DESIGN AND PERFORMANCE OF THE HELICALLY COILED BOILERS OF TWO AGR POWER STATIONS IN THE UNITED KINGDOM

M. EL-NAGDY, A.D. PAPA
Babcock Energy Ltd,
London, United Kingdom

Abstract

The Hartlepool and Heysham-I AGR stations have been commissioned and operating since 1983. The main features, of the design of the helical once-through boilers raising the steam for power generation, are outlined. The modifications to the feed inlet flow ferrules, necessary to improve the boiler performance and optimize the power output, have been described. Comparisons between the thermal and hydrodynamic performance of the boilers before and following these alterations are given. The improvements in the computer code predictions of the plant performance have also been presented.

1. INTRODUCTION

The Hartlepool and Heysham-I 1300 M.W. AGR power stations are fitted with helically coiled boilers manufactured by Babcock Energy Ltd. Each boiler comprises a reheating section and a once-through high pressure heating surface in the same pod casing. The design and performance of both the heating surfaces and external boiler plant were subject to operating temperature limits imposed by material properties limitations and gas side corrosion and water/steam side stress corrosion constraints. Safety considerations, during early operation, had set up an upper limit of 78.5% M.C.R. for the plant operation. Plant measurements, operating experience and results, from performance analyses for various operating conditions, since 1983, indicated that operating the plant above 75-80% M.C.R. would invoke these considerations and temperature limitations. Description of the boiler design and plant arrangement and assessment of early plant performance [1] were presented at the last Specialists' Meeting on Heat Exchanging Components in Duesseldorf in the Federal Republic of Germany (16-19 April 1984). However an outline of the main features will be given here for completeness.

In view of this, Babcock and other organisations concerned in the U.K. continued the assessment and analysis of the thermal and hydrodynamic performance of the boiler at selected load conditions to ensure the safe operation of the plant within the design constraints and investigate ways of increasing its performance. As a result of these studies it became apparent that it would be necessary to alter the feed flow distribution in the high pressure section of the boiler to achieve appreciable increase in the power generated within these constraints. This only involved changing the hydrodynamic resistances of the ferrules fitted to the feed inlet headers of the boilers either by selectively reaming out some of the currently installed ferrules or alternatively replacing them by high impedance ferrules.

Extensive performance analyses which include detailed mathematical modelling of the heating surfaces, description of the hardware changes and plant measurements have been carried out. Detailed comparisons between the performance of the boiler plant, prior to and following the modifications of the feed flow ferrules will be discussed and presented in the following sections. The measurements from the comprehensively instrumented boiler plant will also be compared with the predictions of the specially developed computer codes that employ 2-D models of the heating surfaces and interbanks.

2. DESIGN FEATURES AND LIMITATIONS

The helical design concept was selected for the manufacture of the heating surfaces of the once-through boiler plant for the Hartlepool and Heysham-I nuclear power stations for its simplicity and optimum usage of the available space in the reactor concrete pressure vessel. The surface arrangement adopted (Fig. 1) is simple where the tube helix angle, pitch and length are the same for all the 19 high pressure section and 13 reheater heating surface helices. This has resulted in a considerable simplification of the tube manufacture and coiling and the assembly of the boiler surface.

Right from the start, in addition to space envelope limitations and gas side pressure drop considerations, the design of the heating surfaces has been subject to operating temperature constraints imposed by the physical, mechanical and corrosion resistance properties of the materials available at the design stage some 20 years ago in the mid-sixties. Beside these design constraints on the internal boiler components, additional limitations were specified for the operation of the boiler plant external to the pressure vessel to safeguard the integrity of the high pressure pipe-work and turbine during the economic life of the station. Design optimisation studies, given the above constraints and limitations had resulted in the selection of three materials for the manufacture of the heating surface components; carbon, 9% chromium and 316 stainless steels. The ferritic materials have been employed in the economiser and the evaporator sections and the austenitic material in the superheating and the reheating sections of the boiler.

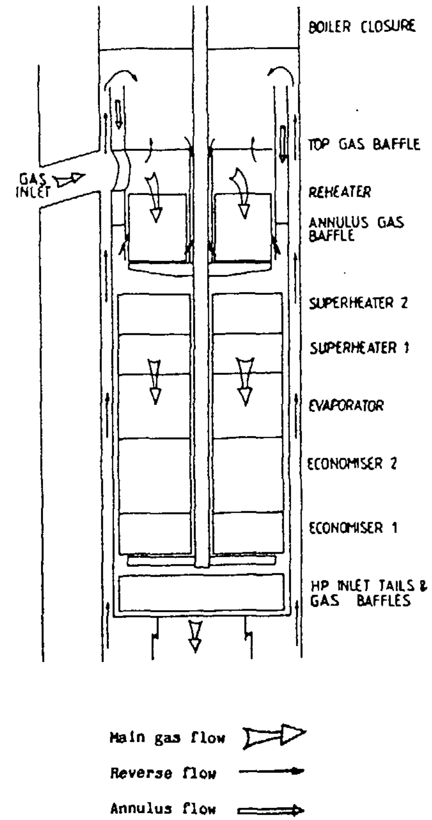


Fig. 1 Pod boiler heating surface arrangement

To increase the boiler static stability and achieve uniform superheater outlet steam temperatures and consequently optimum power output with various plant performance asymmetries, a water phase restrictor tube section and feed flow distribution ferrules (Fig. 2a) were fitted at the inlet of the coils of the high pressure section. The sizing of these ferrules was based on the operating conditions envisaged at the design stage of the plant allowing for known geometrical and hydrodynamic/thermal performance asymmetries that include manufacturing and boiler assembly tolerances, helix diameter effects and gas flow distribution and by-passing (Fig. 1). Experience and plant measurements during early commissioning and raise power testing have shown that alteration to the ferrule size distribution was necessary to achieve the full M.C.R. conditions. Two alternatives were pursued namely the reaming out the bore of the ferrules fitted to selected helices or when convenient replacing the installed ferrules by a high impedance two stage ferrule [2] design (Fig. 2b). In both cases an increase in the generated power with a significantly improved performance within the plant operating constraints has been achieved.

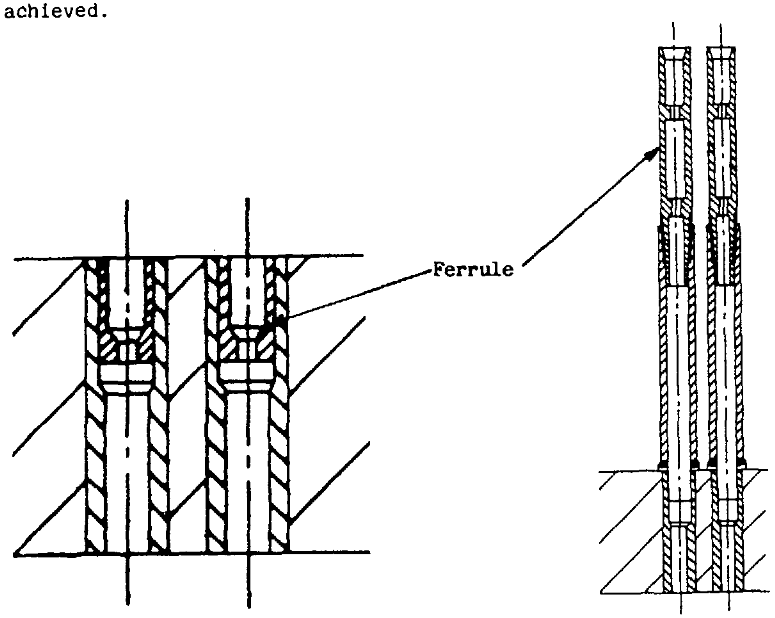


Fig. 2a **Original feed flow ferrules** Fig. 2b **Two stage feed flow ferrules**

3. INSTRUMENTATION / FEED FLOW DISTRIBUTION

The boiler plant terminal conditions including feed flows, temperatures and pressures are measured and continuously monitored by the station data collection computer system [described in reference 1]. In addition to these measurements, the superheater outlet headers of all boiler pod units are fitted with thermocouples for measuring the temperature of the steam issuing from individual superheater tail pipes connected to almost all the helices forming the high pressure section of the boiler. To ensure adequate monitoring of the conditions of the heating surface components and provide suitable data for performance analyses, one boiler pod unit from each of the Hartlepool and Heysham-I stations have been comprehensively fitted with thermocouples for measuring the gas and metal temperatures at selected locations on the boiler heating surfaces (Fig. 3). Measurements from these specially instrumented pods and terminal conditions of the other pods, together with performance assessments employing two-dimensional computer codes have been used to trim the terminal conditions of the non-instrumented pods to ensure that they operate within the specified design and operational constraints. To provide reliable information on the feed flow distribution, special flow measuring ferrules were installed, after boiler referruling, in the feed inlet headers. The pressure drop across three ferrules fitted to selected tubes connected to the inner, middle and outer helices of the high pressure section have been used, after calibration, to calculate the feed flow rates in individual tubes. Such measurements are also important for the validation of, and increasing the confidence in, the 2-D computer codes employed in the predictions of the boiler performance.

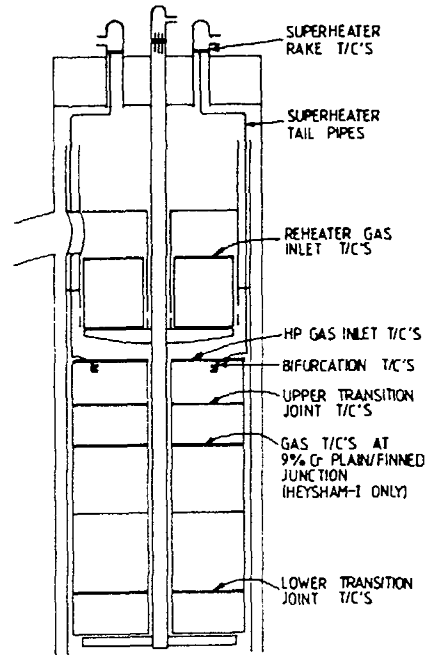


Fig. 3 **Thermocouple positions**

Despite the similarity between the geometries and construction of the two boiler units, the temperature profiles at the 9% Cr/ss transition joints were markedly different. The Heysham-I boiler temperature profile (Fig. 6b top) drooped monotonically from the outer helix next to the boiler casing to the inner helix adjacent to the support spine. On the other hand the Hartlepool boiler temperature profile (Fig. 4a) peaked near both the casing and the spine and showed a trough with a minimum in the region of the middle helices. This could only be partly explained by the replacement of the top section of the finned 9% Cr tubing by a plain 9% Cr tube section in the Heysham boilers. This change in the H.P. heating surface construction might have affected the heat transfer and the gas side hydrodynamic performance of the bank in such a way to contribute to the observed difference between the temperature profiles at the transition joints. Other factors contributing to this difference include the gas flow distribution in the reheater and gas flow by-passing in both the H.P. and reheater heating surfaces (indicated in Fig. 1).

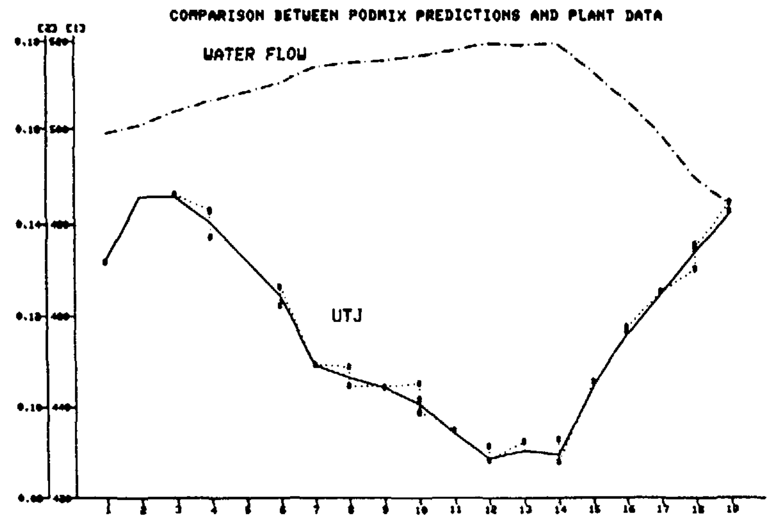


Fig. 4a UTJ temperatures and water flow rates for Hartlepool R1 (before referruling)

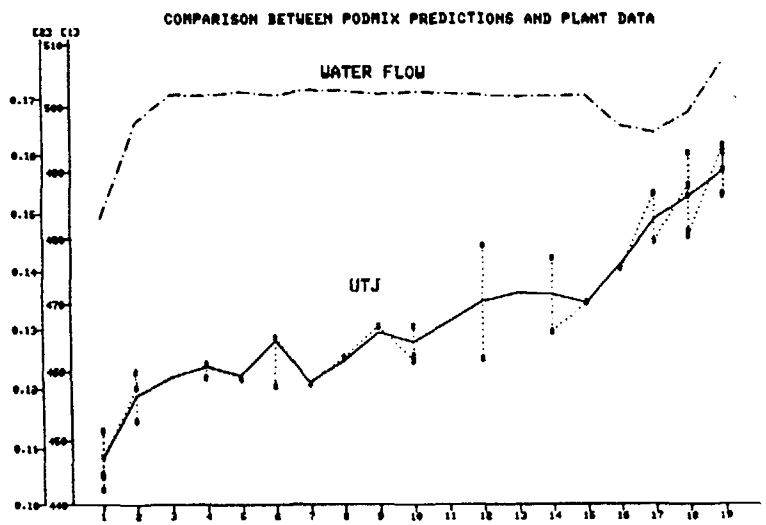


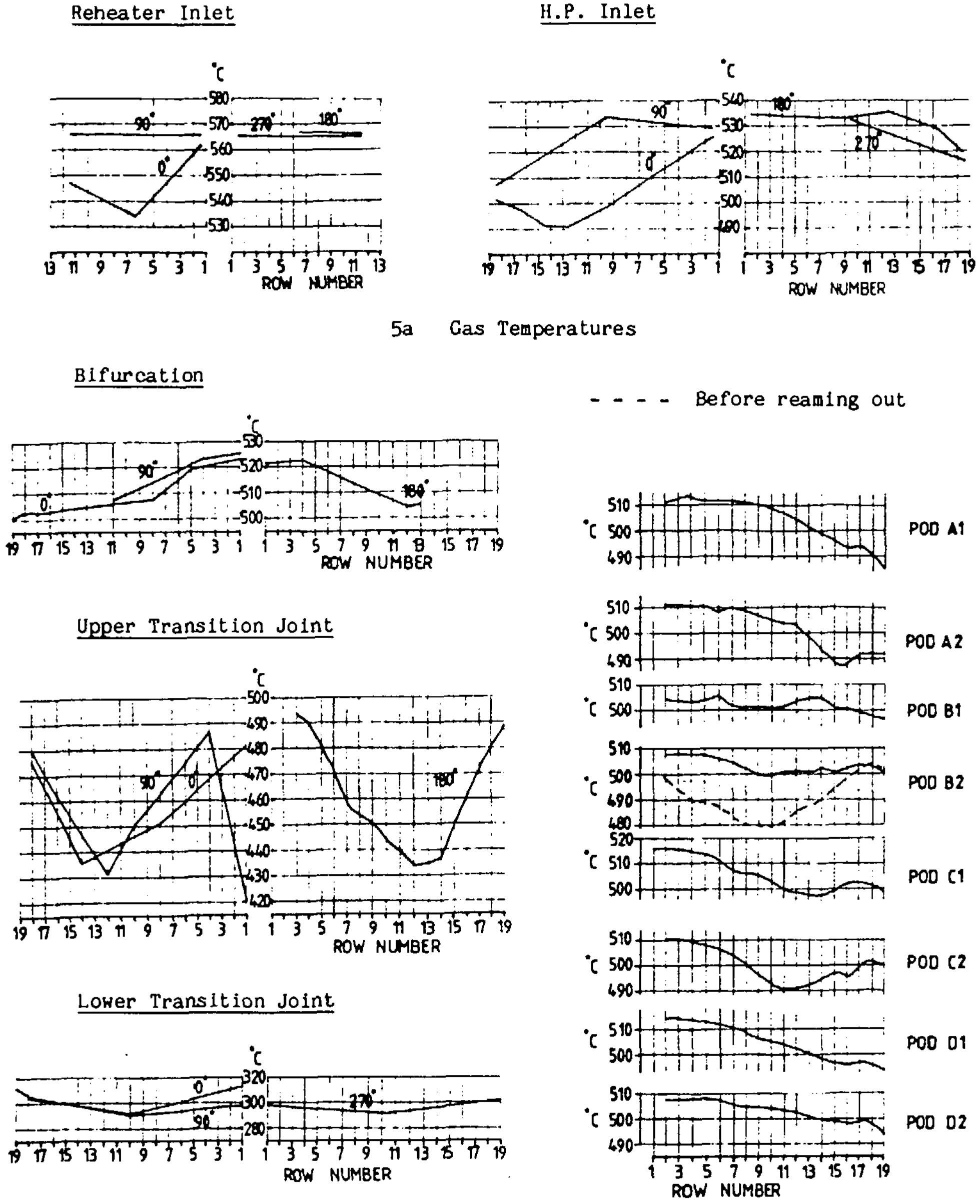
Fig. 4b UTJ temperatures and water flow rates for Heysham R1 (after referruling)

A clear dependence of the temperature profiles in the heating surface on the feed flow distribution in the H.P. section had been indicated by the results of the early analyses of the boiler performance, particularly at the 9% Cr/ss upper transition joint (UTJ). A close correlation exists between the temperature at this location, which is one of the operating constraints, and the predicted distribution of the feed flow in the boiler helices. This correlation had been observed, at the start of the power raising programme, for both the instrumented boiler units of the Hartlepool and Heysham-I stations as shown in Figs. 4a and 4b. Thus to alter the above observed non-uniform temperature profiles significantly and improve the performance of the boilers, it would be essential to modify the feed flow distribution in the H.P. bank with the aim of increasing the power output by achieving flat temperature profiles within the specified constraints at the upper transition joints location. The success of this improvement would obviously rely upon the knowledge of the feed flow distribution, provided by the flow measuring ferrules over a wide range of operating conditions.

4. MONITORING THE THERMAL PERFORMANCE OF THE BOILERS

The performance monitoring of the boilers with the originally installed feed flow ferrules at the various power levels had continued since the early power raising testing in 1983/1984. Plant measurements were collected via the station data acquisition computer to assess the boiler performance and provide data for computer code verification and development. The predictions of the internal thermal conditions in the non-instrumented boiler units where no measurements exist, particularly at the upper transition joint (UTJ), are required to ensure operation within the operating constraints. The measured terminal conditions of these units together with the superheater outlet steam temperatures measured by the rake thermocouples have been employed by the computer codes to calculate the boiler internal conditions. The two-dimensional mathematical models built into these codes were initially verified using the internal measurements provided by the specially instrumented boiler units. The performance monitoring of the boiler plants continued following the referruling of all the boilers of the Heysham-I reactors and the second Hartlepool reactor and the selective reaming out of the Hartlepool Reactor-1 ferrules.

The performance of the Hartlepool and Heysham-I boilers, at representative operating conditions, are presented in Figs. 5-7. The gas temperature profiles, at the inlets of the reheater and the H.P. boiler section, are plotted in Fig. 5a. These gas temperature measurements, which are typical of the Hartlepool instrumented boiler pod unit performance, are given at four azimuthal positions 0° , 90° , 180° and 270° relative to the centre line of the boiler gas inlet duct. The profiles shown demonstrate clearly that the gas temperatures in the banks are not uniform either circumferentially or radially. In addition, the temperature profile of the gas entering the reheater bank at the 0° azimuthal position exhibits a dip in the middle of the reheater helices. This reflects the incomplete mixing of the liner up-flow cold gas with the hot gas entering the boiler via the reactor gas outlet duct. The profiles of the measured tube metal temperatures at the above azimuthal positions for three axial locations in the boiler are also shown in Fig. 5b.



5a Gas Temperatures

5b Metal Temperatures

5c Steam Outlet Temperatures

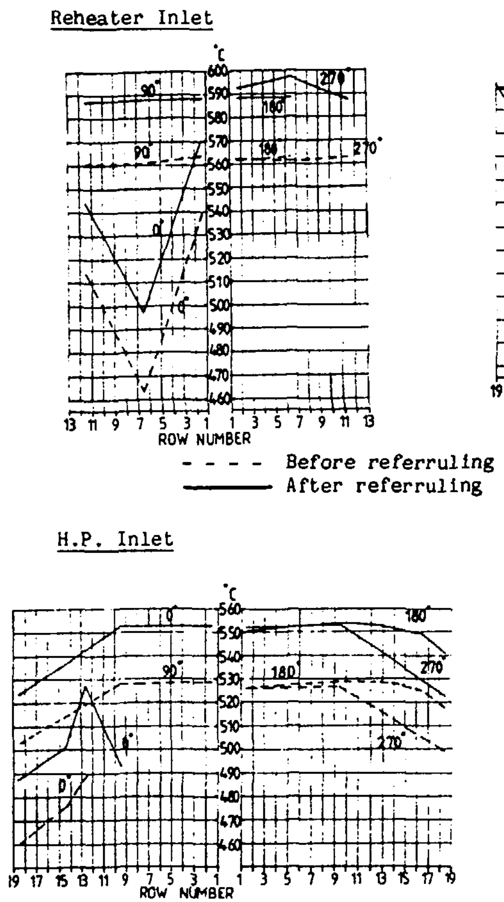
Fig. 5 Hartlepool R1 Temperature Profiles

These axial locations are at the carbon steel/9% Cr. steel lower transition joint (LTJ) in the economiser region, the UTJ in the superheater region and the H.P. bifurcations (BIF) joining the superheater outlet tails to the heating surface at the H.P. exit. The metal temperature profiles are obviously non-uniform and the bifurcation tube metal temperatures are higher in the inner helices near the spine than they are at the outer edge of the bank next to the casing. The upper transition joint temperature profile exhibits a trough in the middle helices and the LTJ temperatures also show a non-uniform profile.

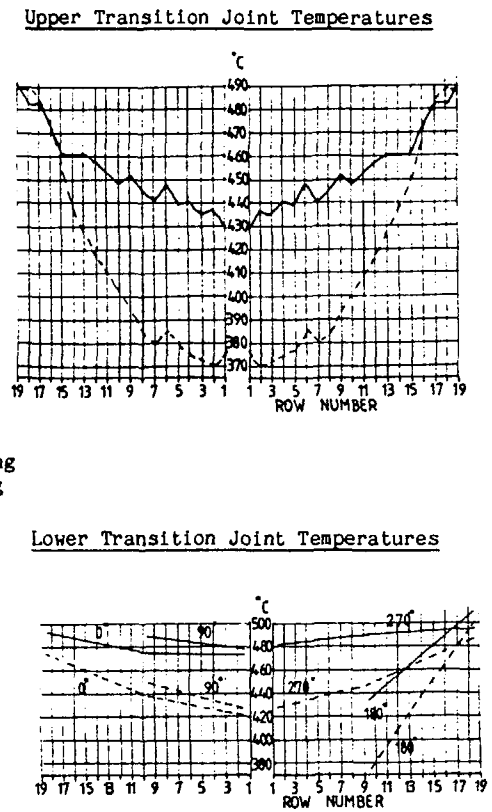
The superheater steam temperatures, measured by the rake thermocouples in the outlet headers, are plotted in Fig. 5c. The non-uniform temperature profiles shown are associated with selected operating conditions following the reaming out of the ferrules in the outer two rows of the 'B2' boiler pod unit. The temperature profile of this unit before reaming out is also plotted in Fig. 5c to show the improvement achieved following this modification. The 'B1' boiler unit has since been reamed out and it is also intended to ream out selected ferrules in the 'C' quadrant boilers to improve its performance.

Similar to Hartlepool, the gas and tube metal temperatures, of the Heysham-I instrumented boiler unit, are respectively shown in Figs. 6a and 6b for typical operating conditions before and after referruling the boilers in 1985-1986. The superheater outlet steam temperatures, after referruling as indicated by the rake thermocouples for all the boiler pod units, are shown in Fig. 6c. A comparison between the superheater outlet steam temperatures measured before and after boilers referruling is also shown in Fig. 6d for the four boiler units which were initially fitted with rakes. Examination of the temperature profiles presented in these figures reveals the great improvements in the boiler performance after referruling as indicated by the flattening of the UTJ metal temperature and the superheater outlet steam temperature profiles shown in Figs. 6b and 6d. For approximately the same power levels, the spread in the measured metal temperatures at the UTJ has decreased from 117 •C to 67 •C while the spread in the superheater outlet steam temperatures improved from 32-62 •C to 5-15 •C.

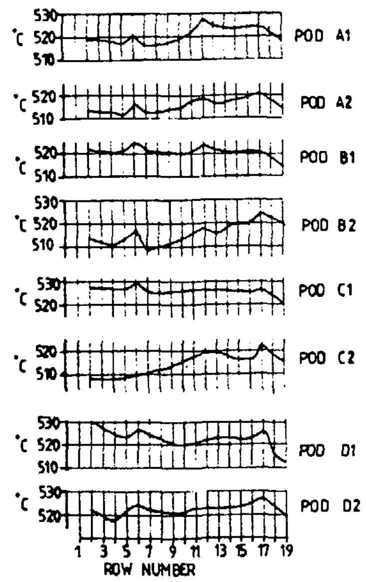
These figures also show clearly the drooping in the UTJ temperature profile from the outer to the inner helices, particularly before referruling, and the non-uniform gas temperature profiles at the H.P. and reheater bank inlets and the 9% Cr. finned/plain tubing transition region. The tilt in the superheater outlet steam temperature profiles (Fig. 6d) from the outer towards the inner boiler helices has also been greatly reduced after referruling. The effectiveness of referruling the boilers is demonstrated by the relatively small spreads (Fig. 7) in the UTJ metal temperatures measured at various power levels after referruling. As the power level increases the temperature profiles change from convex shape to a drooping type temperature distribution tilting towards the spine. For the load range shown, the temperature spread is within 30-67 •C compared with 120 •C before referruling.



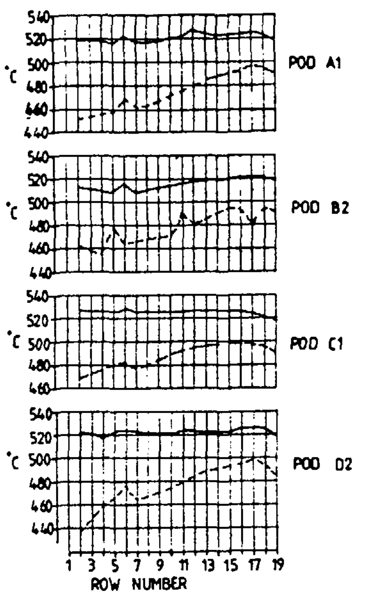
6a Gas Temperatures



6b Metal Temperatures



6c Steam Outlet Temperatures



6d Steam Outlet Temperatures before and after refferuling

Fig. 6 **Heysham-I R1 Temperature Profiles**

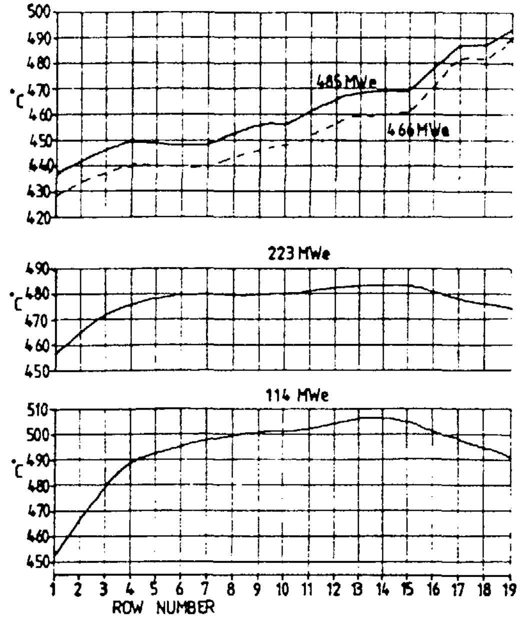


Fig. 7 **Heysham R1 UTJ temperature profile at various power levels**

5. PREDICTIONS OF THE PERFORMANCE OF THE BOILERS

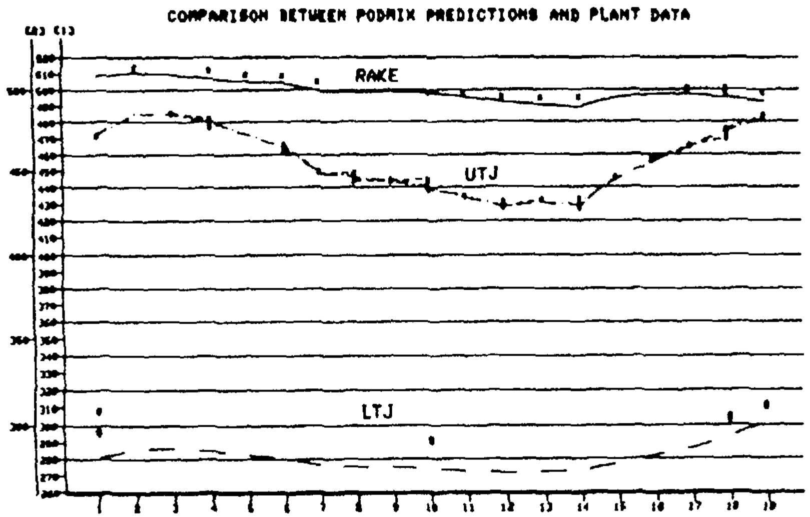
Early during the manufacture of the boilers, experimental rigs were constructed and operated to provide the heat transfer, pressure drop and thermal mixing data required for the design of the plant. The results from the comprehensive programmes of testing, carried out during the design and manufacturing stages, were utilized to develop a series of mainly one-dimensional computer codes to calculate the performance of the boilers over the specified load range. For recent predictions of the boiler performance, using the measured plant temperatures, pressures and flow rates as discussed earlier, 2-D computer programs have been developed and verified. The data base, included in these codes to represent the geometrical details, the arrangement of the heating surfaces and the heat transfer and hydrodynamic characteristics of the boiler banks, utilize the experimental results obtained earlier. The elements of this data base have been carefully checked, revised and regularly updated by a working group from the CEGB and Babcock to reflect the experience gained from the planned raise power testing and operating the boiler plant since commissioning.

Extensive investigations have also started since 1984 to develop and verify the associated two-dimensional computer models representing the boiler plants of both the Hartlepool and Heysham-I stations. Geometric details of the individual boilers, which affect the gas flow distribution, have been carefully examined and represented in these models. These include dimensional surveys of the coiled heating surfaces, the supporting structure and casings.

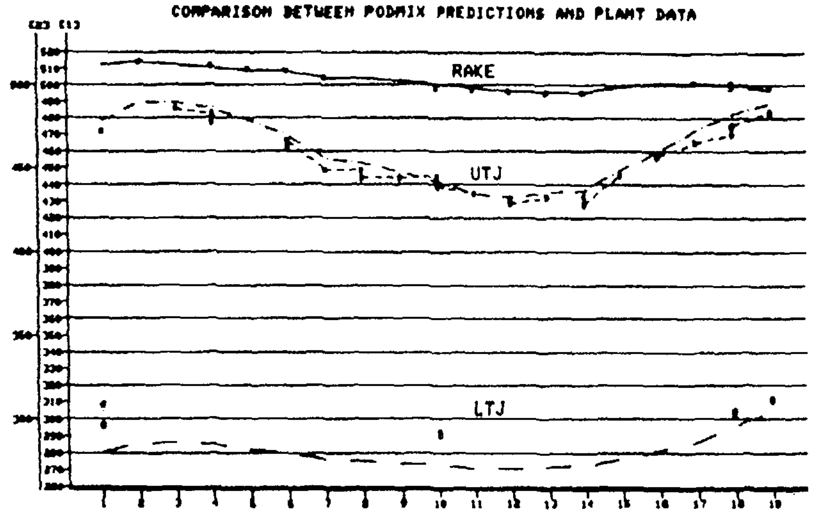
The above investigations resulted in the development of a calculations procedure which allowed fitting the models to plant data over a wide range of operating conditions representative of the plant performance. Since its development, the procedure has also been used for adjusting the models data base to achieve minimum prediction errors at all the boilers instrumented locations. The procedure involves minimising the differences between model predictions and target values derived from plant measurements at a particular location and comparison of the predictions with plant measurements at the other instrumented locations in the boiler. Currently minimisation can be performed for any of the rakes steam temperatures, the bifurcation or the UTJ metal temperatures.

For model verification, the procedure was applied either at the UTJ or the rakes of the instrumented boiler units to obtain the best possible fit to plant data. The predictions at other locations were also compared with boiler measurements to assess the quality of the fit. For the best fit, it was necessary to adjust the gas flow areas of the H.P. section within the manufacturing tolerances of the boiler heating surfaces. These adjustments take into account the thermal movements of boiler components. It was also necessary to adjust some details of the reheater model. On satisfactory verification, the same calculations procedure was used, conserving the reheater model to predict the performance of the non-instrumented boiler units by fitting the predictions, at the rakes, to the measurements of the superheater outlet steam temperatures. Using this procedure, it has been possible to construct one boiler model for each of the stations which were satisfactorily employed to predict and assess the performance of the boilers before and after referruling. The two models used a common data base except for details of gas flow distribution, bypass and mixing characteristics in the reheater region. However the differences between these models are fast becoming small and it will be possible soon to use the same boiler model for both Hartlepool and Heysham-I.

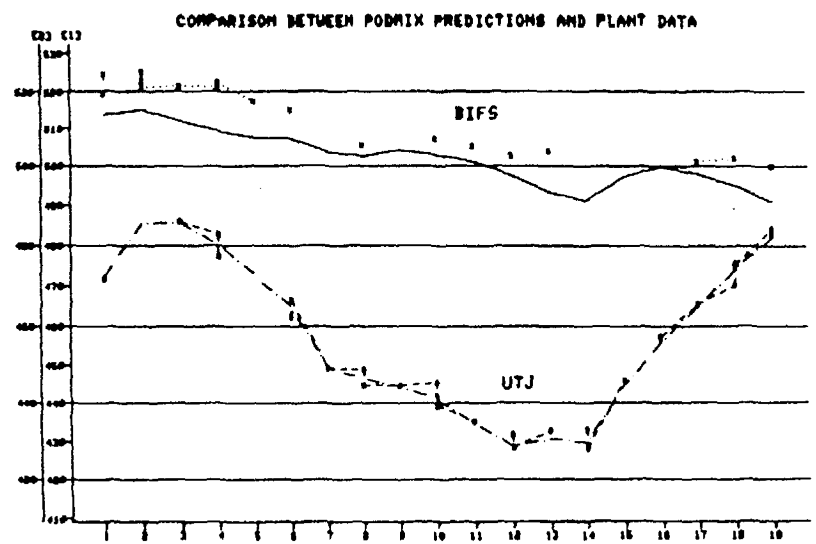
Comparisons between the early predictions of the 2-D models and plant data before referruling were reported in references 3 and 5 which also contain details of the data base and the models used. The comparisons, between plant data and the calculations of the performance of the boilers, presented below are based on work performed by Babcock Energy Ltd. using the CEGB computer code PODMIX, described in reference 4 by Fallows. A selection of the results obtained are presented graphically to demonstrate the use of the calculations procedure to predict the performance of the Hartlepool and Heysham-I boilers. The results are for typical 80% M.C.R. operating conditions following the reaming out of some of the originally installed ferrules in Reactor-1 at Hartlepool and referruling of the Heysham-I boilers. The Hartlepool results are presented in Figs. 8 and 9 for the instrumented and the non-instrumented boiler units respectively. Comparisons between plant measurements and program predictions of the superheater outlet steam temperatures and the UTJ and LTJ metal temperatures are shown, for the UTJ best fit, in Fig. 8a and in Fig. 8b for the rake best fit predictions. Fig. 8c shows comparisons between predictions and plant measurements of the bifurcation and UTJ metal temperatures for the UTJ best fit. The predictions and measurements of the H.P. inlet gas temperatures are plotted in Fig. 8d, for the two types of best fit. The predictions of the UTJ metal temperatures and comparisons between plant data and predictions of the superheater outlet steam temperatures are shown in Fig. 9 for all the pods including the specially instrumented unit.



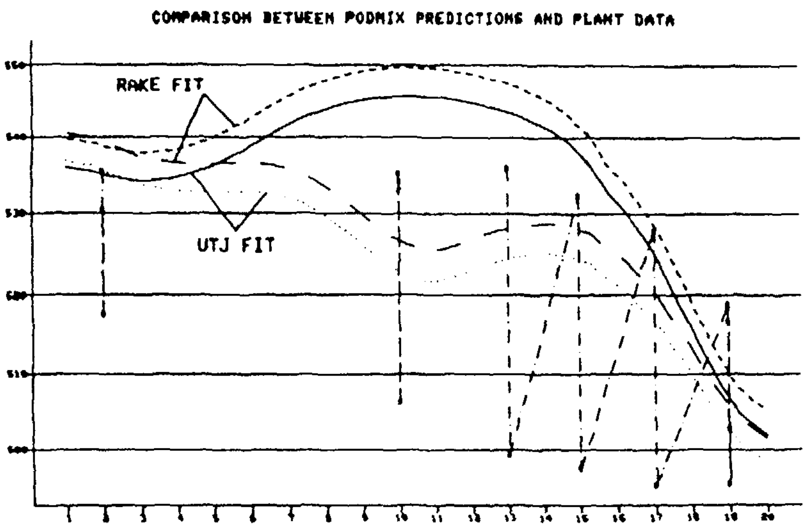
8a LTJ, UTJ and Rake temperatures (UTJ fit)



8b LTJ, UTJ and Rake temperatures (Rake fit)

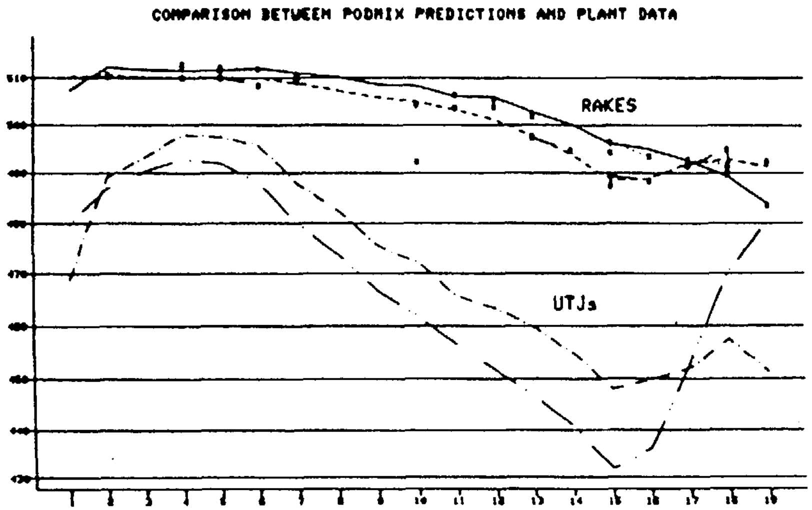


8c Bifurcation and UTJ temperatures (UTJ fit)

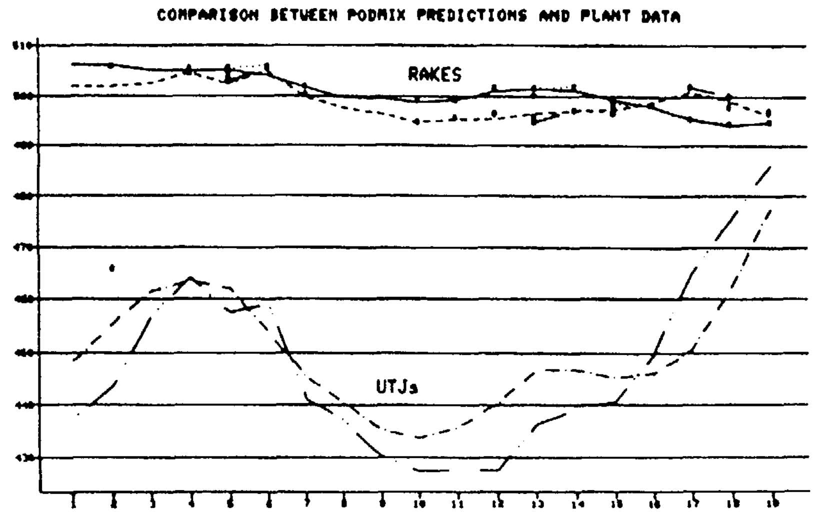


8d H.P. Gas Inlet Temperatures (UTJ and Rake fit)

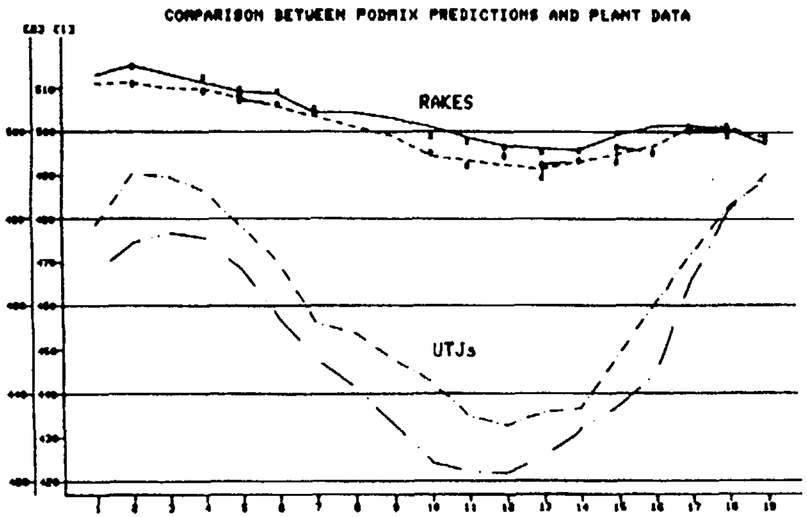
Fig. 8 Comparison of PODMIX predictions with plant data for Hartlepool R1



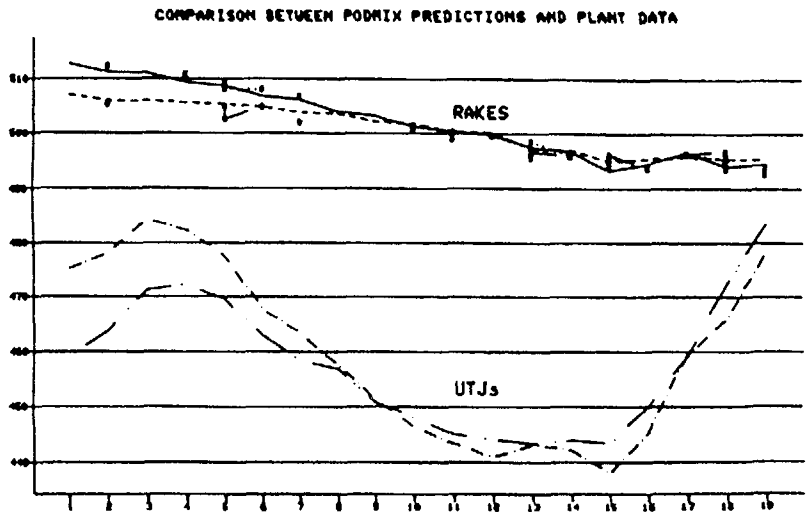
9a UTJ and Rake temperatures for Boiler A



9b UTJ and Rake temperatures for Boiler B

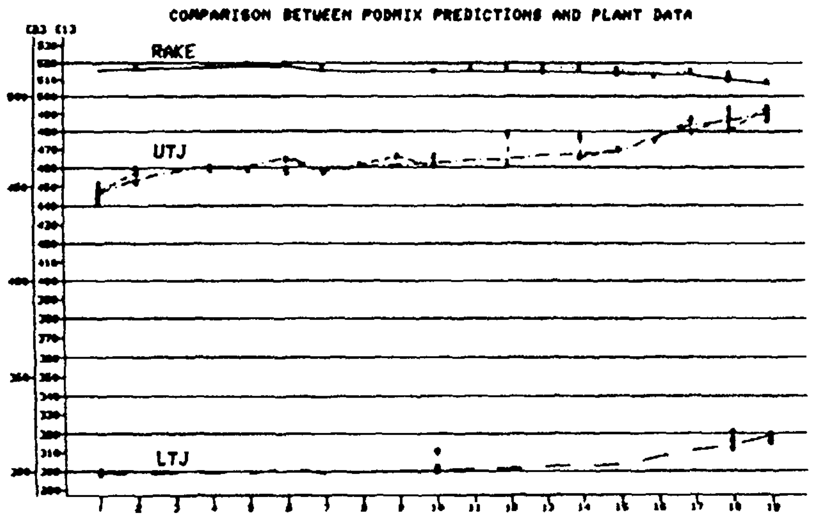


9c UTJ and Rake temperatures for Boiler C

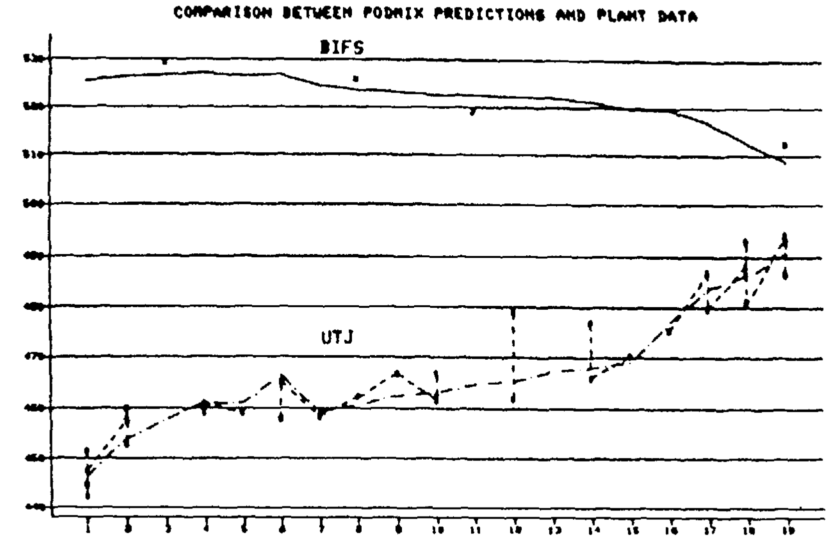


9d UTJ and Rake Temperatures for Boiler D

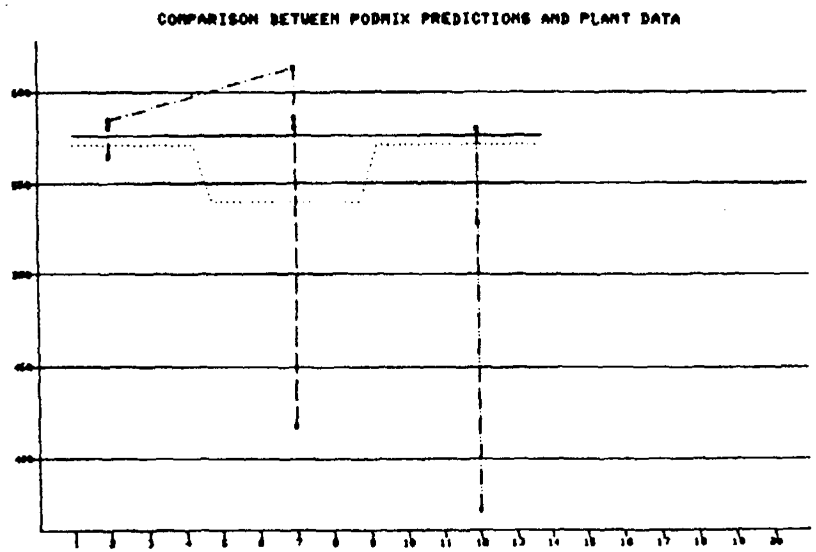
Fig. 9 Comparison of PODMIX predictions with plant data for Hartlepool R1



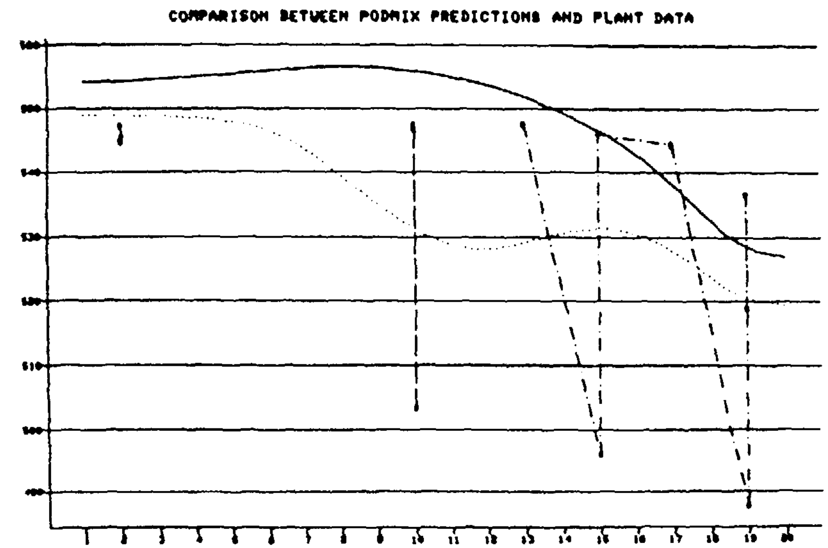
10a LTJ, UTJ and Rake temperatures (UTJ fit)



10b UTJ and Bifurcation temperatures (UTJ fit)



10c Reheater Gas Inlet Temperatures



10d H.P. Gas Inlet Temperatures

Fig. 10 Comparison of PODMIX predictions with plant data for Heysham R1

Generally the models, developed to fit precisely (within the calculation error band) the data at the UTJ, provide better predictions of the boiler performance than those associated with the best fit at the rakes. However the modelling has been recently improved so that fitting to either the UTJ or the rakes provide equally good predictions of the performance of the boilers. The improvements are mainly in the reheater region of the boiler. The comparisons presented in Fig. 10 are associated with such a model developed for the Heysham boilers. The superheater outlet steam and the bifurcation, UTJ and LTJ metal temperature profiles of the instrumented boiler unit are shown in Figs. 10a and 10b. The gas temperature profiles at the inlets to the reheater and the H.P. sections of the instrumented pod are plotted in Figs. 10c and 10d which also show the corresponding plant measurements.

6. CONCLUSION

The helical boilers for both the Hartlepool and Heysham-I AGR stations which were commissioned in 1983-1984 have been successfully producing power since then. The non-uniform metal temperature profiles inside the boilers were improved and the plant power output has been optimized within the operating limits by referruling the Heysham-I and Hartlepool Reactor-2 boilers and reaming out selected ferrules fitted to some of the Hartlepool Reactor-1 boiler units. The 2-D computer models, developed to calculate the thermal and hydrodynamic performance of the boilers, were verified against plant data and employed to predict the operating conditions following boiler referruling. The power capabilities of the boiler plant can be achieved fully by further tuning of the replaced ferrules. This can easily be carried out, with minimum outage time using specially designed tools after rapid removal of the newly installed demountable feed headers.

7. ACKNOWLEDGEMENT

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