combination of changes in EU and Irish Electricity legislation, ESB decided in early 2000 to replace all the then existing peat fired power stations with two new plants using the latest efficient and environmentally friendly technology. Foster Wheeler's Circulating Fluidized Bed (CFB) combustion technology was selected to accomplish this following competitive tendering. These peat burning stations were built in the Irish Midlands, with the first unit of 100 MWe capacity built at Lanesborough, Co Longford and another of 150 MWe built at Shannonbridge, Co. Offaly. Foster Wheeler was the turnkey contractor as well as the boiler supplier for both plants.

The initial operation of both units was very satisfactory. Both units met with good margin the strict environmental standards imposed. A huge benefit of the modernization of the plants has been vastly increased efficiency. Performance tests were carried out on both units with Foster Wheeler achieving the heat rate and the output specified in the contract, both with some margin.

However, early into the operation of the units inspection revealed heavy fouling and external tube corrosion of the Superheater 2 and Reheater 1B boiler tube panels. ESB and Foster Wheeler embarked on a program to actively work together to develop solutions to address the aggressive conditions experienced by the heat exchanger surfaces and the boiler tube fouling. The solution resulted in the installation of new, higher specification materials in the convective pass of both boilers.

As a result of this unique supplier / client teamwork, the performance of the plants has been excellent since the material upgrade, with both plants operating at close to 100 % availability.

### 1 INTRODUCTION

Historically, peat has played a major role in Ireland's energy equation, thanks to extensive reserves in the Irish Midlands and the west of the country which are managed by Bord na Móna. Peat forms part of

Ireland's indigenous sources of energy used for power generation along with hydropower and small quantities of natural gas. ESB began using peat for commercial electricity generation in the 1950s. By the early 1960s, more than a third of Ireland's electricity was generated in peat-fired plants. Today, despite electricity generation from peat representing 10% of installed capacity, peat is still seen as an important strategic national resource. Peat harvesting and use is also a valuable source of local employment.

Power Generation from peat commenced with solid fuel chain grate boilers followed by a transition to pulverised fuel with hammer mills. Ireland's unpredictable climate makes harvesting homogenous peat quality almost impossible, and peat composition varies, even in geographically local areas.

## **2 ESB CFB PROJECT**

With existing peat-fired capacity nearing the end of its useful life, ESB – Ireland's largest electricity generating and distribution company – decided in early 2000 to replace peat plants at Shannonbridge (125 MWe) and Lanesboro (85 MWe) dating from the 1970s and 1980s, as well as older peat plants in Counties Mayo, Offaly and Kerry, with two new peat fired power generation plants. The units to be replaced were characterised by a low efficiency (28%) and a high cost base. Environmental issues were also of concern, as the emissions of the older plants (Particulates: 3,000 mg/Nm<sup>3</sup>, SO<sub>2</sub>: 450 mg/Nm<sup>3</sup>, NO<sub>x</sub>: 650 mg/Nm<sup>3</sup>) would not be able to meet the emissions requirements of the LCP directive. The decision to replace existing units was also expedited by changes in EU and Irish Electricity legislation, leading to full market opening in 2005.

After a bidding process, the EPC-Contract was awarded to Foster wheeler in 2002 to build West Offaly Power (WOP) and Lough Ree Power (LRP). ESB appreciated Foster Wheeler's extensive expertise in CFB technology and their experience with peat fired boilers. This was demonstrated in Foster Wheelers extensive reference list which stretched back over 35 years and included over 70 Circulating Fluidised Bed (CFB) and Bubbling Fluidised Bed (BFB) units firing peat either as a primary or secondary fuel.

The units were taken into commercial operation in 2004/5. Both new units featured an identical design, and were based on Foster Wheeler's advanced CFB technology incorporating fully integrated steam cooled solids separator design and return leg designs, INTREX™ Superheater / Reheater and partial step grid design. Using INTREX™ as a last stage of superheating /reheating allowed state-of-the-art steam temperatures to be used in the new boilers. WOP is rated at 150 MWe and LRP at 100 MWe.

Based on studies and combustion trials at Foster Wheeler's R&D Centre in Finland, a number of special features have been integrated into the design. The boiler envelope consists of a CFB furnace, cyclone separator and a crossover duct to the convective pass, where the Reheater 1, Superheater 1 and 2 and Economizer 2 tube circuits are. This is followed by another convective pass that contains economizer 1 and the air heaters. The tubes in the Reheater and Superheater circuits were originally manufactured from 7 CrMoVTiB 10-10 (T24) material. Fig. 1 shows a cross section of the boiler in WOP.

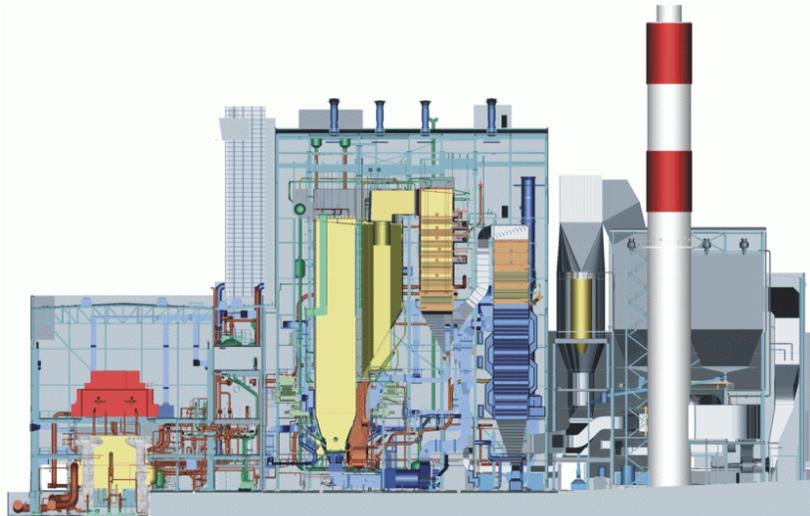


Figure 1: A Cross section layout drawing of the ESB's new CFB based power plant

The ESB boilers utilize moderate fluidizing velocity in the furnace, which is an important feature of Foster Wheeler's CFB technology. Furthermore, the design features a partial step grid next to the fuel feeding points to transfer heavy particles effectively into the bottom ash removal system.

Fuel feeding in ESB boiler design consists of two feeding lines, each of them feeding one line along the long walls of the furnace. The fuel is pneumatically fed into the furnace via a total of seven (West Offaly) or five (Lough Ree) feeding chutes providing a good fuel mix in the whole bed area of the furnace.

To control emissions to atmosphere, both, boilers benefit from CFB combustion design features such as low and uniform temperature profile in the furnace and staged combustion. To meet the NO<sub>x</sub> emissions targets of 200 mg/Nm<sup>3</sup> NO<sub>x</sub>, the boilers are equipped with an ammonia injection (SNCR) system for the control of the nitrogen oxide emissions, however use of this equipment is not required. To keep the SO<sub>2</sub> emissions below the limit of 200 mg/Nm<sup>3</sup>, the units have an in-furnace limestone feeding system and an additional DeSO<sub>x</sub> CFB-absorber located at the outlet of the boiler second back pass. A Bag House is used to control particulate emissions below the target of 30 mg/Nm<sup>3</sup>. With these primary measures both LRP and WOP boilers can easily meet their emission targets. The typical emissions from the units are 180 mg/Nm<sup>3</sup> NO<sub>x</sub>, 100-150 mg/Nm<sup>3</sup> SO<sub>2</sub> (LRP), 0-50 mg/Nm<sup>3</sup> SO<sub>2</sub> (WOP) and <10 mg/Nm<sup>3</sup> of particulates.

### 3 COMMISSINING AND INITIAL OPERATION EXPERIENCE

The Boilers were commissioned in late 2004 (Lough Ree) and early 2005 (West Offaly). Commissioning was on a tight schedule and was aimed at optimising the boilers for base load running. Performance tests were carried out on both units with Foster Wheeler achieving the heat rate and the output specified in the contract, both with some margin. Subsequently and due to a high wind penetration into Ireland's electricity market, extensive low load running was required. This was facilitated by the large turn down ratio of the fuel feeding system and also the capability to take the rear wall firing out of service without having a major impact on the final steam temperatures. Some modifications were made to the air control to make this process easier and to reduce transients when taking fuel feeding lines out of service. The boiler was tuned by Foster Wheeler Process Department to enable a smooth transition to a low load operation.

While the initial operational experience of the new CFB plants was very positive, inspections of the West Offaly Power boiler carried out by Foster Wheeler and ESB in October 2005 revealed heavy fouling and external tube corrosion of the Superheater 2 and Reheater 1B boiler tube panels.

These heat exchangers are located at the top of the first back pass of the boiler. The boiler tube surface temperatures are typically between 490 °C to 515 °C. The flue gas temperature in this area range from 750 °C to 870 °C. A number of tube leaks were also experienced on one occasion in the Reheater 1B circuit. Boiler tube samples were taken from the affected tube panels for further investigation and tubes were replaced to secure operation until a final replacement was possible.

In January 2006, Foster Wheeler submitted a proposal to replace the Superheater 2 and Reheater 1B tube banks. They concluded that the corrosion of the SH 2 and RH 1B was so severe that these two tube banks must be replaced during the 2006 WOP outage.

It became evident early into the plants operation that the level of in-furnace SO<sub>2</sub> capture was greater than expected. Further fuel analysis indicated that there were higher levels of soluble calcium in the peat than originally anticipated. This calcium was capable of adsorbing all of the SO<sub>2</sub> produced in the furnace in the case of WOP. In LRP there were periods where all of the SO<sub>2</sub> was being adsorbed, and periods where the SO<sub>2</sub> was of the order of 100 – 150 mg/Nm<sup>3</sup>. The bogs supplying WOP were producing a different fuel quality than those supplying LRP. This high inherent sulphur capture in the furnace was making conditions more favorable for high temperature corrosion.

## **4 FOULING AND CORROSION**

### **4.1 High Temperature Corrosion.**

Despite its vast experience of peat fired boilers, ESB as a utility had never before experienced a corrosion mechanism of this type. Apart from the new CFB technology used in the new boilers compared to the old pulverized fuel boilers, the principle difference between the old and new combustion process was the furnace exit temperatures and the SO<sub>2</sub> production. The old peat boilers operated with a furnace exit temperatures in the region of 1100 °C and SO<sub>2</sub> in the region of 1700 mg/Nm<sup>3</sup>.

Foster Wheeler, in conjunction with ESB, launched a process to identify the root cause of the corrosion and to develop a commercial solution. Both parties were committed to this process, and as a result new features to protect heat surfaces against corrosion were developed. This assessment involved a number of steps described below.

### **4.2 Identification of the Corrosion Mechanism:**

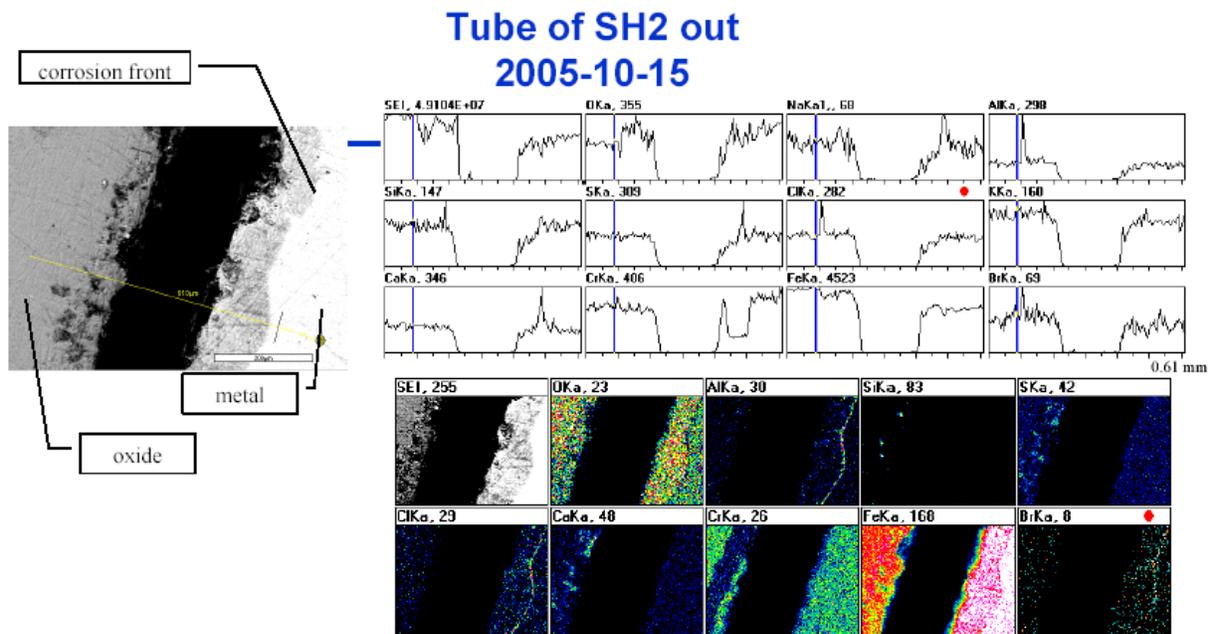
The boiler tubes removed in 2005 were assessed by both Foster Wheeler and ESB. The corrosion mechanism was determined using a combination of a deposit analysis and metallography. The original material (T24) was experiencing a grain boundary attack followed by a general wastage of the grains.

Fig. 2 shows a typical boiler tube surface, showing an outer layer of ash under which there lies a layer of white salt. An analysis of the salt layer by EDAX showed it to contain alkali halides.

An analysis of the deposits showed the nature and distribution of the corrosive species, see Figure. 3.



Figure 2: SH 2 tube LRP.



Cl and Br was detected on the grain boundary, depth of 100  $\mu$ m from surface

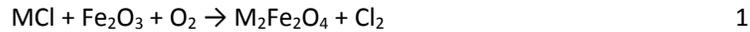
Figure 3: A section through the corroded T24 Superheater tubes showing distribution of various elements. Note: The line analysis is a mirror image of the mapping analyses.

In addition to boiler tube sampling, typical peat was sent to VTT, Finland, to undergo a combustion trial in a pilot scale 100 kW CFB test rig as part of the process to understand fully the combustion process leading to the production of alkali halide deposits. During this test, deposit coupons, cooled to Re-heater temperatures, were inserted after the cyclone separators. The deposits that collected on the coupon surface were analysed and were shown to contain a high concentration of alkali halides. In addition, a high content of alkali halide vapour was present in a sample of flue gas extracted after the separators.

The cause of the external corrosion was determined to be active oxidation, caused by the formation of alkali halides in the combustion process, which pass through the cyclone separators and condense on the convective pass. Individually, alkali halides such as sodium chloride and bromide and potassium chloride and bromide have melting points greater than 770 °C. However, when the alkali halides condense onto the boiler tubes of the convective pass, a eutectic mixture forms with a melting point of the order of 480 – 540

°C. This melting temperature is in the region of the Super-heater and the Reheater tube operating temperatures. The alkali halide salt mixture therefore exists in a semi molten state on the tube surfaces. The halides are free to migrate to the metal tube oxide surface, and can attack the boiler tube material according to the following reactions:

1. Reaction of alkali halides with the outer metal oxide:



Where M = Na, K

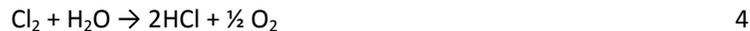
2. The free chlorine produced in reaction 1 migrates to the metal surface and reacts with the iron, nickel or chromium:



3. The metal chloride has a high vapour pressure and migrates to the oxide front, where it is oxidized:



4. The released chlorine is free to restart the cycle or is itself oxidized in the high moisture flue gas to produce HCl:



In this series of steps, the metal is aggressively consumed by the chlorine to produce a loosely adhered metal oxide.

This type of corrosion is well known and documented in the power industry, but it is more often associated with waste to energy boilers, or boilers burning agri-biomass than in peat fired boilers. In both of these instances, the fuels contain high amounts of chlorine and high amounts of alkalis.

### 4.3 Fuel Composition

This corrosion type and rate were unexpected based on the peat composition. The peat fuel for both LRP and WOP contains 0.07 % chlorine, 0.01 % bromine, 0.02 % sodium and 0.01 % potassium on a dry basis. The sulphur content of the peat is of the order of 0.45 – 0.55 %. The molar ratio of sulphur to chlorine can be used as an indicator of the corrosive properties of the fuel; fuels with S/Cl values > 4 are considered to be “un-corrosive” while fuels with a molar S/Cl ratio below 4 are considered corrosive. The peat delivered to LRP has a typical S/Cl molar ratio of 9.3. In WOP the ratio is 8.3. Both values are clearly on the uncorrosive side of the ratio.

SO<sub>2</sub> and more importantly SO<sub>3</sub> formation is critical in adsorbing the alkali halides formed in the combustion process. There are a number of patented technologies describing processes whereby sulphates are injected into the furnace to artificially increase the SO<sub>3</sub> content of the flue gas in order to consume the alkali halides according to reaction 5 below:



From initial firing of the boilers, it was clear that the in-furnace capture of SO<sub>2</sub> from the flue gas was extremely efficient. In WOP, without limestone addition, the SO<sub>2</sub> produced in the furnace is typically < 50 mg/m<sup>3</sup>. The peat contains 0.45 – 0.55 % sulphur and 1.0 – 1.4 % calcium. The majority of the fuel calcium is in the “active” form, meaning that it is acetate soluble, and is therefore available for capture of SO<sub>2</sub> in the furnace in much the same way as limestone is used for SO<sub>2</sub> capture. The fuel molar ratio of Ca/S is 1.5 – 2.5, indicating that any SO<sub>2</sub> produced in the furnace will be adsorbed by the calcium in the peat.

In the absence of SO<sub>2</sub> the conversion of vapour phase alkali halides into alkali sulphates as per reaction 5 cannot occur. Despite the low amounts of alkalis and halides in the fuel, the absence of protective SO<sub>2</sub> in the flue gas means that almost all of the alkali halides produced in the combustion process condense on the boiler tubes.

This is reflected in the different corrosion rates seen in WOP and LRP. As mentioned, in LRP, furnace SO<sub>2</sub> can be of the order of 100 – 150 mg/m<sup>3</sup>. This level of SO<sub>2</sub> allows reaction 5 to proceed, and reduces the quantities of alkali halides produced, which leads to a lower corrosion rate in LRP than is seen in WOP, where the SO<sub>2</sub> never exceeds 50 mg/m<sup>3</sup>.

#### 4.4 Proposed Solutions:

Once the corrosion mechanism was confirmed, a number of options were proposed and assessed to determine their effectiveness in either eliminating the corrosion or in reducing the corrosion rate to levels that would allow both WOP and LRP to meet their availability targets. The options included:

1. Liquid Chemical Additives:

Liquid solutions of sulphates have been shown to adsorb alkalis when injected into the furnace. The sulphate will react with the alkali halides as per reaction 5 above producing an alkali sulphate and free HCl. An increase in the HCl content of the flue gas is indicative of successful alkali capture. Discussions into liquid additive testing and the possibility of their use as a solution was undertaken but proved too expensive to carry out even on a trial basis.

2. Material Testing:

In October 2005 a collaborative approach was adopted to the testing of a range of materials with the objective of finding the most cost effective and beneficial solution given the remaining lifetime of the plants.

While the material selection process was progressing and as a suitable replacement material had not yet been identified, at this early stage it was not considered prudent to carry out a wholesale tube replacement program in 2006 in WOP. However, the unit ran the risk of experiencing a number of tube leaks in 2006/2007. A decision was made to use an upcoming outage opportunity to make a selective replacement of the worst affected tubes with the original material as well as the removal of some of the RH 1B. This made it possible to conduct further investigative work in order to identify the most appropriate solutions.

Once the mechanism was determined, a number of candidate materials were selected on the basis of their performance in similar operational conditions. The materials selected included some nickel alloys and a number of conventional and super austenitic stainless steels. A typical multi tube sample is shown in Figure 4. These were installed in both the Reheaters and Superheaters in LRP and WOP. Overlaid and coated tubes were also installed. After a period of approximately 2000 hours, a selection of the samples were removed, assessed and corrosion rates determined and extrapolated. A subsequent sequence of assessments carried out on longer term (6k, 8k, 11k and 32k hours) samples indicated some non linear corrosion rate behavior for certain materials, e.g. AC66. However, certain trends were developing allowing decisions to be made on more suitable candidate replacement materials. It emerged that a 347 grade stainless steel was performing in a satisfactory manner, and on the basis of metallographic assessments, a fine grained, low carbon variant of the material was deemed to be the best suited for the conditions, see Figures 5 and 6. The role of surface carburisation and galvanic corrosion at welds had to be understood and incorporated into the material selection and fabrication process. Wall loss rates were determined and used to calculate the nominal wall thickness required to give a minimum of 5 years service life at the relevant operation temperatures and pressures.

Compliance with the design code was also an important consideration in the selection process.

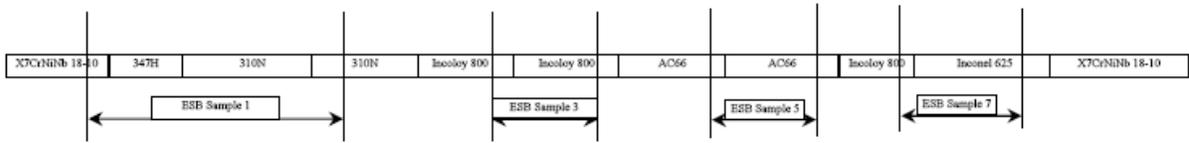


Figure 4: Multi tube 'Rainbow Sample' used in SH2 WOP.

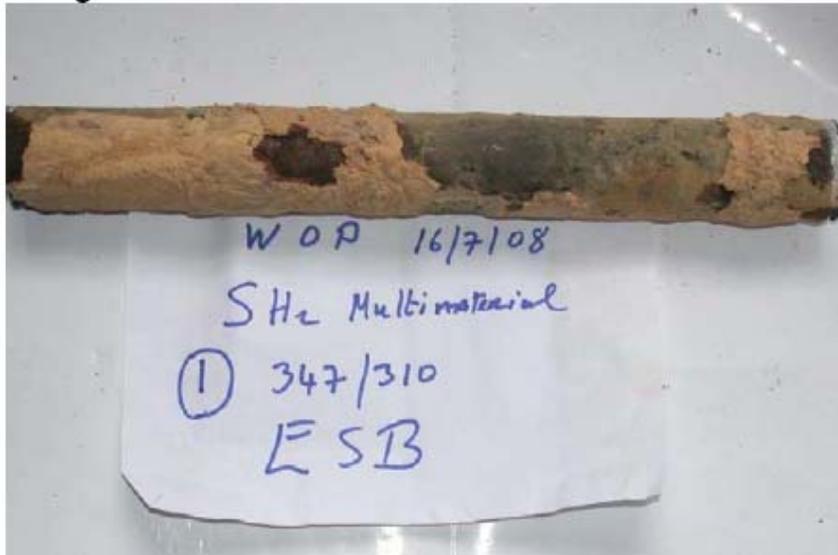


Figure 5: Section of Rainbow Sample after 8,596 hours



Figure 6a: Sand Blasted Surface of 347H after 8,596 service hours

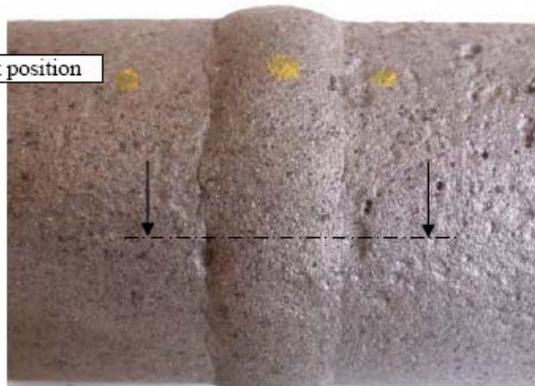


Figure 6b. Sand Blasted Surface of 310N after 8,596 service hours

### 3. Low O<sub>2</sub> Testing:

In order to increase the formation of SO<sub>2</sub>, Foster Wheeler proposed lowering the O<sub>2</sub> content of the furnace from 2.2 % to 1.2 % for a period of 3 weeks. The aim of this test was to starve the furnace of oxygen, which would inhibit the binding of the SO<sub>2</sub> released by the fuel with the calcium. Under these conditions, it was proposed that the SO<sub>2</sub> would remain in the gaseous phase and could therefore bind with the alkalis as per reaction 5 above. While the amount of SO<sub>2</sub> produced in the furnace increased,

the test failed due to the fact that starving the boiler of oxygen also inhibited the conversion of SO<sub>2</sub> to SO<sub>3</sub>, a requirement for alkali capture.

#### 4. Solid Additives:

Ash from a PF coal boiler was identified as a potential solid sorbent for alkalis. Coal ash is high in aluminium silicates, which are known to adsorb alkalis irreversibly to produce sodium/potassium aluminium silicates. However, once the coal ash was analysed, it was shown to be unsuitable for use as a sorbent, as the high temperatures seen in a PF boiler convert the aluminium silicates into an inert form that is unsuitable for alkali adsorption.

#### 5. Lowering the temperature at the SH 2 outlet/RH1B inlet

This was done in Nov/Dec 2005 in WOP and subsequently in LRP in an attempt to bring the Superheaters and Reheaters out of the alkali halide melting point zone. This was possible by tuning the INTREX™ heat exchangers to allow a lower steam temperature at the Superheaters and Reheaters and recovering the steam temperature in the INTREX™ heat exchangers. There was some evidence that lowering the temperature here had some effect in slowing the corrosion rate, but the reduction in temperature was limited.

#### 6. Tube Shielding

Some tube shielding tests were carried out and proved very effective. Even when installed on a corroded tube the corrosion almost stopped. However this would not be a long term viable solution.

#### 7. Change the material of the SH and RH tubes.

Following extensive tests and discussions and sharing of research between ESB and Foster Wheeler metallurgists, 347 H was selected as the material that would give the most cost effective solution for ESB. While it was possible to find a standard material that would meet the specification, ESB and Foster Wheeler considered the grain size and carbon content as important features of the material. With this in mind, quality checks were made on the Material certs to ensure that the required carbon content was low enough and that a review of the heat treatment was carried out to ensure that the grain size would not increase. Of particular importance was the post bending stress relieving to ensure that the grain size was not increased. This was closely monitored by Foster Wheeler. Selection of 347H proved a very cost effective solution as the next most suitable material was almost 5 times the cost.

## 5 EXPERIENCE TO DATE WITH 347H

To monitor the behavior of the 347H grade stainless steel a detailed collaborative programme was developed and implemented during the outage opportunities that arose in 2006, 2008 and 2011. This consisted of in-situ wall thickness measurements using a procedure that would be dependably repeatable and a sampling programme to observe any changes in macroscopic and microscopic behavior. The results from the longest term samples (~35k hours) are broadly in line with those from the shorter term tests. The tests show a linear rate of corrosion related wall loss, which is within the amount required to yield a 5 year minimum service life. The use of low carbon, fine grained material with solution annealed bends and similar metal filler weld materials has proved beneficial.

## 6 SUMMARY OF THE REPAIR WORK

Foster Wheeler and ESB agreed to replace the first pass heat exchangers with 347 H. This plan was carried out in LRP in 2010 and in WOP in 2011. This entailed the removal of the first pass heat exchangers of the boiler except for the economiser which had to be supported before cutting out the top banks. The installation of the new heat exchangers and the replacement of two Superheater headers due to the geometry of the new Superheater bundles also took place. The estimated time scale for the project was 140 days but was completed in 117 days. The quality of welding was excellent. 100% x-ray inspection out of the welds yielded a very small number of weld failures.

Since returning to service in September 2010, LRP ran continuously for over 200 days without a stop or a shut down. The plant has continued to give high availability with good experience of low load running. WOP returned to service at the end of August 2011 and has been running similarly to LRP with no adverse effects on the boiler. The success of this project and the plants can be attributed to the close working relationship between Foster Wheeler and ESB.