Health and Safety Executive

Treatment of feed water for steam boilers using magnetic devices

Phase 3: Experimental Programme

Prepared by **TUV NEL**
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Research Report

Health and Safety Executive

Treatment of feed water for steam boilers using magnetic devices

Phase 3: Experimental Programme

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HSE commissioned TUV NEL to investigate the treatment of feed water for steam boilers using magnetic devices. The key aims of the project were:

- to provide the HSE with an independent assessment of the ability of magnetic devices to treat feed water for shell or coil steam boilers; and
- to identify possible situations where magnetic devices could impair boiler safety.

The contract was divided into five phases the first of which was a literature search. The second phase was concerned with device selection in which suppliers of Magnetic Water Treatment Devices (MWTD) were identified and a judgement made of their engineering credibility and support capability. Magnetic treatment devices from four suppliers were recommended for evaluation.

This report describes the work carried out for Phase 3 of the project. This phase comprised the experimental programme executed to compare the performance of magnetic treatment devices from the four suppliers recommended in Phase 2. The chosen units were fitted to a test boiler system which enabled the effectiveness of the devices to be evaluated when operating across a range of boiler surface heat fluxes.

The device demonstrating the best performance was to be evaluated over a longer time period in Phase 4 of the work.

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CONTENTS

EXECUTIVE SUMMARY

Increased publicity regarding the use of magnetic water treatment devices (MWTDs) in industrial process plant has been accompanied by claims that these devices can replace traditional chemical treatment regimes. There is, however, a lack of scientific evidence in support of these claims. Concerns have been expressed that magnetic water treatment devices may be applied inappropriately in situations which might lead to dangerous plant failures. A particular cause of concern is the use of such devices on steam boiler plant. Careful water treatment is a prerequisite of the operation of steam boilers to prevent fouling of the heat transfer surfaces. Fouling can lead to overheating of the boiler surfaces and this can result in catastrophic failure. HSE has therefore commissioned TUV NEL to undertake a rigorous study into the use of magnetic water treatment devices on steam boilers. The work was undertaken in several distinct phases.

Phase 1 comprised a review of literature relating to magnetic water treatment devices for industrial steam boilers, and a survey of the typical heat flux levels encountered in the industry. The review sought to extract a consensus from the literature examined, but found that this was difficult due to conflicting claims for magnetic devices. Key operating parameters which influence the performance of MWTDs were, however, identified.

Phase 2 addressed the issue of selecting a representative sample of MWTDs from the large number of devices available to form the basis of a scientific assessment. Four devices were selected for trial.

In Phase 3 (the subject of this report) these devices were each fitted to an instrumented steam boiler. The rate of temperature increase with time of the boiler heating surfaces was used to give an indication of the rate of fouling taking place. The fouling rate occurring with each MWTD was compared with that occurring with untreated water. Only one of the devices assessed showed any apparent benefits. Repeat tests with this unit however did not replicate the original result. This suggests that performance of MWTDs may be inconsistent in service and therefore widespread adoption of such devices in service may be undesirable without site specific validation.

The evidence from these trials therefore indicates that the four magnetic water treatment devices selected did not consistently prevent fouling on the hot surfaces of a steam boiler. A consequence of this finding is that it is not possible to endorse without qualification magnetic treatment of feed water for the prevention of boiler fouling.

1 INTRODUCTION

HSE commissioned TUV NEL to investigate the treatment of feed water for steam boilers using magnetic devices (RSU REF: 4211/R32.084). The key aims of the project were:

- To provide the HSE with an independent assessment of the ability of magnetic devices to treat feed water for shell or coil steam boilers
- To identify possible situations where magnetic devices could impair boiler safety.

The contract was divided into five phases the first of which was a literature search[1]. The second phase[2] was concerned with device selection in which suppliers of Magnetic Water Treatment Devices (MWTD) were identified and a judgement made of their engineering credibility and support capability. Magnetic treatment devices from four suppliers were recommended for evaluation.

This report describes the work carried out for Phase 3 of the project. This phase comprised the experimental programme executed to compare the performance of magnetic treatment devices from the four suppliers recommended in Phase 2. The chosen units were fitted to a test boiler system which enabled the effectiveness of the devices to be evaluated when operating across a range of boiler surface heat fluxes.

The device demonstrating the best performance was to be evaluated over a longer time period in Phase 4 of the work.

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1 A Review of Literature concerning Magnetic Water Treatment Devices for use on Steam Boilers NEL Report No. 181/2001, August 2001
2 Treatment of Feed Water for Steam Boilers using Magnetic Devices. Phase 2: Device Selection and Test Facility NEL Report No. 319/2001, December 2001

2 APPROACH

The approach chosen for the experimental programme was to use a commercially available steam generating shell boiler as the main element of the facility and to fit an additional heating surface comprising an electrically heated water tube section. The shell boiler contained all the necessary feed water systems, blowdown systems and standard safety controls. The unit selected operated at a low heat flux (16 kW/m^2 average) and demonstrated the effectiveness of the magnetic water treatment devices in controlling scaling in lightly loaded shell type boilers. The electrically heated section provided heat fluxes of up to 250 kW/m^2 and demonstrated the potential effectiveness of the devices when used in conjunction with highly rated shell or water tube boilers.

Each of the four magnetic water treatment devices were fitted in accordance with the manufacturer's instructions and the boiler was operated until noticeable fouling took place. The relative effectiveness of each of the test units in controlling fouling was assessed on this basis.

3 DEVICES SELECTED

A total of 15 manufacturers of magnetic water treatment devices were identified via internet and literature searches. These manufacturers were approached to establish whether they could supply devices for a specified duty for two steam boilers of different nominal evaporation rate. Eight manufacturers indicated that they could supply suitable devices and from these four devices were selected for evaluation. Table 1 lists the installation requirements specified by the various manufacturers together with any usage guidance supplied.

Table 1 Device installation requirements and usage advice

Manufacturer / device ID	*Location of MWTDs*	*Known limitations*	*Requirement for oxygen scavenging*	*Water analysis required?*	*Remarks*
Manufacturer A [Device A]	Boiler feed, feed water tank make up and condensate return	None mentioned pH should settle between 9 and 12	Not required with deaerated feed water > 82° C	No Specified TDS concentration be held below 1500 ppm	Claim many boiler applications
Manufacturer B [Device B]	Boiler feed	Heat flux < 35 kW/m^2	None necessary with feed water deaeration. Anodic protection optional.	Yes Phosphates <2ppm Iron + manganese <0.5 ppm	
Manufacturer C [Device C]	Boiler feed	None advised	No guidance given	No	Claim suitable for calorifiers and heat exchangers
Manufacturer D [Device D]	Boiler feed	None advised	No guidance given. Claim tubes are coated with thin aragonite film that protects tubes from O_2.	Yes	

It is worth noting that all four manufacturers advocate fitment of their units to the boiler feed pipe downstream of the feed pump. This location is specifically cited in research literature[3] as being unsuitable due to low flow rates and intermittent operation. However, the installation arrangements for Device A include the use of additional magnet units fitted to the feed tank make-up and condensate return lines.

[3] *Baker, J S and Judd, S J. Magnetic Amelioration of Scale Formation Water Research, Pergamon Press, 30(2): 247-260, 1996*

4 TEST FACILITY

Figures 1 to 5 show general views of the test facility. Figure 6 shows a line diagram of the service connections.

The shell boiler was a near-standard Cochran Borderer unit with a rated evaporative capacity of 50 kg/h F & A 100 ºC with a burner rating of 35 kW. The boiler was modified with additional tappings to allow fitment of an external electrically heated tube section located vertically as shown in Figures 7 and 8. This heater had a rating of 7 kW. Originally circulation of boiler water through the heated section was to have been maintained using a circulating pump. However, due to reliability problems the pump unit was removed and circulation took place by means of thermosyphon action. Appendix 1 describes the calculations carried out to predict circulation flowrates under this regime. Two electrical heating elements were wound on to the outer surface of the heater body as a two-start helix. These were connected in opposite polarity to ensure no electromagnetic flux was generated in the heater. Appendix 2 details the calculations carried out to ensure all induced magnetic fields were cancelled by the chosen winding method. These calculations were confirmed by magnetic flux measurements carried out prior to testing and these are listed in Appendix 3. Four thermocouples were located at either end of the heater close to the bore. These were used to measure metal temperatures at the inlet and outlet of the heater tube. Tube wall temperature rise was used as an indication of surface fouling.

Four additional manholes were fitted to the boiler shell, as shown in Figures 1 and 2, to facilitate the fitment of thermocouples to the waterside metal surfaces of the furnace and smoke tubes. The precise locations of the thermocouples are indicated in Figure 9. Temperature rise measured at these locations together with flue gas temperature were used to indicate any fouling of the boiler surfaces.

Certain thermocouples were also connected to a PLC controlled safety trip system to ensure shutdown of the boiler in the event of overtemperature conditions. Additional inputs to the safety system included the standard low water and overpressure boiler trips together with high TDS alarms and various storage tank level trips. The PLC system also controlled tank filling operations and feed heating.

A PC based data acquisition system logged temperature, pressure and flowrate parameters from the system throughout the device trials.

Steam from the boiler passed firstly through a water separator and thence to a surplussing valve. This valve controlled the operating pressure in the boiler by increasing discharge flowrate when boiler pressure exceeded the set-point. In operation, flow was controlled such that the steam flowrate matched the evaporation rate of the boiler at the set pressure. By this means boiler pressure was controlled without operation of the burner pressurestat. Therefore, burner firing was continuous throughout the period of testing. Steam from the surplussing valve was passed to a water cooled condenser via a pressure reducing valve. Steam condensate could either be returned to the feed tank or passed to waste, as detailed in Figure 6.

Industry standard steam fittings and boiler mountings were used in the test facility to ensure that the materials in contact with the steam and condensate were representative of normal practice. A Spirax-Sarco conductivity probe mounted in the boiler water space was used to control the level of Total Dissolved Solids (TDS) in the boiler by means of intermittent blowdown from a mid-level tapping. Timed bottom blowdown could also be utilised if desired.

5 TEST PROGRAMME AND DISCUSSION OF RESULTS

The boiler was commissioned using industry standard chemical water treatment and run for a short period to stabilise operation. Feed water was provided from a small demineralising plant to ensure low levels of total hardness. The temperatures measured on the furnace and smoke tube surfaces were recorded together with the temperatures at the inlet and outlet of the high-flux heater and the flue gas entering the chimney. These measurements represented the baseline operating temperature levels for a clean boiler.

The boiler was then operated, without any form of water treatment, using medium hard feed water from a borehole at the test site. Boiler pressures of 6.9 bar and 9.5 bar were utilised and various power settings from 10-100% were set on the high-flux heater. These runs were carried out to establish the maximum rates of fouling to be expected without any form of treatment, as indicated by the rate of temperature increase of the heating surfaces.

Table 2 summarises the test sequence carried out during this phase of the work.

Table 2 Initial test programme sequence

Sequence no.	*Description*	*Days run*
	Boiler cleaned	
1	Standard chemical treatment (10 bar, 100% high-flux heater power)	3
2	Untreated, 6.9 bar, 10% High-flux heater power	3.5
3	Untreated, 6.9 bar, 40% High-flux heater power	3.5
4	Untreated, 10 bar, 10% High-flux heater power	5.5
5	Untreated, 10 bar, 40% High-flux heater power	5.5
6	Untreated, 10 bar, 100% High-flux heater power	7
	Boiler cleaned	

Figure 10 shows the results of this series of trials. The figure shows the average temperatures recorded by the thermocouples fitted close to the bore of the high flux heater at both inlet and outlet.

5.1 CHEMICALLY TREATED WATER

Testing started with a conditioning period of three days running using standard chemical treatment. Average high-flux heater metal temperatures of 224 ºC were recorded at 10 bar boiler pressure and 100% heater power.

5.2 INITIAL UNTREATED TESTS

The conditioning period was followed by runs without any form of water treatment using water directly from the site borehole. The high flux heater wall temperatures are shown in Figure 10. No significant trends in metal temperature were noted over the duration of test runs 1 to 5, Table 2. High-flux heater temperature did of course increase with increased pressures and heater duties. After a total of 19 days elapsed running time at intermediate duties, boiler operating conditions were returned to the full load settings of 10 bar pressure and 100% heater duty (test point 6, Table 2). At this point average high-flux heater surface temperatures were found to be some 9 ºC higher than those initially measured with chemical treatment during the conditioning period. This suggests that some light fouling had in fact been ongoing throughout the preceding running period. At the 10 bar full power condition significant fouling took place almost immediately, as is evident from the temperature gradients from this point on (see Figure 10). On inspection, at the end of the test, the heater was found to be fouled with a calcium carbonate deposit.

The surface temperatures of the boiler furnace and smoketubes and the flue gas exit temperature showed no significant variation throughout this series of tests other than that due to the different saturation temperatures at the two operating pressures used. No significant increase in surface temperature due to fouling was noted.

Following cleaning, the boiler was again run with standard chemical treatment for three days. The temperatures measured in the side loop were within a degree of the original measurements at 223 ºC.

5.3 TRIALS OF MAGNETIC DEVICES

From the above it became evident that no significant fouling, sufficient to cause surface temperature rise, could be expected in a short test period. The exception to this was fouling within the high flux heater when operated at the maximum power setting. At full power significant temperature rise could be expected within a period of three days if the magnet devices were ineffective in controlling fouling. This factor was therefore chosen as the criterion for comparison between the four magnet devices. Each device would be operated with a nominal boiler pressure of 10 bar and with the high flux heater on full power until significant temperature rise was noted on the high flux heater metal surfaces.

Prior to the installation of each device the boiler and high flux heater surfaces were cleaned. The boiler system was then operated for a period of three days on standard chemical treatment and demineralised feed water. This was undertaken to ensure that each magnetic device test was preceded by an identical baseline test. The initial three day test also allowed the boiler to be monitored for repeatable baseline performance ensuring that no drift with time was occurring. Following thorough flushing of the boiler and feed tank, each magnetic device was fitted and the system was filled using medium hard feed water from the borehole. The system was then operated until fouling was apparent. Table 3 details the test sequence carried out.

Figure 11 shows comparative results of all the MWTDs. These are discussed individually in the following sections.

5.3.1 Device A

The installation for Device A comprised a number of individual magnets which were strapped on to the external surfaces of the appropriate pipework including the boiler feed pipe between the pump and check valve, the copper pipe conveying the make-up feed to the feed tank and the condensate return line although, for the tests carried out, condensate was run to waste and not back to the tank. Electrical bonding was carried out to ensure electrical continuity throughout in accordance with the manufacturer’s recommendations. The manufacturer of Device A also stated that Total Dissolved Solids (TDS) should be maintained below 1500 ppm or 3000 μS/cm in conductivity terms. No other manufacturer specified a TDS value but, to ensure comparability, all testing was carried out with TDS held to this level by means of automatic side blowdown.

It should be noted that the results of the tests with Device A, which commenced with 10 bar boiler pressure and 100% high-flux heater power, must be compared with the results of the corresponding untreated water tests. Thus, Day 19 of the untreated tests in Figure 11 corresponds to Day 1 of the tests with Device A fitted.

Table 3 Magnetic device test sequence

Test sequence	*Action*
1	Boiler cleaning
2	Stabilising run with chemical treatment
3	Test Device A
4	Boiler cleaning
5	Repeat test using untreated water
6	Boiler cleaning
7	Stabilising run with chemical treatment
8	Test Device B
9	Boiler cleaning
10	Stabilising run with chemical treatment
11	Test Device C
12	Boiler cleaning
13	Stabilising run with chemical treatment
14	Test Device D

With Device A there was some indication that minor fouling took place initially. However, after 18 days, average side loop temperatures had increased by only 9 ºC and the high rate of fouling present at this condition with no treatment was not present. Indeed no further increase in temperature was observed until the test was suspended after 27 days elapsed running. This suggested that the device was having some beneficial effect. A longer trial period would however, be required to confirm the performance of the unit.

5.3.2 Repeat runs with no treatment

As Device A apparently had some beneficial effect, it was necessary to confirm that fouling took place in a short period when no treatment device was installed. To this end, Device A was removed and the boiler and heater surfaces were cleaned. A repeat run was then carried out using untreated borehole water. No initial conditioning run was carried out.

Figure 10 shows that fouling within the high flux heater commenced almost immediately and that after four days running outlet side temperature exceeded the maximum recorded during the initial trials using untreated water. This confirmed the fact that fouling would occur almost immediately with untreated water.

5.3.3 Device B

On completion of the untreated water repeat runs the boiler and high flux heater surfaces were again cleaned and a conditioning run on standard chemical treatment with demineralised feed water was completed. Device B was then fitted to the feed pipe in accordance with the manufacturer's instructions.

Figure 11 shows that the device had no influence on fouling within the high flux heater. Comparing the results from Day 1 of the tests with Device B fitted with results from Day 19 of the tests with untreated water, inlet and outlet metal temperatures were very close to those measured with untreated water. Figure 12 shows an expanded plot of the time period of interest. It was perhaps unsurprising that Device B was ineffective, as the manufacturer's recommendation was for equipment having a maximum heat flux of 35 kW/m^2. The heat flux within the high flux heater at maximum power is 250 kW/m^2. The test did however, provide a direct comparison with the Device A installation.

5.3.4 Device C

Device C was fitted in the same location as Device B. However, Device C differed from the other devices tested in that it comprised a large electro-magnet powered from an external DC supply. Operating conditions during test were identical to the other units however.

As in the previous trials, the boiler and high flux heater surfaces were cleaned prior to carrying out a conditioning run using chemical treatment.

Figure 12 shows that no beneficial influence was evident when using the device. Inlet and outlet metal temperatures within the high flux heater were very similar to those recorded during the untreated runs and also in tests with Device B fitted and outlet temperature had risen from 225 °C to 290 °C after five days running.

5.3.5 Device D

Device D was fitted to the boiler feed pipe. As in previous tests the unit was fitted after boiler and high flux heater surface cleaning had been carried out and after a three day conditioning run on chemical treatment had been completed.

Again, Figure 12 indicates that the device was ineffective in controlling fouling within the high flux heater unit. The gradient of the outlet side temperature rise was somewhat lower than with the other units. Seven days running time was required to reach 290 °C, rather than five days with Devices B and C. However, this is unlikely to be significant and the rate of fouling showed no signs of decreasing with time.

5.4 GENERAL OBSERVATIONS

Figures 13 to 24 show the condition of the boiler heating surfaces before and after each device trial. Due to the relatively short periods of operation the surfaces were not extensively fouled. This observation confirmed the absence of fouling which was indicated by the lack of any surface temperature rise recorded over the duration of the trials (Figure 25). Any minor variation in boiler surface temperatures was entirely due to changes in saturation temperature corresponding to small variations in boiler operating pressure. In general, the heating surfaces were lightly corroded after each operating period but the corrosion deposits were purely cosmetic and easily removed. The only observation of note was that the deposits present following the Device A trial appeared to have a somewhat different appearance and consistency than those from the other trials. The significance of this observation was unclear. An insufficient quantity of deposit material was present to enable full chemical analysis to be undertaken.

Figures 26 to 28 show views of the surface deposits formed inside the high flux heater. These figures show the appearance of the heater bore following the untreated runs and the trials of Devices B and D, respectively. A clear dividing line was evident between the fouled surface and the unfouled bore of the heater. This corresponded closely to the area covered by the heater windings and confirmed the dependency of fouling on local heat flux levels. The bore of the heater following the trials of Device C was visually identical to Figure 28, whilst the deposits formed during the Device A trials were minimal. Limited chemical analysis of the deposits from the untreated runs indicated that the main constituent was calcium carbonate.

Figure 29 shows the variation of the apparent TDS concentration over time, derived from conductivity measurement, during the trials of the magnetic devices. It is clear that, following an initial settling period, the automatic blowdown system was able to maintain TDS concentrations at a steady level. The same final level was maintained for each magnetic device. The relatively low rate of build up in TDS concentration during the early part of the untreated water trials is due to the reduced power settings in the early phases. This led to a reduced demand for feed water. Monitoring TDS levels by measuring conductivity can, however, be misleading as the conductivity reading only relates to compounds held in solution and takes no account of any deposition on the heating surfaces or the shell bottom. If higher precipitation rates occur with certain treatment devices, conductivity levels may remain low even if the rate of surface fouling increases.

It is apparent that, of the four devices examined, Device A showed the most promising results. Over the relatively short period of the tests this system alone was able to control fouling in the high flux heater unit. However, testing over a greatly extended period, equivalent to the duration of the boiler inspection cycle, would be required to fully assess the ability of the devices to control boiler fouling.

Corrosion control is also an important factor. The manufacturer of Device A claims that oxygen scavenging is not required with de-aerated feed water at temperatures above 82 °C. An extended trial period would be required to test the validity of this claim. Adequate control of both surface fouling and corrosion would have to be demonstrated if magnetic water treatment was to be deemed safe for UK boiler installations.

At low heat flux levels, insufficient fouling took place to enable a comparison between the performance of the different devices to be undertaken. However, it would seem reasonable to assume that Device A would be no less effective at low heat flux levels than the other devices.

It would be beneficial to carry out trials with a range of heat flux levels in the high flux heater. The time required to form significant fouling deposits could be assessed for a number of power settings stepping down from 250 kW/m^2 to 25 kW/m^2. These tests could be run in parallel with the extended duration boiler surface fouling trials. The variable heat flux trials would quantify the maximum heat flux levels at which Device A was able to control fouling for adequate time periods.

There would still be some cause for concern even if extended trials of Device A confirmed its effectiveness in controlling fouling. There is clearly significant variation in performance between the units evaluated. It seems evident that certification of individual systems would be required before systems offered for sale could be deemed fit for purpose. Certification would necessarily involve trials over an extended period of operation.

5.5 CHEMICAL ANALYSIS OF WATER SAMPLES

Table 4 lists the results of chemical analysis of water samples taken during tests using untreated water while Table 5 list corresponding data for the test programme on the various magnetic water treatment devices. There are few obvious trends in the data, especially when comparing the results from Devices B, C and D, which generated data similar in most respects to data obtained during operation on untreated borehole water. With Device A there is an apparent reduction in total hardness in the boiler water samples from that measured in the feed tank. This was evident even in the first boiler water sample drawn at the end of the first day of operation. The significance of this result is, however, unclear.

The iron concentration levels measured during the trials with Device A may, however, be significant. Iron concentrations in the feed tank were an order of magnitude higher at the conclusion of the tests on this device compared with the values measured during the trials of the other devices. The concentration measured in the boiler rose from 0.8 ppm at the start of the trial to 2.89 ppm at the conclusion. The change in concentration appears to have been due to variations in the quality of water drawn from the borehole, as no condensate was returned to the feed tank from the boiler system. The effect of this factor is unclear, but iron concentration levels may be significant in the operation of magnetic devices, although none of the device suppliers indicated that iron concentrations should be held within specified limits. It became evident that if robust conclusions were to be drawn from the experimental programme, it would be necessary to test Device A on water having a constant, low level of iron concentration and to test the other devices with high iron concentrations. The following section describes tests carried out in an attempt to gather additional data on this aspect of the device’s performance.

Table 4 Water analysis results when running with untreated water

		Untreated Water				
		Feedtank				***Boiler***
Component	***Unit***	***23/02/04 pre-trial***	***23/03/04***	***27/03/04 Post-trial***	***07/06/04 Post-trial***	***12/03/04***
pH			8.1			9.6
TDS	ppm		385			1750
Conductivity	uS/cm	500	560	600	650	2500
Total hardness	ppm $CaCO_3$	142	104	151	187	119
Total alkalinity	ppm HCO_3		12			4
Calcium	ppm		44			120
Copper	ppm		0.02			0.03
Iron	ppm		0.11			0.15
Potassium	ppm		3.9			28
Magnesium	ppm		9.6			1
Manganese	ppm		0.02			<0.01
Sodium	ppm		53			370
Silicon	ppm					
Chloride	ppm		110			580
Nitrite	ppm		<1			<1
Nitrate	ppm		<5			<5
Sulphate	ppm		18			66

Table 5 Water analysis results from tests with magnetic water treatment devices

		Device A					*Device B*			*Device C*			*Device D*		
		Feedtank		*Boiler*			*Feedtank*	*Boiler*		*Feedtank*	*Boiler*		*Feedtank*	*Boiler*	
		190804	*170904*	*260804*	*090904*	*170904*	*250105*	*250105*	*280105*	*090305*	*090305*	*140305*	*210405*	*210405*	*270405*
Component	***Unit***						*pre-trial*	*pre-trial*	*post-trial*	*pre-trial*	*pre-trial*	*post-trial*	*pre-trial*	*pre-trial*	*post-trial*
pH		7.06	7.9	10.9	10.9	11.1	8.2	9.7	10.5	7.8	10.4	10.2	8.2	10.6	10.3
TDS	ppm	455	385	1610	1750	1750	522	715	1720	594	894	2360	644	1220	1930
Conductivity	uS/cm	651	564	2300	2480	2480	717	1009	2430	816	1261	3260	900	1668	2690
Total hardness	ppm $CaCO_3$	210	180	64	44	44	133	92	79	129	112	135	145	116	130
Total alkalinity	ppm HCO_3		240	182		182	24.46	3.05	4.2	22.81	3.41	3.66	15.49	3.29	3.66
Calcium	ppm		55.31	18.93		25.7	87	70	61	83	89	94	100	90	97
Copper	ppm		0.51	0.03		0.05	0.05	0.06	0.02	0.02	0.01	<0.01	0.02	0.01	<0.01
Iron	ppm		3.5	0.77		2.89	0.08	0.1	<0.03	0.09	0.21	0.07	0.11	0.25	0.05
Potassium	ppm		3.66	30.55		33.69	4	9.3	33	4.2	11	30	4.1	14	21
Magnesium	ppm		8.68	1.68		4.2	12	0.71	0.84	13	1.8	2.1	15	1.6	1.7
Manganese	ppm		0.12	0.02		0.07	0.26	<0.01	<0.01	0.01	<0.01	<0.01	0.21	<0.01	<0.01
Sodium	ppm		51.24	402.1		462.1	50	110	330	62	140	430	72	200	350
Silicon	ppm		5.76	2.85		3.93	4.3	0.71	0.51	4.2	0.21	0.5	4.4	0.22	0.38
Chloride	ppm		50	390		410	67	150	550	102	242	840	107	368	690
Nitrite	ppm		<0.3	<0.3		<0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<1
Nitrate	ppm		7.9	14		<0.5	<1	<1	<1	<1	<1	0.43	0.11	<1	<0.1
Sulphate	ppm		14	140		120	86	180	180	83	180	140	110	170	110

5.6 REPEAT TESTS ON DEVICE A

Device A was the only device which showed promise with regard to control of fouling in regions of high heat flux. With this device however, measured iron concentrations in the boiler at the end of the test period were significantly higher than those occurring during trials of the other devices. Repeat testing of Device A was therefore undertaken in an attempt to assess this system's performance with lower iron concentrations in the feed water and hence within the boiler shell.

A period of seven months had elapsed between the conclusion of the initial test programme and the start of the repeat tests. Analysis of the borehole water prior to the start of the repeat trial showed that iron levels in the supply had risen to the high level of 9.4 ppm, from the value of 3.5 ppm recorded at the conclusion of the original trials of the device. Clearly, feed water with this level of iron concentration was unsuitable for the repeat tests and therefore, an extended period of draw-off from the borehole was commenced in an attempt to obtain a reduction in iron concentration.

Borehole operation during this period proved extremely problematic and although iron concentrations fell steadily over time, the borehole supply suffered from frequent interruption due to silting. Eventually, however, a concentration of 1.1 ppm was obtained. Unfortunately, total hardness in the borehole supply also fell during this period from 270 ppm $CaCO_3$ to only 31 ppm. As the target iron concentration was less than 1 ppm, it was decided to operate with borehole water diluted in the ratio 1.5:1 with the local tapwater supply. As the tapwater had a total hardness in the range 20-25 ppm, it was felt that such dilution would not further reduce hardness significantly but would achieve a significant reduction in iron concentration. It was realised that such a course of action would significantly alter the chemical composition of the feed water from that used in earlier trials. It was however, felt that evaluating the performance of the Device A under such conditions would be a worthwhile exercise in that it would indicate whether the possible benefits suggested by the original trial could be maintained with feed waters of different composition.

Figure 30 shows the variation in feed water iron concentration and total hardness over the duration of the repeat tests.

As in the previous studies, the boiler was chemically cleaned prior to the start of the tests. Prior to fitting the device, a stabilisation test using chemically treated demineralised water was carried out as per earlier trials. During this period the borehole supply was kept running (undiluted), although not being used in the boiler, and hardness was monitored by measuring conductivity in the feed supply tank. Conductivity did not vary significantly during the 3-4 day period of the trial. The supply was kept active in order to maintain low iron concentrations for the magnet device trials.

Unfortunately, mechanical and electrical failures prevented early execution of the trial and a significant delay occurred prior to testing the magnet device. It was not possible to maintain flow from the borehole during the entire period of the delay and when analysis of the (diluted) feed water was carried out at the start of the test, the iron concentration had risen to over 6 ppm.

Due to the use of diluted feed water with low total hardness it was recognised that an extended running period would be required to build up TDS concentrations in the boiler to the levels attained in previous tests. For this reason the side loop heater power was maintained at a low level (580 W) until indicated TDS (conductivity) levels in the boiler exceeded 2000 uS/cm. This corresponded to the levels attained within two days operation with higher total hardness feed water during previous tests (Figure 29). By this means the general TDS levels in the boiler when the high flux heater was operating at full power were similar to those occurring during earlier tests. Figure 31 shows the TDS levels recorded during the repeat tests. The dip in TDS level at day 21 of the test was due to a sticking blowdown valve on the boiler which resulted in excessive feed water supply. TDS levels recovered when this problem was resolved and normal blowdown had resumed during the last day of testing.

During the conditioning period the iron concentration in the (diluted) feed water fell to below 2 ppm and continued to fall during the full power run to a final value of 1.4 ppm at the end of the test. Feed water iron concentration was therefore, below 2 ppm during the period of full power testing.

The iron concentration present in the boiler during testing was however, quite different. At the start of the low power conditioning run the boiler was flushed repeatedly using diluted borehole water prior to final filling. Therefore, the hardness and iron content of the water in the boiler shell were equal that of the feed water. Over the duration of the conditioning run, boiler water hardness increased as expected, as TDS levels rose. However, the iron content also rose significantly to a value of 11 ppm. The exact mechanism leading to this rise in concentration is unknown. However, it is possible that corrosion of the boiler surfaces during the extended test period may have been responsible to some extent. Over this period feed water iron content decreased significantly and thus excess iron in the feed water could not have been responsible. The iron content in the water samples was analysed by the Optical Emission Spectroscopy technique which has sufficient accuracy to discriminate the magnitude of the change in concentration indicated. Figures 34 to 36 show the condition of the boiler surfaces at the end of the repeat tests and comparison with Figures 32 to 33 indicates that significant corrosion had taken place. Both hardness and iron concentration in the boiler water fell to low levels by the end of the full power test. This may however, have been due to the excess boiler blowdown which took place during day 21 of the trial.

Due to the factors noted above, control of boiler water iron content during the full power tests was not as desired. Concentration varied from high (11 ppm) to low (0.2 ppm) levels over the duration of the test. The low level at the end of testing is difficult to explain, especially as the final concentration in the boiler was well below that of the feed water at the time of sampling. As samples were only drawn at the beginning and end of the test, however, the minimum level reached in the feed water supply during the period of excess blowdown is unknown.

The full results of water sample analysis are listed in Table 6.

Figure 37 shows that no fouling of the side loop heater took place whilst the heater power was held at 580 W. When the full power setting of 7000W was applied fouling commenced immediately and temperatures in the side loop heater rose at a rate similar to that noted during the earlier trials when fouling was apparent (see Figures 11 and 12). Figure 38 shows the fouled bore of the high flux heater.

Evidently, the ability of Device A to control fouling in regions subject to high heat flux levels is unpredictable and seems to be critically dependent on the composition of the feed water. The degree of variation of boiler water iron concentration during testing, however, means that correlation between iron concentration and fouling performance is difficult. At first glance it would appear that Device A is only effective when the iron concentration in the feed water is high. Whilst this may be true the mean iron concentration of the water within the boiler shell was in fact higher during the repeat tests than that occurring during the original trial.

The variation in performance of Device A with different feed water compositions does, however, reinforce the conclusion that magnetic water treatment devices must be assessed on an individual basis for any given installation. On the evidence of this test programme it would therefore be inadvisable to sanction the use of magnetic water treatment devices for steam boilers without carrying out such individual assessments.

Table 6 Water analysis results for original and repeat trials of Device A

Component	*Unit*	*Initial device trials*					*Repeat trials*				
		Feedtank		*Boiler*			*Feedtank*			*Boiler*	
		19.08.04	*17.09.04*	*26.08.04*	*09.09.04*	*17.09.04*	*22.11.06*	*7.12.06*	*15.12.06*	*7.12.06*	*15.12.06*
							1	*2*	*3*	*2*	*3*
pH		7.06	7.9	10.9	10.9	11.1	7.3	7.7	7.7	11	11
TDS	ppm	455	385	1610	1750	1750	66	170	220	1200	1100
Conductivity	uS/cm	651	564	2300	2480	2480	120	290	380	2100	1900
Total hardness	ppm $CaCO_3$	210	180	64	44	44	50	99	110	240	73
Total alkalinity	ppm HCO_3		240	182		182	30	90	100	52	44
Calcium	ppm		55.31	18.93		25.7	17	33	37	80	28
Copper	ppm		0.51	0.03		0.05	0.3	0.25	0.21	0.42	0.03
Iron	ppm		3.5	0.77		2.89	6.3	1.9	1.4	11	0.23
Potassium	ppm		3.66	30.55		33.69	0.57	2.6	3.7	34	39
Magnesium	ppm		8.68	1.68		4.2	1.7	3.9	4.7	10	0.61
Manganese	ppm		0.12	0.02		0.07	0.05	0.08	0.17	0.34	0.01
Sodium	ppm		51.24	402.1		462.1	5.5	26	33	370	350
Silicon	ppm		5.76	2.85		3.93	2	2.7	2.9	4.6	0.9
Chloride	ppm		50	390		410	6.3	29	37	450	390
Nitrite	ppm		<0.3	<0.3		<0.3	0.43	0.27	0.22	3.6	0.2
Nitrate	ppm		7.9	14		<0.5	1.1	0.57	0.85	13	4.6
Sulphate	ppm		14	140		120	21	30	36	190	230

6 CONCLUSIONS

(a) At low heat flux levels, such as those occurring in the boiler shell, insufficient fouling took place to enable the effectiveness of the devices tested to be quantified.

(b) In the high flux heater, a heat flux of 250 kW/m^2 produced significant fouling in a period of between 5 and 7 days operation with Devices B, C and D. A similar degree of fouling took place when operating with untreated borehole water.

(c) With Device A fitted, the high flux heater was able to operate continuously at 250 kW/m^2 until the test was concluded after a period of 28 days. No significant fouling took place during this period.

(d) A rise in the iron concentration in the feed water was noted during the trial of Device A. This may necessitate additional tests on the other devices using feed water with increased iron levels. Testing of Device A with low iron concentrations may also be required.

(e) During the repeat trials with different water composition, Device A was unable to prevent fouling of high heat flux regions. Due to variation of iron content during testing, it was not possible to correlate accurately iron concentration with fouling performance. However, it was shown that the effectiveness of Device A was highly dependent on the composition of the feed water.

(f) Extended duration trials of up to 14 months would be required to confirm the effectiveness of magnetic devices in controlling fouling in regions of high heat flux. Such trials would have to be carried out at the installation at which the devices were proposed for use. This would confirm safety of operation for a period corresponding to the boiler inspection cycle.

(g) Some corrosion of the heating surfaces was noted following all of the test periods. Whilst not excessive, this indicated a potential problem which may become significant in the longer term. Extended duration trials would be required to quantify the effects of using magnetic treatment without anti-oxidant chemicals.

7 RECOMMENDATIONS FOR FUTURE WORK

None of the devices examined performed well in reliably controlling the fouling of heating surfaces in regions of high heat flux. There may be an application for certain devices in low heat flux applications, but only if adequate corrosion control can be demonstrated. The manufacturers of Device A claim that oxygen scavenging is not required with their device if feed water temperature is held above 82 °C. These claims were not borne out in the tests. Longer term evaluation would be required to fully examine this factor. It is therefore recommended that Device A is fitted to an existing boiler plant, on-site in a hard water area. The effectiveness of the device in controlling both fouling and corrosion could then be assessed over a 14 month period. During this period the boiler should be operated on a normal duty cycle but without any chemical treatment of the feed water. For reasons of safety, however, boiler inspections should be undertaken at three month intervals throughout the test period and an additional overtemperature safety system installed.

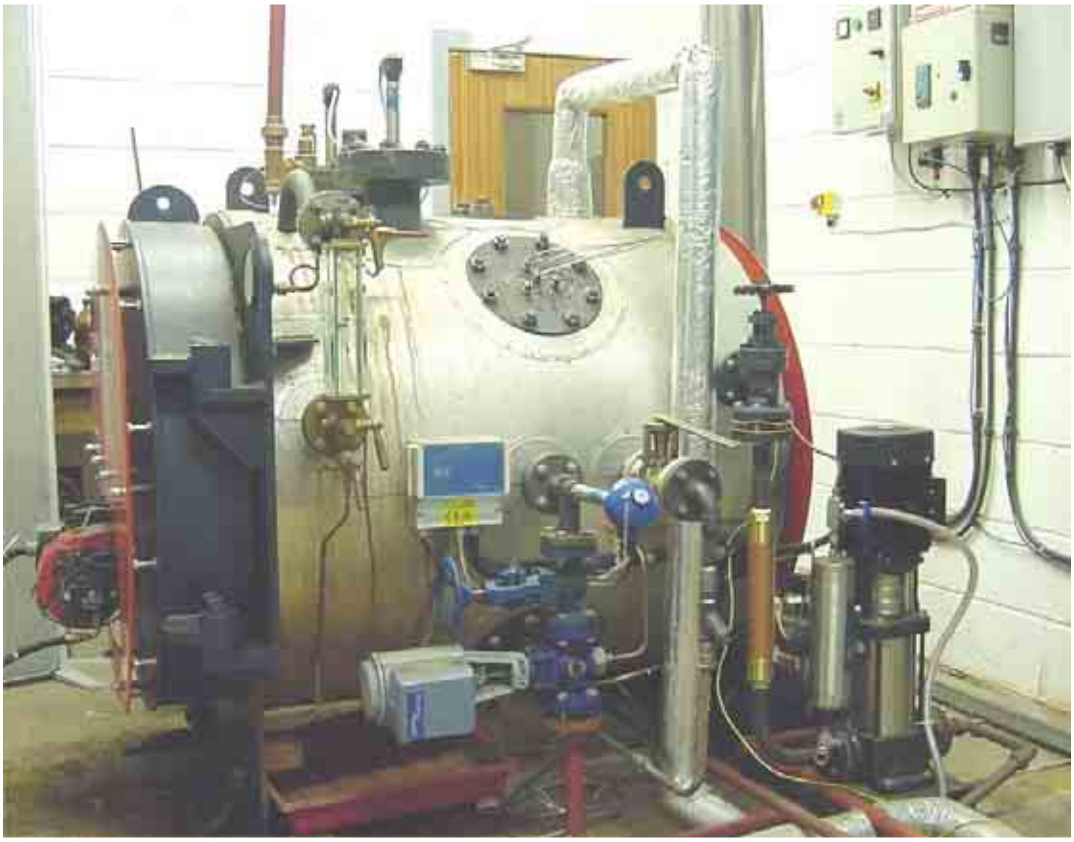

Figure 1 General arrangement of test boiler

Figure 2 View of boiler showing a thermocouple access port

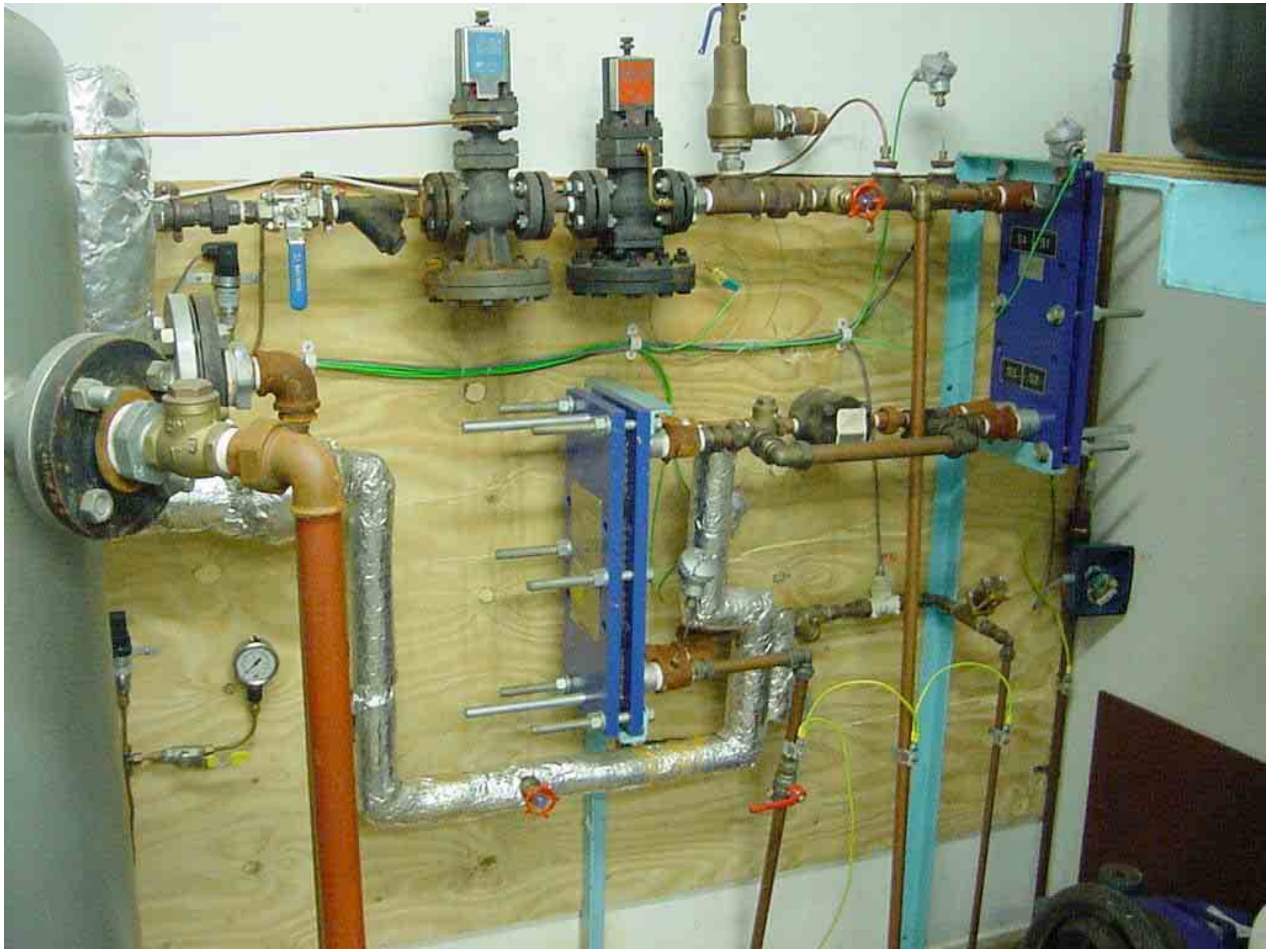

Figure 3 Steam control circuit components

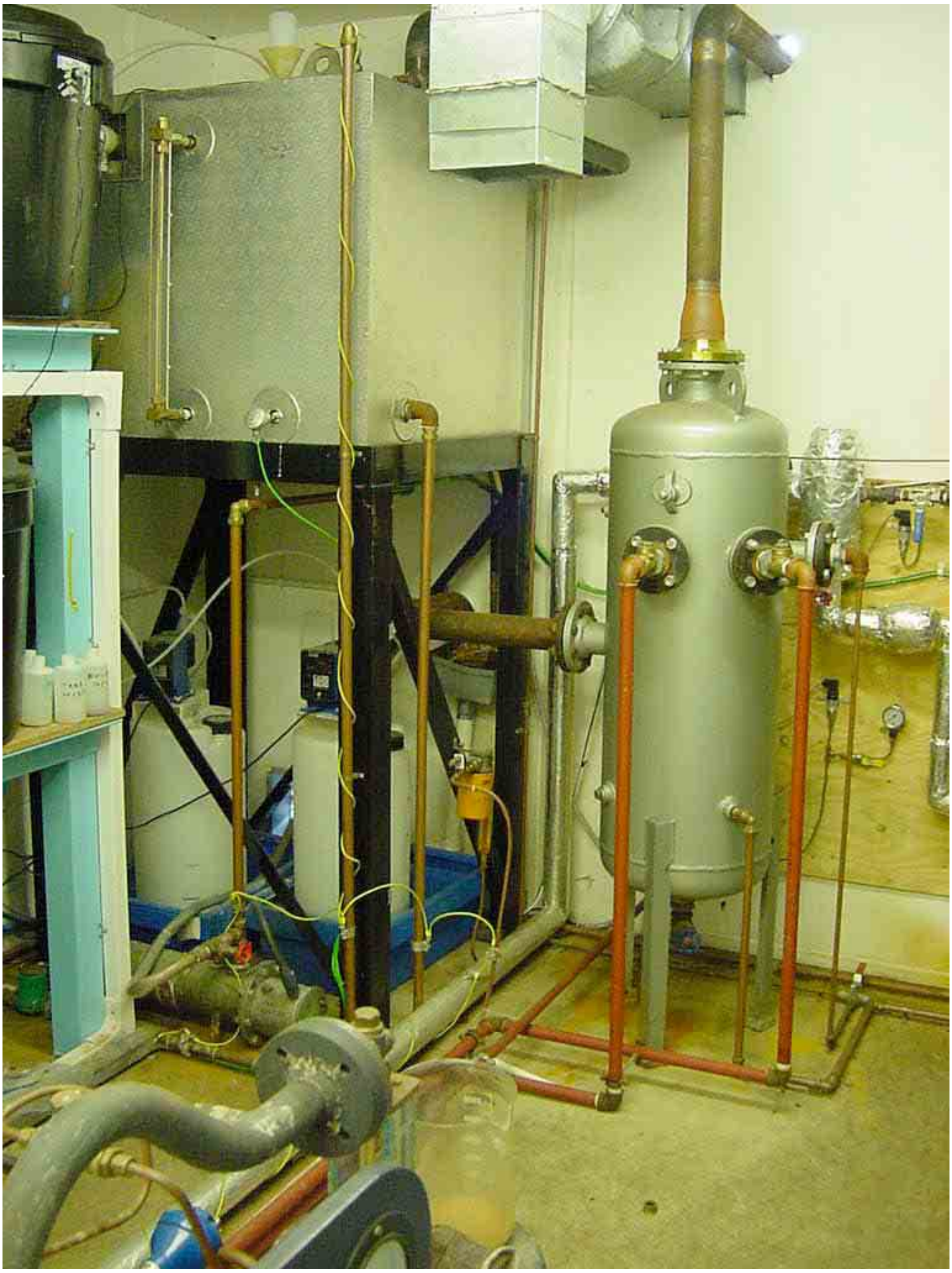

Figure 4 Feed tank, chemical dosing system and blowdown vessel

Figure 5 Water mixing tanks and borehole supply reservoir

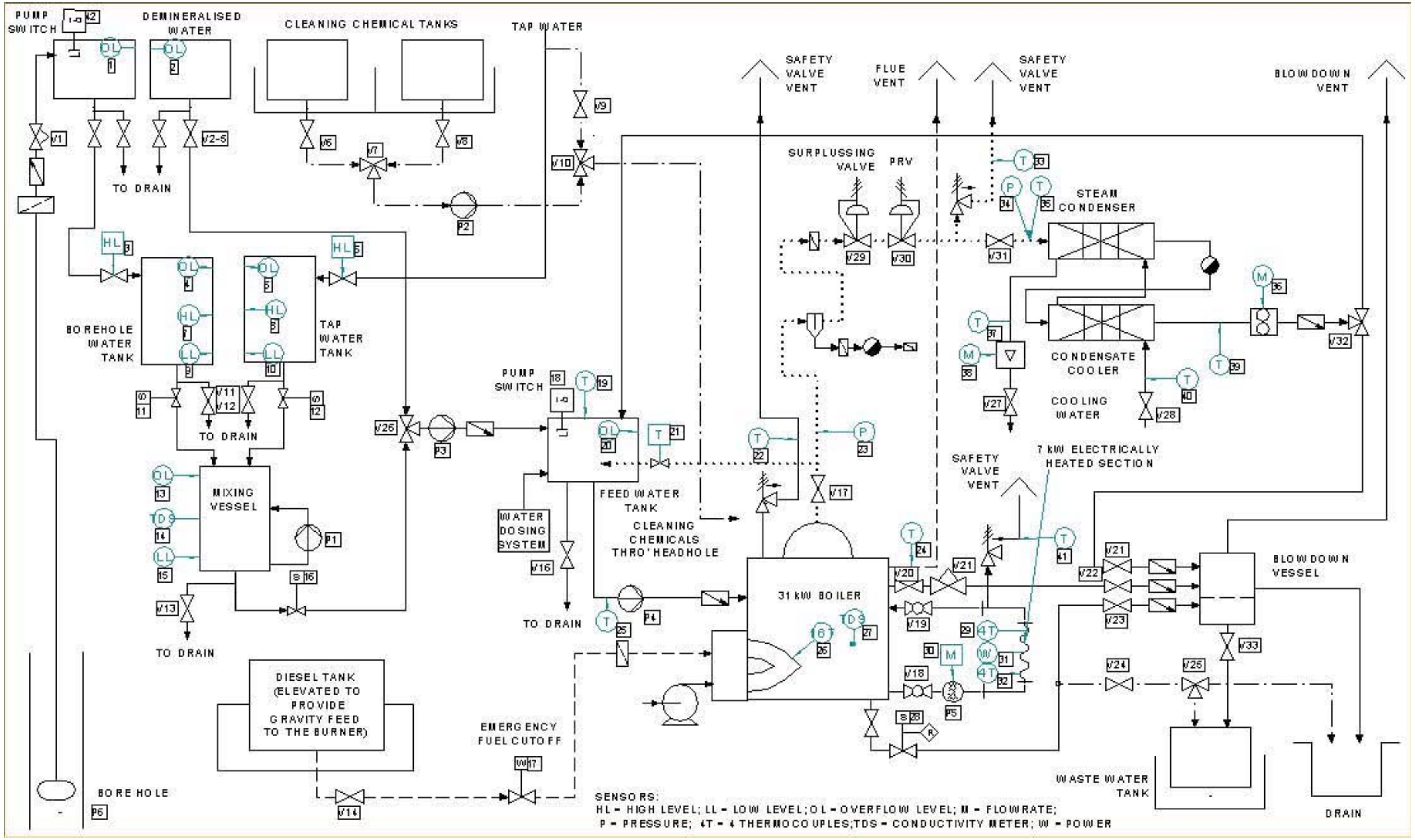

Figure 6 Service connections and steam circuit

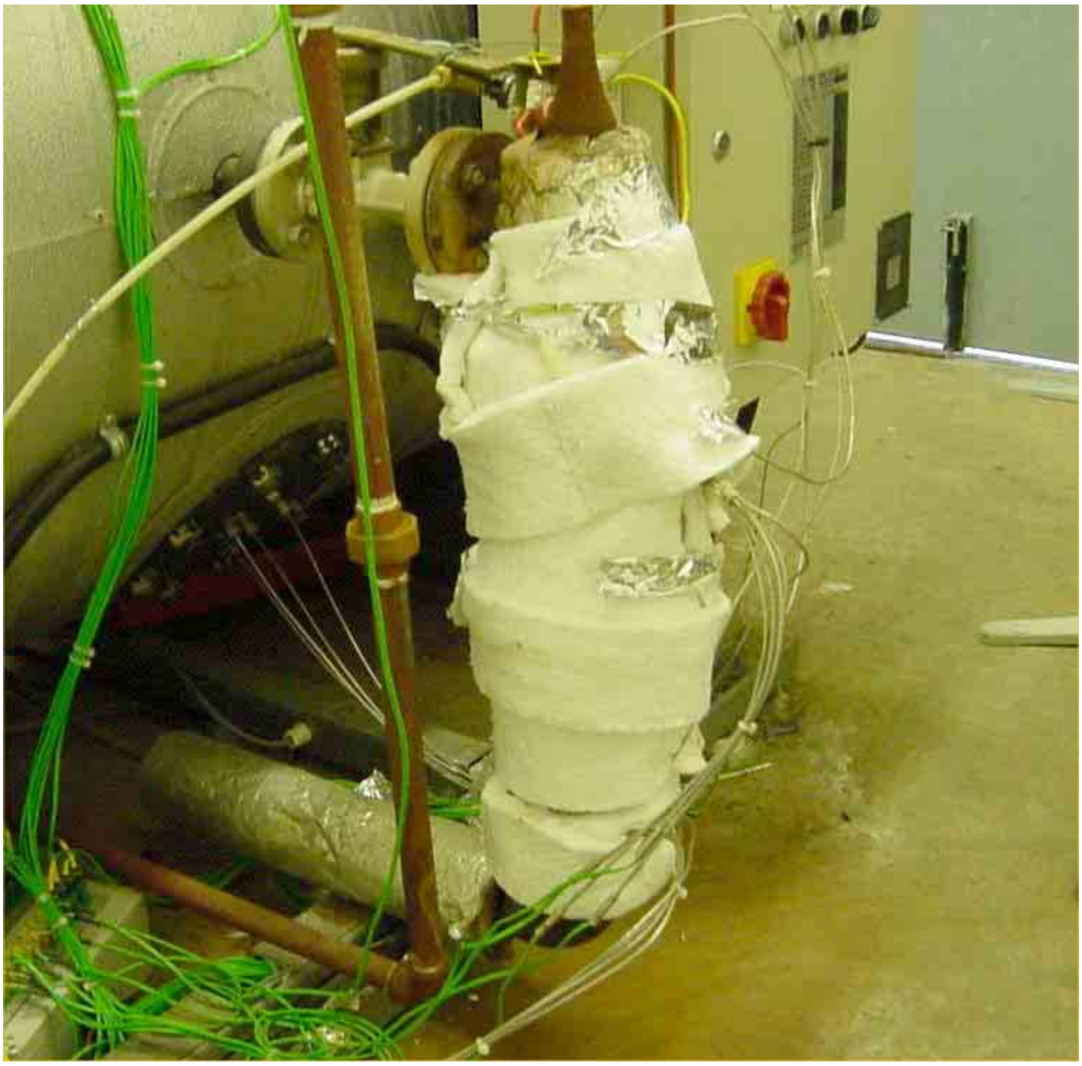

Figure 7 Electrically heated vertical tube section during application of insulation

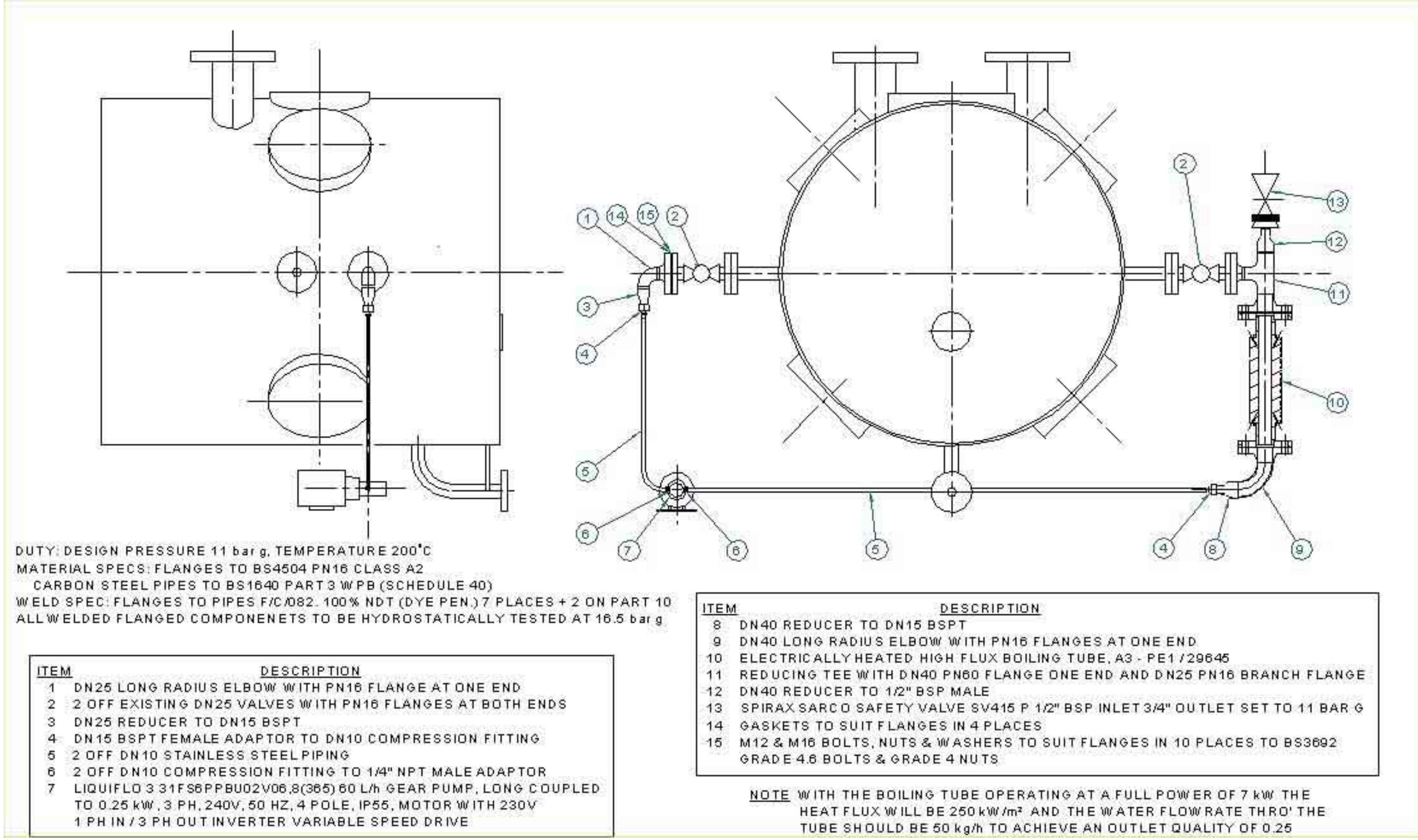

Figure 8 Arrangement of additional electrically heated section on boiler (high flux heater)

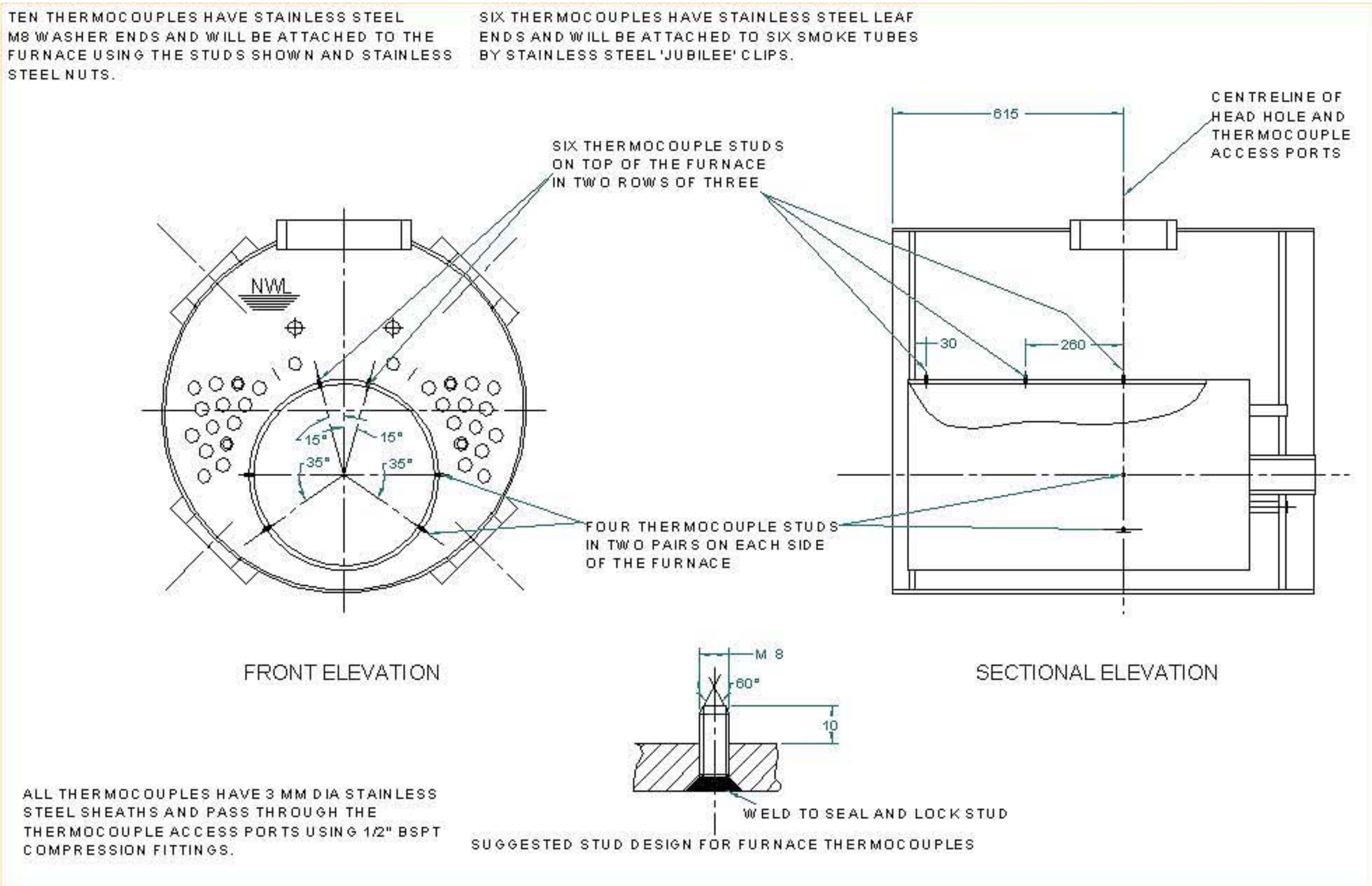

Figure 9 Thermocouple locations inside boiler shell

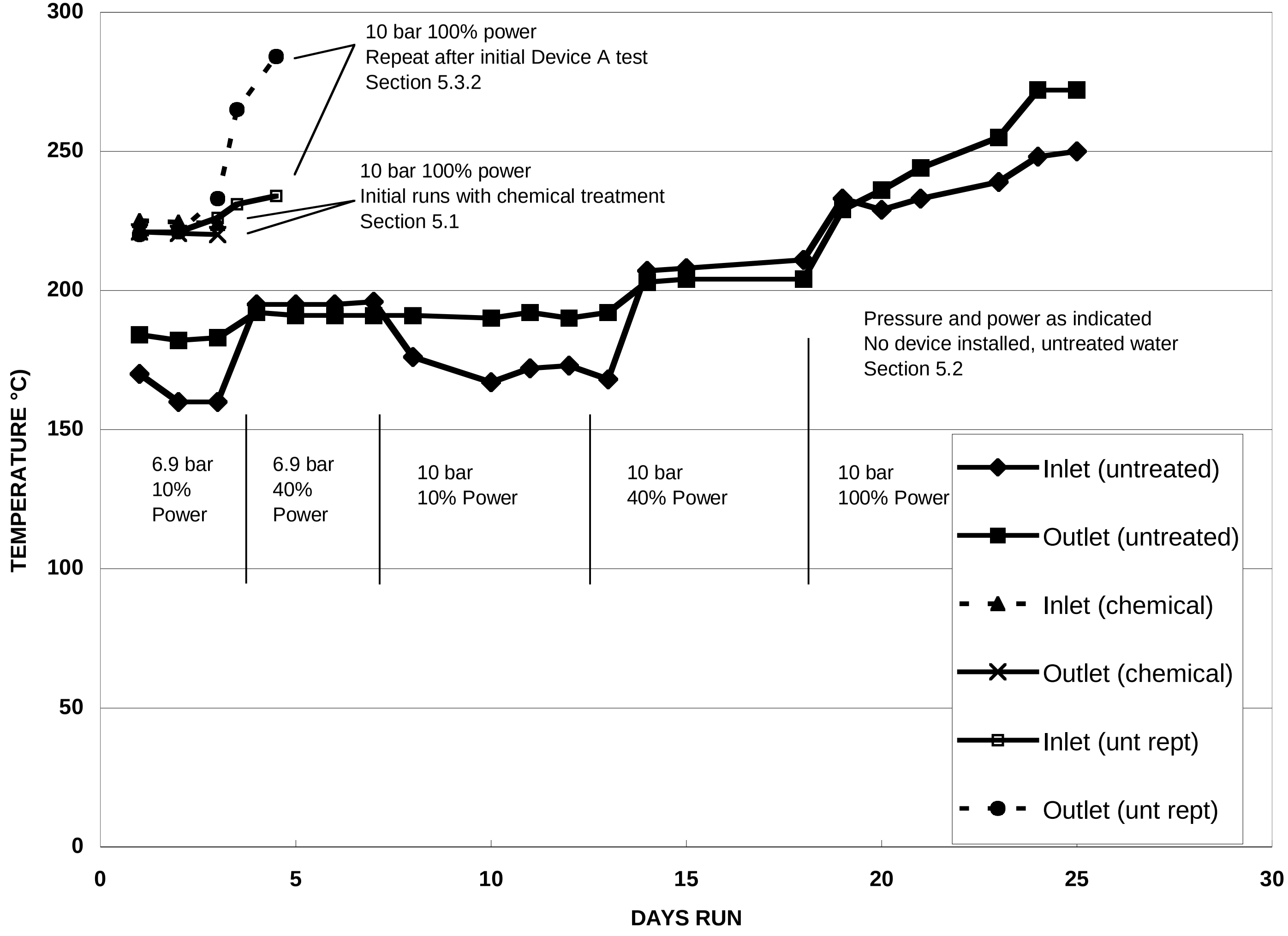

Figure 10 High flux heater wall temperature measurements at inlet and outlet

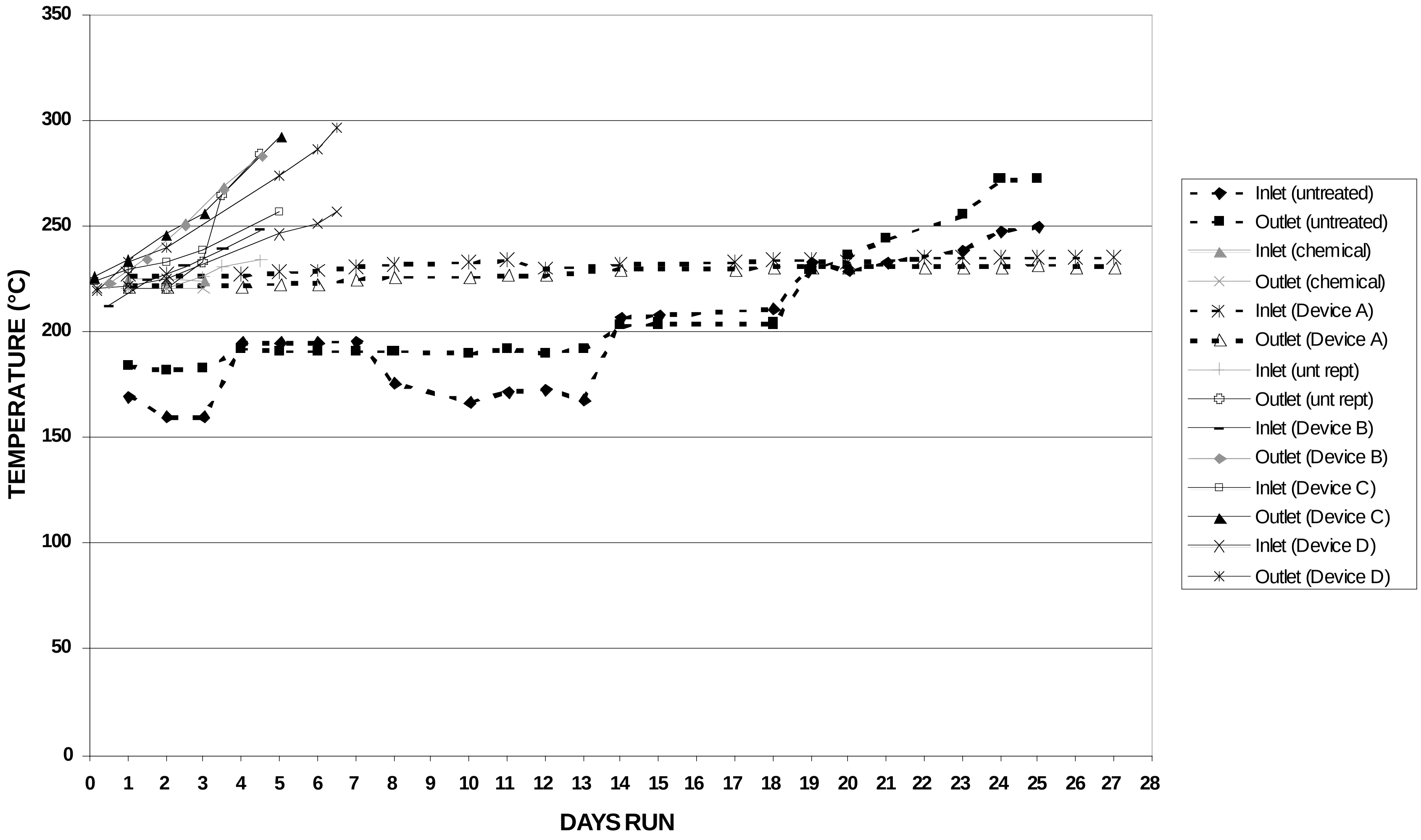

Figure 11 High flux heater wall temperature measurements at inlet and outlet

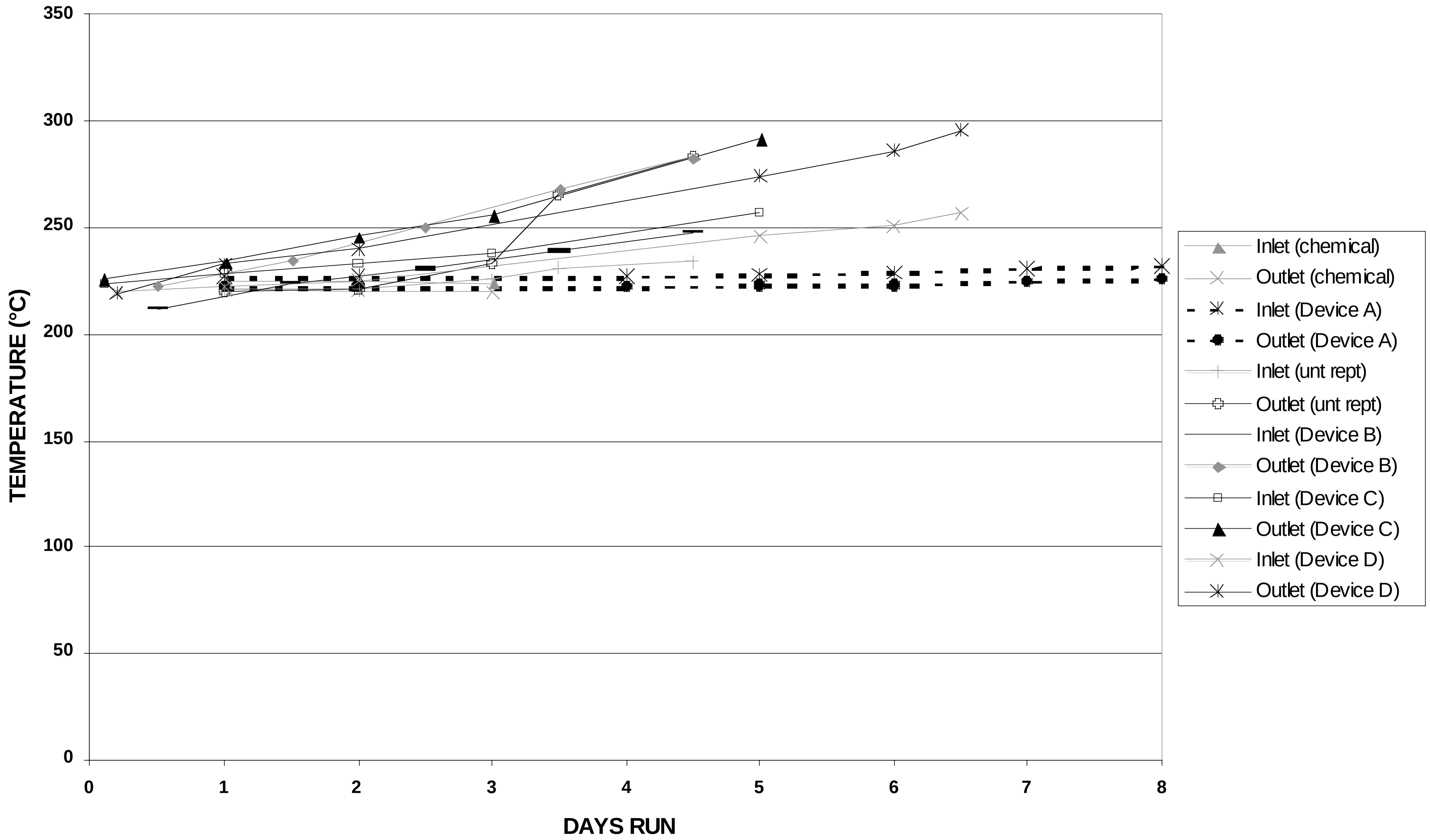

Figure 12 High flux heater wall temperature measurements at inlet and outlet

Figure 13 Smoke tubes prior to untreated runs

Figure 14 Smoke tubes after untreated runs

Figure 15 Smoke tubes prior to tests with Device A

Figure 16 Smoke tubes after tests with Device A

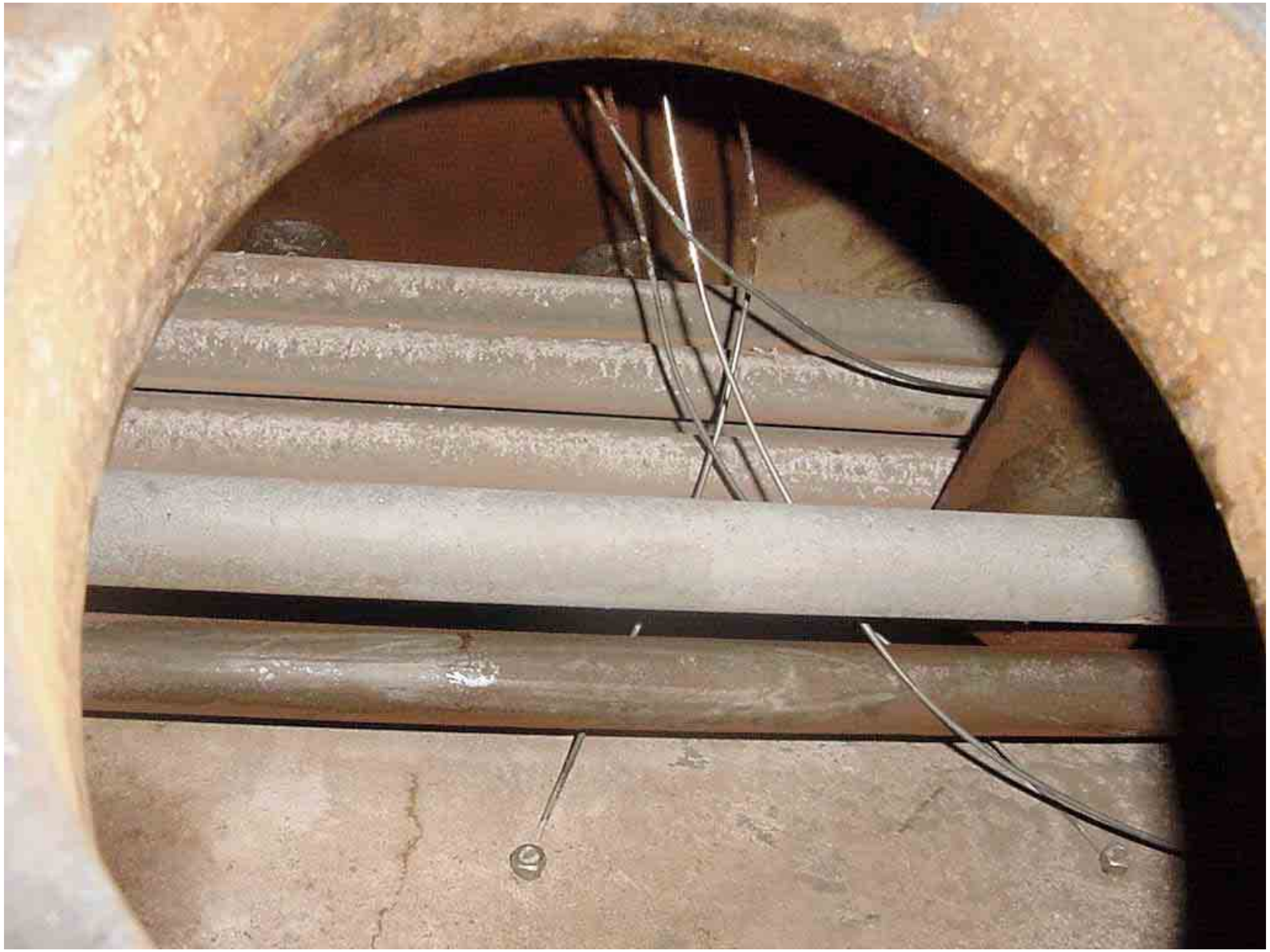

Figure 17 Smoke tubes before repeat runs with no treatment

Figure 18 Smoke tubes after repeat runs with no treatment

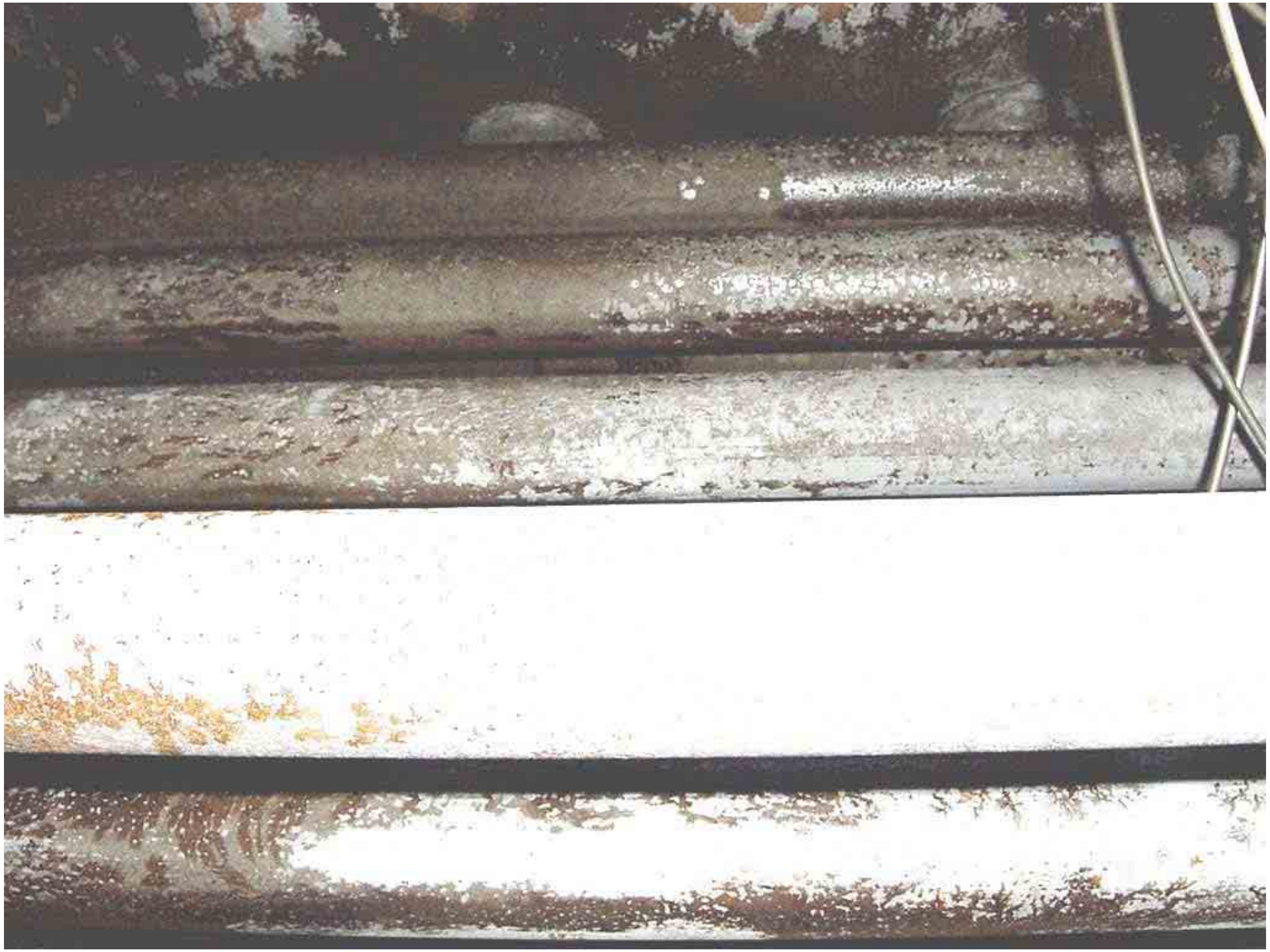

Figure 19 Smoke tubes before tests with Device B

Figure 20 Smoke tubes after tests with Device B

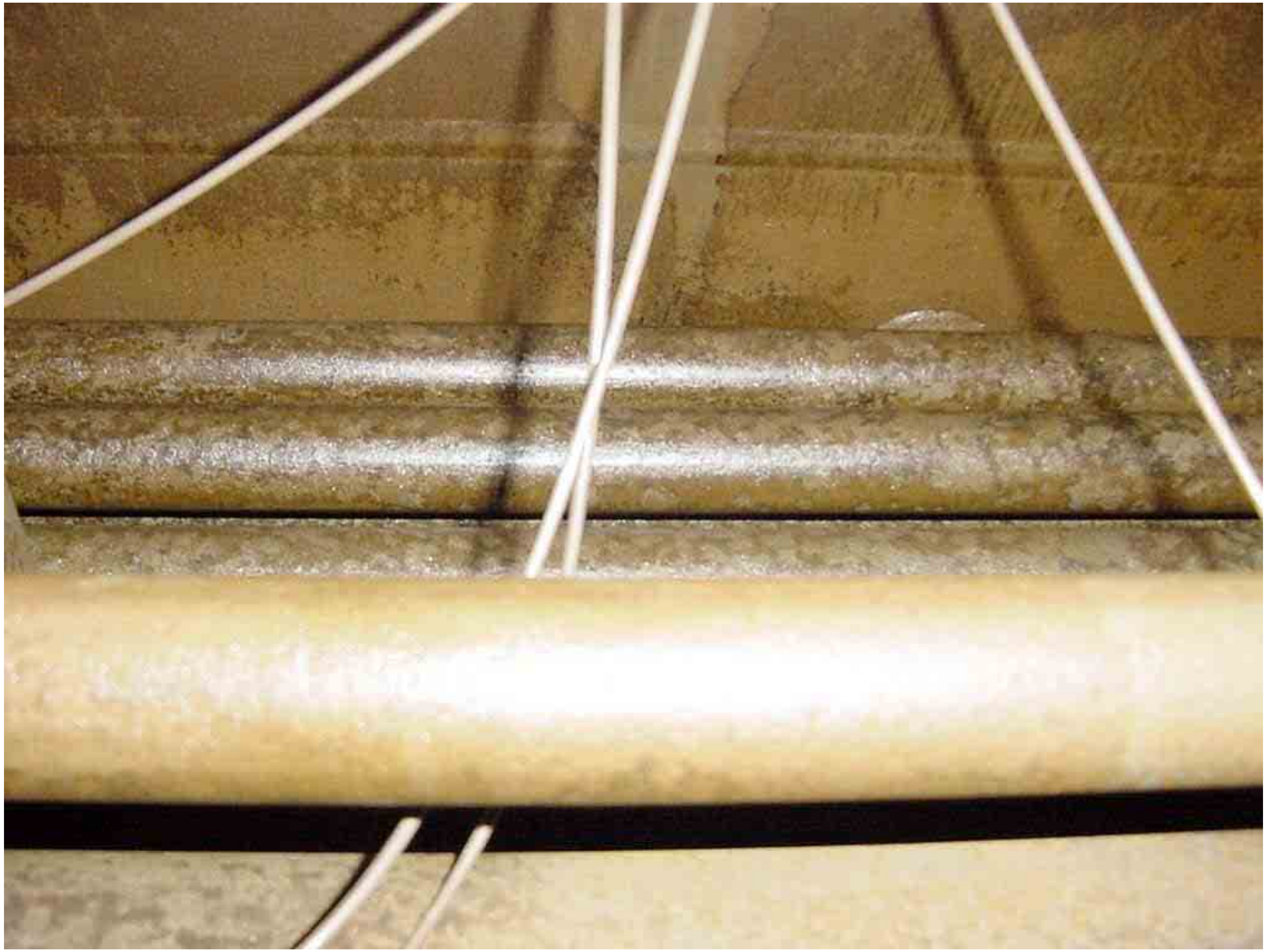

Figure 21 Smoke tubes before tests with Device C

Figure 22 Smoke tubes after tests with Device C

Figure 23 Smoke tubes before tests with Device D

Figure 24 Smoke tubes after tests with Device D

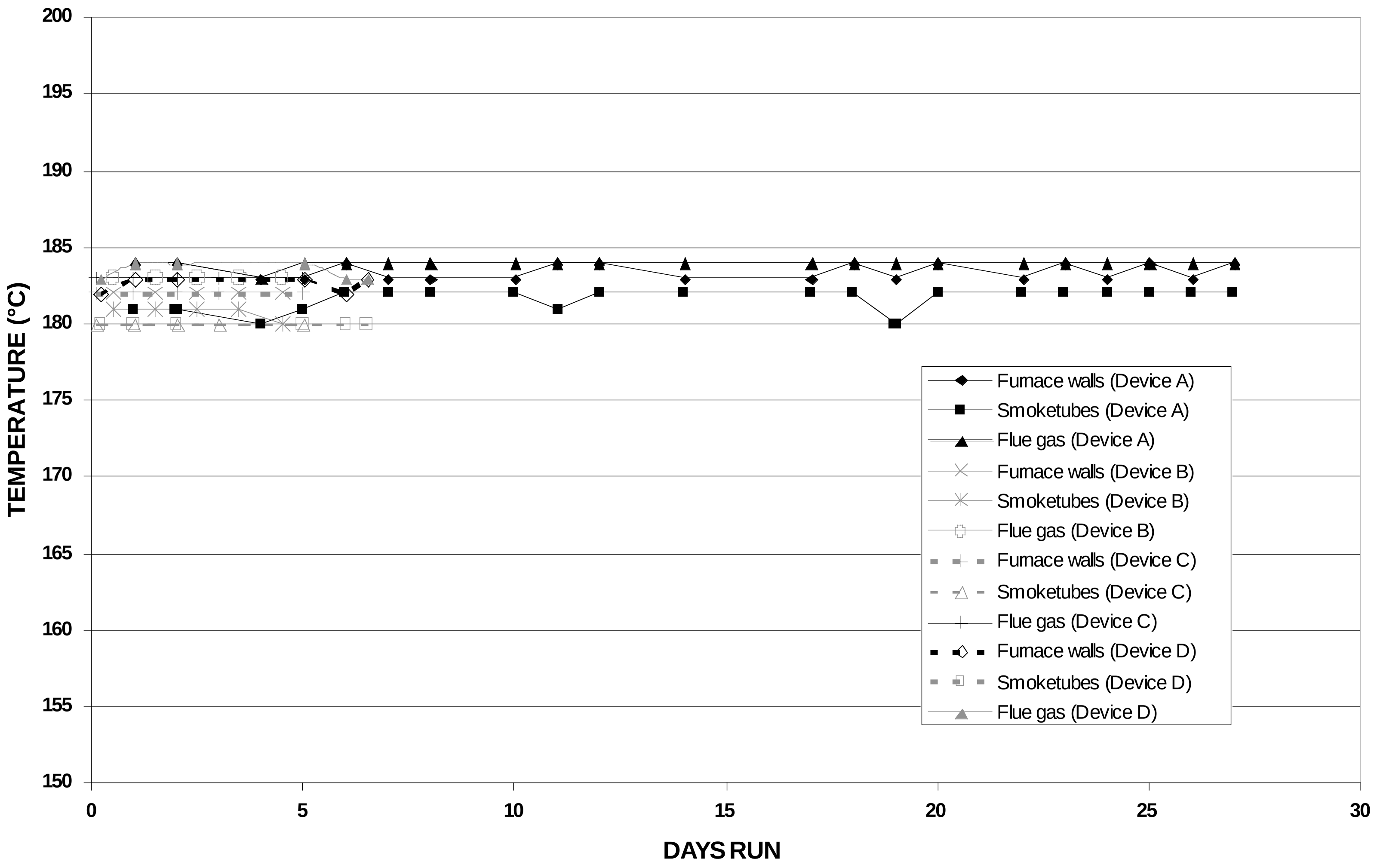

Figure 25 Boiler surface temperature measurements

Figure 26 Interior of high flux heater after untreated runs

Figure 27 Interior of high flux heater after trials with Device B

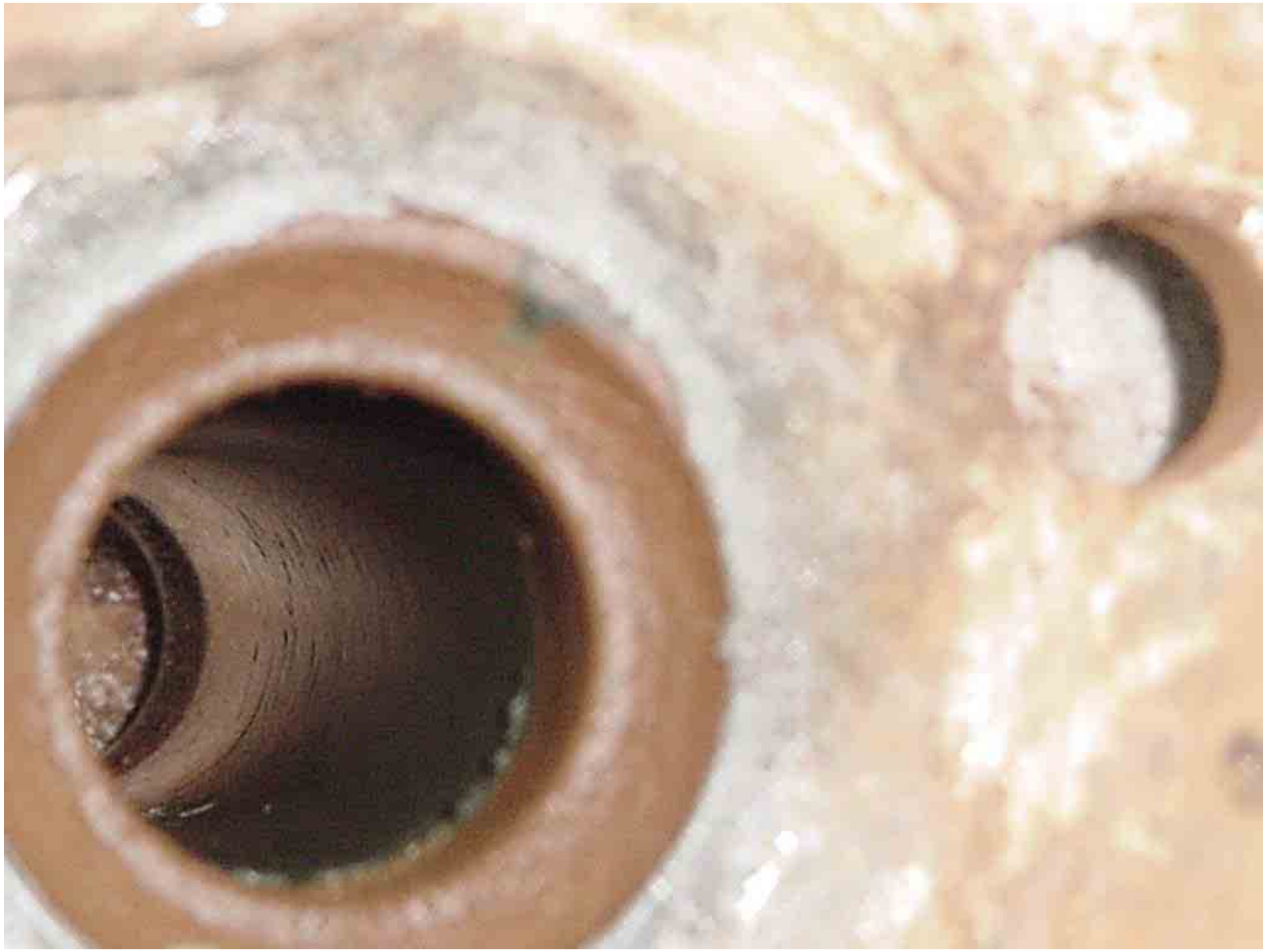

Figure 28 Interior of high flux heater after trials with Device D

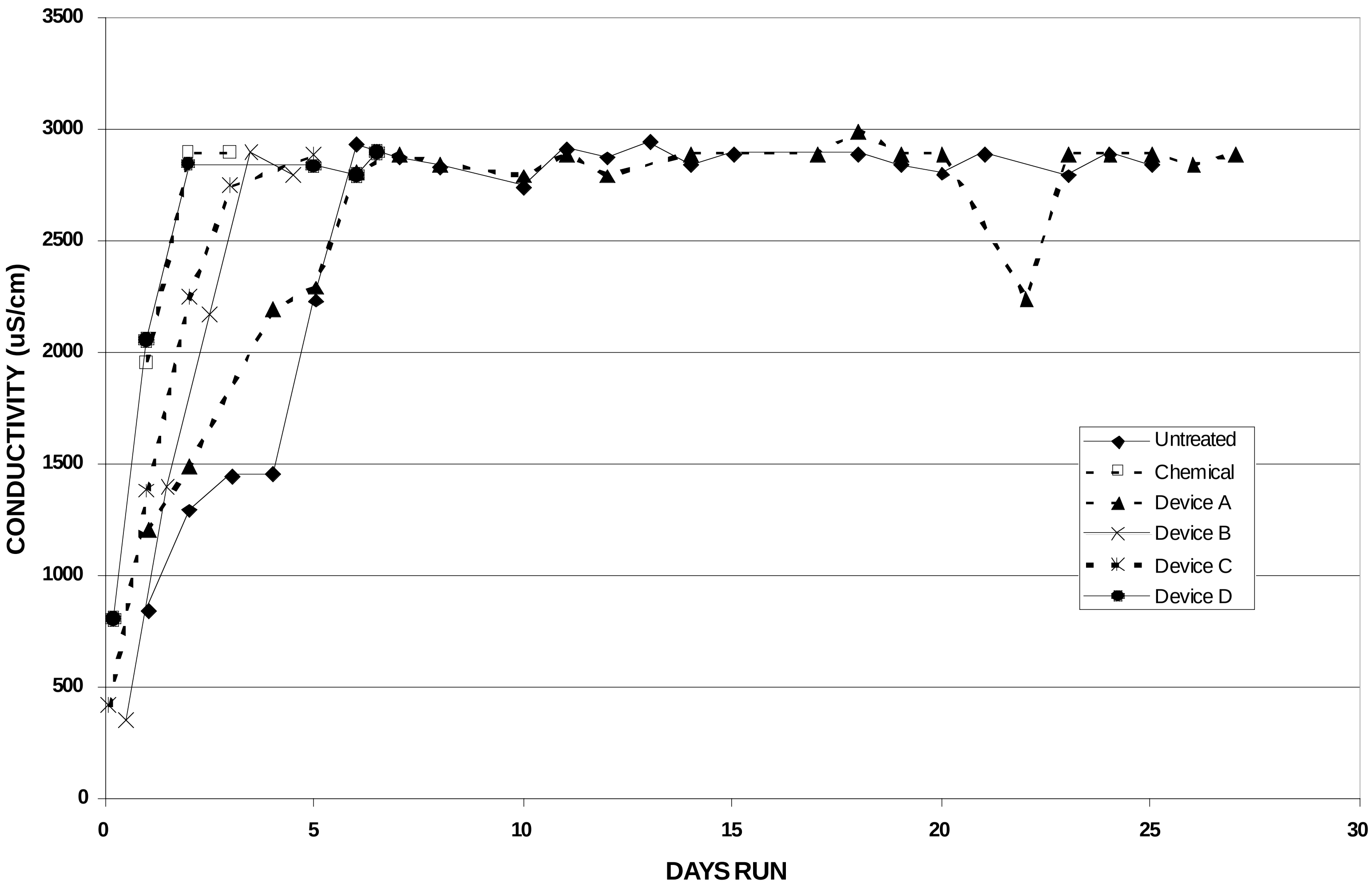

Figure 29 Boiler water total dissolved solids (conductivity) trends

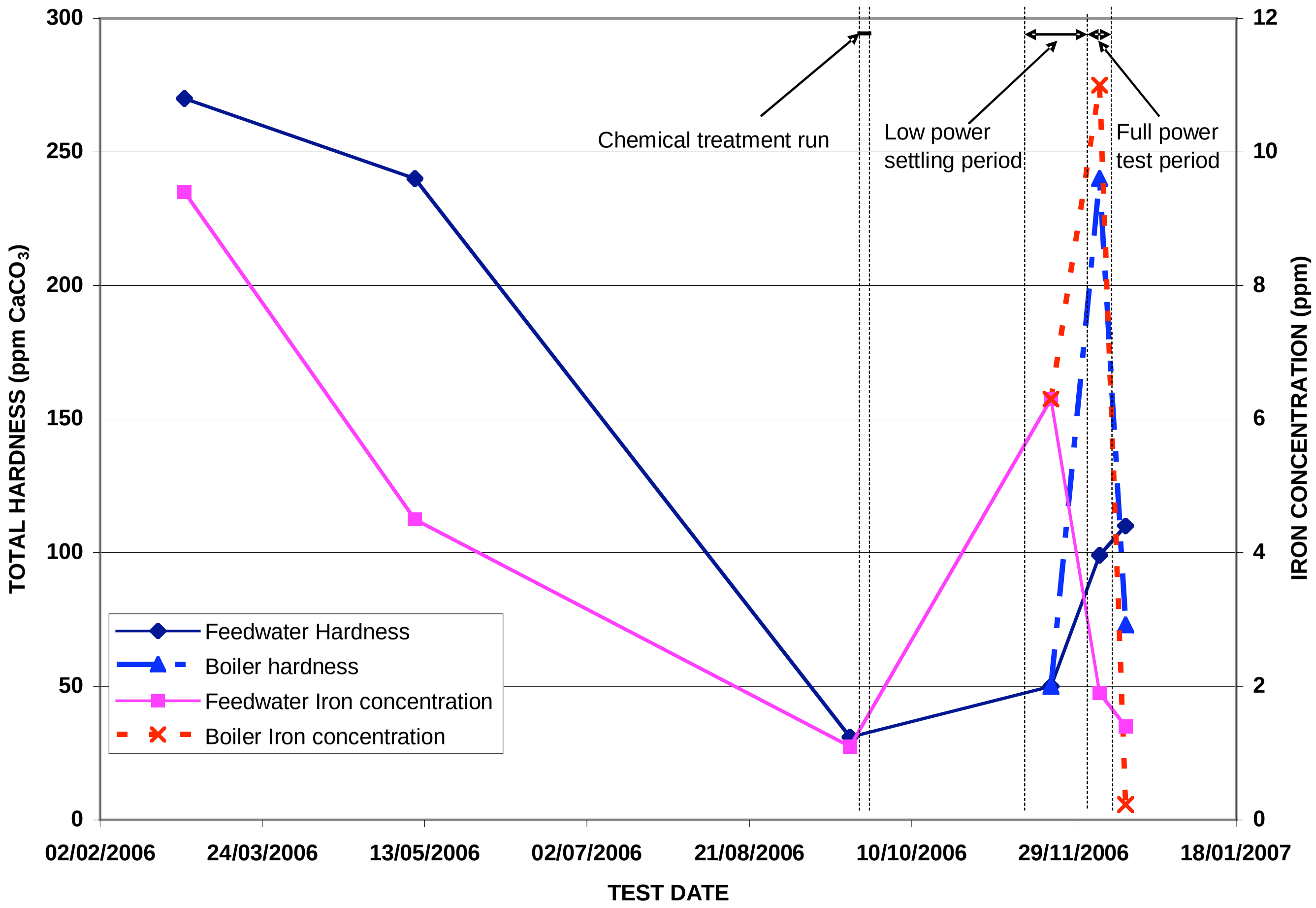

Figure 30 Variation in water constituents during repeat tests on Device A

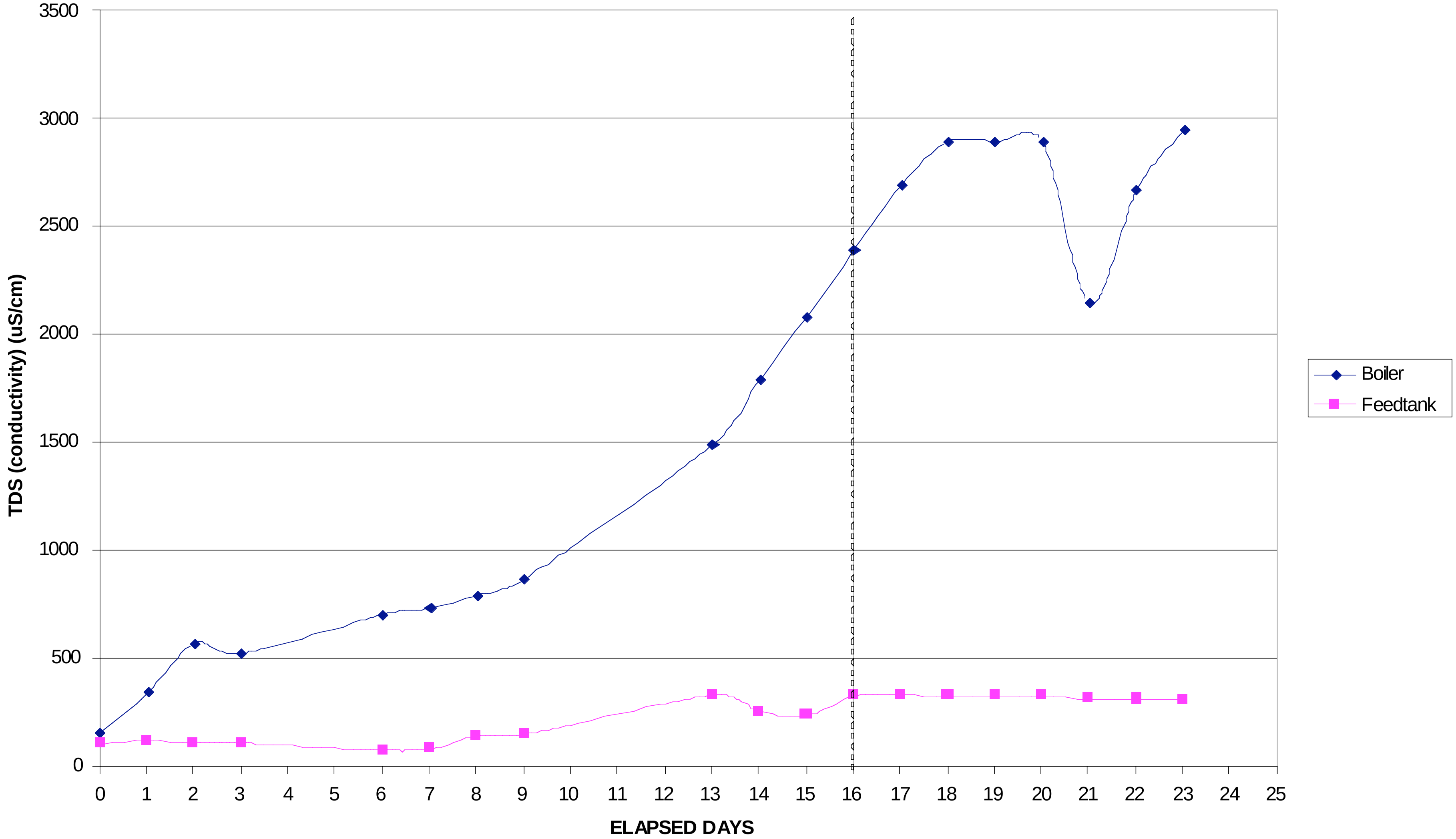

Figure 31 Variation in indicated tds levels during repeat tests on Device A

Figure 32 Cleaned boiler surfaces prior to repeat tests on Device A

Figure 33 Cleaned boiler surfaces prior to repeat tests on Device A

Figure 34 Boiler surfaces after repeat tests on Device A

Figure 35 Boiler surfaces after repeat tests on Device A

Figure 36 Close up of stay tube following repeat tests on Device A

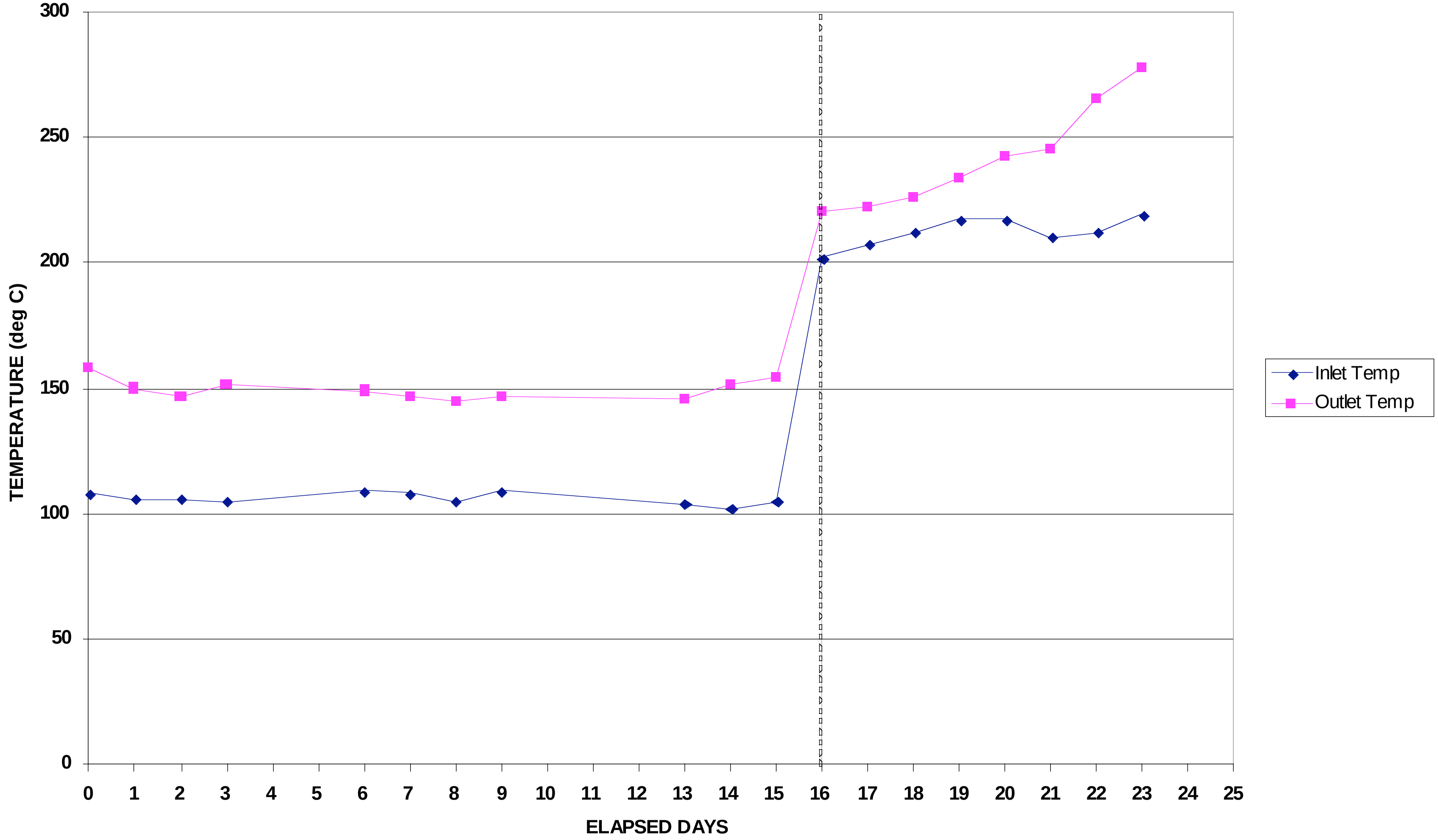

Figure 37 High flux heater temperatures during repeat tests on Device A

Figure 38 Fouled surface of high flux heater following repeat tests on Device A

APPENDICES

APPENDIX 1 PREDICTED THERMOSYPHON WATER FLOWRATES THROUGH THE EXTERNAL ELECTRIC HIGH HEAT FLUX BOILING TUBE LOOP

A1.1 INTRODUCTION

Figure 8 shows the arrangement of the electrically heated high flux boiling loop. Item 7 on the drawing was a positive displacement gear pump which the manufacturer claimed would handle boiler water at pressures to 11 barg. However, the pump failed twice after short periods of time and an alternative means of circulating boiler water through the loop had to be found. The reason a positive displacement pump had been specified was that the required small water flowrates could be metered by choosing appropriate pump speeds.

A1.2 NATURAL CIRCULATION

The water in a boiler shell is not pumped around the furnace or the smoke tubes because natural circulation provides sufficient water movement. Consequently the question arose as to whether natural circulation would provide adequate water flowrates through the high flux boiling loop.

Vertical shell and tube heat exchangers are often arranged in thermosyphon loops to heat process fluids in oil refineries and chemical processing plant. The Heat Transfer and Fluid Flow Service (HTFS) software, TASC 5, can simulate this arrangement and this software was used to model the high flux boiling loop.

A1.3 CALCULATIONS

The boiling loop was modelled with the correct pipe lengths, bore sizes and bends and the heat input to the water in the electrically heated boiling tube was assumed to be 7 kW. TASC 5 predicted that the water flow would be 330 kg/h with 12.6 kg/h steam mixed in with the water above the boiling tube returning to the boiler. That gave a predicted steam quality of 3.8% returning to the boiler.

The calculations were repeated with an orifice 1 mm thick and a bore of 2.6 mm fitted at the inlet to the boiling tube and TASC 5 predicted that with this significant extra restriction the water flowrate would reduce to 50 kg/h but the quantity of steam generated would remain at 12.6 kg/h. That is, the steam quality returning to the boiler would be 25%.

A1.4 CONCLUSIONS

The nominal bore of the smallest piping in the boiling loop was 10 mm and even if a restriction as small as 2.6 mm was included in the circuit the predicted water flow through the loop would be sufficiently large to prevent dry out in the high flux heater. It was concluded therefore that without any additional restrictions in the loop the high heat flux loop would operate safely and satisfactorily without a pump.

APPENDIX 2 PREDICTED MAGNETIC FIELD WITHIN THE ELECTRICALLY HEATED HIGH HEAT FLUX BOILING TUBE

A2.1 MAGNETIC FIELD CALCULATIONS

Calculations were carried out to estimate the likely magnetic field strength inside the tube of the electrically heated high flux boiling tube.

The boiling tube was 402 mm long with a bore 34 mm diameter. Two Thermocoax standard SEI 30/1000 3.5 kW heaters were wound into 2 start semi-circular grooves on the outside of the boiling tube. The heater coaxial wires were 3 mm diameter and the mean diameter of the two coils was 88 mm with an overall coil length of approximately 260 mm. The coils were connected so that the maximum 16 amp current through each coil was equal and opposite to the current through the other coil. In this way the magnetic fields induced by the coils would tend to cancel each other. However, the coils could not occupy exactly the same physical space and so small fields could be expected inside the boiling tube.

A convenient way of estimating the field strength inside the boiling tube was to make use of one of the worksheets from a Mathcad electronic handbook[A1] which is based on earlier published material[A2]. The worksheet describes the application of the Bio-Savart Law to Helmholtz coils and shows how the magnetic fields of two co-axial coils interact. Figure A2.1 shows the configuration.

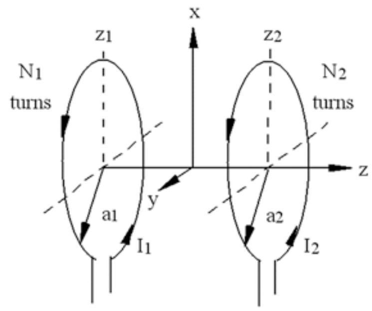

Figure A2.1 Co-axial electric coils

One coil from one boiling tube heater and one adjacent coil from the other heater were considered with opposite currents of 16 amps and the appropriate geometry. The worksheet calculated the field along the Z axis in the plane of one coil to be +0.018 gauss and -0.018 gauss for the other 3.2 mm away with a zero field mid-way between. This amounts to fields of less than 1/25th of the Earth's typical field of 0.5 gauss. It should also be noted that the boiling tube was machined from carbon steel which would shield the bore of the tube from magnetic fields.

A2.2 CONCLUSIONS

As a result of these calculations it was concluded that the electrically heated boiling tube would have a negligible magnetic impact on the boiler water.

A2.3 REFERENCES

A1 *Whites KW, Visual Electromagnetics for Mathcad*, Section 4.3, Problem 4.3.4

A2 *Paul CR, Whites KW, Nasar SA, Introduction to Electromagnetic Fields*, MacGraw-Hill companies Inc.

APPENDIX 3 MAGNETIC FLUX MEASUREMENTS TAKEN IN THE BOILER ROOM

A3.1 INTRODUCTION

The purpose of the measurements was to check the magnitude of the magnetic fields in the boiler room at various locations and compare these with measurements of the fields produced by the Magnetic Water Treatment Devices. The measurements were carried out using a Hirst GM05 Gaussmeter, Ser.No. GM5177, owned by EMC Hire Ltd, Item No. 1701. The measurements were taken with the axial probe, Type AP002, unless stated otherwise. A few measurements were taken with the transverse probe, Type TP002. The axial probe was 5 mm OD and the magnetic field density sensor was close to the probe tip. The transverse probe was 10 mm OD and the sensor was approximately 25 mm from the tip and so it was not possible to use this sensor for measurements close to a surface. The range of the instrument was from 2 μT (2×10^{-6} Tesla) to 3 T (that is 0.02 to 30,000 gauss). The uncertainties of the readings are ±0.35% with a 95% confidence level. It should be noted that the strength of the earth's magnetic field is approximately 0.5 gauss at the earth's surface that is equivalent to 0.05 mT

A3.2 HIGH HEAT FLUX HEATING COIL

Alternating electric current heats the two coils wound in a double helix on the heater. The current flow in each coil is in the opposite direction to the other coil. Axial direction alternating magnetic flux density measurements were taken in the centre of the coil, where the water flows, with full electric power applied and no discernable magnetic field could be found. An alternating RMS reading of 0.05 mT was obtained by touching the windings on the outside of the coil.

A3.3 BURNER BLOWER MOTOR

Touching the casing the highest AC RMS reading was 1.89 mT.

A3.4 FEED PUMP MOTOR

Touching the casing the highest AC RMS reading was 0.26 mT.

A3.5 HIGH HEAT FLUX GEAR PUMP

Around the gear pump the AC RMS reading was zero. Touching the motor casing the highest AC RMS reading was 2 mT. The gear pump was dispensed with once the tests on the magnetic water treatment devices were underway.

A3.6 FEED WATER TANK CIRCULATING PUMP

Touching the casing the highest AC RMS reading was 0.9 mT. By the circulating pump itself the highest AC RMS value was 0.07 mT.

A3.7 BOILER ROOM

The DC magnetic flux density readings taken at many points around the boiler room ranged between 0.24 and 0.29 mT.

A3.8 MAGNETIC WATER TREATMENT DEVICE A

The peak DC readings that could be obtained by touching the pole ends for the four large devices were 248.5, 264.5, 263.8 and 245 mT. The peak readings for the two smaller devices were 181.2 and 152.3 mT.

A3.9 MAGNETIC WATER TREATMENT DEVICE B

The peak DC reading that could be obtained by inserting the axial probe into the device was 123.1 mT.

A3.10 MAGNETIC WATER TREATMENT DEVICE D

The construction of this device was such that it was difficult to take any readings. The transverse probe registered a 0.343 mT DC peak which was little different from the background readings of up to 0.29 mT.

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Health and Safety Executive

Treatment of feed water for steam boilers using magnetic devices

Phase 3: Experimental Programme

HSE commissioned TUV NEL to investigate the treatment of feed water for steam boilers using magnetic devices. The key aims of the project were:

- to provide the HSE with an independent assessment of the ability of magnetic devices to treat feed water for shell or coil steam boilers; and

- to identify possible situations where magnetic devices could impair boiler safety.

The contract was divided into five phases the first of which was a literature search. The second phase was concerned with device selection in which suppliers of Magnetic Water Treatment Devices (MWTD) were identified and a judgement made of their engineering credibility and support capability. Magnetic treatment devices from four suppliers were recommended for evaluation.

This report describes the work carried out for Phase 3 of the project. This phase comprised the experimental programme executed to compare the performance of magnetic treatment devices from the four suppliers recommended in Phase 2. The chosen units were fitted to a test boiler system which enabled the effectiveness of the devices to be evaluated when operating across a range of boiler surface heat fluxes.

The device demonstrating the best performance was to be evaluated over a longer time period in Phase 4 of the work.

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