THE EARLY OPERATION OF THE HELICAL ONCE-THROUGH BOILERS AT HEYSHAM 1 AND HARTLEPOOL

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Abstract

The Heysham 1 and Hartlepool AGR Reactors are equipped with 'pod' boilers set into the walls of the Pre-stressed Concrete Pressure Vessel. Each Reactor unit has eight pod boilers, which are of a somewhat unique single pressure, once through, helically wound type incorporating a reheater. The pods are provided with a limited amount of strain gauge and thermocouple instrumentation concentrated mainly in two specially instrumented boilers at each site.

During commissioning prior to power raising, extensive noise and vibration tests utilising the special strain gauge instrumented boilers, gave encouraging results. This has led to an increase in coolant gas mass flow of 5% above the design level.

Following power raising in 1983 and 1984, detailed boiler performance testing, mainly using the special thermocouple instrumented boilers, showed that the actual behaviour differed from the computer design predictions. A major temperature tilt existed across the boiler tubes resulting in higher than predicted temperatures in the outer radius rows of tubes and the reverse situation in the inner tubes. The effect differed in magnitude between Hartlepool Reactor 1 and the other three Reactors probably due to construction differences.

As a result output was initially limited to approximately 58% of design (380 MW (Generated)).

A major programme of altering the flow control ferrules was carried out during the first statutory overhauls in 1985 and 1986. The initial results from Heysham 1 were not very encouraging (a gain of 70 MW(e)) but further computer model correlations led to revised patterns in Heysham and Hartlepool Reactor 2 which have since yielded improvements in output potential of up to 200 MW(e).

The paper discusses the commissioning test results described above and describes the details of the extensive work carried out to achieve higher output.

1 PLANT DESCRIPTION

The Heysham 1 and Hartlepool AGR Reactors are equipped with 'pod' boilers set into the walls of the Pre-stressed Concrete Pressure Vessel (Figure 1). Each Reactor unit has eight pod boilers, which are of a somewhat unique single pressure, once through, helically wound type incorporating a reheater. The pods are provided with a limited amount of strain gauge and thermocouple instrumentation concentrated mainly in two specially instrumented boilers at each site.

Each boiler pod receives 450 kg/sec of hot CO_2 gas at 650 Deg C, and inlet feed water at 157 Deg C, and generates high pressure steam at 171 bar (2480 lb/in^2) leaving at a temperature of 543 Deg C. Reheated steam leaves at a pressure of 39 bar (573 lb/in^2) and a temperature of 539 Deg C. Feed/steam flow is 60 kg/sec (per pod) and the heat transferred is 190 megawatts (per pod).

Figures 2 & 3 illustrate the general layout of the design.

Appendix A contains a detailed summary of the design and instrumentation.

2 SUMMARY OF COMMISSIONING PROGRESS

The commissioning of the boilers at Heysham 1 and Hartlepool took place in two distinct phases.

a) Engineering Runs prior to Power Raising

These took place in the period 1981-3, and consisted of both Unfuelled and Fuelled Engineering Runs. Progress was delayed by plant faults associated with fuel plug units and gas circulators. Before and during these runs the basic pressure integrity of the boilers was proved by hydraulic testing, extensive testing on the feed control and dump control systems was completed satisfactorily, and a large programme of noise and vibration testing took place (See Section 3).

b) Power Raising

Boiler testing during power raising commenced in 1983 and was continued in 1984 when significant generation was achieved. At each stage of the power raising commissioning programme, a series of control system tests was carried out, in order to optimise the control system settings, and detailed monitoring of boiler performances took place. A significant part of the testing of the automatic start up phases involved the boiler performance during the 'boil-back' process when steam production is initially stimulated. In addition the boiler performance during single boiler isolation and reconnection was investigated. The boiler performance testing mainly consisted of monitoring the superheat and metal temperatures on the instrumented boiler, in order to obtain data for correlation with design prediction, and to ensure that at all times

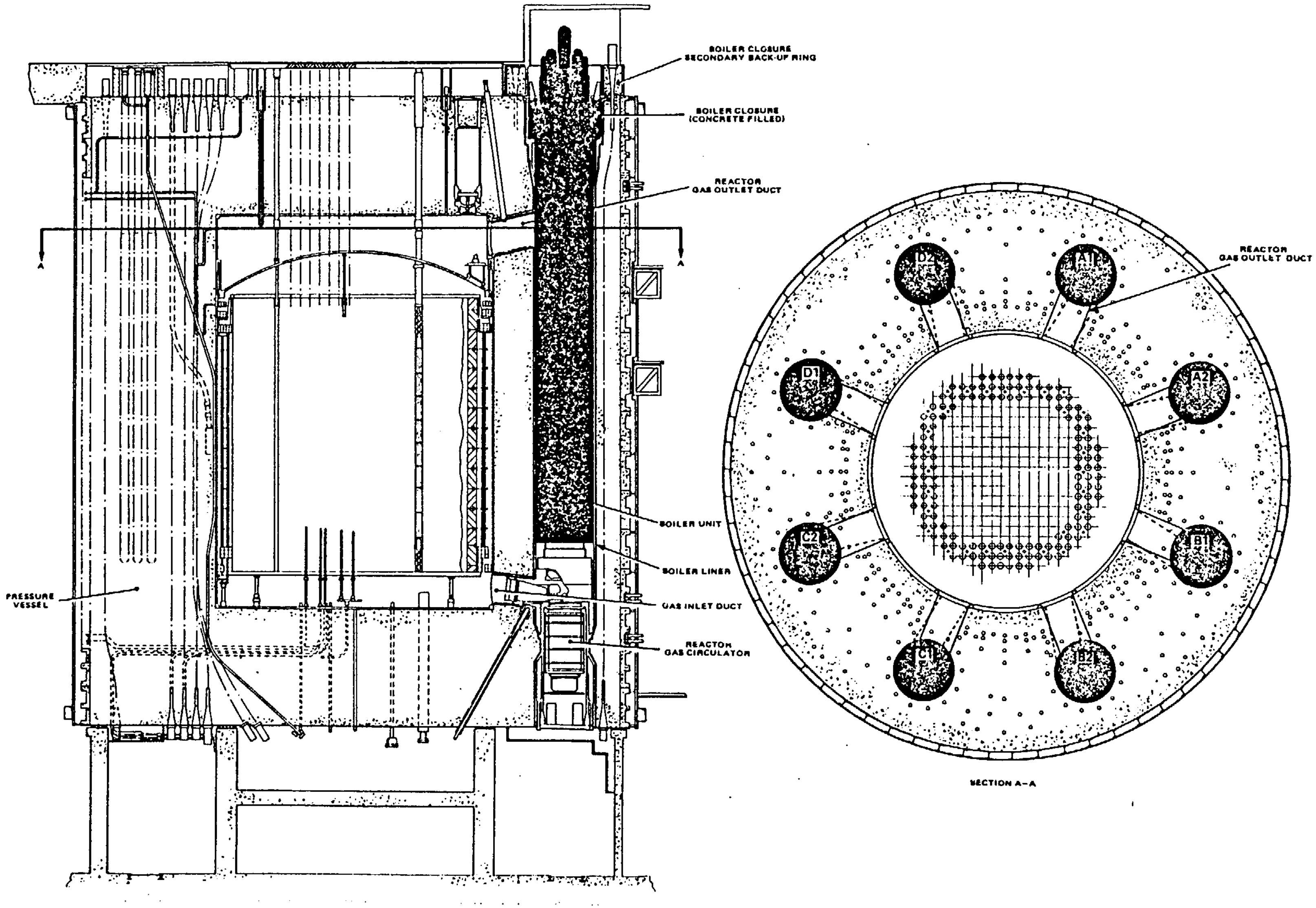

FIG.1. Pressure vessel showing location of boilers.

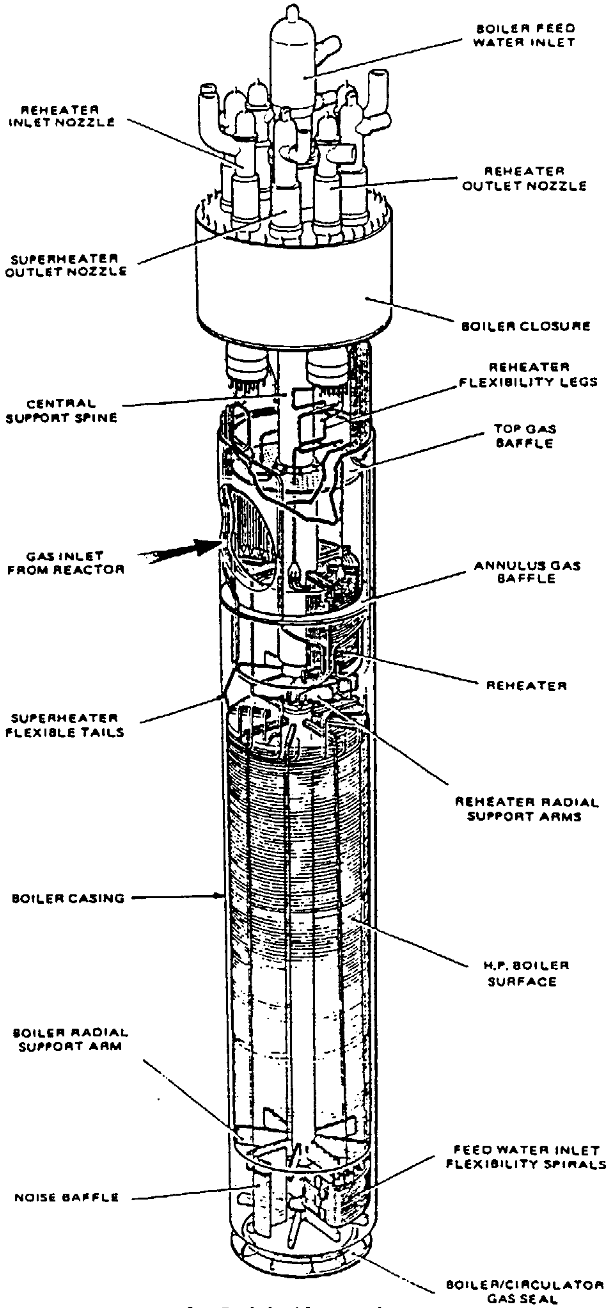

FIG.2. Pod boiler unit.

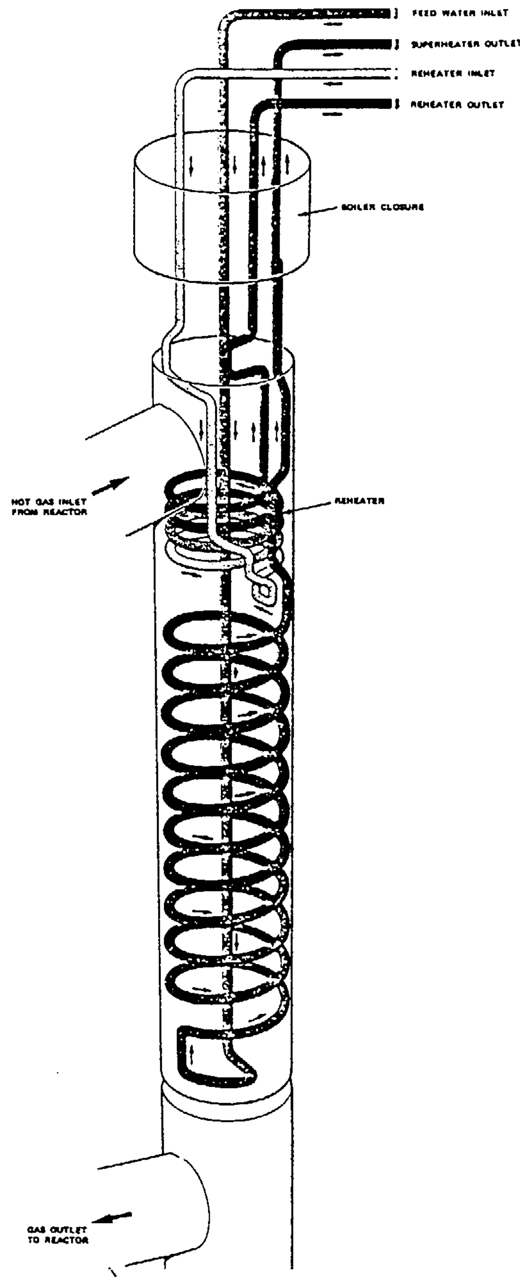

FIG.3. Boiler functional diagram.

these parameters remained within the design constraints. The results from these tests then determined the power output which could be achieved.

3 BOILER VIBRATION

Earlier experience on the British designs of gas cooled reactors indicated that flow induced vibration of boiler tubing could be a serious problem, leading to tube fretting during operation. As a result of this experience there was some concern during the construction period that similar problems could arise at Hartlepool and Heysham 1. In order to ensure that a high standard of information could be obtained during commissioning, several boiler pods at each station were instrumented with strain gauges and/or accelerometers. During the fuelled engineering runs in 1982-3, the vibration responses of the instrumented boilers were monitored as part of a programme of measurement covering the complete gas circuit, including the reactor internal structures, the gas circulators, the boilers, and the fuel and plug unit assemblies. Measurements were taken over a range of gas densities, flows up to design levels, and at temperatures up to 282 Deg C. Nitrogen injection also took place to correct the acoustic conditions to design levels. This programme of measurement was supplemented by further monitoring during the power raising period, when higher gas temperatures (up to 556 Deg C) were achieved. The effects of single boiler isolation were also measured.

The main finding of the tests were that changes in vibration levels with flow and gas conditions were modest. During the engineering runs the maximum estimated stress levels were generally in the range 2-4 MN/m^2 with peak values of up to 6 MN/m^2. These compare with design predictions of 4.5 MN/m^2 and a maximum allowable design value of 7.4 MN/m^2. Sliding wear effects were also of relatively low amplitude.

During the power raising tests, estimated stress levels reached a maximum of 4.3 MN/m^2 in the radial direction, and 2.3 MN/m^2 in the axial direction, both below the design limit of 7.4 MN/m^2. Estimates of sliding wear were in the range 0.08 - 0.15 mm^3/30 days, well below the limit for 30 year design life of 1.23 mm^3/30 days.

Further monitoring of boiler vibration has continued through the period of operation, and although the instrumentation failure rates are now increasing (as was expected) no significant ageing effects have come to light.

As a result of the excellent performance indicated by these tests, an application to increase the reactor coolant mass flow to 105% of design level for normal operation (as an aid to higher output) was approved by the Safety Authorities at the end of 1986.

4 DIFFERENTIAL THERMAL/HYDRAULIC BEHAVIOUR BETWEEN TWO PODS IN A QUADRANT

A boiler quadrant consists of two pod units connected together on the feed inlet end and the steam outlet end. Both inlet and outlet to each pod is via penetrations at the top of each unit. The feed pipe to each quadrant rises to the top of a pod pair then splits to feed each pod separately via a 'pod-valve'. The pod-valves are normally used to control the flow to each pod separately. The high pressure steam outlet from each pod exits via four penetrations to a primary header at the pod top level. The primary headers then run approximately 45 feet down before they join together at the secondary header.

Post-trip, the gas circulators run down to pony motor speed and emergency feed is fed into the boilers to remove the decay heat. To prevent differential feeding, the pod valves were initially signalled to spring open.

In 1983, during the first reactor trip tests from boiler steaming conditions, analysis of boiler gas outlet temperatures indicated that only one pod of each quadrant pair was receiving significant feed flow. The other pod was exhibiting stagnation or reverse flow.

This was attributed to the fact that, due to slight differences in boiler/pod valve pressure drop, one pod of a pair would always flood through before the other. Having filled the helical section and the primary header, the flow path down to the secondary header created a large negative syphonic gravity head that caused all the flow to go to that pod and starve the other.

The solution to this problem was to make use of the pod valves post-trip, by closing them in and creating an additional parasitic pressure loss to counteract the gravity head of a falling primary head line. Due to variations in the characteristic of each pod-valve, each was individually calibrated to obtain an 'end-stop' position to provide the extra pressure drop, and the logic of operation was altered to close the valves in post trip, instead of the original design concept to move them to the fully open position.

These changes in plant and operating procedures successfully solved the problem.

5 BOILER PERFORMANCE TESTS

5.1 Operating Constraints

The major constraints on boiler operation are:

a) To maintain a minimum superheat level at the entry to the austenitic section, to prevent stress corrosion cracking.

This minimum level has, after extensive research effort, been chosen as 30 Deg C. A statistical analysis is carried out to ensure that not more than 5 tubes per reactor are running with less than 30 Deg C superheat.

b) To limit the maximum upper transition joint weld between the 9% chrome and the austenitic section to 500 Deg C to minimise creep damage.

c) To maintain a high water quality, primarily to complement a) above, with oxygen control to minimise erosion-corrosion damage.

Water quality is maintained at all times by the use of a 100% flow condensate polishing plant. Ingress of contaminants is prevented from reaching the boilers by chloride ingress trip protection. Typical water quality targets are shown in Appendix B.

The temperature constraints can only be met by the careful choice of operating terminal conditions. These were derived during raise power from the internally instrumented boiler pods on Reactor 1 at Heysham 1 and Reactor 1 at Hartlepool, together with the individual tube steam outlet temperature instrumentation on some other pods.

5.2 Performance Tests

Prior to commissioning, predictions of operating conditions had been made based on current knowledge of material properties, rig work and computer modelling. Operating Schedules were derived, to be checked during progressive increases in power level.

During the raise power tests on Heysham Reactor 1 in 1984, the actual behaviour was found to differ from the predictions. A major radial temperature tilt existed across the boilers at the upper transition joint region, resulting in a lower than predicted minimum superheat at the inner tube rows and a higher than predicted maximum weld temperature at the outer tube rows.

To minimise the effect, operating conditions were adjusted by reducing the boiler gas inlet temperature and feed-flow, whilst maintaining a high gas flow. An interim relaxation of the minimum superheat requirement was also approved, valid for the first 10,000 hours of operation, up to the first statutory outage.

The operating conditions eventually attained at Heysham 1 were a feed-flow of 67% of design and a gas flow of 100% of design. This gave an observed minimum superheat of 30 Deg C and an observed maximum weld temperature at the upper transition of 490 Deg C on the instrumented pod (See Figure 4). An electrical generation of about 380MW was achieved, approximately 58% of design.

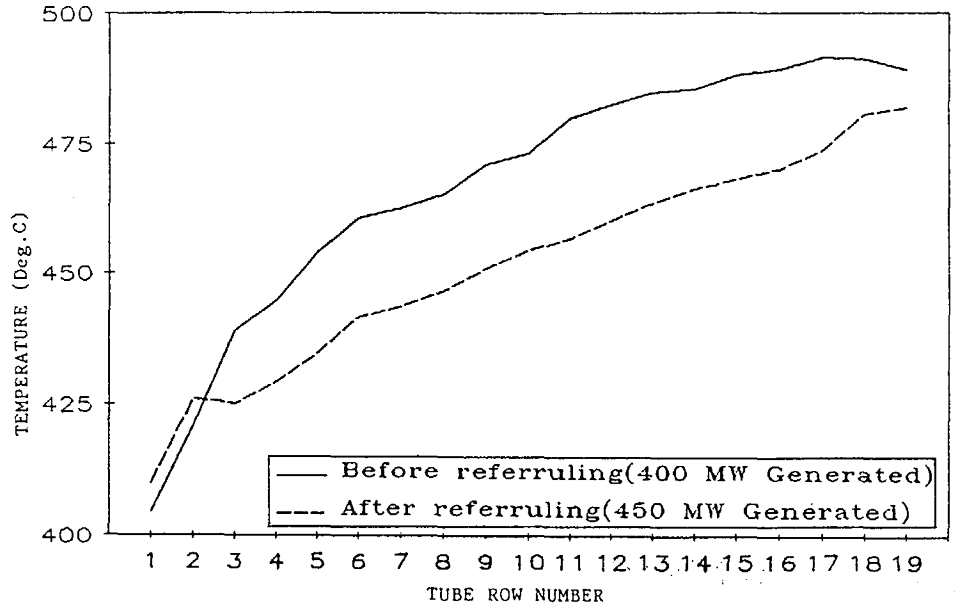

FIG.4. Heysham 1 Power Station - Reactor 1: Upper transition joint temperatures before and after referruling.

The Reactor 2 at Heysham 1 was operated at the same conditions on Reactor 1, as there was no special instrumentation fitted. Terminal conditions were matched, which suggested that the boilers were similar in overall performance to Reactor 1.

At Hartlepool, the temperature tilt problem was not as great on Reactor 1. A feed-flow of 80% of design was achieved at maximum gas flow together with an electrical generation of 490MW, approximately 74% of design.

Hartlepool Reactor 2, however, showed signs of the tilts experienced at Heysham 1 and its load was limited to 420MW generated, approximately 63% of design.

Meanwhile, validation of a computer model PODMIX was being done using the data from the instrumented pods at Heysham 1 and Hartlepool. The model was then used to derive a new pattern of inlet ferrules to adjust the water flow distribution, hence reducing the tilt in temperatures.

The computer modelling work, combined with some research into the manufacture of the boilers, revealed that the reason for the difference between Hartlepool Reactor 1, and the Heysham 1 boilers together with Hartlepool Reactor 2, was in the tightness of the coil winding.

Earlier boilers had proved difficult to enter into their boiler casings, and the winding technique was modified to wind tighter. This, however, produced boilers with the inner rows wound tight to the spine, reducing gas flow area, and the outer rows being clear from the casing, increasing the gas flow area.

The change in technique occurred during the manufacture of the Hartlepool Reactor 2 boilers onward to both Reactors at Heysham 1.

Ironically, due to an early problem with one of the Reactor 1 boilers at Hartlepool, a Reactor 2 boiler was used in its place. During operation, it was observed to exhibit some of the tilt characteristics of the Heysham boilers. This and other small variances was cured on Reactor 1 by reaming some of the outer row ferrules to increase the flow to the hotter tubes. The Reactor 1 boiler in Reactor 2 showed no signs of the tilt exhibited on the other seven pods.

6 REFERRULING

Heysham Reactor 1 was referruled during its first statutory outage in 1985. This involved the removal of the old welded in ferrules, the welding in of a ferrule upstand, and the fitting of screw-in ferrules. During initial temperature raising towards the end of the outage, higher than normal moisture levels were observed on the gas side. Leaks were located and repaired on C and D boilers at the tube-plate to upstand welds. Additional cycling of the other boilers proved no other leaks to be evident.

The Reactor was returned to power in January 1986. During power raising, it became clear that the referruling pattern, whilst giving some improvement, had not completely removed the temperature tilt. From approximately 50% power, it had been necessary to increase gas flow at a greater rate than feed flow.

At a load of 78.5% of design feed flow, the instrumented boiler was judged to be operating within constraints. However, with the aid of the individual tube outlet steam temperature measurement now fitted to all pods, it was evident that not all boilers were running as well as the instrumented one.

The PODMIX model was used to assess the non-instrumented boilers and conditions had to be modified to get all boilers running within constraints. The final conditions were 73.5% design feed flow and 100% gas flow. The generated load was about 450MW, approximately 68% of design. Figure 4 indicates the new temperature pattern.

Meanwhile, the second Reactors at both sites were undergoing their first outages. There was time available to use the information gained from the Reactor 1 performance to make PODMIX calculations to change some of the ferrules in the second reactors.

Reactor 2 at Heysham 1 was returned to service although delays were again caused by two boiler leaks similar to those discovered on Reactor 1, and the operating conditions derived from the PODMIX calculations. Load has been taken to 80% of design feed flow, with a gas flow of 95% design, the reactor load being limited to 1178MW thermal due to the High Pressure Back-up Cooling Safety Case. Figure 5 shows that the radial tilt has been substantially reduced, compared to the situation prior to referruling. (It should be noted that these figures are not direct measurements, they are inferred from the superheater outlet readings, corrected by PODMIX analysis to represent the transition joint region). Similar performance was achieved at Hartlepool.

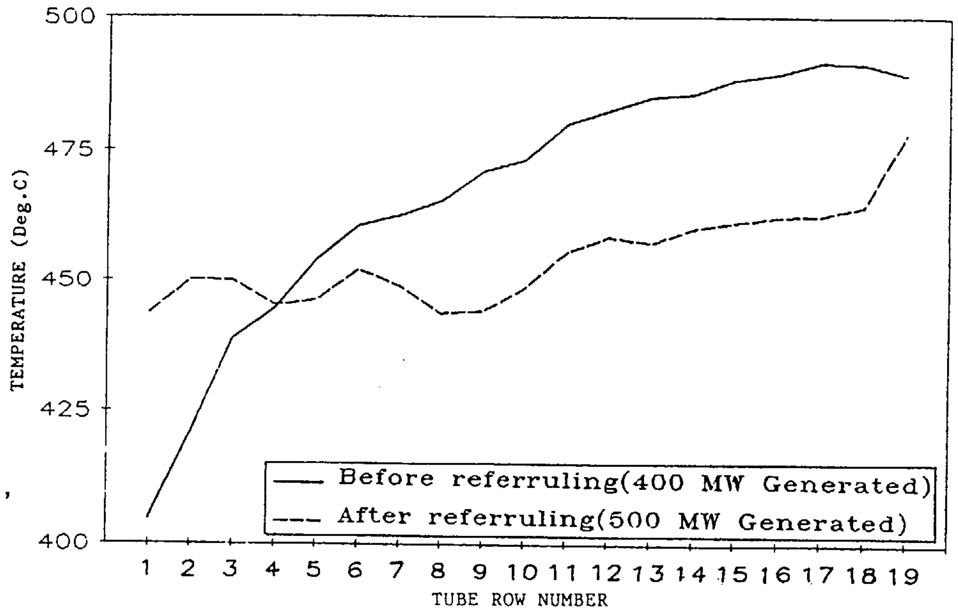

FIG.5. Heysham 1 Power Station - Reactor 2: Upper transition joint temperatures before and after referruling.

Boiler loads of 85% have been achieved during three quadrant operation, suggesting that on clearance of all relevant safety cases and with the relaxation of gas flow limit to 105% loads in excess of 85% design should be possible. (570 MW (Generated)).

At Hartlepool, the Reactor 1 performance following the limited reaming activities yielded performance figures similar to that achieved on the second reactors after referruling.

7 FUTURE PROGRAMME OF WORK

Assessments of boiler performance are continuing with the aid of the special instrumentation and the computer model PODMIX. Small boiler to boiler differences exist, due primarily to build tolerances.

A proposal to isolate the reheater on each boiler in turn is being pursued, to verify whether reheater differences are affecting the gas inlet profile to the high pressure boiler. This information will enhance the PODMIX model, allowing quicker progress to the 'ideal' ferrule pattern for each pod unit.

The final state will probably be each boiler individually ferruled so that maximum output can be obtained from all pods.

Opportunities are likely to be taken during refuelling outages in 1987/88 to improve the ferrule patterns on the second reactors at both sites. The ease of doing this is aided by the provision of de-mountable headers on these reactors.

On Reactor 1 at Heysham, further pattern changes are likely to be completed during the next statutory outage in 1988.

The work on Reactor 1 at Hartlepool is still under review.

Operating constraints are also being reviewed urgently, with a view to reducing the superheat margin to 20 Deg C, and increasing the metal temperature limit to 510 Deg C, at least in the short term pending further changes in ferrule patterns.

8 ACKNOWLEDGEMENTS

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5 CEGB Nuclear Safety Committee Paper 2153, Addendum 1, Operating Experience at Heysham 1 Reactor 1 Boilers following Return to Power

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7 TPRD/L/2598/P83: PODMIX, A Two Dimensional Model for calculating the steady state performance of a Hartlepool/Heysham 1 pod boiler unit, CEGB.

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APPENDIX A

SUMMARY OF BOILER DESIGN AND INSTRUMENTATION

1 INSTRUMENTATION

Each reactor incorporates four boilers; a boiler consisting of two pod boiler units which are connected on the feedwater and steam lines. The eight boiler pod units are arranged in vertical cylindrical steel lined pods within the concrete pressure vessel and are designated A1, A2, B1, B2, C1, D1 and D2.

The general arrangement of the pod boiler unit is shown in figure 1 and schematically in figure 2. Each boiler unit is suspended in its pod from the closure head which seats and bolts on the pod liner flange. Beneath each boiler unit is situated a gas circulator, also connected to the boiler by a bolted flange.

2 THE POD BOILER UNIT

The boiler heating surface is arranged in the form of concentric multi-wound helices wound around and suspended from a central support spine. The boiler unit comprises the high pressure surface and a reheater surface mounted above the high pressure surface.

The high pressure surface comprises two economisers, an evaporator stage and three superheater stages (Fig 3). Each circuit of the HP surface consists of one continuous tube length, comprising in an upward sequence: economiser, evaporator and superheater. The 285 tubes are equal in length, achieved by changes in helix pitch to compensate for changes in row diameters.

There are 19 rows, six tubes in the inner row, increasing one tube per row to 24 tubes in the outer row. The heating surface consists of lengths of carbon steel, 9% Cr, 1% Mn steel and austenitic type 316 stainless steel tubing welded into a composite length utilizing welded transition pieces. Superheated steam leaves the boiler through one of four superheater outlet headers.

Each of the 285 tubes in the boiler are fed individually from the feed tube plate through a restrictor tube, which is fitted with a ferrule at the tube plate end.

The reheater is located above the superheater. The heating surface consists of 13 helically wound concentric coils. The inner coil has 12 tubes, each subsequent coil has two more tubes than the previous coil, giving 36 tubes in the outer coil. The total number of tubes is 312; steam entry and exit is via two inlet and two outlet headers.

3 INSTRUMENTATION

3.1 Original Supply

Two boiler units in Reactor 1 were specially instrumented during manufacture. Boiler Unit 1C1 is instrumented with 99 thermocouples at representative points within the actual boiler unit to measure the CO_2 gas temperatures and also to measure transition joint metal temperatures, at both upper (S.S./9Cr junction) and lower (9% Cr/Carbon Steel junction) transition joints.

The thermocouples used are 1.58mm; Nickel Chrome/Nickel Alumel.

No internal temperature instrumentation is fitted to boilers in Reactor 2.

3.2 Thermocouple Rakes

Following development during the reactor construction period five of these devices were installed into one superheater header on pods 1A1, 1B2, 1D2 and two headers on pod 1C1.

The device comprises an array of 19 thermocouples and is located inside a superheater header. This enables a sample of superheated steam temperatures to be obtained from that header (approximately 50% of tubes in that header). No similar instrumentation was fitted to the second reactor, but following the referrulling exercise, every pod on all boilers now contains at least one thermocouple rake.

3.3 Vibration Instrumentation

A selection of approximately 150 strain gauges was fitted to one boiler pod at each site. Approximately 130 accelerometers were fitted to another pod. In addition, a further set of accelerometers and strain gauges were fitted to a specially instrumented boiler pod (MA31) on Reactor 2 at Heysham.

APPENDIX B

TYPICAL BOILER INLET FEEDWATER CHEMISTRY

pH	9.2 @ 25 Deg C
Ammonia	500 ug/Kg
Hydrazine	40 ug/Kg
Oxygen	Controlled to 15 ug/Kg $\pm$ 3
Direct Conductivity	4.5 uS/cm @ 25 Deg C
After Cation Conductivity	< 0.08 uS/cm @ 25 Deg C
Sodium	< 2.0 ug/Kg
Chloride	< 2.0 ug/Kg
Sulphate	< 2.0 ug/Kg
Reactive Silica	< 5.0 ug/Kg
Iron	< 5.0 ug/Kg
Copper	< 2.0 ug/Kg