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ENERGINET.DK PROJECT NUMBER PSO 6520: "CORROSION MEASUREMENTS AT AMV2/AVV2 WITH BIOMASS DUST FIRING"; DONG ENERGY / VATTENFALL A/S: "FIRESIDE CORROSION TESTING WITHIN AVEDØRE UNIT 2 DECEMBER 2005 – JUNE 2006"

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SUMMARY

Biomass dust firing represents a considerable risk in terms of fireside corrosion of furnace and superheater / reheater tubing in utility boilers operating at high temperatures and pressures. The risk of severe or even catastrophic fireside corrosion rates at Avedore warranted the de-rating of the boiler and an associated considerable loss in efficiency. In order to examine the corrosion rates, a number of fireside corrosion probe exposures have been conducted within the Avedore Unit 2 boiler whilst firing a range of wood / fuel oil and gas blends, with differing levels of coal fly ash addition. The probes utilised a range of tubing alloys either already present in the boiler, or that were potential candidates for replacement tubing. The measured metal losses and associated wastage rates have been assessed with the conclusions from the test work summarised in this report.

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CONCLUSIONS

1. Corrosion of the various specimens can be characterised according to the type of material. Low alloy ferritic specimens suffered general metal loss forming duplex corrosion scales. Martensitic steels initially formed chromia scales which suffered irregular breakdown and wastage with slight subsurface attack and the growth of duplex corrosion scales. The austenitic stainless steels and the nickel based weld overlay also formed chromia scales that suffered isolated breakdown to give rise to pitting and internal attack, with duplex corrosion scale growth.

2. The specimens exposed at higher temperatures showed greater tendency for corrosion scale and ash interaction, with the outer scale being defective, loosing chromium into the outer scale and ash, and the finding of low levels of ash derived elements in the inner corrosion scales.

3. With the formation of duplex corrosion scales it would be most likely that corrosion rates would follow parabolic rather than linear kinetics, although rates would likely remain higher than would be the case without corrosion scale and ash interaction.

4. With the range of materials exposed, and the variations in coal fly ash additions, it has been impossible to quantify the effects of changes in fuel composition. However, in general, operation of the Avedore boiler with higher percentage blends of wood fuel resulted in greater wastage rates.

5. The higher alloy materials in general performed significantly better than the low alloy ferritic materials. Questions remain as to the performance of copper containing austenitic materials such as SAVE25 which performed worse than the TP347HFG when exposed at the highest wood fuel blend, but performed better when lower proportions of wood were fired. Careful consideration of the future fuel mix would be required prior to the selection of SAVE25 as an alternative tubing material.

6. No clear trends in ash compositions could be discerned with changes in fuel composition. Most ash deposits comprised mixtures of inert, alumino-silicate, coal fly ash derived particulate material, together with amorphous / sintered material containing greater proportions of alkali metals and sulphur. Only low levels of vanadium were found (<3%) in any of the ash examined. Trace levels of potentially aggressive elements including chlorine, zinc, arsenic and lead were occasionaly identified.

7. In comparison with the probe exposures conducted in the wood and straw fired Amager boiler, the Avedore specimens generally exhibited lower wastage rates, although the rates measured following the first exposure with the highest percentage wood content were greater and similar to those measured after exposure in Amager.

8. In comparison with the probe exposures conducted at pilot scale, the Avdore wastage rates were slightly lower than those measured after exposure to the softwood fuels, and substantially lower than those measured after exposure to the straw and hardwood fuels.

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1 INTRODUCTION

Between November 2004 and April 2005, a series of pilot scale fireside corrosion probe exposures were conducted in the 1MW$_{\text{Thermal}}$ Combustion Test Facility located at Power Technology. The research programme was jointly funded by ENERGI E2 and the Elkraft System, Project Number FU2203, "BIOMASS DUST FIRING" [1]. Subsequently, a series of short to medium term corrosion probe exposures has been completed within Avedore Unit 2 and Amager Unit 2 boilers, again whilst burning a range of biomass fuels either alone, or in combination with other fuels such as oil or gas. The tests conducted between December 2005 and June 2006 in the Avedøre boiler are reported in this document, whilst the tests conducted in the Amager Unit are reported separately [2].

2 TESTING, POST EXPOSURE EXAMINATION AND MEASUREMENT

Four batches of corrosion probes were exposed in the Avedore Unit 2 boiler between December 2005 and June 2006, these have been identified as batches 1, 1b, 2 and 3. The type and number of probes exposed is listed in Table 1. Exposure locations within the boiler were determined by availability of access ports in suitable positions (Figure 1). The furnace wall probes were located in the upper furnace section at 50.2m elevation, below the first stage of superheaters, 1.5m from the nearest soot blower. The superheater probes were positioned at two different elevations, 56.0m, below the final superheater, and at 59.6m, between the final superheater and reheater tube banks. Both superheater probe locations were 1.1m from the nearest soot blowers. Soot blowing was routinely conducted once per day during the probe exposures. No flue gas temperature measurements were made during the probe exposures. Test durations and fuel selection were outside of the control of the test programme and subject to the commercial operation of the power plant.

The fuels combusted during the corrosion probe exposures were not analysed and hence the composition was unknown. However, the fuel diet comprised blends of wood dust pellets, heavy fuel oil and natural gas. In addition, local to uppermost burners were injection points for the introduction of coal fly ash additive, used to modify the fouling and corrosion characteristics of the combustion environment. The proportions of the fuels and fly ash additions varied both between and during the tests. Average fuel input during the corrosion exposures expressed by thermal input can be seen in Table 2.

The first batch of probes were delivered to Avedore, installed and exposed by Power Technology engineers. Subsequent batches of refurbished probes were freighted to Avedore for exposure by ENERGI E2 / DONG Energy engineers. After removal from the boiler and allowing to cool, the test specimens were given a protective coating of cold curing epoxy or polyester resin, prior to return to Power Technology for laboratory examination.

A PC based data logging system was utilised that employed Isolated Measurement Pods (IMPs) to monitor the probe metal temperatures. The IMPS were located close to the corrosion probes, with the data returned to the logger using a single sheathed pair of cables. Unfortunately, the data logger suffered occasional failures during some of the exposures resulting in the loss of some temperature data. During the periods of missing data, it was known that the boiler remained in operation, and as such it remained possible to determine the total exposure periods and estimate sample temperatures.

2.1 Probe Technology

The probes were of the same design as that previously employed whilst fireside corrosion testing at pilot scale, with the exception of longer carrier tubes to permit access through the power station boiler wall [1]. The furnace wall type probes were positioned such that the specimen was flush with the gas side of the boiler furnace wall tubing. The superheater probe bodies were approximately 2m in length, permitting the samples to be exposed a minimum of 1m from the furnace wall.

A single furnace wall specimen was carried into the combustion environment on the front face of each air-cooled, precision metrology, corrosion probe (Figure 2). Each corrosion coupon was exposed to a specific metal temperature with the local environment being determined by the position within the boiler and the fuel fired. The utilisation of two thermocouples embedded at different depths in the specimen facilitated the determination of the temperature gradient through the sample. Further, extrapolation of this temperature gradient forward allowed accurate determination and control of the surface metal temperature. No attempt was made to measure the local gaseous environments during the probe exposures.

The superheater type corrosion probes each carried 10 individual corrosion coupons, which comprised various typical boiler tube materials (Figure 3). These were exposed to a range of metal temperatures and furnace environments as determined by location in the furnace. Cooling air was introduced through the centre tube to the end sample and passed along the internal surface of the samples before exhausting external to the boiler. The cooling air was heated as it traversed the samples, resulting in a temperature gradient along the length of the probe.

A broad range of alloy materials were utilised, the majority of which represented the existing materials employed Avedore Unit 2. In addition, alternative alloys that may find application in retrofitting or replacing existing stages were also used. These included X10CrMoVNb9-1 (T91), SAVE25 and IN625 weld overlay. The material nominal compositions, together with alternate designations, can be found in Table 3. The materials used to manufacture the specimens were standard boiler tube stock / weld overlays and all of the exposed specimens were manufactured with a surface ground, 0.4Ra finish.

The specimens exposed, together with the individual exposure times and temperatures, are shown in Tables 4 – 7. The measured probe exposure temperatures can also be seen in Figures 4 – 14.

2.2 Metal Loss and Wastage Rates

The short duration of the exposures requires that very accurate measurements of the metal loss be obtained in order to be able to discern differences in losses between specimens. Traditional methods of measuring the change in thickness of coupon samples after corrosion exposure, such as micrometer or weight loss measurements, do not posses the required accuracy and can not measure the extent of any internal attack. Further, utilisation of these methods would have resulted in the destruction of the corrosion and ash scales, preventing their characterisation.

Accordingly, metal losses were measured on polished metallographic cross sections using a digital image analysis technique, developed previously under a Powergen / EPRI Tailored Collaboration Programme, in which the corrosion scales and ash layers were retained [3].

Upon receipt at Power Technology, the corrosion probes were dismantled and the specimens mounted in cold curing epoxy resin. Once cured, the samples were sectioned perpendicular to their exposed and corroded surfaces, before grinding and polishing to a 1μm finish. Non-aqueous lubricants were used at all stages of specimen preparation, in order to prevent the loss of water soluble corrosion products and ash species.

In determining the furnace wall specimen metal loss, the technique compares the position of the corroded surface, as identified by a series of approximately 300 measurements across the flat disc specimen diameter, with a projected original surface position. The original surface position is determined by extrapolating a line between small sections of un-corroded, original surface at the edge of the sample that were protected from corrosion by an electroplated nickel coating. The total depth of attack is measured, including actual surface recession and any associated grain boundary or internal attack. Using this technique it has been shown that metal loss can be determined with an accuracy of ± 1μm.

Metal loss measurement on the cylindrical superheater type specimens are determined at up to 48 positions spaced 7.5° apart around the specimen circumference. Without an original surface reference, the preferred measurement technique determines surface recession by measurement of the internal scale thickness. Total corrosive attack is determined by the addition of any grain boundary or internal attack. Measurement of the internal scale thickness again enables a measurement accuracy of ± 1μm. Where the corrosion scale has spalled, metal loss determination falls back on the measurement of the specimen wall thickness, again by digital image analysis, and comparing this measurement with an original wall thickness made prior to exposure using a coordinate measurement machine. The latter technique possesses an accuracy of approximately ± 10μm.

The measured metal losses, together with the corresponding calculated wastage rates are shown in Tables 4 – 7. The superheater specimen metal mean parabolic wastage rates are further shown in Figures 15 - 18.

2.3 Ash and Corrosion Scale Characterisation

The retained corrosion scales and ash deposits on each of the specimens were characterised by optical microscopy, with types of attack (general, pitting, internal, etc) and ash morphologies (particulate or amorphous) recorded (Tables 8 – 16). Selected specimens were then further examined using Scanning Electron Microscopy (SEM), coupled with energy dispersive X-ray spectroscopic analysis (EDS). Back scatter electron images of those samples examined in the SEM are shown in Figures 19 - 39. The elemental composition as determined by EDS of the various phases identified in the SEM are presented in Tables 17 – 37. Note that, where no values are reported, the particular element was absent or below the limits of detection (approximately 0.2%). Associated with each table is a list of phases present within the ash deposit as implied by the x-ray analyses.

3 DISCUSSION

3.1 Alloy Composition

A wide range of alloy materials were employed in the corrosion probe exposures. These covered the normal range of chromium contents expected to be found in boiler tubing, with the 13CrMo44 material being the lowest specification alloy containing approximately 1% chromium and SAVE25 being the highest alloy grade containing approximately 23% chromium. With increasing chromium expected to provide the greatest improvement in corrosion resistance, a wide range in corrosion performance could be expected for the selected materials. The nickel based weld overlay IN625 would also be expected to perform well with a very good corrosion resistance due to its very low iron content.

Whilst chromium would be expected to have the greatest influence on corrosion resistance, other alloying additions made to improve creep rupture strength may have positive or negative effects. For example, copper additions have been associated with a decrease in corrosion performance in some aggressive environments [2].

Due to the anticipated improvements with increasing alloy content, the lower alloy materials were exposed only to lower metal temperatures, whilst high alloy materials were exposed to the higher metal temperatures. Whilst this strategy mirrors the material selection process in actual boiler design, it has rendered difficult the assessment of the effect of changes in metal temperature on the corrosion process.

The test materials used during the project can be divided in to four broad groupings:

- Low Alloy Ferritic Steels
- Martensitic Stainless Steels
- Austenitic Stainless Steels
- Nickel (weld overlay) Based Alloy

Regardless of the particular test exposures, or corrosion probe type, the type of corrosive attack suffered by each of these material groups can be summarised as follows:

The low alloy ferritic steels (1 – 2% chromium) exposed at relatively low metal temperatures, exhibited general, uniform wastage, in the process forming dense, duplex, predominantly oxide corrosion scales. The outer scales frequently incorporated particulate ash material, much of which was probably derived from the coal fly ash introduced to the boiler local to the burners. Given the dense, duplex nature of the corrosion scales, these would be expected to be protective, limiting further attack through formation of a diffusion barrier. As such, it could be expected that parabolic corrosion kinetics would apply, with apparent attack (or linear wastage rates) decreasing with longer exposure periods. As would be expected for low alloy steels forming protective corrosion scales at relatively low metal temperatures, the inner spinel ($(Fe, Cr)_3O_4$) scale retained the chromium from the alloy and contained little or no ash derived elements such as potassium or chlorine, whilst the outer scale comprised magnetite (Fe_3O_4) and embedded ash particles (alumino-silicates) (Tables 17,18, 20, 29 & 34).

The martensitic stainless steels (9 – 12% chromium) tended to be exposed at hotter metal temperatures than the ferritic materials. The chromium content of these alloys would enable the initial formation of protective chromia (Cr_2O_3) scale, although with continued exposure this breaks down readily to again give duplex, predominantly oxide scales. The irregular breakdown of the chromia scale gives rise to general, but irregular wastage. In addition, these materials frequently suffer slight internal attack of the steel under the solid internal corrosion scale, forming a feathered edge to the corroded surface. With the higher exposure temperatures for these materials there was greater risk of attack and dissolution of the (outer) corrosion scale by any aggressive ash species. Other indications of the more aggressive nature of the ash deposits at these higher temperatures are the inclusion of trace levels of potassium and occasionally chlorine within the inner corrosion scales, together with the finding of chromium leached from the inner scale into the outer corrosion scale and at low levels in the ash deposit (Tables 19, 23, 27, 28, 30 & 36). With the partial dissolution of the duplex corrosion scales it could be expected that lesser protection would be achieved

The austenitic stainless steels (15% or more chromium) were generally exposed at the highest metal temperatures. These again contain sufficient chromium that a highly protective chromia scale should be formed on initial exposure. In most cases, much of the exposed sample surfaces remained unaffected by the corrosive environment encountered in the boiler, with the chromia scale remaining intact and there being no observable corrosion damage. However, all of the austenitic samples exhibited localised breakdown of their protective chromia scales to give rise to pitting attack, with frequent internal attack below the pitting damage. Again, duplex corrosion scales were formed. However, the protection offered by the duplex scales was frequently reduced by the interaction of the outer scales with, in particular, amorphous ash deposits. This led to the outer corrosion products forming a defective, non-protective, dispersed oxide within the ash deposit. Analyses of the corrosion scales again confirmed the corrosive nature of the ash deposits, with traces of potassium and chlorine detected in the inner corrosion scales, whilst chromium was leached into the outer corrosion scales and ash deposits (Tables 21, 22, 24 - 26, 31, 32, 35 & 37). As above, the degradation of the corrosion scales would be expected to diminish their protective performance and greater wastage rates would occur compared to environments where no scale degradation occurred. Indeed, the occurrence of any significant pitting attack after exposures of austenitic materials for tens or hundreds of hours demonstrates the corrosive nature of the combustion environment with the fuels burnt. Ordinarily, in less corrosive environments, such as coal fired boilers, it would not be expected to find breakdown of the chromia scales and the formation of corrosion pitting after such short periods; an initiation period of several thousand hours is normal before any pitting would be identified.

The nickel based weld overlay material IN625 frequently finds application in aggressive boiler environments, such as chloride rich, waste or biomass boilers, where its high nickel and molybdenum contents and low iron content give rise to excellent corrosion resistance. As with the austenitic alloys it readily forms a protective chromia scale. In these trials, the IN625 material suffered only minor, isolated pitting damage, again with slight subsurface or interdendritic attack. Similar to the austenitic and martensitic steels, the inner corrosion scales formed within the corrosion pits contained high levels of chromium, and the outer scale and ash deposits also contained chromium removed form the inner scale. The inner scale also contained enhanced levels of niobium and molybdenum, together with traces of potassium and chlorine. In comparison to other samples the IN625 specimen from superheater probe 88 also exhibited relatively large (up to 3%) vanadium in the ash deposits and corrosion scales (Table 33).

The general observed trends as a function of alloy material and exposure temperatures are summarised in Table 38.

3.2 Metal Losses and Wastage Rates

As the corrosion specimens examined in this program exhibited at least partially protective, duplex corrosion scales, it would be reasonable to assume that parabolic rather than linear wastage rates applied. Parabolic wastage rates were determined according to the following equation:

$$K = M^2 / T$$

Where K = the parabolic wastage rate constant at a given temperature expressed as $cm^2.s^{-1}$

M^2 = the corrosion loss (total depth of attack) squared expressed as cm^2

T = the exposure period in s

In Tables 4 – 7, metal losses in microns have been converted to both linear and parabolic wastage rates. Comparing the 95th percentile (95%ile), maximum or mean measured metal losses for the first batch of probe exposures, with the later exposures, suggested that the first batch underwent substantially greater linear wastage rates than the specimens exposed during the later exposures. Indeed, the mean metal losses for the first batch where approximately half of that suffered by the second batch, despite the second batch being exposed for more than ten times the duration of the first batch. As suggested above, when comparing the superheater probe parabolic wastage rates, the differences are less extreme, although the rates obtained during the first batch of exposures, where generally higher than those obtained during the second batch, with the third batch again being slightly lower. In comparing the parabolic wastage rates for the furnace wall type corrosion probes there was little or no difference in wastage rate discernable between the first and second batch.

Despite the expected increase in corrosion rates with increasing metal temperature for a given material, it can be seen from the trends in Figures 15 – 17 that there was a general decrease in measured wastage rate with increasing metal temperature along the individual superheater probes as the higher chromium content alloys were exposed. Figure 18 also presents the mean parabolic rate data but for only the TP347HFG material which was exposed on each of the probes. In general it can be seen that the highest wastage rates were obtained during the first batch of exposures (probes 84 – 86). There was less difference between the second (probes 87 – 89) and third (probes 90 – 91) batches, although the third batch appeared to have suffered slightly lower rates.

It has been suggested above that minor alloying additions of copper, whilst good in terms of creep resistance, might be detrimental in terms of corrosion resistance. Comparison of the measured data for the copper containing SAVE25 specimens with adjacent TP347HFG specimens exposed at similar temperatures has shown that, during the first batch of exposures, the SAVE25 material performed relatively badly, despite it possessing a slightly higher chromium content. In contrast, during the second batch of exposures, the SAVE25 specimens exhibited a significantly better corrosion resistance than the TP347HFG specimens. As such, careful consideration of the future fuel selection would be required if SAVE25 were to be considered as an alternative alloy to replace any existing TP347HFG tubing.

3.3 Fuel Usage / Influence

As has been noted above, the Avedore Unit 2 plant load and fuel mixtures were determined by operational and commercial needs. As such, the timing and duration of the probe exposures were planned as far as possible to coincide with periods of operation with particular ranges of fuel blends. The initial Batch 1 probe exposures had been intended to operate for 50 hours to enable a comparison with the short term probe exposures conducted in Power Technology's pilot scale Combustion Test Facility, conducted during a previous biomass dust testing campaign [1]. Unfortunately, this initial exposure was stopped prematurely when the plant was brought off load. Later batches of probes achieved significantly longer exposures.

The previous pilot scale test campaign exclusively examined the corrosive effects associated with the combustion of a range of wood and straw dust fuels without the support of any oil or gas firing. In contrast, during all of the testing conducted at Avedore, blends of wood fuel pellets were combusted with differing percentages of heavy fuel oil and gas. It was understood that the wood pellets were produced from a range of wood sources and that together with the fuel oil, no chemical analysis were determined. However, in general it could be expected that the corrosive constituents of the wood fuel would be alkali metals (sodium and potassium) and chlorides or sulphates, whereas corrosion associated with heavy fuel oil would be due to the formation of molten vanadium or sulphate containing ash species.

From Table 2 it can be seen that for the later exposures there was a general trend of reduction in wood content and a corresponding increase in the heavy fuel oil content, expressed as a percentage heat content of the fuel blend. The coal fly ash addition rate also varied between tests. The variation in fuel blends would imply a greater corrosive influence from the wood / biomass derived ash species during the first test, with an increasing influence of the typical vanadium or sulphatic ash species derived from the fuel oil in the latter tests. Variations in blend ratios within particular test exposure periods may have complicated this further.

As noted above, the highest wastage rates were determined after the initial batch one set of probe exposures, implying that the higher wood content ($52.8\%_{\text{thermal}}$) in the fuel during this exposure period played an important part in the corrosion mechanism. The reduction in wood content to $35.1\%_{\text{thermal}}$ during the second batch of exposures yielded a significant reduction in wastage rates, although the further reduction to $16.3\%_{\text{thermal}}$ during the third batch exposures did not yield much further reduction in wastage rates. Whilst changes in the fuel make up would likely have a large influence on the corrosion rates, it remains possible that the changes in the rate of coal fly ash addition may also have contributed to the changes in wastage rates. It has been impossible from the current set of exposures to determine the relative effects of fuel blend and ash addition. However, it can be seen that the highest rates occurred after the first batch of probe exposures, where the greatest percentage of wood was fired, and the lowest coal fly ash additions were made. Similarly, it can not be determined whether there would have been a greater reduction in the wastage rates during the final batch of exposures if the coal fly ash addition rate had remained high at approximately 6 tonnes par hour, rather than the 4.3 tonnes per hour actually achieved.

Whilst changes in fuel blends and coal fly ash addition rates would be expected to alter the composition of the ash in the boiler, neither the optical or SEM and x-ray analysis examinations showed any obvious consistent changes in ash appearance or compositions. Many samples reportedly retained little ash on removal from the boiler, prior to encapsulating with resin. However, the general trends in ash morphology and composition could be discerned.

All of the samples exhibited ash which contained a large proportion of solid, spherical particles, which, when analysed, predominantly comprised various alumino-silicate, inner materials. Other particulate materials present included calcium sulphate, magnesium phosphate, iron oxides and mixed barium / titanium oxides. Much of the particulate material was believed to have originated from the fly ash additions local to the burners, and would be considered inert, providing a dilution effect for other more aggressive ash species. Calcium phosphate (DCP) was used as an additive in the previous pilot scale test exposures to modify / reduce propensity for slag formation, and reduce the corrosive effects of the deposited ash [1]. Whilst the phosphate in the Avedore samples was predominantly associated with magnesium, it could have a similar effect to DCP.

The hotter specimens from the superheater probes also frequently exhibited amorphous or sintered ash deposits which were most probably at least partially molten during the exposure. This ash material tended to include higher percentages of potassium, sulphur and phosphorous when compared with the bulk, general ash compositions, although the alkaline earth elements magnesium, calcium and barium were also detectable within this ash mixture.

Despite large differences in the proportion of fuel oil combusted during the different exposures, there was little variation in the quantities of vanadium deposited in the ash. In virtually all samples examined the vanadium concentrations remained below 1%, with the only exceptions being from the second batch of exposures, where up to 2.5% vanadium was identified in the particulate ash material, with up to 3% identified in the mixed scale and ash retained on the IN625 weld overlay specimen from superheater probe 88. These vanadium concentrations are much lower than that which would be associated with the formation of molten and aggressive vanadyl-vanadate ash deposits.

In general, the ash deposits were very complex comprising, numerous elements. Both beneficial elements such as the alkaline earth metals (Mg, Ca & Ba) which raise ash melting temperatures were identified, together with detrimental elements such as the alkali metals (Na, K) which, when associated with sulphur, tend to lower ash melting temperatures. Trace levels of other elements including zinc, arsenic and lead could also be identified, with these latter elements also having the tendency to reduce ash melting temperatures. Low levels of chlorides could also be detected in many ash deposits, but there were no obvious concentrations of this aggressive element detected in the corrosion scales or at the scale metal interface.

3.4 Comparison of Wastage Rates When Co-Firing Straw And Wood

A parallel corrosion probe study was conducted at Amager power plant with a single batch of two superheater type corrosion probes (95 and 96) exposed for 442 hours in Unit 2 from mid March until the end of the heating season on 31st March 2007. The results of this test are reported separately [2].

The fuel utilised at Amager was substantially different to those examined during the probe trials at Avedore. Whilst the Avedore fuels contained varying quantities of wood, heavy fuel oil and gas, together with the coal fly ash additive, the Amager fuel essentially comprised two thirds wood pellets and one third straw, with only minimal (<0.1%) heavy fuel oil. The two corrosion probes employed similar specimen material combinations as that used during the first two batches of probe exposures at Avedore, although the more recently sourced Sanicro25 material replaced the SAVE25 material used in the earlier Avedore tests.

In general, the mean measured parabolic wastage rates for the ferritic materials exposed at Amager were comparable with the high rates observed during the Avedore batch one exposure. The austentic materials exposed in the second pass at Amager to relatively low metal and gas temperatures / heat fluxes, exhibited wastage rates comparable to the lower rates measured in batches two and three from Avedore. The austenitic materials exposed in the first pass of Amager to higher metal and gas temperatures, exhibited generally higher wastage rates, with the Sanicro25 specimen in particular suffering the greatest rate measured for any of the specimens in either boiler (Figure 40).

The ash deposits retained on the corrosion probes from Amager were significantly larger and comprised a solid mass rather than the friable, powdery ash deposits from Avedore. When examined optically and in the SEM, the ash deposits were found to predominantly comprise dense, solid potassium sulphate with lower levels of other typical ash derived species. Discrete particles rich in chlorine were occasionally identified associated with potassium.

SEM examination of the severely damaged Sanicro25 specimen revealed it to have suffered subsurface and grain boundary attack, in places leading to exfoliation of the surface metal grains. The copper containing Sanicro25 material performed significantly worse than the adjacent TP347HFG samples exposed at similar temperatures, this despite it possessing a higher chromium content.

3.5 Comparison of Pilot and Full Scale Plant Studies

For comparison purposes, Figure 41 shows the mean parabolic wastage rates for the samples previously exposed whilst firing a range of biomass dust fuels after short term, nominally 50 hour exposures in the pilot scale Combustion Test Facility [1]. As with the plant based exposures, the probes utilised a range of alloy material similar to that used in plant, with the low alloy materials exposed at the lowest temperatures. Whilst difficult to observe due to the expanded y axis, the data for the Estonian and Canadian softwoods and the Junkers wood blend + additive (DCP) fuels are only slightly higher than that for the highest rates after exposure in Avedore or Amager. In contrast, the pilot scale data for the Junkers Hardwood and straw based fuels were significantly greater than any of the power plant based exposures.

All of the fuels used at pilot scale were burnt with out any oil or gas support, and without any coal fly ash injection. The softwoods had very low ash content and were relatively benign with only very low levels of aggressive alkali metals or chlorides. In contrast, the straw and Junkers hardwood contained significantly greater quantities of both alkali metals and chlorides, with these being implicated in the dramatically accelerated wastage.

4 CONCLUSIONS

1. Corrosion of the various specimens can be characterised according to the type of material. Low alloy ferritic specimens suffered general metal loss, forming duplex corrosion scales. Martensitic steels initially formed chromia scales which suffered irregular breakdown and wastage with slight subsurface attack and the growth of duplex corrosion scales. The austenitic stainless steels and the nickel based weld overlay also formed chromia scales that suffered isolated breakdown to give rise to pitting and internal attack, with duplex corrosion scale growth.

2. The specimens exposed at higher temperatures showed greater tendency for corrosion scale and ash interaction, with the outer scale being defective, loosing chromium into the outer scale and ash, and the finding of low levels of ash derived elements in the inner corrosion scales.

3. With the formation of duplex corrosion scales it would be most likely that corrosion rates would follow parabolic rather than linear kinetics, although rates would likely remain higher than would be the case without corrosion scale and ash interaction.

4. With the range of materials exposed, and the variations in coal fly ash additions, it has been impossible to quantify the effects of changes in fuel composition. However, in general, operation of the Avedore boiler with higher percentage blends of wood fuel resulted in greater wastage rates.

5. The higher alloy materials in general performed significantly better than the low alloy ferritic materials. Questions remain as to the performance of copper containing austenitic materials such as SAVE25 which performed worse than the TP347HFG when exposed at the highest wood fuel blend, but performed better when lower proportions of wood were fired. Careful consideration of the future fuel mix would be required prior to the selection of SAVE25 as an alternative tubing material.

6. No clear trends in ash compositions could be discerned with changes in fuel composition. Most ash deposits comprised mixtures of inert, alumino-silicate, coal fly ash derived particulate material, together with amorphous / sintered material containing greater proportions of alkali metals and sulphur. Only low levels of vanadium were found (<3%) in any of the ash examined. Trace levels of potentially aggressive elements including chlorine, zinc, arsenic and lead were occasionaly identified.

7. In comparison with the probe exposures conducted in the wood and straw fired Amager boiler, the Avedore specimens generally exhibited lower wastage rates, although the rates measured following the first exposure with the highest percentage wood content were greater and similar to those measured after exposure in Amager.

8. In comparison with the probe exposures conducted at pilot scale, the Avdore wastage rates were slightly lower than those measured after exposure to the softwood fuels, and substantially lower that measured after exposure to the straw and hardwood fuels.

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[1] Davis, C. J.; “Elkraft System Project Number FU2203, "Biomass Dust Firing" ENERGI E2: Pilot Scale Studies of the Fireside Corrosion Performance of Furnace Wall and Superheater / Reheater Tube Materials Exposed Whilst Firing Wood or Straw Derived Biomass Fuels”, PT/05/BB909/R, 2005

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[3] Davis, C. J., James, P. J., Pinder, L. W.; “Fireside Corrosion in Pulverised-Coal-Fired Boilers: Effect of Coal Chlorine and Combustion Parameters”, EPRI, Palo Alto, CA: 2001. 1001350

Table 1: CORROSION PROBES EXPOSED AT AVEDØRE POWER STATION

Probe Number	Batch	Specimen(s)	Location	Exposure Dates	Exposure Duration
Furnace Wall Type Corrosion Probes					
FW328	1	FW328	East Side 48m, HBK10CQ002	14-16/12/2005	32.5
FW329	1	FW329	West Side 48m, HBK10CQ001	14-16/12/2005	32.5
FW330	1b	FW330	West Side 48m, HBK10CQ001	17/12/05 – 05/01/2006	480
FW331	2	FW331	West Side 48m, HBK10CQ001	12/04 – 03/05/2006	500
FW332	2	FW332	East Side 48m, HBK10CQ002	12/04 – 03/05/2006	500
Superheater Type Corrosion Probes					
SHTR84	1	8401 - 8410	West Side (North) 58.3m	14-16/12/2005	33.9
SHTR85	1	8501 - 8510	West Side (South) 58.3m	14-16/12/2005	32.0
SHTR86	1	8601 - 8610	East Side 54.3m	14-16/12/2005	33.0
SHTR87	2	8701 - 8710	East Side 54.3m	12/04 – 03/05/2006	500
SHTR88	2	8801 - 8810	West Side (South) 58.3m	12/04 – 03/05/2006	501
SHTR89	2	8901 - 8910	West Side (North) 58.3m	12/04 – 03/05/2006	500
SHTR90	3	9001 - 9010	East Side 54.3m	30/05 – 08/06/2006	203
SHTR91	3	9101 - 9110	West Side (South) 58.3m	30/05 – 08/06/2006	202

Table 2: Fuel Combinations Utilised During Corrosion Testing

	Wood Pellets (%)	Heavy Fuel Oil (%)	Gas (%)	Straw (%)	Total (GJ/hour)	Coal fly ash (ton/hour)	Note
Batch 1	52.8	36.6	10.6	0	1848	2.2	Typically fixed rates although increased oil burn at end of exposure
Batch 1b	35.1	61.0	3.9	0	2653	6.5	Typically 50% wood, 50% oil mixture with some periods with only oil and only oil at end of exposure
Batch 2	35.1	48.1	16.8	0	2516	6.2	Start-up on oil, typical 50% Wood, 25% Oil & 25% Gas. Some periods without wood
Batch 3	16.3	72.4	11.3	0	2153	4.3	12 hour periods with mainly oil and gas (0-50%), 12 hour periods with 50% wood, 25% Oil & 25% Gas

Table 3: TEST ALLOYS AND NOMINAL COMPOSITIONS

Alloy	Alternative Designation		Composition (%)											
			C	Si	P	S	V	Cr	Mn	Fe	Ni	Nb	Mo	Others
13CrMo44	1.7335, T11	Min						0.80	0.30				0.44	
		Max	0.15	0.15				1.25	0.61	Balance			0.65	
10CrMo910	1.738, T22	Min	0.08	0.08				2.00	0.40				0.90	
		Max	0.14	0.14	0.03	0.025		2.50	0.80	Balance			1.10	
X10CrMoVNb9-1	1.4903, T91	Min	0.08	0.08			0.18	8.5	0.3		0.03	0.06	0.85	N 0.03–0.07, Al 0.04
		Max	0.12	0.12	0.02	0.01	0.25	9.5	0.6	Balance	0.07	0.10	1.05	
X20CrMoV12-1	1.4922	Min	0.17	0.17			0.25	10.00			0.30		0.80	
		Max	0.23	0.23	0.03	0.03	0.35	12.50	1	Balance	0.80		1.20	
Eshette1250		Min	0.05	0.05			0.15	14.0	5.50		9.0	0.75	0.8	B 0.003–0.009
		Max	0.15	0.15	0.03	0.03	0.40	16.0	7.00	Balance	12.0	1.2	1.2	Ti 0.05
TP347HFG	SA-213	Min	0.06	0.06				17.0			9.00			Nb 8*%C–1.0
	SA-213M	Max	0.10	0.10	0.04	0.03		20.0	2	Balance	13.0			
SAVE25		Min	0.12	1.5	0.03	0.01		24.0	2.0	Balance	22.0	0.6		W 0.8-2.8
		Max	0.05					21.0			15.0	0.3		Cu 2.0-4.0
IN625 (weld overlay)		Min									63 (balance)			Ti 0.14
		Max						21		5.8			8.5	Nb+Ta 3.4

Table 4: EXPOSURE CONDITIONS, MEASURED METAL LOSSES AND CALCULATED WASTAGE RATES FOR THE FURNACE WALL SAMPLES EXPOSED IN AVEDØRE UNIT 2

Sample Number	Material	Time At Temperature	Mean Surface Temperature	Measured Metal Loss			Linear Wastage Rate			Parabolic Wastage Rate (*10^{-12})		
				95%ile	Max	Mean	95%ile	Max	Mean	95%ile	Max	Mean
		(Hours)	(°C)	(µm)	(nmh^{-1})	(cm^2s^{-1})	(cm^2s^{-1})	(cm^2s^{-1})	(µm)	(nmh^{-1})	(nmh^{-1})	(nmh^{-1})
FW328 (Batch 1, 50.2m E side)	13CrMo44	32.5	475.6	5.0	6.8	2.6	154	209	80	2.1	3.9	0.6
FW329 (Batch 1, 50.2m W side)	10CrMo910	32.5	471.9	5.4	7.2	3.6	166	222	112	2.5	4.5	1.1
FW330 (Batch 1B, 50.2m W side)	X20CrMoV121	454	521.9	7.1	11.0	3.5	16	24	8	0.3	0.7	0.1
FW331 (Batch 2, 50.2m W side)	13CrMo44	500	456.4	22.8	26.4	16.2	46	53	32	2.9	3.9	1.5
FW332 (Batch 2, 50.2m E side)	10CrMo910	500	471.2	17.0	20.9	10.0	34	42	20	1.6	2.4	0.6

Table 5: BATCH ONE OF SUPERHEATER PROBES EXPOSED 14-16/12/2005, EXPOSURE CONDITIONS, MEASURED METAL LOSSES AND CALCULATED WASTAGE RATES

Probe	Sample	Material	Time At Temperature	Surface Temperature	Measured Metal Loss			Linear Wastage Rate			Parabolic Wastage Rate (*10^{-12})		
					95%ile	Max	Mean	95%ile	Max	Mean	95%ile	Max	Mean
			(Hours)	(°C)	(µm)	(µm)	(µm)	(nmh^{-1})	(nmh^{-1})	(nmh^{-1})	(cm^{2}s^{-1})	(cm^{2}s^{-1})	(cm^{2}s^{-1})
84 (59.6m W Side)	1	13CrMo4-4	33.9	433.8	8.1	9.6	4.7	239	282	140	5.4	7.5	1.8
	2	10CrMo9-10	33.9	464.0	12.6	15.5	10.2	372	459	301	13.0	19.8	8.5
	3	X20CrMoV12-1	33.9	490.4	7.0	11.8	4.9	205	349	143	4.0	11.4	1.9
	4	T91	33.9	525.0	7.6	8.4	5.2	225	248	153	4.8	5.8	2.2
	5	X20CrMoV12-1	33.9	532.0	6.7	8.7	4.4	199	255	129	3.7	6.1	1.6
	6	Esheete 1250	33.9	547.2	7.1	29.6	3.7	210	873	108	4.1	71.8	1.1
	7	TP347HFG	33.9	558.7	8.0	12.3	3.0	236	364	90	5.2	12.5	0.8
	8	Save25	33.9	566.4	11.0	20.1	4.4	325	593	129	10.0	33.1	1.6
	9	TP347HFG	33.9	570.0	6.3	7.4	2.9	185	219	86	3.2	4.5	0.7
	10	IN625	33.9	581.3	3.3	5.0	1.0	98	149	29	0.9	2.1	0.1
85 (59.6m W Side)	1	13CrMo4-4	32.0	476.1	14.5	16.5	10.2	454	517	318	18.3	23.7	9.0
	2	10CrMo9-10	32.0	509.0	9.3	13.3	7.6	291	417	236	7.5	15.5	5.0
	3	X20CrMoV12-1	32.0	536.5	8.9	9.8	5.3	277	305	164	6.8	8.3	2.4
	4	T91	32.0	558.6	12.0	13.5	8.6	375	422	268	12.5	15.9	6.4
	5	X20CrMoV12-1	32.0	575.4	12.4	14.5	7.1	388	453	223	13.4	18.2	4.4
	6	Esheete 1250	32.0	586.8	8.9	14.3	5.0	279	447	155	6.9	17.8	2.1
	7	TP347HFG	32.0	592.9	11.0	13.3	3.9	344	417	123	10.5	15.4	1.3
	8	Save25	32.0	593.7	18.7	28.2	6.7	585	883	208	30.5	69.2	3.8
	9	TP347HFG	32.0	589.1	13.7	18.0	5.8	429	562	181	16.4	28.1	2.9
	10	IN625	32.0	591.5	7.0	12.7	2.0	219	396	61	4.2	14.0	0.3
86 (56.0m E Side)	1	13CrMo4-4	33.0	447.2	23.4	25.5	11.2	710	774	340	46.2	54.9	10.6
	2	10CrMo9-10	33.0	477.9	14.7	20.7	8.4	446	626	254	18.2	35.9	5.9
	3	X20CrMoV12-1	33.0	506.1	7.2	8.7	4.7	219	265	142	4.4	6.4	1.8
	4	T91	33.0	542.0	13.8	14.0	8.9	417	426	269	15.9	16.6	6.7
	5	X20CrMoV12-1	33.0	554.8	15.8	17.3	8.0	479	523	242	21.0	25.1	5.4
	6	Esheete 1250	33.0	575.3	15.7	20.5	8.7	476	620	264	20.8	35.3	6.4
	7	TP347HFG	33.0	593.3	16.3	32.5	8.3	494	984	251	22.4	88.8	5.8
	8	Save25	33.0	608.8	15.7	42.2	6.8	477	1278	206	20.8	149.7	3.9
	9	TP347HFG	33.0	621.7	23.6	26.4	8.4	716	800	253	47.0	58.6	5.9
	10	IN625	33.0	649.3	22.5	26.6	7.1	681	805	216	42.5	59.4	4.3

Table 6: BATCH TWO OF SUPERHEATER PROBES EXPOSED 12-17/04/2006, EXPOSURE CONDITIONS, MEASURED METAL LOSSES AND CALCULATED WASTAGE RATES

Probe	Sample	Material	Time At Temperature	Surface Temperature	Measured Metal Loss			Linear Wastage Rate			Parabolic Wastage Rate (*10^{-12})		
					95%ile	Max	Mean	95%ile	Max	Mean	95%ile	Max	Mean
			(Hours)	(°C)	(µm)	(µm)	(µm)	(nmh^{-1})	(nmh^{-1})	(nmh^{-1})	(cm^2s^{-1})	(cm^2s^{-1})	(cm^2s^{-1})
87 (56.0 E Side)	1	13CrMo4-4	500	488.0	18.8	36.4	13.3	38	73	27	2.0	7.4	1.0
	2	10CrMo9-10	500	513.9	30.1	33.9	18.9	60	68	38	5.0	6.4	2.0
	3	X20CrMoV12-1	500	538.4	18.9	27.2	10.4	38	54	21	2.0	4.1	0.6
	4	T91	500	561.5	33.7	35.5	21.0	67	71	42	6.3	7.0	2.4
	5	X20CrMoV12-1	500	583.3	28.7	32.2	15.8	57	64	32	4.6	5.7	1.4
	6	Esheete 1250	500	603.7	33.2	46.6	16.8	66	93	34	6.1	12.1	1.6
	7	TP347HFG	500	622.8	33.5	46.5	12.9	67	93	26	6.2	12.0	0.9
	8	Save25	500	640.5	7.2	8.7	3.5	14	17	7	0.3	0.4	0.1
	9	TP347HFG	500	654.5	17.6	46.9	6.8	35	94	14	1.7	12.2	0.3
	10	IN625	500	695.8	43.7	52.3	9.4	87	105	19	10.6	15.2	0.5
88 (59.6m W Side (S))	1	13CrMo4-4	501	470.9	31.1	35.8	20.6	62	72	41	5.4	7.1	2.4
	2	10CrMo9-10	501	500.9	29.7	31.9	20.4	59	64	41	4.9	5.6	2.3
	3	X20CrMoV12-1	501	527.9	14.2	20.3	7.4	28	40	15	1.1	2.3	0.3
	4	T91	501	551.9	32.4	37.6	18.3	65	75	37	5.8	7.8	1.9
	5	X20CrMoV12-1	501	573.0	29.4	33.9	13.5	59	68	27	4.8	6.4	1.0
	6	Esheete 1250	501	591.0	33.4	36.0	14.5	67	72	29	6.2	7.2	1.2
	7	TP347HFG	501	606.0	15.3	20.8	5.7	31	41	11	1.3	2.4	0.2
	8	Save25	501	618.1	4.7	5.3	2.0	9	11	4	0.1	0.2	<0.1
	9	TP347HFG	501	625.3	6.9	16.7	4.1	14	33	8	0.3	1.5	0.1
	10	IN625	501	644.3	13.7	16.0	6.2	27	32	12	1.0	1.4	0.2
89 (59.6m W Side (N))	1	13CrMo4-4	500	410.1	11.6	13.4	7.6	23	27	15	0.7	1.0	0.3
	2	10CrMo9-10	500	445.9	30.4	33.5	17.6	61	67	35	5.1	6.3	1.7
	3	X20CrMoV12-1	500	478.5	13.5	16.8	8.2	27	34	16	1.0	1.6	0.4
	4	T91	500	508.0	34.5	41.9	21.7	69	84	43	6.6	9.8	2.6
	5	X20CrMoV12-1	500	534.4	26.6	30.0	15.8	53	60	32	3.9	5.0	1.4
	6	Esheete 1250	500	557.7	6.5	6.7	4.6	13	13	9	0.2	0.2	0.1
	7	TP347HFG	500	577.9	21.5	29.6	9.4	43	59	19	2.6	4.9	0.5
	8	Save25	500	595.0	4.3	5.8	2.5	9	12	5	0.1	0.2	<0.1
	9	TP347HFG	500	606.6	18.9	23.5	6.7	38	47	13	2.0	3.1	0.2
	10	IN625	500	631.0	14.6	15.9	6.2	29	32	12	1.2	1.4	0.2

Table 7: BATCH THREE OF SUPERHEATER PROBES EXPOSED 30/5 – 08/06/2006, EXPOSURE CONDITIONS, MEASURED METAL LOSSES AND CALCULATED WASTAGE RATES

Probe	Sample	Material	Time At Temperature	Surface Temperature	Measured Metal Loss			Linear Wastage Rate			Parabolic Wastage Rate (*10^{-12})		
					95%ile	Max	Mean	95%ile	Max	Mean	95%ile	Max	Mean
			(Hours)	(°C)	(µm)	(µm)	(µm)	(nmh^{-1})	(nmh^{-1})	(nmh^{-1})	(cm^2s^{-1})	(cm^2s^{-1})	(cm^2s^{-1})
90 (56.0m E Side)	1	10CrMo9-10	203	460.4	7.2	8.5	5.2	36	42	25	0.7	1.0	0.4
	2	X20CrMoV12-1	203	495.1	8.7	9.2	5.5	43	45	27	1.0	1.2	0.4
	3	10CrMo9-10	203	525.2	19.2	20.9	13.3	95	103	66	5.1	6.0	2.4
	4	X20CrMoV12-1	203	550.7	7.6	8.3	4.7	38	41	23	0.8	0.9	0.3
	5	TP347HFG	203	571.5	7.2	8.3	3.8	36	41	19	0.7	0.9	0.2
	6	X20CrMoV12-1	203	587.7	14.6	18.3	7.2	72	90	36	2.9	4.6	0.7
	7	TP347HFG	203	599.2	5.7	6.0	3.1	28	30	15	0.4	0.5	0.1
	8	TP347HFG	203	606.1	9.4	16.0	5.0	46	79	25	1.2	3.5	0.3
	9	TP347HFG	203	607.4	9.4	14.8	4.5	46	73	22	1.2	3.0	0.3
	10	TP347HFG	203	609.8	6.7	8.9	3.1	33	44	15	0.6	1.1	0.1
91 (59.6m W Side (S))	1	10CrMo9-10	203	461.0	15.9	19.9	11.1	78	98	54	3.4	5.4	1.7
	2	X20CrMoV12-1	203	488.7	5.5	7.9	4.0	27	39	20	0.4	0.9	0.2
	3	10CrMo9-10	203	513.7	17.1	26.1	10.1	84	129	50	4.0	9.3	1.4
	4	X20CrMoV12-1	203	536.0	7.3	10.8	4.1	36	53	20	0.7	1.6	0.2
	5	TP347HFG	203	555.6	5.2	8.7	2.8	26	43	14	0.4	1.0	0.1
	6	X20CrMoV12-1	203	572.5	12.8	15.0	7.2	63	74	35	2.2	3.1	0.7
	7	TP347HFG	203	586.6	4.9	5.1	3.9	24	25	19	0.3	0.4	0.2
	8	TP347HFG	203	598.0	6.8	9.0	3.0	33	44	15	0.6	1.1	0.1
	9	TP347HFG	203	603.8	3.6	4.4	2.1	18	21	10	0.2	0.3	0.1
	10	TP347HFG	203	613.7	2.5	5.1	1.8	13	25	9	0.1	0.3	<0.1

Note: Exposure terminated after boiler brought off load. Boiler subjected to "Band and Clean" ash removal / soot blowing prior to probe removal.

Table 8: OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS FOR FURNACE WALL TYPE SPECIMENS

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
FW328 (13CrMo44, 475.6)	Scale almost 100% detached from metal surface, but present over almost full length. Scale mostly duplex, with interface between inner and outer characterised by slight separation. Outer scale contains fine ash particles and often shows haematite overlay. Inner scale is thinner than outer. This may show a very thin, darker phase at the scale/metal interface.	Minimal particulate ash retention.
FW329 (10CrMo910, 471.9)	Outer scale almost 100% detached from inner scale, but present over almost full length of sample. Inner scale still mostly attached to metal surface. Outer contains fine ash particles and often shows haematite overlay. Inner scale is thinner than outer.	Minimal particulate ash retention.
FW330 (X20CrMoV121, 512.9)	Fragmentary, thin, duplex oxide scale present adjacent to metal surface over most of sample. Some thicker areas adherent. Outer layer contains ash particles. Some darker phase scale at the metal scale interface.	Minimal particulate ash retention.
FW331 (13CrMo44, 456.4)	Thick duplex scale over most of surface. Outer scale dense, often separated from fragmented inner scale. Outer scale very uneven thickness and contains lots of spherical ash particles.	Mixture of particulate and amorphous ash deposit.
FW332 (10CrMo910, 471.2)	Thick duplex scale over most of surface. Outer scale dense, often separated from fragmented inner scale. Outer scale very uneven thickness and contains lots of spherical ash particles.	Mixture of particulate and amorphous ash deposit.

Table 9: OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS RETAINED ON SUPERHEATER PROBE 84, BATCH ONE, EXPOSED AT 59.6m WEST (NORTH) SIDE, 33.9 HOURS

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
1 (13CrMo44, 433.8)	Uniform wastage with duplex oxide scale. Outer scale incorporating spherical particulate ash material.	Fine particulate ash retained to rear of specimen. Radiant crown retains occasional larger translucent ash particles up to approximately 100 µm stuck to corrosion scale.
2 (10CrMo910, 464.0)	Uniform wastage with duplex oxide scale. Outer scale incorporating spherical particulate ash material.	Fine particulate ash retained to rear of specimen. Radiant crown retains occasional larger translucent ash particles up to approximately 100 µm stuck to corrosion scale.
3 (X20CrMoV121, 490.4)	Uniform wastage with duplex oxide scale. Outer scale incorporating spherical particulate ash material.	Fine particulate ash retained to rear of specimen. Radiant crown retains occasional larger translucent ash particles up to approximately 100 µm stuck to corrosion scale.
4 (T91, 525.0)	Uniform wastage with duplex oxide scale. Outer scale incorporating spherical particulate ash material.	Large particulate ash to radiant crown up to 175mm diameter. Suggestion of sintering of ash particles to radiant crown.
5 (X20CrMoV121, 532.0)	Very thin duplex oxide scale.	Suggestion of sintering of ash particles to radiant crown.
6 (Esheete1250, 547.2)	Infrequent breakdown of initially formed chromia layer over majority of specimen. Outer scale affected by scale fluxing. Scale predominantly oxide with occasional sulphide.	Ash agglomeration to radiant surface. Occasionally associated with additional attack and partial scale fluxing / re-precipitation of un-protective iron oxide.
7 (TP347HFG, 558.7)	Infrequent breakdown of initially formed chromia layer over majority of specimen. Generally, but not exclusively, outer scale only affected by scale fluxing. Scale predominantly oxide with occasional sulphide.	Ash agglomeration to radiant surface. Occasionally associated with additional attack and partial scale fluxing / re-precipitation of un-protective iron oxide.
8 (SAVE25, 566.4)	Infrequent breakdown of initially formed chromia layer over majority of specimen. Generally, but not exclusively, outer scale only affected by scale fluxing. Scale predominantly oxide with occasional sulphide. Slight internal attack ahead of solid scale.	Ash agglomeration to radiant surface. Occasionally associated with additional attack and partial scale fluxing / re-precipitation of un-protective iron oxide.
9 (TP347HFG, 570.0)	Infrequent breakdown of initially formed chromia layer over majority of specimen.	Little ash retained.
10 (IN625, 581.3)	Negligible breakdown of initial chromia scale. Only very minor localised oxidation.	Little retained ash. No discernible scale / ash interaction.

Table 10: OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS RETAINED ON SUPERHEATER PROBE 85, BATCH ONE, EXPOSED AT 59.6m WEST (SOUTH) SIDE, 32 HOURS

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
1 (13CrMo44, 476.1)	Uniform wastage with duplex, predominately oxide scale. Outer scale incorporating spherical particulate ash material.	Fine particulate ash retained to rear of specimen.
2 (10CrMo910, 509.0)	Uniform wastage with duplex, predominately oxide scale. Outer scale incorporating spherical particulate ash material. Occasional inter-diffusion of scale and larger ash particles to radiant half of specimen.	Fine particulate ash retained to rear of specimen.
3 (X20CrMoV121, 536.5)	Uniform wastage with duplex, predominately oxide scale. Outer scale incorporating spherical particulate ash material. Relatively thin scale	Fine particulate ash retained to rear of specimen.
4 (T91, 558.6)	Uniform wastage with duplex, predominately oxide scale. Outer scale incorporating spherical particulate ash material.	Large particulate ash to radiant crown up to 175mm diameter. Suggestion of sintering of ash particles to radiant crown.
5 (X20CrMoV121, 575.4)	Irregular general attack. Duplex, predominantly oxide scale.	Sintering of ash particles to radiant crown.
6 (Esheete1250, 586.8)	Irregular breakdown of initially formed chromia layer. Scale predominantly oxide with occasional sulphide.	Ash agglomeration to radiant surface. Associated with partial outer scale fluxing.
7 (TP347HFG, 592.9)	Infrequent breakdown of initially formed chromia layer over majority of specimen. Occasional large ash particles / agglomerated ash associated with very defective external scale. Scale predominantly oxide with occasional sulphide.	Ash agglomeration to radiant surface. Associated with partial outer scale fluxing.
8 (SAVE25, 593.7)	Infrequent breakdown of initially formed chromia layer over majority of specimen. Occasional large ash particles / agglomerated ash associated with very defective external scale. Scale predominantly oxide with occasional sulphide. Slight internal attack ahead of solid scale.	Ash agglomeration to radiant surface. Associated with partial outer scale fluxing.
9 (TP347HFG, 589.1)	Infrequent breakdown of initially formed chromia layer over majority of specimen.	Little ash retained.
10 (IN625, 591.5)	Negligible breakdown of initial chromia scale. Only localised corrosion, occasionally forming defective un-protective scale. Some scale / ash interaction.	Little ash retained

Table 11: OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS RETAINED ON SUPERHEATER PROBE 86, BATCH ONE, EXPOSED AT 56.0m EAST SIDE, 33 HOURS

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
1 (13CrMo44, 447.2)	Irregular general wastage with duplex predominately oxide scale. Outer scale incorporating spherical particulate ash material. Negligible scale / ash interaction.	Mixture of fine and coarse particulate ash, with coarse ash exhibiting signs of agglomeration. Occasional indications of coarse needle like crystalline ash particles. White irregular crystalline ash interspersed with particulate ash.
2 (10CrMo910, 477.9)	Uniform general wastage with duplex predominately oxide scale. Outer scale incorporating spherical particulate ash material. Negligible scale / ash interaction.	Mixture of fine and coarse particulate ash, with coarse ash agglomeration. Occasional indications of coarse needle like crystalline ash particles at outer edges of thickest ash deposits. White irregular crystalline ash interspersed with particulate ash.
3 (X20CrMoV121, 506.1)	Uniform slight general wastage with duplex predominately oxide scale. Outer scale incorporating spherical particulate ash material. Possible slight scale / ash interaction.	Mixture of fine and coarse particulate ash, with coarse ash sintering / agglomerating. Coarse needle like crystalline ash particles frequent close to radiant crown in thickest ash deposits. White irregular crystalline ash interspersed with particulate ash.
4 (T91, 542.0)	Uniform general wastage with duplex predominately oxide scale. Outer scale incorporating spherical particulate ash material. Possible slight scale / ash interaction.	Mixture of fine and coarse particulate ash, with coarse ash sintering / agglomerating. White irregular crystalline ash interspersed with particulate ash.
5 (X20CrMoV121, 554.8)	Uniform general wastage with duplex predominately oxide scale. Occasional more localised deeper attack, sometimes associated with slight scale ash interaction. Outer scale partly taken up into ash deposit forming un-protective layer. Inner scale remains intact. Outer scale incorporating spherical particulate ash material.	Mixture of fine and coarse particulate ash, with coarse ash sintering / agglomerating. White irregular crystalline ash interspersed with particulate ash.
6 (Esheete1250, 575.3)	Irregular breakdown of initially formed chromia layer. Uniform general wastage with duplex predominately oxide scale. Occasional more localised deeper attack, sometimes associated with scale ash interaction and re-precipitation of un-protective oxide dispersed in ash. Inner scale intact, outer scale incorporating particulate ash.	Mixture of fine and coarse particulate ash, with coarse ash sintering / agglomerating. White irregular crystalline ash interspersed with particulate ash.

Table 10 continued		
7 (TP347HFG, 593.3)	Irregular breakdown of initially formed chromia layer to specimen rear. Uniform general wastage with duplex predominately oxide scale. Slight internal attack. Occasional more localised deeper attack, sometimes associated with scale ash interaction and re-precipitation of un-protective oxide dispersed in ash. Inner scale intact, outer scale incorporating spherical particulate ash.	Mixture of fine and coarse particulate ash, with coarse ash sintering / agglomerating. White irregular crystalline ash interspersed with particulate ash.
8 (SAVE25, 608.8)	Irregular breakdown of initially formed chromia layer to specimen rear. Otherwise irregular general wastage with duplex predominately oxide scale. Slight internal attack. Occasional more localised deeper attack, sometimes associated with scale ash interaction and re-precipitation of un-protective oxide dispersed in ash. Inner scale intact, outer scale incorporating spherical particulate ash.	Mixture of fine and coarse particulate ash, with coarse ash sintering / agglomerating. White irregular crystalline ash interspersed with particulate ash.
9 (TP347HFG, 621.7)	Irregular breakdown of initially formed chromia layer. Otherwise irregular general wastage with duplex predominately oxide scale. Slight internal attack. Occasional more localised deeper attack, sometimes associated with scale ash interaction and re-precipitation of un-protective oxide dispersed in ash. Inner scale intact, outer scale incorporating spherical particulate ash.	Mixture of fine and coarse particulate ash, with coarse ash sintering / agglomerating. White irregular crystalline ash interspersed with particulate ash.
10 (IN625, 649.3)	Irregular breakdown of initially formed chromia layer. Otherwise irregular general wastage with duplex scale. Occasional more localised deeper attack, frequently associated with scale ash interaction where outer scale was taken up into ash deposit. Inner scale remains essentially intact but appears laminated. Outer scale incorporating spherical particulate ash.	Mixture of fine and coarse particulate ash, with coarse ash sintering / agglomerating. White irregular crystalline ash interspersed with particulate ash.

Table 12: **OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS RETAINED ON SUPERHEATER PROBE 87, BATCH TWO, EXPOSED AT 56.0m EAST SIDE, 500 HOURS**

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
1 (13CrMo44, 488.0)	General attack all around resulting in duplex scale. Outer oxide intimate contact with ash and separated from inner scale. Lesser attack and very little ash over the rear.	Particulate ash accumulation towards crown
2 (10CrMo910, 513.9)	General attack all around resulting in duplex scale, although much of this had spalled. Outer oxide intimate contact with ash and separated from inner scale. Lesser attack and very little ash over the rear.	Slight ash / scale interaction. Particulate ash accumulation towards crown
3 (X20CrMoV121, 538.4)	General attack all around resulting in duplex scale. Outer scale contains fine ash particles. Attack front over the crown appears more uneven than around the back.	Slight ash / scale interaction. Particulate ash accumulation towards crown
4 (T91, 561.5)	General attack all around resulting in duplex scale.	Slight ash / scale interaction. Particulate ash accumulation towards crown
5 (X20CrMoV121, 583.3)	General attack and duplex scales around crown and beyond ±90° towards the rear. Less breakdown to rear, mostly covered by very thin scale.	Some particulate ash retained over crown.
6 (Esheete1250, 603.7)	General attack and duplex scales around crown and beyond ±90° towards the rear, breaking down to slight pitting attack and occasional internal attack. Less breakdown to rear, mostly covered by very thin scale.	Some particulate ash retained over crown.
7 (TP347HFG, 622.8)	Mostly still in protective regime, with sporadic duplex pitting attack over crown and radiant half of specimen	Some particulate ash retained over crown.
8 (SAVE25, 640.5)	Almost entirely in protective regime with only very slight duplex breakdown just over crown.	Some particulate ash retained over crown.
9 (TP347HFG, 654.5)	Very little attack. Surface still mostly in protective regime with occasional deep pitting / duplex attack. No attack over rear.	Thick, semi-sintered ash over crown. Little ash elsewhere.
10 (IN625, 695.8)	Many indications of possible pitting / duplex scale formation, but scale invariably separated from surface.	Negligible ash retained, especially over crown.

Table 13: OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS RETAINED ON SUPERHEATER PROBE 88, BATCH TWO, EXPOSED AT 59.6m WEST SIDE (SOUTH), 501 HOURS

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
1 (13CrMo44, 470.9)	General attack all around, but slightly deeper attack over crown than rear. Duplex scale formation	Adherent, sintered ash over crown.
2 (10CrMo910, 500.9)	General attack all around, but slightly deeper attack over crown than rear. Duplex scale formation	Sintered fine ash overlays crown, but ash absent from rear.
3 (X20CrMoV121, 527.9)	General attack all around, although irregular to radiant crown. Duplex scale incorporating fine ash particles in uneven outer scale.	Sintered fine ash covering to radiant half of specimen. Little or no ash visible over rear
4 (T91, 551.9)	General attack all around, although irregular to radiant crown. Duplex scale incorporating fine ash particles in uneven outer scale.	Sintered fine ash covering to radiant half of specimen together with lots of fine, light grey needle like crystals precipitated in outer ash. Little or no ash visible over rear
5 (X20CrMoV121, 573.0)	General attack all around, although irregular to radiant crown. Duplex scale incorporating fine ash particles in uneven outer scale.	Sintered fine ash covering to radiant half of specimen together with lots of fine, light grey needle like crystals precipitated in outer ash. Little or no ash visible over rear
6 (Esheete1250, 591.0)	Approximate 50/50 mix of thin chromia and pitting attack with duplex scale over crown. Outer layer appears intimately mixed with sintered ash overlay. Some sulphide in the inner layer. Rear exhibits negligible damage with only sporadic, shallow breakdown to form pitting attack with duplex scales.	Sintered fine ash covering to radiant half of specimen together with lots of fine, light grey needle like crystals precipitated in outer ash. Little or no ash visible over rear
7 (TP347HFG, 606.0)	Almost entirely in protective regime with only very rare breakdown of chromia to form shallow pitting attack with duplex scales.	Sintered ash over crown, shows light grey needle like crystals over attack areas.
8 (SAVE25, 618.1)	Almost entirely in protective regime with only very rare breakdown of chromia to form shallow pitting attack with duplex scales.	Fine, sintered ash over crown. Very little ash to rear.
9 (TP347HFG, 625.3)	Almost entirely in protective regime with only very rare breakdown of chromia to form shallow pitting attack with duplex scales.	Relatively thick, sintered, fine ash with light grey needle like crystals over the crown. No ash to the rear.
10 (IN625, 644.3)	Almost entirely in protective regime, although some small areas of breakdown to give pitting attack duplex scales towards sample crown.	Relatively thick, sintered, fine ash with light grey needle like crystals over the crown. No ash to the rear.

Table 14: **OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS RETAINED ON SUPERHEATER PROBE 89, BATCH TWO, EXPOSED AT 59.6m WEST SIDE (NORTH), 500 HOURS**

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
1 (13CrMo44, 410.1)	General attack all around, but slightly deeper attack over crown than rear. Duplex scale formation	Sintered fine ash over crown. Little ash over the rear.
2 (10CrMo910, 445.9)	General attack all around, but slightly deeper attack over crown than rear. Duplex scale formation with outer scale incorporating particulate ash.	Sintered fine ash over crown. Little ash over the rear.
3 (X20CrMoV121, 478.5)	General attack all around, but slightly deeper attack over crown than rear. Duplex scale formation. Appears to be more attack over rear. Inner oxide is fragmentary, especially over the crown.	Sintered, fine ash overlay over crown, without light grey needle like crystals.
4 (T91, 508.0)	General attack all around, but slightly deeper attack over crown than rear and with shallow internal attack in places. Duplex scale formation. Occasional areas where protective chromia has only just broken down.	Light grey needle like crystals in ash on crown. Thinner, sintered ash over rear.
5 (X20CrMoV121, 534.4)	General shallow attack over most of the sample resulting in duplex scale growth, although some of the rear is still in the protective regime.	Sintered ash overlays the crown, with some light grey needle like crystal formation. No ash to rear.
6 (Esheete1250, 557.7)	General shallow attack over most of the sample resulting in duplex scale growth, although some of the rear is still in the protective regime.	Sintered ash overlays the crown, with some light grey needle like crystal formation. No ash to rear.
7 (TP347HFG, 577.9)	Mixture of protective chromia and pitting attack over crown with duplex scale. Some slight, shallow, internal attack beneath the inner scale under the pits. Chromia essentially intact over the sides and back, with very occasional, slight, very shallow breakdown.	Sintered ash overlays the crown, with some light grey needle like crystal formation. No ash to rear.
8 (SAVE25, 595.0)	Believed to be protective chromia all around, but poor resin retention prevented accurate assessment.	Lost during resin coating / preparation
9 (TP347HFG, 606.6)	Mixture of protective chromia and pitting over crown. Mostly protective over the sides and rear, with very sporadic, shallow breakdown to give pitting attack.	Sintered, fine ash, but without needle like crystals. No ash to rear.
10 (IN625, 631.0)	Mostly protective chromia, with occasional breakdown to pitting attack with duplex scale formation.	Lost during resin coating / preparation

Table 15: **OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS RETAINED ON SUPERHEATER PROBE 90, BATCH THREE, EXPOSED AT 56.0m EAST SIDE, 203 HOURS**

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
1 (10CrMo910, 460.4)	General attack, deeper to front, with duplex scale. Inner scale separated from outer scale by a thin, pale grey phase. Outer scale contains dense dispersion of fine (<3µm) ash particles and sulphide.	Very occasional, large, translucent, ash particles adhering to crown, negligible ash to rear.
2 (X20CrMoV121, 495.1)	General attack, deeper and irregular to front, with duplex scale. Inner scale separated from outer scale by a thin, pale grey phase. Outer scale contains dense dispersion of fine (<3µm) ash particles and sulphide.	Very occasional, large, translucent, ash particles adhering to crown, negligible ash to rear.
3 (10CrMo910, 525.2)	General attack, deeper to front, with duplex scale. Inner scale separated from outer scale by a thin, pale grey phase. Outer scale contains dense dispersion of fine (<3µm) ash particles and sulphide.	Very occasional, large, translucent, ash particles adhering to crown, negligible ash to rear.
4 (X20CrMoV121, 550.7)	General attack, deeper and irregular to front, with duplex scale, although areas of protective chromia remain. Inner scale separated from outer scale by a thin, pale grey phase. Outer scale contains dense dispersion of fine (<3µm) ash particles and sulphide.	Very occasional, large, translucent, ash particles adhering to crown, negligible ash to rear.
5 (TP347HFG, 571.5)	Much of specimen retains protective chromia scale with only minor break down giving rise to slight pitting, especially towards sides.	Occasional small ash agglomerates, negligible ash to rear.
6 (X20CrMoV121, 587.7)	Much of specimen retains protective chromia scale with only minor break down giving rise to slight pitting, especially towards sides.	Occasional small ash agglomerates, negligible ash to rear.
7 (TP347HFG, 599.2)	Occasional very shallow pitting attack over crown forming duplex scales.	Occasional small ash agglomerates, negligible ash to rear.
8 (TP347HFG, 606.1)	Occasional very shallow pitting attack over crown forming duplex scales.	Occasional small ash agglomerates, negligible ash to rear.
9 (TP347HFG, 607.4)	Occasional very shallow pitting attack over crown forming duplex scales.	Occasional small ash agglomerates, negligible ash to rear.
10 (TP347HFG, 609.8)	Occasional very shallow pitting attack over crown forming duplex scales.	Occasional small ash agglomerates, negligible ash to rear.

Table 16: **OPTICAL MICROSCOPY CHARACTERISATION OF CORROSION SCALES / ASH DEPOSITS RETAINED ON SUPERHEATER PROBE 91, BATCH THREE, EXPOSED AT 59.6m WEST SIDE (SOUTH), 203 HOURS**

Sample Number (Alloy, Temperature °C)	Corrosion Characteristics	Ash Characteristics
1 (10CrMo910, 461.0)	General wastage over crown with duplex oxide layer. Lesser attack to rear. Outer scale contains dense dispersion of fine ash particles.	Thin sintered ash overlaying crown
2 (X20CrMoV121, 488.7)	General shallow attack all around sample. Few, small ash particles incorporated into outer scale all around	Thin layer of sintered ash overlays scale.
3 (10CrMo910, 513.7)	General wastage over crown with duplex oxide layer. Lesser attack to rear. Outer scale contains dense dispersion of fine ash particles.	Thin sintered ash overlaying crown
4 (X20CrMoV121, 536.0)	General shallow attack all around sample. Few, small ash particles incorporated into outer scale all around	Thin layer of sintered ash overlays scale.
5 (TP347HFG, 555.6)	Minimal chromia breakdown although some pitting damage with duplex scale formation. Some evidence of ash-scale interaction.	General 20µm thick sintered ash layer over radiant half of sample, negligible ash to rear.
6 (X20CrMoV121, 572.5)	General, irregular attack all around sample. Few, small ash particles incorporated into outer scale all around	General 20µm thick sintered ash layer over radiant half of sample, negligible ash to rear.
7 (TP347HFG, 586.6)	Minimal chromia breakdown although some slight pitting damage with duplex scale formation. Some evidence of ash-scale interaction.	General 20µm thick sintered ash layer over radiant quarter of sample, negligible ash to rear.
8 (TP347HFG, 598.0)	Minimal chromia breakdown although some slight pitting damage with duplex scale formation. Some evidence of ash-scale interaction.	General 20µm thick sintered ash layer over radiant quarter of sample, negligible ash to rear.
9 (TP347HFG, 603.8)	Minimal chromia breakdown although some slight pitting damage with duplex scale formation. Some evidence of ash-scale interaction.	General 20µm thick sintered ash layer over radiant quarter of sample, negligible ash to rear.
10 (TP347HFG, 613.7)	Minimal chromia breakdown although some slight pitting damage with duplex scale formation. Some evidence of ash-scale interaction.	General 20µm thick sintered ash layer over radiant quarter of sample, negligible ash to rear.

Table 17: **ENERGY DISPERSIVE SPECTROSCOPY (EDS) RESULTS BATCH 1 FURNACE WALL PROBE 329, 10CrMo910, EXPOSED WEST SIDE, 50.2M, AT 471.9°C FOR 32.5 HOURS**

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		68.4	1.1	0.6	7.5	13.1	0.3	0.7	0.7	0.7	1.1			0.2		4.9									
Particulate Ash	Max	67.6	2.9	1.1	9.0	20.9	0.7	2.8	0.5	1.5	1.8	0.3		0.3		7.7	0.2	0.2	0.2	0.4					
	Min	63.8	0.3	0.2	6.9	11.0	0.7	0.2		0.3	0.4					1.6									
Mixed Outer Scale & Ash		57.1			0.6	2.5	0.4	3.2			0.7	0.2		0.9	0.2	33.9				0.2	0.3				0.2
Inner Scale		19.6		1.1	1.9	1.7		1.6				0.4	0.2	1.6	0.3	68.6	1.4					0.8			

Implied Compounds In Ash: Alumino-Silicates

Table 18: EDS RESULTS BATCH 1B FURNACE WALL PROBE 330, X20CrMoV121, EXPOSED WEST SIDE, 50.2M, AT 521.9°C FOR 454 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Mixed Outer Scale & Ash	Max	65.9	1.4	0.8	7.9	12.9	1.2	10.9	0.4	1.5	9.0	0.2	1.1	1.3	0.3	12.4	2.1		0.2	0.3		0.2		0.3	
	Min	62.6	0.2	0.2	1.8	3.3	0.3	2.7		0.3	0.4		0.5	0.5		4.8									
Outer Scale	Max	61.9			0.7	0.7		2.7			0.4		0.2	1.7	0.2	34.1	3.4		0.2						
	Min	59.3			0.6	0.7		2.7			0.4			0.9		32.1									
Inner Scale	Max	60.5			0.4	1.0	0.4	3.2					0.3	12.0	0.5	27.1	1.6	0.2	0.4			0.7			
	Min	56.9			0.2	0.9	0.4	1.2					0.2	9.6	0.4	22.3		0.2							

Implied Compounds In Ash: Alumino-Silicates, Calcium Sulphate

Table 19: EDSRESULTS BATCH 2 FURNACE WALL PROBE 331, 13CrMo44, EXPOSED WEST SIDE, 50.2M, AT 456.4°C FOR 500 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Particulate Ash		64.9	1.2	0.9	6.3	9.5	0.8	6.0	0.5	2.2	2.3	0.2	0.2	0.2		4.9									
Amorphous Ash	Max	64.7	2.4	0.7	2.9	5.5	0.9	11.2		4.1	1.6	0.2		0.5	0.2	6.3	0.2		0.4			0.4			
	Min	64.0	1.6	0.5	2.8	4.2	0.5	10.7		4.1	1.5			0.4		5.9			0.4			0.3			
Mixed Outer Scale & Ash	Max	56.3		0.5	2.6	3.6	0.4	6.9		0.2	0.7		0.2	0.3	0.2	29.9						0.2			
	Min	55.2		0.4	2.2	3.2	0.3	5.8		0.2	0.6			0.2		29.1						0.2			
Inner Scale	Max	57.8		0.2	0.3	1.1	0.2	12.1	0.2		0.2			1.1	0.4	38.2				0.2		1.0			
	Min	47.7				0.9		1.5						0.8		36.5						0.6			

Implied Compounds In Ash: Alumino-Silicates, Calcium Sulphate, Alkali (sodium / potassium) sulphate

Table 20: **EDS RESULTS BATCH 2 FURNACE WALL PROBE 332, 10CrMo910, EXPOSED EAST SIDE, 50.2M, AT 471.2°C FOR 500 HOURS**

Material		Atomic percentage																						
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		66.2	0.9	0.7	6.4	9.6	0.6	5.0	0.4	1.8	2.2	0.2	0.3	0.3		4.7		0.3							
Amorphous Ash		66.5	1.8	1.0	2.8	5.0	0.5	10.4	0.2	3.8	1.5			0.2		5.2		0.6				0.2			
Particulate Ash	Max	66.4	0.8	0.8	6.7	9.7	0.8	9.0	0.4	3.0	2.8	0.2	0.5	0.4		4.4		0.6		0.2					
	Min	66.2	0.5	0.3	4.5	7.4	0.6	4.4	0.4	1.4	1.7		0.5	0.3		4.1		0.4		0.2					
Outer Scale		58.1		0.2	0.4	0.5	0.2	1.8					0.2	0.7		38.0						0.2			
Inner Scale		56.2		0.2	0.2	1.0		4.6	0.2					2.5	0.3	33.9						1.6			

Implied Compounds In Ash: Alumino-Silicates, Calcium Sulphate, Alkali (sodium / potassium) sulphate

Table 21: EDS RESULTS BATCH 1 SUPERHEATER SAMPLE 8407, TP347HFG, EXPOSED WEST (N) SIDE, 59.6M, AT 558.7°C FOR 33.9 HOURS

Material		Atomic percentage																						
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		64.6	0.6	0.5	8.0	10.5	1.2	3.3	0.2	1.0	1.8	0.2		1.2		5.8	0.7								
Particulate Ash		64.3	0.5	0.5	7.1	10.9	0.9	4.1	0.3	0.8	3.3			1.1	0.2	4.8	0.6								
Amorphous Ash	Max	68.2	0.9	0.6	8.0	10.4	7.7	5.5	0.3	1.2	3.4	0.3	0.2	1.5		7.7	0.8	0.2		0.3					
	Min	63.0	0.2		3.4	7.7	1.7	2.5		0.3	1.0			0.6		3.4	0.3								
Mixed Outer Scale & Ash	Max	66.7	0.8	0.7	4.5	8.9	1.6	5.9	0.3	0.7	4.4	0.2		2.0	0.3	22.4	1.4								
	Min	59.9	0.2	0.2	0.9	5.6	0.3	1.9		0.3	0.5			0.8		6.7	0.8								
Inner Scale	Max	54.0			0.5	2.0		7.1			0.4		0.2	19.7	1.0	15.3	4.7	0.2	0.2	0.2	0.3	0.4			
	Min	50.3			0.4	1.5		6.2			0.2		0.2	17.5	0.6	12.8	3.5				0.3				

Implied Compounds In Ash: Alumino-Silicates, Calcium Sulphate, Alkali (sodium / potassium) sulphate, Magnesium Phosphate

Table 22: EDS RESULTS BATCH 1 SUPERHEATER SAMPLE 8408, SAVE25, EXPOSED WEST (S) SIDE, 59.6M, AT 566.4°C FOR 33.9 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		66.7	0.5	0.8	8.2	12.2	0.6	1.3	0.6	0.7	1.8	0.6		1.3		3.3	0.8	0.2							
Amorphous Ash		70.9			12.0	0.4	13.6	0.4	0.2		0.5			0.6		1.9	0.7								
Particulate Ash	Max	68.2	1.0	0.8	14.4	21.2	0.9	12.4	0.2	2.8	11.3	0.3	0.2	1.1		3.6	1.2	0.2	0.2	0.3	0.3				0.4
	Min	63.0	0.3	0.6	1.3	3.0	0.2	0.5	0.2	1.1	0.3	0.2	0.2	0.6		1.9	0.5								0.2
Mixed Outer Scale & Ash	Max	65.5	0.3	0.2	2.7	3.5	1.7	8.4		0.4	7.2			3.6		20.4	3.5	0.2						0.2	
	Min	62.7	0.2	0.2	2.5	3.5	1.7	2.1		0.3	0.3			1.9		7.0	1.2	0.2						0.2	
Defective Scale		59.0	0.3	0.3	1.2	2.2	0.2	4.2		0.2	1.5			2.8		20.0	7.6	0.2							
Inner Scale	Max	57.0	0.2	0.4	0.4	0.9	0.2	7.1			0.3	0.2		21.7	0.5	11.2	3.0	0.2	0.3		0.3	0.4		0.5	
	Min	56.4						4.9						20.9	0.2	9.2	2.1	0.2	0.3		0.3	0.4		0.4	

Implied Compounds In Ash: Alumino-Silicates, Calcium Sulphates

Table 23: EDS RESULTS BATCH 1 SUPERHEATER SAMPLE 8605, X20CrMoV21, EXPOSED EAST SIDE, 56.0M, AT 554.8°C FOR 33 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Amorphous Ash	Max	72.8	0.8	0.2	1.7	3.4	2.0	8.9	0.4	4.0	7.3	0.2		2.6	0.2	15.9	0.4						0.2		0.2
	Min	62.8	0.3	0.2	0.8	2.5	2.0	6.3		0.5	1.9			0.3		2.5	0.2						0.2		
Mixed Outer Scale & Ash	Max	63.4	0.6	0.5	4.5	6.5	0.5	4.4	0.2	3.1	1.5	0.3		7.0		20.4	0.2				0.2	0.8			
	Min	62.4	0.4	0.2	0.6	2.6	0.2	1.0		0.7	0.5			1.3		14.1	0.2								
Inner Scale		59.8	0.3		0.7	0.9		1.1		0.3	0.3		0.3	7.2	0.3	26.5	0.6		0.6	0.2		0.4			

Implied Compounds In Ash: Alumino-Silicates, (Potassium, Calcium) Sulphate, (Chromium, Iron) Oxides, (Barium, Titanium) Oxides

Table 24: EDS RESULTS BATCH 1 SUPERHEATER SAMPLE 8606, Esheete1250, EXPOSED EAST SIDE, 56.0M, AT 575.3°C FOR 33 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash	Max	66.1	1.5	3.0	4.8	12.2	2.2	2.3	0.2	0.6	5.7	0.4		0.9	0.3	5.2	0.4								
	Min	63.7	0.7	2.5	3.8	10.1	1.2	0.8	0.2	0.5	5.3			0.4	0.3	3.8	0.2								
Amorphous Ash		65.3	0.5		1.8	2.7	0.5	12.4		0.2	10.5	0.2		0.5	0.2	4.4	0.4								
Particulate Ash	Max	67.7	5.4	9.5	7.2	18.3	12.8	0.3	0.3	1.5	15.5	0.5		0.4	1.0	22.7	0.2		0.2	0.2			0.2		
	Min	61.6	0.3	1.0	1.0	2.5	0.2	0.2		0.2	1.1	0.2				0.8									
Mixed Outer Scale & Ash	Max	62.6	0.8	0.9	4.5	5.1	1.2	4.8	0.2	0.6	4.0	0.3	0.3	2.0	0.8	19.7	0.8	0.3	0.3	0.2					
	Min	62.0	0.5	0.8	1.5	2.8	0.2	1.4		0.2	1.1	0.2	0.2	0.8	0.3	19.0	0.5								
Inner Scale	Max	53.6	0.2	0.7	0.5	2.1		11.0		0.2	0.4	0.2	0.3	15.6	3.6	14.3	2.9		0.4	0.2	0.5	1.1			
	Min	53.6				2.0		7.0						15.6	3.5	11.8	2.9				0.5	1.1			

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, Magnesium Phosphate, (Barium, Titanium) Oxides

Table 25: EDS RESULTS BATCH 1 SUPERHEATER SAMPLE 8607, TP347HFG, EXPOSED EAST SIDE, 56.0M, AT 593.3°C FOR 33 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		66.3	0.5	0.8	8.9	13.7	0.5	1.0	0.5	0.9	1.4	0.3		0.8		3.5	0.4								
Particulate Ash		64.4		0.3	12.5	13.4	0.3	0.7		1.1	0.7	0.4		0.8		4.6	0.4								
Mixed Outer Scale & Ash	Max	66.4	0.8	1.3	3.8	4.9	0.8	6.0	0.2	0.8	5.7	0.2	0.3	3.2	0.3	23.1	1.6		0.2						
	Min	61.0	0.2	0.2	2.4	3.5	0.5	1.8		0.4	0.6		0.2	1.4		8.9	0.6								
Inner Scale	Max	60.2	0.5	0.2	0.5	1.8	0.3	8.9	0.3	0.2			0.2	17.6	0.6	15.1	2.6		0.4		0.7				
	Min	53.1			0.4	1.1	0.2	3.7						16.5		13.3	2.1								

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, Calcium Sulphate

Table 26: EDS RESULTS BATCH 1 SUPERHEATER SAMPLE 8608, SAVE25, EXPOSED EAST SIDE, 56.0M, AT 608.8°C FOR 33 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		67.1	0.8	3.8	4.6	11.4	2.0	0.9	0.2	0.5	4.7	0.2		0.5		2.2	0.4	0.3							
Amorphous Ash		57.8	1.2	0.5	1.6	23.6	0.4	0.3	0.2	0.3	1.8		0.2	2.1		6.6	1.9	0.3	0.2						
Particulate Ash	Max	67.3	5.1	11.8	9.1	16.6	11.8	5.3	0.2	1.9	11.3	0.2		1.1	0.4	4.6	4.9	0.8	0.5	0.3					0.2
	Min	61.9	0.3	0.7	1.1	2.7	0.4				0.6			0.2		0.8									
Mixed Outer Scale & Ash		59.8	0.5	0.8	6.2	9.1	0.5	0.8		1.0	0.6	0.2		1.8		13.0	5.0	0.3							
Inner Scale		53.3	0.5	0.2	0.5	1.5		7.6			0.2			23.7	0.3	8.4	3.7	0.3						0.5	

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, Calcium Sulphate, Magnesium Phosphate

Table 27: EDS RESULTS BATCH 2 SUPERHEATER SAMPLE 8703, X20CrMoV121, EXPOSED EAST SIDE, 56.0M, AT 538.4°C FOR 500 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		64.9	1.0	4.9	2.9	6.0	4.2	5.3		1.3	5.7	0.3		0.3	0.2	2.5		0.3							
Amorphous Ash	Max	67.6	0.6	3.0	1.8	2.9	0.8	14.3		2.5	10.6			0.3	0.2	1.4							1.4		
	Min	66.6		1.3	0.6	1.3	0.8	11.6		0.5	7.7			0.2		1.1									
Particulate Ash	Max	66.0	2.8	13.8	5.2	9.8	13.1	5.1		1.7	13.5	0.3		0.5	0.5	3.5		0.5	0.3	0.2		0.4			
	Min	61.0	0.3	2.3	0.8	1.8	1.3	0.3		0.2	2.3					0.8									
Mixed Outer Scale & Ash	Max	64.0	0.8	3.4	3.8	5.1	1.2	11.8		2.9	5.9			2.3		25.5	0.2	0.3	0.2	0.5		0.5	0.2		
	Min	58.4		0.6	2.5	4.4	0.9	1.1		0.3	0.4			0.5		3.6		0.2				0.3			
Inner Scale	Max	48.7	0.4	1.3	2.0	1.7	1.3	7.9	0.5	0.3	1.0		0.6	13.0	0.4	31.2	0.2			0.7	0.7	3.4			
	Min	45.7		1.0	0.8	1.5	0.4	0.9		0.3	0.9		0.3	11.3		23.7					0.7				

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, Calcium Sulphate, Magnesium Phosphate

Table 28: EDS RESULTS BATCH 2 SUPERHEATER SAMPLE 8704, T91, EXPOSED EAST SIDE, 56.0M, AT 561.5°C FOR 500 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash	Max	66.5	0.8	3.5	3.5	8.0	2.3	6.8		1.4	6.3	1.0			0.2	2.5		0.2							
	Min	66.1	0.8	3.1	3.3	5.8	2.1	4.8		1.1	6.1	0.5			0.2	1.8		0.2							
Amorphous Ash		67.4	0.5	2.5	1.4	2.8	2.1	11.3		1.5	8.6					1.2									
Particulate Ash	Max	71.0	2.9	10.0	5.1	15.3	9.6	8.6	0.6	3.3	12.6	13.9	2.0	0.4	1.1	18.9	0.2	1.3	0.3	0.6			6.1		2.0
	Min	62.9		0.4	1.1	1.5					1.1					0.7									
Mixed Outer Scale & Ash	Max	63.5		1.4	3.2	4.7	1.0	5.3		0.8	2.5	0.3	0.3	1.0	0.3	24.1									
	Min	60.7		0.6	3.2	3.6	0.8	2.6		0.2	0.8		0.2	0.5		17.8									
Inner Scale	Max	56.2	0.3	1.5	0.4	1.2	0.7	4.5			0.4	0.8	0.3	9.1		32.2		0.2							
	Min	55.9		0.5		0.9	0.6	2.4			0.2	0.8	0.2	8.0		27.5									

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, Calcium Sulphate, Magnesium Phosphate, (Barium, Titanium) Oxides

Table 29: EDS RESULTS BATCH 2 SUPERHEATER SAMPLE 8802, 10CrMo910, EXPOSED WEST (S) SIDE, 59.6M, AT 500.9°C FOR 501 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Amorphous Ash		66.9	1.0	1.2	3.1	4.3	1.5	10.0		1.9	3.1		0.2	0.3		6.2			0.2				0.2		0.2
Particulate Ash	Max	66.5	1.0	9.7	5.5	8.3	12.6	6.2	0.3	1.9	3.1	0.2	0.4	0.5		2.2			0.2	0.2					0.2
	Min	64.9	0.4	1.0	1.3	2.2	2.1	3.3		0.4	2.5	0.2	0.3	0.5		1.9									
Mixed Outer Scale & Ash		56.2		1.1	3.1	4.7	0.8	3.3		0.3	0.7		0.2		0.3	28.7					0.2	0.4			
Inner Scale		57.7		0.8	0.3	1.0	0.3	0.5			0.2			2.5	0.2	35.9						1.1			

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, (Potassium, Calcium) Sulphate, Magnesium Phosphate

Table 30: EDS RESULTS BATCH 2 SUPERHEATER SAMPLE 8804, T91, EXPOSED WEST (S) SIDE, 59.6M, AT 551.9°C FOR 501 HOURS

Material		Atomic percentage																					
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		68.0	0.5	2.2	3.3	5.6	2.0	7.8		1.9	5.2	0.2		0.4	0.2	2.4									0.2
Amorphous Ash		64.7	1.6	4.6	0.8	1.3	8.5	6.1		1.7	2.0			0.3	0.4	7.1			0.5	0.2					
Particulate Ash	Max	66.0	1.6	5.8	6.1	12.8	7.3	11.0		5.0	5.6	0.2	0.3	0.2	0.4	4.1	0.2		0.2	0.4					0.5
	Min	64.0	0.8	3.5	0.7	1.2	1.3	0.9		2.0	1.5				0.2	1.5									
Mixed Outer Scale & Ash		63.8	0.2	0.5	3.5	5.8	0.7	2.7		0.8	1.4		0.2	0.7		19.2									
Inner Scale	Max	57.9	0.4	0.4	0.4	1.4		2.9		0.3	0.4			8.3	0.5	28.3	0.2		0.2			0.7			
	Min	56.6			0.4	0.9		2.3						7.9	0.5	28.3						0.5			

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, (Potassium, Calcium) Sulphate, Magnesium Phosphate

Table 31: EDS RESULTS BATCH 2 SUPERHEATER SAMPLE 8807, TP347HFG, EXPOSED WEST (S) SIDE, 59.6M, AT 606.0°C FOR 501 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		66.5	0.6	0.9	4.6	6.8	1.9	7.4		1.7	4.6	0.2		0.8		2.7	0.3								0.2
Amorphous Ash		66.4	0.6	0.9	4.2	6.3	2.2	7.8	0.2	1.6	4.9	0.2		0.9		2.9	0.3			0.2					0.2
Particulate Ash	Max	66.8	0.9	1.2	5.4	7.6	1.5	14.2	0.3	1.8	9.3			1.1		2.1	0.3		0.2	0.2			0.4		0.8
	Min	66.2	0.3	0.7	2.6	1.6	1.3	6.4	0.2	0.4	4.2			0.8		1.8	0.2								0.2
Mixed Outer Scale & Ash	Max	65.3	0.4	1.3	6.7	9.7	3.4	4.9		2.9	2.1	0.2	0.2	1.9	0.2	8.9	0.6			0.3					
	Min	63.5	0.2	0.8	2.8	7.1	2.3	4.6		1.6	2.0			1.2	0.2	3.2	0.5								
Inner Scale		59.9	0.7	0.3	1.3	3.2	0.7	3.0		0.8	0.4	0.2		13.1	0.5	13.3	1.5		0.3		0.5				

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, (Potassium, Calcium) Sulphate, Magnesium Phosphate

Table 32: **EDS RESULTS BATCH 2 SUPERHEATER SAMPLE 8809, TP347HFG, EXPOSED WEST (S) SIDE, 59.6M, AT 625.3°C FOR 501 HOURS**

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
General Ash		65.2	0.6	0.6	6.0	9.3	2.6	4.8		2.6	2.9		0.2	1.0		3.1	0.4		0.2	0.2					
Amorphous Ash	Max	64.6	0.7	1.1	6.3	11.2	2.3	7.0		2.9	4.0		0.3	1.3		5.2	0.4			0.2					0.2
	Min	63.7	0.5	0.5	5.0	6.7	1.6	3.5		2.8	1.9		0.2	1.0		3.8	0.3			0.2					0.2
Particulate Ash	Max	67.5	0.5	0.9	7.9	11.9	2.6	7.4		3.8	4.8	0.2	0.3	1.1		2.6	0.5		0.3	0.3					
	Min	63.4	0.5	0.2	4.0	6.5	2.3	2.5		1.5	1.7			0.9		2.3	0.3			0.2					
Mixed Outer Scale & Ash		59.6	1.2	1.2	2.7	8.9	0.5	1.4		0.7	0.5	0.2		2.4	0.2	19.4	0.8		0.2					0.2	
Inner Scale		59.5			0.9	2.6	0.2	4.6		0.3			0.2	17.4	0.7	12.4	1.0				0.6				

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, (Potassium, Calcium) Sulphate, Magnesium Phosphate

Table 33: EDS RESULTS BATCH 2 SUPERHEATER SAMPLE 8810, IN625, EXPOSED WEST (S) SIDE, 59.6M, AT 644.3°C FOR 501 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Particulate Ash	Max	65.9	1.2	1.4	6.6	9.2	2.7	7.4		2.9	3.3	0.2	2.5	1.0	0.2	1.1	5.4			0.4			1.4		0.5
	Min	63.6	0.7	1.2	3.6	5.5	1.1	5.4		2.1	1.9		0.2	0.8		0.9	1.4								
Mixed Outer Scale & Ash	Max	65.8	1.5	2.1	4.6	8.0	2.5	7.9		2.9	5.2	0.2	3.0	4.6	0.3	1.7	7.3		0.4	0.2	0.4				0.2
	Min	61.4	0.7	0.9	3.1	5.0	1.5	3.2		1.3	1.2		1.0	1.0		0.9	3.6		0.2						
Inner Scale	Max	58.3	0.4	1.3	0.8	2.2	0.2	8.0	0.4	0.7	0.4	0.5	0.6	21.5	0.3	0.6	9.2		0.7	0.2	3.9	8.4			0.3
	Min	53.4		0.4	0.5	1.1		6.5			0.3	0.3	0.3	10.2		0.3	4.9				1.4	2.5			

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, (Potassium, Calcium) Sulphate, Magnesium Phosphate

Table 34: EDS RESULTS BATCH 3 SUPERHEATER SAMPLE 9003, 10CrMo910, EXPOSED EAST SIDE, 56.0M, AT 525.2°C FOR 203 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Particulate Ash	Max	70.3	2.6	13.5	4.7	9.9	12.3	15.8		5.0	15.0	0.3	1.4		0.3	18.0		0.4	0.2						0.9
	Min	61.7		0.4	0.2	0.4		0.2			1.4					2.1									
Mixed Outer Scale & Ash	Max	68.8	0.4	1.4	3.6	5.9	2.0	6.0		1.2	3.9		0.7	0.4	0.2	25.3				0.2		0.2			
	Min	58.7	0.2	0.9	2.4	5.2	1.0	2.0		0.2	1.3		0.2	0.2		7.9									
Inner Scale		54.5	0.2	0.7	0.6	1.3	0.3	3.2			0.4			2.1	0.2	35.8						0.7			

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, (Potassium, Calcium) Sulphate, Magnesium Phosphate

Table 35: EDS RESULTS BATCH 3 SUPERHEATER SAMPLE 9005, TP347HFG, EXPOSED EAST SIDE, 56.0M, AT 571.5°C FOR 203 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Particulate Ash	Max	67.7	1.4	11.1	10.1	15.3	9.3	14.0	0.2	1.4	18.4	10.7	0.6	0.7	0.2	24.6	0.5	0.6	0.5	0.3	0.4	0.2	0.8	0.3	
	Min	60.1			1.1	2.2					0.5			0.2		1.8									
Mixed Outer Scale & Ash	Max	66.3	0.7	3.9	3.5	6.7	1.7	10.0	0.2	3.3	5.7	0.3	0.2	1.3	0.6	15.3	1.2			0.2		0.3		0.2	
	Min	65.2	0.3	0.9	0.3	1.0		3.2		0.7	2.0			0.6		5.8	0.4								
Inner Scale	Max	64.0	1.3	0.2	0.6	1.6	0.4	3.1		0.2	0.5		0.5	16.3	0.6	15.8	1.6	0.2	0.3	0.3	0.6	0.4			
	Min	58.0			0.5	0.9		1.7			0.4			16.0	0.5	12.2	0.7					0.3			

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, (Potassium, Calcium) Sulphate, Magnesium Phosphate, (Barium, Titanium) Oxides

Table 36: EDS RESULTS BATCH 3 SUPERHEATER SAMPLE 9106, X20CrMoV121, EXPOSED WEST SIDE (S), 59.6M, AT 572.5°C FOR 203 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Amorphous Ash	Max	67.6	0.6	0.9	4.9	7.7	2.2	14.3		1.1	12.7	0.2	0.7	1.3		4.5				0.3					0.2
	Min	66.6			0.5	0.8		4.9		1.1	3.0			0.6		4.1				0.2					
Particulate Ash	Max	68.5	1.3	0.7	9.2	23.9	0.2	1.6	0.5	1.3	1.5	0.2		1.2	0.4	11.8		0.2	0.5	0.4		0.7	0.2		
	Min	64.3			3.6	9.2				0.2						2.2									
Mixed Outer Scale & Ash	Max	66.0	1.1	3.6	4.0	8.9	2.2	6.4	0.5	0.8	3.6	0.2	1.8	4.5	0.2	29.0	0.6	0.4	0.5	0.4		0.5	0.3		0.3
	Min	57.3		0.2	1.7	3.9		0.2			0.2			1.3		6.0									
Inner Scale	Max	55.1	0.5		0.5	1.6	0.2	3.6		0.4	0.3		0.7	15.8	0.5	27.6	0.8	0.6		0.2	0.2	0.7			
	Min	53.6				1.2		1.3					0.4	12.7		23.9						0.5			

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, Calcium Sulphate

Table 37: EDS RESULTS BATCH 3 SUPERHEATER SAMPLE 9108, TP347HFG, EXPOSED WEST SIDE (S), 59.6M, AT 598.0°C FOR 203 HOURS

Material		Atomic percentage																							
		O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	As	Nb	Mo	Ba	W	Pb
Amorphous Ash		64.7	4.4	1.8	0.3	3.7		9.3		9.5	0.7			0.9	0.2	3.8	0.6					0.4			
Particulate Ash		65.3	0.6	0.9	10.9	15.4		0.5		1.0	1.0	0.3		0.6		2.9	0.3								
Mixed Outer Scale & Ash	Max	65.7	0.9	1.5	5.7	11.0	2.7	5.0		1.7	2.9	0.2	0.3	4.6	0.2	15.8	0.7	0.2		0.4					
	Min	61.4	0.5	0.6	3.4	6.2	0.8	3.1		0.8	1.0		0.2	1.5		3.6	0.4								
Inner Scale	Max	57.3			1.0	2.0	0.3	4.9			0.4	0.2	0.2	29.2	1.2	17.4	2.1	0.3	0.4	0.2	0.4	0.9			
	Min	51.9			1.0	1.7		0.6			0.2		0.2	16.3	0.2	9.4	0.8		0.4						

Implied Compounds In Ash: Alumino-Silicates, Iron Oxides, (Potassium, Calcium) Sulphate

Table 38: GENERALISED SUMMARY OF TRENDS IN EXPOSURE TEMPERATURES, WASTAGE RATE AND DAMAGE MORPHOLOGY FOR THE MATERIALS EXPOSED IN AVEDØRE

Alloy	Temperature Exposure Range (°C)	Wastage Rates	Linear / Parabolic	Damage Morphology
13CrMo44	410 - 488	High	Parabolic	General wastage
10CrMo910	426 - 525	High	Parabolic	General wastage
T91	508 - 561	Medium	Parabolic	Irregular general wastage, slight subsurface attack
X20CrMoV121	478 - 588	Medium	Parabolic	Irregular general wastage, slight subsurface attack
Eshette1250	547 - 603	Low	Parabolic	Mixture of protective chromia with no observable metal loss and irregular general wastage or pitting with slight subsurface attack
TP347HFG	556 - 655	Low	Parabolic	Mixture of protective chromia with no observable metal loss and irregular general wastage or pitting with slight subsurface attack
SAVE25	566 - 640	Low	Parabolic	Mixture of protective chromia with no observable metal loss and irregular general wastage or pitting with slight subsurface attack
IN625	581 - 696	Low	Parabolic	Predominantly retains protective chromia with no observable attack, but with some pitting and subsurface damage

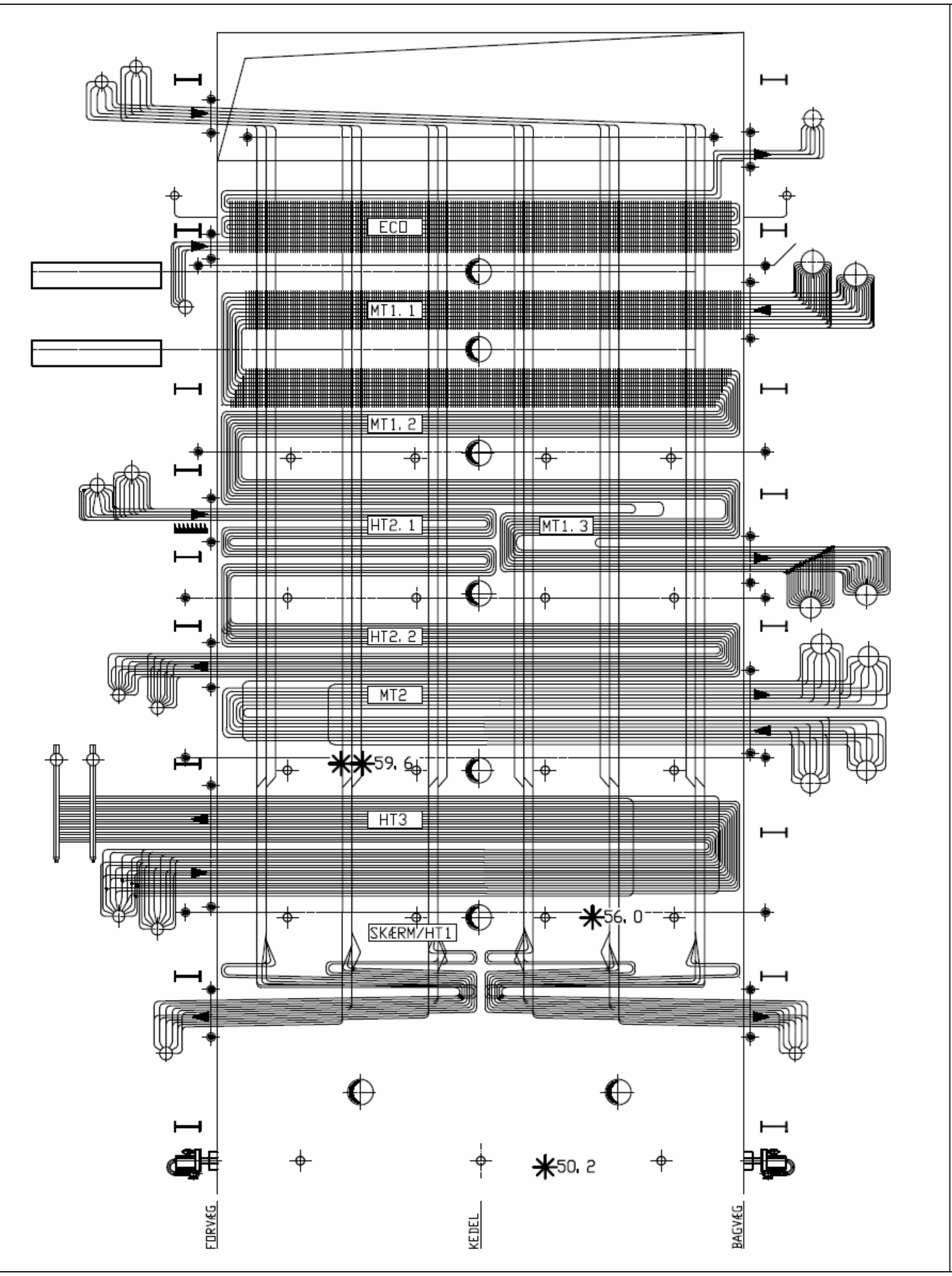


Figure 1: SCHEMATIC DRAWING OF AVEDØRE UNIT 2 BOILER UPPER FURNACE INDICATING THE POSITION OF THE PROBE EXPOSURE PORTS AT 50.2, 56.0 AND 59.6M ELEVATIONS

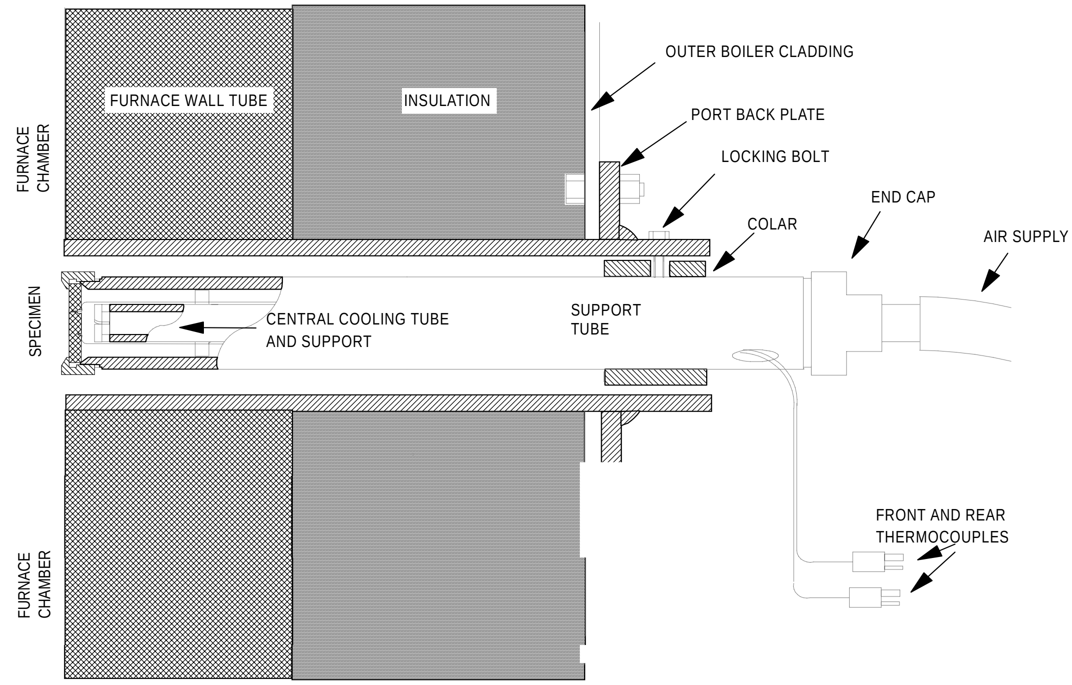


Figure 2: **SCHEMATIC DRAWING OF A FURNACE WALL CORROSION PROBE AS EXPOSED WITH SPECIMEN FLUSH WITH FURNACE WALL**

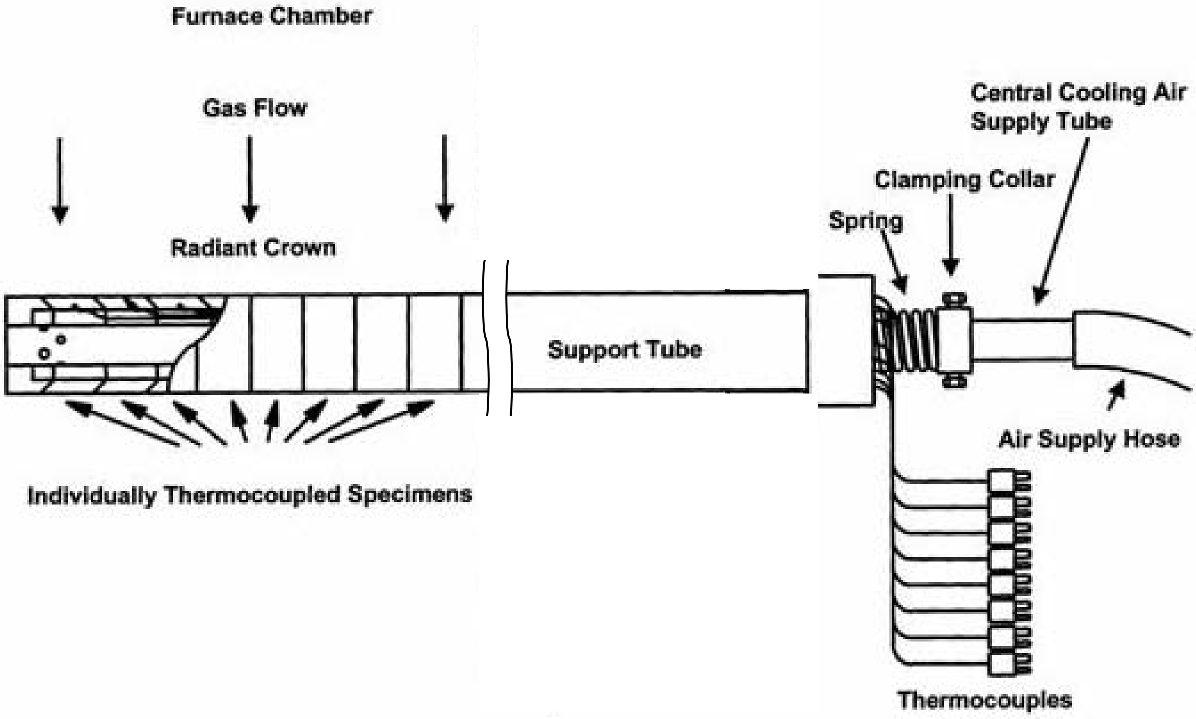


Figure 3: **SCHEMATIC DRAWING OF A SUPERHEATER / REHEATER CORROSION PROBE**

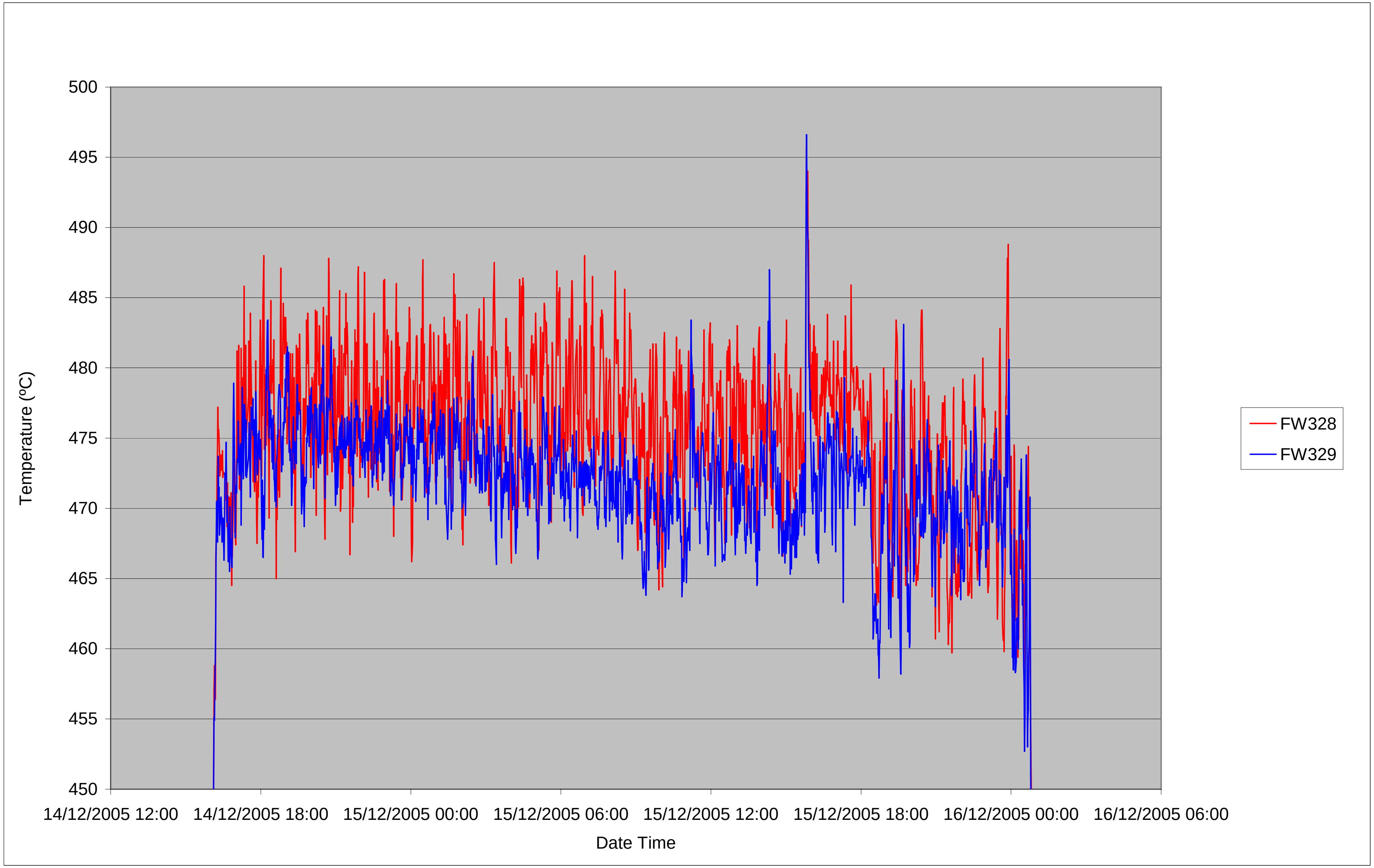


Figure 4: **BATCH ONE FURNACE WALL SPECIMEN SURFACE TEMPERATURES**

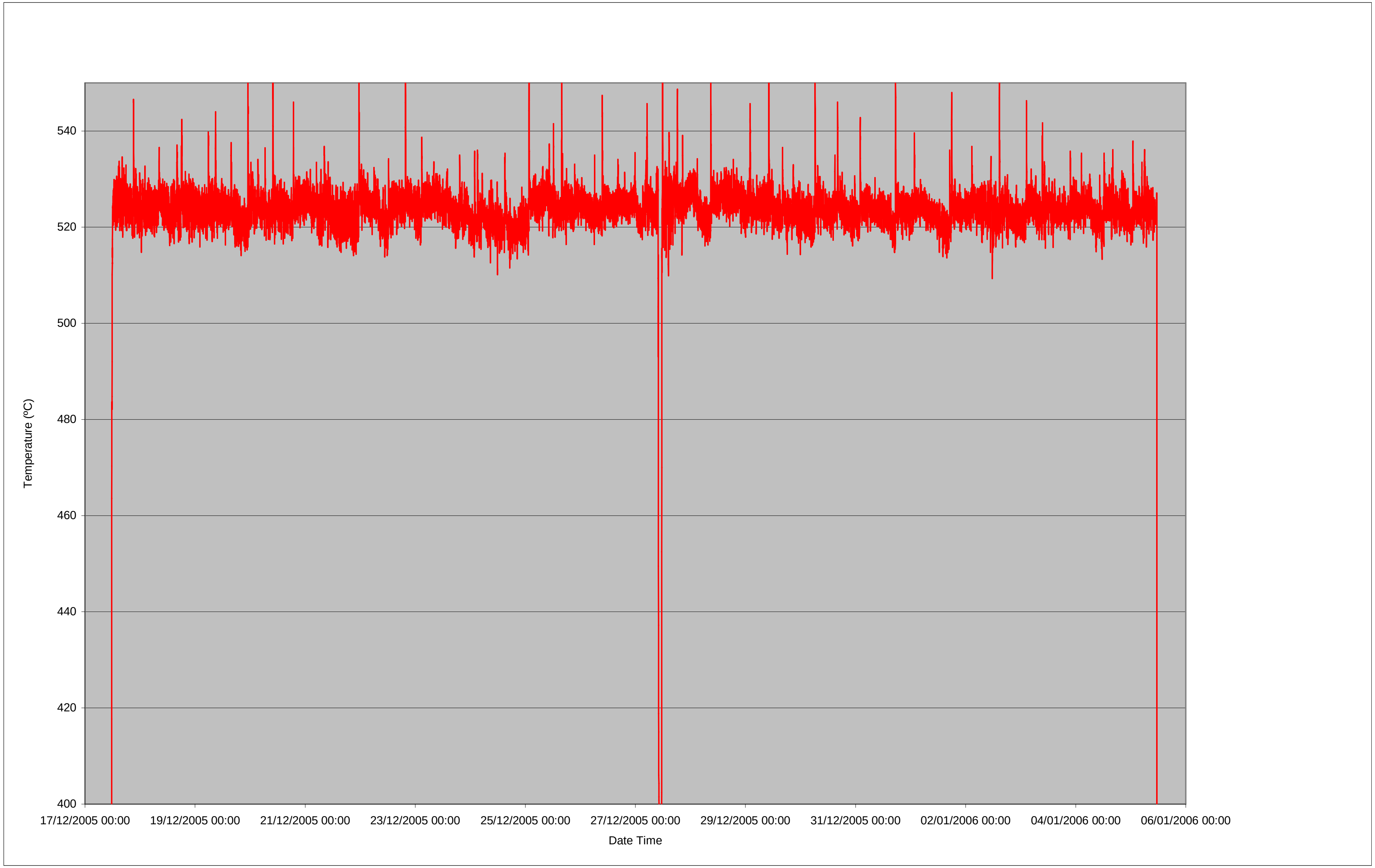


Figure 5: **SINGLE FURNACE WALL PROBE EXPOSED IMMEDIATELY FOLLOWING FIRST BATCH (BATCH 1B)**

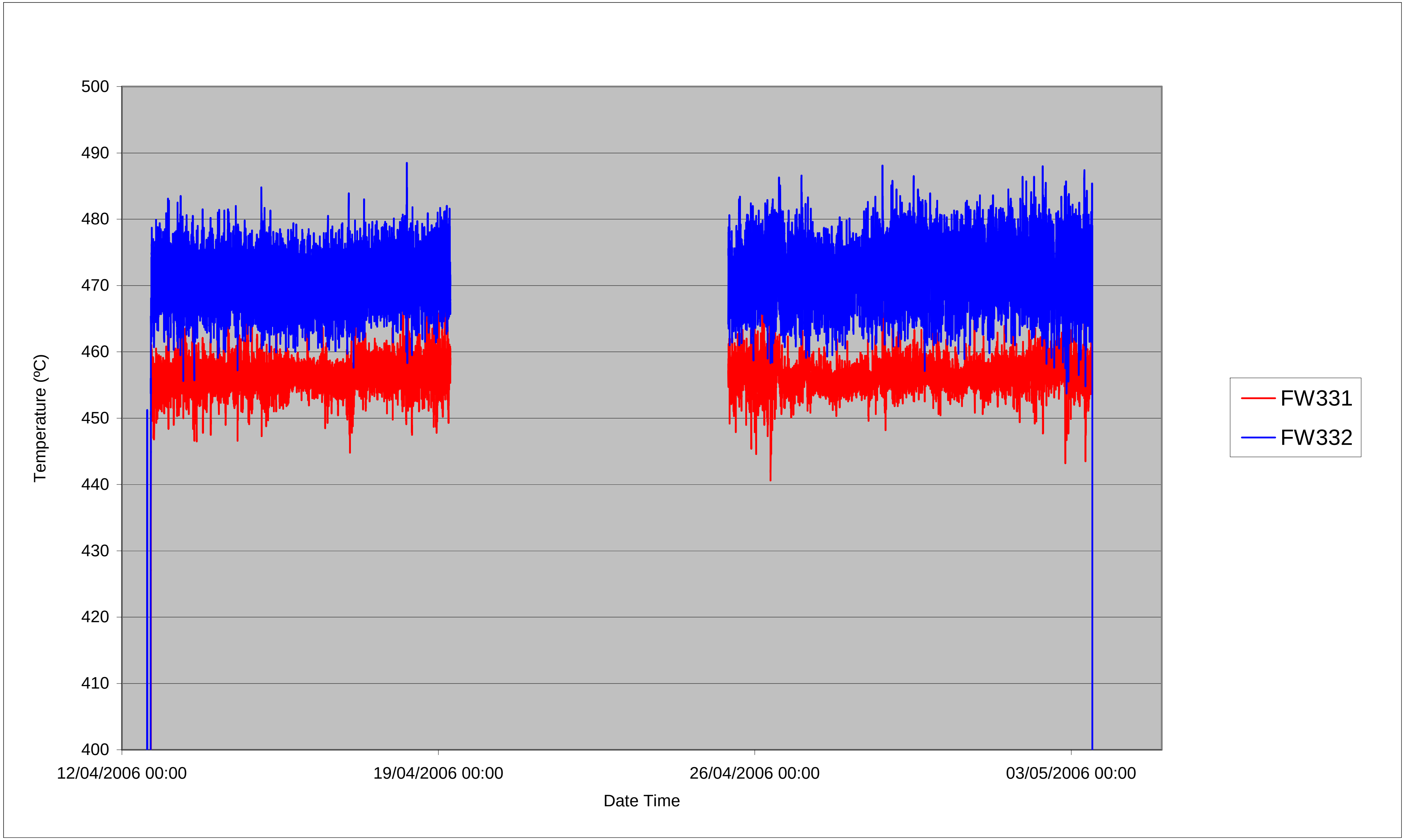


Figure 6: BATCH TWO FURNACE WALL PROBES SPECIMEN SURFACE TEMPERATURES

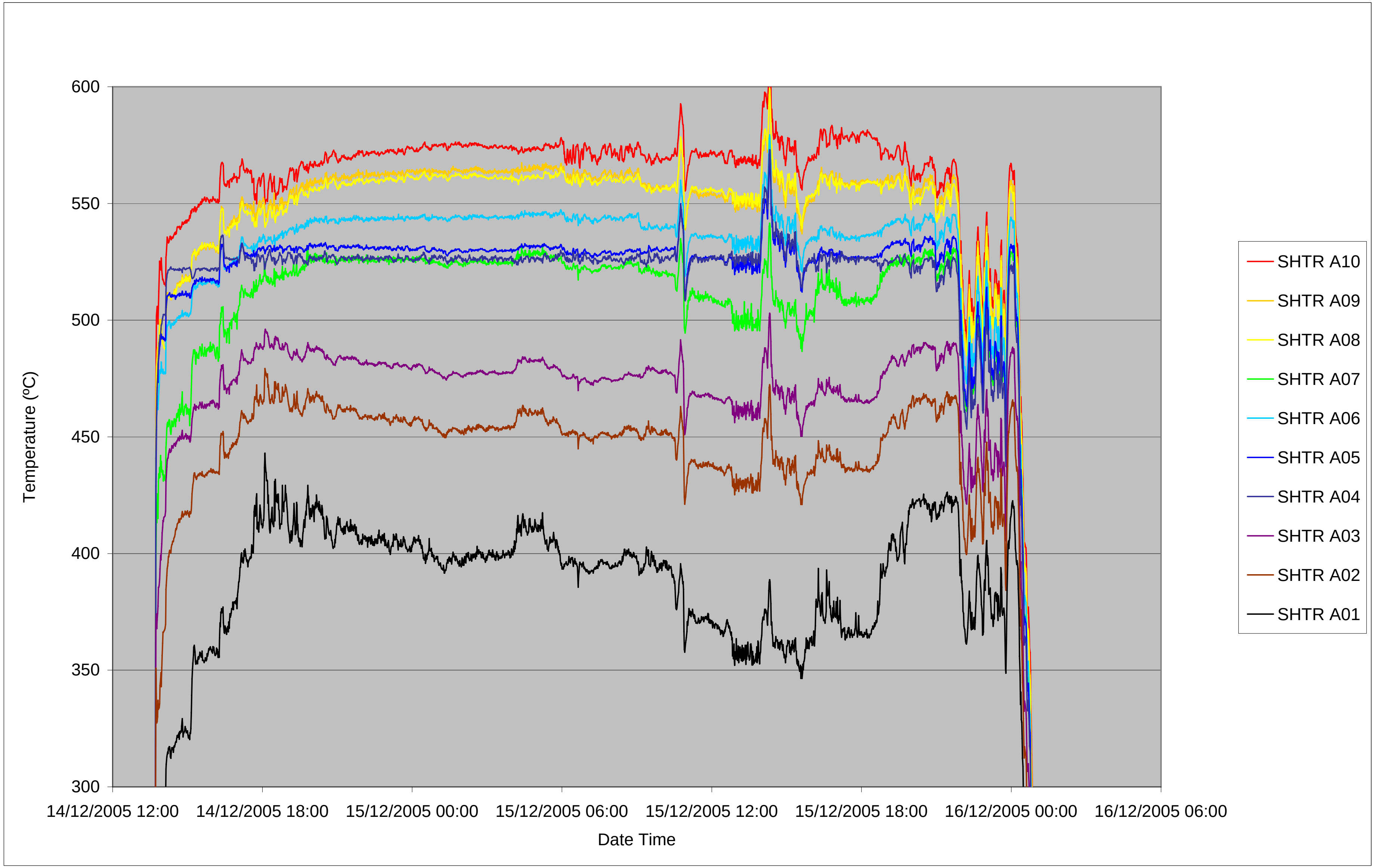


Figure 7: **BATCH 1 SHTR84 INDIVIDUAL SAMPLE MEASURED TEMPERATURES**

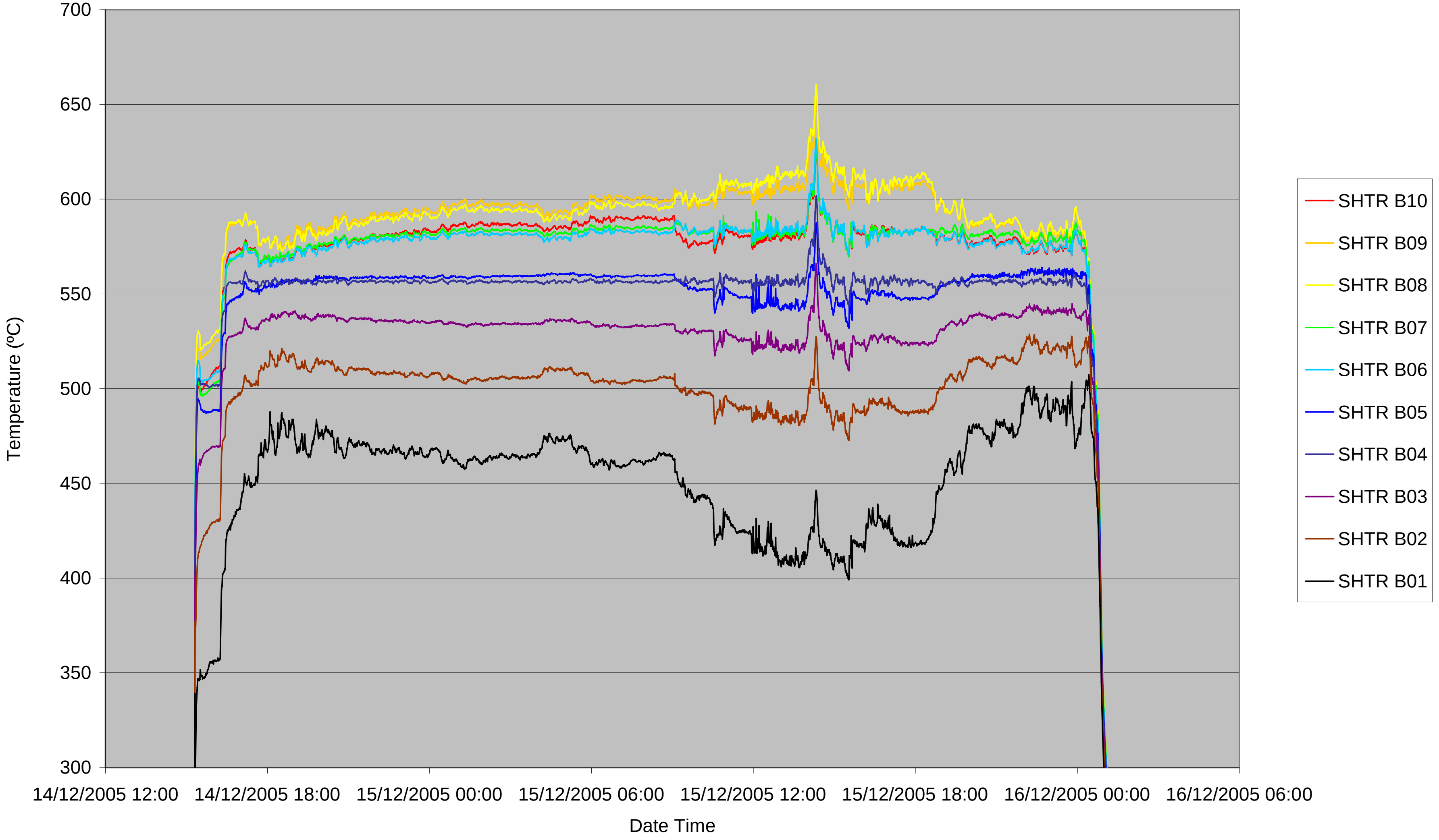


Figure 8: **BATCH 1 SHTR85 INDIVIDUAL SAMPLE MEASURED TEMPERATURES**

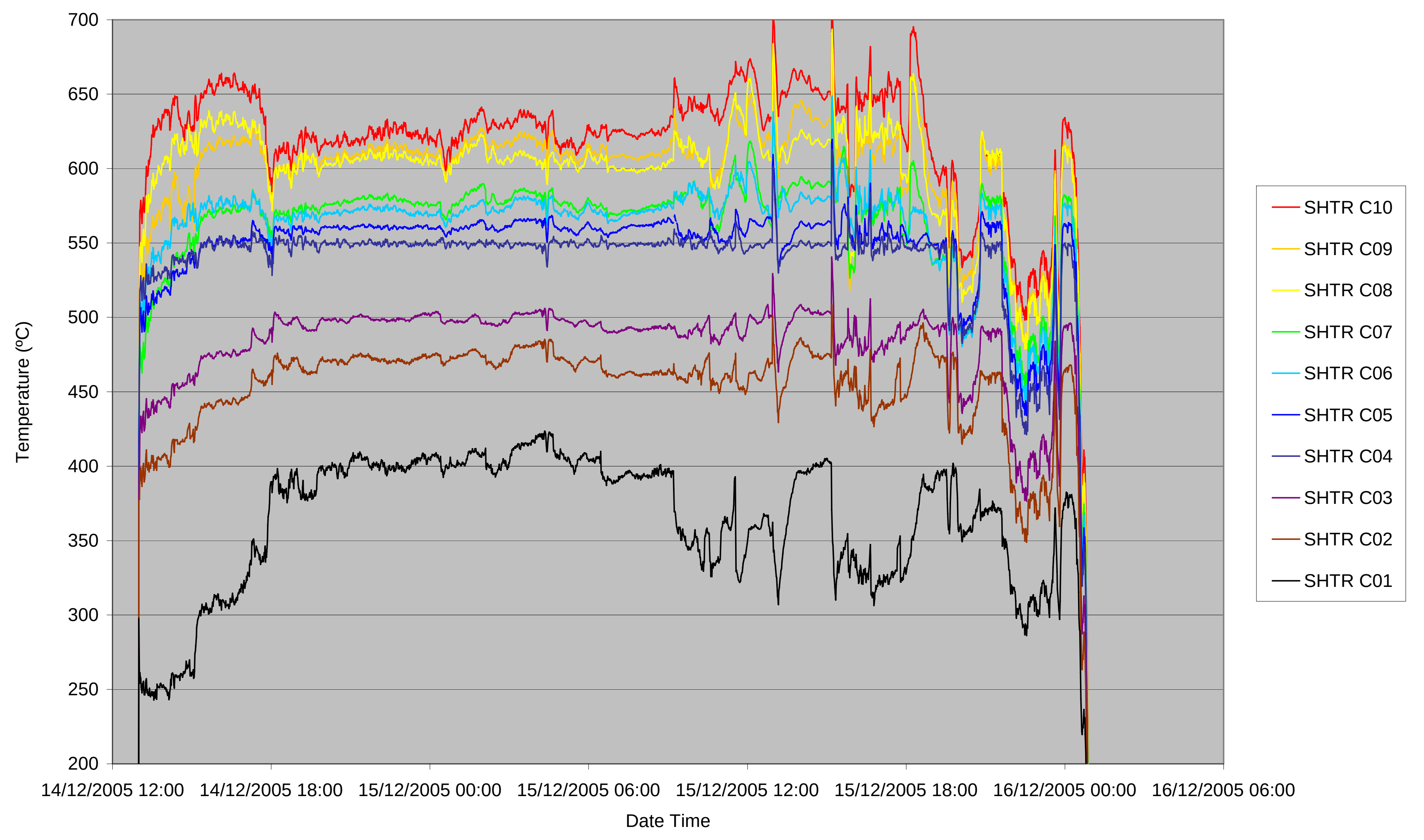


Figure 9: **BATCH 1 SHTR86 INDIVIDUAL SAMPLE MEASURED TEMPERATURES**

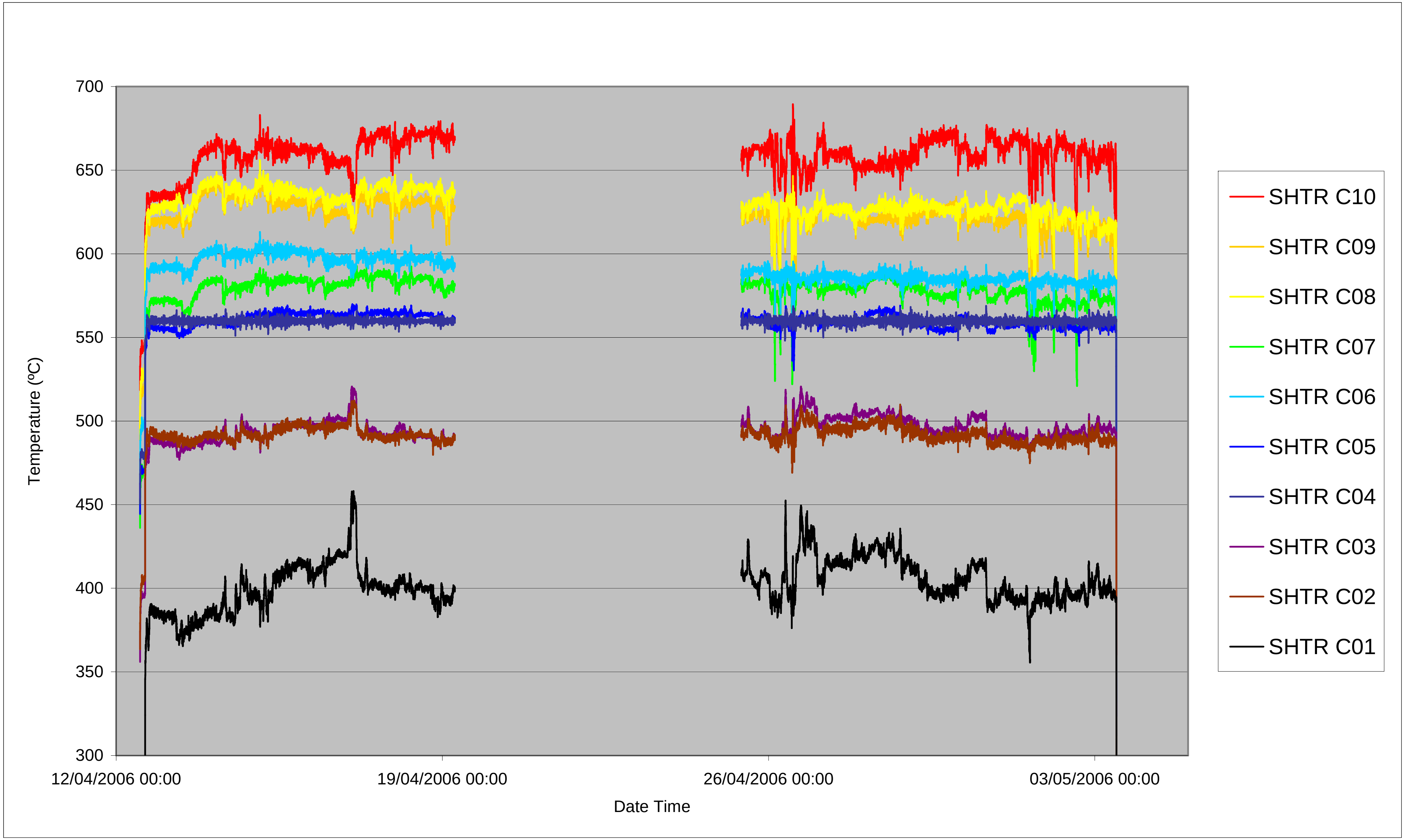


Figure 10: **BATCH 2 SHTR87 INDIVIDUAL SAMPLE MEASURED TEMPERATURES**

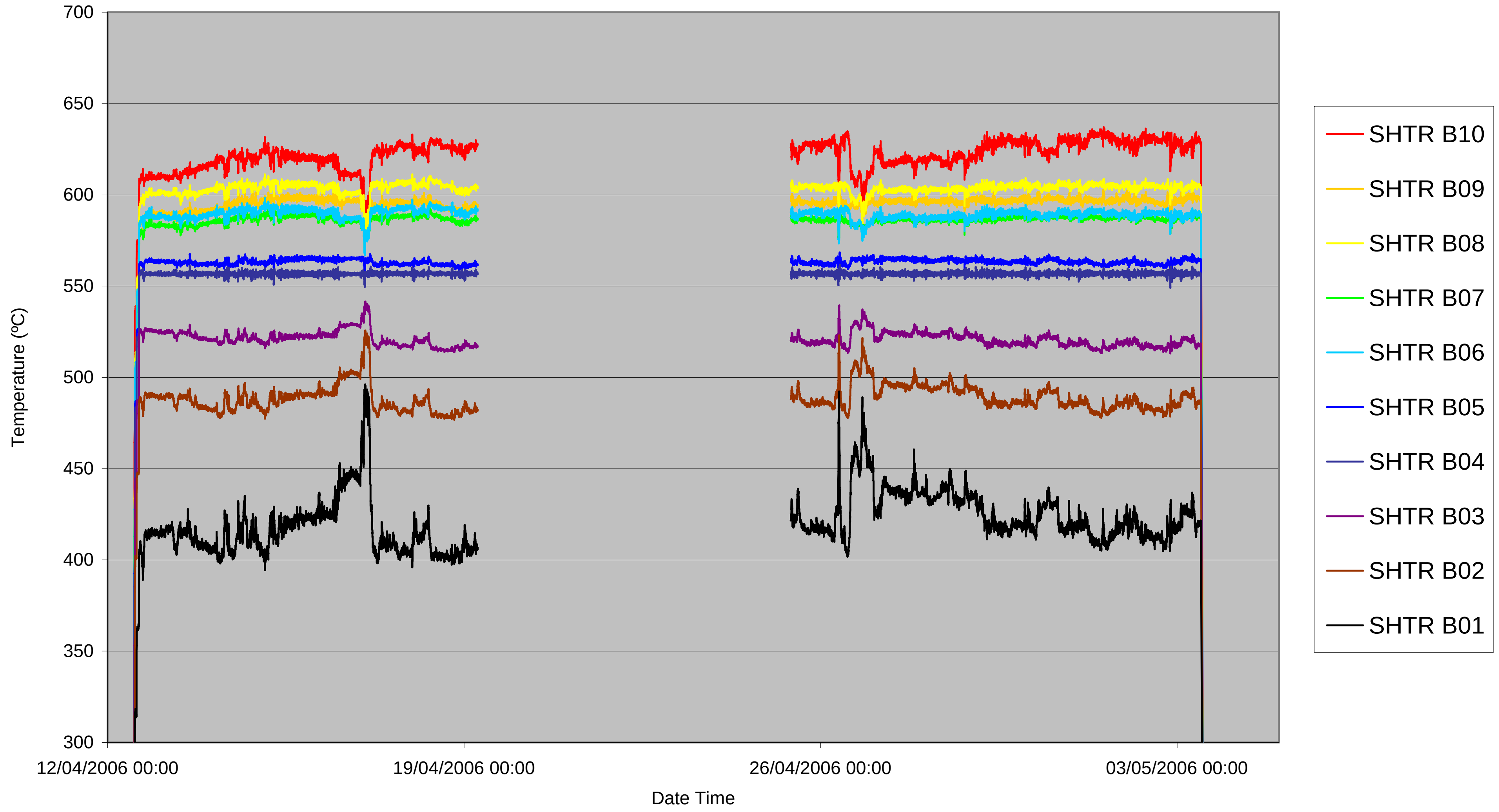


Figure 11: **BATCH 2 SHTR88 INDIVIDUAL SAMPLE MEASURED TEMPERATURES**

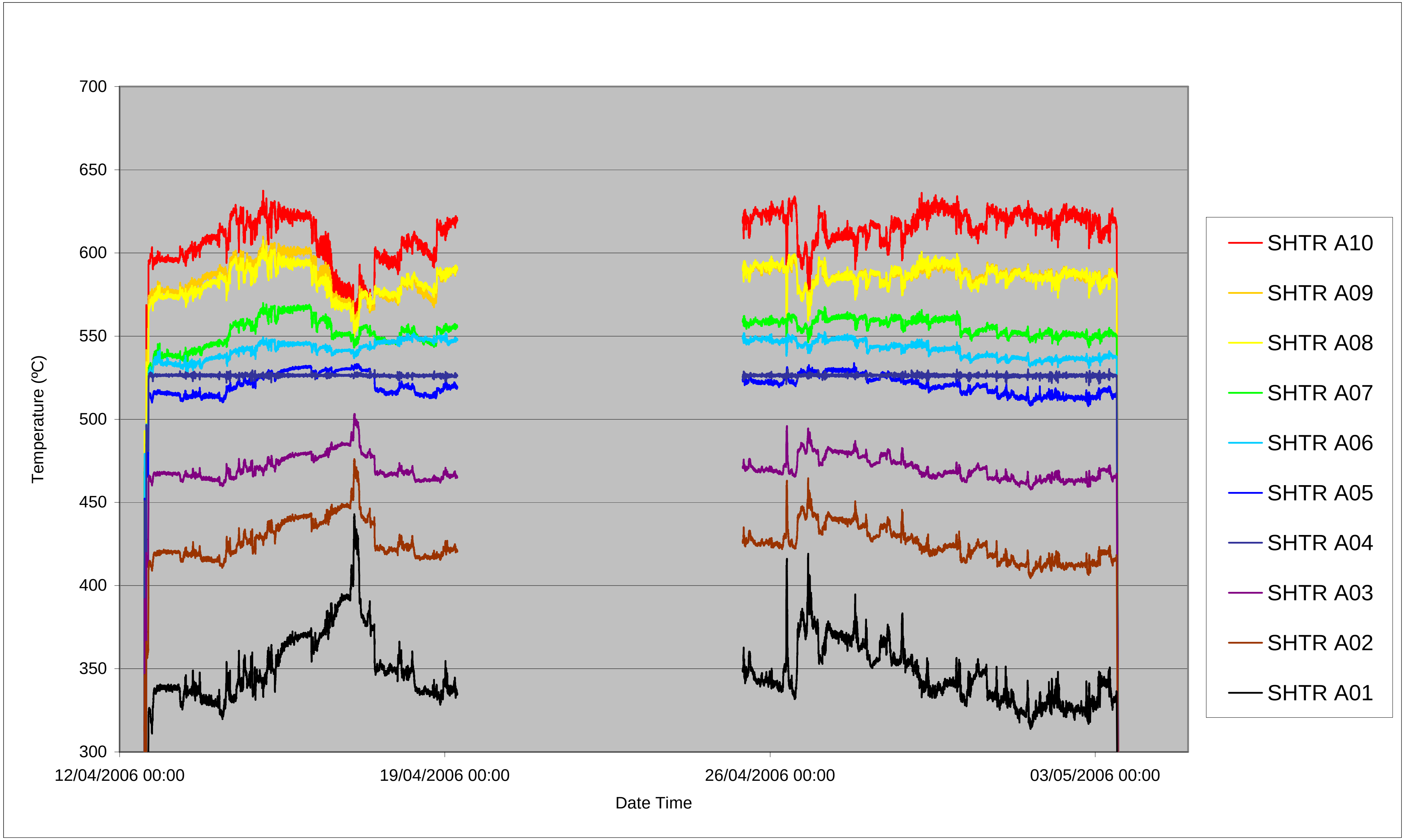


Figure 12: **BATCH 2 SHTR89 INDIVIDUAL SAMPLE MEASURED TEMPERATURES**

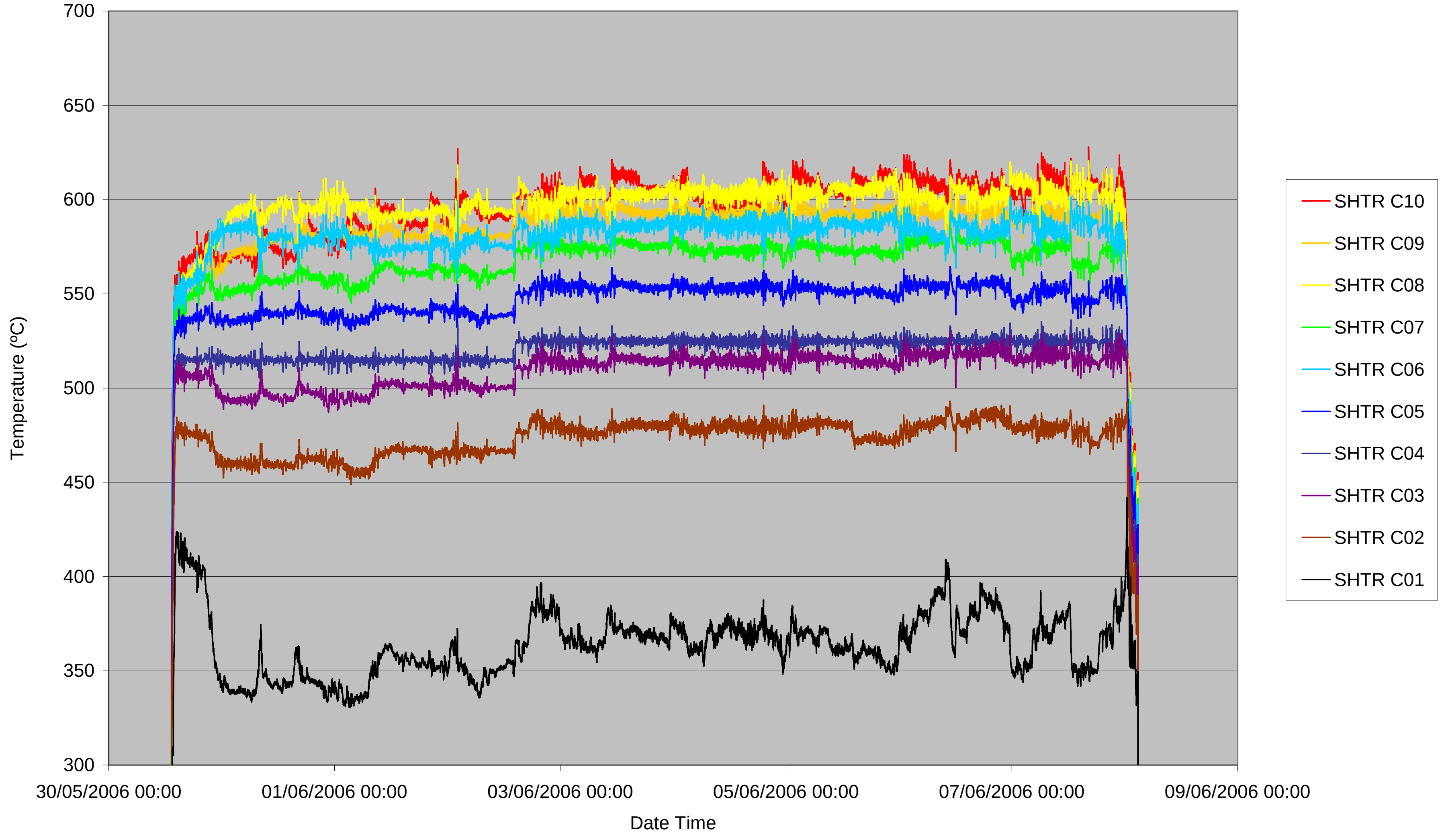


Figure 13: **BATCH 3 SHTR90 INDIVIDUAL SAMPLE MEASURED TEMPERATURES**

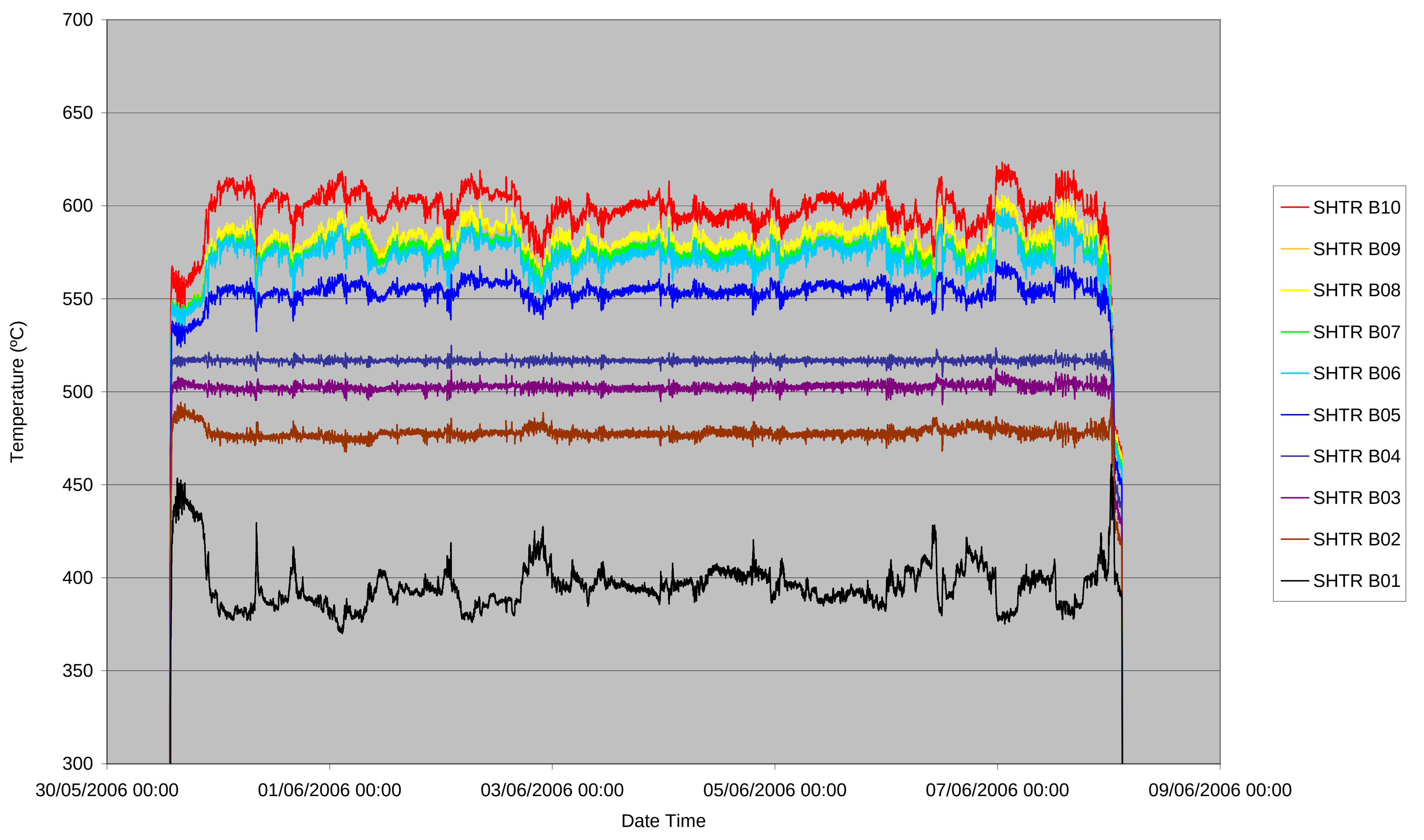


Figure 14: **BATCH 3SHTR91 INDIVIDUAL SAMPLE MEASURED TEMPERATURES**

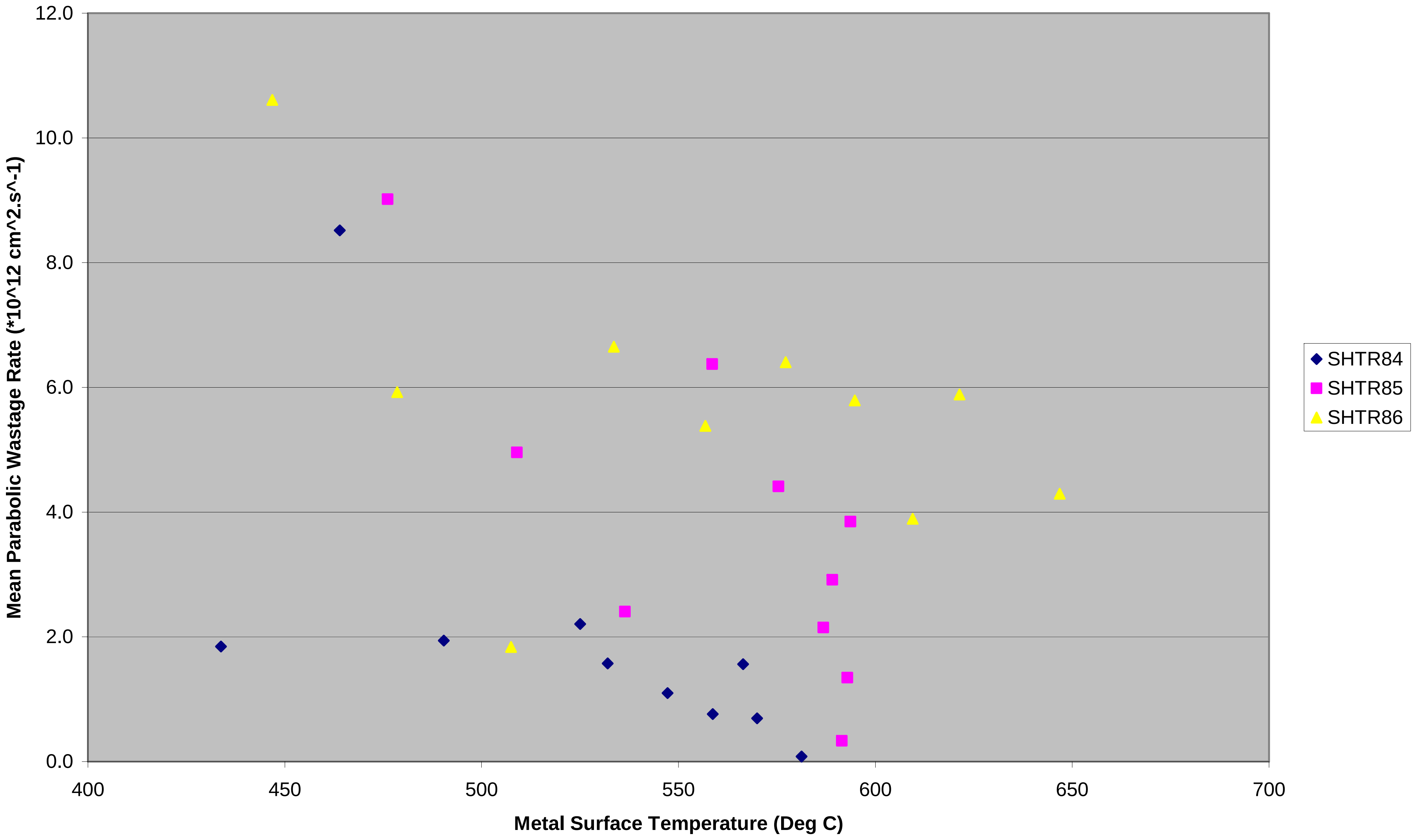


Figure 15: BATCH 1 SUPERHEATER CORROSION PROBES MEAN PARABOLIC WASTAGE RATES AFTER APPROXIMATELY 33 HOURS EXPOSURE

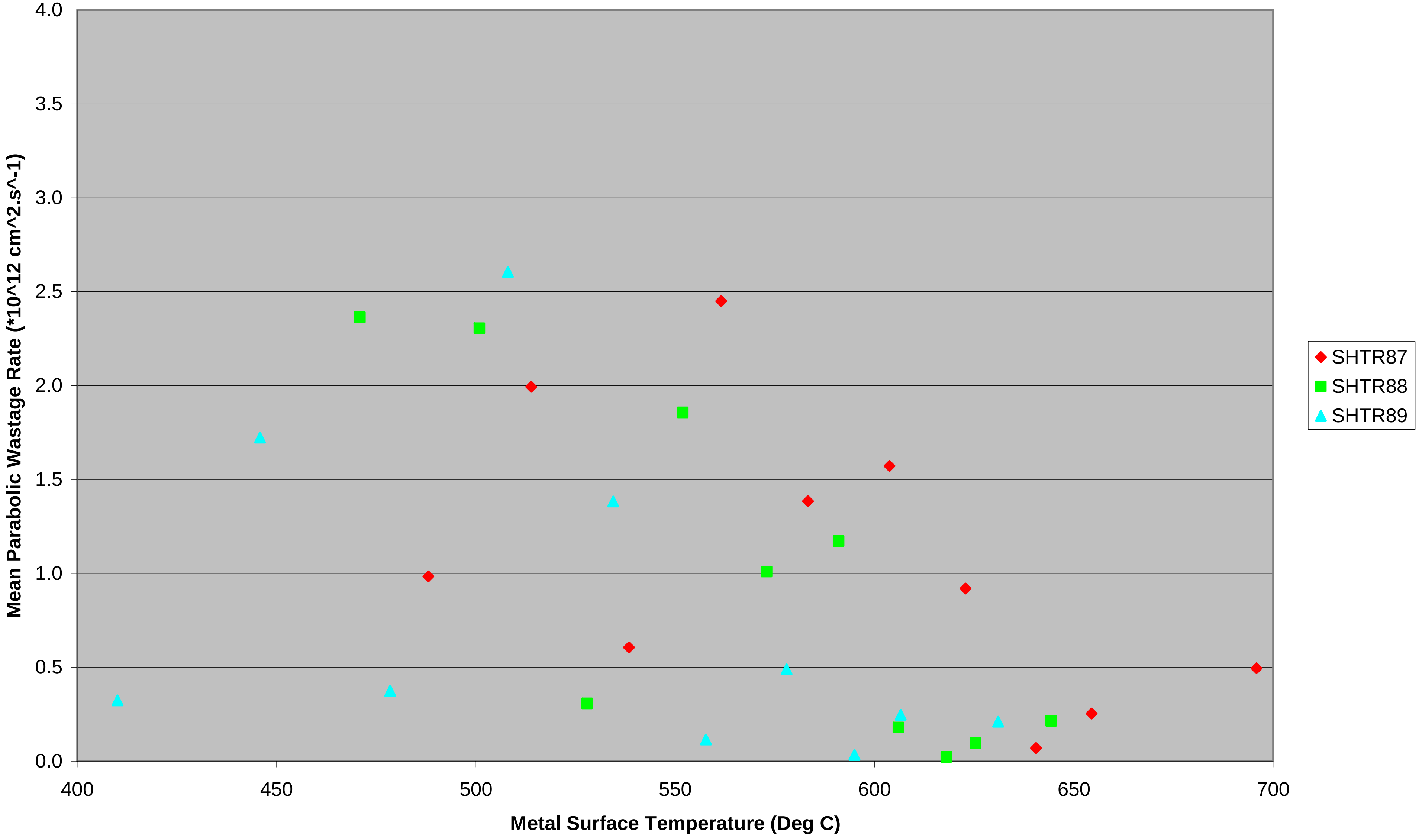


Figure 16: BATCH 2 SUPERHEATER CORROSION PROBES MEAN PARABOLIC WASTAGE RATES AFTER APPROXIMATELY 500 HOURS EXPOSURE

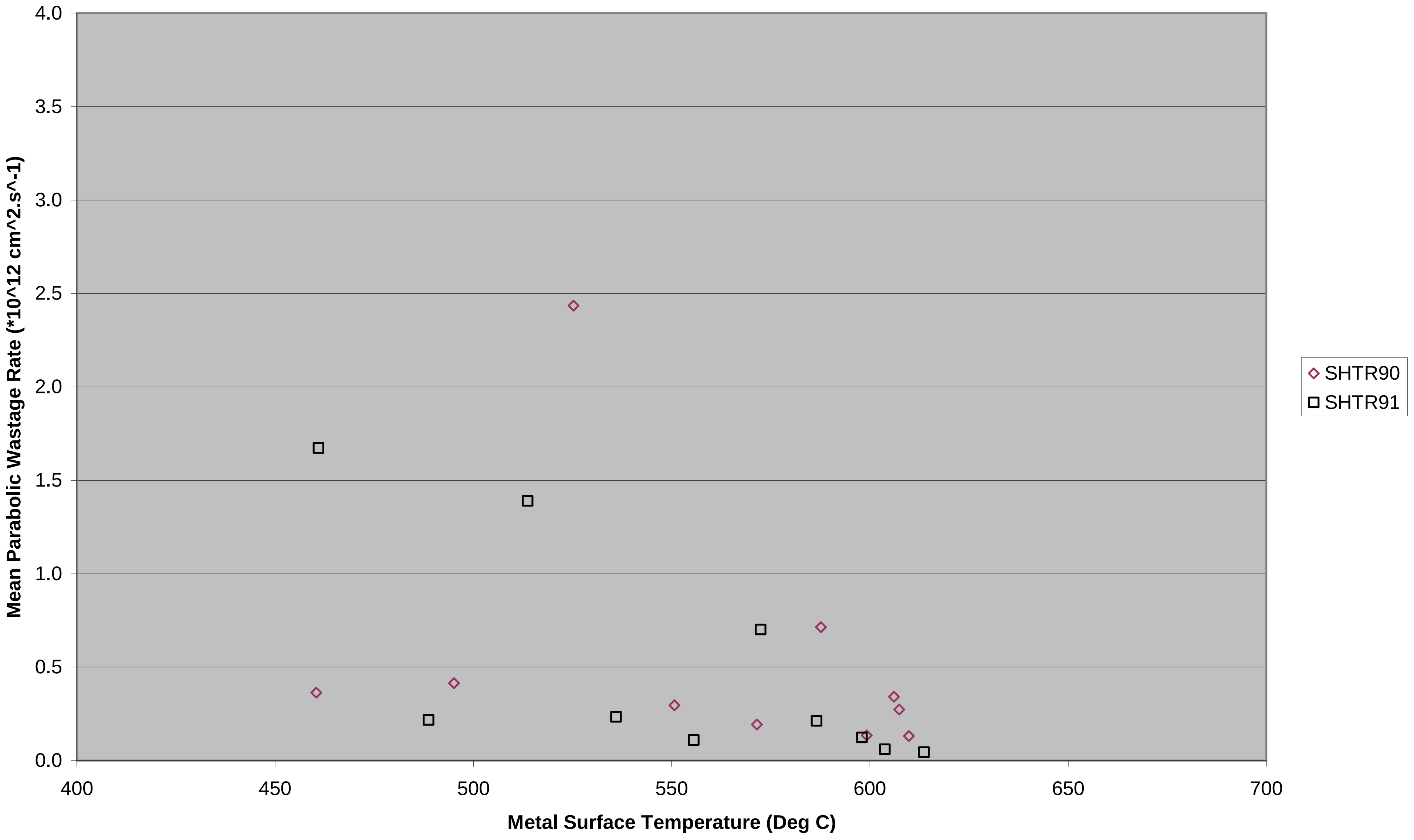


Figure 17: BATCH 3 SUPERHEATER CORROSION PROBES MEAN PARABOLIC WASTAGE RATES AFTER 203 HOURS EXPOSURE

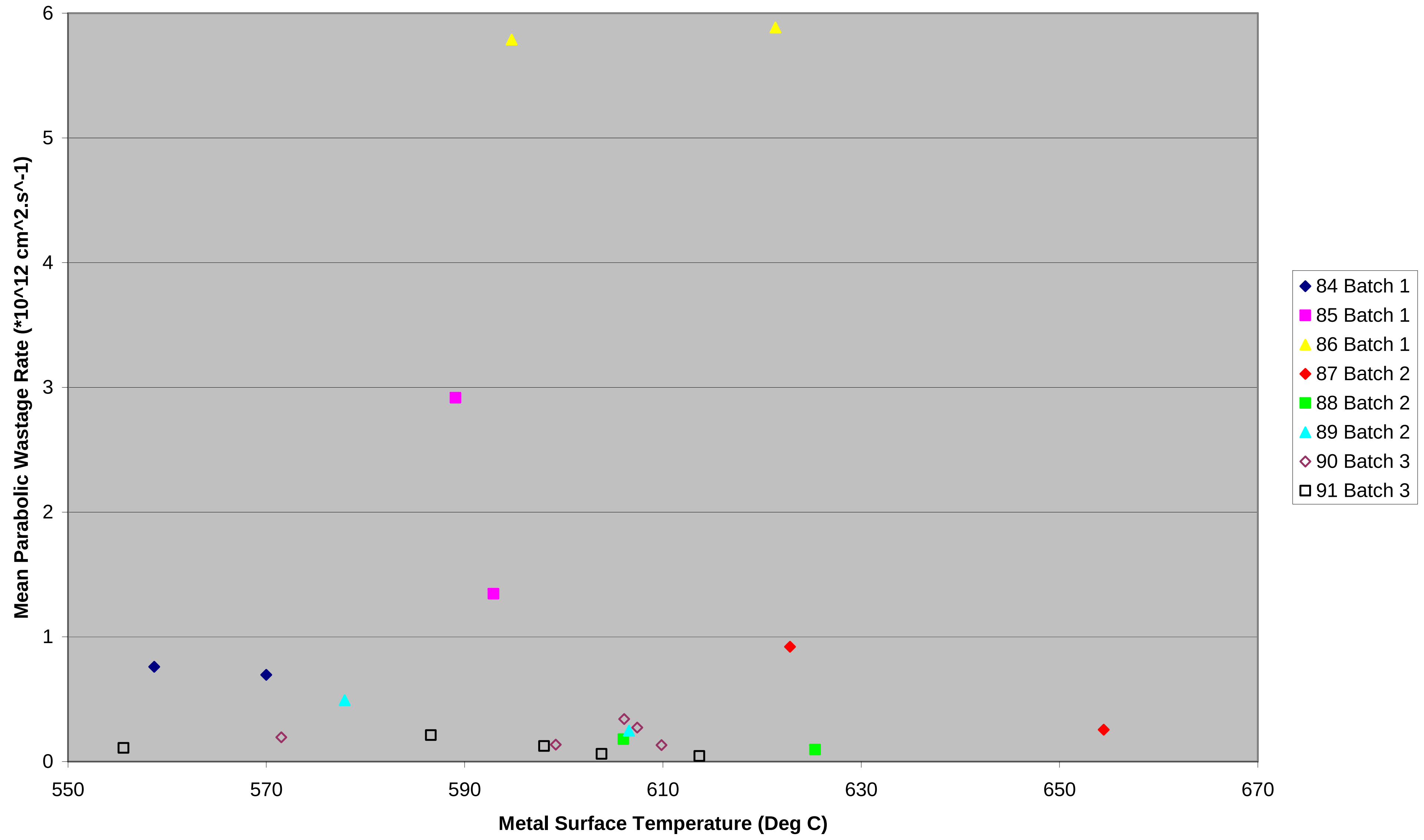


Figure 18: TP347HFG SUPERHEATER SPECIMENS MEAN PARABOLIC WASTAGE RATES

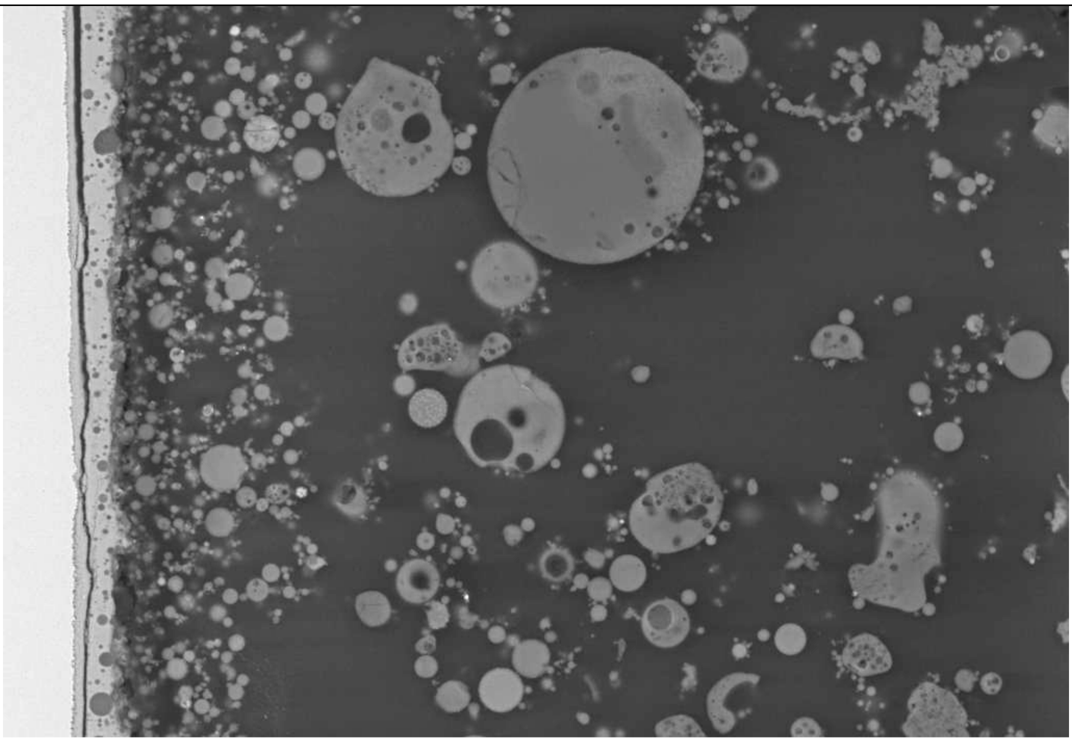


Figure 19: **BATCH 1, FW329, 10CrMo910, 471.9°C, 32.5 HOURS, BACK SCATTER ELECTRON IMAGE SHOWING DUPLEX CORROSION SCALE WITH PARTICULATE ASH DEPOSIT**

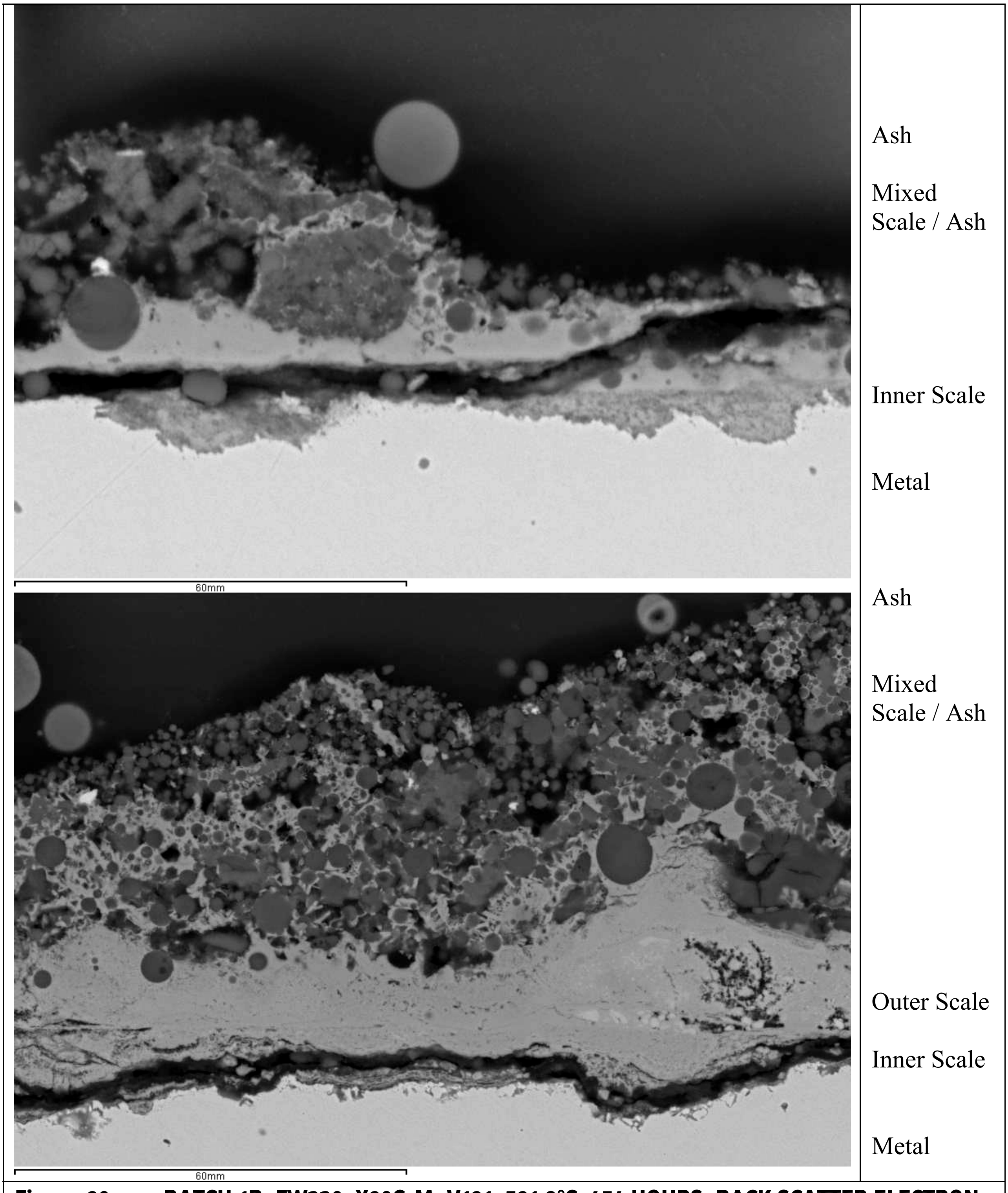


Figure 20: **BATCH 1B, FW330, X20CrMoV121, 521.9°C, 454 HOURS, BACK SCATTER ELECTRON IMAGES OF DUPLEX CORROSION SCALE WITH OUTER SCALE INCORPORATING PARTICULATE ASH MATERIAL**

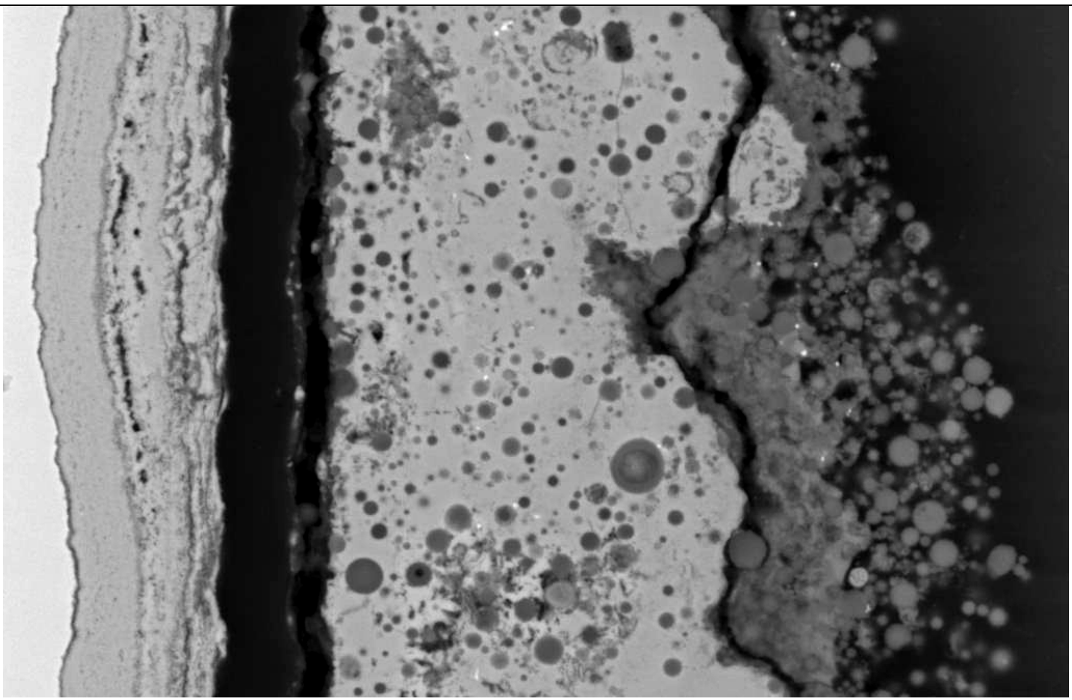


Figure 21: BATCH 2, FW331, 13CrMo44, 456.4°C, 500 HOURS, BACK SCATTER ELECTRON IMAGE OF (FRACTURED) DUPLEX SCALE, WITH OUTER SCALE INCORPORATING PARTICULATE ASH, AND OVERLAID BY AGGLOMERATING / PARTICULATE ASH

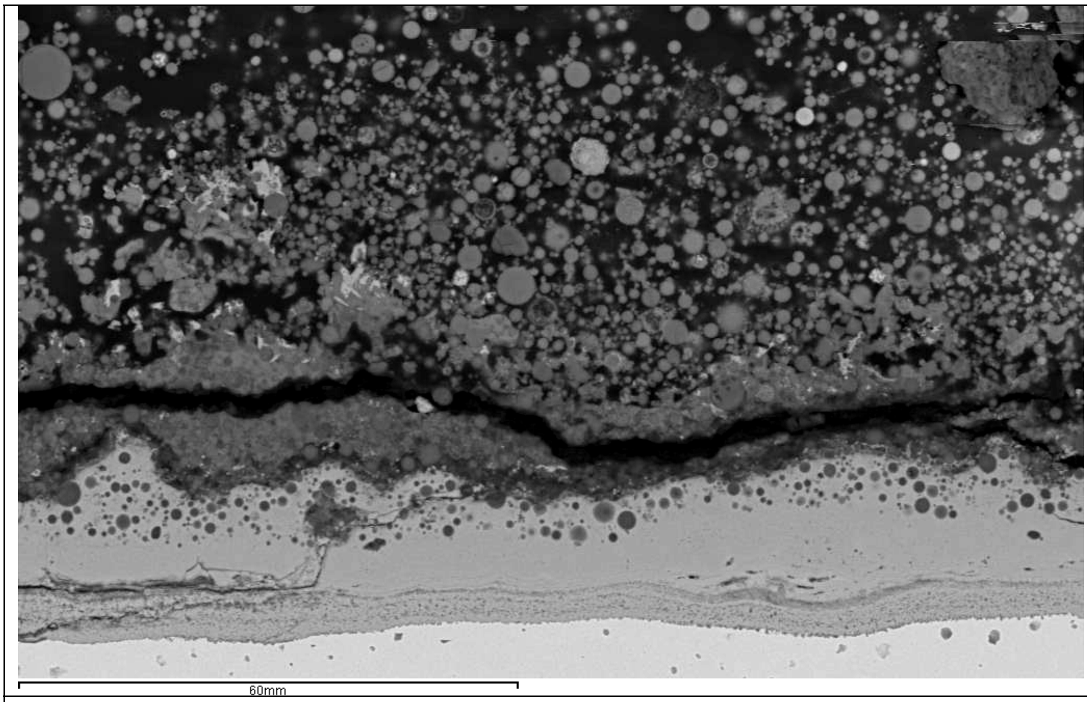


Figure 22: BATCH 2, FW332, 10CrMo910, 471.2°C, 500 HOURS, BACK SCATTER ELECTRON IMAGE OF DUPLEX SCALE, WITH OUTER SCALE INCORPORATING PARTICULATE ASH, AND OVERLAID BY AGGLOMERATING / PARTICULATE ASH

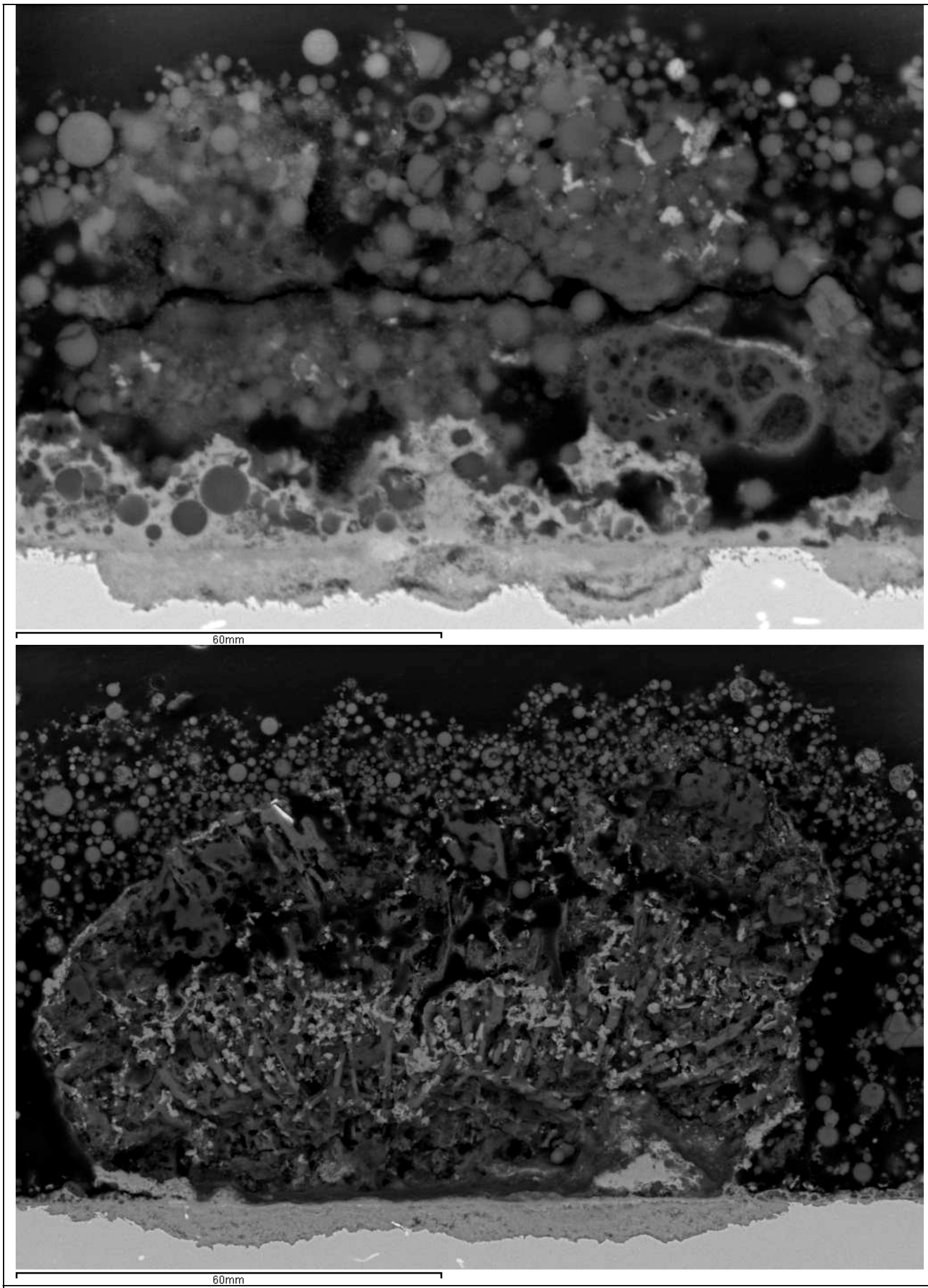


Figure 23: **BATCH 1, SHTR84, SPECIMEN 7, TP347HFG, 558.7°C, 33.9 HOURS, BACK SCATTER ELECTRON IMAGES SHOWING IRREGULAR CORROSION / PITTING WITH OUTER CORROSION SCALE MIXED WITH AMORPHOUS AND PARTICULATE ASH**

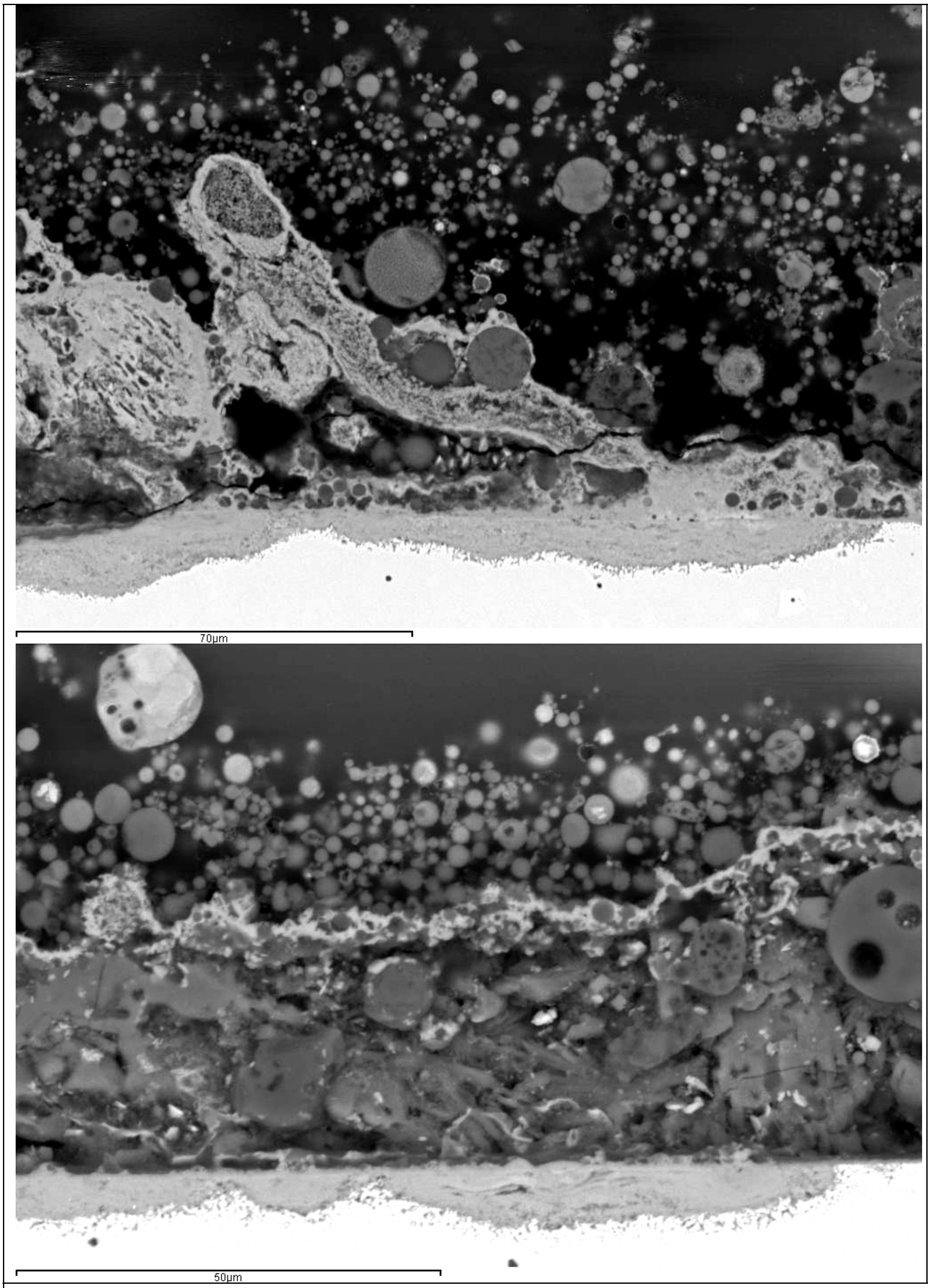


Figure 24: BATCH 1, SHTR84, SPECIMEN 8, SAVE25, 566.4°C, 33.9 HOURS, BACK SCATTER ELECTRON IMAGES SHOWING IRREGULAR CORROSION / PITTING AND SUB-SURFACE ATTACK, WITH DEFECTIVE OUTER CORROSION SCALE MIXED WITH AMORPHOUS AND PARTICULATE ASH

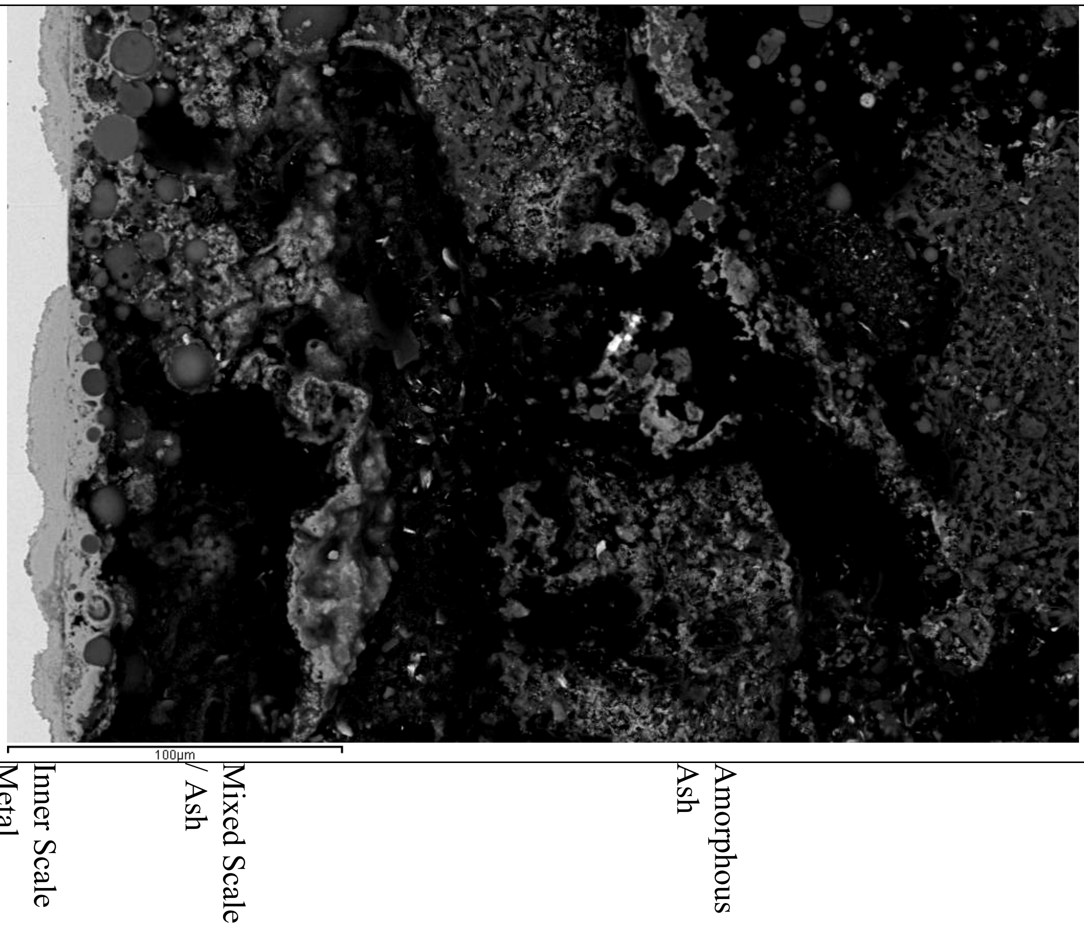


Figure 25: **BATCH 1, SHTR86, SPECIMEN 5, X20CrMo121, 554.8°C, 33 HOURS, BACK SCATTER ELECTRON IMAGE SHOWING IRREGULAR BREAKDOWN OF THE INITIALLY PROTECTIVE CHROMIA SCALE TO GIVE A DUPLEX CORROSION SCALE OVERLAID BY AN AMORPHOUS ASH DEPOSIT**

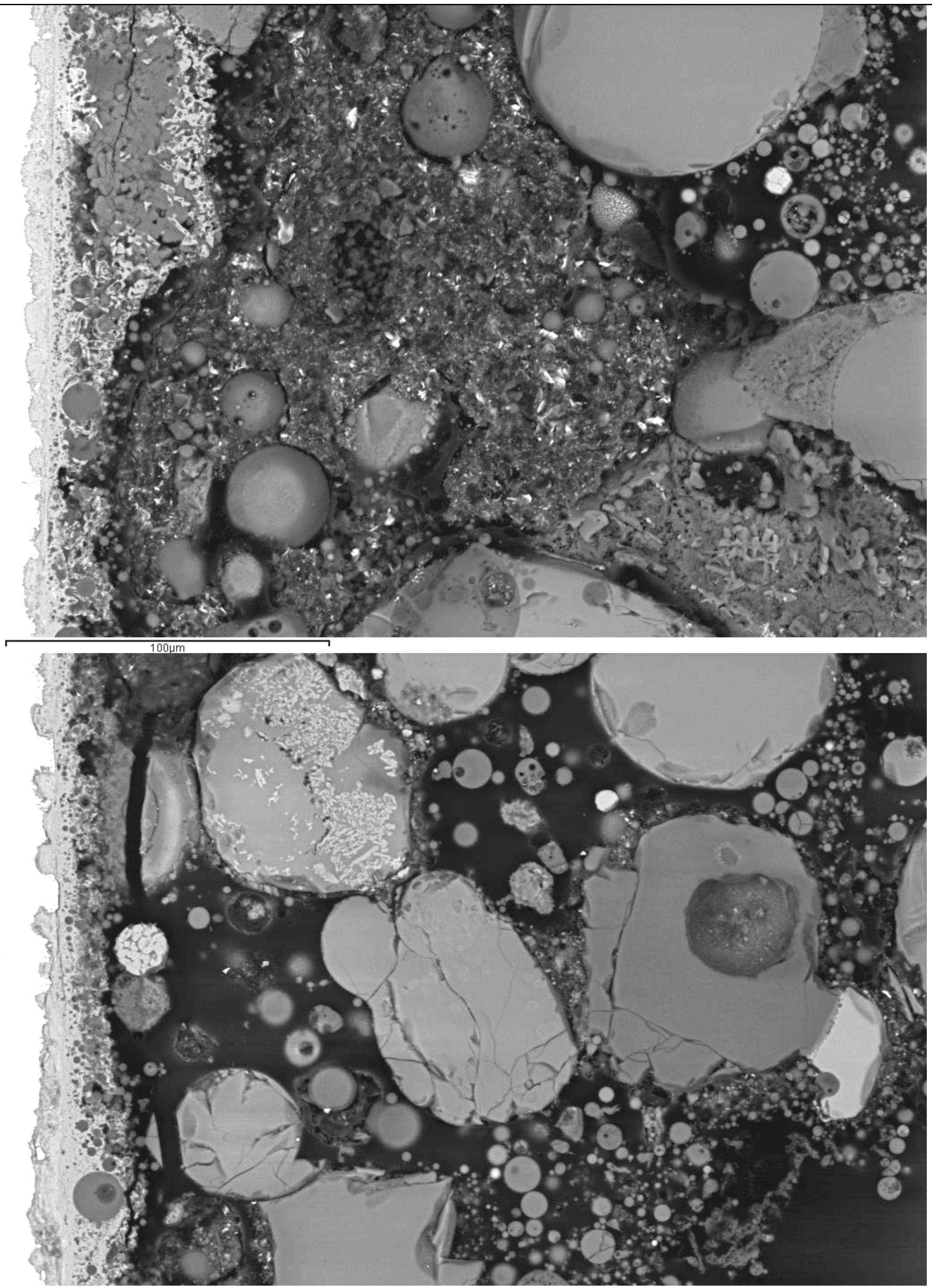


Figure 26: BATCH 1, SHTR86 SPECIMEN 6, ESHEETE1250, 575.3°C, 33 HOURS, BACK SCATTER ELECTRON IMAGE SHOWING IRREGULAR, GENERAL ATTACK FORMING A DUPLEX CORROSION SCALE OVERLAID BY PARTICULATE AND AMORPHOUS ASH

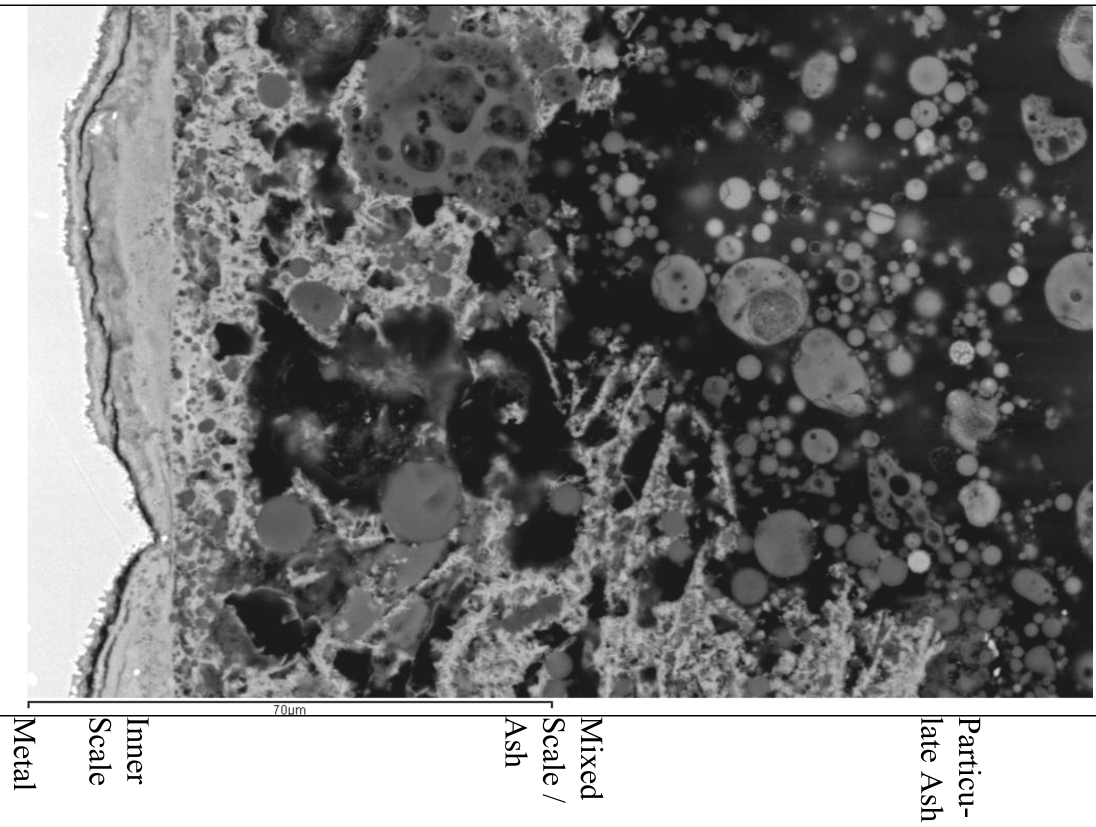


Figure 27: BATCH 1, SHTR86, SPECIMEN 7, TP347HFG, 593.3°C, 33 HOURS, BACK SCATTER ELECTRON IMAGE OF A DUPLEX CORROSION SCALE WITH A DEFECTIVE OUTER SCALE

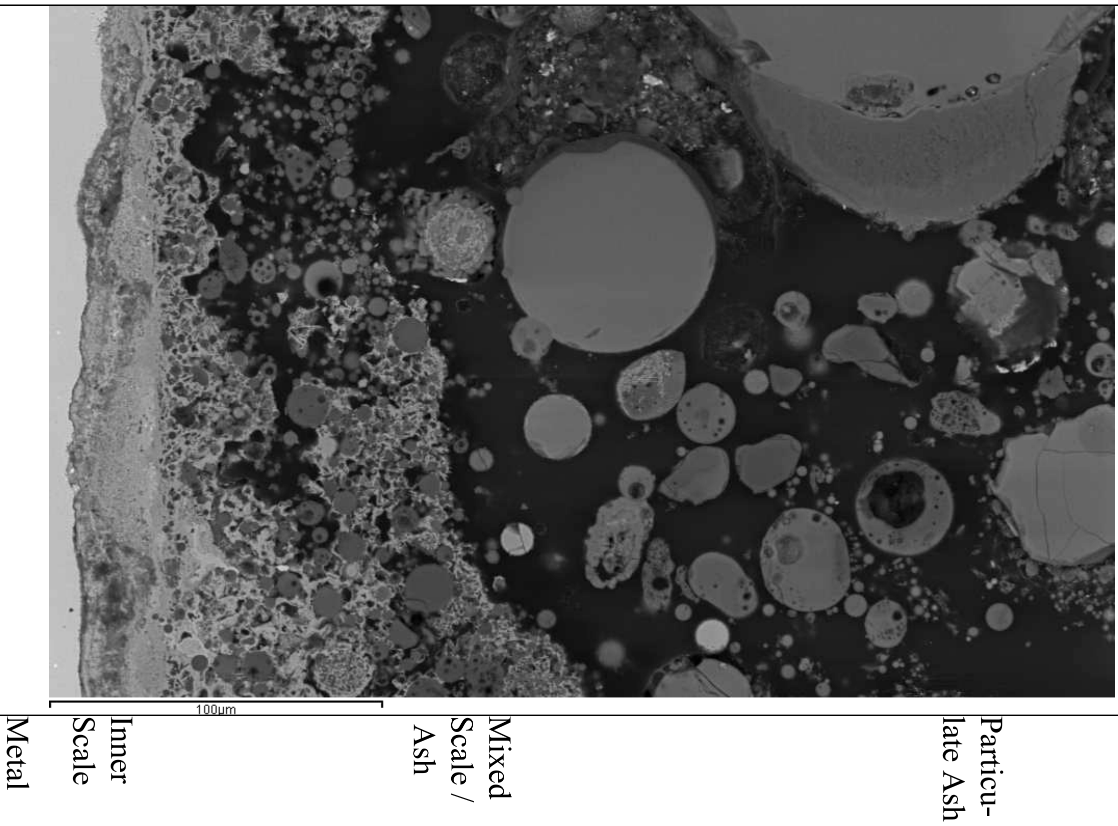


Figure 28: BATCH 1, SHTR86, SPECIMEN 8, SAVE25, 608.8°C, 33 HOURS, BACK SCATTER ELECTRON IMAGE OF DUPLEX SCALE AND PARTICULATE ASH DEPOSIT

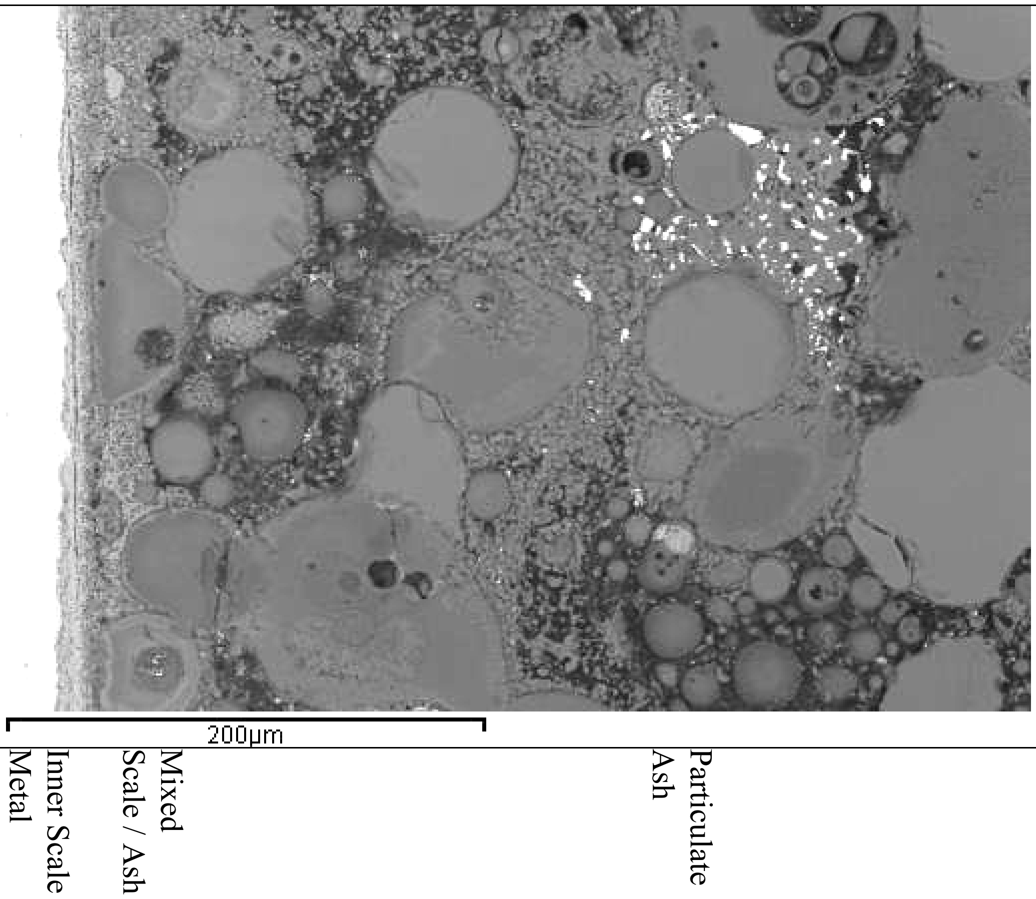


Figure 29: BATCH 2, SHTR87, SPECIMEN 3, X20CrMoV121, 538.4°C, 500 HOURS, BACK SCATTER ELECTRON IMAGE SHOWING IRREGULAR, GENERAL ATTACK AND DUPLEX CORROSION SCALE OVERLAID WITH PARTICULATE ASH MATERIAL (BRIGHT MATERIAL BARIUM RICH)

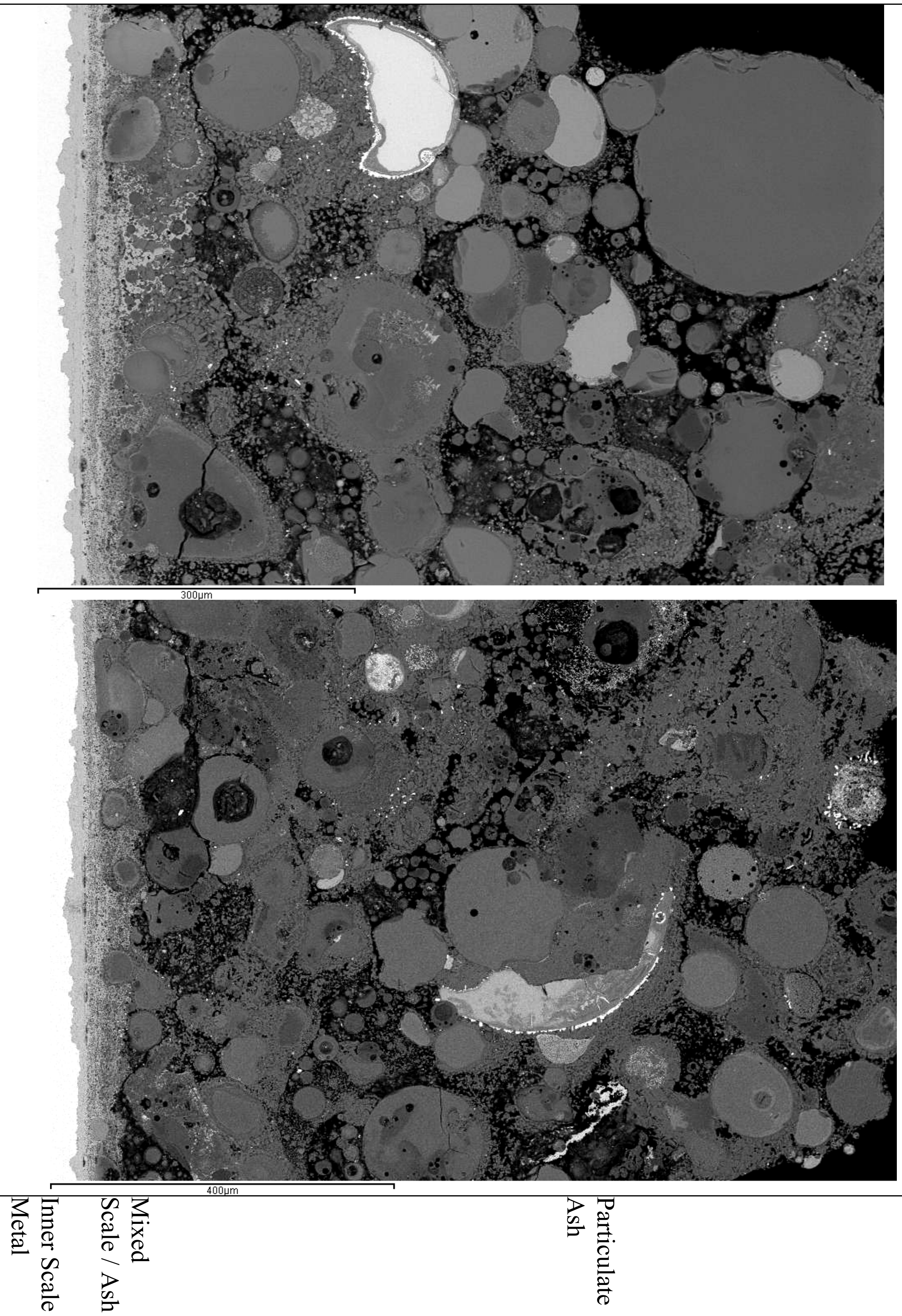


Figure 30: BATCH 2, SHTR87, SPECIMEN 4, T91, 561.5°C, 500 HOURS, BACK SCATTER ELECTRON IMAGES SHOWING IRREGULAR, GENERAL ATTACK AND DUPLEX CORROSION SCALE OVERLAID WITH PARTICULATE ASH MATERIAL (BRIGHT MATERIAL BARIUM RICH)

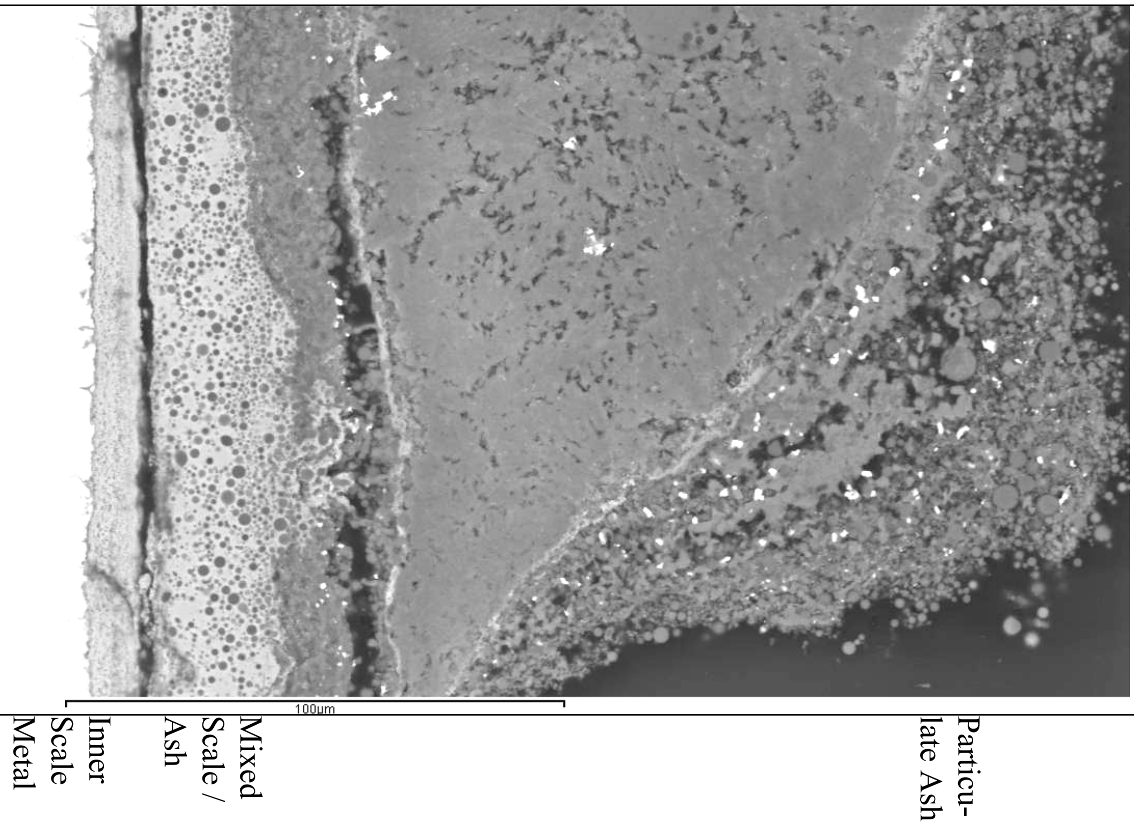


Figure 31: BATCH 2, SHTR88, SPECIMEN 2, 10CrMo910, 500.9°C, 501 HOURS, BACK SCATTER ELECTRON IMAGE OF UNIFORM WASTAGE, DUPLEX SCALES AND AMORPHOUS ASH

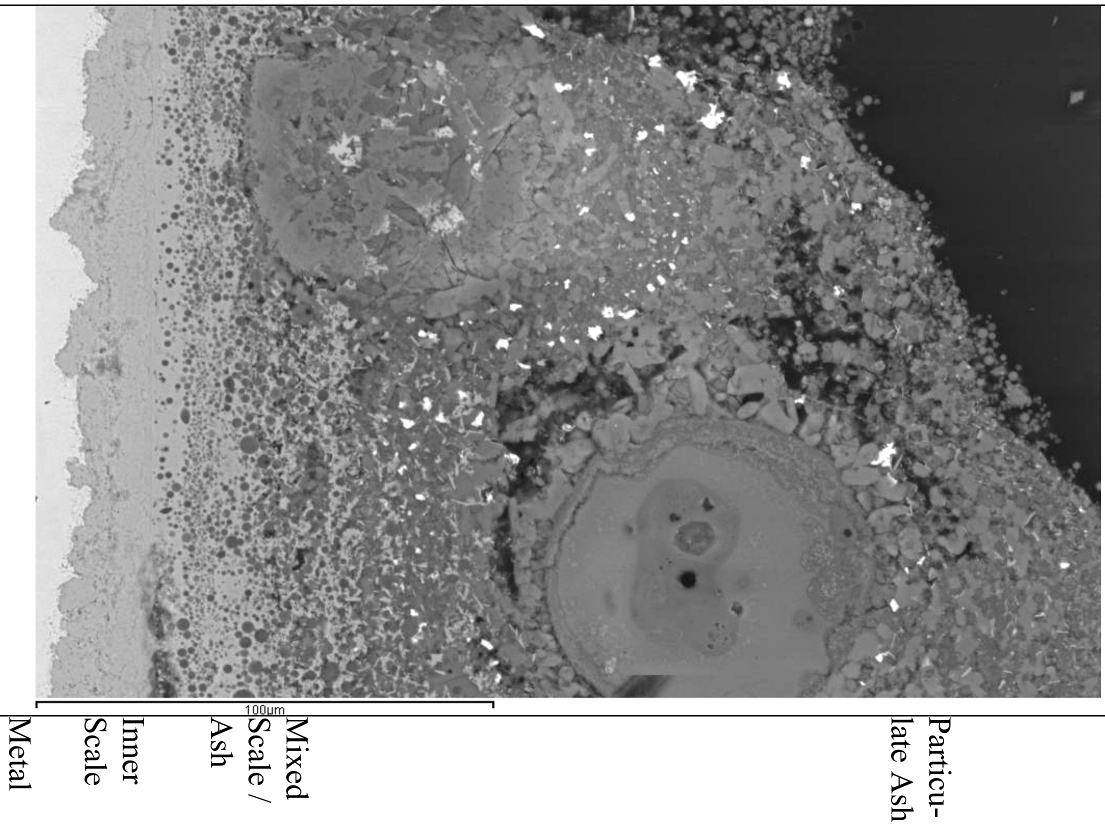


Figure 32: BATCH 2, SHTR88, SPECIMEN 4, T91, 551.9°C, 501 HOURS, BACK SCATTER IMAGE OF IRREGULAR WASTAGE, DUPLEX SCALES AND PARTICULATE / AMORPHOUS ASH

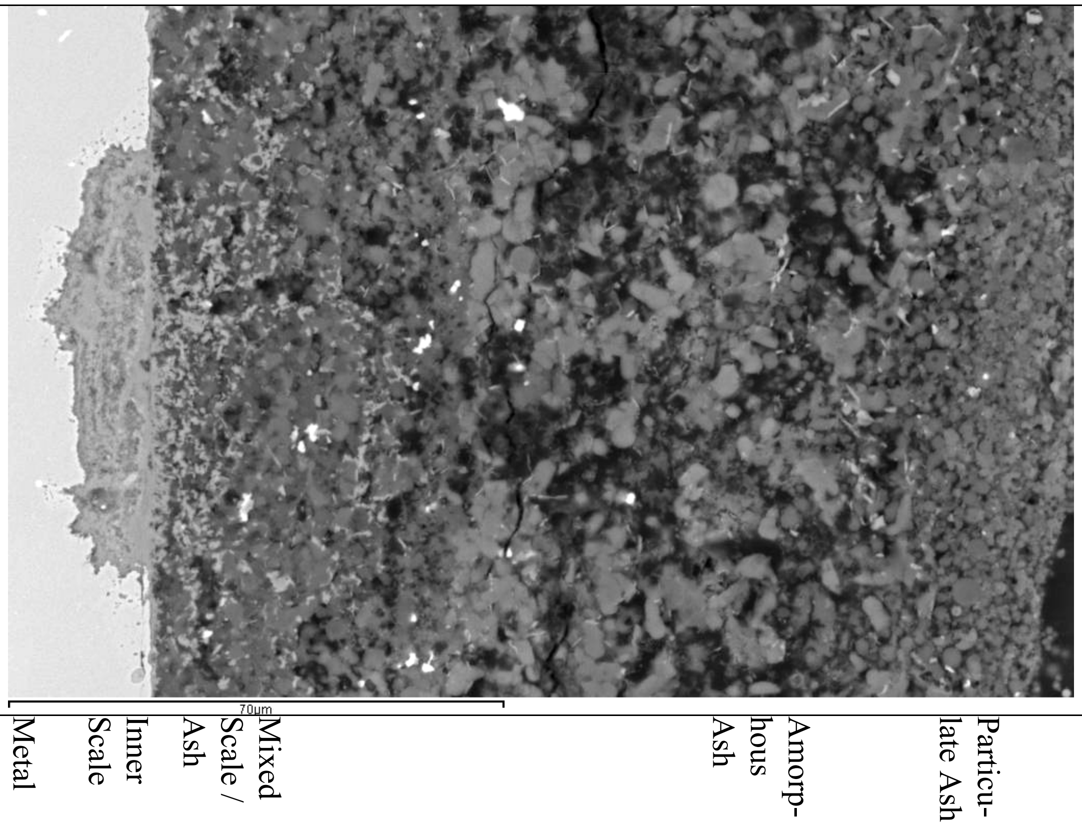


Figure 33: BATCH 2, SHTR88, SPECIMEN 7, TP347HFG, 606.0°C, 501 HOURS, IMAGE OF PITTING / SUBSURFACE ATTACK. DEFECTIVE OUTER SCALE MIXED WITH ASH

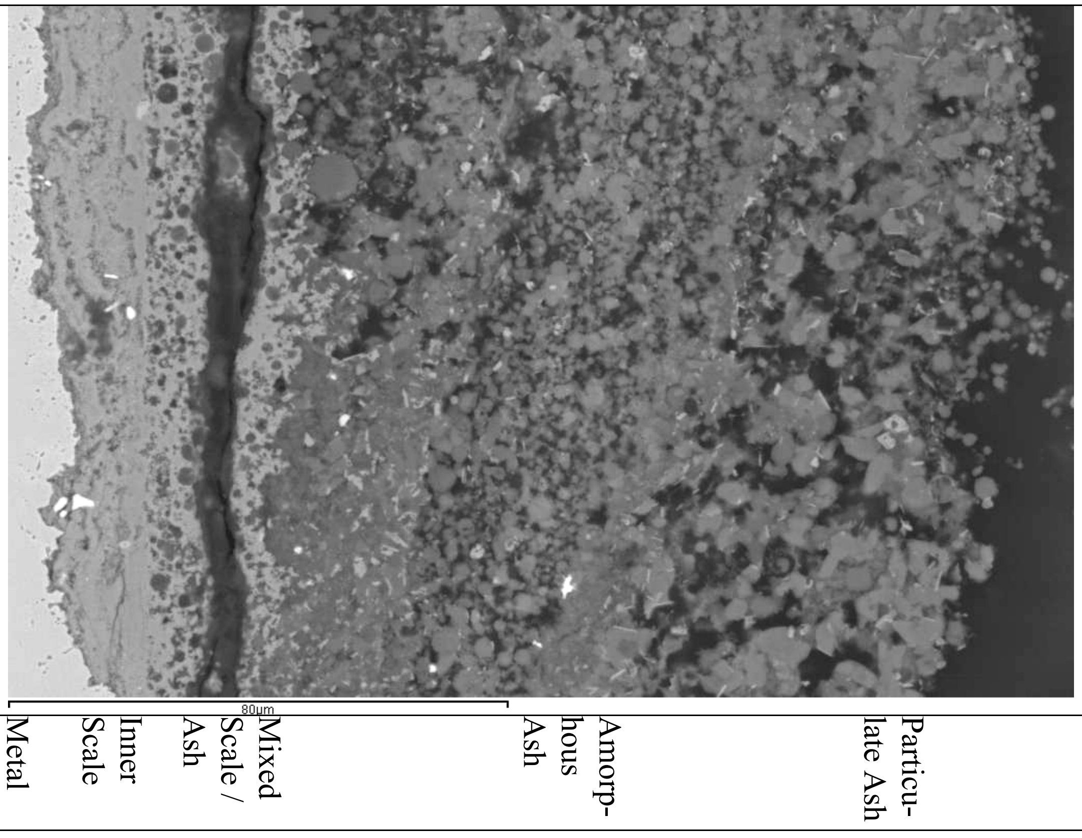


Figure 34: BATCH 2, SHTR88, SPECIMEN 9, TP347HFG, 625.3°C, 501 HOURS, IRREGULAR / SUBSURFACE ATTACK AND OUTER SCALE / ASH INTERACTION

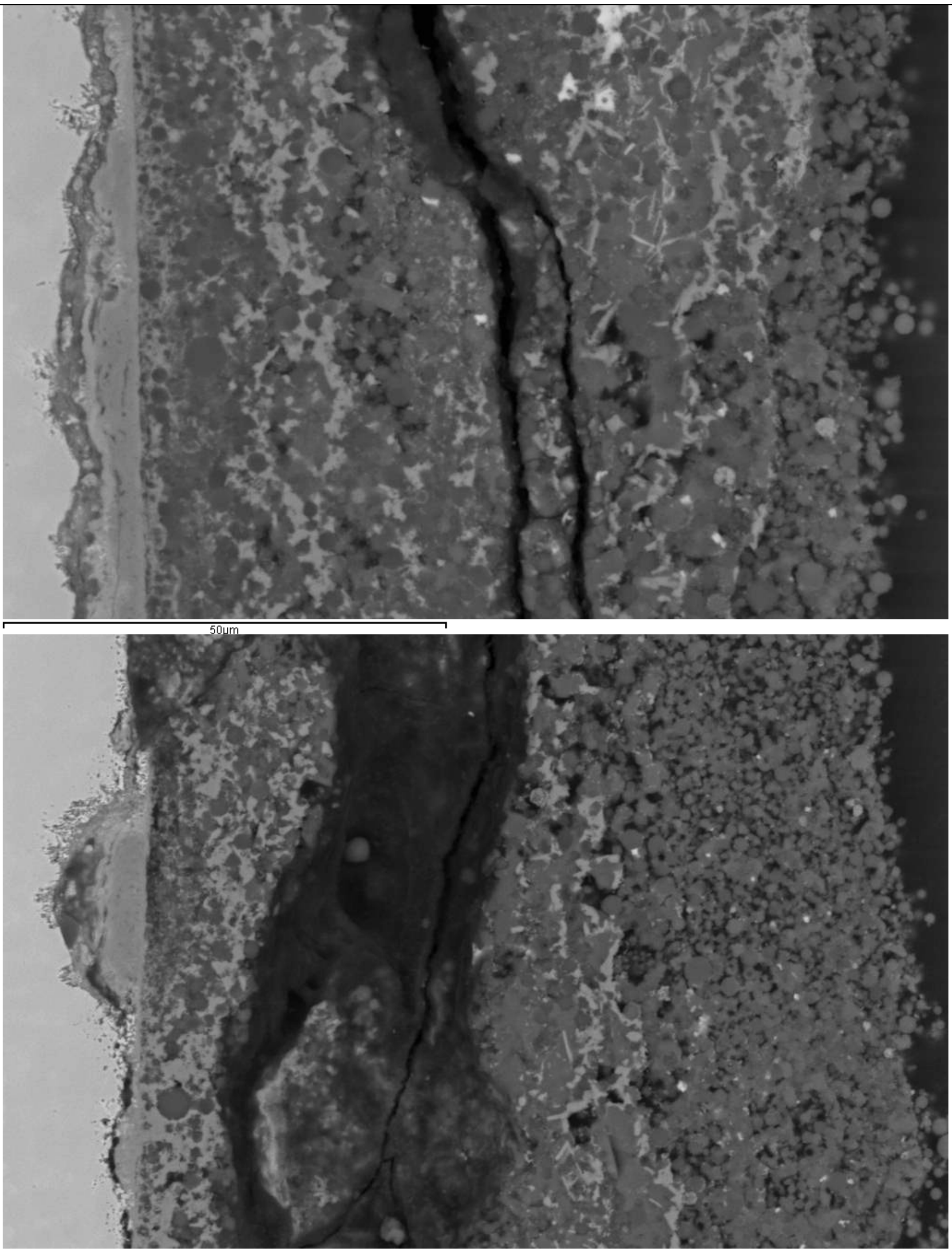


Figure 35: BATCH 2, SHTR88, SPECIMEN 10, IN625, 644.3°C, 501 HOURS, BACK SCATTER ELECTRON IMAGES OF IRREGULAR / PITTING AND SUBSURFACE ATTACK. OUTER CORROSION SCALE INTERACTING WITH AMORPHOUS ASH DEPOSIT

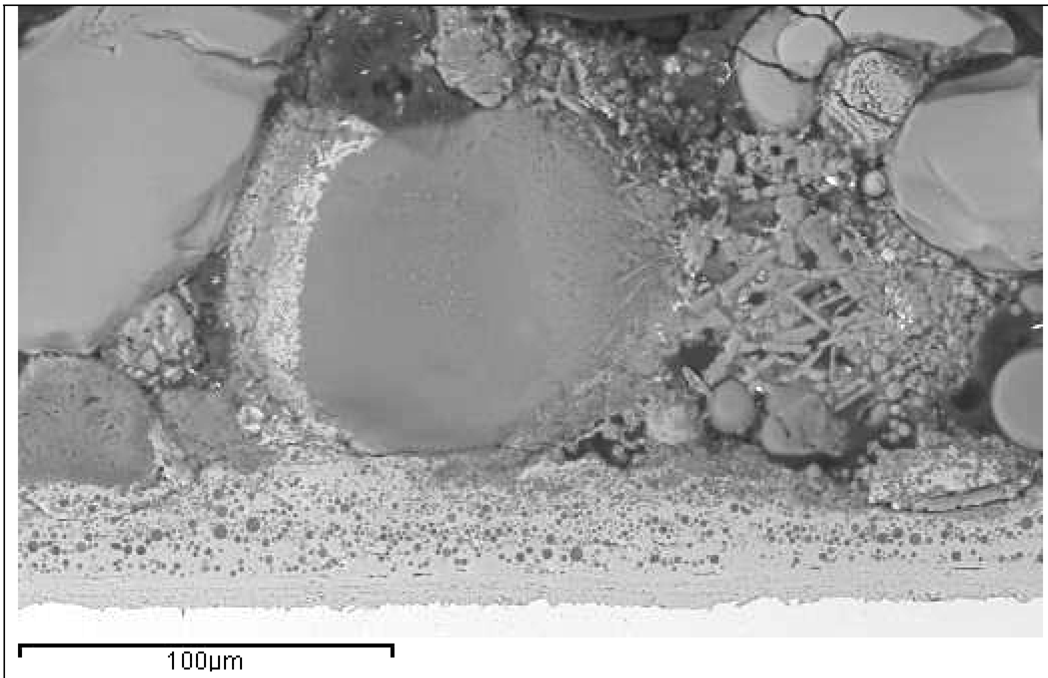
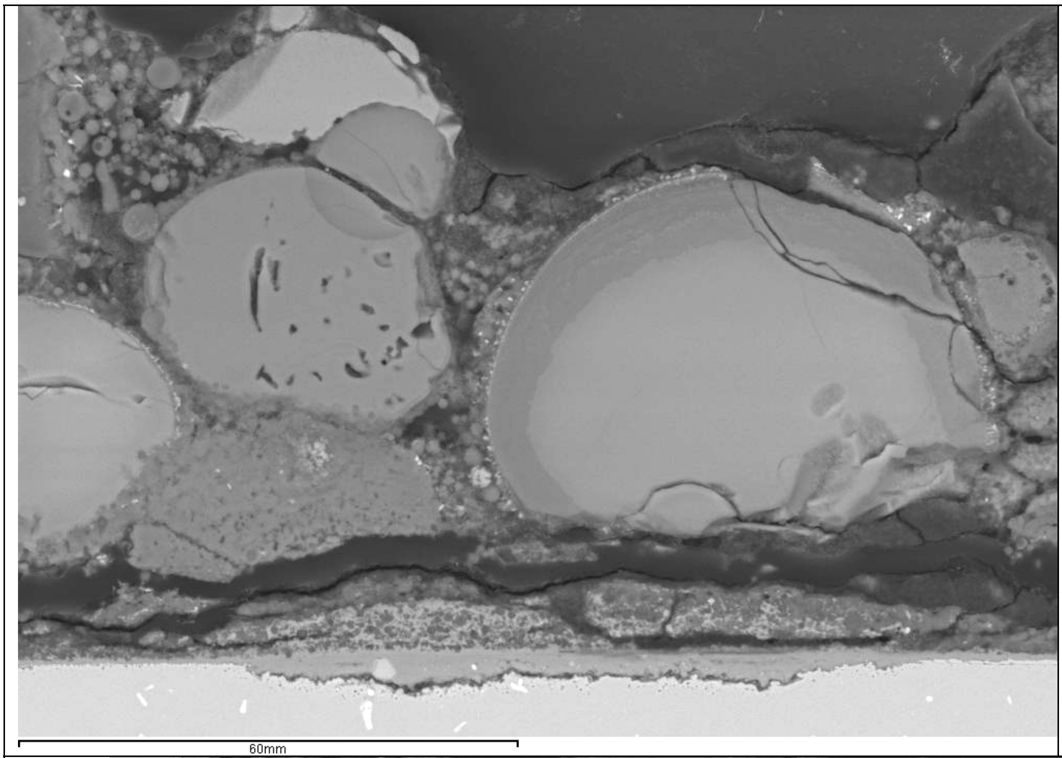


Figure 36: **BATCH 3, SHTR90, SPECIMEN 3, 10CrMo910, 525.2°C, 203 HOURS, BACK SCATTER ELECTRON IMAGE OF GENERAL ATTACK AND DUPLEX CORROSION SCALES OVERLAID BY PARTICULATE / CRYSTALLINE ASH MATERIAL**



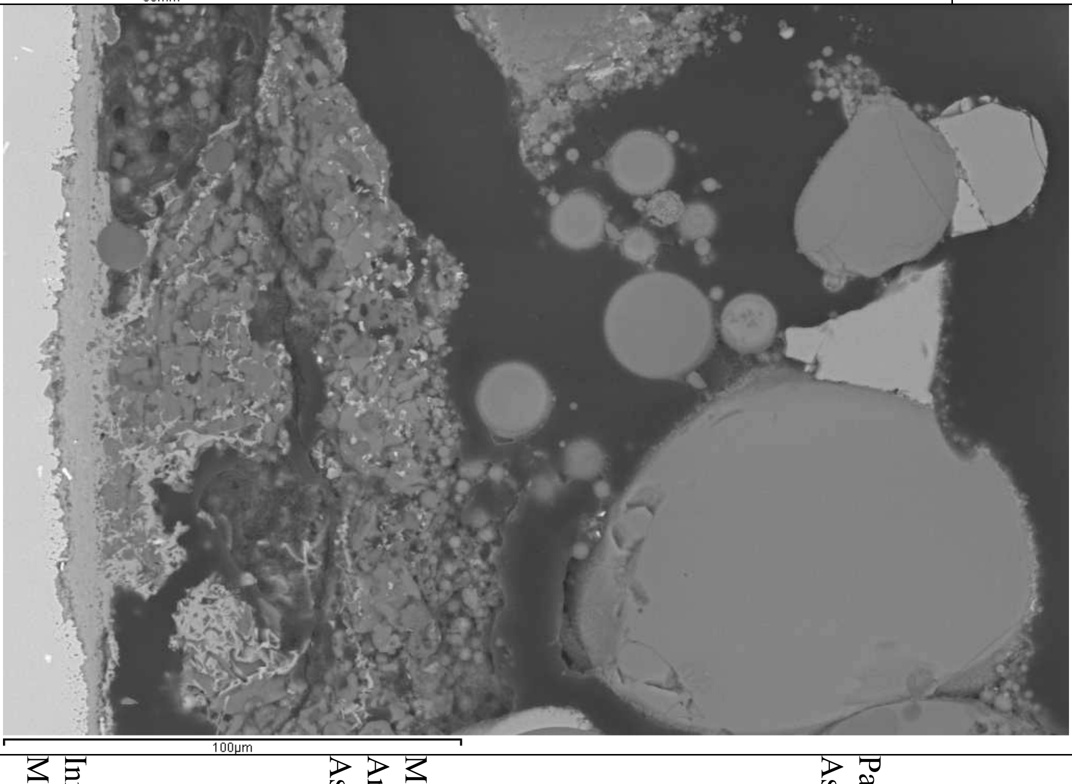


Figure 37: **BATCH 3, SHTR90, SPECIMEN 5, TP347HFG, 571.5°C, 203 HOURS, BACK SCATTER ELECTRON IMAGES OF IRREGULAR BREAKDOWN OF INITIAL CHROMIA SCALE TO GIVE IRREGULAR GENERAL ATTACK AND DUPLEX CORROSION SCALES. OUTER SCALE INTERACTING WITH OVERLYING AMORPHOUS ASH DEPOSIT**

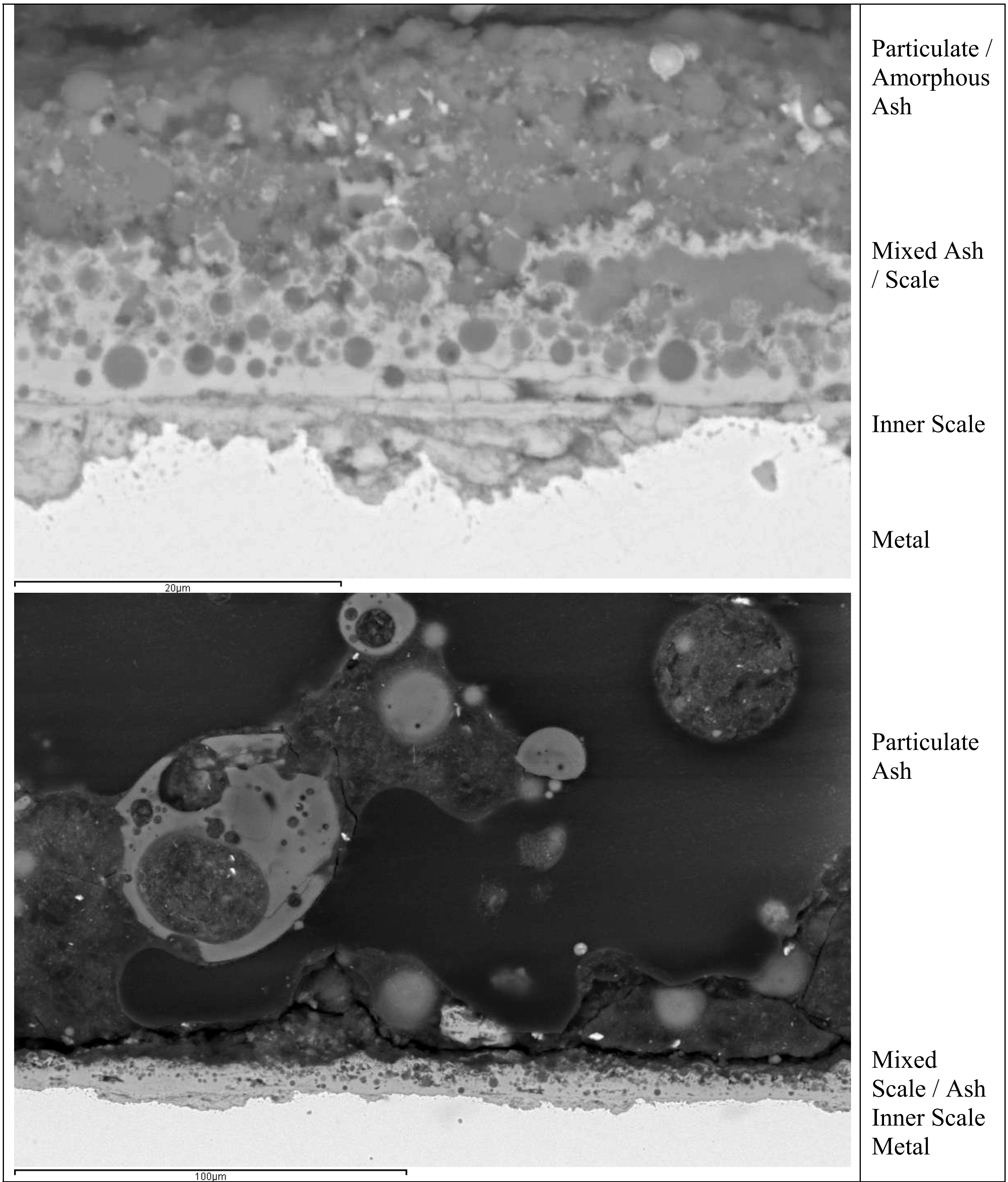


Figure 38: **BATCH 3, SHTR91, SPECIMEN 6, X20CrMoV121, 572.5°C, 203 HOURS, BACK SCATTER ELECTRON IMAGES SHOWING IRREGULAR AND SLIGHT SUBSURFACE ATTACK GIVING RISE TO DUPLEX CORROSION SCALES OVERLAID BY AMORPHOUS / PARTICULATE ASH MATERIAL**

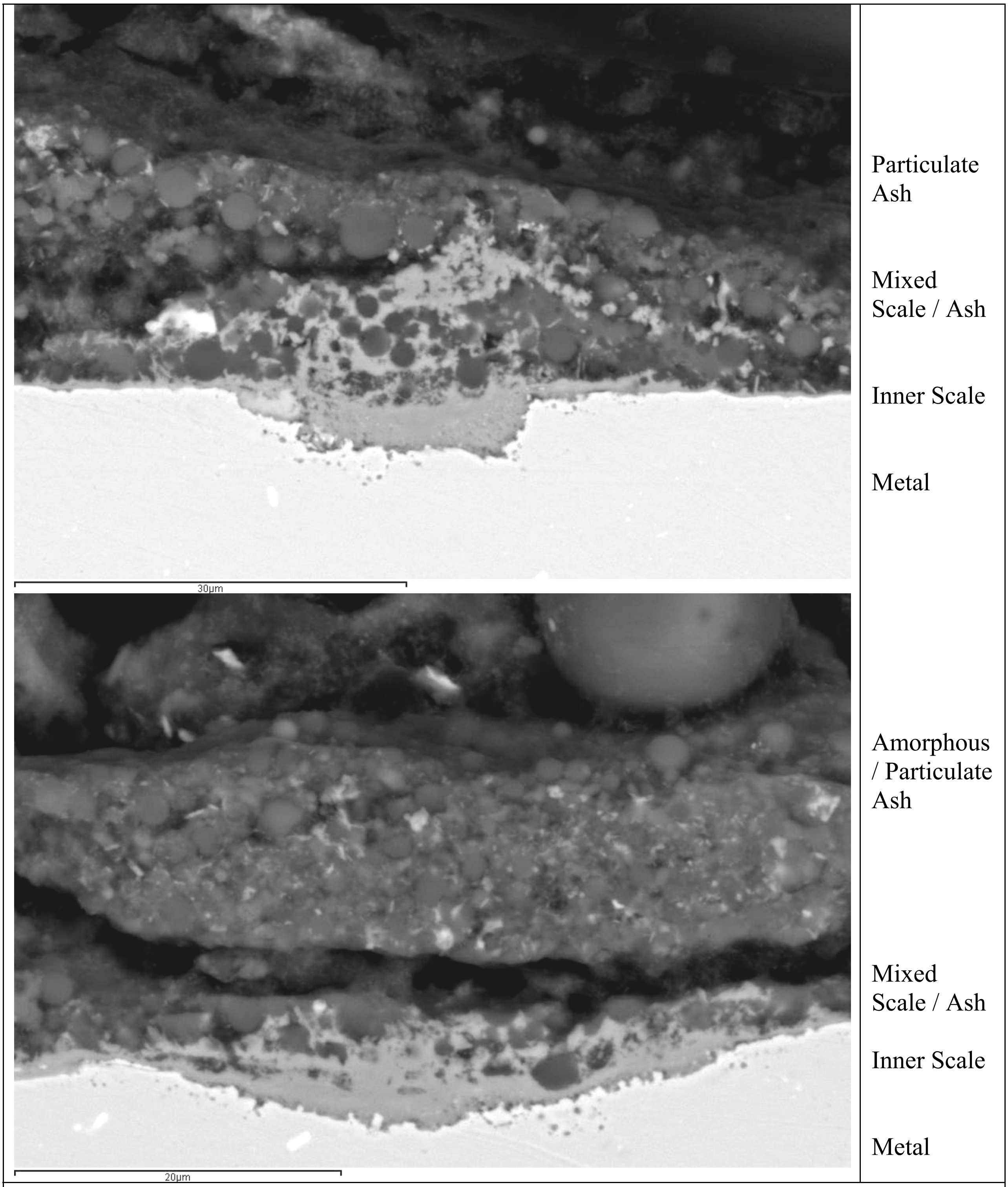


Figure 39: BATCH 3, SHTR91, SPECIMEN 8, TP347HFG, 598.0°C, 203 HOURS, BACK SCATTER ELECTRON IMAGES SHOWING PITTING / SUBSURFACE ATTACK WITH DUPLEX CORROSION SCALES. OUTER CORROSION SCALE INTERACTING WITH OVER LYING AMORPHOUS / PARTICULATE ASH DEPOSIT

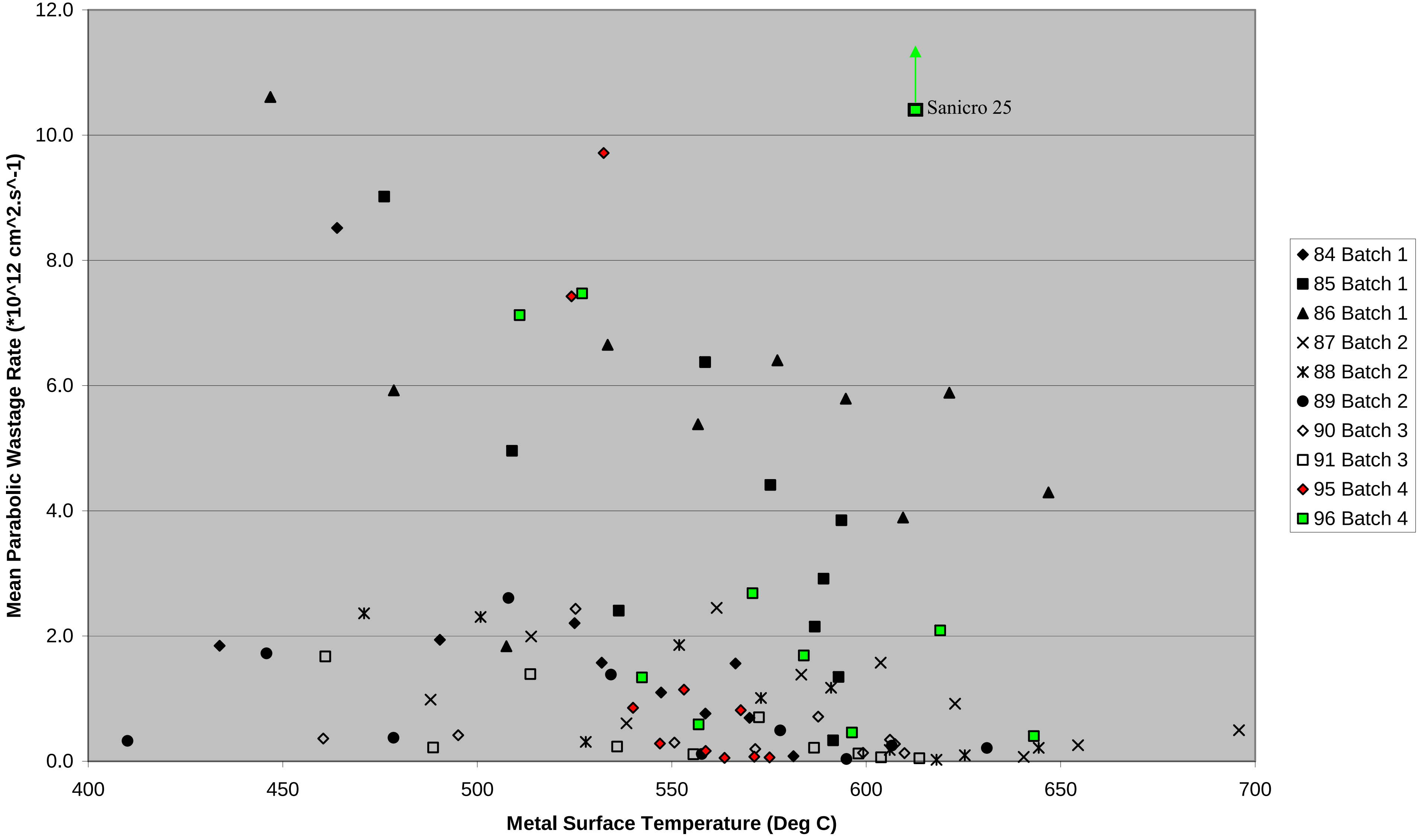


Figure 40: COMPARISON OF WASTAGE RATES MEASURED AT AVEDØRE (Batches 1,2 & 3) AND AMAGER (Batch 4) POWER PLANTS

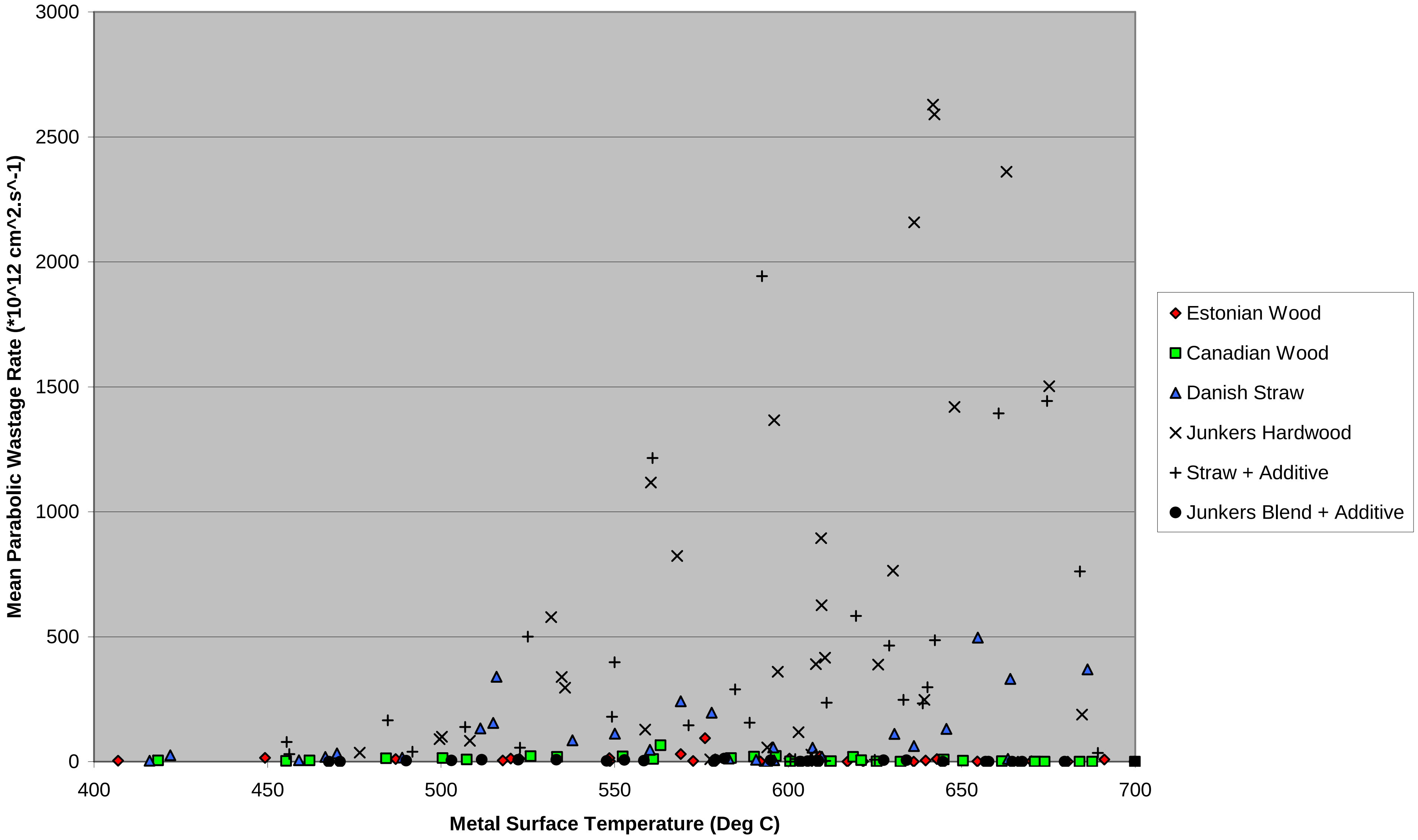


Figure 41: **WASTAGE RATES MEASURED AFTER SHORT TERM (approx. 50 hours) PILOT SCALE TESTING**