A new process for preparing pitches from anthracene oil has been developed. This process, named 'Ecopitch process', involved four sequential cycles each of which included a thermal oxidative condensation step followed by thermal treatment and distillation. The unreacted anthracene oil obtained in each cycle was used as the feedstock for the next cycle. It was observed that the unreactive anthracene oil required severer operational conditions (i.e. temperature) for being polymerised as the number of processing cycles increased. After four cycles, the polymerisation capability of the anthracene oil was depleted.

Bulk samples and their fractions from all stages of the process were characterised in terms of their molecular mass distribution and structural features. These samples were used to develop and validate methods based on laser desorption mass spectroscopy and nuclear magnetic resonance. The pyrolysis behaviour and the capacity of the anthracene oil derivatives to generate carbon materials were also investigated.

The feasibility of using anthracene oil derivatives as impregnation and binder agents in the production of graphite electrodes was studied. Preliminary results suggest that these pitches are suitable for use as impregnation agents. However, their application as binders requires further studies. One of the most important goals attained in this project is the excellent capacity of anthracene oil derivatives to develop mesophase, and consequently, to produce advanced carbon materials (e.g. carbon fibres, graphitic carbons and activated carbons for application in energy storage).

Modelling of the anthracene oil polymerisation was performed as a base for the scaling-up of the process. Tests in batch mode involved the study of the main parameters that affected the final properties and quality of the pitch obtained from the anthracene oil. A computational model was also developed and tested in order to simulate the experimental conditions inside a pitch production reactor. This model showed that the critical point in the reacting system is the injector which corresponded to the zone of largest energy release.

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IMPECABL: Improving environmental control and battery life through integrated monitoring systems

R. M. Poultney

Corus UK Limited Teesside Technology Centre, P O Box 11, Grangetown, Middlesbrough
Cleveland TS6 6US, UNITED KINGDOM

J.-P. Gaillet, D. Streiff

Arcelor Research Centre de Pyrolyse du charbon de Marienau
Parc d'Activités Forbach Ouest, F-57612 Forbach Cedex, FRANCE

F. Liesewitz, F. Huhn

DMT GmbH, Cokemaking Technology Division
Am Technologiepark 1, D-45291 Essen, GERMANY

J. W. Patrick, R. Barranco

School of Chemical & Environmental Engineering
University of Nottingham, Nottingham NG7 2RD, UNITED KINGDOM

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FINAL SUMMARY

Introduction

The aim of this research was to develop an integrated package of innovative coke oven monitoring systems. Early identification of potential problem areas will assist in enabling coke oven life to be extended to more than 40 years, whilst maintaining consistency of battery operations, productivity and coke quality. The ultimate goal is to reduce environmental emissions and increase coke oven life through rapid identification of brickwork problems and chamber defects, thus enabling early remedial action and repairs. This was carried out under the following work packages (WP).

- Work Package 1 Equipment Design
- Work Package 2 Internal Chamber Monitoring
- Work Package 3 External Monitoring
- Work Package 4 Data Processing
- Work Package 5 Assessment of Carbon Deposits
- Work Package 6 Plant Trials
- Work Package 7 Programme Management

Work Package 1: Equipment Design

Tasks 1.1/1.2 Examination/selection/initial evaluation of available instrumentation/sensors types

Objective

- To determine the optimum designs of the equipment to be constructed for coke oven monitoring.
- To evaluate initial concept designs for construction of the equipment, including an optical regenerator inspection system combined with a cleaning device.
- To select and evaluate an optimum inspection/cleaning system and types of sensors and equipment to be used for monitoring.

Results

CPM performed a preliminary test to inspect coke oven chamber walls during pushing, by means of cameras mounted on the pusher ram using the frame of a previous ECSC research contract(1). This preliminary test showed the feasibility of the project. On the basis of earlier experience in the field of coke oven inspection, CPM had to develop new optical sensors to be incorporated into the automatic chamber wall observation system.

Using technology developed for the Videofil Machine(2), CPM designed a new viewing head in order to reach a wider field of view around 105°, to obtain a smaller objective, to avoid overheating, to optimise the objective window cleaning, and to simplify the insulation. Tests of the new camera head were performed in cold conditions to verify the performances of this new equipment. Some difficulties occurred during the tests, due to cable connection problems inside the camera head. The original design was modified to support vibrations better and avoid disconnections. The camera was tested then in hot conditions, and some problems with insulation and settings were solved. The camera settings were adjusted to improve the image quality and the thermal insulation around the camera head was optimised.

For the regenerator inspection system, two different concepts for an optical regenerator inspection system were analysed by DMT: camera operation inside the regenerator sole flue, and camera operation outside the regenerator sole flue. Owing to the lower impact of thermal stresses and minor optical impacts by dust, analysis of different inspection systems resulted in the decision to develop a mirror/camera system, which allowed camera operation outside the hot and dusty regenerator sole flue. The selected system was made of a combination of a video camera and a swivelling mirror. The mirror was arranged in a small module mounted on a movable slide, which can be introduced into the regenerator sole flue for inspection purposes.

For the regenerator cleaning system, different types of nozzles were tested in the laboratory at different air pressures for removal of dust and other deposits from the regenerator brickwork by use of pressurised air. Laboratory testing of different types of nozzles showed different blowing forces of the nozzles. Preference was given to a nozzle type with a medium blowing force because of its suitable assembly dimensions. For the combined inspection/cleaning system, a cleaning device with three nozzles was identified as an optimal system. The nozzles were connected in parallel, so that a good adaptation to the length of the checker brick slots could be achieved.

Different types of instruments and sensors were researched, examined and evaluated before selection for the flue temperature, tie-bar load and oven top deflection monitoring equipment constructed by Corus. Information about suitable sensors and insulation was shared between Partners throughout the project.

Task 1.3 Concept: laboratory carbon deposition rig

Objective

- To determine the optimum designs of the equipment to be constructed for simulation of carbon deposits.

Results

Alternative designs of a laboratory-scale carbon deposition rig were considered and evaluated by Nottingham University (UNOTT) before the concept was finalised. The system was designed specifically to produce carbon deposits of a similar nature and under comparable conditions to those appertaining in industrial coke ovens.

Work Package 2: Internal Chamber Monitoring

Task 2.1 Development of automated viewing/recording

Objective

- Development of an automated system for regular observation and recording of the internal condition of coke oven chambers by Arcelor Research with CPM. The ultimate goal was to reduce environmental emissions and increase coke oven life through rapid identification of brickwork problems and chamber defects, thus enabling early remedial action/repair.

Results and Applications

CPM carried out preliminary investigations to inspect coke oven chamber walls during pushing by means of cameras mounted on the pusher ram. Although, as mentioned in the Scientific and technical description, other workers have attempted to build systems to monitor wall conditions. None have incorporated the monitoring system within the pusher ram assembly, but instead they built very large, expensive carrier-modules that interfere with normal battery operations and pushing schedules.

The developed system was therefore unique in offering on-line observation and recording of chamber condition and roof carbon build-up during normal operation at relatively low cost. Based on the earlier expertise of CPM, the designed and constructed automatic chamber wall observation system includes two micro-cameras mounted on the pusher ram, in order to observe the refractory brickwork of one wall during the pushing operation and the opposite wall during the return of the pusher ram. In the design, all video and operating signals are conveyed through a coaxial cable using multiplexing technology. This mode of data transmission had been tested successfully as part of earlier investigations. Figure 1 presents a schematic diagram of the complete chamber wall observation device developed by CPM.

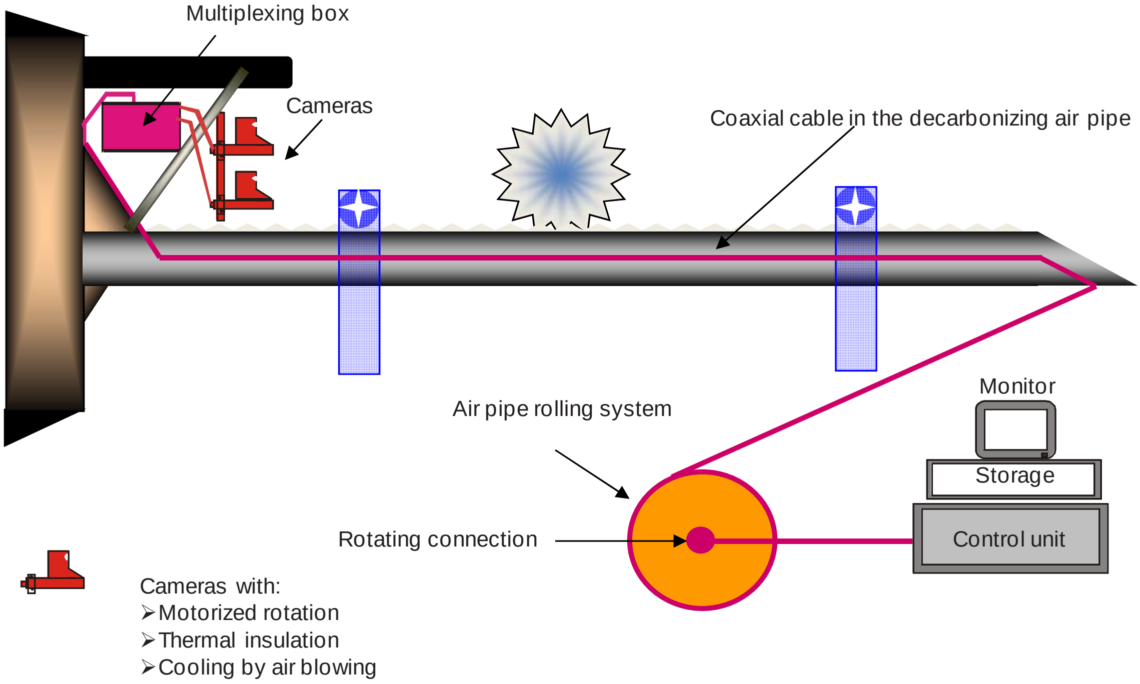


Fig. 1 Scheme of the CPM chamber wall observation device

Task 2.2 Investigation of carbon deposit rates/type

Objective

- Evaluation survey of samples and data from partners' coke oven plants.

Results and Applications

A number of coke oven batteries were surveyed, and the type, quantity and location of carbon deposits were evaluated. A comprehensive literature survey demonstrated the complexity of both the nature of coke oven carbon deposits and the possible influence of the carbonisation conditions and the charged coal blend. Moisture content played an important role through the provision of its oxygen and hydrogen components. This review and preliminary examination led to a classification of the carbon deposits into two types, namely laminar and spherulitic, by means of polarised light microscopy of their micro-textures.

Task 2.3 Development of carbon deposition rig

Objective

- Development of a laboratory-scale carbon deposition rig to simulate carbon build-up in industrial coke ovens. The rig will enable the factors identified in the above survey to be confirmed through laboratory tests, thus highlighting particular aspects of operation that may be changed to minimise future carbon deposition and its associated operational and environmental problems.

Results and Applications

A rig for the bench-scale provision of carbon deposits, of similar nature to those found in commercial coke oven operations, was devised, built, and successfully operated. The rig was essentially an electrically-heated furnace containing a coal carbonisation retort. On top was a ceramic tube acting as the free-space required for cracking evolved volatile matter, which took place as a preliminary to the deposition of carbon. In this free space, silica slides were placed to collect samples of the carbon. The different zones of the rig, namely carbonisation, cracking and deposition, could be heated at different rates and to different final temperatures. This rig provides a laboratory-scale facility for the controlled investigation of the effects of the different factors involved in carbon deposition, such as coal type, charge moisture content, rate of heating, deposition temperature, nature of deposition surface, etc.

Work Package 3: External Monitoring

Task 3.1 Development of a prototype regenerator inspection system

Objective

- Development of a flexible system for inspection of regenerators and regenerator sole flues that can be used to detect damage at the sole, in the lower regenerator brickwork, and blockages of the gas flow through the regenerator.

Results and Applications

A first prototype inspection system, consisting of a manually-adjustable, swivelling welding mirror, a slide and rod mechanism and a standard camcorder, was constructed and tested in the laboratory on a cold test checker brick without any cleaning device. Under laboratory conditions, the Prototype 1 inspection system worked very well. Later plant trials were conducted with this prototype in Task 6.5 under very hot conditions in the regenerator of a German coke plant. However, plant trials showed that the Prototype 1 had to be improved further, due to the following weak points:

- insufficient optical characteristics of the welding mirror
- poor accuracy of the inclination of the mirror by manual mirror adjustment
- poor illumination
- insufficient zoom range of the standard camcorder.

Tasks 3.2/3.3 Integration of cleaning system/Testing/optimisation prototype regenerator equipment

Objectives

- Development of an effective regenerator cleaning system that can be combined on demand with the inspection system.
- Optimisation of the combined regenerator inspection/cleaning system.

Results and Applications

A second prototype inspection system was developed with optimisation of the following equipment: use of a new movable slide and a swivelling mirror made from optical glass, radio-controlled adjustment of the swivelling mirror, integration of air-cooled electronics, use of a new camcorder with temporary additional external illumination, integration of a cleaning system with three air nozzles with common use of pressurised air for cleaning regenerator brickwork and cooling the electronics. Development of a third simplified prototype inspection system took place without any cleaning device. Both prototypes were tested in trials at a German coke plant in Task 6.5.

Task 3.4 Development of automated flue temperature monitoring

Objective

- Development of an automated flue temperature monitoring system for optimised control of battery heat distribution and reduced environmental emissions.

Results and Applications

Semi-automated equipment was developed to measure vertical wall flue temperature distribution and to video flue walls for damage and carbon growth assessment. An insulated, water-cooled measuring head was designed to be driven down flues from a mobile trolley, which can be wheeled along the battery top.

Task 3.5 Development of tie-bar monitoring

Objective

- Development of a tie-bar load measurement system for continuous monitoring of forces acting on the battery steelwork and associated movement.

Results and Applications
Laboratory experiments took place to develop load sensors for fitting on to the top tie-bars of ovens for continuous measurement of loads on buckstay springs. Progressive changes were made to improve the load cells and the insulated cables carrying data to a logger on top of the battery, as early plant trials took place (see Task 6.2).

Task 3.6 Development of oven top deflection monitoring

Objective:

- Development of an oven top deflection monitoring system that will continuously record brickwork movement on the battery top.

Results and Applications
A battery top deflection measurement system was developed for regular assessment of the oven top brickwork profile and early detection of abnormal deviations. Initial experiments took place with ultrasonic displacement transducers attached to the charge car, but these picked up charge car activity and were not sufficiently sensitive. A new system was developed with Class II laser sensors attached to a moveable beam, which also carried the control and display units and was adjustable for rail spacing, rail height and battery width.

Work Package 4: Data Processing

Task 4.1 Oven image analysis software development

Objective
- Software development for mapping oven wall condition and damage.

Results and Applications

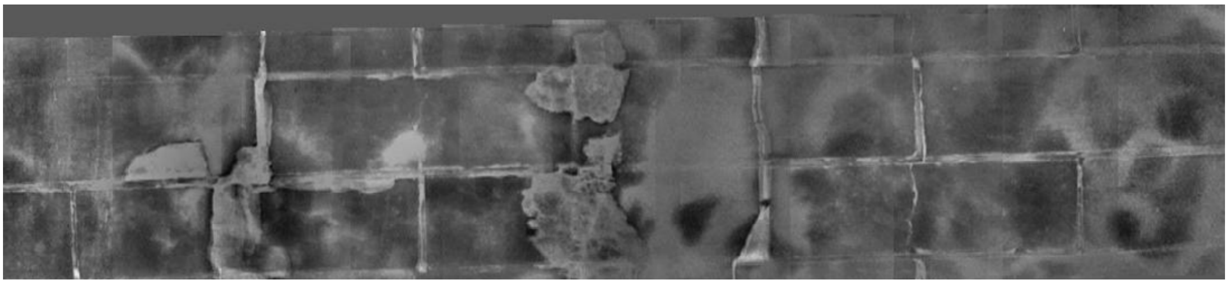


Fig. 2 Picture of a wall part generated by the processing software

Due to the development of several image processing packages, the coke oven wall inspection image processing software is able to generate a picture of each wall. Figure 2 is an example of the result given by the software. The generated picture clearly shows that it is possible to identify the damage location and the extent of any damage. Cracks and wear are easy to identify by human eye. A complete wall picture shows the location of the different defects. The duration of a single wall data treatment is around 30 minutes. The software calculation time was optimised within the project.

Task 4.2 Video recording of regenerator condition

Objectives
- Provision of efficient, reliable and rapid data transfer from the monitoring system to the end-user in a clear and readily understandable format.
- Optimisation of video software for organisation and archiving video recording data.

Results and Applications
For video recording and editing and archiving of video data, RISA (Regenerator Inspection System Archive) was developed and tested. The database used commercial software from ULEAD Systems. Functions for input data, and search functions were implemented additionally into RISA by DMT, using EXCEL. RISA was tested successfully with full functionality.

Task 4.3 Real-time flue temperature data transfer

Objective
- Development of real-time data processing systems for display of vertical flue temperature profiles.

Results
Corus developed real-time transfer of processing data from the flue temperature measurements and electronic camera. This generated vertical flue temperature profiles and video images for viewing immediately on the rig display unit and on an independent computer (sited in the battery control room, if desired by the plant).

Task 4.4 On-line relay of tie-bar strain data

Objective
- Provision of efficient, reliable and rapid live data transfer from the monitoring system to the end-user in a clear and readily understandable format.

Results
Software was developed for the tie-bar system to provide continuous monitoring either on a data logger, which can be downloaded at regular intervals, or by data transfer from individual ovens directly to the battery control room by hardwire or Ethernet connection.

Task 4.5 Software development for oven top deflection

Objective
- Provision of efficient, reliable and rapid data transfer from the monitoring system to the end-user in a clear and readily understandable format.

Results
Software has been developed for oven top deflection monitor to log data during plant trials to produce analogue values from all sensors in real time, as the monitor is moved along the battery. Successful programmes were written to digitise these values, make corrections for inclination, and collate data from different runs, so that three-dimensional profiles of the battery top can be produced.

Task 4.6 Image analysis software: carbon characterisation

Objective
- Development of computerised image analysis for characterisation of carbon deposits.

Results and Applications
For the measurement of the volume porosity of the carbon deposits, a fully automated method was devised, based on the examination of polished sections by optical microscopy and computerised image analysis. A computer programme was developed to generate a mosaic of up to 30 x 30 images. Adjacent frames were captured and assessed quantitatively, whilst the material cut by the frame edges was saved and subsequently measured, before the results were merged to provide data representative of the whole mosaic. The programme has the additional feature of being able to make measurements over a wide range of pore sizes, from micropores covered by single images to macropores, which may be so large that they overlap single images, but they can be measured by combining captured images.

The programme has been developed further to characterise the texture of deposited carbon by differentiating between laminar and spherulitic carbon using a combination of differences in grey levels, optical appearance, degree of anisotropy and porosity to achieve the required discrimination. This facility therefore provides a useful, efficient (in terms of time taken to make the measurements), and rapid means of quantitatively assessing the porosity and nature of the carbon material forming the deposits.

Work Package 5: Assessment of Carbon Deposits

Task 5.1 Sampling of carbon deposits

Objective

- Sampling of carbon deposits from production ovens.

Results

Samples of roof and wall carbon deposits from five Corus plants were supplied to UNOTT with available information about origin, blends and operating conditions (see Task 2.2).

Task 5.2 Analysis and laboratory trials

Objective

- Characterisation of carbon deposits using new analytical techniques.

Results and Applications

Twenty samples of carbon deposits from commercial coke ovens were received for analysis, mostly from the oven walls. The samples were sliced parallel to the plane of deposition to provide several sections representing adjacent deposition layers. From the analysis of the carbon micro-texture, it was established that in general the predominant material in most of the samples was laminar carbon, especially in the sections deposited furthest from the oven wall.

Generally, spherulitic carbon was observed in material adjacent to the deposition surface, which was the oven wall. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) were also used to analyse the surface morphology and the graphitic nature of the deposits, respectively. The spherulitic nature of the deposit adjacent to the oven wall and the layer-like nature of the predominant laminar carbon were confirmed by the SEM analysis, but the limited XRD analysis did not show any unequivocal information about the degree of ordering of the graphitic nature of the two textural types identified by the microscopic analyses. Although the analyses lead to the conclusion that the initial deposits on silica surfaces of a coke oven are generally of the spherulitic type with subsequent carbon deposits being of a laminar nature, neither the mechanisms involved in the deposition of the two types nor a clear indication of their graphitic order has been resolved.

Task 5.3 Effects of blend composition on deposits

Objective

- Relate carbon deposits to coal type, blend composition and charge conditions.

Results and Applications

In preliminary studies to determine the significance of the composition of the coal blend charged to a coke oven on the carbon deposition, the bench-scale carbon deposition rig was used to provide a series of samples. Primarily using SEM, it was established that the deposition varied with distance from the refractory surface and with volatile matter source irrespective of the cracking temperature. As expected, more carbon was deposited when the deposition site was closer to the source of the volatile matter, and the size of the spheres constituting the spherulitic carbon increased with cracking temperature from about 500 nm at 700°C to 2500-4000 nm at a cracking temperature of 1100°C. The potential of the system was to provide valuable information regarding the most significant parameters in the mechanism and kinetics of carbon deposition and their relative significance.

Task 5.4 Influence of charge conditions on deposits

Objective

- Investigate the mechanism of carbon deposition in coke ovens and evaluate means of minimising future carbon deposition and its associated operational and environmental problems.

Results and Applications

Time constraints prevented experimental work to determine the influence of charge conditions on the deposition of carbon. However, the literature survey indicated that, although the temperature, type and concentration of the volatile species to be cracked are the dominant factors in carbon deposition, the properties of the deposition surface also exert an influence. This may provide an explanation for the mechanism behind the deposition of carbon materials with different textures, with spherulitic carbon being deposited on the silica of the coke oven walls and subsequent layers of laminar carbon being formed at the surface of the previously deposited carbon. The literature search also revealed that additional influential factors include charge moisture levels, probably through the effects of the constituent oxygen and hydrogen, the hydrogen transfer potential of the tars and the presence or absence of coal fines.

Work Package 6: Plant Trials

Task 6.1 Installation/testing of internal wall scanning system

Objective

- Oven chamber wall surveys to detect early damage of the refractory brickwork, thereby allowing timely preventative maintenance rather than major repairs.

Results and Applications

As planned, the use of the inspection device did not affect production, because the observation was performed during normal pushing operation. The performance of the whole chamber wall observation device was tested first in the Carling coke plant. The results were satisfactory, but the system was not reliable enough, thus complementary trials were performed in the Dillingen coke plant.

The chamber wall observation system implemented in Dillingen coke plant gave satisfactory results in terms of image quality, field of view and reliability. This device is relatively easy to install on any pushing machine, because it is not water-cooled. Only air coming from the decarbonising air pipe is blown permanently. The reliability of this system was improved considerably at Dillingen coke plant. The autonomy of this system is more than three hours without any risk to the electronics and the camera head. Consequently, it is possible to observe more than fifteen different ovens during this period of time.

Task 6.2 Installation/testing of tie-bar monitor hardware

Objective

- Installation of tie-bar monitoring systems for a continuous assessment of battery steelwork stress/brickwork movement and early warning of potential problems.

Results and Applications

Load sensors of the successful design were fitted to pairs of tie-bars at the top of individual ovens for continuous measurement of loads on buckstay springs along two batteries. Collected data demonstrated that changes in the loads on sensors can be identified with specific plant events, and observed load variations are not limited to actions in the ovens between the monitored buckstays. These sensors could be fitted on most tall batteries.

Task 6.3 Installation/testing of oven top machine hardware

Objective

- Installation of oven top deflection monitoring systems for assessment of battery steelwork stress/brickwork movement and early warning of potential problems.

Results and Applications

The system was tested successfully along two batteries, and produced a three-dimensional profile of the top of each battery. It could be used on any top-charged battery.

Task 6.4 Survey of wall temperature distribution

Objective

- Survey of vertical wall flue temperature distributions for optimisation of battery heating control.

Results and Applications

Trials of the automated monitoring system were carried out on two batteries, and produced temperature and vision profiles of each flue to aid battery heating control and refractory repairs. Useful comparisons could be made between flues with problems and those operating normally. This monitor could be applied on any battery.

Task 6.5 Application regenerator inspection/cleaning system

Objective

- Application of the regenerator inspection/cleaning equipment in plant trials.

Results and Applications

Tests with three prototype regenerator inspection systems (Prototypes 1 and 3: without any cleaning device, and Prototype 2: with a combined cleaning device) were run in the regenerator sole flue of a German coke plant. As described in Task 3.1, Prototype 1 showed some weak properties in the plant trials, so that an optimised Prototype 2 was developed.

Testing of Prototype 2 showed that this system allowed detailed inspection and analysis of brickwork damage in the lower part of the regenerator, but upper parts cannot be reached by the system. Problems occurred in inspection of deeper sections of the inspection channel because of twisting of the air hoses (air supply for the cleaning device and cooling of electronics) and malfunctions of the servo of the swivelling mirror, due to insufficient air cooling in this part of the inspection channel.

The cleaning device of the Prototype 2 showed a good cleaning efficiency in plant trials. However, because it raised dust, no optical inspection was possible during cleaning. Owing to the problems with dust, inspection and cleaning were separated in the Prototype 3, a simplified inspection system without any cleaning device and without any temperature-sensitive electronics placed inside the hot inspection channel of the regenerator. Severe, medium and low damage of regenerator brickwork could be monitored well in plant trials with the simplified Prototype 3.

Task 6.6 Comparative trials plant/laboratory carbon deposits
Task 6.7 Evaluation/correlation of plant data

Objectives

- Survey of carbon deposits following application of monitoring systems/corrective procedures.
- Data evaluation, its correlation with plant operations and conclusions relating to recommended actions for improving operations and prolonging battery life.

Results and Applications
The literature survey suggested that changes in oven operation can reduce carbon deposits, but do not change their nature. Alterations to oven operation following plant trials have reduced carbon growth, so it was impossible to obtain further samples within the time-scale of this project. Consequently, the new monitoring data have been evaluated in comparison with plant operations, and conclusions have been drawn with respect to actions required for improving operations and prolonging battery life.

The carbon deposition studies have increased knowledge of their formation to aid their reduction. This will lead to lower pushing forces and reduced brickwork damage during pushing and therefore refractory repair costs. Improved brickwork condition will reduce stack and door emissions, and increase chamber life and productivity, as the number of ovens left empty for draughting decrease.

The development of the chamber wall observation device has produced a reliable monitor. Data given by the chamber wall observation are useful to the refractory maintenance team, and so implementation in an ArcelorMittal coke plant is being undertaken.

Various severe problems in the long-time operation of coke plants, like the collapse of the regenerator brickwork, may result from slight damage to the brickwork and blockages of regenerator channels by deposits of soot and dust. Now, these problems have become more critical in older coke plants. In the past, operators of older coke plants had not been in a position to identify and control the early stages of brickwork damage because of a lack of powerful and easy systems for inspection of the regenerator brickwork. Plant trials with the newly-developed Prototype 3 swivelling mirror/camera equipment showed that with this system blockages of regenerator channels and slight, medium and severe damage of the regenerator brickwork can be monitored and identified easily and clearly. Improved operation and prolonged battery life can be expected, when brickwork inspection is run at regular intervals using such an inspection system. Already at an early stage, damage can then be monitored and localised for timely refurbishment, before progress of damage will result in collapse of complete sections of brickwork. Much more expensive measures for rebuilding large brickwork sections accompanied by losses of coke production can be avoided.

The new monitoring data have been evaluated in comparison with plant operations. Tie-bar and oven top deflection and flue temperature and vision monitoring permit reductions in stresses on battery fabric, and decreased maintenance and refractory repair, and reduced underfiring gas costs and environmental emissions. Over time, these improvements in operations will prolong battery life, and they could be applied to many batteries in Europe.

SCIENTIFIC AND TECHNICAL DESCRIPTION OF RESULTS

1. OBJECTIVES OF THE PROJECT

1.1 INTRODUCTION

Prolongation of battery life is dependent on many factors, including the initial selection of coal blend composition to minimise excessive pressure development during carbonisation[(3)], charging conditions, battery heating control and pushing operations. Failure to maintain strict control over these factors and oven scheduling leads to rapid deterioration of the battery fabric, unacceptable gaseous and particulate emissions, and increased energy consumption[(4)]. Even with best practice operation, it is inevitable that ongoing battery repairs will be an essential requirement to extend battery life, especially refurbishment of brickwork. Since the advent of silica welding, many refractory repairs can be carried out with the majority of the battery under normal operation, but it is vital to undertake them at the earliest opportunity.

Most coke plants in the European Community were designed for an expected life of 20-25 years, but many are now over 30 years old. To extend life to 40-50 years with minimal emissions to meet environmental targets and predicted demand by 2020, increasing attention is needed to prevent damage and expensive repair work. Optimisation of battery life, productivity improvements, reductions in fugitive emissions, and consistency of operations require the application of monitoring systems for evaluating oven chamber and regenerator condition, and a sophisticated, proactive approach to heat regulation and flue temperature control. Otherwise, problems resulting in irreversible damage and increased emissions frequently go undetected until they become major issues.

This research takes a fully integrated approach to monitor and assess vital areas of importance in and around the coke oven chambers, by the development and application of sophisticated monitoring systems to evaluate critical areas throughout the battery. Problems include the presence of minor brickwork faults, roof and wall carbon deposits, structural abnormalities, and deviations in battery temperature. The focus of this project has been to provide the coke oven manager with a wide range of investigative and monitoring tools for early identification and rectification of these problems, while maintaining consistent coke quality and production. Innovative automated monitoring equipment has been designed and constructed to examine critical areas of the battery in detail, including the regenerators, individual oven chambers, individual heating flues, tie-bars and the profile of brickwork on the oven top. A key feature of all the systems was efficient transfer of data with output in user-friendly format. These achievements will lower oven repair and energy costs, reduce carbon deposition rates and emissions, and enhance coke quality.

1.2 OBJECTIVES

The aim of this research was to develop an integrated package of innovative coke oven monitoring systems to prolong oven life to more than 40 years, whilst maintaining the consistency of battery operations, productivity and coke quality. Figure 3 illustrates the areas where partners have contributed to the research. The ultimate goal is to reduce environmental emissions and increase coke oven life through rapid identification of brickwork problems and chamber defects, thus enabling early remedial action or repair. This has been achieved through the following objectives:

- Development and industrialisation of an automated system for regular observation and recording of the internal condition of coke oven chambers, to detect early damage to the refractory brickwork and enable timely preventive maintenance.
- Development of a flexible system for inspection of regenerators and regenerator sole flues, which can be used to detect damage at the sole and at the lower regenerator brickwork, and gas flow blockages through the regenerator.
- Development of an effective regenerator cleaning system, which can be combined with the inspection system for intelligent clearing of blockages, to provide improved combustion conditions, optimised flue temperature distribution and reduced stack and pushing emissions.
- Development of semi-automated equipment for monitoring vertical wall flue temperature distribution, to optimise battery heating control, lower energy inputs, and reduce pushing forces and environmental emissions.
- Development and installation of tie-bar load sensors for continuous evaluation of the forces acting on the battery steelwork, and rapid detection of abnormal movement variations.
- Design and installation of a battery top deflection measurement system for assessment of the oven top brickwork profile and early detection of abnormal deviations.
- Determination of the principal mechanism in the formation and deposition of wall and roof carbon.
- Detailed survey and characterisation of wall and roof carbon deposits, and their deposition rates with respect to coal type and charge conditions, to minimise carbon deposits and their associated operational and environmental problems.

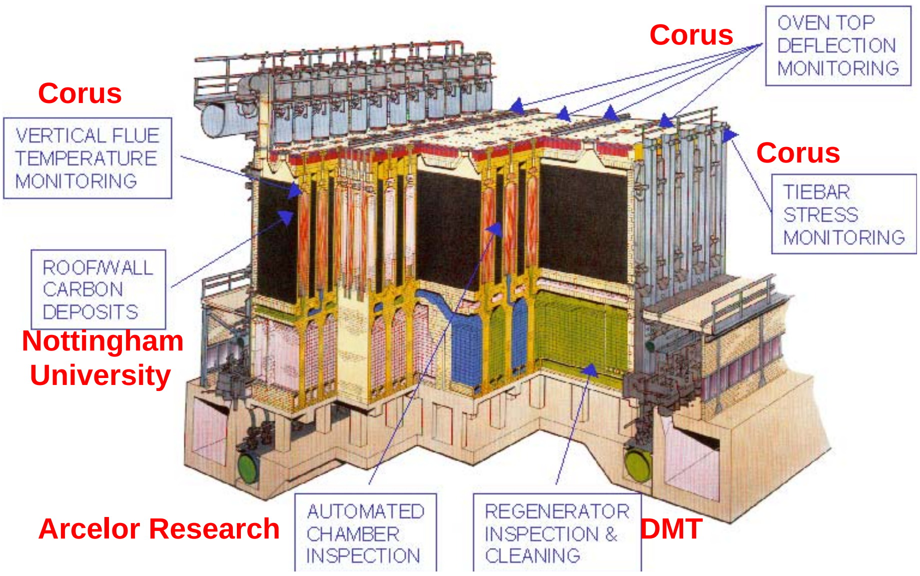


Fig. 3 Cross-section of a coke oven showing Partners' Research Areas

2. COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACCOMPLISHED

Appendix 7 shows the Initial Plan in Technical Annex Form 1-3 and its final 2008 revision after a 6-month prolongation was granted for the project in 2007. The request for the prolongation occurred, because the plant trials of one partner were postponed by the selected plant in 2006. The issue was resolved by undertaking the trials on two different batteries, but this required adaptations to the equipment to fit the different plants. The prolongation only affected the timetable for the research.

The length of time and effort required to design and construct some of the equipment in the project were underestimated in the initial plan, but everything was completed within the project. Owing to the extended time for building plant rigs and the laboratory carbon deposition rigs, there was insufficient time to re-investigate the extent and type of carbon deposits in the way originally envisaged in Task 6.6. Carbon deposits take time to grow, and changes to operational parameters after the monitoring trials reduced growth rates. Consequently, evaluation of the effectiveness of the application of the new monitoring systems to the coke ovens had to take place in other ways. There were also minor deviations from the original objectives due to plant requirements and the results of initial tests. Preliminary plant trials showed that continuous assessment of the oven top brickwork profile did not give accurate results due to the effects of charge car movements, so a new manually-controlled system was designed and constructed to make regular assessments. Overall, the planned activities were accomplished with a few minor alterations.

3. DESCRIPTION OF ACTIVITIES AND DISCUSSION

3.1 Work Package 1: Equipment Design

Task 1.1 Examination of available instrumentation/sensors

Due to the highly-demanding conditions around coke oven batteries, the selection of durable components, which work in hot and dusty environments, was essential. The first phase of the project was to source and examine available instruments and sensors, which might be utilised in the construction of plant monitoring and laboratory simulation equipment. Information about suitable sensors and insulation was shared between Partners throughout the project. Corus examined a range of different types of instruments and sensors for the flue temperature, tie-bar load and oven top deflection monitoring equipment.

During the preliminary tests by CPM for the chamber monitoring system, a black and white SONY XC73 camera, which was more sensitive than a colour camera, was set up with a motor allowing a 180° rotation. This camera offered the possibility of external synchronisation, but it had no automatic shutter. Consequently, the exposure must be controlled by an external trigger. Seen in Fig. 4, this camera head was also equipped with a temperature sensor to prevent any overheating. This temperature was permanently displayed on the control unit of the device.

Three artificial means were used to increase the field of view of the camera:

- The camera head was mounted out of the axis of the pusher beam to increase the distance between the chamber wall and the CCD sensor, and consequently the field of view.
- The camera head was turned by an angle of 10° with respect to the wall perpendicular.
- The CCD sensor was turned 90° in order to have the highest resolution in the vertical direction.

These preliminary tests clearly showed some problems that needed to be solved:

- The manual shutter of the camera was inefficient. In practice, the operator could not adjust the shutter correctly for variations in light, which occurred rapidly.
- The porthole progressively became dirty, despite air blowing at this point. The addition of a high-performance oil-separator filter did not solve this problem. It was obvious that the diameter of this porthole was too large, and that it would be necessary to reduce it.
- The field of view was relatively poor, showing only two brick courses in spite of all the artificial means adopted to enlarge the pictures.

For all these reasons, a new objective lens with a wider field of view and a smaller lens window was specially designed and built. The new objective lens offered a wider field of view of 116° in the vertical direction instead of 72° and a very small window (see Fig. 5). In addition, the camera head included a new WATEC 525EX camera with an automatic shutter. The shape of the camera head also made insulation easier.

Fig. 4 First sensor design

Fig. 5 New camera head design

Task 1.2 Selection/initial evaluation of sensor types

Chamber monitor

In order to test the sensors, trials in cold and hot conditions were performed by CPM. Details are presented in Appendix 1. The cold trials concluded when the newly manufactured camera head functioned well. The new camera fitted by CPM had increased benefits in terms of image quality and field of view, although some distortion was noticed.

In order to test the mechanical and thermal resistance of the camera head as well as the image quality, some tests in industrial ovens were performed at Carling coke plant. During the trials, the camera block was introduced inside an empty oven, where the temperature was around 950°C. The multiplexing box stayed outside the oven, although initially it was intended to enter the oven at the same time as the camera (when the inspection device is installed on the pusher ram). The cooling air came from the plant air system, and the pressure was set at 7 bar and immediately connected to the multiplexing box.

The camera was introduced through the charging hole down to 1 m from the oven bottom. The camera stayed in the oven for approximately 1.5 minutes. This duration corresponded to the time for the ram to travel from its entrance into the oven until its exit. The first images were too dark, and a poor setup of the shutter was observed. Nevertheless, the trials were performed in order to assess the quality of the insulating material and the thermal resistance of the camera.

During the first trial, the insulation was too thick and accumulated too much heat, so the temperature rose and the camera head was damaged. After replacement of the material, a new trial was carried out in the Carling coke plant under the same conditions as the first one, except that the insulation of the camera body was reduced from five to three layers of DELCERAM insulating band. These trials were successful in terms of image quality (see Fig. 6) and the thermal insulation. The decrease in the thickness of the insulation allowed the heat accumulation to be dissipated during 10 minutes pauses (see Fig. A2.1, Appendix 2, Task 2.1).

Probably, the camera air cooling will be more efficient with the installation of the inspection device on the pusher ram. During the preliminary trials, the air came from a pipe located on the oven, which already heated the cooling air. The different trials showed the good performance of the new camera head in terms of use, wideness of the field of view and image quality. The final camera head fulfilled CPM requirements.

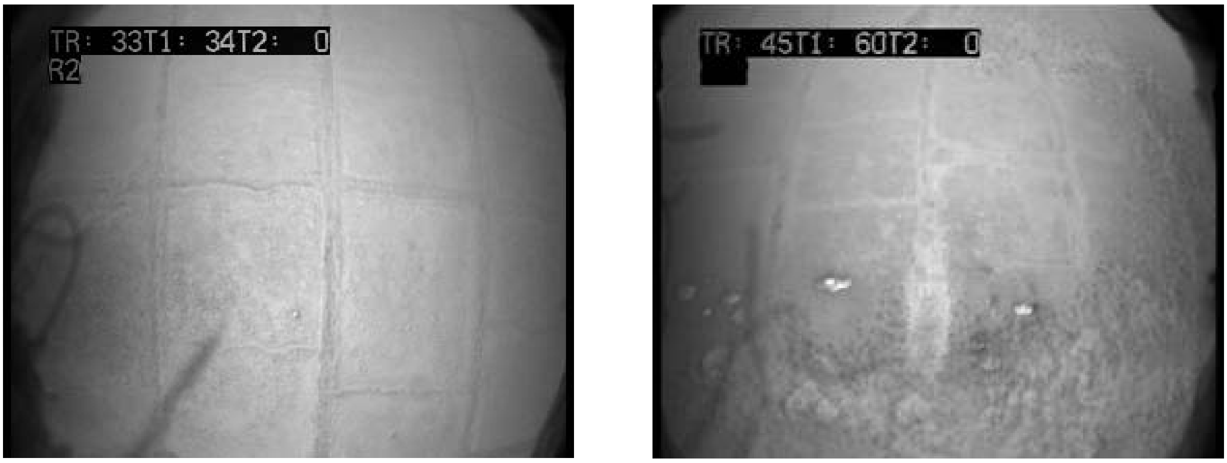


Fig. 6 Brick joints clearly visible

Regenerator inspection system

Two different concepts were initially analysed for an optical regenerator inspection system:

A) Camera operation inside the regenerator sole flue:

advantages: spatial proximity to the object to be inspected, possibility of looking directly upward into the regenerator brickwork , transfer to 90° to the sole flue axle.
disadvantages: high impact of the camera by thermal stresses and dust, cramped space.

B) Camera operation outside the regenerator sole flue:

advantages: lower impact of the camera to thermal stresses and dust, inspection components can be constructed simpler and more cheaply.
disadvantages: necessity for optical adjustment of the video camera in axial direction of the sole flue including 90°-redirection of the point of view into the regenerator brickwork.

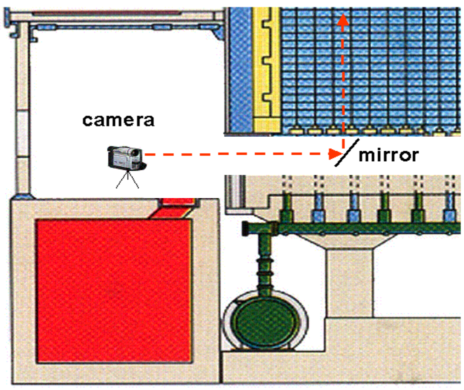


Fig. 7 Principle of the inspection system

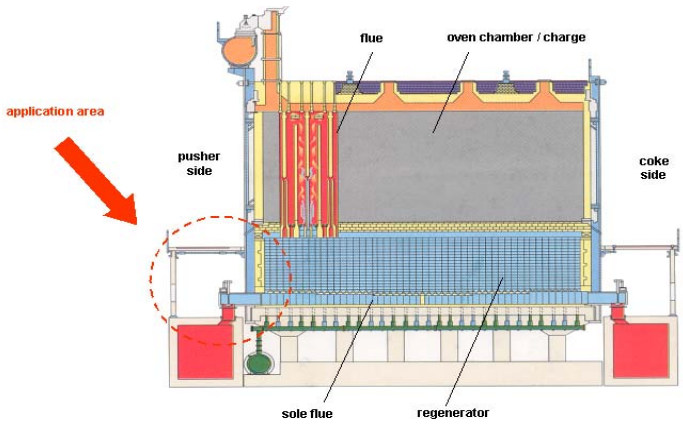


Fig. 8 Application area of the inspection system

Preference was given to the development of an inspection system according to concept B with the following standard components: a video camera combined with a swivelling mirror, which is arranged in a small module mounted on a slide for movement of the mirror into the regenerator sole flue. A light source can be located by the mirror module or beneath the camera. Shown schematically in Fig. 7, this system may be combined with a cleaning device. The regenerator area, which can be inspected with the selected system, is shown in Fig. 8.

Regenerator cleaning system

Different types of commercially-available nozzles were tested in the laboratory at different air pressures to find suitable nozzles for an air-based cleaning system, which could be applied in combination with an inspection system to remove deposits from the regenerator brickwork by air blowing. Nozzles, that showed high blowing forces in the laboratory tests, did not meet the geometrical requirements for use in the regenerator sole flue. One type of nozzle, which met the geometrical requirements, had a medium blowing force. This nozzle was selected for the cleaning system, as the blowing force of the nozzle can be enforced by raised air pressure. The selected nozzle, which can be adapted to the length of the checker brick slots by parallel connection of three nozzles, is shown in Fig. 9 with its laboratory test results. The concept of a combined inspection/cleaning system can be seen in Fig. 10.

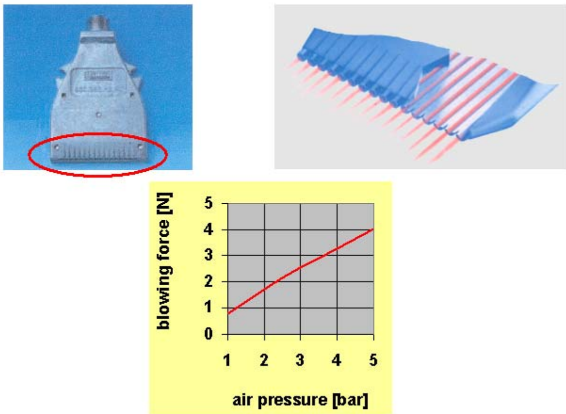


Fig. 9 Well-adapted nozzle for the cleaning system

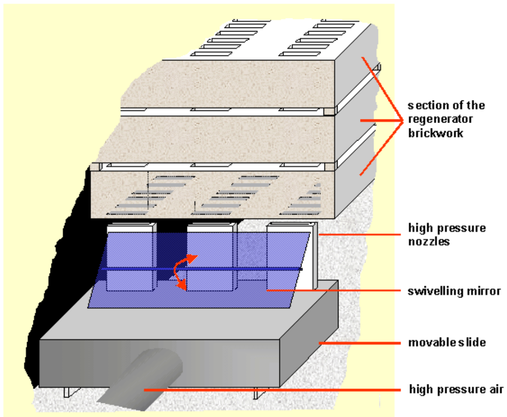


Fig. 10 Concept of a combined inspection/ cleaning system

Flue temperature and vision, tie-bar and oven-top deflection monitors

After making preliminary equipment designs, Corus evaluated optical and thermal sensors, load cell devices and displacement transducers for flue temperature and vision, tie-bar and oven top deflection measurements. Experiments took place in the laboratory and sometimes on plant to evaluate the sensors to aid selection. When problems occurred with the equipment in the laboratory or on plant, further investigations were made of alternative devices to improve or re-design the rigs.

Task 1.3 Concept: laboratory carbon deposition rig

Alternative designs for the carbon deposition rig were evaluated in the light of previously-described rigs and previous studies(5). The outcome of this assessment was the concept of a rig, which essentially consisted of an electrically-heated vertical-tube furnace in which the deposition probe was suspended with provision for appropriate mixtures of gases and/or vapours to be fed to the furnace at controlled flow rates and selected temperatures.

Following some initial tests with a simple rig and a comprehensive literature search with respect to carbon deposition and its mechanism of formation in coke oven plants, the initial design concept was altered to try to ensure effective simulation of the carbon deposition in a commercial coke plant. In the previous studies, the pyrolytic carbon deposits differed in appearance from some available coke oven carbon deposits. The main modification to the initial design was made to facilitate the carbonisation of coal to emulate the generation and composition of the volatile matter found in the free space of an industrial oven. In effect, the bottom zone of the assembly provided the coal carbonisation facility (see Task 2.3 below).

3.2 Work Package 2: Internal Chamber Monitoring

Task 2.1 Development of automated viewing/recording

Generally, oven conditions are assessed through visual observation of the chamber walls just after pushing. This evaluation requires a high level of expertise, and it is very time-consuming and it is also subjective. In addition, these inspections are more and more difficult to carry out at regular intervals, because of machine automation and unmanned operations.

The system developed by CPM allowed the inspection of both coke oven chamber walls during pushing by means of a camera head mounted at the back of the pusher ram. Some pictures of the devices are presented in Appendix 2, Task 2.1. The camera head observes one wall during the pushing operation and the opposite wall during the return of the pusher ram. All the video and the operating signals are conveyed through a single coaxial cable by using a multiplexing technology.

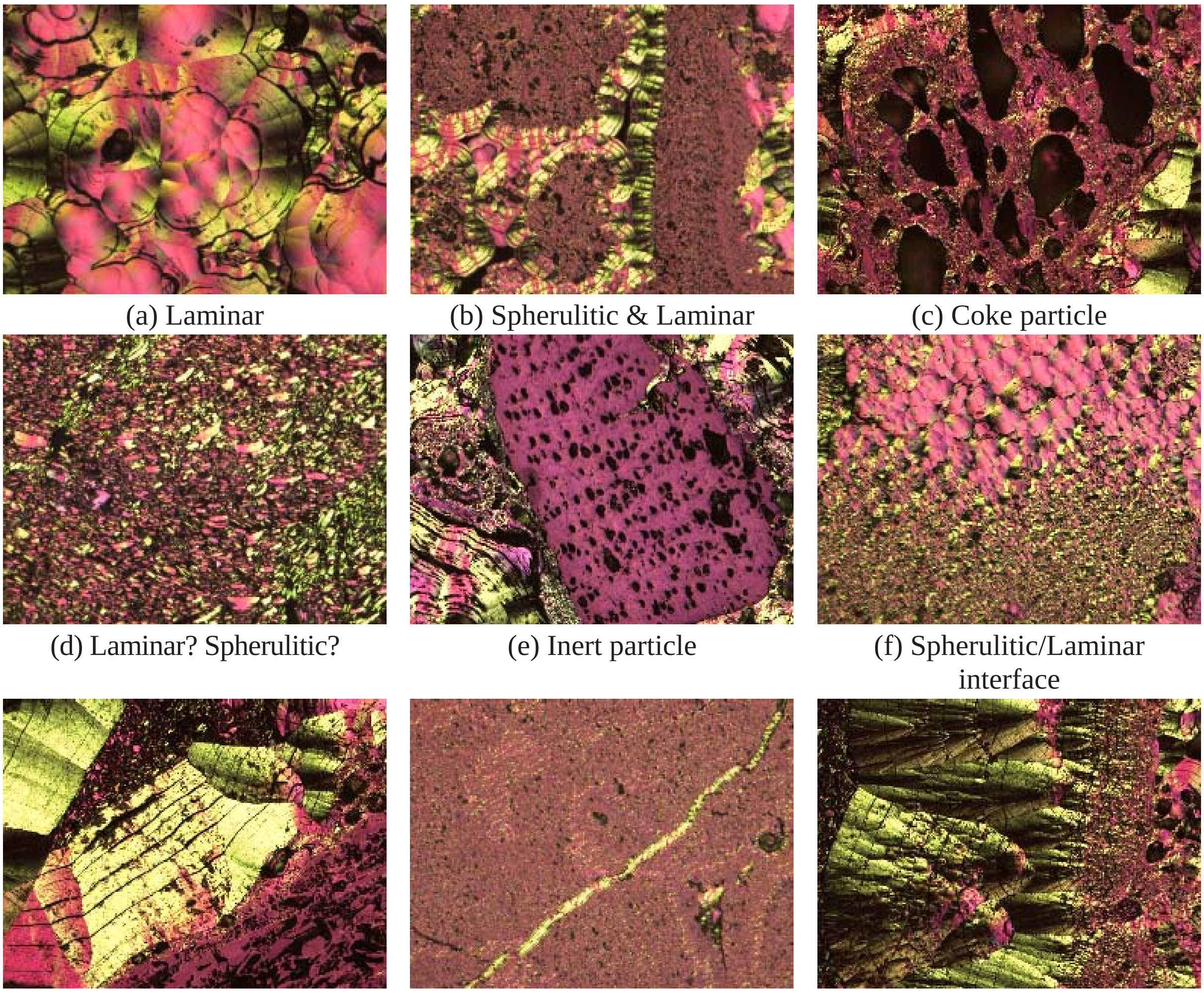
At one end, a heat resistant electronic box was installed near the camera head. At the other end, a de-multiplexing and control box was installed in the operating cabin of the pusher ram, as well as a television monitor and a digital videotape recorder. The coaxial cable, which links the multiplexing box to the control unit, is inserted inside the decarbonising air pipe of the pushing machine and passes through a rotating electrical connector, installed at the end of the tubular shaft of the air pipe rolling system.

The chamber wall observation device is not water-cooled. Only air coming from the decarbonising air pipe is used to avoid overheating of the whole system. Part of the decarbonising air is used to cool the coaxial cable, the electronic components of the multiplexing box, as well as the camera. Air is also ejected just in front of the objective in order to avoid dust deposits on the lens. Before use, this air is de-dusted and de-oiled in an additional air treatment system. In addition, the cables between the decarbonising air pipe, the multiplexing box and the camera head were protected by stainless steel sheets insulated with different layers of ceramic fibre. The camera head and the camera are also protected by ceramic fibre (see Fig. 11).

Fig. 11 Insulated camera, electronics and cables

Task 2.2 Investigation of carbon deposit rates/type

Corus surveyed a number of batteries to evaluate the type, quantity and location of carbon deposits within coke ovens, and to assess the corresponding data in relation to battery operating conditions, coal blend properties and their effects on pushing characteristics. Samples were supplied to UNOTT to assist their evaluation of the type, quantity and location of carbon deposits. Within the collection period, changes in blend composition between Corus plants were not sufficiently significant to provide variations in the deposits. Carbon deposits from other European batteries were supplied by other Partners. Samples of a plant coal blend and oil (sometimes used for bulk density control) were also supplied for experiments in the UNOTT carbon deposition rig.



(a) Laminar | (b) Spherulitic & Laminar | (c) Coke particle
(d) Laminar? Spherulitic? | (e) Inert particle | (f) Spherulitic/Laminar interface
(g) Laminar/Inert | (h) Spherulitic & laminar stripe | (i) Laminar/Coke

Fig. 12 Polarised-light micrographs of carbon deposits (x 200 magnification)

Pyrolytic carbon is formed by the decomposition of hydrocarbons in an oxygen-free environment. A literature survey showed that several different types of pyrolytic carbon, exhibiting a broad variety of microstructures, have been identified and described. However, the terminology and descriptions of these materials are not consistent, and so it was necessary to devise a suitable classification system, as a first step in classifying carbon deposits.

Shemeryankin(6) identified three different types of pyrolytic carbon, which he described as lustrous carbon with a laminar structure, soot particles, and fibrous carbon in the form of long fibres or threads. Krebs(7,8) also reported three main types of carbon found in coke oven deposits, and defined these as pyrolytic carbon, carbon black and carbonised coal particles. Another classification system using polarised-light microscopy (PLM), reported by Gray and Cathcart(9) and by Bokros(10), defined the observed microstructures as isotropic (without any growth features and low optical reflectance), laminar and columnar or granular.

Nagata(11) also established that different types of carbon are formed depending on their location within the coke oven. Wall and roof carbon deposits were found to contain what was termed columnar structures, but the texture appeared to be similar to that termed laminar carbon by others. Roof carbon contained less columnar material and more so-called granular carbon, which corresponded in appearance to spherulitic carbon, together with some coal-derived coke. Jomoto and Matsuoka[12] also identified two types of coke oven carbon deposits. That attached directly to the wall or roof was classified as a primary deposit, whilst that which subsequently accumulated on top of the primary deposit was termed a secondary deposit. These differences are not surprising, since the mechanism of elemental carbon formation by pyrolysis of hydrocarbons is a complex process involving gas-phase decomposition reactions, nucleation of liquid micro-droplets, diffusional transport of the nuclei to the surface and dehydrogenation to form carbon[13].

This review and the examination of roof and wall carbon deposits by PLM led to the adoption of a classification primarily into two types of carbon texture, laminar and spherulitic. Laminar carbon appeared as corn-shaped columnar texture, and spherulitic carbon has a grainy mosaic-type appearance (see Fig.12).

Task 2.3 Development of carbon deposition rig

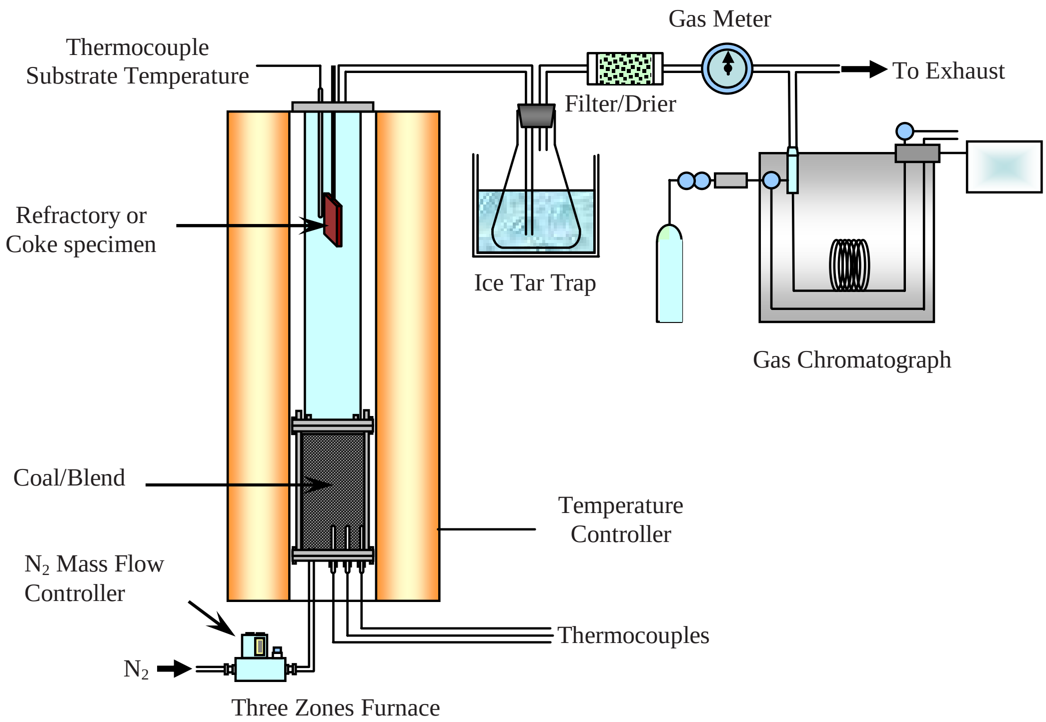


Fig. 13 Final design of carbon deposition rig

After several modifications due to operational problems, the rig for laboratory-scale deposition of carbon gradually evolved into that shown in Fig. 13. The rig comprised a vertically-mounted, electrically-heated tubular furnace surrounding a lower carbonisation retort. Above the retort, a ceramic tube containing the rectangular silica slide to collect the carbon deposits was attached. The volatile matter released from the carbonisation of a 100 g sample of coking coal, at 4°C/min from ambient to 700°C or 900°C, passed through an intermediate zone of the assembly, which acted as a cracking reactor and an upper carbon deposition zone. The latter two zones were heated at a faster heating rate of 10-12°C /min, so that when the carbonisation retort reached about 350°C and 500°C, the deposition zone was at 700°C and 900°C respectively.

The temperatures were monitored by suitably positioned thermocouples with the intermediate and upper zones maintained at a final temperature of 1150°C. In the carbonisation retort, the temperature profiles at three different positions enabled three main regions to be distinguished. The first region is characterised by a regular increase in temperature up to 100°C for over 30 minutes corresponding to the evolution of moisture. After the water has evaporated, the temperature in the coal charge increases regularly at the same rate as that of the wall. The low thermal conductivity of the coke produced and the absorption of heat by the endothermic pyrolysis reactions are responsible for the temperature differences within the retort. The charge temperature then becomes more uniform when the pyrolysis reactions have ceased, as shown by the reduced temperature gradients. These temperature gradients are considered to be comparable with those of industrial coke ovens, and consequently, the deposition conditions simulate industrial conditions. The final version of the deposition rig worked well and provided an excellent means of carrying out basic studies of carbon deposition under conditions, that appertain during the carbonisation of coal blends in coke ovens.

3.3 Work Package 3: External Monitoring

Task 3.1 Development of a prototype regenerator inspection system

A first prototype inspection system without any cleaning equipment was developed and constructed with the following components:

- swivelling welding mirror mounted on a slide with linkages for movement of the slide and manual adjustment of the mirror
- standard camcorder.

A photograph of the Prototype 1 inspection system is shown in Fig. 14. After testing in the laboratory, functions of this inspection system were investigated in WP 6, Task 6.5 under real conditions at a regenerator in a German coke plant.

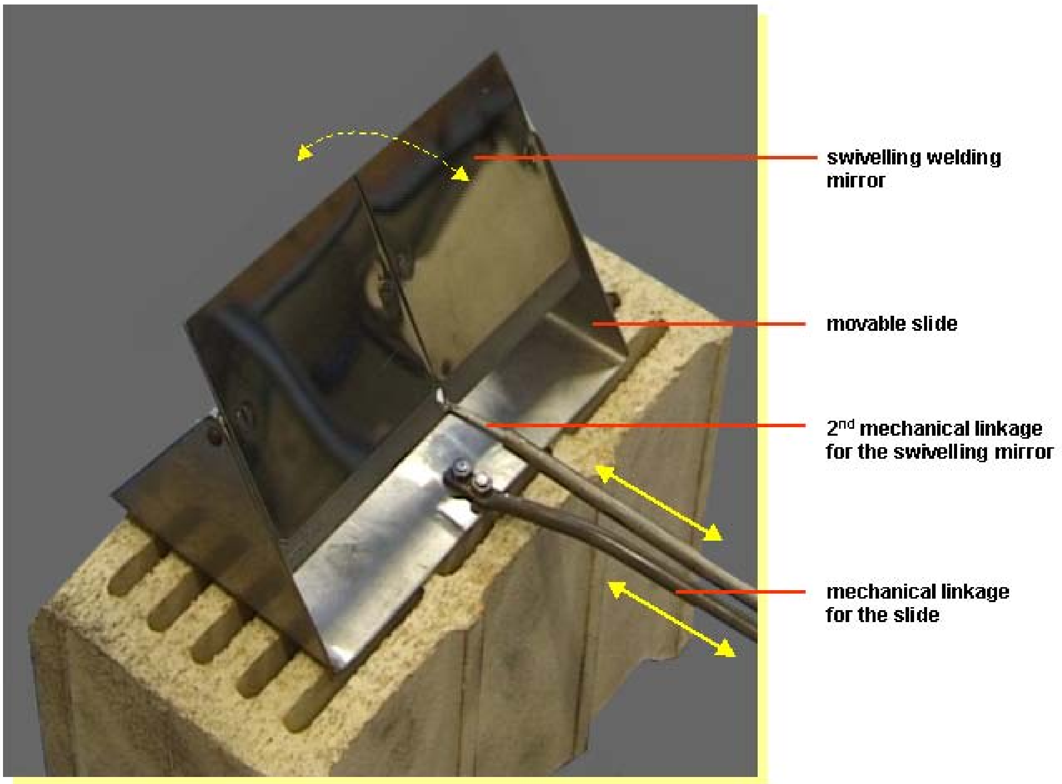
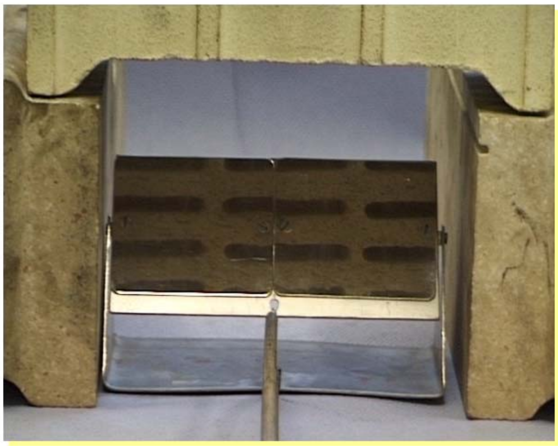


Fig. 14 Prototype 1 inspection system



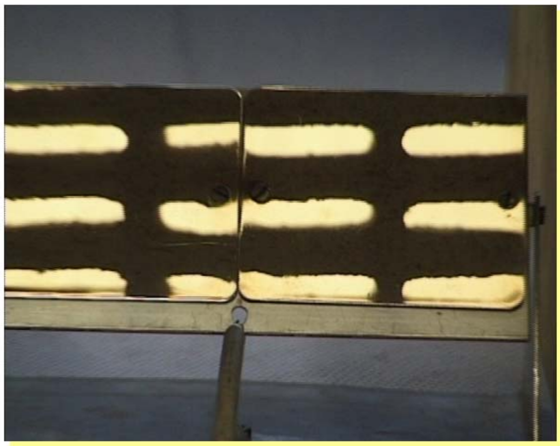


Fig. 15 Camcorder view of the swivelling mirror of Prototype 1 inspection system at a cold test checker brick

Fig. 16 Application of Prototype 1 inspection system with incidence of daylight through a cold test checker brick

Photographs from laboratory testing are shown in Figs. 15 and 16, with light effects from temperature radiation in a hot regenerator simulated by the incidence of daylight (in Fig. 16). In laboratory trials with a cold test checker brick, single brightened slots of the regenerator brickwork could be made visible with the Prototype 1 inspection system. However, later plant trials in WP 6 showed that the optical characteristics of the welding mirror were only mediocre under hot regenerator conditions. Additionally, some other weak points were identified for the Prototype 1 inspection system in the plant trials (see Task 6.5).

Task 3.2 Integration of cleaning system

Cleaning equipment with three air nozzles was integrated into an optimised Prototype 2 inspection system (developed in Task 3.3) to remove dust and other abrasive deposits from the regenerator brickwork by air blowing air. Photographs of the combined inspection/cleaning system are shown in Fig. 17.

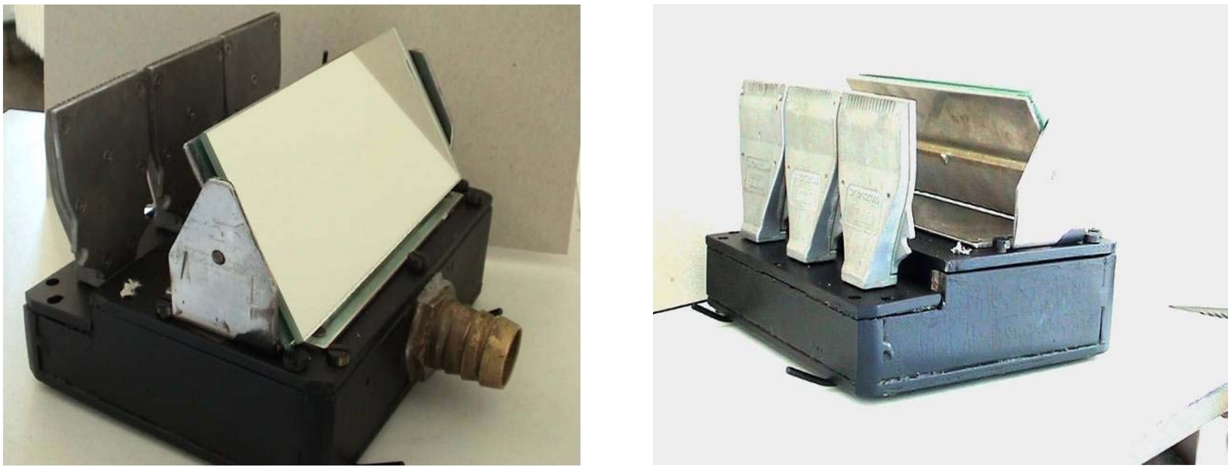


Fig. 17 Combined inspection/cleaning system

The combined inspection/cleaning system was tested in plant trials (see WP 6). Large quantities of dust and other deposits could be blown away from the brickwork in the lower sections of the regenerator with the integrated cleaning equipment. Whether brickwork cleaning also reached upper parts of the regenerator could not be monitored with the inspection system. Additional illumination was applied in the Prototype 2 inspection system to make details of brickwork damage and cleaning effects visible. With additional illumination, however, swirling dust during cleaning caused too much backscattering of light in the video recordings, so that simultaneous optical inspection and cleaning were not possible (see WP 6).

Task 3.3 Testing/optimisation prototype regenerator equipment

Due to poor results from the Prototype 1 inspection system in plant trials, an optimised Prototype 2 inspection system was developed, which was combined with the air nozzle cleaning equipment. Optimisation of the inspection system was achieved with the following components:

- new movable slide with a radio-controlled swivelling mirror made from optical glass
- integrated common air supply for brickwork cleaning and cooling of electronics
- new camcorder (IR- and visible mode) with temporary additional illumination

A sketch of the optimised Prototype 2 inspection system is shown in Fig. 18. This system was tested in plant trials at a regenerator of a German coke plant in Task 6.5. Results showed that conditions of lower brickwork sections of the regenerator can be analysed in detail with this system, if inspection is run without simultaneous brickwork cleaning. However, problems in handling of the inspection equipment occurred in the deeper parts of the regenerator sole flue with twisting of air supply hoses and insufficient air cooling causing temporary malfunctions of the servo used for adjustment of the swivelling mirror.

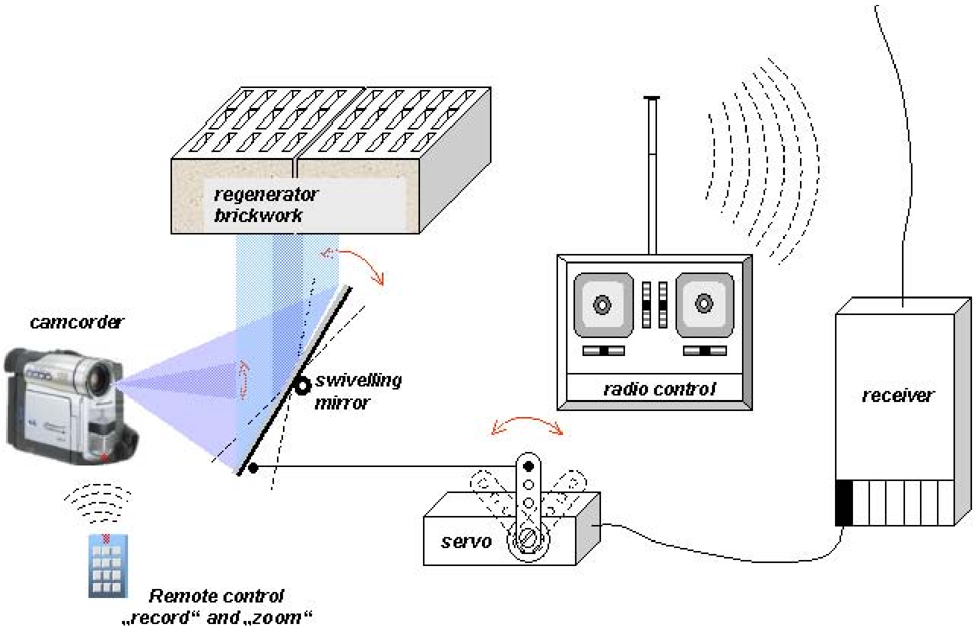


Fig. 18 Optimised Prototype 2 inspection system

Fig. 19 Simplified Prototype 3 inspection system

Due to the discovery that simultaneous optical inspection and cleaning of the regenerator brickwork are not possible (in Task 3.2), and taking into account the operational problems of the Prototype 2 inspection system in deeper sections of the regenerator sole flue, a much simplified Prototype 3 inspection system was developed without any cleaning and cooling devices. This prototype (shown in Fig. 19) was based on a moveable mirror/slide-system, in which the mirror has to be adjusted manually before the start of inspection. Tests at the regenerator of a German coke plant showed that the simplified Prototype 3 inspection system can be applied successfully without any heat protection in the regenerator sole flue at temperatures in the range of 240-290°C.

Task 3.4 Development of automated flue temperature monitoring

Corus designed an automated flue monitoring device to measure temperature profiles and record the condition of flue walls by video. Vision monitoring was added to the original plan of equipment for the temperature data collection. The proposal was for a rig with an insulated, water-cooled measuring head driven down flues from a mobile trolley wheeled along the battery top. The design incorporated a trolley holding all the equipment for the monitor, including the power supply, control box and the temperature and video display units. There was also a trough to supply water for cooling and pumping down the retractable, umbilical, measuring head, which would be stored on a motor-geared, rotatable drum.

Laboratory trials took place on materials for use in the monitor and equipment selected under Task 1. The heat-resistance and insulation of components of the rig were of critical importance for this application, and so information on insulation was shared between project Partners. Experiments were carried out on different types of insulating materials and methods of combining and cooling them to provide insulation for the measuring head and maintain its interior below 80^{o}C, so that an electronic camera could be used. Potential lightweight, portable, water-resistant, video inspection systems were investigated during trials in a pilot-scale coke oven before selection of a suitable camera and video capture and transfer system. Laboratory tests were also carried out on the drum and other parts of the rig before they were assembled, and control of every aspect of it was checked. The form of data transfer was modified to suit plant requirements (see Task 4.3).

Task 3.5 Development of tie-bar monitoring

A tie-bar load measurement system was designed for continuous monitoring of the forces acting on battery steelwork. Load cells were developed for fitting to tie-bars at the top of individual ovens for continuous measurement of loads on buckstay springs with a logging system. They were trialled in the laboratory until the correct calibration specification was identified. In initial plant trials, there were problems with cables burning, and so a range of insulating materials was investigated in a laboratory test facility to improve the design. Alternate laboratory and plant trials took place with increasingly heat-resistant insulation and a new connection system was developed, so that damaged cables could be changed without removing the load cell from service. Since the durability of the cabling continued to be a problem on the small battery selected for initial plant trials, it was decided to create a new system for trials on a taller battery. Two new load cells were constructed with greater sensitivity to changes in load, and this design was utilised successfully in all subsequent plant trials.

Task 3.6 Development of oven top deflection monitoring

A battery top deflection measurement system has been developed for regular assessment of oven top brickwork profiles and early detection of abnormal deviations, including bracing failures. Initial experiments took place with an ultrasonic sensor attached to the charge car, but accuracy was adversely affected by signal noise from charge car weight and movement and the large footprint of the sensor. Consequently, the oven top monitoring system was redesigned for measurement of the surface of the battery top by six laser displacement sensors (with CCD detectors) mounted on a ‘stand alone’ beam spanning the width of the battery.

The new version was constructed with a beam mounted on wheeled carriages, which run on the charge car rails. It was made adjustable for rail spacing, rail height and battery width, and it has an accurate positioning system to provide comparisons between trials. A dual axis inclinometer was fitted to allow compensation for charger rail deviation. As the beam is pushed along the battery manually, measurements can be isolated from disturbances caused by the charge car. The sensors use Class II lasers fitted into protective casings for safe use on plant. Data from the three control units for the six measuring heads are collected at regular distances along a battery and transferred to a logger, with the oven number and beam inclination for both X and Y horizontal planes. An accurate positioning system enables comparisons to be made in the oven top profile over months and years. Figure 20 shows the oven top deflection monitor being positioned on the battery top.

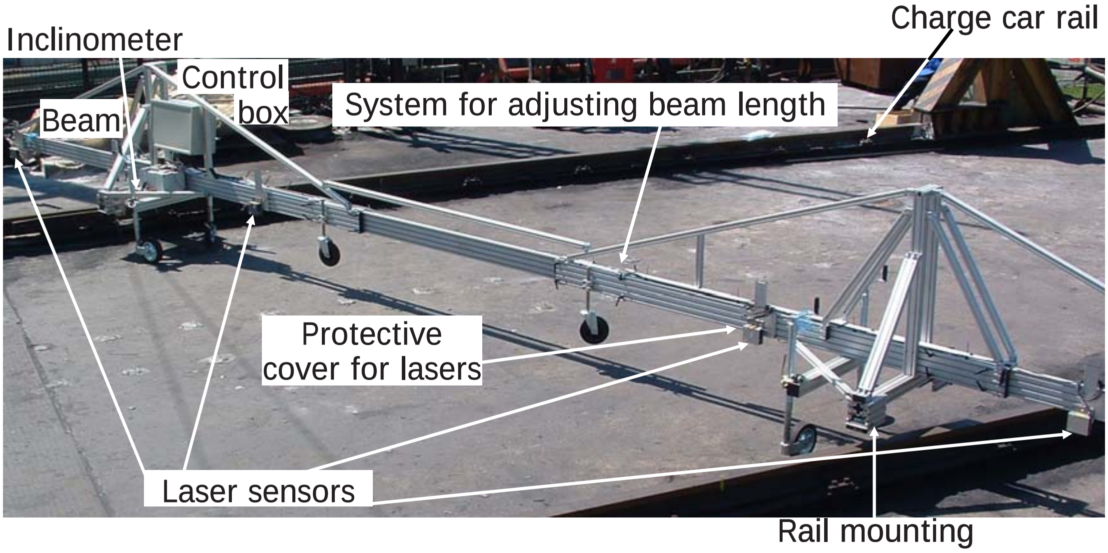


Fig. 20 Oven top deflection monitor on battery top

3.4 Work Package 4: Data Processing

Task 4.1 Oven image analysis software development

The camera was designed with a very large angle in order to increase the field of view. Consequently, the original images extracted from the inspection video presented several difficulties, which needed treatment with automated software. The development of the software was carried out in ArcelorMittal Maizières Research laboratory. The processing software was based on the Python programming language, which could provide a rectified picture of each oven wall. The objective of the development was to rebuild a plane image of each oven wall, using the video from the chamber wall observation devices developed by CPM.

Basically, two phases were defined for the development. The first phase related to the transformation and correction of the optical part, and the second dealt with rebuilding the picture of a complete wall. In order to evaluate the complexity of the coke oven wall inspection images processing problem, the video was analysed with some open source software.

The main processing packages that required development were defined and listed as follows:
- Establishment of a realistic model of optical transformation
- Implementation of a transformation model package to correct strong geometrical distortion related to the large angle of view, including spherical and projection distortions
- Correction of interlacing effects
- Normalisation of strong contrast variation problems among the images
- Determination of the optical centre
- Stitching package for the transformed images
- Creation of cartography for a wall surface.

Due to the development of several image processing packages, the coke oven wall inspection image processing software was able to generate a picture of each wall. Figure 2 is an example of the result given by the software. The treatment of the image obtained for a single wall takes around 30 minutes. The software has been developed, but the calculation time has to be optimised.

The generated picture presented above clearly shows that it is possible to identify the damage location and the extent of any damage. Cracks and wear are easy to identify by human eye. A complete wall picture permits location of different defects. A complete description of the packages is presented in Appendix 4, Task 4.1.

Task 4.2 Video recording of regenerator condition

For the organisation and archiving of the data files obtained from video recording, basic software from ULEAD Systems was used by DMT to develop and optimise RISA (Regenerator Inspection System Archive). Functions for data input and search functions were implemented additionally into RISA, using EXCEL. The input data mask and a screenshot of RISA are shown in Figs. 21 and 22.

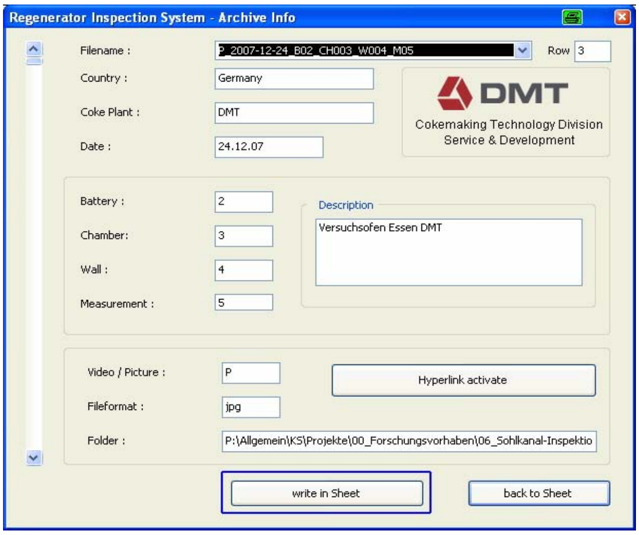


Fig. 21 Input data mask of RISA

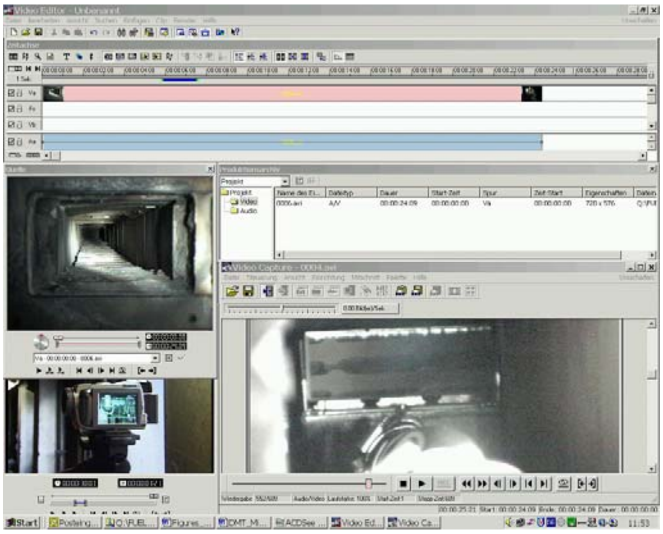


Fig. 22 Screenshot of RISA

Task 4.3 Real-time flue temperature data transfer

Before the flue temperature and vision monitor was assembled, computer control of each part was tested and software issues were dealt with. Software innovations were made to synchronise the data from the picture capture and encoder position and to run it remotely in wire-less mode as well as manually. Images were captured on computer and stored with depth and temperature data. Problems with interference and noise were solved with new software and minor modifications to the rig.

Although the original plan included real-time data transfer to the battery control room computer for monitoring and optimisation of battery heating control, this was not wanted by plant personnel (owing to the large volume of data during short time spans). Consequently, the proposal was modified to real-time data transfer to the rig and to an independent computer, which could be located in the control room. Data were processed to provide temperature and photographic maps and comparisons between trials. Discussions took place with DMT about applying some of their regenerator inspection system software to store data after trials.

Task 4.4 On-line relay of tie-bar strain data

Wireless data transfer and software regimes were set up to enable tie-bar load data to be collected reliably from all sensors on data loggers via a radio link. To suit the preferences of different plants, flexibility was built into the method of collecting data. The system was designed so that plant personnel could observe tie-bar condition with the possibility that major abnormalities, such as breakage, could generate an alarm.

Task 4.5 Software development for oven top deflection

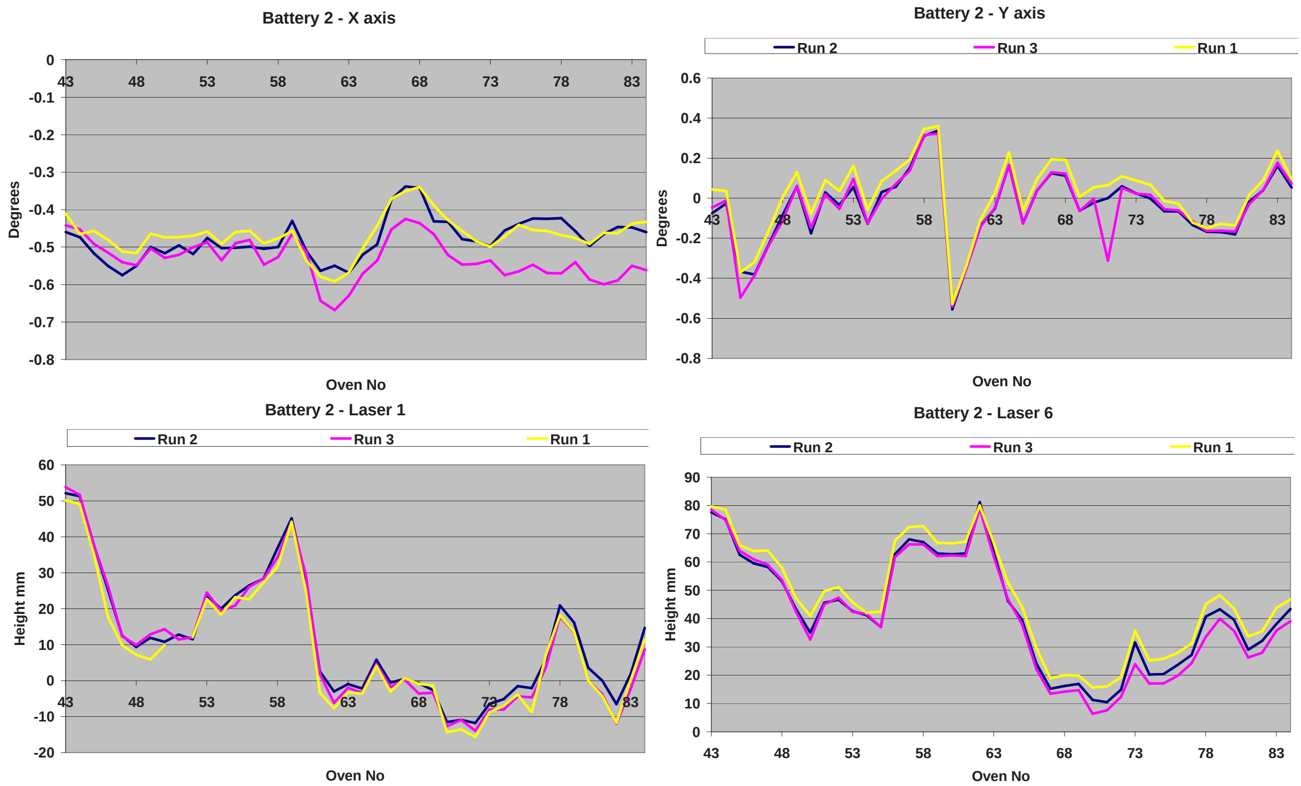


Fig. 23 Graphical representation of raw oven top data from inclinometer and Lasers 1 and 6

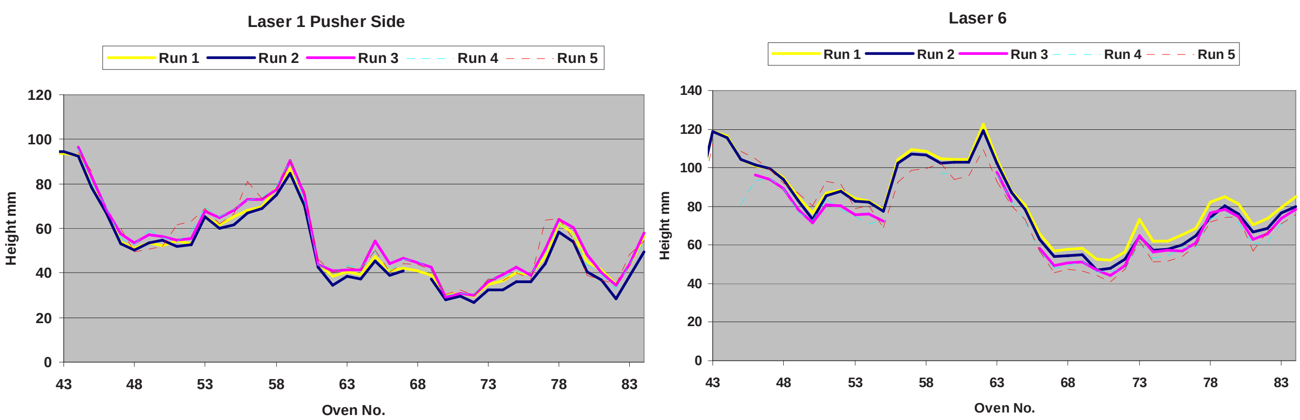


Fig. 24 Corrected data for Lasers 1 and 6

Software was written for the oven top deflection monitor to convert the raw data for the inclinometer and the lasers into two-dimensional graphs and to correct the graphs against the reference point for the batteries and for variations in rail height. Figure 23 shows a graphical representation of the raw data for the x and y axes of the inclinometer and Lasers 1 and 6 as the oven top monitor travelled along Battery 2 in the first plant trial. Corrected data for these lasers are illustrated in Fig. 24. Further software was developed to collate data from different runs to give a three-dimensional profile of the battery top (see

Task 6.3), which can be compared with results from future trials and produce a three-dimensional representation of changes in oven top profiles.

Task 4.6 Image analysis software: carbon characterisation

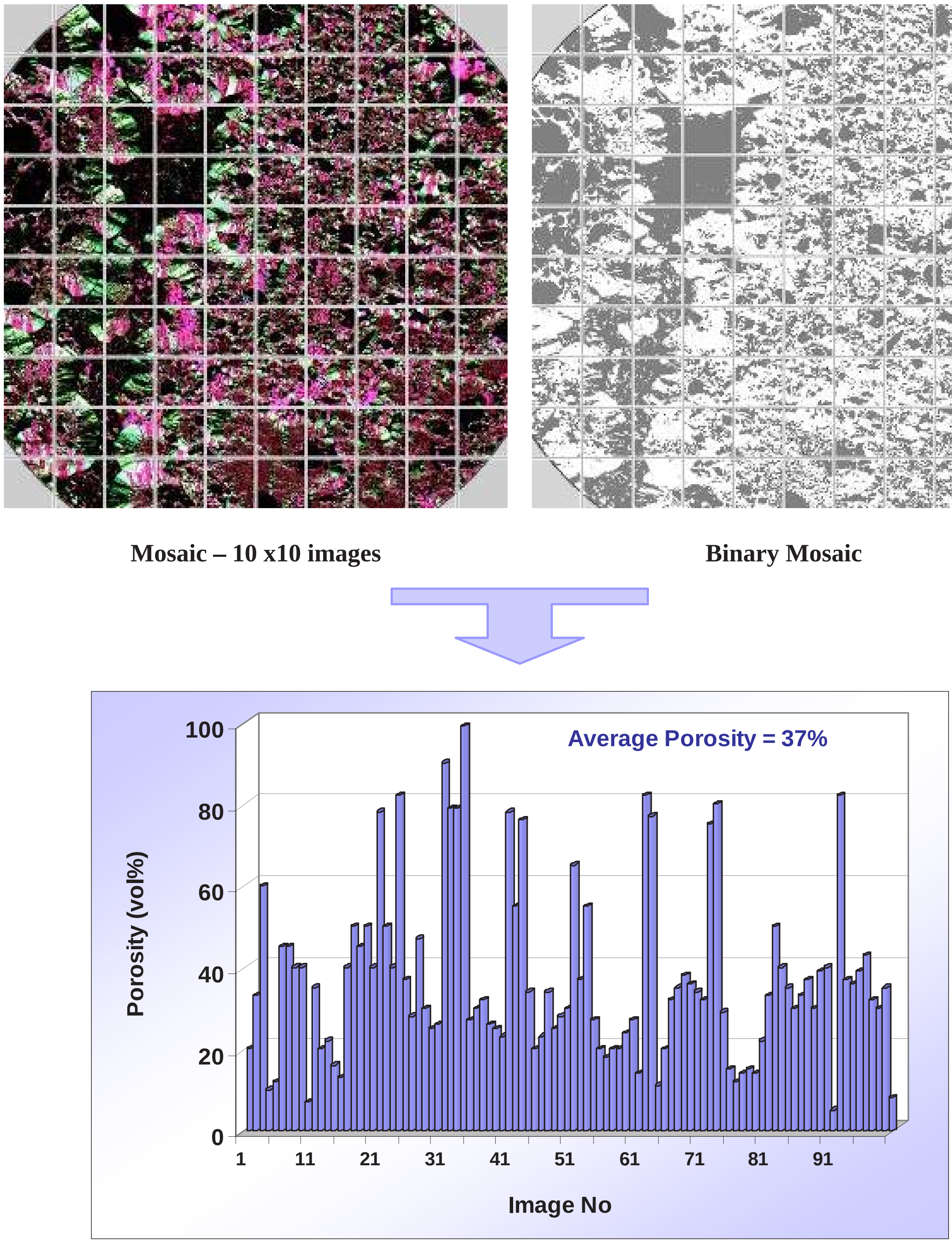


Fig. 25 Porosity measurement by image analysis

Using optical microscopy, a fully automatic image analysis method for the determination of coke porosity was developed, based on a versatile image-processing system. Images of an entire polished sample of carbon deposits can be captured automatically by the system for further processing and analysis. The developed programme is capable of generating a mosaic of up to 30 x 30 images, enabling porosity of the entire mosaic to be determined. This has the potential to estimate individual pore sizes and pore-size distributions. The main feature of the method is that adjacent frames are captured and the material inside each frame is quantitatively assessed, whilst that cut by the frame edges is saved and measured before the results are merged to produce data representative of the whole of the mosaic. Figure 25 illustrates the image processing sequence of this programme for a mosaic sampled from a carbon deposit. For this sample, U, the porosity was assessed as 37% by volume. Another advantage of this method is that small pores can be measured readily by processing single images, whilst macropores, which may not be completely shown in single images, can be analysed by combining images to generate suitable mosaics.

The image analysis was subsequently developed to characterise the texture of the carbon material. This system was capable of differentiating between the laminar and spherulitic carbon in the deposits. It was envisaged that fissures in concentric circles are characteristic of laminar carbon and could be one of the main features to help in distinguishing between the carbon forms. However, it was established that the difference in grey levels, optical appearance, degree of anisotropy and porosity which could facilitate the required discrimination. A problem still to be resolved is that caused by the presence of coal and coke-like particles.

3.5 Work Package 5: Assessment of Carbon Deposits

Task 5.1 Sampling of carbon deposits

Twenty samples of industrial roof and wall carbon deposits from five Corus plants and from DMT were supplied to UNOTT for analysis with available information about origin, blends and operating conditions (see Task 2.2). Listed in Appendix 5, these samples were primarily carbon deposits from coke oven walls with a few from the oven roof and one from the oven charge-hole.

Task 5.2 Analysis and laboratory trials

The carbon deposits were cut into several layers parallel to the deposition plane and mounted in resin for preparation as polished sections, which were examined initially by polarised-light microscopy (PLM) shown in Fig. 12 above (in Task 2.2). A considerable amount of laminar pyrolytic carbon exhibiting the corn-shaped texture described by Krebs[(7,8)], was observed in all of the samples, especially in those sections furthest from the deposition surface. Spherulitic carbon was also observed, and this tended to be present in the sections nearer to the oven-wall surface. In some cases, spherulitic carbon appeared to be encrusted with several layers of laminar carbon, whilst coke-like particles and others, identified as inertinite particles, were also observed.

The surface morphology of the carbon deposits was also analysed by scanning electron microscopy (SEM). As with the PLM analysis, a variety of microstructures was observed. The material found nearest to the wall-side of the deposits consisted mainly of spherulitic carbon, whilst fibre-like material appeared to be present in the wall-side of deposit H. However, in general, laminar carbon was the predominant species in all the samples. Laminar carbon comprises the major entity in the coke-side of all the samples examined, in agreement with the PLM analysis. Evidence of some gasification of the coke-side carbon was apparent in some cases. The scanning electron microscope provided supplementary information to that obtained through polarised-light microscopy about the nature of the carbon material deposited and confirmed the differences identified in the materials.

Series of micrographs of the carbon deposits sliced perpendicular to the deposition plane were also taken and merged to ascertain any significant difference in the various layers from the wall-side to the coke-side. Clear difference in the packing density of the layers was observed. The profiles show a strong tendency for the deposits to be less dense at the wall-side with the exception of sample M, which showed little variation in packing density. This particular sample was the thickest sample received and had a high concentration of mineral matter. Another sample, deposit V, which was generally a very compact deposit with some porosity at the centre and tending to be denser not only at the deposition side but also near to the wall. The thickness of this deposit was nearly 14 mm. In all cases the material at the wall-side appeared to be mainly spherulitic whilst that at the deposition side appeared to be mainly laminar. Clearly, there is evidence of a preference for the initial deposition of spherulitic carbon at the oven wall followed by a subsequent deposition of carbon of a laminar nature. It is tempting to suggest that this difference may be a function of the surface on which the deposition takes place with silica surfaces promoting spherulitic carbon formation and carbon surfaces favouring the formation of laminar carbon. But, this is simply a hypothesis at this stage and considerable more work is required to determine the validity of this and indeed, the relevance of it in terms of minimizing undesirable carbon deposition.

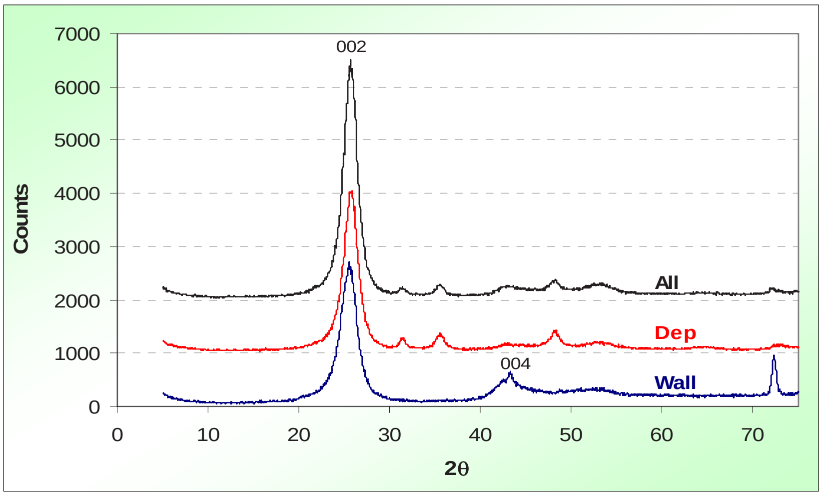


Fig. 26 XRD diagrams for industrial oven carbon deposit B

Representative samples of carbon deposits including carbon material from the wall-side and the deposition side were analysed by X-ray diffraction (XRD), see Fig. 26. The 2-theta dimension for the main peak, for the crystalline reflection 002, is virtually identical for all the samples at around 25.7 degrees corresponding to graphitic carbon. The peak height indicates the magnitude of the degree of ordering of the carbon layer planes and the carbon material from the wall-side and the deposition side appear to have a similar degree of order. The appearance of a small 004 peak at 43.3 degrees indicates that the material at the wall-side has the more orderly graphitic structure. For sample I, there was evidence from both the 002 and the 004 reflections of the wall-side material being more graphitic than the deposition side carbon with the reverse being the case for the deposit G. The fact that there appear to be no marked differences in the carbon structure at the atomic level implies that the different carbon entities identified are a figment of the structure and texture on a larger scale and involving the porous structure.

Task 5.3 Effects of blend composition on deposits

The composition of the coal blend charged to a coke oven has a strong influence on the nature of the volatile species and the temperature and rate of their evolution, and as a consequence of this, the blend composition is an important factor in wall and roof carbon deposition. From laboratory carbonisation tests, Jomoto[12] found that the carbon deposition rate is directly related to the charge volatile matter content. Models incorporating terms for gas velocity, in terms of volatile matter and moisture per unit of void space per unit time, established that a 1% increase in volatile matter led to a 6-7% increase by weight in the carbon deposition rate.

Krebs[7,8] also emphasised the importance of the temperature at which the released primary tars are cracked. They found deposition to increase more than five-fold as the cracking temperature increased from 850°C to 1000°C. They also identified a modifying effect of moisture on the pyrolysis tars with high moisture levels, that is above 8% by weight, encouraging the formation of oxygenated low molecular weight tars which readily crack to form laminar carbon deposits. Lower moisture, <8%, led to the production of more aromatic tars, which ultimately lead to spherulitic type carbon deposits. These effects were shown by Pajak[14] to be related to the hydrogen transfer abilities of the tars, with low ability to transfer hydrogen leading to more carbon deposition during secondary cracking. Nagata[11] also reported that increased volatile matter content, as well as increased concentration of additives, such as asphalt pitch and crude tar, increased carbon deposition.

Samples of the carbon material deposited on silica slides from the carbonisation of coking coal in the laboratory-scale carbonisation rig were examined initially by SEM. The rate and extent of the deposition appeared to vary with distance from the gas source irrespective of the cracking temperatures, and it is clear that maximum deposition takes place nearer to the gas source. SEM examination of the carbon deposited at 700°C showed it to be spherulitic carbon with significantly smaller sphere size than that deposited at 900°C, which was again smaller that that produced at 1100°C. This limited study appears to confirm that the initial deposition on a silica surface is of spherulitic carbon. It is unfortunate that time restraints prevented further tests, which could have elucidated the role of the nature of the surface on both the type of carbon deposited, the rate of deposition and on the relative influence of the possible factors involved in the deposition.

Task 5.4 Influence of charge conditions on deposits

There was insufficient time to carry out all the laboratory trials to determine the influence of charge conditions on carbon deposition, but the literature search revealed some of the more important effects. Generally, although carbon deposition depends primarily upon the temperature, type and concentration of the source gas, it also is influenced by the surface properties of the substrate on which the carbon is deposited. In the case of coke oven deposits, additional factors include the moisture content of the coal charge, the hydrogen transfer ability of the intermediate tars, and the presence or absence of coal fines.

Krebs(7) assessed the effect of moisture content and found that below 8% by weight moisture two layers were formed, a spherulitic layer adjacent to the refractory surface and an outer layer of larger cone-shaped units of laminar carbon. As moisture content increased, the thickness of both layers decreased, and above 8% moisture only laminar carbon was deposited. Nakagawa(15,16) also considered moisture content, as it was found that the coal moisture control process (which reduced the moisture from 9-10% to 5-6% by weight) increased the amount of roof carbon. As the deposited carbon also had an increased ash content, a secondary effect of the dryness was suspected, in terms of increased fines. Laboratory studies confirmed that the deposition rate was greater in the presence of coal fines. Nakagawa(15) also found that the presence of coal fines tended to increase deposit build-up, especially at the start of the carbonisation, when this was enhanced by the bonding effect of the tarry material evolved. In laboratory carbonisations, Jomoto(12) found that the rate of carbon deposition could be related, not only to the coal volatile matter and the moisture content of the charge, but also to temperature of the deposition surface. From modelling studies, Nagata(11) and Yoshida(17) concluded that oven temperature was the most significant effect. Notych(18) also reported that high free space temperature caused increased carbon deposition.

Nagata(11) reported that gas velocity had little effect on carbon deposition. Considering the condition of the deposition surface, Kasaoka(19) found that carbon deposition was enhanced where cracks in the oven brickwork occurred, and concluded that smooth, defect-free surfaces inhibit the initiation of carbon deposition.

3.6 Work Package 6: Plant Trials

Task 6.1 Installation/testing of internal wall scanning system

The first tests of the whole chamber wall observation system were carried out at the Carling coking plant instead of Fos sur Mer coke plant. Fos sur Mer commissioned a new coke oven battery at that time, and the pushing machines were not available for the implementation of the device. Carling coke plant was selected for proximity reasons.

As planned, the use of this device did not affect production, as the observation was performed during normal pushing operations. The installation of the whole system on one pusher machine of the Carling coke plant required steps, which are detailed in Appendix 6, Task 6.1. Two tests were carried out with the inspection of one wall during the pushing operation and the opposite wall during the retraction of the pusher ram. To avoid large distortion of the images, the camera head was perpendicular to the observed wall. The images were of very good quality (see Fig. 27). The new camera head allows at least four brick layers to be viewed, instead of maximum two layers with the old camera head.

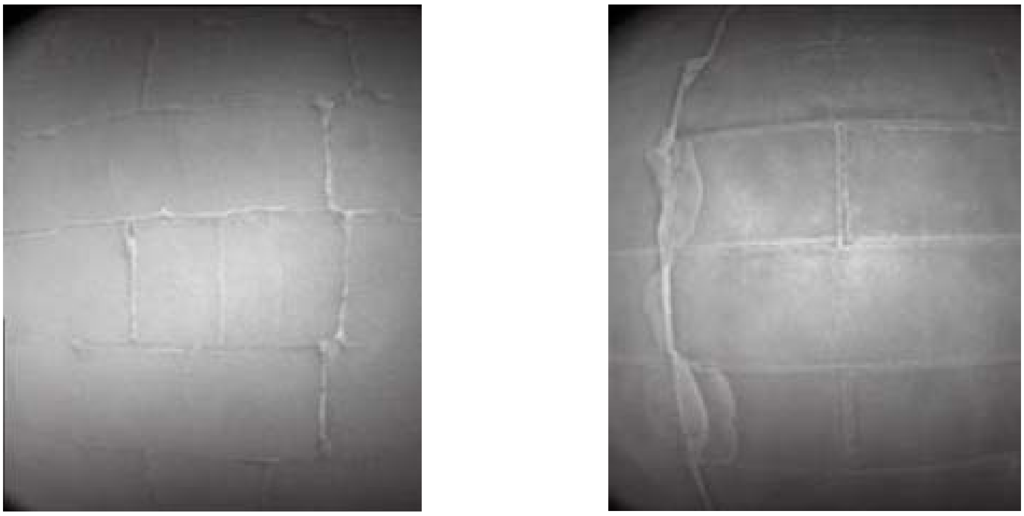
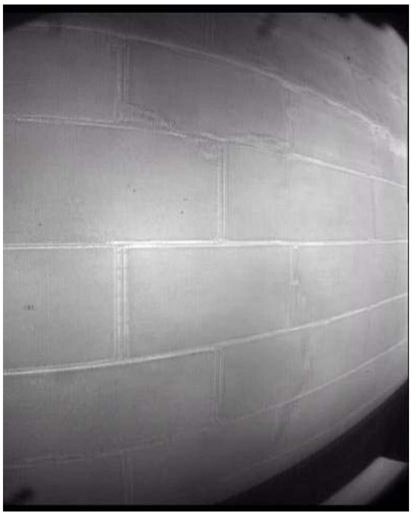


Fig. 27 Chamber wall observation in Carling coke plant

Perpendicular view



View with a 10° angle

Fig. 28 Chamber wall observation in Dillingen coke plant

Some problems occurred during the second test with loss of video signal. This problem did not come from the camera head itself (whose temperature had only increased by 5°C), but from the coaxial cable. After the plant test, this cable melted inside the decarbonising air pipe due to the air cutting out after each push (since the capacity of the compressor was not large enough to ensure permanent air blowing). In addition, this air decarbonising pipe was located on the top of the pusher ram (not inside it), and consequently, it was subjected to high temperatures during the pushing operation. It would be necessary either to blow air permanently or to protect the whole length of this air pipe against heat to avoid this phenomenon.

A second tests series was performed in Dillingen in order to increase the device reliability, and it was possible to control fifteen oven chambers during pushing in a three hour period. As in the first trials at Carling, it was necessary to install the complete device and to adapt the Dillingen pusher ram. The most time-consuming activity was the installation of the coaxial cable in the decarbonising air pipe. The results were satisfactory in terms of field of view, image quality (distortion, clarity) and temperature resistance.

In addition several tests were performed to optimise the direction of view:

- Camera head strictly perpendicular to the chamber wall,
- Camera head oriented with a 10° angle in order to increase the field of view.

Figure 28 shows that it is possible to observe more than six brick courses with a 10° angle. The chamber wall observation system implemented in Dillingen coke plant gave satisfactory results in terms of image quality, field of view and reliability. This device is relatively easy to install on any pushing machine because it is not water-cooled. Only air coming from the decarbonising air pipe is blown permanently. The reliability of this system was improved considerably at Dillingen coke plant. The autonomy of this system is greater than three hours, without any risk to the electronics and the camera head. Consequently, it is possible to observe more than fifteen different ovens during this period of time.

Task 6.2 Installation/testing of tie-bar monitor hardware

A number of trials were carried out with the first version of a load cell sensor installed on the top tie rods of a coke oven buckstay. On the first battery, failure of the washers occurred after a few days due to excessive temperatures and mechanical damage, disrupting data communications between the computer and load cell. Equipment returned to the laboratory still worked when rewired, but the cables were damaged. After a series of laboratory tests, insulation of the cables was improved progressively, but problems still arose on plant. Since they were specific to the design and operation of the small battery used for these trials, taller batteries were selected for subsequent trials and the sensor system was redesigned.

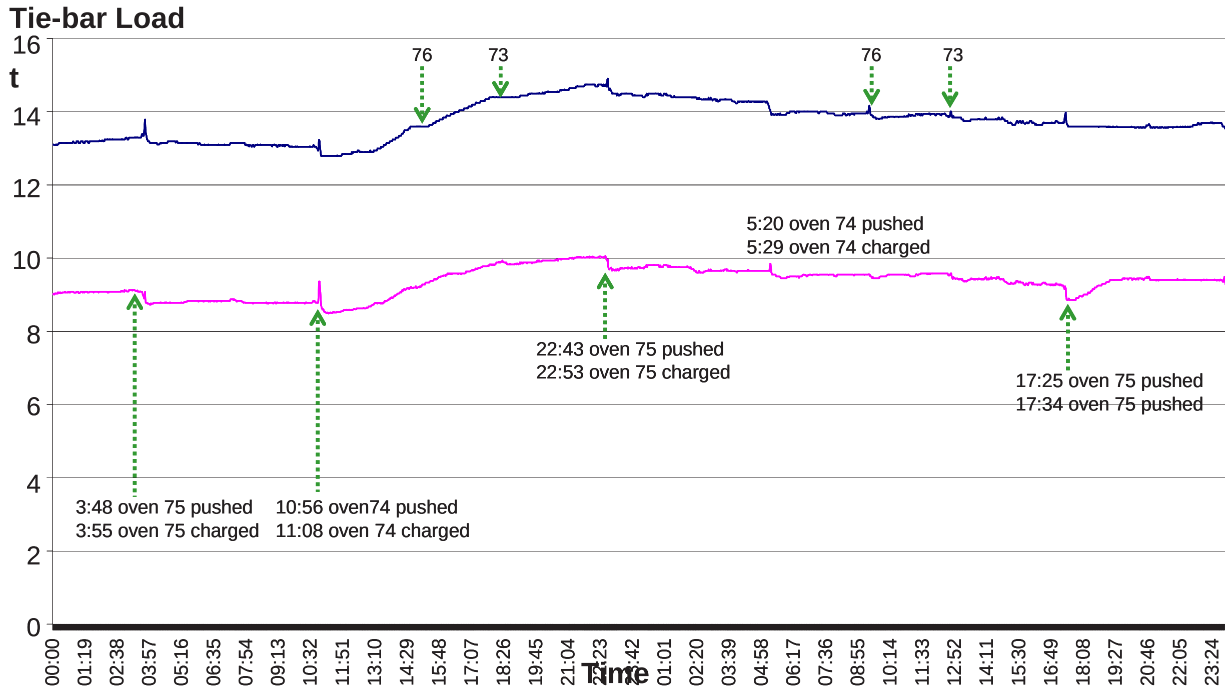


Fig. 29 Changes in tie-bar loads on Buckstay 75 with charging and pushing of adjacent ovens

The new design of load cell was installed on the tie-bars of one buckstay on a taller battery. After successful operation for several months, a further six sensors were fitted at intervals along the length of two batteries. Data were collected on a logger and could be sent via an Ethernet connection or hard-wired to the plant control system. Changes in the loads on sensors were monitored, and these could be identified with specific plant events. Figure 29 demonstrates that observed load variations were not limited to actions in the ovens adjacent to the monitored buckstays, as even charging and pushing of ovens 73 and 76 were identifiable in data collected from load cells on Buckstay 75. In Fig. 30, increased loads in the blue line on 03. May and 07. May suggest a problem on the Sensor 8 side of Buckstay 11, as changes in Sensor 7 (dark green line) are much less and more gradual. Larger variations in data from turquoise line (Sensor 4) suggested that something was wrong. Since the red data on the other tie-bar from this pair (Sensor 3) mirrors the load changes in Sensor 4 (but at a much lower level), it is likely that the problem was electrical. Plant checks were carried out and they showed no problem with the tie-bars on this buckstay, so sensor replacement was required.

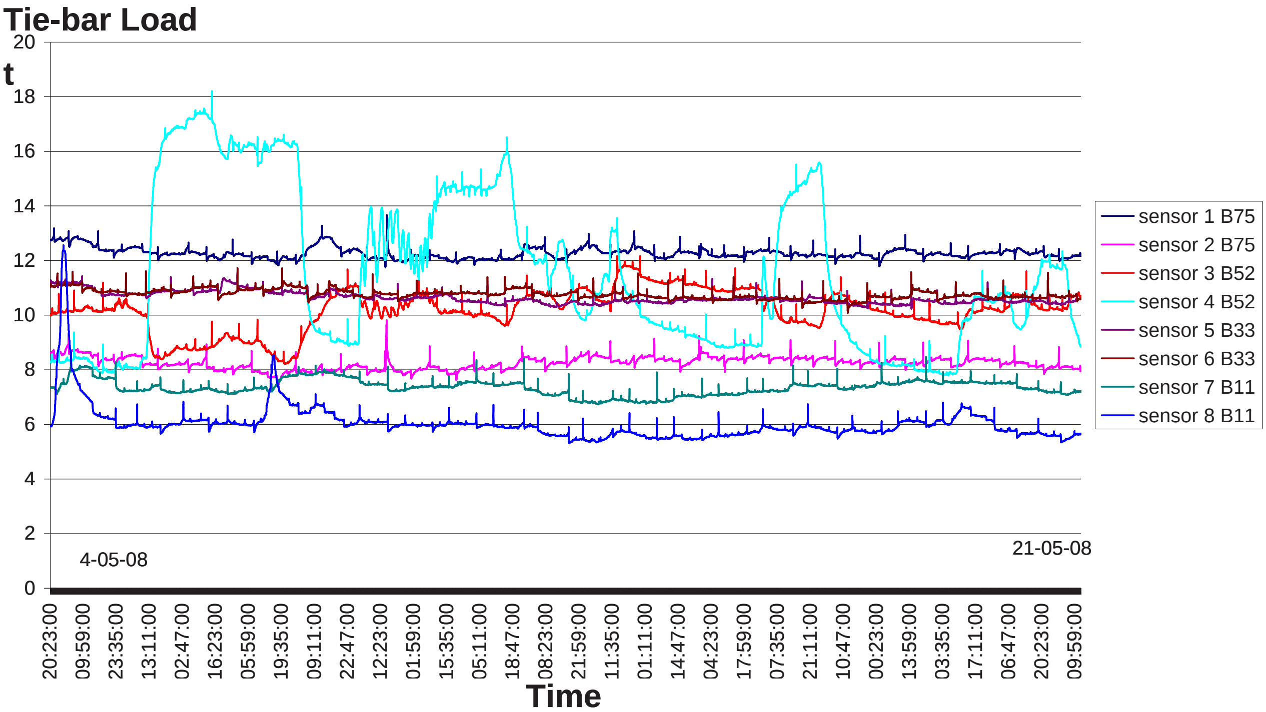


Fig. 30 Tie-bar load data from 8 sensors over 18 days

Task 6.3 Installation/testing of oven top machine hardware

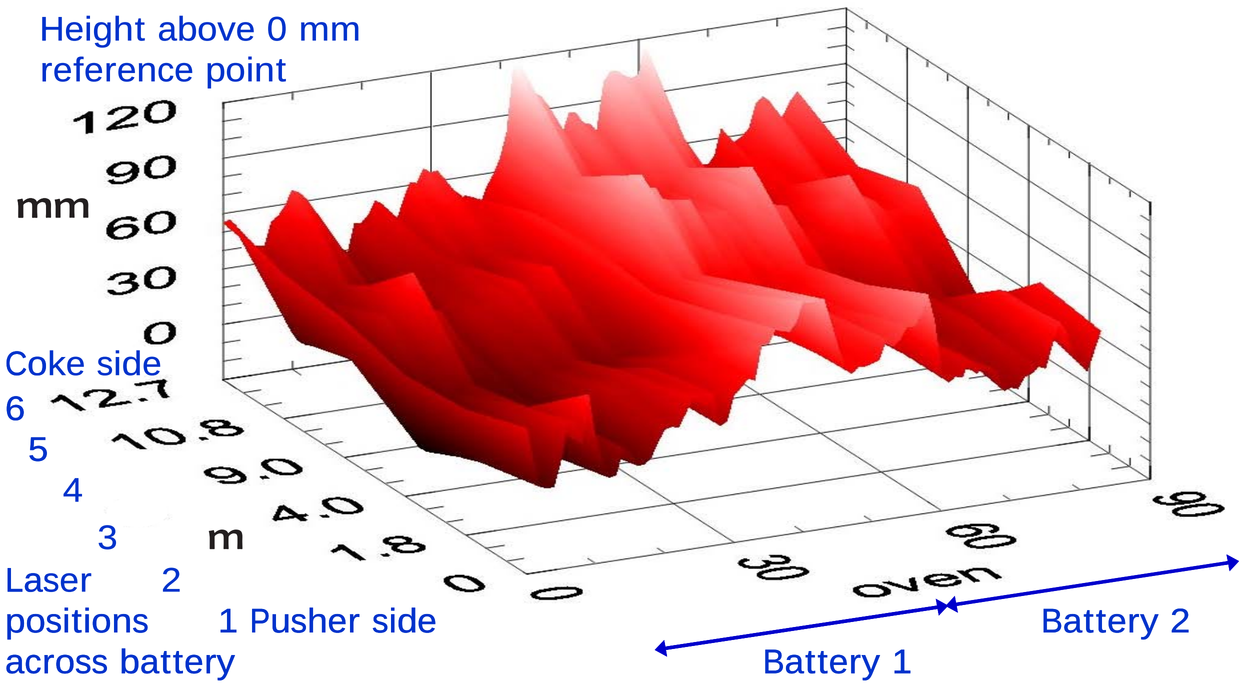


Fig. 31 Surface height variations along and across two batteries

Initial experiments took place with ultrasonic displacement transducers attached to the charge car, but these picked up charge car activity and were not sufficiently sensitive. Trials at heights of 1 m and 2.5

m above the battery top showed that the signal beam width on the target area was too large, and noise picked up by the filtered signal made it appear unstable. Even with suppression of objects by the sound lobe, if the sensor was not correctly positioned to avoid charge car rails and charging port lids, it would detect these and give a false reading.

A new system was trialled with Class II laser sensors attached to a moveable beam. A total of five runs were made in two plant trials, when the oven top deflection monitor was pushed along the length of two adjacent batteries. Using the developed software, a series of graphs were obtained showing variations across the oven top and along the length of the batteries. Repeatability of results was good between different runs (as shown in Fig. 24, Task 4.5). Figure 31 illustrates the three-dimensional surface profile map produced from a compilation of the trial data.

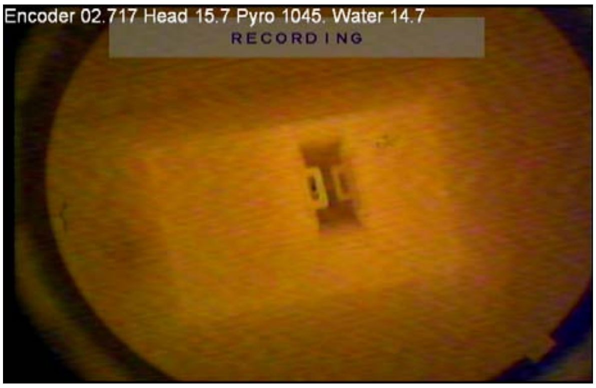
Task 6.4 Survey of wall temperature distribution

Fig. 32 Automated flue temperature and vision monitor in position on the battery top

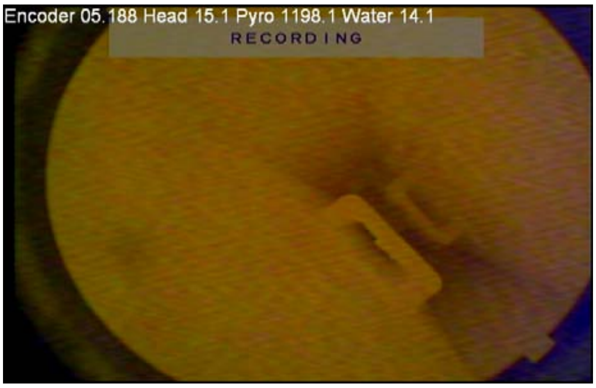
Plant trials of the automated flue temperature and vision monitor were carried out to examine a number of flues in the walls of chambers from different parts of two coke oven batteries. Figure 32 shows the insulated, water-cooled measuring head about to be driven down a flue from the mobile trolley. Vertical flue temperature and vision profiles were viewed in real time on the monitor, and stored for comparison with future trial data. Figure 33 illustrates four views taken as the camera descended into a flue in Wall 5. In order to lower the umbilical head into the battery smoothly, the top of each flue was cleaned before monitoring, and small amounts of carbon descended to the bottom of the flue, as shown in Fig 33a (where they burnt up). The upper coke oven gas (COG) and lower blast furnace gas (BFG) burners were clearly visible in the flue. The effectiveness of the insulation and cooling are apparent from the temperatures of the head (15-16^{o}C) and water (13-15^{o}C) recorded on the photographs.

Figure 34 illustrates the thermal profiles measured in Flues 6 and 7 of Wall 44 where Flue 7 was much hotter than Flue 6. As the pyrometer does not measure below 800^{o}C, changes in temperature are only shown from about 1.8 m below the battery top. Video monitoring was also carried out on these two flues because it was believed that cleaning equipment may have been dropped down Flue 6. However, the video demonstrated that there were no obstructions remaining in Flue 6, but its thermal profile had been affected adversely by previous actions. Further plant investigations are taking place and when repairs have been carried out and heating control has been improved, temperature and vision monitoring of these flues will occur again.

(a) 2 m from battery top showing deposits in flue



(b) 2.7 m from battery top showing 2 burners



(c) 5.2 m from battery top at level of COG burner

(d) 6.5 m from battery top at level of BFG burner

Fig. 33 Photographs from video descending into flue on Wall 55

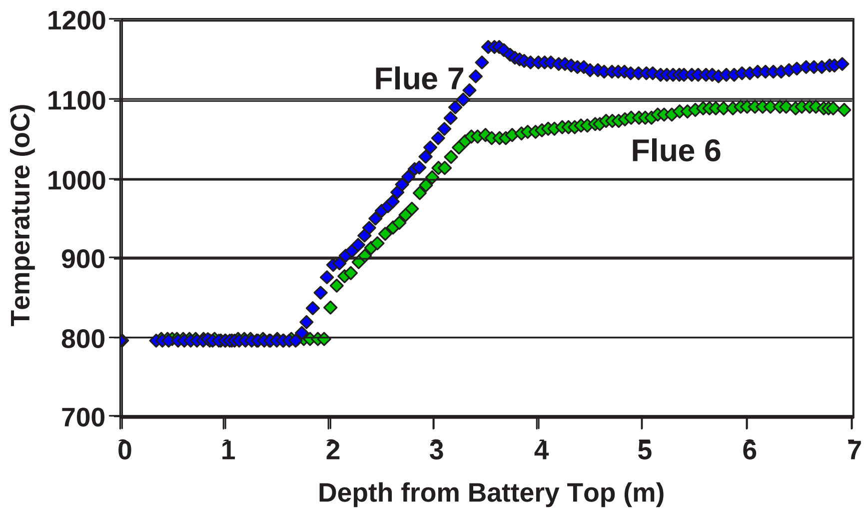


Fig. 34 Thermal profiles of adjacent flues in Wall 44

Task 6.5 Application regenerator inspection/cleaning system

All plant trials were conducted on a regenerator of a German coke plant.

A) Prototype 1 inspection system (without cleaning equipment)

Figure 35 shows photographs taken from the inspection of the sole flue of the coke plant at heating flue No. 28 with the Prototype 1 inspection system, in which the position and swivelling angle of the welding mirror was adapted and controlled manually. The two photographs were shot with a standard camcorder from different positions of the moveable slide, and with different inclinations of the swivelling mirror. In spite of darkness, from a total of 15 slots of the single brick six to eight slots were made visible by incident light from temperature radiation in upper parts of the regenerator brickwork. Small tears/breaks and deposits of dust and ceramic mortar can be roughly identified, but they were not made clearly visible with a satisfactory optical resolution. The welding mirror showed good resistance against thermal stresses, but only mediocre optical properties. Enhanced lighting was needed for the camcorder.

Fig. 35 Photographs of regenerator brickwork inspection with Prototype 1 inspection system

B) Prototype 2 inspection system with combined cleaning equipment

A radio-controlled swivelling mirror, made from optical glass, and a new camcorder, which could be operated with temporary additional lighting in two modes (visual/IR-mode), were used in the Prototype 2 inspection system to improve the quality of optical inspection. Air nozzles were combined with the optical equipment in this system to allow cleaning of regenerator brickwork as well as inspection. Photographs taken with the improved Prototype 2 inspection system in the visual mode, without running the combined cleaning equipment, are shown in Fig. 36.

As shown in Fig. 36, the quality of photographs taken with the improved Prototype 2 inspection system is excellent and much better than with the Prototype 1 inspection system, as long as the added cleaning equipment is not operated during inspection. Photographs shot with the Prototype 2 inspection system before the start, during the start, during operation and after operation of the added cleaning equipment are shown in Fig. 37. It is evident that optical inspection of the regenerator brickwork is disturbed to a great extent during operation of the cleaning equipment by rising dust, which causes too much backscattering of light during cleaning (bottom left photograph).

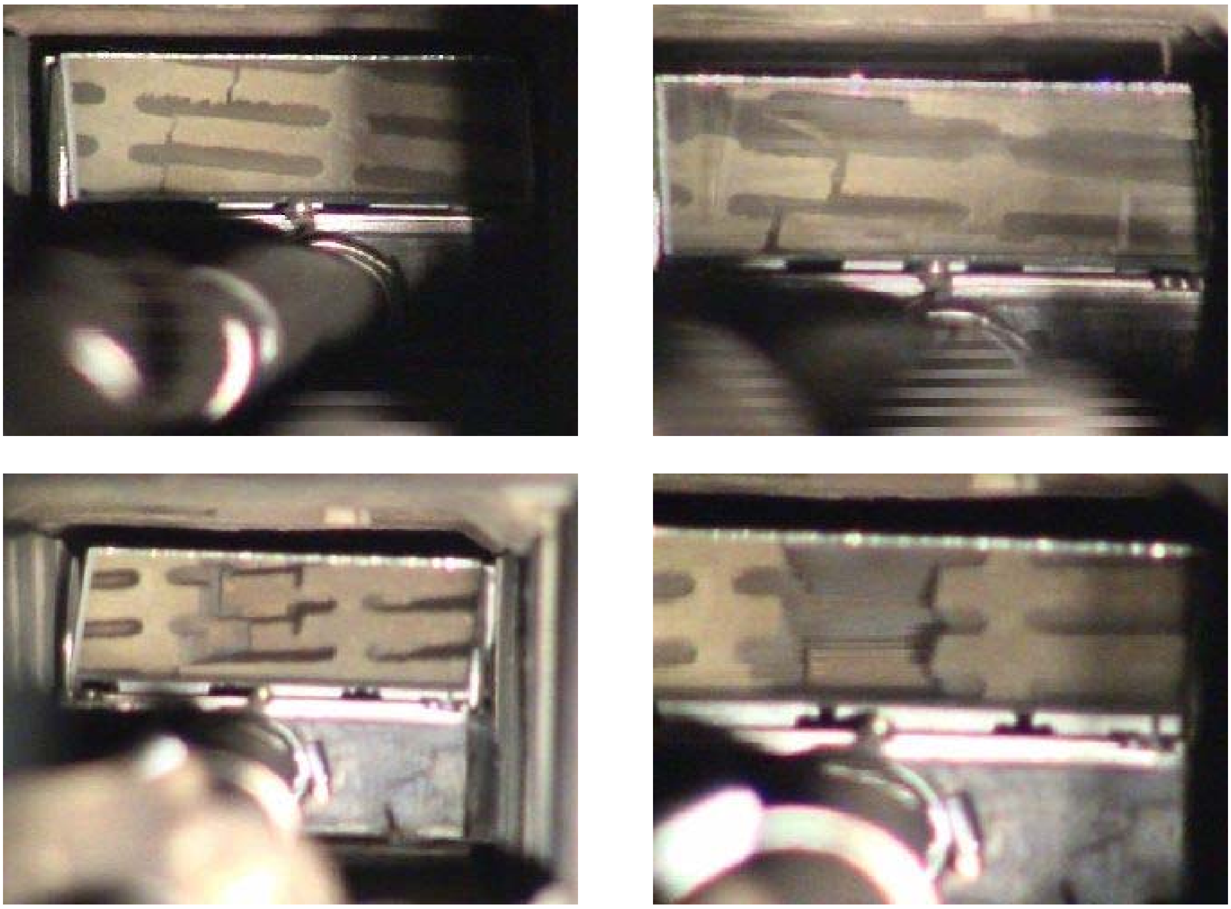


Fig. 36 Photographs of regenerator brickwork inspection with the Prototype 2 inspection/cleaning system without operation of the cleaning equipment (camcorder: visual mode)

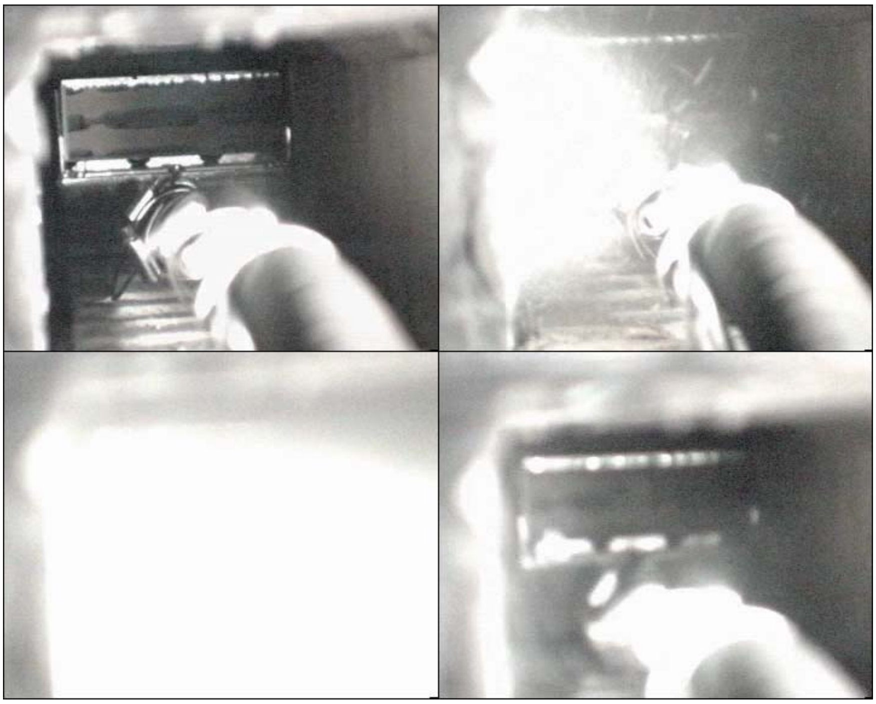
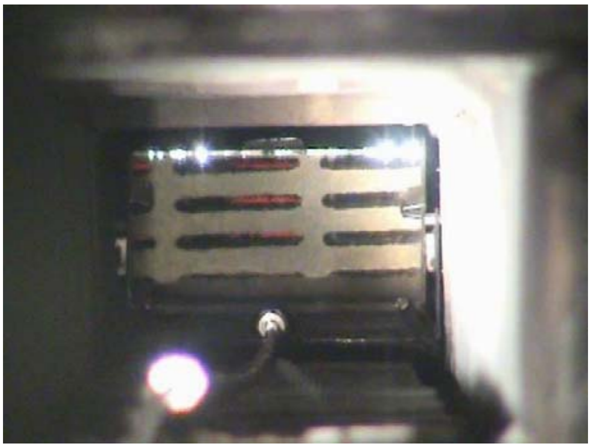
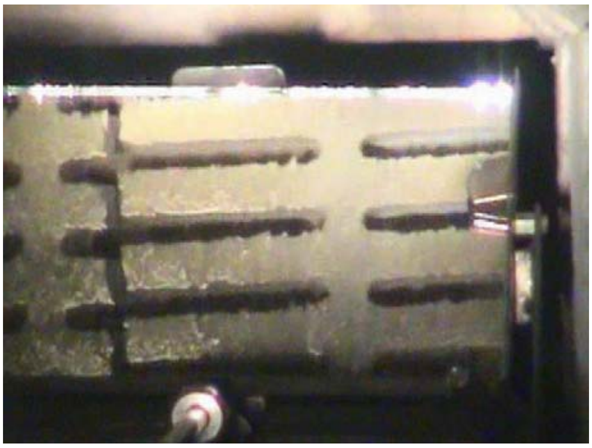


Fig. 37 Photographs of regenerator brickwork inspection with the Prototype 2 inspection/cleaning

top left before start of cleaning
top right start of cleaning
bottom left during operation of cleaning equipment
bottom right after operation of cleaning equipment

C) Simplified Prototype 3 inspection system (without cleaning equipment)





undamaged brickwork damaged brickwork

Fig. 38 Photographs of regenerator brickwork inspection with the simplified Prototype 3 inspection system

Inspection results obtained with the second prototype inspection system during operation of the cleaning equipment showed that inspection and cleaning have to be separated. For simple inspection without simultaneous cleaning, a simplified third inspection system was developed and tested (with no cooling device and manual adjustment of the swivelling mirror). Photographs shot with the third simplified prototype inspection system are shown in Fig. 38. The quality of photographs taken with the simplified third inspection system is as good as with the more complex second inspection system. Brickwork damage can be identified and made visible with high optical resolution.

Task 6.6 Comparative trials plant/laboratory carbon deposits
Task 6.7 Evaluation/correlation of plant data

Estimating the time and effort required for developing and constructing novel monitoring devices and arranging plant availability for industrial trials was difficult. Consequently, many plant trials took place towards the end of the project with insufficient time for new carbon deposits to grow after the trials. Although one examined sample grew to a thickness of 15 mm in three months, most carbon was deposited at a slower rate than that. Alterations to oven operation following plant trials have reduced carbon growth, so it was impossible to obtain further samples within the time-scale of this project. Comparative investigations between plant and laboratory carbon deposits took place before the new monitoring devices were employed on plant, but the literature survey suggested that changes in oven operation can reduce carbon deposits, but do not change their nature. The new monitoring data have been evaluated in comparison with plant operations, and conclusions have been drawn with respect to actions required for improving operations and prolonging battery life.

The carbon deposition studies have increased knowledge of the formation of deposits to aid their reduction, which will lead to lower pushing forces and less brickwork damage during pushing and therefore reduced refractory repair costs. Improved brickwork condition will reduce stack and door emissions, and increase chamber life and productivity, as the number of ovens left empty for draughting decreases.

The development of the chamber wall observation device has been carried out in this project. The device is now reliable, and the data given by the chamber wall observation are useful to the refractory maintenance team. The implementation of such a device in one of ArcelorMittal coke plants is under way.

The continuous assessment of tie-bar condition provides immediate notification of tie-bar failure. Although monitoring has taken place throughout the second half of the project duration, failure has not occurred yet on the batteries selected for these plant trials, because many of the ovens had been rebuilt a few years before the commencement of this research. The plant favoured installation of the monitoring system to reduce the probability of tie-bar failure and serious structural distortion of buckstays or frames. This is reducing their maintenance and repair costs and environmental emissions via oven door leakages, and it will prolong battery life. Additionally, the system is protecting oven integrity by providing early detection of dangerously high coking pressures and pushing forces, which may cause structural damage to battery fabric.

Battery top profile monitoring has demonstrated the unevenness of the tops of the two batteries tested (see Fig. 31). Changes in the profile over the next few years will provide early warning of abnormal deviations and opportunity for investigation and repair before critical deterioration of ovens. Battery top emissions and maintenance and repair costs will be reduced. No brickwork movement has been detected around charge hole lids due to roof carbon build-up, but on the surveyed batteries roof carbon tended not to be deposited on the lids.

Automated measurement of vertical flue temperature distribution and has demonstrated which flues and parts of the batteries required changes to their heating control and distribution to reduce underfiring gas costs and CO_2 and NO_x emissions. Video mapping has identified the flue walls with refractory damage, so that they can be monitored to reduce refractory repair costs. Used regularly over a long period of time, this monitor should enhance coke quality and consistency through more controlled carbonisation conditions and extend battery life.

Various severe problems in the long-time operation of coke plants, like uncontrolled combustion of the underfiring gas, uneven heating/overheating of the regenerator brickwork and the oven chamber walls, partial collapse of the regenerator brickwork and losses of coke production, may result from damage of the regenerator brickwork and blockages of regenerator channels by deposits of soot and dust. Nowadays these problems have become more critical at older coke plants, because they are often operated beyond their planned lifespan of typically 20-25 years. In the past, operators of older coke plants had not been in a position to identify and control the start of brickwork damage, because of a lack of effective and easy systems for inspection of regenerator brickwork. Plant trials with the newly-developed swivelling mirror/camera equipment showed that blockages of regenerator channels and slight, medium and severe damage of the regenerator brickwork can be monitored and identified easily and clearly with this new system. An improved operation and a prolonged battery life can be expected, when brickwork inspection is run at regular intervals with such an inspection system. Already, the start of damage can then be monitored and localised for timely repair, before progressive damage results in collapse of complete brickwork sections and much more expensive measures for rebuilding of large sections of brickwork, accompanied by losses of coke production.

4. CONCLUSIONS

1. A variety of instruments and sensors were investigated and tested in the laboratory and sometimes on plant to aid the design of the monitoring devices and laboratory carbon deposition rig.

2. A number of coke oven batteries were surveyed, and samples of roof and wall carbon were collected from five of them for examination in the project. A laboratory-scale carbon deposition rig was designed and successfully developed to provide carbon deposits of a similar nature to those produced in commercial ovens. This facility is able to examine, both independently and in conjunction, the influence of the several operational factors which affect carbon deposition, in addition to that of the nature of the surface on which the deposit occurs. An examination was carried out to determine the magnitude of the influence of deposition temperature and proximity to the source of the gaseous material being cracked, on the nature of the carbon deposited.

3. In spite of good optical results obtained from laboratory tests on a cold test checker brick, later plant trials in WP 6 showed that the optical characteristics of the Prototype 1 inspection system were not sufficient to meet the inspection requirements in a hot regenerator. Consequently, the system had to be improved for advanced inspection. The air nozzle cleaning system could be

operated successfully to clean lower sections of the regenerator brickwork, but, due to optical problems caused by rising dust, optical inspection was not possible during cleaning.

Simultaneous optical inspection and cleaning of the regenerator brickwork, which was tested with the Prototype 2 inspection system, is not possible due to optical problems caused by dust raised during cleaning. Good inspection results with a detailed brickwork analysis were obtained with this system, when brickwork sections were inspected within the entrance area of the regenerator sole flue without simultaneous brickwork cleaning. However, operational problems occurred when inspecting brickwork in deeper parts of the sole flue. To run optical inspection without any problems emerging from simultaneous cleaning with a system as simple as possible, a much simplified Prototype 3 inspection system (without any cleaning and heat protection devices) was developed and successfully tested in the regenerator sole flue at temperatures in the range of 240-290°C.

An automated flue temperature monitor was designed and constructed with the inclusion of a video camera for mapping flue wall damage and deposits. The rig comprises an insulated, water-cooled measuring head, control box and temperature and video display units, mounted on a mobile trolley for wheeling along the battery top.

Strain sensors were developed successfully for fitting to tie-bars at the top of individual ovens for continuous measurement of loads on buckstay springs with a logging system. A battery top deflection measurement system was created with six laser displacement sensors mounted on an adjustable beam spanning the width of the battery and mounted on wheeled carriages (which run on the charge car rails), for regular assessment of oven top brickwork profiles and early detection of abnormal deviations, including bracing failures.

4. Testing results showed that RISA is a powerful tool for the organisation and archiving of all data obtained from video recording of optical regenerator brickwork inspection. With some slight modifications, RISA can also be used as software tool for organisation and archiving of measuring data in other applications than video recording of regenerator brickwork inspection.

   Software was written to provide computer control of each element of the flue temperature monitor, and to enable temperature data and video images to be viewed in real-time on the monitor and on an independent computer. Data transfer systems were also set up for continuous collection and processing of tie-bar strain data. For the oven top deflection monitor, software was developed to convert raw data into three-dimensional profiles of the battery top.

5. A characterisation of the nature of the carbon material forming the deposits was devised using polarised light microscopy. The carbon material in the deposits was split into two categories, namely laminar or spherulitic, on the basis of the appearance of their textures. This identification of the two types was confirmed by scanning electron micrographs, which provided further evidence of the differences in the textural arrangement of these two entities at a much larger magnification. An image analysis programme was devised to characterise the deposits in terms of their porous structure, and a subsequent development led to the computerised estimation of the two identified carbon textural types.

   Analysis of many deposits from commercial ovens showed that in general the initial deposition on the silica wall or roof was carbon of the spherulitic type with subsequent carbon deposition being predominantly laminar. Scanning electron microscopy of the deposits demonstrated a variation in density with distance from the oven wall. In general, the density of the deposit increased with distance from the oven wall. It can be concluded tentatively that the carbon initially deposited at the oven wall is of the less dense spherulitic type with subsequent carbon deposits being of the more compact laminar texture. This would appear to indicate an effect of the nature of the surface on which deposition occurs, but sufficient exceptions were observed in the analysis of these coke oven deposits to demonstrate that, in addition to the nature of the deposition surface, there are likely to be several other factors influencing the nature of the deposits.

Using the bench-scale carbon deposition rig, it was established that the rate and extent of deposition diminished with increasing distance from the source of the volatile matter being cracked. As determined by scanning electron microscopy, the size of the spheres in the spherulitic carbon, which was deposited in these tests, increased with the deposition temperature. Prolonged deposition runs would be required to establish if the carbon deposited under these conditions changed from spherulitic to laminar in nature.

From an exhaustive review of the literature, it was determined that the influence of charge conditions on the deposition of carbon in coke ovens was primarily through the type and concentration of the volatile species generated during the carbonisation process. The deposition temperature is a major influence and the charge moisture is a contributory factor, probably through the effects of the constituent oxygen and hydrogen on the cracking of the volatiles and potential for capping of free radical species. Other potential contributory factors include the presence of coal fines and the nature of the evolved tars through their hydrogen transfer potential.

6. Eight load cell sensors of the final design were installed on tie-bars across two batteries and have transmitted data for many months. Results show changes in load with pushing and charging of ovens and specific plant events, such as problems with sections of the battery and plant stoppages. Successful plant trials were carried out by the oven top deflection monitor, which produced profiles of surface height variations along and across batteries.

The oven top deflection monitor permitted full battery top surface profiles to be made. Profiles have demonstrated the unevenness of the tops of the two batteries tested (see Fig. 31). Changes in the profile over the next few years will provide early warning of abnormal deviations and opportunity for investigation and repair before critical deterioration of ovens.

Automated flue temperature monitoring enabled a full crosswall temperature and vision survey to be completed rapidly on an oven without interfering with oven top machines. Temperature mapping of walls aided battery heating control optimisation. Video recording and storage of wall conditions enabled damage and carbon deposits to be monitored, in order to facilitate repair before flues reach a critical state.

The Prototype 1 regenerator inspection system showed insufficient optical properties because of poor lightning. Brickwork damage could only be identified very roughly, and details could be made visible just with low optical resolution. The improved Prototype 2 inspection system gave excellent photographs if the added cleaning equipment was not operated during inspection. During cleaning, optical inspection was disrupted by rising dust. As the simplified Prototype 3 inspection system did not contain any cleaning equipment, photographs with the same high quality and optical resolution were obtained as with the more complex Prototype 2 inspection system.

5. EXPLOITATION AND IMPACT OF RESEARCH RESULTS

5.1 Applications

As a result of this project, the chamber wall observation device development has been completed, and the device can now be used to perform inspections on complete walls. The device will be used to check the wall condition as well as the evolution of damage.

With its simple assembly the Prototype 3 inspection system can be adapted to the geometric dimensions of different regenerator systems. It can be operated easily, so that its acceptance by coke plant operators should be expected. Effective removal of deposits from lower parts of the regenerator brickwork can be achieved with a successfully tested, pressurised, air-based nozzle system.

Successful plant trials have been carried out to measure flue temperatures and examine refractory walls, to monitor loads on tie-bars and to collect battery top profiles. Automated flue temperature and vision monitoring could be applied to any flues on any battery, because the monitor is mobile and self-contained and only requires services which are commonly available on all plants. These include a crane to transfer the monitor on and off the battery top, clean, cooling water to fill the trough, and an office power source for recharging the control computer batteries. The oven top deflection monitor is similarly mobile and self-contained and suitable for use on any gravity-charged battery. To accommodate stamp-charged batteries, its current frame design would require slight modifications. Tie-bar strain monitoring is also applicable to most plants, providing the tie-bars are long enough to accommodate the load sensors and the cabling is not damaged by proximity to the ovens. Preliminary trials on a short battery demonstrated that it was difficult to insulate cabling adequately, if it was very close to the oven doors, but installations on taller batteries have not given any problems.

5.2 Technical and Economic Potential for the Use of the Results

The major benefits from this research is the potential for prolongation of the working life of coke ovens, from an original design lifetime of 25 years up towards 50 years and the associated reduction in environmental emissions. Additionally, significant economic gains are also expected because preventative and remedial actions can be taken before problems become critical, reducing oven repair and energy costs and assisting the maintenance of consistent coke quality and production. This could mean the difference between relatively minor silica repair work and eventual major wall damage, necessitating through wall repairs (which are very expensive in terms of materials and lost production).

Improved temperature distribution in the battery results in better combustion efficiency and reductions in underfiring gas usage, which could reduce CO_2 emissions and gas costs (by 15%, since there is such a difference between the best and worst values reported within Europe). Consequently, carbon deposits may be reduced or prevented, increasing oven availability and therefore annual production (because ovens do not need to be left empty for draughting). At present, the option of applying coal moisture control to blends (to improve coke quality and increase production) is not favoured by most companies in Europe, because of its tendency to increase carbon deposits. If carbon deposition can be reduced, bulk density and coke output could be increased (perhaps by 3%) by controlling moisture.

The laboratory-scale deposition rig offers the potential to establish the details of the basic mechanisms involved in the deposition of carbon in commercial coke ovens through a comprehensive examination of all the factors, which have been identified as potentially of influence including the nature of the deposition surface. To do this requires a series of tests in which potential influential factors are varied in a controlled manner to determine their relative significance, which is an impossible operation for commercial ovens. The rig can provide the information required to determine ways and means of mitigating, if not eliminating, carbon deposition in commercial operations, with due cognisance of the constraints imposed by the scale of these operations.

As presented in this report, the inspection device developed by CPM will be used to perform coke oven chamber wall inspections. Such inspections can be used to identify the origin of defects and damage, and allow proactive maintenance. It is obvious that small damaged areas are easier to repair than large ones, and repairing small defects is also cheaper than the treatment of large ones.

With the simplified Prototype 3 inspection system, damage to brickwork in the lower sections of coke plant regenerators can be identified early and with high accuracy in an easy way. The start of brickwork damage can be detected before it reaches a more severe, critical condition. This will help coke plant operators to start brickwork repairs earlier and avoid high costs for repair of severe damage. Due to the impact of brickwork damage on emissions at the battery stacks of coke plants, application of the developed inspection system is also an effective tool to control emissions.

Flue temperature and vision monitoring allow battery heating control optimisation and improve flue maintenance. The temperature monitoring head enables a full crosswall temperature and vision survey to be completed rapidly on an oven without interfering with oven top machines. Video recording and storage of wall conditions enable damage and carbon deposits to be monitored, in order to facilitate repair before flues reach a critical state. Tie-bar strain monitoring permits the integrity of battery to be monitored continuously for evaluation of steelwork stress and movement. Oven top deflection monitoring offers early detection of abnormal distortion.

5.3 Dissemination

Investigations were made into patent filing for one of the devices developed during the project. However, these showed that the cost of the patent would be far greater than the benefits derived from it, because the cost of producing and installing the monitor was relatively small now it has been developed. Consequently, the decision was taken not to pursue patent filing for any of the monitors.

A number of publications and conference presentations have resulted from the project in order to disseminate the research within the European Community.

- Patrick J W, Barranco R: 'Carbon Deposits: formation, Nature and Characterisation', oral presentation, Coal Research Forum, Coal Conversion Division, Joint Meeting with the Coke Oven Managers` Association at Scunthorpe, April 2006.
- Barranco R, Patrick J, Wu T, Poultney R, Barriocanal C, Diez A: 'Optical microscopy and SEM study of pyrolytic carbon deposits from coke ovens', Proceedings of the 2007 International Conference on Coal Science & Technology, Nottingham, UK.
- Patrick J, Barranco R: 'Carbon Deposits: Formation, Nature and Characterisation', The Year-Book of the Coke Oven Managers' Association 2007, 122-135.
- Nivoix F and Gaillet J P: 'Development of a coke oven chamber wall observation device', Steelmaking Days, Paris, 13-14 December 2007.
- Barranco R, Patrick J, Wu T: 'Characterisation of Pyrolytic Carbon by Optical Microscopy and Image Analysis', oral presentation, 7th European Conference on Coal Research and its Applications, 3rd-5th September 2008, Cardiff, Wales.
- Poultney R M and Bennigon C R: 'Coke Oven Monitoring Systems - Oven Top Deflection and Tie-bar Strain Monitoring', oral presentation, 68th European Coke Committee Meeting, Linz, 10. April 2008.
- Poultney R M: 'Improving Environmental Control and Battery Life through Integrated Monitoring Systems', oral presentation, The Coke Oven Managers' Association, Scunthorpe, UK, 13. November 2008.
- Poultney R M: 'Development of Monitoring Devices to Evaluate Battery Condition for Service Life Pronlongation', oral presentation, 32nd International Cokemaking Conference, Czech Republic, 19.-20. November 2008.
- Poultney RM: 'Improving Environmental Control and Battery Life through Integrated Monitoring Systems', paper to be published in The Year-Book of the Oven Managers' Association 2009'.

6. LIST OF FIGURES

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APPENDIX 1

Work Package 1: Equipment Design

Task 1.1 Examination of available instrumentation/sensors

Flue temperature, tie-bar strain and oven top deflection monitoring equipment

A major problem in the selection of instrumentation for coke oven applications was heat-resistance, and this increased the length of time required to develop some devices. Corus investigated a number of different types of instrumentation and sensors for flue temperature, tie-bar strain and oven top deflection monitoring equipment. A lightweight, portable video inspection instrument, with a built-in light source for viewing poorly-accessible locations, was selected for flue temperature monitoring. It had a CCD camera designed to function in harsh working environments, constructed from high-impact, heavy-duty plastic to withstand shock and vibration. Figure A1.1 illustrates the standard and infrared cameras available with this system. TFT-LCD technology presented a clear, full video image. As the camera was water-resistant to a depth of 30 m, it could be water-cooled. The display unit had an integral video capture system using a compact flash card, so that images can be stored as single frames or video clips. Figure A1.2 illustrates the ultrasonic sensor selected for initial oven top deflection monitoring tests.

Fig. A1.1 Standard and IR cameras

Fig. A1.2 Pepperl+Fuchs ultrasonic sensor

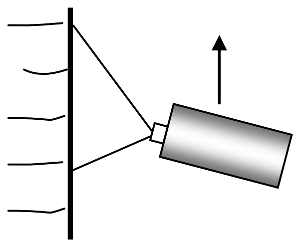

Fig. A1.3 10^o angle of Sony camera

Task 1.2 Selection/initial evaluation of sensor types

Internal Chamber Monitoring

Trials in cold conditions

At first, trials were carried out in order to test and settle the camera. The aim was to check the functioning of the electronic multiplexing box for data transport and synchronization. Additionally, the shutter, the rotation control and the temperature display were verified. During these tests, the image and clarity of the new camera (WATEC 525 EX) and of the former one (SONY XC 73) were compared. Owing to its higher vertical field of view (vertical: 116°, horizontal: 72°) compared to the Sony camera (vertical: 52°, horizontal: 72°), the WATEC was set up with a 90° angle. This installation should allow a larger wall view (approximately five bricks courses instead of two with the former camera).

At Fos sur Mer, the Sony camera had been moved with a 10° angle with respect to the wall under observation in order to increase the field of view to three brick courses (see Fig. A1.3). Unfortunately, this configuration created a perspective, that made the data treatment more complex. These cold trials concluded with the manufacture of a new camera head, which functioned well. The new camera fitted the requirements of CPM in terms of image quality and the field of view had been increased, although some distortion was noticed.

Trials in hot conditions

In order to test the mechanical and thermal resistance of the camera head as well as the image quality, some tests in industrial ovens were performed at Carling coke plant. For these tests, the camera head was introduced vertically through a charging hole into an empty oven. The camera was connected to the supply sheath and protected with an insulating DELCERAM band. During this trial, the rotating system was ignored. The band was wound up the camera head (see Fig. A1.4) and an opening was made in front of the objective (in Fig. A1.5).

Fig. A1.4 Insulated camera head

Fig. A1.5 Opening

The camera head was set at the end of a half inch, 4.5 m long steel tube insulated with a ceramic fibre sheath. The camera supplying sheath was also fixed to the tube and connected to the multiplexing box. The whole device was bound to a jacking-up device (see Fig. A1.6).

Fig. A1.6 Camera head fixed at the end of a tube before introduction inside an empty oven

During the trials, the camera block was introduced inside an empty oven where the temperature was around 950°C. The multiplexing box, which initially was intended to enter the oven at the same time as the camera (since the inspection device was designed to be installed on the pusher ram), stayed out of the oven. The cooling air came from the plant air system with the pressure set at 7 bar and was connected immediately to the multiplexing box. A high temperature coaxial cable, used to transfer the data, connected the multiplexing box and the control unit, the recorder and the monitor. The camera was introduced through the charging hole down to 1 m from the bottom of the oven, and it stayed in for approximately 1.5 minutes. This duration corresponded to the time between the entrance and exit of the ram in the oven.

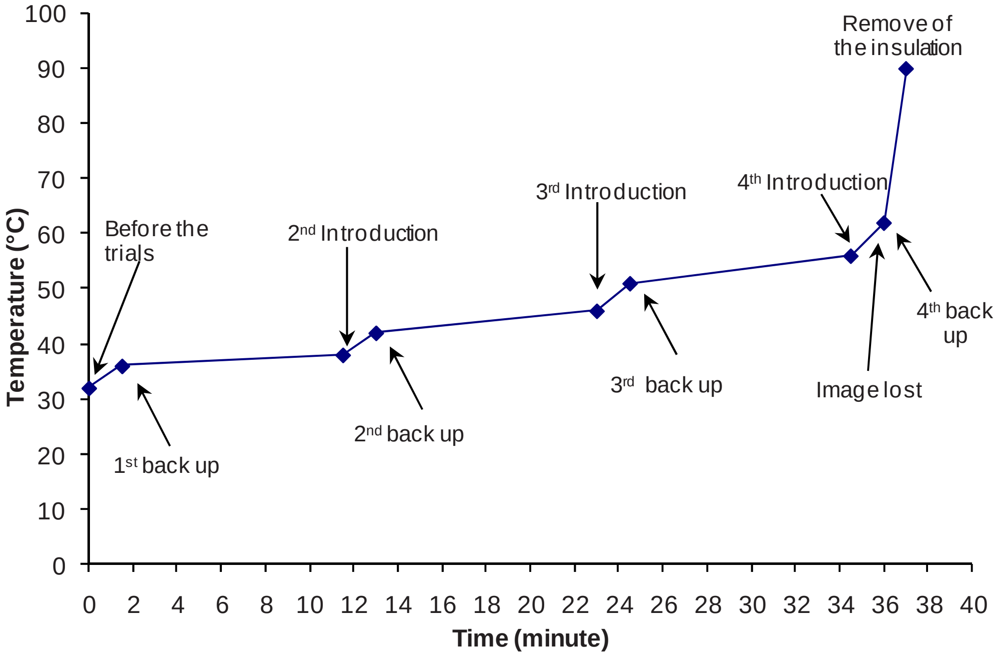

Figure A1.7 Camera temperature evolution during the hot trials

At the start of the first trial, the camera temperature was 32°C. The first images obtained were too dark and the setup of the shutter was observed to be poor. Nevertheless, trials were performed in order to test the insulating material quality and the thermal resistance of the camera. On removal from the oven, the camera temperature was 36°C. After a 10 minute pause (the usual time between two pushing operations), the test was repeated several times (see Fig. A1.7). The trials were stopped after the fourth introduction of the camera, because the image was lost. At this time, the camera temperature was 64°C, but the temperature continued to increase and quickly rose up to 80°C. It was necessary to remove the insulation in order to cool the camera down as quickly as possible, because the insulation was too thick and accumulated too much heat. The 10 minute pauses were not long enough to compensate for the heat transfer to the camera block. Consequently, heat damaged the rotating system, as this mechanical system was covered by a wide stainless steel part (see Fig. A1.8). The metal had become hot and some internal plastic pieces melted (as shown in Fig. A1.9).

Fig. A1.8 Rotating device

Fig. A1.9 Camera damage

Fortunately, the camera body was made from a fairly thin external metallic tube, and blowing cool air on to it was enough to compensate for the heat transfer between the camera body and the electronics. Nevertheless, after inspection in the CPM workshop, it appeared that an electronic card support was broken. This failure of the card disconnected the camera, which explained the loss of the images during the fourth test.

The whole device was sent to the supplier for refurbishment, and the shutter speed was set up correctly at CPM, as the supplier had set it to 1/2000 sec. In cold conditions, the image quality was perfect, but this setup was not appropriate for observing walls at temperatures around 1000°C. The shutter speed was modified and validated by using the laboratory oven, which initially had been built to calibrate an infrared pyrometer. The camera was aimed at the internal wall of this oven, which was set to reach a temperature of 1000°C. This camera has ten different shutter speeds (off, 1/50, 1/250 1/500, 1/1000, 1/2000, 1/5000, 1/10000, 1/100000 and automatic). All of these were tested and the most adaptable was 1/10000 sec. However, the camera may be shaken during the pushing or retraction of the pusher ram, and then it may be closer to or further from the wall or see some warmer or colder parts of the wall. Finally, the shutter was set up in automatic mode.

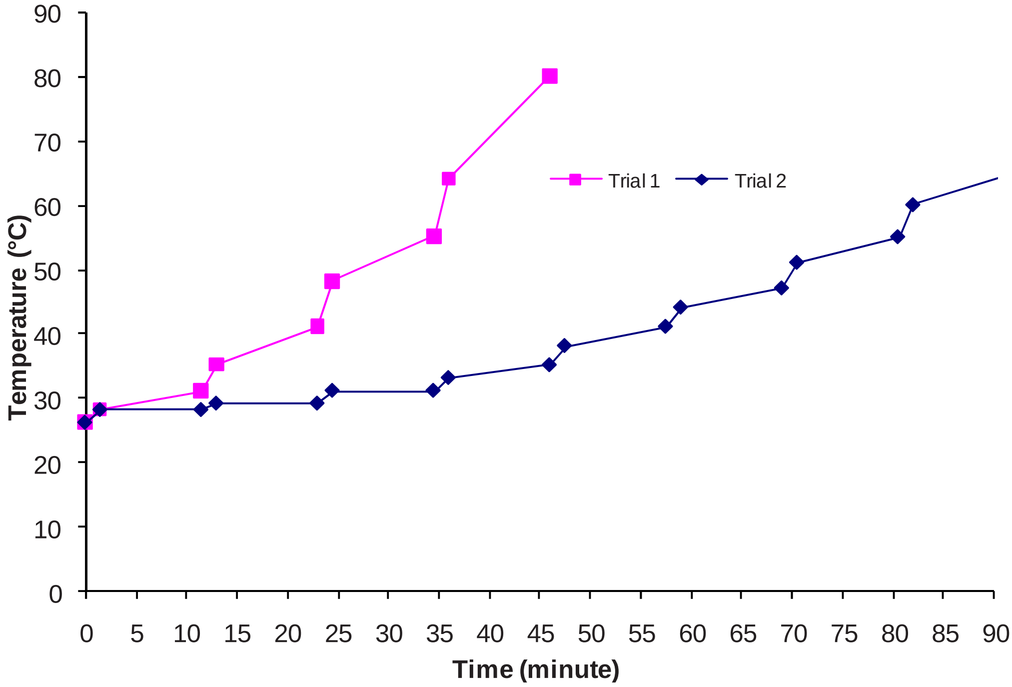

Fig. A1.10 Comparison of the camera temperature between the two trials

After repair of the material, a new trial was carried out in the Carling coke plant under the same conditions as the first one. However for this trial, the insulation of the camera body was reduced from five to three layers of DELCERAM insulating band. These trials were successful in terms of image quality (see Fig. 6 in WP1) and thermal insulation. The decrease in the insulation reduced the heat accumulation during the 10 minute pauses (as shown in Fig. A1.10).

The camera air-cooling will probably be more efficient when the inspection device is installed on the pusher ram. During these trials, the air was coming out from a pipe located on the oven, which already heated the cooling air. The different trials showed the good performance of the new camera head in terms of use, wideness of the field of view and image quality. The final camera head fitted CPM requirements.

Regenerator inspection system

DMT started with a detailed analysis of the conditions inside the regenerator of a coke plant. The optical inspection of areas, which are difficult to access, can be done by means of mirrors, endoscopes, cameras or combined systems. As a result of this analysis, two different concepts were identified for an optical inspection system:

A) Inspection system with a camera operated ***inside*** the sole flue

- This favours spatial proximity to the object and the possibility of looking directly upward into the brickwork of the regenerator, transferred to 90° to the sole flue axis. The load on the system due to high temperatures and dust as well, as the cramped space, is unfavourable. In particular, the necessity for inserting the inspection system to a depth of approximately 8 m or more is critical.

B) Inspection system with a camera operated ***outside*** the sole flue

- This favours the reduction of the temperature and dust load for the system. The components can be simpler and cheaper.
- The necessary optical adjustment of the video camera in the axial direction of the sole flue including 90°-redirection of the point of view into the brickwork of the regenerator is unfavourable.

Preference was given to the development of an inspection system according to concept B. The inspection system would be based on standard components. A video camera would be used in combination with a swivelling mirror (in Fig. A1.11) arranged in a small module mounted on a slide. This module would be moved into the regenerator sole flue and positioned under the flue to be examined. On demand, the inspection system may be combined with a cleaning system (as shown in Fig. A1.12).

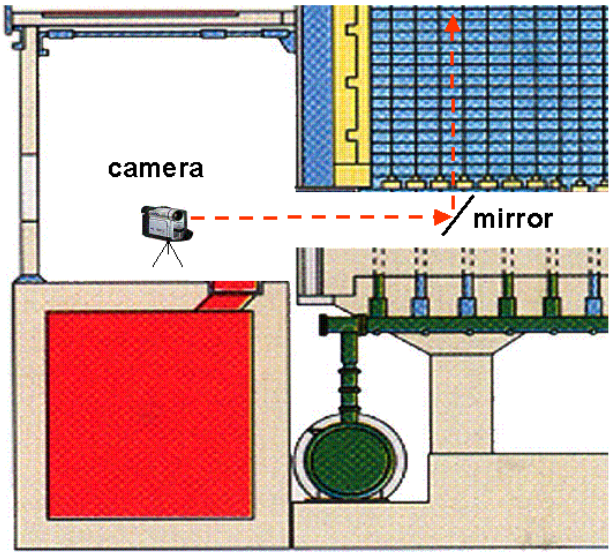

Fig. A1.11 Camera/mirror combination for an inspection system

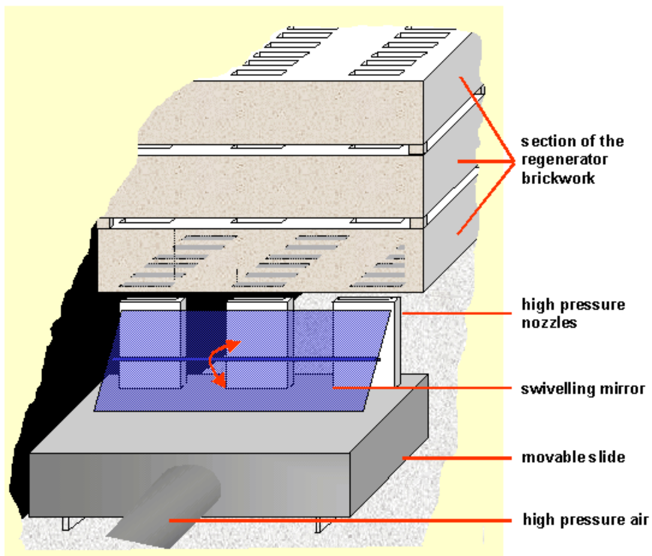

Fig. A1.12 Concept for a combined inspection/cleaning system

Regenerator cleaning system

Different types of commercially-available nozzles were tested in the laboratory at different air pressures to find suitable nozzles for an air based cleaning system, which could be applied in combination with an inspection system to remove deposits from the regenerator brickwork by air blowing.

The following parameters were checked in the selection of suitable nozzles:

- blowing force (should be high)
- air consumption (should be low)
- spraying angle (should be adjustable to the limited free space inside the sole flue)
- noise (should be low)

By means of a scale model, several types of nozzles were tested in the laboratory at different air pressures and object distances (Fig. A1.13) to determine the blowing force. Some examples of tested nozzles and their blowing force are shown in Fig. A1.14.

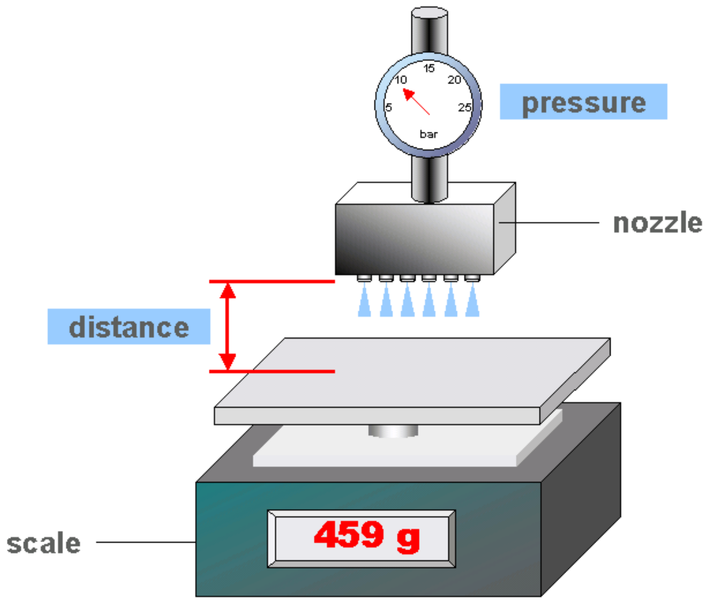

Fig. 1.13 Laboratory equipment for testing nozzles

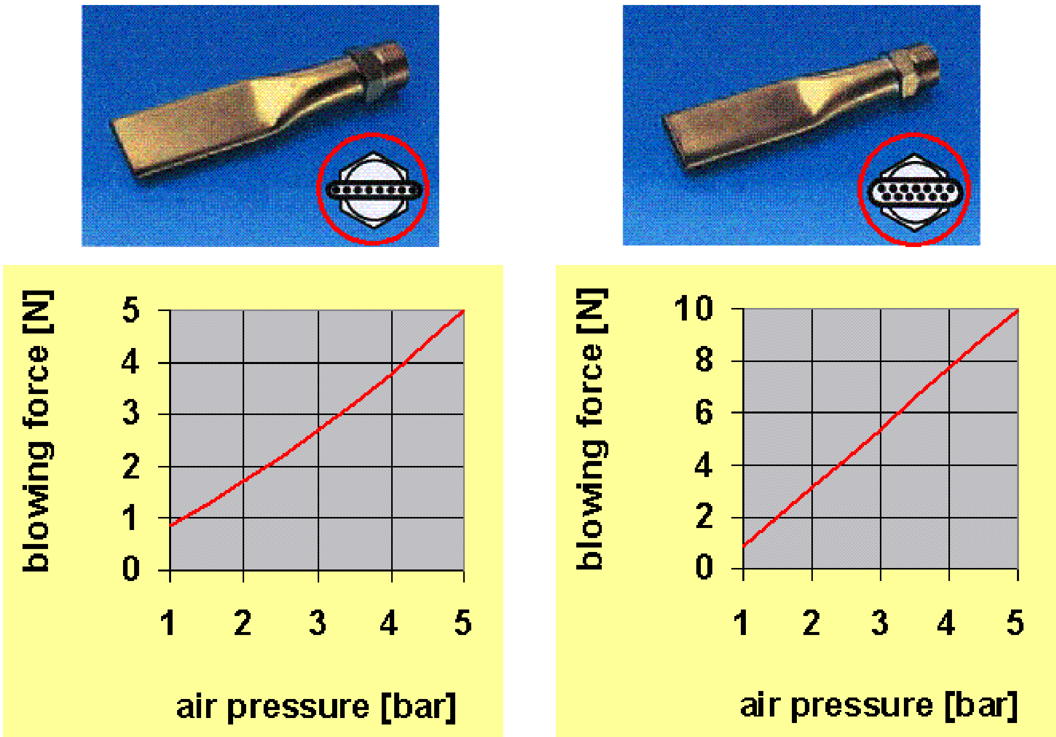

Fig. 1.4 Examples of tested nozzles

On the basis of the results obtained in the laboratory tests, the nozzle type shown in Fig. A1.15 was selected because the cleaning system can be adapted very well to the length of the checker brick slots with this nozzle type, for example three nozzles connected in parallel (Fig. 1.16). The blowing force of the selected nozzle, which is lower than the blowing force of other tested nozzles, can be enforced by a raised air pressure.

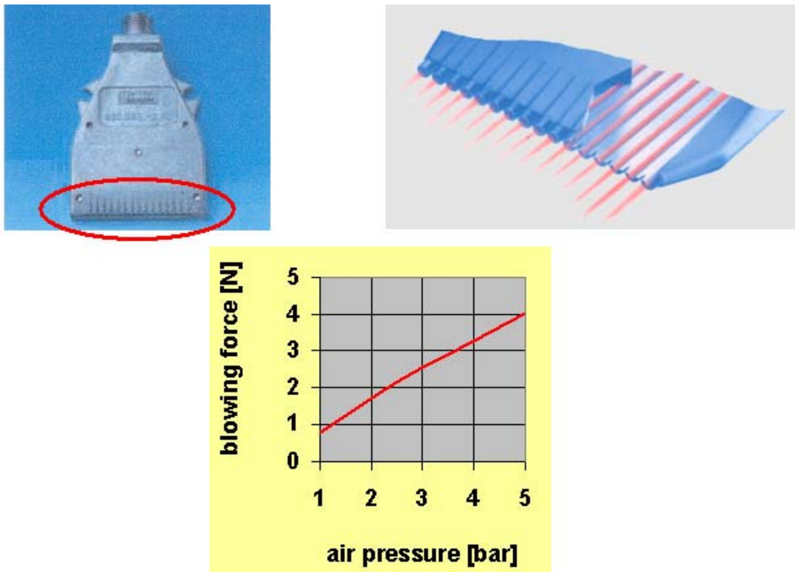

Fig. 1.15 Selected nozzle

Fig. 1.16 Parallel connection of 3 selected nozzles adapted to the length of checker brick slots

Flue temperature monitoring equipment

During the selection and evaluation of suitable equipment for flue temperature monitoring, discussions took place with an instrumentation expert. Optical and thermal sensors and displacement transducers were investigated. Investigations of data loggers led to two being selected for flue temperature monitoring. Portable, video inspection and video capture and transfer systems were borrowed for evaluation in laboratory trials before the final selection was made. Motor gearboxes and radio-off transmission were also investigated.

Tie-bar strain monitoring equipment

Load washers were selected and calibrated for plant use after initial laboratory trials. Investigations were undertaken to find data collection equipment and connecting leads, which could withstand the hostile, high temperature environment on top of a battery. Burning of cables in early plant trials resulted in the selection and evaluation stage being extended beyond that expected in the original plan, as cabling with increasing levels of insulation and increasing temperature-resistance was required.

Oven top deflection monitoring system

Table A1.1 Advantages and disadvantages of ultrasonic and laser sensors for oven top monitoring

Ultrasonic Sensors	Laser Sensors
Advantages: Inexpensive Variable range, one sensor will measure both modes of operation Accurate Reliable Low power consumption Disadvantages: Sensor footprint too large	Advantages: Accurate Reliable Easily aligned Small sensor footprint Disadvantages: Expensive Two lasers needed to suit the modes of operations Poor performance on dark surfaces

Table A1.1 shows the results of investigations of ultrasonic and laser sensors. Despite the advantages of laser sensors, the reluctance of plants to use them for safety reasons led to initial trials being carried out with ultrasonic sensors. Shown in Fig. A1.2, a Pepperl+Fuchs UC-4000-30GM ultrasonic sensor was suspended from a crane and tested at heights of 1 m and 2.5 m in the laboratory before plant trials (see Appendix 6, Task 6.3). In both cases, the manufacturers quoted accuracy of $\pm$1 mm could be achieved, when placing and moving a strip of material 0.1 m by 0.5 m beneath the sensor, indicating that the objects could be detected. Preliminary plant trials showed that a system attached to the charge car picked up a lot of noise and was insufficiently sensitive. Consequently, laser devices were re-examined and a Class II laser system was identified, which was already approved for use elsewhere on plant.

Task 1.3 Concept: laboratory carbon deposition rig

Initially, alternative designs for the carbon deposition rig were evaluated in the light of previously described rigs and previous studies[5]. In essence, the rig design was for an electrically heated vertical tube-furnace in which a deposition surface could be suspended. Provision was to be made for mixtures of gases and/or vapours to be fed to the furnace at controlled flow rates and at various temperatures, see Fig. A1.17. On the basis of a literature search (in WP2, Task 2.2), alternative designs for the carbon deposition rig were assessed. The final version selected was designed to simulate effectively the carbon deposition on a coking plant (see Fig. A1.18). The main modification to the original design of the furnace was inclusion of the facility to carbonise a coal charge in a retort to generate the required volatile species, to provide a better simulation of the volatile matter found in the free space of an industrial coke oven. The bottom zone of the furnace was used to carry out the carbonisation step with the temperature of the charge monitored by three thermocouples placed in the lower part of the retort. The middle and upper zones were designed to be held at selected temperatures up to 1150^{o}C. Refractory slices positioned in the top zone provided a deposition surface, which could be removed for examination and analysis of the deposited carbon.

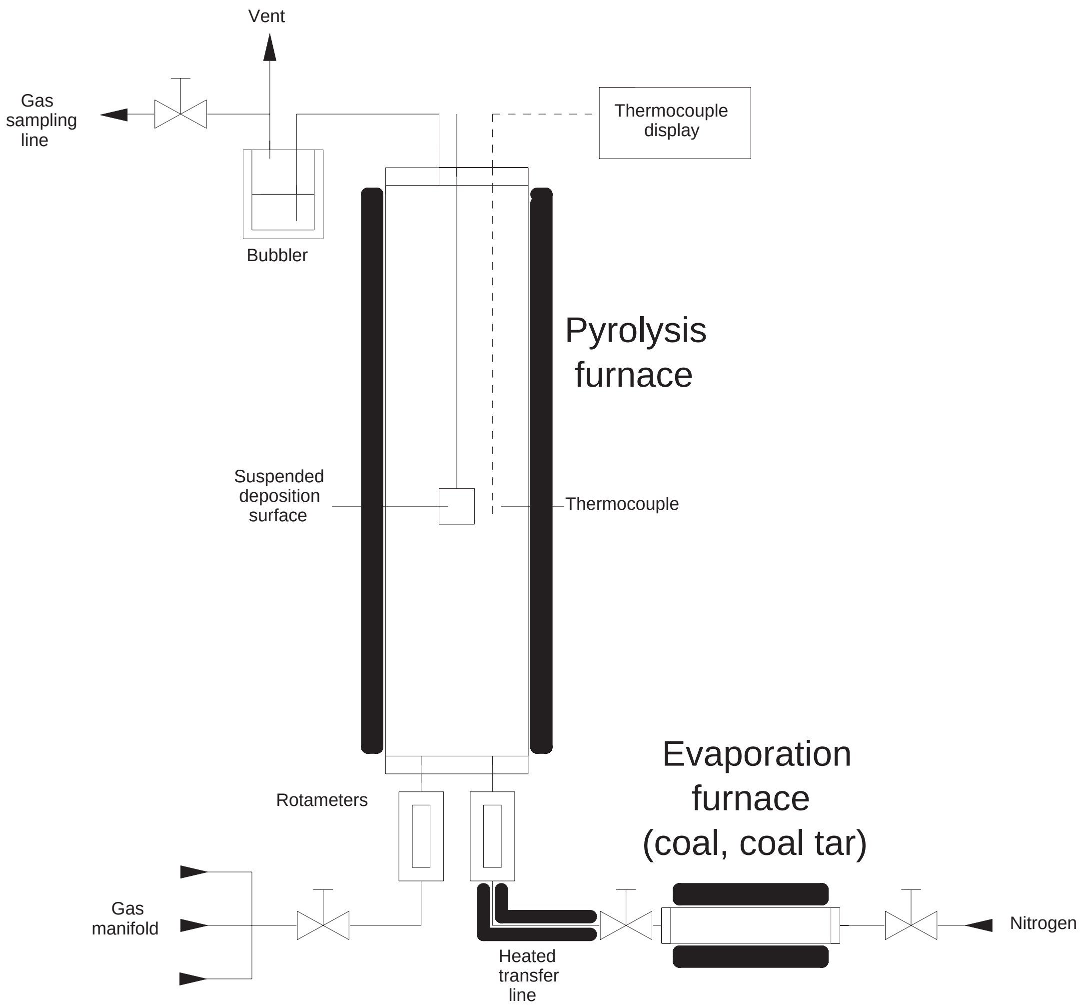

Fig. A1.17 Diagrammatic representation of laboratory-scale carbon deposition rig

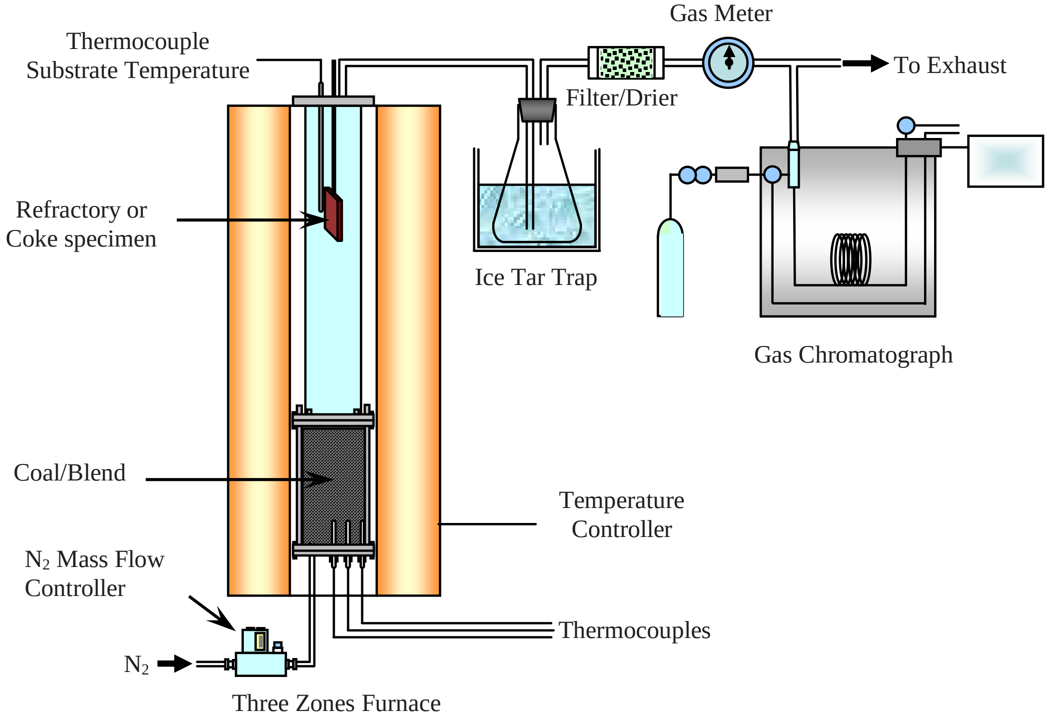

Fig. A1.18 Final design of carbon deposition rig

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APPENDIX 2

Work Package 2: Internal Chamber Monitoring

Task 2.1 Development of automated viewing/recording

Fig. A2.1 Camera head without stainless part

Fig. A2.2 Camera head without insulation

Fig. A2.3 Multiplexing box

Fig. A2.4 Demultiplexing box

Task 2.2 Investigation of carbon deposit rates/type

Samples

Fig. A2.5 Roof carbon in situ

Samples of roof and wall carbon deposits were obtained from five different Corus batteries (see Task 5.1), and supplied to UNOTT. Figure A2.5 shows the appearance of a carbon deposit in a Battery 3 oven, and Figs. A2.6 and A2.7 illustrate some of the textures in roof and wall deposits from Batteries 1 and 2.

Fig. A2.6 Layering in Sample A roof carbon deposit parallel to the oven wall

(scale bars are 1 cm)

Fig. A2.7 Wall carbon deposits - L: brick pattern from wall, N: globular laminar carbon on coke-side

Carbon deposition

During the production of coke, the evolved volatiles flow alongside the oven walls and into the free space above the charge. Some hydrocarbon components in the volatile are able to decompose pyrolytically. Thermal conditions exist, which allow some of the resulting compounds to deposit on the various solid surfaces in the coke oven. Their adhesion to the brickwork can be strong and their reactivity low, so that their removal has proved problematical. Conventional practice is to burn off the carbon deposits in an empty oven, and this causes loss in productivity and brickwork damage which leads to environmental problems[19,20].

Classification of pyrolytic carbons

Pyrolytic carbon is formed by the decomposition of hydrocarbons in an oxygen-free environment and exhibits a broad variety of microstructures[21]. Some attempts to describe and characterise the various pyrolytic carbon forms have been made by various authors. Shemeryankin[6], for instance, reported three different types, namely lustrous carbon with a laminar structure, soot particles, and fibrous carbon in the form of long fibres or threads. Krebs[7,8] also reported three main types of carbon found in coke oven deposits. The materials, in this case, were defined as pyrolytic carbon, carbon black, and carbonised coal particles. Another classification system using polarised light microscopy was reported by Grey and Cathcart[9] and further used by Bokros[10]. The microstructure observed were defined as isotropic (without any growth features and optical reflectance), laminar and columnar or granular.

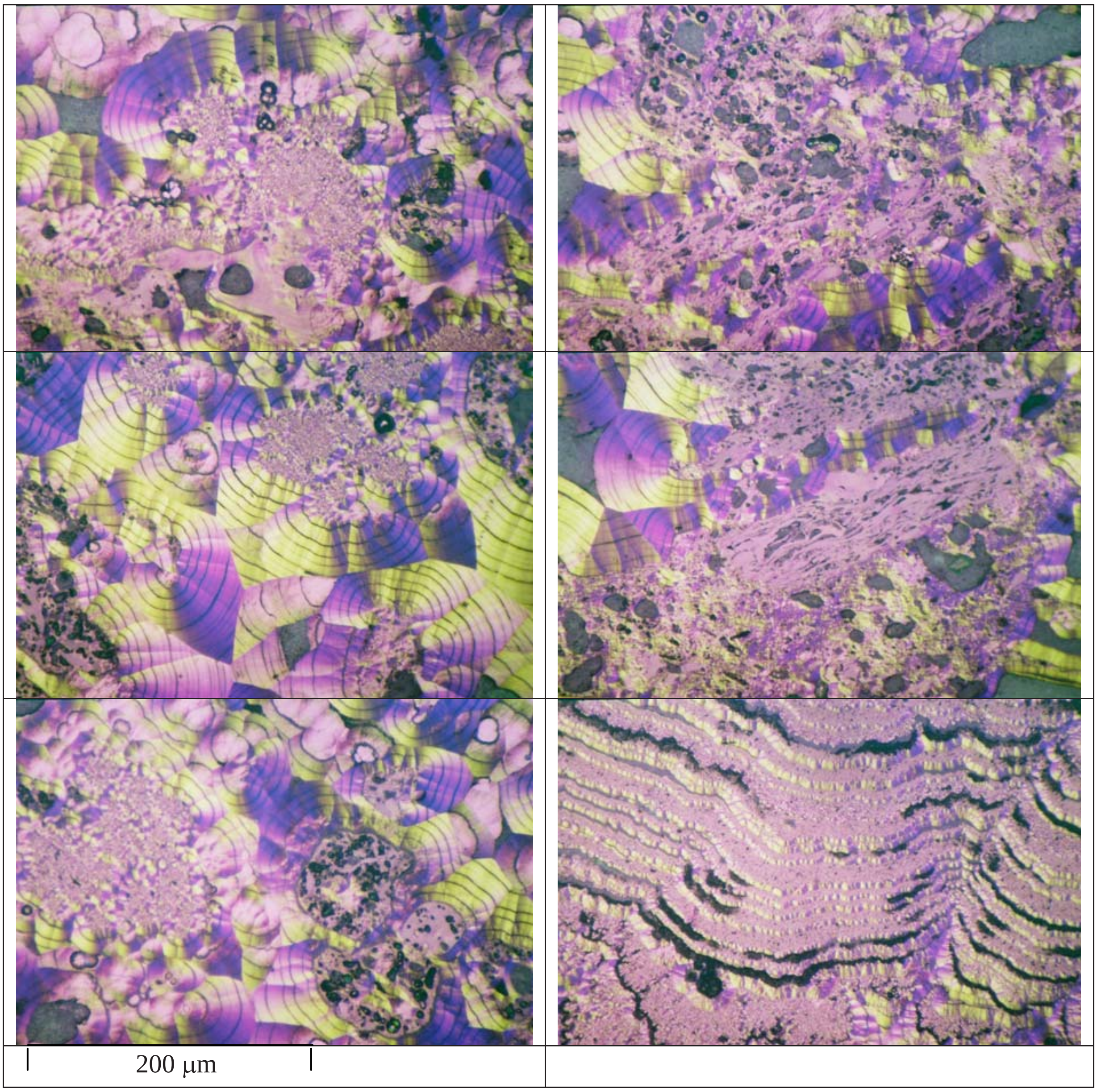

Fig. A2.8 Polarised light micrographs of coke oven carbon deposits

Different types of carbon were also found to be formed depending upon their location within the coke oven[11]. Deposits from the wall and roofs of a Japanese coke oven were found to contain what was termed columnar structures. The texture would appear to be similar to that termed laminar carbon by others. However, the roof carbon sample was found to contain less columnar carbon and more of what was termed granular carbon and also some coal-derived coke. The so-called granular material corresponds in appearance to spherulitic carbon. Jomoto and Matsuoka[12] also identified two types of carbon deposit in coke ovens. The material attached directly to the wall or roof was laminar in structure and was classified as 'primary deposit'. The material which accumulated subsequently on top of the primary deposit was granular and was termed 'secondary deposit'.

Krebs[7] assessed the effect of moisture content in the charge coal on the type of deposit formed. Below 8% moisture, two layers of deposit were seen. Adjacent to the refractory wall, spherulitic carbon was found, but the outer layer comprised larger, cone-shaped units of laminar pyrolytic carbon. As moisture content was increased, the thickness of both layers decreased, and only laminar carbon deposits were found above 8% moisture.

From the literature, it is clear that not only are there different types of pyrolytic carbon, but the terminology and descriptions are not consistent. Different types of deposits are also found in different locations within the coke oven. An initial examination of samples of roof and wall carbons by polarised light microscopy led to the adoption of a classification of the deposits into two textural types; laminar carbon, which has a corn-shaped columnar texture, and spherulitic carbon with a grainy mosaic type texture (see Fig. A2.8).

Mechanisms of carbon deposition

The mechanism of elemental carbon formation by pyrolysis of hydrocarbons is a complex process. It involves gas-phase decomposition reactions, nucleation of liquid micro-droplets, diffusional transport of the nuclei to the surface and dehydrogenation to form carbon(13). There are large temperature gradients within an oven, and a large range of coal particle sizes and gas passages. When an oven is charged these gradients may reduce, but do not disappear altogether(15). It was found that the presence of coal fines tends to increase deposit build-up especially at the start of carbonisation. This is enhanced by the bonding effect of tarry material evolved during the initial stages of cokemaking. As vapour-deposited carbon is very low in ash content, the extent to which fines have been incorporated into the deposit may be estimated by its ash content.

Shemeryankin(6) proposed a mechanism for the formation of carbon deposits in coke ovens. Fine coal is entrained and settles on walls and roof surfaces during charging. Adhesion is thought to be aided by condensing tar vapours. As the temperature in the free space and on the walls rises, hydrocarbons are pyrolysed and deposited as a thin film of pyrolytic carbon. Combustion of the outer layer of the deposit occurs, preferentially of coke fines, when the oven is pushed. This action produced porosity in the outer layer of the deposit. During subsequent carbonisation cycles, coke oven gas penetrates into the voids where it decomposes and fills up the porosity. Shemeryankin(6) also provided further evidence of the effect of coal fines on the thickness of deposit build-up. From the known build-up rate of carbon of 0.01 mm per coking cycle, the annual thickness of deposit should be no more than 6-10 mm, whereas actual deposit formation has been reported as being much faster than that.

Nagata(11) concluded from the predominance of the columnar, that is the laminar pyrolytic type of carbon, that most of the carbon deposit is formed by direct surface decomposition of activated hydrocarbon molecules in the gas phase. This is much in line with the mechanism proposed by Shemeryankin(6) assuming the deposit was collected over many coking cycles, but fails to explain the origin of the granular type of carbon that was also observed. The explanation may have been provided by Krebs(7), who believe that pyrolytic carbon differs in appearance according to how it was formed. If the molecules grow in the gas phase and later diffuse to the walls they form spherulitic carbon, which may correspond to what was described as ‘granular’. If deposition from the vapour phase occurs directly on the walls, a laminar deposit is produced.

Moisture content of the charge also influences the formation mechanism. Oxygen containing compounds increase sharply between 8% and 10% moisture, coinciding with an equally sharp rise in deposition(8). Deposits are essentially due to the cracking of low molecular weight components such as alkanes, phenols, and alkyl-substituted aromatic compounds in the primary tar. Alkyl chains undergo cracking reactions, and the new components then undergo condensation to form the carbon deposits. At moisture contents greater than 8%, a high percentage of oxygenated and low molecular weight components lead to a high facility for cracking. Below 8% moisture the tar is more aromatic and cracks less easily, leading to a direct association of hydrocarbons in the gas phase to form the spherulitic texture.

Nakagawa(15) looked more closely at the adhesion mechanism for coal fines. They ruled out van der Waals and electrostatic adhesion, as deposition of coke and alumina fines was not observed in the absence of coke oven gas in their laboratory experiments.

Factors which affect deposit build-up

Generally carbon deposition depends upon the temperature, type and concentration of source gas and the surface area of the substrate. In the case of deposits in coke ovens, additional factors include the moisture content of the charge coal, the hydrogen transfer ability (HTA) of the intermediate tars, and the presence or absence of coal fines, as seen in the previous section.

Jomoto[(12)] developed a simple growth rate model, which predicts 0.6 mm/day at 800ºC with a charge containing 30% volatile matter and 10% moisture. Nagata[(11)] determined the thickness of adhered carbon in a 250 kg test oven after a coking cycle, to compare it to the output of their model. The model predicted 0.03 mm at the bottom and 0.05 mm nearer the top of the oven, which corresponded well with reality. Nakazaki[(22)] worked on the basis that about 4.9 kg of carbon was deposited in each cycle, which also gave around 0.05 mm deposit thickness, using the supplied oven dimensions and making an assumption of an apparent density of 1.7 g/cm³. Nakagawa[(15)] suspended small pieces of refractory in a coke oven and found that the deposition per cycle varied between 20 mg/cm² and 80 mg/cm² depending on the position in the oven, assuming the same apparent density, which would make a much thicker deposit between 0.1 mm and 0.5 mm.

Depositions from laboratory-scale experiments were reported by Krebs[(7)]. They varied between less than 0.2 g and just over 1g per kilogramme of coal at different temperatures and between about 1g to about 2.5 g at different moisture contents. Unfortunately, expressing the deposition rate in this way makes comparisons difficult.

Jomoto[(12)] conducted laboratory experiments in an 8 kg test oven and found that the carbon deposit growth rate in mm/day can be related to the temperature of the adhesion surface, volatile matter and moisture content of the charge. The relationship was directly proportional to the volatile matter content, and required a downward correction for increasing moisture content. The models by Nagata[(11)] and Yoshida[(17)] are almost identical except for the choice of Arrhenius constants. They introduced an expression for the gas velocity in terms of the volatile matter and moisture per unit void area per unit time. Integrated into a larger descriptive model for the operation of a 250 kg test oven, they reached the same conclusions. Maximum deposition occurred at 3 m above the bottom of the oven corresponding to the region with the highest wall temperature. A 1% increase in volatile matter led to a 6-7% increase in the carbon deposition rate. A 1% increase in moisture resulted in a 5-6% increase in deposition, contrary to the previously observed negative effect. Oven temperature had the most significant effect, increasing deposition 1.4 times when the temperature was raised from 1170°C to 1210°C, and 2.1 times when it was raised to 1265ºC.

Krebs[(7,8)] also emphasised the importance of the temperature at which released primary tars are cracked. They found deposition increased more than five-fold, as the cracking temperature increased from 850ºC to 1000ºC. They also identified the modifying effect of moisture on the precursors to deposited carbon, namely the pyrolysis tars. Highly moist coals (>8%) encouraged the formation of oxygenated and low molecular weight tars, which cracked easily and formed laminar carbon deposits. Lower moisture coals (<8%) produce more aromatic tars, which ultimately produced spherulitic textured deposits. The differences in tar properties mentioned above was shown by Pajak[(14)] to be related to their hydrogen-transfer abilities (HTA). It was shown that tars with low HTA values produced more carbon deposits during secondary cracking.

Nagata[(11)] studied the effect of volatile matter in coal on carbon formation, oven surface temperature, the effect of additives, (such as asphalt pitch and crude tar), moisture content of coal, and gas velocity. Increasing volatile matter content, surface temperature and additive concentration all increased carbon deposition. Increases in moisture content were found to correlate with reduced carbon deposition. Gas velocity had little effect on carbon deposition. Notych[(18)] also found that free space temperature had an effect on deposition, with high temperature increasing the problem.

Kasaoka[(19)] found that carbon deposition was enhanced where cracks in the oven brickwork occurred. From this it may be concluded that smooth, defect-free surfaces will inhibit the initiation of carbon deposits in coke ovens. This may be helped by the application of special coatings to the refractory surfaces.

Nakagawa[15] also considered moisture content, as the coal moisture control process (which reduces moisture from 9-10% to 5-6%) was found to increase the amount of carbon deposits especially on the oven roof and ascension pipe. As increased ash was also observed in the deposit, a secondary effect of dryness was suspected in terms of increased fines. At all temperatures investigated, laboratory experiments confirmed that the deposition rate was larger with coal fines than without them. At 884ºC, the concentration of fines was varied and the deposition rate increased significantly. At 20 g/m³, it was in the order of 5 mg/cm²h, at 50 g/m³ in the order of 100 mg/cm²h, at 150 g/m³ over 300 mg/cm²h.

Carbon deposits in coke ovens have been characterised in some detail, and they were found to form progressively and to increase with each carbonisation cycle. Their removal has proved problematical, as their adhesion to the brickwork can be strong and their reactivity low. The carbon forms found on microscopic examination have provided strong evidence for the mechanism of formation. The different operating conditions affecting it have been identified by experimental studies. However, few of these conditions can be controlled, as they are dictated by the process requirements to make the best coke possible. One promising approach has been to make the surface properties of the refractories resistant to carbon deposition. This approach seems to afford minimal disruption to the coking process.

Task 2.3 Development of carbon deposition rig

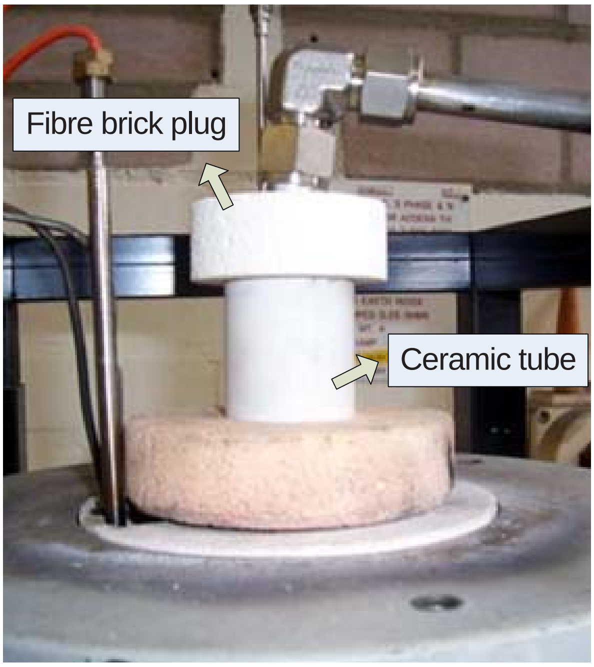

Fig. A2.9 The new ceramic tube and fire-brick plug of the carbon deposition rig

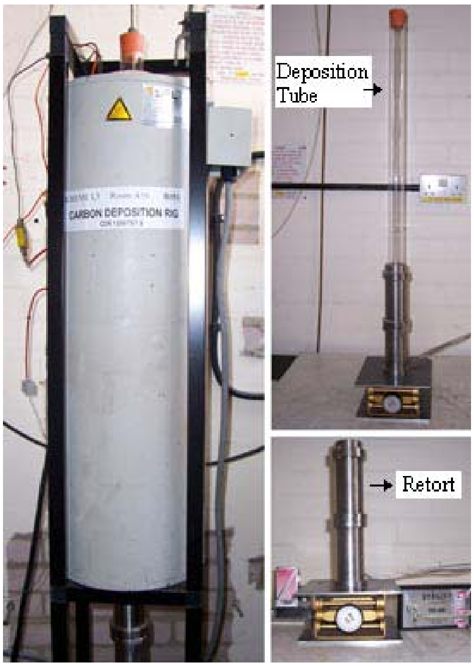

Fig. A2.10 Furnace assembly for carbon deposit rig

In previous studies[5], the pyrolytic carbon deposits were unlike some examples of coke oven wall/roof carbon deposits. Consequently, the deposition rig was developed to give better and more accurate control of the various operational parameters to enable the deposition conditions and feedstock composition to be varied in order to produce carbon deposits in the laboratory of a similar nature to those produced industrially. During commissioning, the most serious operational problem was the partial melting of some of the internal power cables, due to lack of adequate insulation during heating rate and temperature calibration tests. This required the replacement and insulation of the power cables. The quartz deposition tube was found to be too fragile for repetitive tests, as it was susceptible to breakage in the area of contact with the stainless steel carbonisation retort due to different expansion coefficients. This was overcome by the use of ceramic tubes. The rubber bung initially used to seal the top of the tube was not able to withstand the high temperatures attained in the tests, and it had to be replaced with a fire-brick plug as shown in Fig. A2.9. The gas outlet pipe also had to be changed to one with a larger diameter to prevent blockages arising from some condensation of tarry material. The photograph in Fig. A2.10 shows the furnace assembly. Representative temperature profiles for the deposition zone (Ts) and for the carbonisation retort are given in Fig. A2.11.

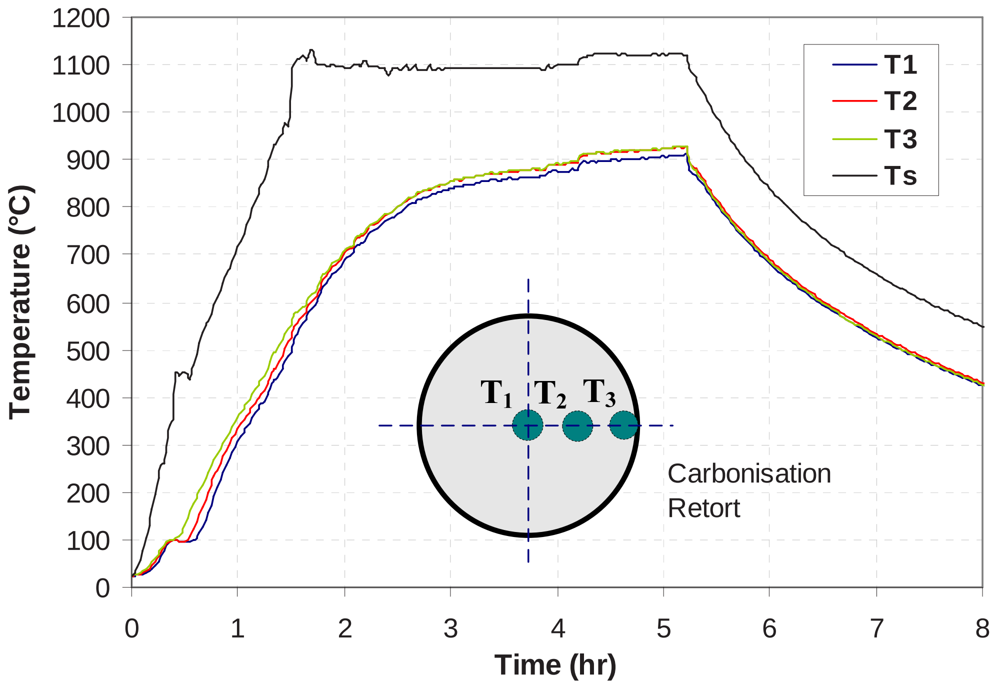

Fig. A2.11 Temperature profiles in the retort and the silica brick slide during carbonisation/deposition

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APPENDIX 3

Work Package 3: External Monitoring

Task 3.1 Development of a prototype regenerator inspection system

Discussions with potential companies for delivery of the components for an optical regenerator inspection system were performed to analyse possible ways for construction of an inspection system. As a result in this initial step, a simple Prototype 1 inspection system was developed and constructed without any cleaning equipment with the following components:

- a swivelling welding mirror, which was mounted on a slide with linkages for movement of the slide into the regenerator sole flue and for manual adjustment of the mirror
- a standard camcorder

A photograph of the Prototype 1 inspection system is shown in Fig. A3.1. Preliminary tests were conducted with this system in the laboratory on a single cold checker brick. Figure A3.2 shows the swivelling mirror at an angle of 45° underneath the cold checker brick. While the camcorder looks perpendicularly at the mirror, the dark slots of the checker brick for distribution of hot flue gas and combustion air can be seen.

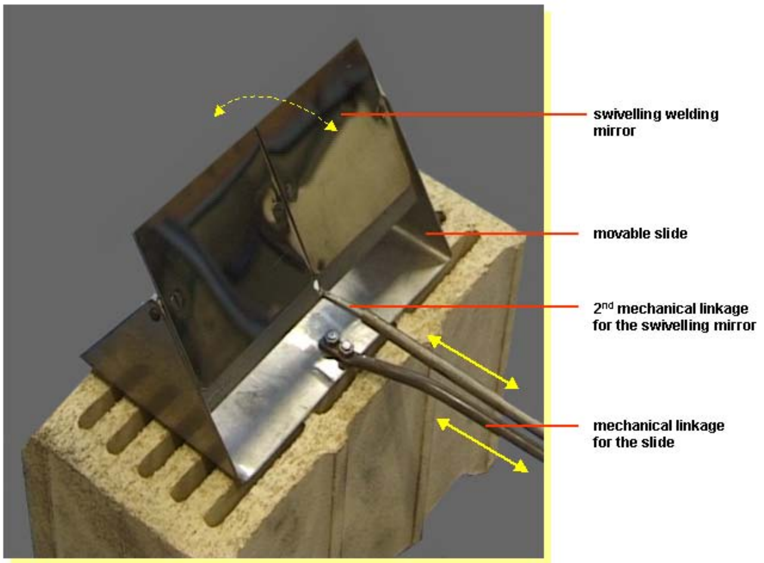


Fig. A3.1 Prototype 1 inspection system

Fig. A3.2 Camcorder view of the swivelling mirror of Prototype 1 inspection system at a cold test checker brick

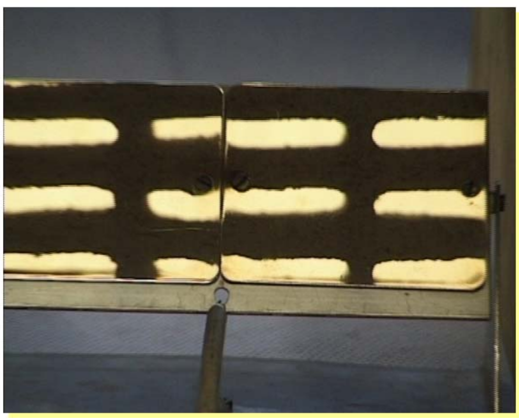


Fig. A3.3 Application of Prototype 1 inspection system with incidence of daylight through a cold test checker brick

Light inside a real hot regenerator caused by temperature radiation was simulated in the laboratory tests by incidence of daylight from above. As shown in Fig. A3.3, single brightened slots of the cold checker brick could be made visible clearly in this way by the Prototype 1 inspection system. With this system, the laboratory results suggest that details of the glowing brickwork above the sole flue should also be made sufficiently visible in a real, hot regenerator. However, plant trials at a German coke plant regenerator (in WP 6), showed that the optical characteristics of the welding mirror used in the Prototype 1 inspection system were only mediocre under hot regenerator conditions (see Appendix 6, WP 6), so that an improved inspection system was developed in Task 3.3.

Task 3.2 Integration of cleaning system

A regenerator cleaning equipment with 3 air nozzles was developed to blow away dust and other deposits from the regenerator brickwork by use of pressurised air. A nozzle type was used that had been selected by laboratory testing in WP1/Task 1.2 (Figs. A1.15-A1.16). Pressurised air was not only used for cleaning, but also for cooling purposes with a common air supply. The cleaning equipment was combined later with an improved Prototype 2 inspection system in Task 3.3. Photographs of the combined inspection/cleaning system are shown in Fig. A3.4. Operation of the cleaning equipment in the Prototype 2 inspection/cleaning system was tested successfully in plant trials at a German coke plant regenerator in WP 6. With it, large quantities of dust and other deposits could be removed from the lower sections of the regenerator brickwork.

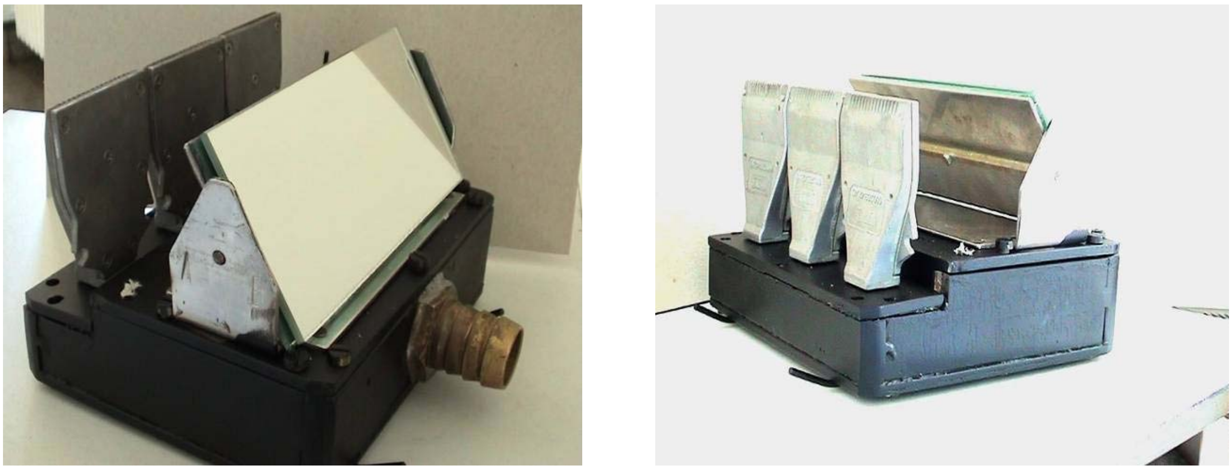


Fig. A3.4 Combined inspection/cleaning system

Task 3.3 Testing/optimisation prototype regenerator equipment

Prototype 2 inspection system

Due to poor results obtained with the Prototype 1 inspection system in plant trials conducted in WP 6 an optimised Prototype 2 inspection system was developed, combined with the cleaning equipment constructed in Task 3.2. Optimisation of the inspection system in the Prototype 2 was achieved with the following components:

- new movable slide with a radio-controlled swivelling mirror made from optical glass
- integrated common air supply for brickwork cleaning and cooling of electronics of the inspection system
- new camcorder (IR- and visible mode) with temporary additional illumination.

A sketch of the optimised Prototype 2 inspection system was shown in Fig. A3.5, and photographs of it with the new camcorder are illustrated in Fig. A3.6. The Prototype 2 inspection system was tested in plant trials at a regenerator of a German coke plant within WP 6 without and with simultaneous operation of the cleaning equipment. When inspection was run without simultaneous operation of the cleaning equipment, results from the plant trials showed that conditions of lower brickwork sections of the regenerator can be monitored and analysed in detail very well with this system. However problems in handling of the inspection equipment occurred in deeper parts of the regenerator sole flue by twisting of air supply hoses and by insufficient air cooling causing temporary malfunctions of the servo used for adjustment of the swivelling mirror.

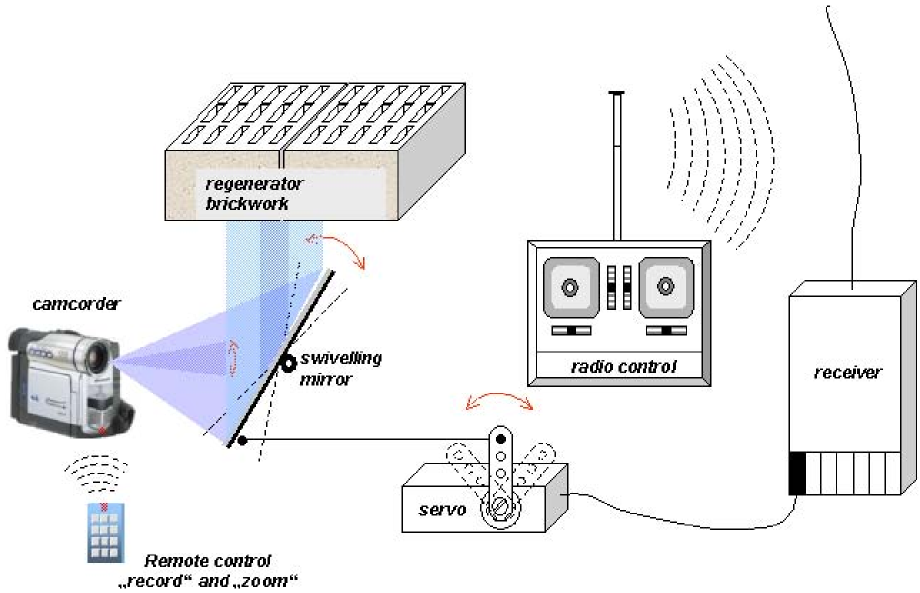


Fig. A3.5 Optimised Prototype 2 inspection system

Fig. A3.6 New camcorder with additional illumination

The Prototype 2 inspection system was tested in plant trials at a regenerator of a German coke plant in WP 6, without and with simultaneous operation of the cleaning equipment. When inspection was run without simultaneous operation of the cleaning equipment, inspection results from the plant trials showed that conditions of lower brickwork sections of the regenerator can be monitored and analysed very well in detail with this system. However, problems in handling of the inspection equipment occurred in deeper parts of the regenerator sole flue due to twisting of air supply hoses and by insufficient air cooling causing temporary malfunctions of the servo used for adjustment of the swivelling mirror.

When the inspection was run with simultaneous operation of the cleaning equipment, results from plant trials in WP 6 showed that optical inspection was not possible during cleaning due to too much backscattering of light in the video recordings caused by swirling dust. Further details of the results obtained with the Prototype 2 inspection system in the plant trials of WP 6 are reported in Appendix 6.

Prototype 3 inspection system

Due to the findings in the WP6 plant trials showing that simultaneous optical inspection and cleaning of the regenerator brickwork is not possible and taking into account the operational problems of the Prototype 2 inspection system in deeper sections of the regenerator sole flue, a much simplified Prototype 3 inspection system without any cleaning and cooling device was developed. This prototype (shown in Figs. 10 and A3.7) is based on a moveable mirror/slide-system, in which the mirror has to be adjusted manually before start of inspection. Tests at a regenerator of a German coke plant (conducted in WP 6) showed that the simplified Prototype 3 inspection system can be applied successfully without any heat protection and cooling in the regenerator sole flue at temperatures in the range of 240-290°C.

Fig. A3.7 Simplified Prototype 3 inspection system

Conclusions

Simultaneous optical inspection and cleaning of the regenerator brickwork, which was tested with the Prototype 2 inspection system, is not possible due to optical problems caused by dust raised during cleaning. Good inspection results with a detailed brickwork analysis were obtained with the Prototype 2 inspection system when brickwork sections were inspected within the entrance area of the regenerator sole flue without simultaneous brickwork cleaning. However, operational problems occurred with this inspection system, when inspecting brickwork in deeper parts of the sole flue. To run optical inspection without problems from simultaneous cleaning with a simple system, a much simplified Prototype 3 inspection system was developed without any cleaning, heat protection and cooling device. It was tested successfully in the regenerator sole flue of a German coke plant at temperatures in the range of 240-290°C.

Task 3.4 Development of automated flue temperature monitoring

Corus have developed a semi-automated unit for measuring vertical wall flue temperature distribution using the latest technologies. It incorporated a power-driven temperature monitoring head to facilitate completion of a full crosswall temperature survey on an individual oven without interfering with oven top machines. Consultations took place with a specialist instrumentation expert, to facilitate use of recent advances in imaging, and thermal data acquisition and transmission technology.

An insulated, water-cooled measuring head was designed to be driven down flues from a mobile trolley, which is wheeled along the battery top. A two-colour pyrometer was selected for temperature measurement with laser sighting, so it would be possible to check if the optics were aligned properly.

The new pyrometer fibre optic was a monofilament optic, requiring less checking than a multi-stranded optic. Temperature data is transmitted via a 4-20 mA link to allow the signals to be fed through slip rings from the reeling drum, to give a reliable, stable signal from the pyrometer.

Investigation of potential systems for video capture in the flues resulted in a decision being made to set up the system to look straight down the flue with a wide angle of view. Trials of the lightweight, portable, water-resistant, video inspection system and a video capture and transfer system were conducted in the hot chamber of the pilot-scale coke oven, to assess which equipment would be most suitable for plant use. Figure A3.8 illustrates the variations between infra-red and standard cameras with and without additional illumination in a hot environment. Wall defects were easier to see with a standard camera than with an infra-red one, and so it was selected. Additionally, it was smaller and therefore easier to cool.

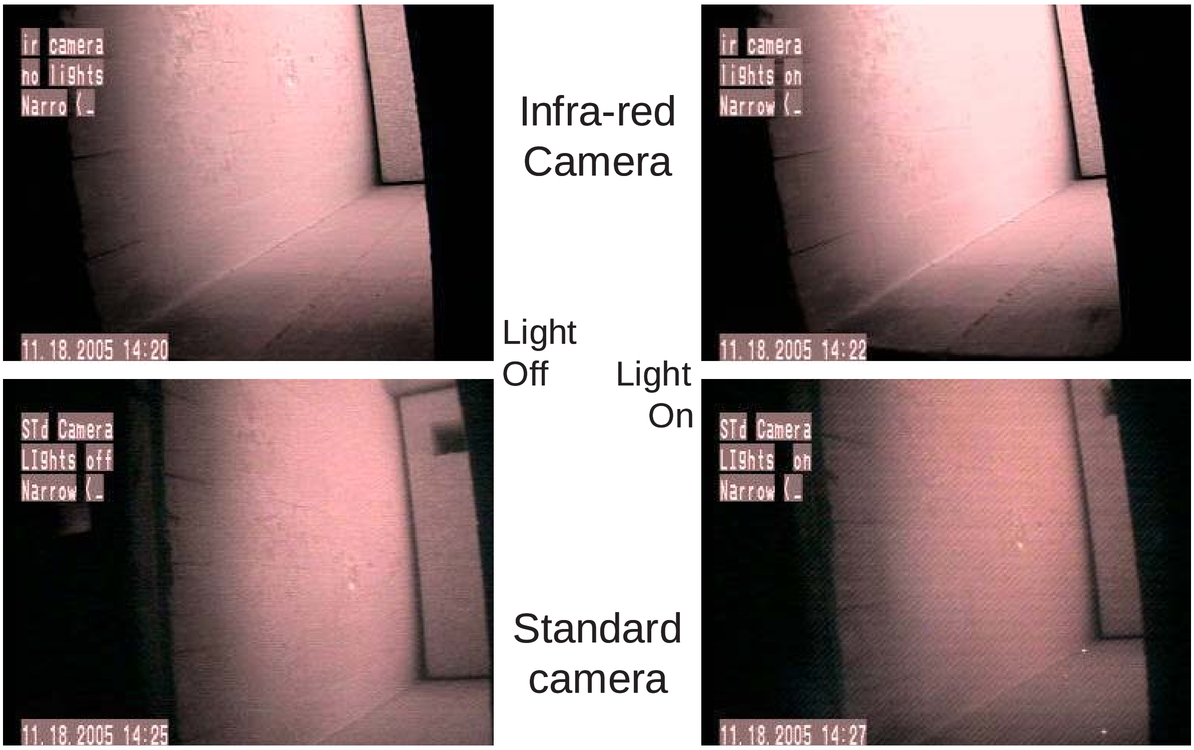
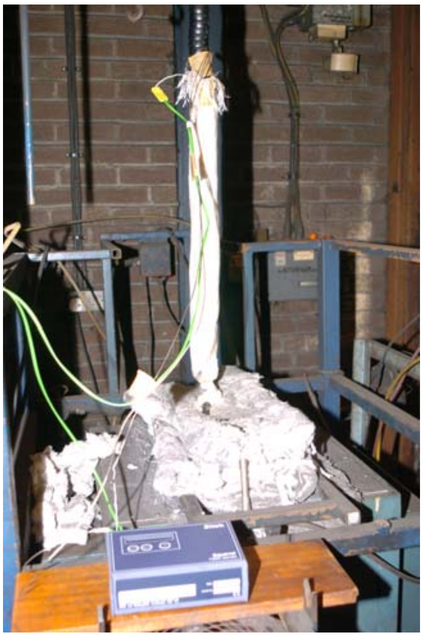


Fig. A3.8 Video capture in a hot pilot-scale coke oven with different cameras and illumination

The video head was designed to fit on to the temperature head with a separate cable to permit measurement of temperature or flue photography or both. Since the video has to be taken under controlled conditions with sufficient time to cool between runs, the rate of flue measurements will be optimised and demand for cooling reduced by removing the video head. The inspection and transmission system was developed to view the video images on the monitor and to store them locally. Consequently, images are captured the rig and simultaneously transmitted with depth and temperature data to a base station computer using radio transmission from the battery top. The design incorporated real-time data transfer, so that vertical flue temperature profiles could be viewed immediately at the point of measurement and on an independent computer. The system also provided temperature mapping of all walls, allowing optimisation of battery heating control.

The design of the delivery system for temperature and video monitoring of flues was dependent on the size and permitted radius of curvature of the umbilical connecting the head to the winding drum. Discussions took place with project partners about insulation, but the limited space meant that the types of insulation used in their applications were not suitable for this monitor and a special system had to be developed. The conduit was designed to carry cooling water to and from the head and electrical and fibre optic cables for the video and temperature data collection. Maintaining the conduit at a safe temperature was imperative, as the selected material was a plastic construction.



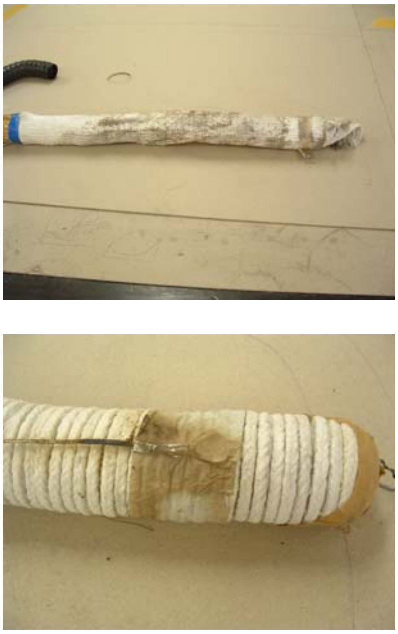


Fig. A3.9 Insulation of conduit

Fig. A3.10 Test piece about to be inserted into the furnace

Fig. A3.11 After test, insulation shows no adverse effects

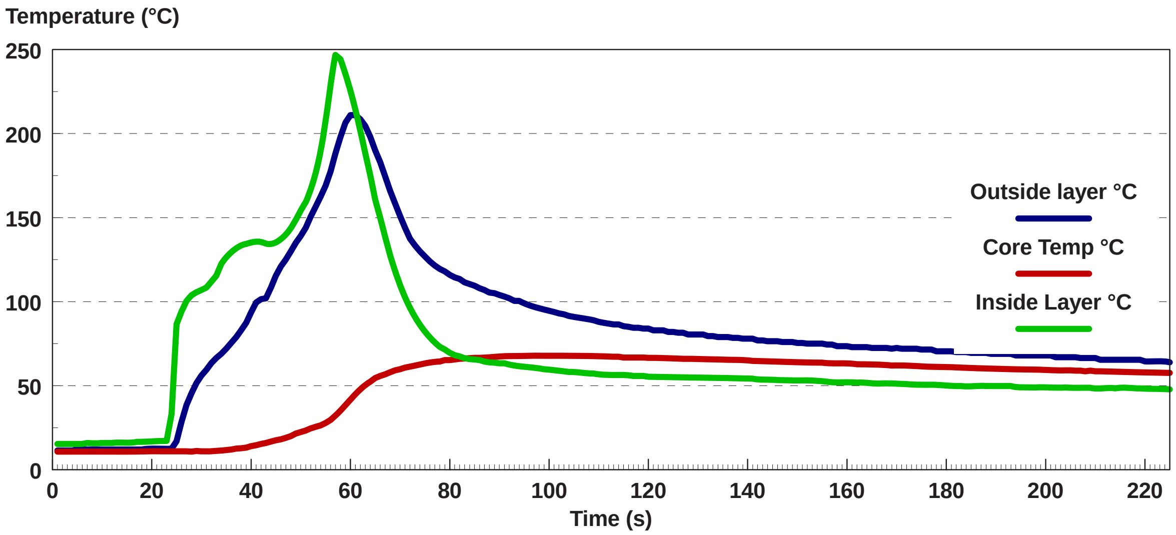


Fig. A3.12 Heating/cooling curves of the core and insulation layers during a furnace test

Figures A3.9-A3.11 show tests carried out on the system. The conduit was wrapped in a flexible insulating tube, around which ceramic rope was spiralled in Fig. A3.9, and a further flexible insulating tube was applied over these layers. Embedded within the layers were thermocouples to monitor the temperature rise during the tests. Prior to insertion into the furnace, the insulation was immersed in water until the whole test piece was saturated, and then the excess water was allowed to drain off for 30 minutes. The furnace temperature was maintained at 1200ºC and the test piece was inserted for 30 seconds (see Fig. A3.10), after which it was removed and allowed to cool naturally. Its core temperature was monitored throughout the heating cycle and after removal from the furnace. After the trials, the test piece was dismantled and checked for the effects of heat on the core. Figure A3.11 demonstrates that there were no adverse effects to the insulation layers from the heating test, and even the plastic core covering remained in tact. In Fig. A3.12, the heating/cooling curve of one of the tests indicates that the core did not rise above 70ºC.

The drum assembly was designed, constructed and attached to the drive system to investigate its suitability and performance. This enabled a simulated load to be used to carry out simulation tests on the drive system response and control. After all the parts of the rig had been tested in the laboratory, the monitor was assembled and further tests and modifications took place to eliminate problems and ensure that every aspect of it could be controlled. Figure A3.13 shows the monitor in the laboratory before the umbilical head was fitted.

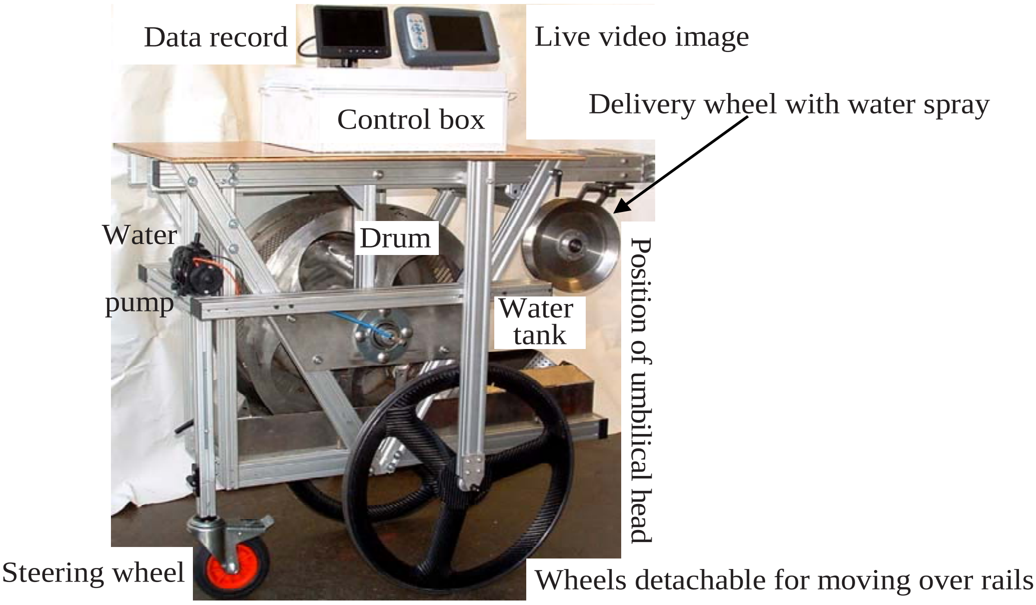


Fig. A3.13 Automated flue temperature and vision monitor without the umbilical

Task 3.5 Development of tie-bar monitoring

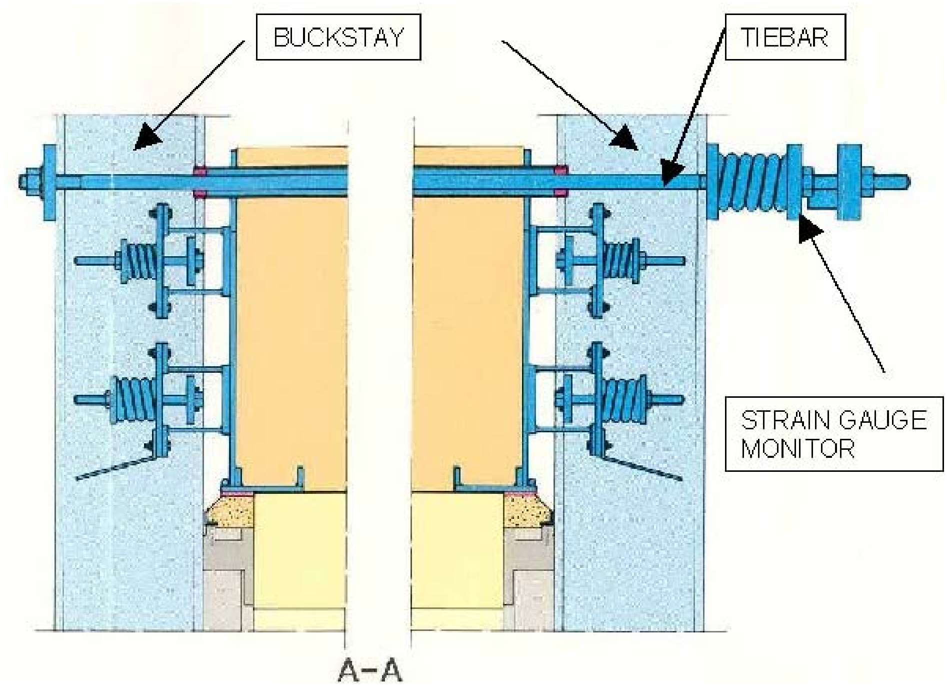


Fig. A3.14 Sectional elevation of coke oven detailing the tie-bar/buckstay arrangement

The top tie-bar/spring arrangement (seen in Fig. A3.14) on the battery performs a number of functions, including buckstay/door-frame restraint and compression/support of battery top brickwork(23), that are of critical importance in the quest for extended battery life and low environmental emissions. One of the main consequences of ageing is the deflection in structural metal framework of the oven, principally as a result of the thermo-mechanical factors. Excess strain and movement of the tie-bar can result in high buckstay temperatures, door-frame distortion and inevitably door leakages. Breakage of tiebars can also occur, in which case rapid remedial action is required to minimise oven damage.

A dedicated monitoring system was designed with load cell sensors mounted at the ends of tie-bars at the top of individual ovens to measure loads on the buckstay springs continuously, for evaluation of the forces acting on the battery steelwork and associated movements. Figure A3.14 shows the position for load cell sensors in the tie-bar and spring arrangement on the battery (which performs a number of critical functions, including buckstay/door-frame restraint and compression/support of battery top brickwork). Excessive strain and movement of the tie-bar can result in high buckstay temperatures, doorframe distortion, door leakages, and tie-bar breakage. From preliminary experiments, the effect of oven charging on tie-bar loads is demonstrated in Fig. A3.15. Abnormal changes can be used for early detection of excessive coking pressures, pushing difficulties and deterioration in the structural integrity of individual ovens, which are all precursors of irreversible refractory damage. A logging system was set up and the strain sensors were trialled in the laboratory, until the correct calibration specification was identified.

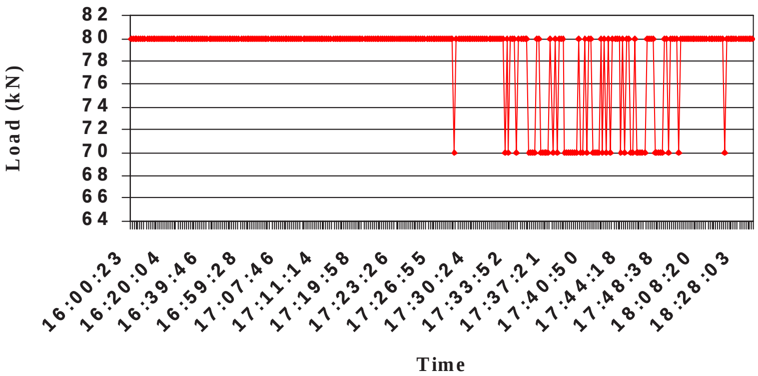


Fig. A3.15 Effect of oven charging on tie-bar loads

Fig. A3.16 Three damaged cables and load washers and improved one in centre

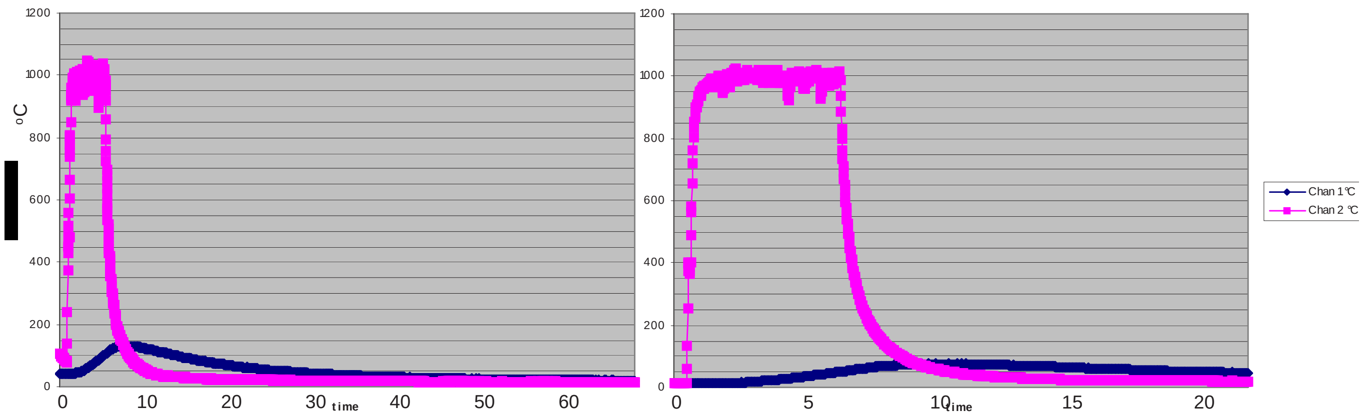


Fig. A3.17 Insulation tests on cables with two different sheathing materials
Chan 1 blue line = internal temperature, Chan 2 pink line = external temperature

Plant trials began with the load cells fitted to a pair of tie-bars on one buckstay, but there were problems with cables burning (see Fig. A3.16). A test facility was used to determine the effectiveness of various types of insulation for the cables. Flame tests were carried out in the laboratory with a range of heat-resistant materials, including silicone/fibre composites, combined with temperature-resistant cable capable of operating at temperatures in excess of 200^{o}C for short periods of time. Figure A3.17 shows graphs from tests of two different sheathing materials, with two thermocouples demonstrating the difference in temperature between the outer and inner surfaces. The outer surface (pink line) was maintained at >1000^{o}C for around six minutes by a butane flame, and the temperature of the inner core (blue line) was monitored. With the first material the core temperature reached 125^{o}C, but the second material was more insulating with a maximum temperature around 80^{o}C. Load cells were constructed for plant trials using the most-insulating material, but the soldered joints between the cables were found to damage easily during installation. Consequently, new load washers were designed with greater sensitivity to changes in load and with a plug/socket system rather than hard-wired sensors. If a cable is damaged, it can be changed without the need to remove the load cell from service. Protection from mechanical damage was achieved using a stainless steel conduit. Figure A3.16 shows three damaged cables and washers and the modified unit with improved insulation in the centre. This new design was successfully installed and continues to operate on plant.

The use of radio communications between the signal conditioning unit and the data logger were investigated to reduce reliance on cabling on the battery top. A washer was put under load, logged with a data logger and data were transferred successfully over a short distance by a radio modem in the laboratory. The system has been set up so that data can be transferred directly from the tie-bars to a plant control room via an Ethernet or hard-wired connection.

Task 3.6 Development of oven top deflection monitoring

Plans were made to carry out oven top profiling measurements with an array of displacement transducers permanently attached to the charge car to facilitate continuous monitoring and recording of the height profile across the full width of the battery top during normal charging operations. Early detection of abnormal distortion will provide the opportunity for remedial action before critical deterioration in oven condition occurs. Site assessments were carried out on two batteries to examine where the monitoring equipment might be fitted. Figure A3.18 illustrates the positions of the sensors in line with the charge hole lid and data logger on a charge car. Since plant personnel were wary of using lasers for safety reasons, ultrasonic sensors were selected for measurement of deflections to $\pm$1 mm.

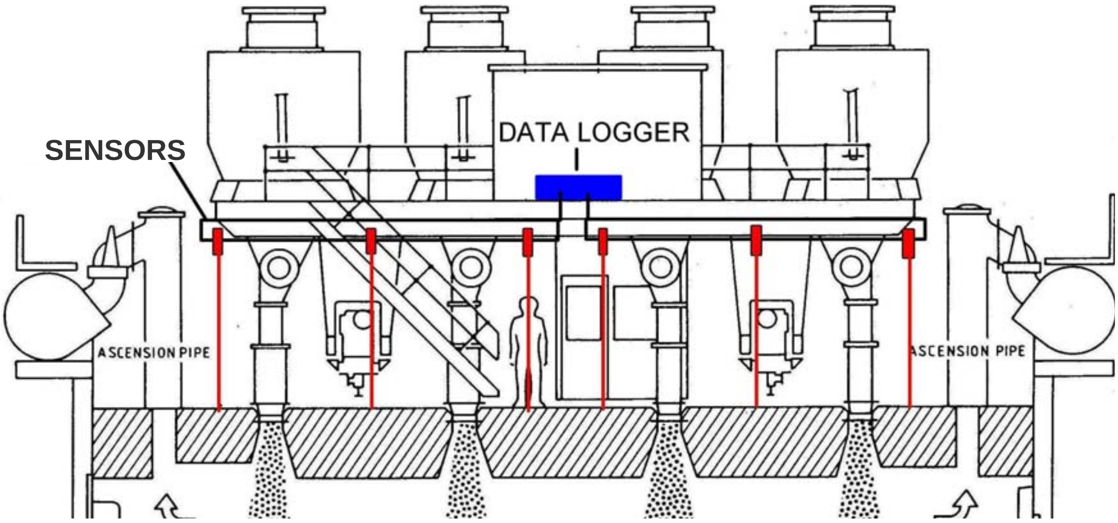
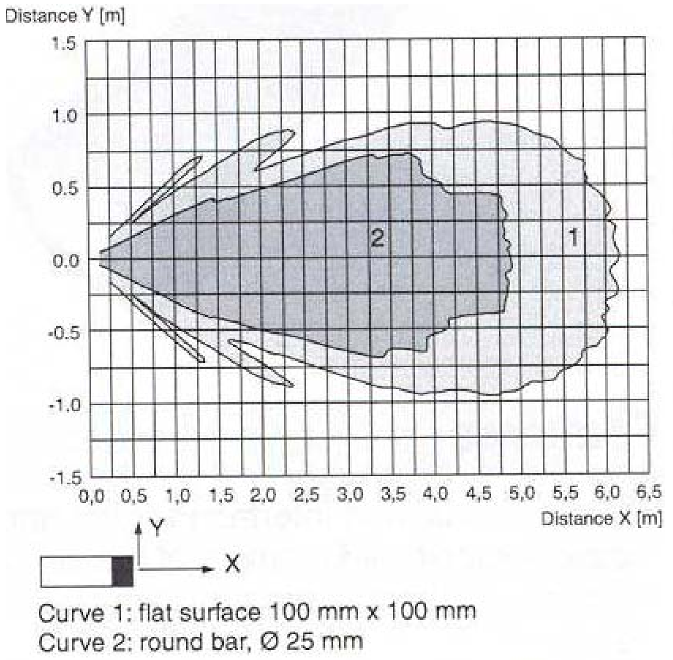
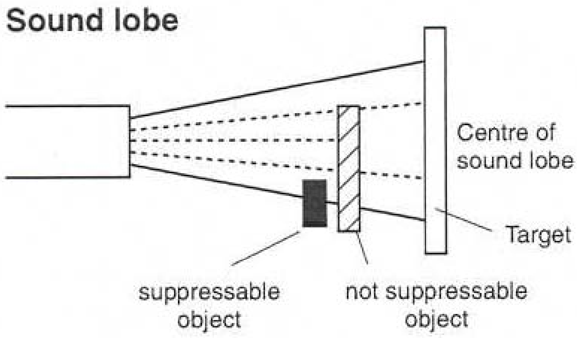


Fig. A3.18 Positions of sensors and data logger on a charge car

Laboratory trials demonstrated problems with the ultrasonic sensors because the signal beam width on the target area was too large. Specifications for the instrument indicated that this should be 0.5 m in diameter when the sensor was set at a test height of 1.0 m, and 1.0 m in diameter with a test height of 2.5 m, as illustrated by Fig. A3.19. If the sensor was not correctly positioned to avoid charge car rails and charging port lids on plant, it would detect these and give a false indication. Testing the sensor in the laboratory showed objects could be suppressed by the sound lobe, reducing the signal beam width to 0.45 m and 0.7 m diameter respectively in cases of objects on the periphery, as shown in Fig. A3.20.

Preliminary plant trials (described in Appendix 6) with the ultrasonic unit highlighted accuracy problems with the large footprint. After investigations of the potential disturbances caused by the charge car weight and movement, it was decided that the original proposal to attach an array of displacement transducers permanently to the charge car was not the best method for obtaining accurate data. Continuous monitoring and recording of data during normal charging operations would provide a large quantity of data, which would be difficult to analyse effectively because of the disturbed readings. Although the comparison in Table A1.1 identified the initial problems with laser measurement techniques, they had improved in terms of variability of surface colour and accuracy on rough surfaces, while the project was being carried out. Applications with Class II lasers were accepted elsewhere on





steel plants, and agreement was reached to use them on the battery top.

Fig. A3.19 Target area beam characteristics Fig. A3.20 Suppression of objects by the sound lobe

Consequently, a new a 'stand alone' unit was designed and constructed, in which a beam is pushed manually along the battery at selected intervals in time, isolated from disturbances caused by charge car weight and movement. To allow trials to be undertaken on different plants, the beam assembly was made adjustable for rail spacing, rail height and battery width (up to 14 m), and designed in two sections to allow easy transportation without specialised vehicles. The height of the battery top surface is measured by six laser displacement sensors mounted on the beam in protective casings. The sensors use Class II lasers and CCD detectors with a measuring range of 400±100 mm. For high measurement stability, the Wide Spot Type were selected, with diffused reflections (caused by irregularities in a rough-surfaced target) averaged to prevent data fluctuations. The sensors work on a triangulation technique, and are operated by a push button, when the beam is in position on the battery. Data from the three control units for the six measuring heads are transferred to a logger, with the oven number and beam inclination for both X and Y horizontal planes. A dual axis inclinometer data compensates for charger rail deviations, and an accurate positioning system is used to enable comparisons to be made in the oven top profile over months and years. After trials in the laboratory, modifications were made to the sliding elements at the beam interconnection points to allow easier assembly of the frame on plant, and stiffening elements were fitted to prevent excessive flexing at the frame ends. Figure 20 showed the final version of the monitor, as it was being positioned on the battery top.

LIST OF FIGURES IN APPENDIX 3

APPENDIX 4

Work Package 4: Data Processing

Task 4.1 Oven image analysis software development

A distorted inspection video was obtained with the chamber wall observation device, and so a series of processes were developed to transform the distorted video images. The developed packages for different functions are presented here.

Extraction of images from the video

The extraction of images in ".png" format was obtained from the coke oven wall inspection video provided by CPM. The frame frequency was calibrated at 25 frames per second in order to restore as much information as possible from the videos. That made approximately 5000 images with a volume of 1.4 G bytes for one video with a duration of around 3 minutes. The two examples of the images extracted from the film are shown in Fig. A4.1.

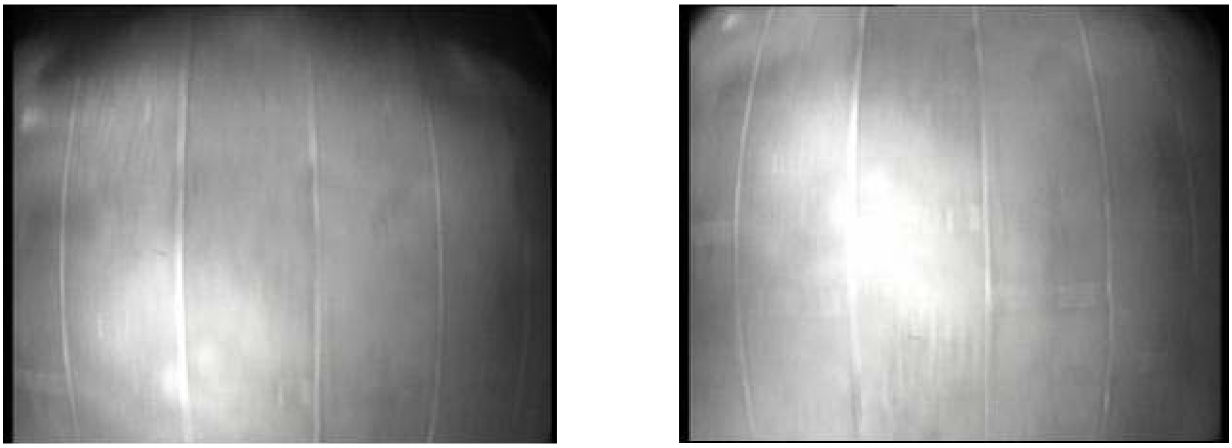


Fig. A4.1 Two image examples extracted from the video showing the distortion, interlacing, optical centre and contrast problems.

Generally, it is apparent that:

- The geometrical distortions (aberrations) are strong (see examples in Fig. A4.1). This effect is primarily due to the aperture size of the miniature optics. Consequently, an image transformation is necessary before other operations.
- The interlacing effect arose in the images (for example, movement, distance), and removal of this effect would make the image clearer.
- The contrast variation of the images was also important, sometimes even saturating the camera sensor. A systematic contrast correction of images was also useful before stitching the images together.
- The optical centre position of the camera varied from one image to another, and required the development of a sophisticated algorithm to identify the exact optical centre position for a perfect transformation and stitching operation.

Processing with open source software

In a preliminary trial, some open source software (Hugin, PTAssembler, etc) was used to analyse and assemble the extracted images. The idea was to estimate the complexity of the processing problem by using the available open sources. Checks were made to see if these available open sources were able to do the transforming and stitching jobs without adding major modifications to the processing packages. An example of an assembly of about thirty successive images processed by the Hugin software is presented in Fig. A4.2 (an open source application with original images extracted from the recorded coke plant video).

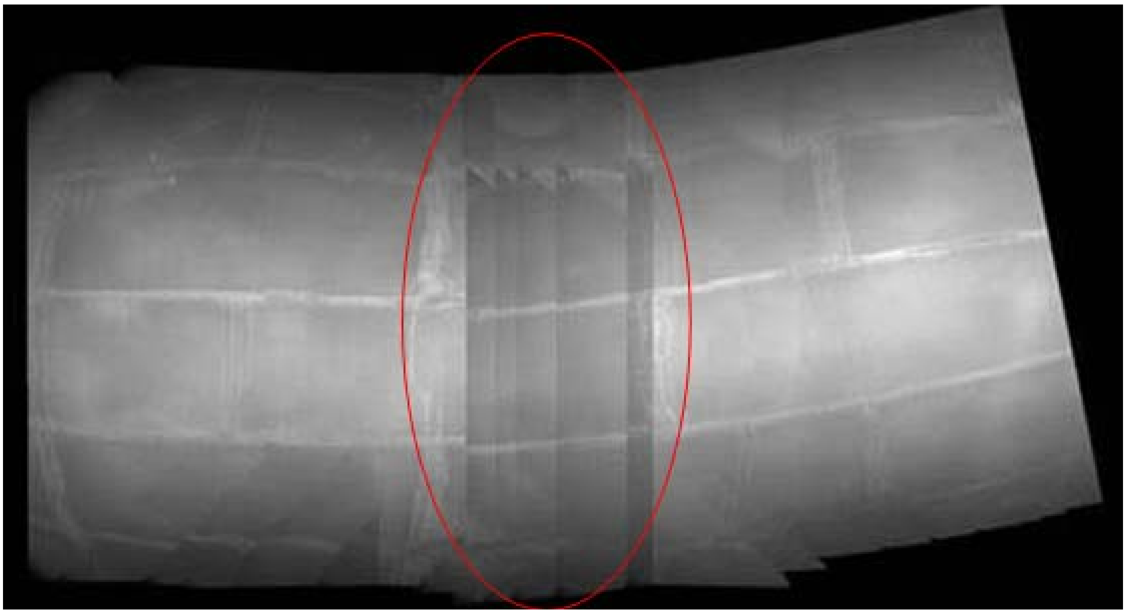


Fig. A4.2 Assembling example of 30 successive extracted images

The transforming and stitching problems occurred in the zone circled in red in Fig. A4.2. In this example, it is apparent that the rectifications and stitching were made poorly, if the extracted images (without transformation) were processed by this software. The major problem was that the distortions (spherical aberrations, projection, translation, etc) were so strong that they were out of the range of the rectification and stitching capacity provided by the open-source software.

Establishment of transformation model

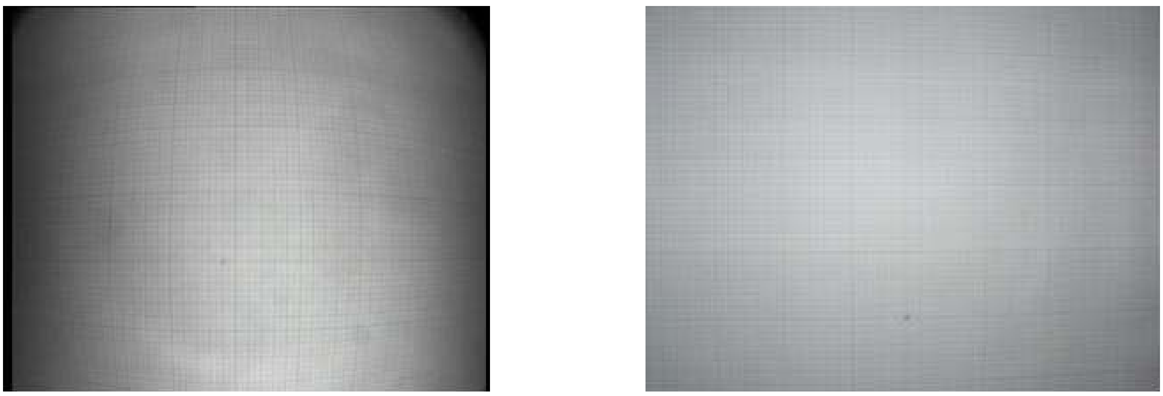


Fig. A4.3 Example of transformation on graph paper

The combined camera system used on the ram created specific distortions of the images. These distortions were not only strongly linked to the setup of the optical objectives and the optical parameters of the selected camera device, but also due to the irregular movement of the discharging ram in the coking chamber.

The combined distortions can be separated into two main types, spherical distortion and projection distortion. The exact parameter information of the setup of the selected objectives was not available, and the theoretical calculation of distortions due to the combined objectives was not realistic. Consequently, a practical approach was adopted, with some images of graph paper being taken in a static state by the same camera used to perform the inspection with a similar mechanical setup of the installation in a coke oven. The pictures in Fig. A4.3 show an example of the image of millimetre graph paper obtained with a similar setup to the camera used in the coke battery (on the left) and obtained in normal conditions without the distortion effect (on the right).

Based on this information, a model was established for correcting distortions with transformation mapping between a distorted image and a normal image. As shown in Fig. A4.4, the model established the relationship between the distance between the optical centre Rdis and Rcorr in the distorted and transformed images, respectively. The model allows pixel-to-pixel non-linear mapping between the distorted image and the transformed image. The relationship between polynomial coefficients "a, b and c" are represented by the following equation:

$$R_{dist} = a \cdot R_{corr}^4 + b \cdot R_{corr}^3 + c \cdot R_{corr}^2 + R_{corr}$$

These polynomial coefficients were obtained by developments of a Matlab package, and they are based on a practical approach (images of graph paper). This package will be rewritten as a sub-package in Python. Obviously, the coefficients are influenced by the setup of optical objectives and corresponding optical parameters of the camera.

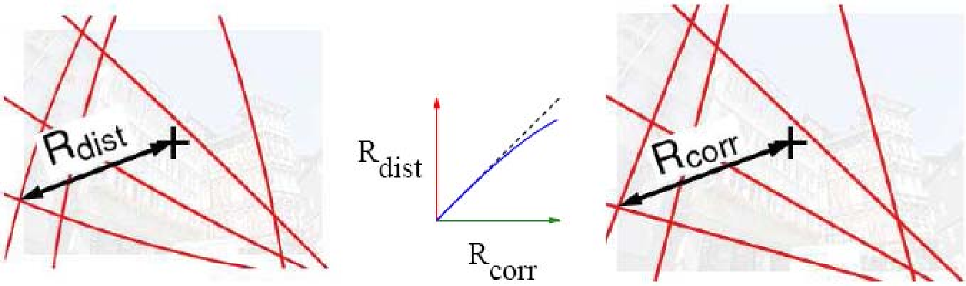


Fig. A4.4 Illustration of the distance and coordinate mapping between a distorted image (on the left) and a transformed image (on the right)

Correction of interlacing effect

A general video recorder records 50 fields per second (pictures with one line out of two) and intermixing two consecutive fields (with half the height) into one frame to get a regular frequency of 25 frames per second. With the camera installed on the moving pusher ram (which travels about 1 m/s), the even lines and the odd lines of one frame were not acquired in exactly the same position. Consequently, a displacement shift can be observed in the images extracted from the recorded video. Suppression of this shift effect was attempted by bringing one field closer in relation to another. However, the optical axis of the camera was not always perpendicular to the battery wall (with a tilt angle of about 10°), and this made it hard to eliminate the interlacing effect completely by combining consecutive fields.

One simplified method of eliminating the interlacing effect is to keep one field of each frame. Then, the missing lines can be completed either by copying the corresponding lines in the direction of movement, or by line-filtering in another direction to keep the size proportional. The method using line filtering does not decrease the image quality much, as can be seen in Fig. A4.5, which has been line-filtered in the perpendicular direction to the movement direction.

Implementation of transformation model

The implementation of the transformation model consisted mainly of introducing three sub-packages: a positions mapping package between distorted image and destination image, a grid interpolation package in distorted images and a cutting-off package for edge effect. This transformation model permits calculation of relative coordinates and distance mapping. However, this is based on a distance mapping, which does not give explicit coordinates values. First, an explicit calculation sub-package of corresponding coordinates in two images (distorted image and transformed image) must be implemented in this step. The second step consists of determining the grid value from the distorted image. The grid value determined by a spline interpolation technique was used in the transformed output image.

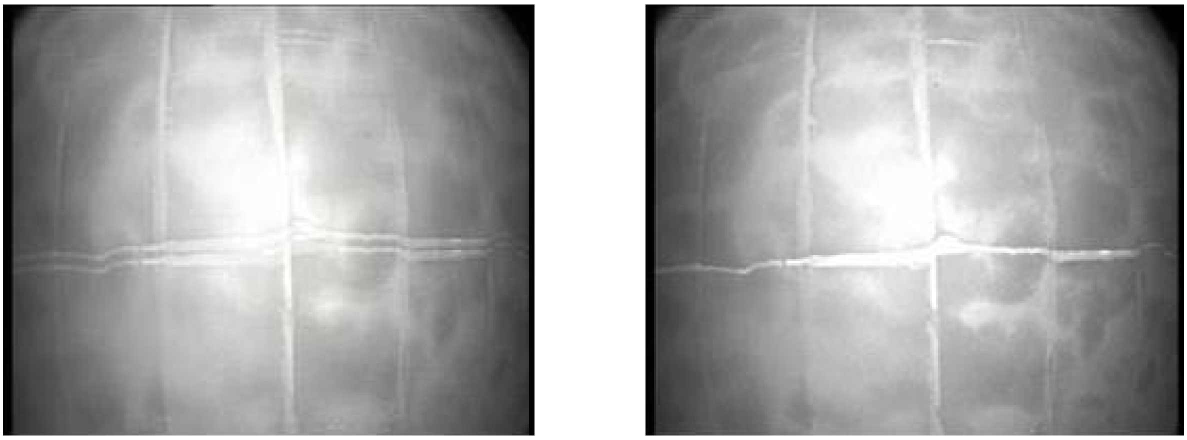


Fig. A4.5 Comparison of images with (on the left) and without (on the right) the interlacing effect

The interpolation function in the second step is given with the calculation package of coordinate mapping in the first step. There is always one part of the image edge that is not completely corrected, due to the inhomogeneously directional distortion (the effect called "edge effect"). A cutting-off operation has been adopted to decrease the edge influence in the stitching operation for forming wall cartography. Two examples of transformed images are shown in Figs. A4.6 and A4.7 for a one millimeter paper image and an inspection image. Figure A4.8 illustrates a 2-dimensional spline interpolation.

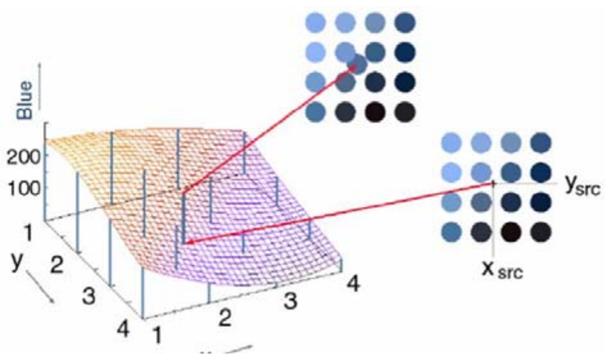


Fig. A4.6 Interpolation model for determining the output grid/colour value of a destination pixel in a transformed image

Stitching package

For the extracted images from the video recorded in a coking plant, the overlap of consecutive images is as high as 95% of the total surface. Thus, an adapted edge cutting-off after the corresponding geometric transformation operations still leaves space for a stitching operation. The selected stitching technique is based on an FFT convolution calculation in the spatial domain. By calculating the convolved values of two consecutive images in a certain zone, statistical analysis follows the evolution of the convolved values and determines the optimum distance between the lines. Obviously, the convolution calculation zone size (windows size) can be enlarged, which modifies the necessary time of calculation for each pair of consecutive images dramatically.

However, a larger size of matching convolution zone of two consecutive images permits a better operation accuracy for line-to-line stitching. Thus, a compromise between necessary calculation time and accuracy of the stitching operation should be set down for this large amount of images (around 5,000 images for a three minute video). The image size after cutting-off is about 250 x 220 pixels. The selected convolution zone size was set as 30 x 30 pixels after certain image trials in order to have a relatively large window of matching. An image stitched / assembled with 10 consecutive images is shown in Fig. A4.9, which is obtained with a convolution calculation zone 20 x 20 in a parameter test. The surface texture of the coke battery wall is well maintained and there is no evident mismatching zone in the image.

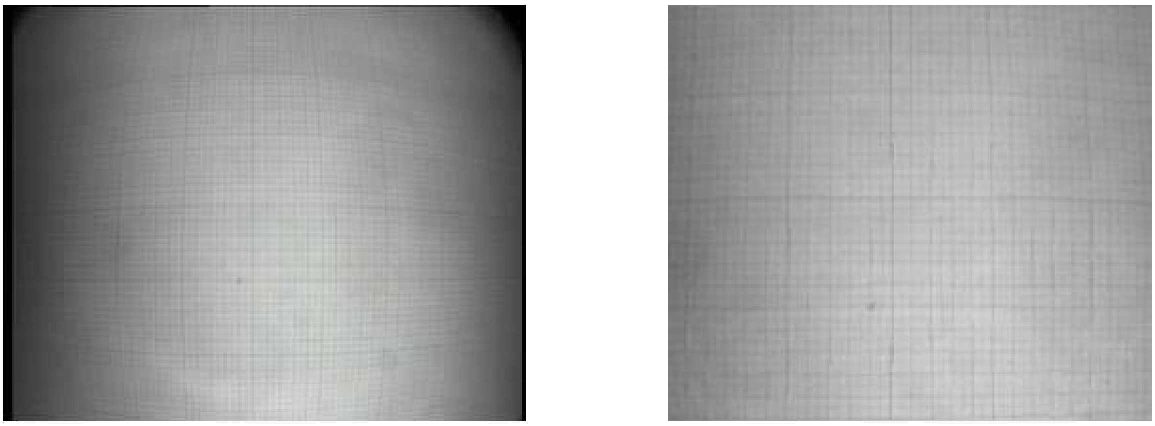


Fig. A4.7 Transformed and cutting-off image (on the right) for millimetre graph paper, compared to the original image (on the left)

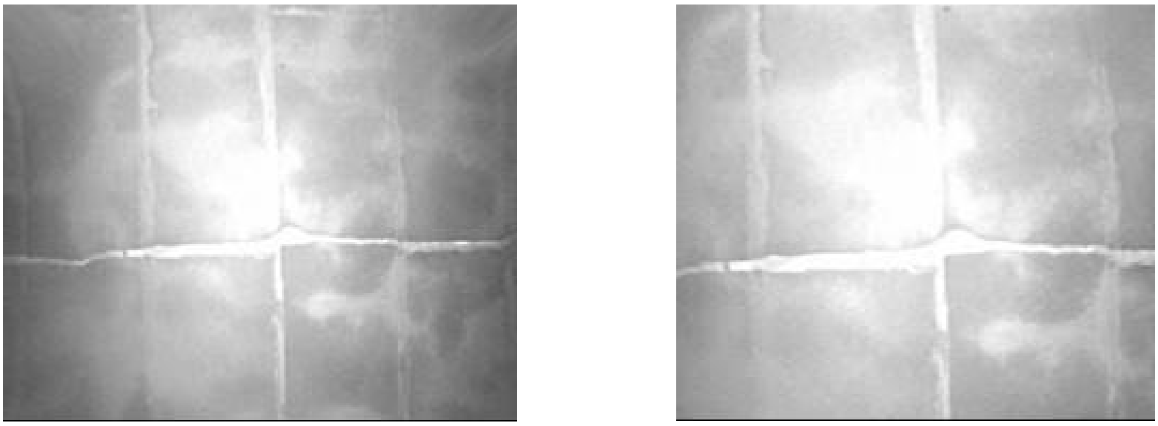


Fig. A4.8 Cutting-off image (on the right) after transforming operation for a video image compared to the transformed image without cutting off (on the left)

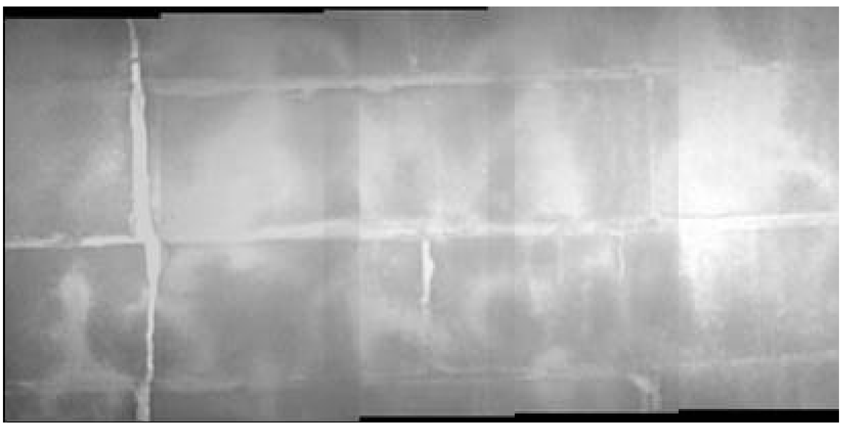


Fig. A4.9 Image stitched using the developed packages to display 10 consecutive original images

Oven wall picture generation

As described above, a series of processing operations were developed and implemented before performing a consecutive image stitching, in order to obtain an integrated wall inspection image. These operations include: image extraction from video, modelling of distortion related to the composed optic system on the camera, image interlacing correction, distortion transformation of each image, cutting-off of the edge effect due to the inhomogeneity of the area of image distortion, and evaluation of stitching parameters. These operations were mainly implemented using an open-source programming language: Python. In practice, the identification of correction coefficients for the transformation of spherical distortion took place with a Matlab script. For stitching a large amount of consecutive images, a frame frequency of 25 frames/s was used in the extraction operation from a video, and a position shift was set as 20 pixels movement between each pair of consecutive images according to the speed of the video camera. The running direction of video camera was considered as fixed (no alternative backward and forward running).

The matching size of the convolution zone has a square form of 30 x 30 pixels, and the common zone of each consecutive pair of images used a merging algorithm to form the new zone of the stitched image. A wall inspection image generated by stitching 300 consecutive images is shown in Fig. A4.10. Three corresponding non-consecutive original images extracted from video were shown at the right side of the stitched image. Geometric distortions of images and the interlacing effect were removed, and the stitching operation was performed correctly. The surface structure and texture of inspected coke oven wall were reconstructed and monitored. The contrast and grid level between images can still be improved.

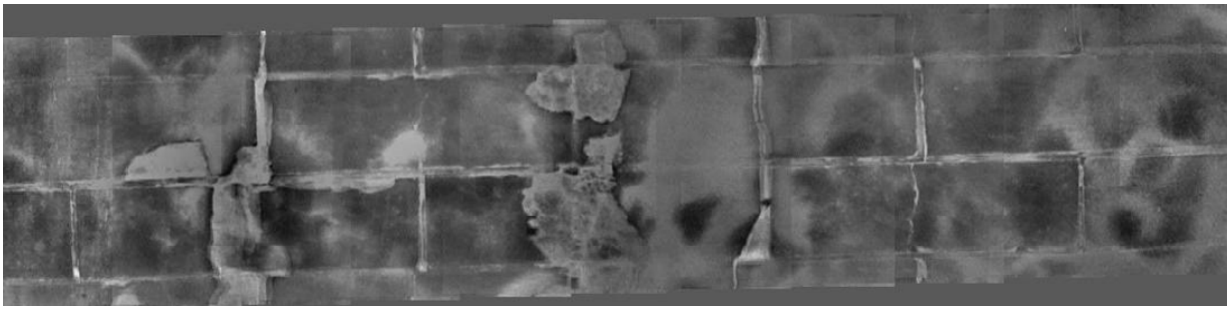


Fig. A4.10 Stitched inspection image of part of the coke oven wall generated from 300 consecutive images extracted from original video

The stitching packages have also been implemented in this application for producing a long and plane inspection image of coke oven wall. The developed packages are now capable of producing a rectified inspection image. As shown in Fig. A4.10, good merging of the common zone and monitoring of the surface state were realised. With the integrated inspection images, it is possible to record, recognise and compare the surface degradation evolution resulting from the videos obtained in a coke battery at different times.

Task 4.2 Video recording of regenerator condition

For the organisation and archiving of the data files obtained from video recording, basic software from ULEAD Systems was used to develop and optimise RISA (Regenerator Inspection System Archive). Functions for input data and search functions were implemented additionally by DMT into RISA on the basis of EXCEL. The input data mask and a screenshot of RISA are shown in Figs. A4.11 and A4.12.

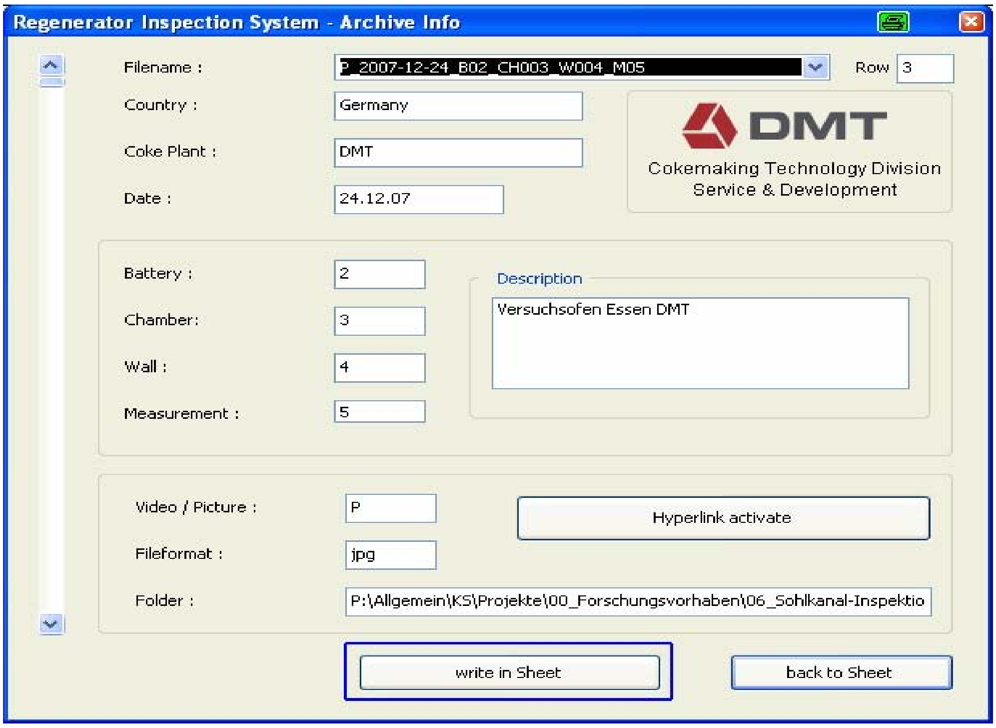


Fig. A4.11 Input data mask of RISA

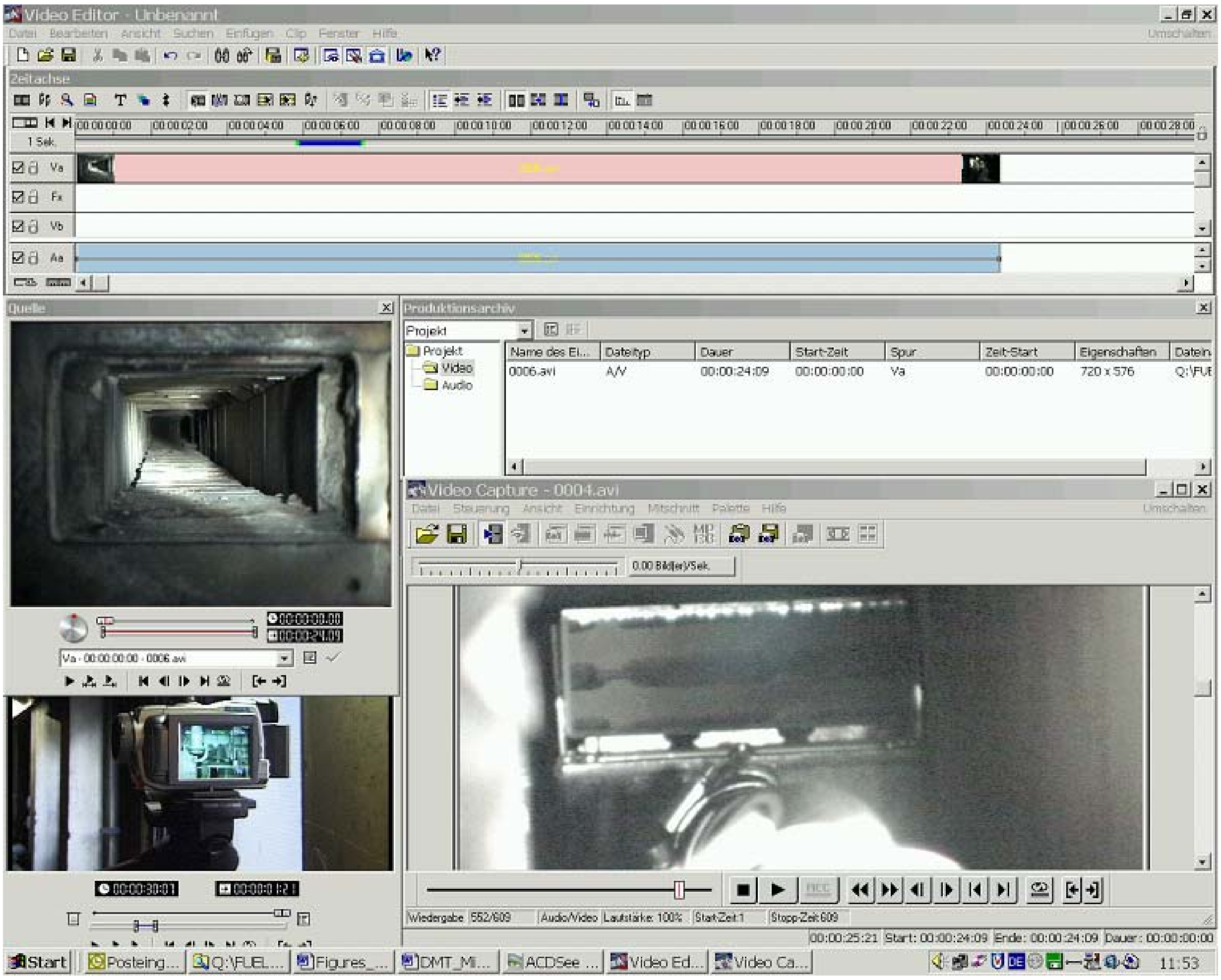


Fig. A4.12 Screenshot of RISA

The input data mask contains the following information:

- general information (filename, country, coke plant, date)
- location of inspection (battery no., chamber no., wall no., measurement no.)
- file details (file format, location of data storage, video/photograph)

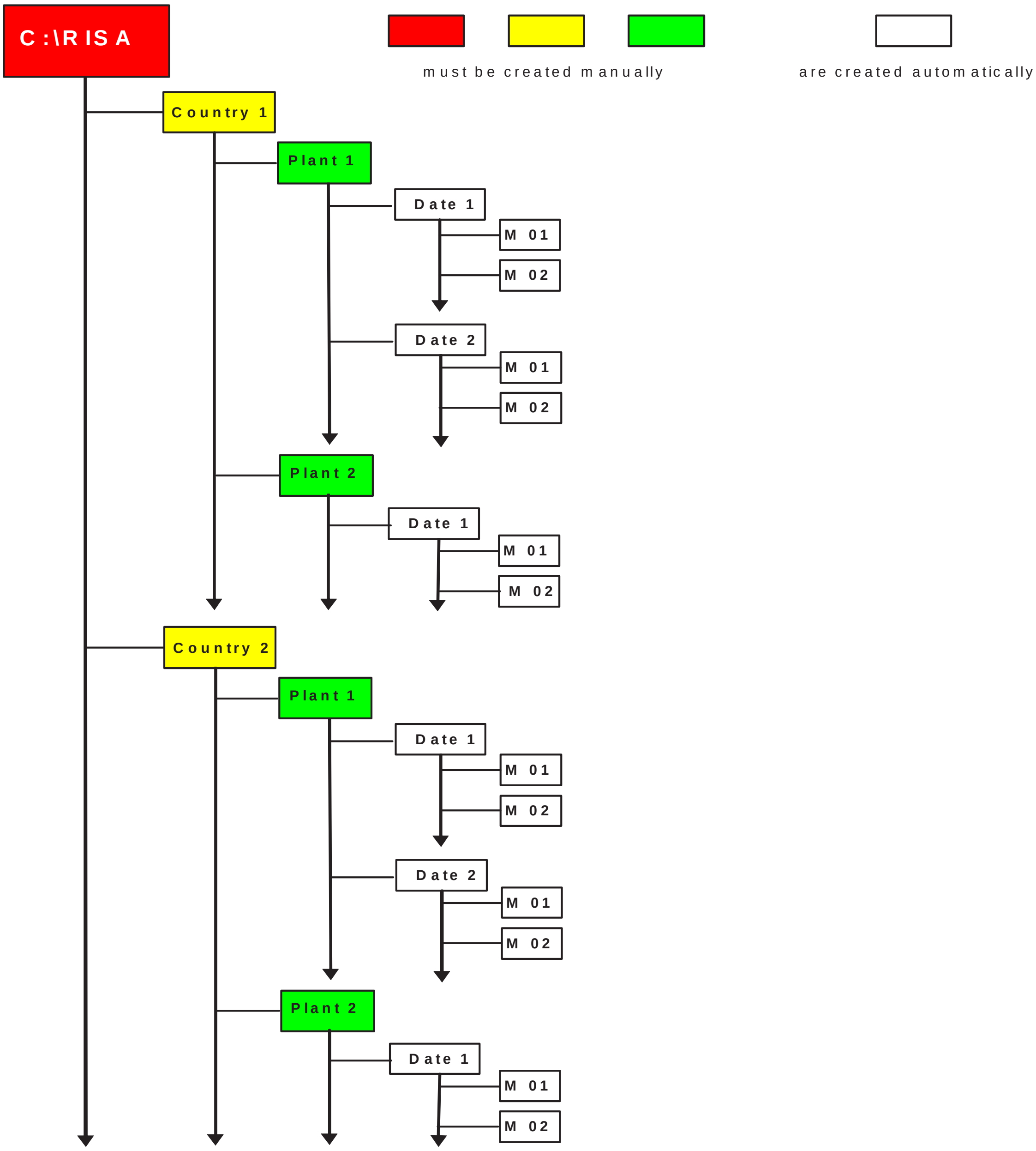


Fig. A4.13 Structure of data archiving in RISA

The filename consists of the following inputs:

P or V	Picture or Video	1 digit
2007	Year	4 digits
12	Month	2 digits
24	Day	2 digits
B02	Battery No.	3 digits
CH014	Chamber No.	5 digits
W015	Wall No.	4 digits
M03	Measurement No.	3 digits

Example: V_2007-12-24_B02_CH014_W015_M03

The structure of data archiving in RISA is shown in Fig. A4.13. Test results showed that RISA is a powerful tool for the organisation and archiving of all data obtained from video recording of optical regenerator brickwork inspection. With some slight modifications, RISA could also be used as a software tool for the organisation and archiving of measurement data in applications other than video recording of regenerator brickwork inspection.

Task 4.3 Real-time flue temperature data transfer

Software systems have been developed for the flue temperature monitor to enable the controller to communicate with the computer. Computer control of each part was tested before assembly, for example, the motor gearbox was run remotely from the computer to check that it could be controlled effectively. Synchronisation was undertaken of the data from the picture capture and encoder position, so that it could be run remotely in wire-less mode as well as manually. Problems were experienced with reading the video signal and noise interference in the temperature readings, which were solved with new software and minor modifications to the rig.

The original proposal included real-time data transfer to the battery control room for monitoring and optimisation of battery heating control, resulting in lower energy inputs, less carbon deposits, lower pushing forces and reduced environmental emissions. However, since the system was never intended for continuous processing, plant personnel did not wish it to be connected directly to the control room computer, because it would provide very large amounts of data during trials, which would interfere with their operation. Consequently, the software was written so that vertical flue temperature profiles could be inspected immediately at the point of measurement on the rig and on a separate computer, which could be based in the control room, when desired. Additionally, data were supplied to plant technical personnel and stored, so that changes between trials could be calculated and monitored. Discussions took place with DMT about applying some of the software they developed for their regenerator inspection system to store automatic flue temperature and vision monitoring data after trials.

Task 4.4 On-line relay of tie bar strain data

Software has enabled tie-bar strain data to be collected reliably from all sensors on data loggers via a radio link, although some problems have been encountered downloading the data. When the pushing machine operates adjacent to the data collection unit, it can interrupt the “line of sight” between logger and computer. A permanent data logging system for all the sensors can operate via an Ethernet or hard-wired connection to the plant control room.

Task 4.5 Software development for oven top deflection

After test work, a programme was created to read both USB and analogue signals in order to generate a calibration table for the oven top deflection monitoring system, because USB access from the laser sensors to the portable computer did not allow multiple data transfer from the units. This was imported into the National Instruments Multifunction Data Acquisition Module, so that the analogue outputs compared with the displayed values on the laser sensor controllers and accuracy was improved. Analogue outputs from the controllers can now be read by the Multifunction Data Acquisition Module with the USB connection.

Software was also developed to change the raw data from the monitoring system into 2-D and 3-D graphs. Graphs can be presented for each of the lasers and for the inclinometer in X and Y directions, inclination-corrected graphs of the battery profiles for each laser and 3-D profiles for the battery top. The software has been set up so that data from each trial can be compared with that from previous trials and graphs of changes in battery top profiles can be produced.

Task 4.6 Image analysis software: carbon characterisation

Some preliminary tests on the optical appearance of carbon deposit samples were carried out by means of polarised light microscopy (PLM) and scanning electron microscopy (SEM). Identification of different microstructures by the two techniques was achieved to provide an aid to the development of the classification system. A versatile image-processing system called KS400 (by Imaging Associates) was selected for processing of the PLM images, and a programme capable of generating a mosaic of several images was developed.

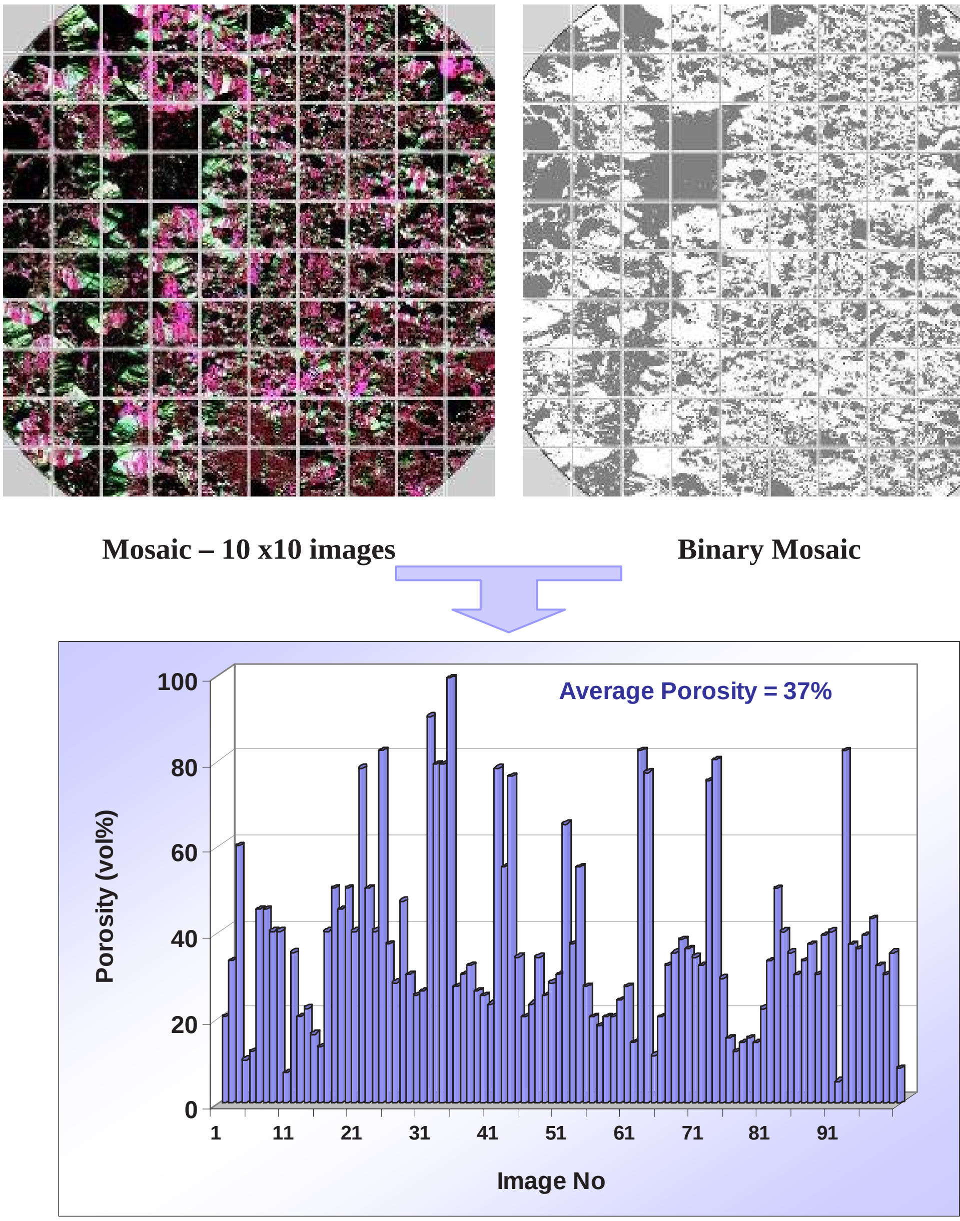


Fig. A4.14 Porosity measurement by image analysis

Images of the entire polished sample of a carbon deposit can be captured automatically by the system for further processing and analysis. The programme developed is capable of generating a mosaic of up to 30 x 30 images, enabling the porosity of the entire mosaic to be determined with the potential to estimate individual pore sizes and size distributions. The main feature of the method is that adjacent frames are captured and the material inside each frame is quantitatively assessed, whilst that cut by the frame edges is saved and measured before the results are merged to produce the data representative of the whole of the mosaic. Figure A4.14 illustrates the image processing sequence of this programme for a mosaic produced from deposited carbon U. The generation of a mosaic from 5 x 6 images by this programme is schematically presented in Fig. A4.15. Another advantage of this method is that small pores can readily be measured by processing single images whilst macropores, which may not be completely shown in single images, can be analysed by combining images to generate suitable mosaics.

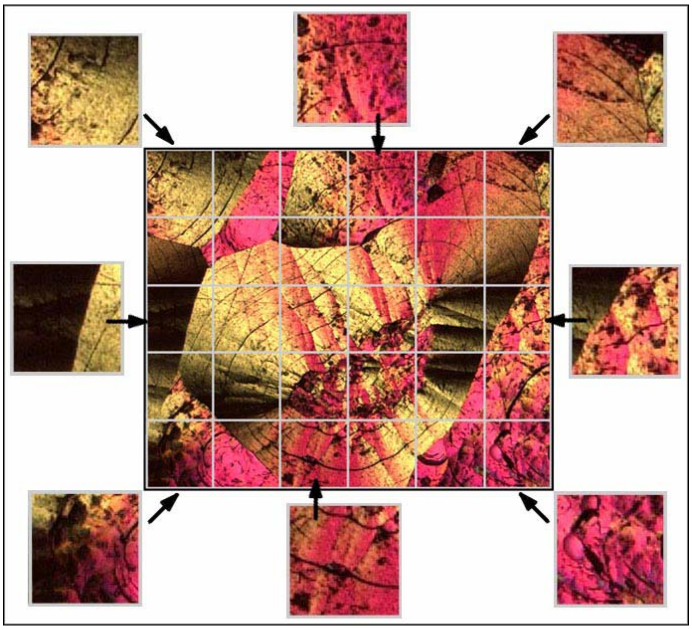


Fig. A4.15 Schematic of the generation of a composite image

Subsequently, the image analysis was developed for the characterisation of the texture of the carbon material. This system was capable of differentiating between the laminar and spherulitic carbon in the deposits. It was envisaged that fissures in concentric circles, which are characteristic of laminar carbon, could be one of the main features to help in distinguishing between the carbon forms. However, it was established that the difference in grey levels, optical appearance, degree of anisotropy and porosity facilitated the required discrimination. Figure A4.16 illustrates the image-processing sequence of this programme for a PLM image taken from a carbon deposit. The programme calculated the carbon to be approximately 70% laminar and 30% spherulitic in line with visual point counting. One problem still to be resolved is that caused by the presence of coal and coke-like particles.

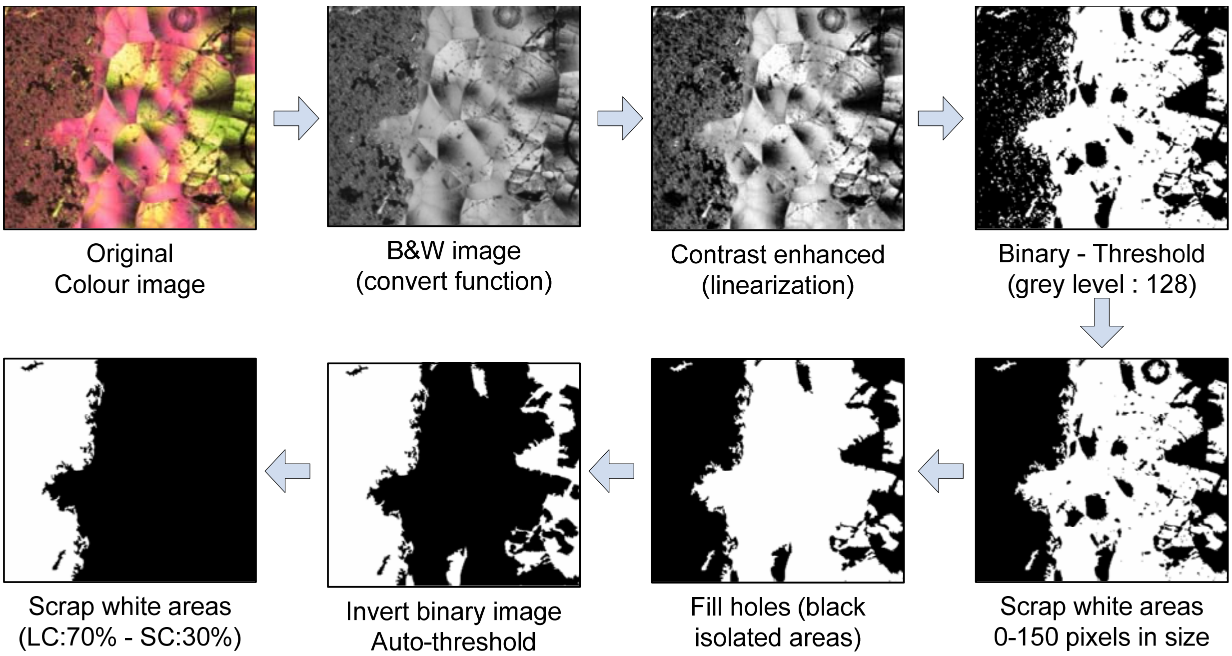


Fig. A4.16 Image analysis programme to distinguish between laminar and spherulitic carbon

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APPENDIX 5

Work Package 5: Assessment of Carbon Deposits

Task 5.1 Sampling of carbon deposits

Table A5.1 Carbon deposit samples received

No	Sample	Code	Source	Type of Material
1	A	EC2290	Corus/Battery 1	Roof/Wall carbon
2	B	EC2302	Corus/Battery 2	Wall carbon
3	C	EC2300	Corus/Battery 3	Roof/Wall carbon
4	D	EC2293	Corus/Battery 3	Roof/Wall carbon
5	E	EC2289	Corus/Battery 4	Roof carbon
6	F	EC2315	Corus/Battery 1	Roof carbon
7	G	EC2316	Corus/Battery 2	Wall carbon
8	H	EC2317	Corus/Battery 2	Wall carbon
9	I	EC2318	Corus/Battery 2	Wall carbon
10	J	EC2319	Corus/Battery 2	Wall carbon
11	K	EC2320	Corus/Battery 2	Wall carbon
12	L	EC2321	Corus/Battery 2	Wall carbon
13	M	EC2322	Corus/Battery 2	Wall carbon
14	N	EC2343	Corus/Battery 2	Wall carbon
15	O	EC2360	Corus/Battery 5	Wall carbon
16	P	EC2361	Corus/Battery 5	Wall carbon
17	S	DMT001	DMT/Probe 1a	Wall carbon
18	T	DMT002	DMT/Probe 1b	Wall carbon
19	U	DMT003	DMT/Probe 2a	Charge-hole carbon
20	V	DMT004	DMT/Probe 2b	Wall carbon

A total of 20 samples from operating coke ovens were analysed. These were primarily carbon deposits from coke oven walls with a few from the oven roof and one from the oven charge-hole. The first three samples received from Corus are shown in Fig. A5.1. Sample A was cut from a large roof carbon deposit. Sample B was from a large sheet-like wall carbon deposit collected from a pusher track. The carbon originated from the oven wall and clearly showed the pattern of the brickwork joints on one side, the other side having been polished by the action of the coke being pushed from the oven. Sample C is several times larger than the previous samples, and was deposited across the oven roof and down the walls of the free space above the coal charge. A further 17 carbon deposit samples were subsequently collected, 13 of them by Corus and 4 by DMT. Information on sample code, source and type of material is given in Table A5.1.

The removal of carbon deposits varies between batteries at Corus. At Batteries 1 and 2 this is done by manual rodding between pushing and recharging. At Battery 3, ovens are drafted for up to 5 days before removal. It should be noted that the removal procedure may affect some of the chemical, physical and optical properties of the carbon deposit. Some information on removal conditions during the time of collection of these samples was provided by Corus. Sample N (Fig. A2.17) was taken from the west wall, at charge top level below charge hole No 1. The oven had previously been 'draughted' to remove all carbon three months before, so that the carbon had built up over this period. Sample O was removed from both walls below charge hole No 2 before pushing. The carbon was relatively soft and easily removed. Carbonising time was 18.41 hours. Temperatures in the flues nearest this charge hole were 1330°C and 1360°C. Sample P was removed from one of the walls below charge hole No 3. This oven was pushed the previous evening and 'draughted' through charge holes Nos. 2 and 3. The carbon was very hard and came off in one piece. Carbonising time was 21.08 hours. Temperatures in the flues nearest this charge hole were 1390°C and 1420°C.

Coke-side Scale: cm

Roof/Wall-side Scale: cm

Carbon deposit – Sample A

Coke-side Scale: cm

Wall-side Scale: cm

Carbon deposit – Sample B

Coke-side Scale: cm

Roof side Scale: cm

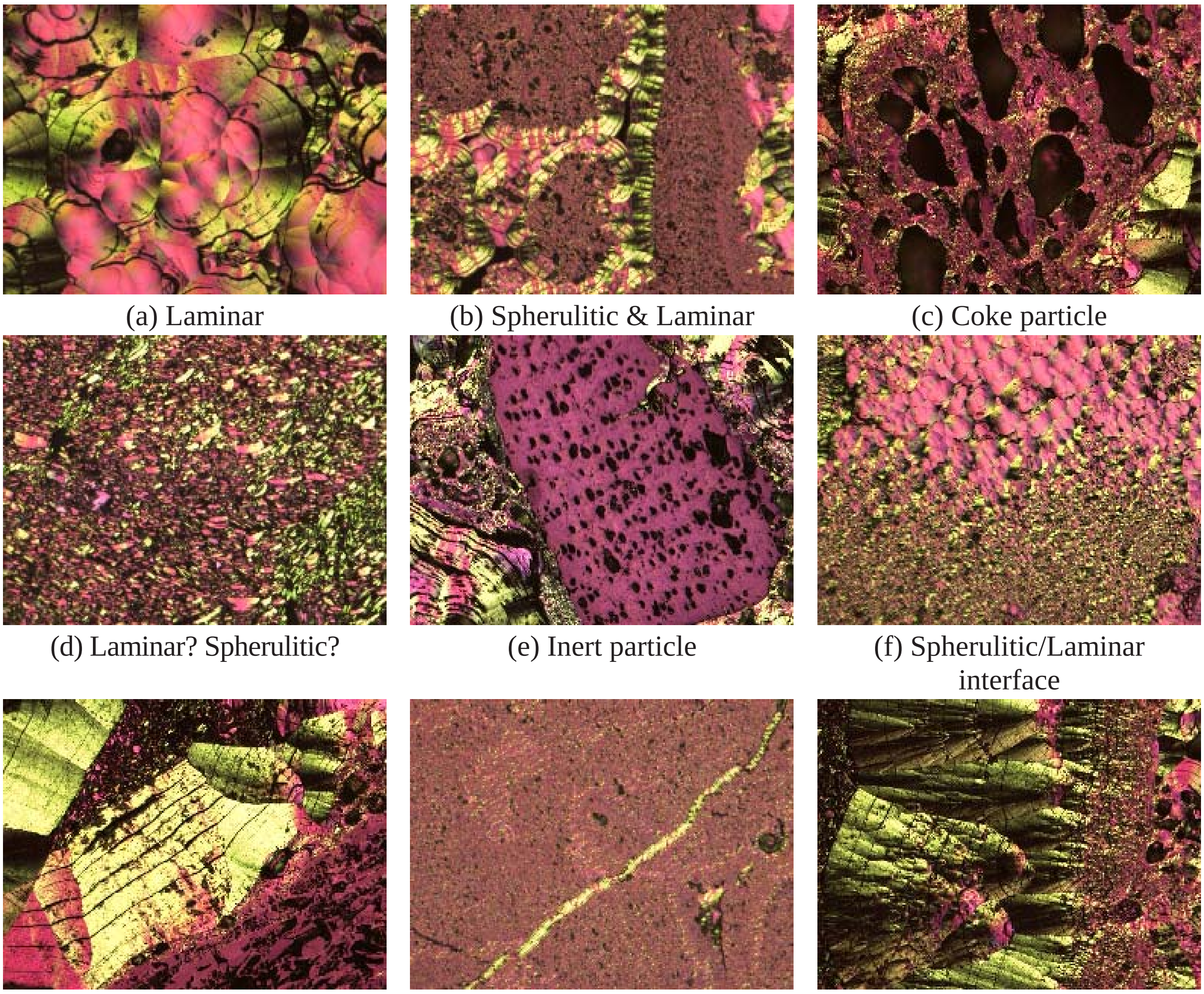
Wall-side Scale: cm

Carbon deposit- Sample C

Fig. A5.1 Photographic record of some carbon deposits

Task 5.2 Analysis and laboratory trials

In preliminary studies, some examples of coke oven carbon deposits were examined by polarised light microscopy to ascertain the nature of the different carbon textures. The complexity of the carbon textures and the differences observed in these samples were demonstrated in Fig. A2.8.



(a) Laminar (b) Spherulitic & Laminar (c) Coke particle

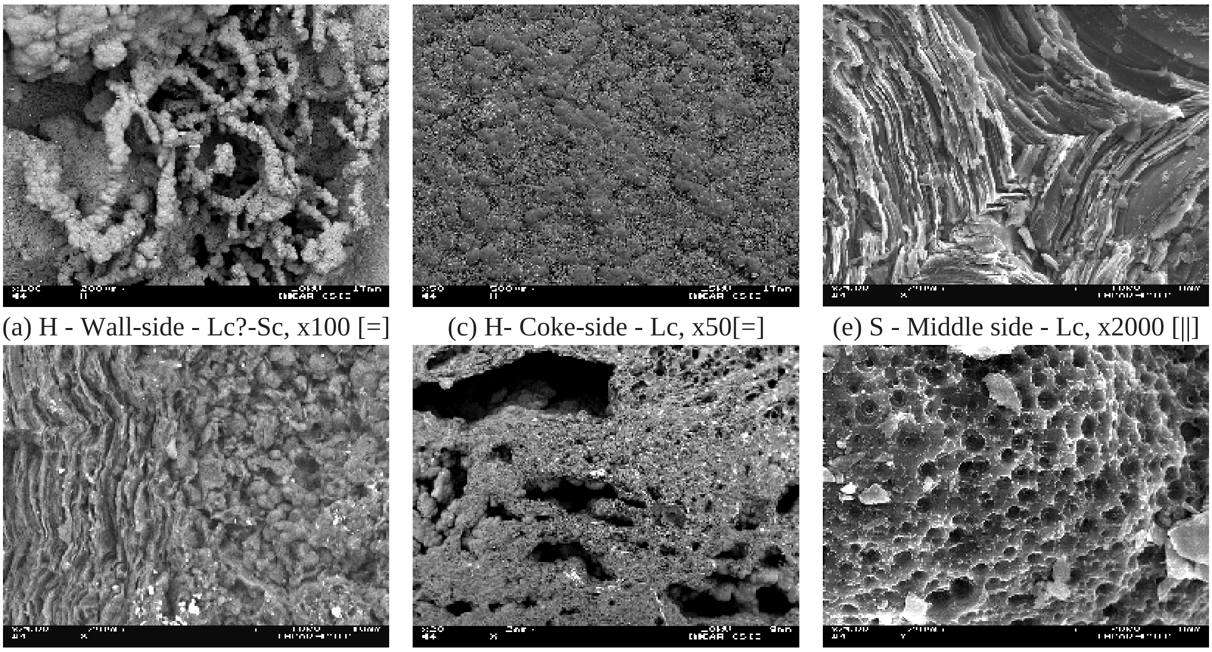
(d) Laminar? Spherulitic? (e) Inert particle (f) Spherulitic/Laminar interface

(g) Laminar/Inert (h) Spherulitic & laminar stripe (i) Laminar/Coke

Fig. A5.2 Polarised-light micrographs of carbon deposits (x200 magnification)

Carbon deposit samples H, J, K, S, T, and U were cut in several layers parallel to the deposition plane and were mounted in resin. Polarised light micrographs of polished sections were obtained for these samples, and are shown in Fig. A5.2. A considerable amount of laminar pyrolytic carbon, which exhibited a corn-shaped texture, was found in most of the samples, particularly further away from the wall. Spherulitic carbon was also observed, mainly in samples H, S and T. This type of carbon tended to be formed nearer to the wall, especially for samples H and S. In some cases, spherulitic carbon appeared to be encrusted with several layers of laminar carbon (See Fig. A5.2b). Particles among the pyrolytic carbon can also be seen. Some of them can be clearly identified as inertinite particles, which might have been carried over with the carbonisation gases (Figs. A5.2e, g). Figure A5.2c shows a coke-like particle also surrounded by laminar pyrolytic carbon. A different texture, which exhibits some degree of orientation, was also found in some of the samples and normally it was surrounded by laminar carbon or filling pores or fissures (Fig. A5.2d). Layers of the deposited carbons, sliced parallel to the deposition plane from samples G, I, L and M, also exhibited mainly laminar material with spherulitic carbon being found in all the samples, but predominantly in proximity to the oven wall.

Surface morphology of carbon deposits B, H, J, S, and T was analysed by scanning electron microscopy (SEM). As with the PLM analysis, a variety of microstructures were observed, and some differences among samples were also evident. SEM micrographs of these features are presented in Fig. A5.3. The material found in the wall-side of carbon deposits B and S appears to consist mainly of spherulitic carbon. In contrast for samples T and J, laminar carbon was found to be the main constituent. Some fibre-like material was identified in the wall-side of sample H (see Fig. A5.3a). Although this appears to be laminar carbon, further analysis is required to confirm this. Laminar carbon comprises the majority of the material on the coke-side of all the samples, which was corroborated by PLM. Some degree of gasification of the carbon material on this side of the deposits was apparent, as shown in Fig. 5.3g. The extent of the gasification of the carbon for samples C and D is expected to be more prominent owing to the removal procedure, which involved drafting for several days. Analysis of the surface morphology of carbon deposits G, I, J, L and M produced similar findings.



(a) H - Wall-side - Lc?-Sc, x100 [=] (c) H- Coke-side - Lc, x50[=] (e) S - Middle side - Lc, x2000 [||]

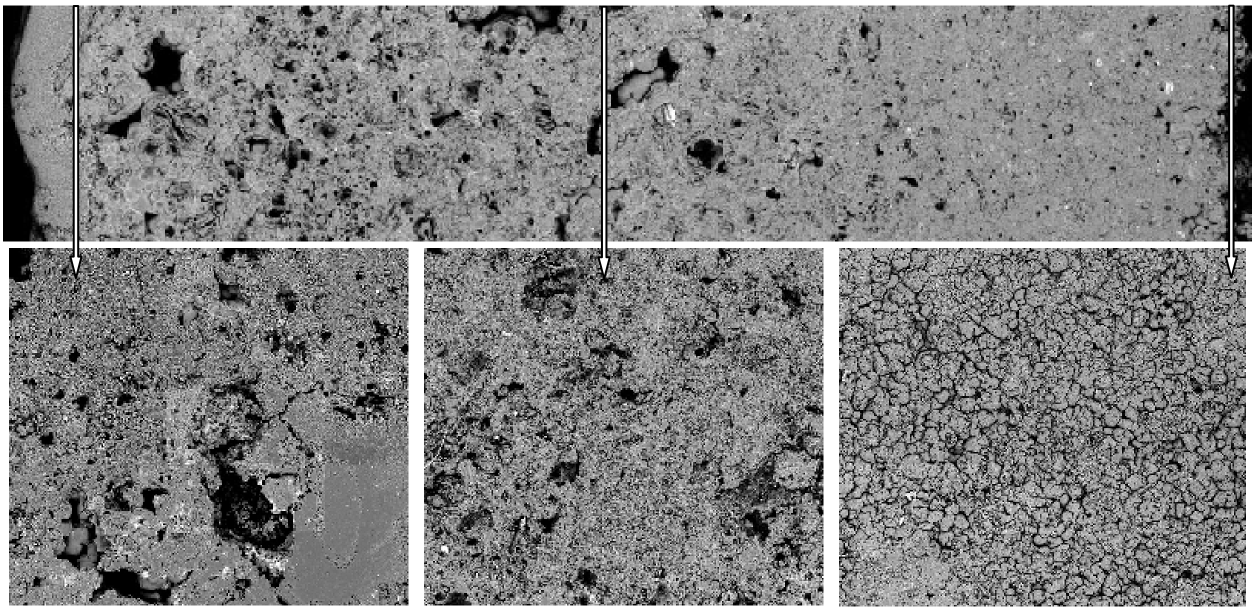
(f) S - Middle side - Lc/Sp, x2000 [||] (h) S - Middle side - Lc/Sc, x20 [||] (g) T - Coke-side - Lc, x2000 [||]

Lc: Laminar carbon, Sc: Spherulitic carbon; [=] Parallel & [||] Perpendicular to the deposition plane

Fig. A5.3 Examples of SEM micrographs of coke oven carbon deposits

A series of micrograph perpendicular to the deposition plane from the wall to the coke-side of carbon deposit B were also taken. They were merged together in order to see whether there was any significant morphological difference of the various carbon layers during deposition (in Fig. A5.4). Some clear difference on the packing density of the layers can be observed. Sample G showed a similar variation in the density of the deposit with, in general, increased density towards the deposition side (Fig. A5.5). Carbon deposits I, J, L and M were examined in a similar way and the profiles for these samples are shown in Fig. A5.6. These again indicated that the deposits were denser towards the deposition side with the exception of sample M, in which there was no noticeable variation in the deposit density. This particular sample was the thickest deposit and had a high concentration of mineral matter. The thickness of the deposits varied from about 4 mm to nearly 9 mm. Carbon deposit V exhibited different behaviour, as its density was higher at both the deposition side and at the wall-side (Fig. A5.7). Generally, this deposit was very dense with some porosity development in the middle of the deposit.

(a) 9x3 images mosaic - perpendicular to the deposition plane [||]



(b) Near Wall-side – Lc-Sc (c) Middle side - Lc (d) Deposition side - Lc

5x5 images mosaics - parallel to the deposition plane [=] (Lc: Laminar carbon, Sc: Spherulitic carbon)

Fig. A5.4 SEM photomicrographs of carbon deposit B

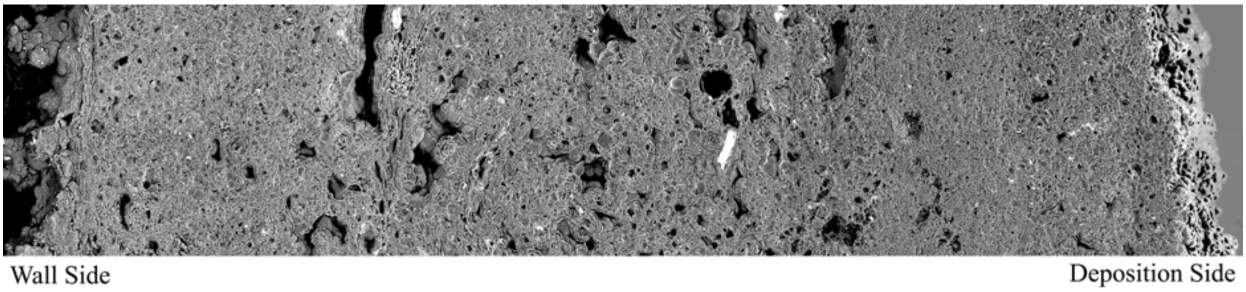


Fig. A5.5 SEM photomicrographs of carbon deposit G (11 x 3 images mosaic)

Representative samples of carbon deposits B, G and I as well as the carbon material from the wall-side and the deposition side were analysed by X-ray diffraction (XRD). An example of the XRD plots is shown in Fig. A5.8 for deposit B. For presentation purposes, the counts for the deposition side and the representative sample plots have been transposed upwards by 1000 and 2000 units respectively. The 2 theta dimension for the main peak, for the crystalline reflection 002, is virtually identical for all the samples at around 25.7 degrees, corresponding to graphitic carbon. The peak height indicates the magnitude of the degree of ordering of the carbon layer planes, and the carbon material from the wall-side and the deposition side appear to have a similar degree of order. The appearance of a small 004 peak at 43.3 degrees indicates that the material at the wall-side has the more orderly graphitic structure. For sample I in Fig. A5.9, there was evidence from the 002 and also the 004 reflections at 43.4 degrees, of the wall-side material being more graphitic than the deposition side carbon. In the case of deposit G, there was little evidence of this variation (see Fig. A5.10).

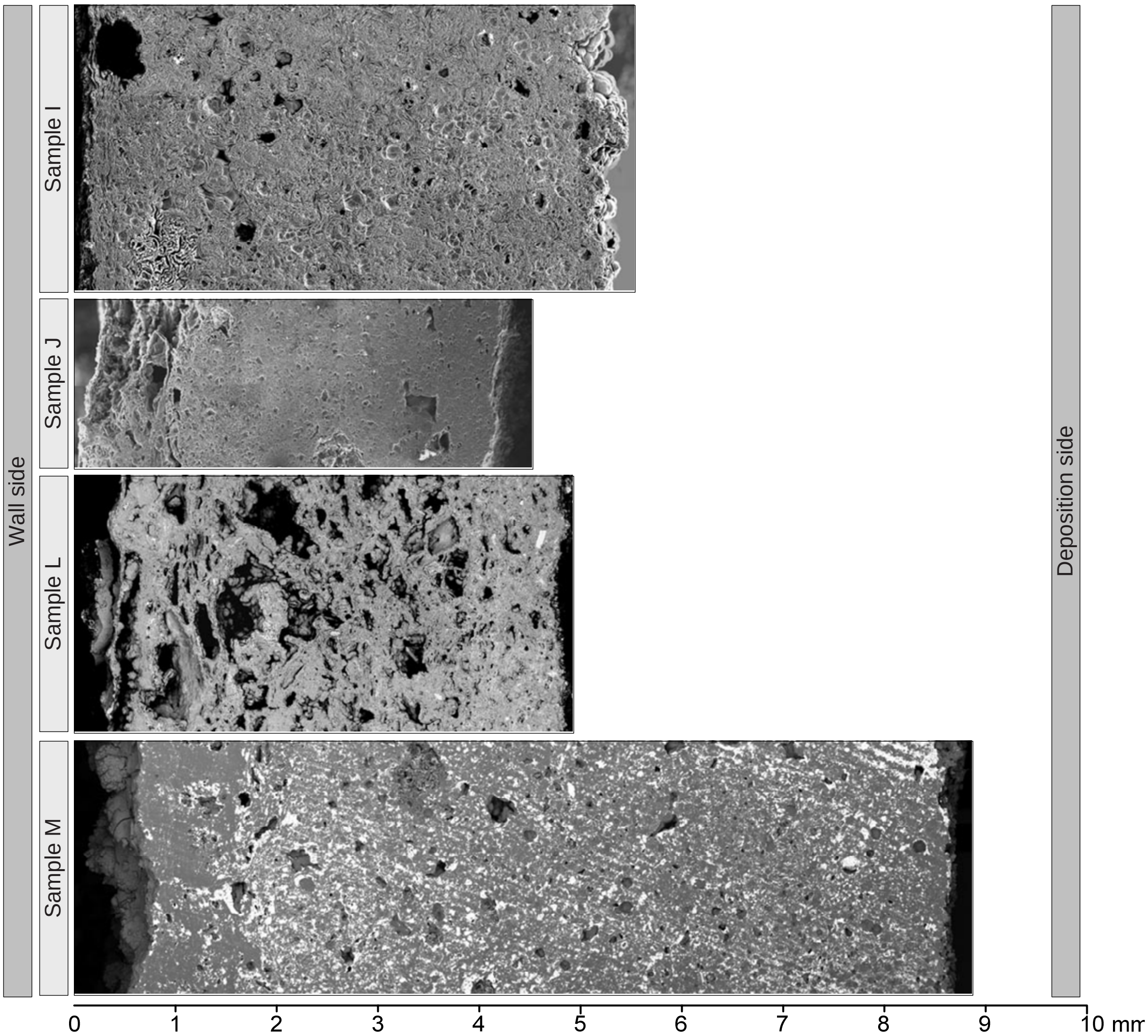


Fig. A5.6 SEM carbon deposit profiles of the carbon material perpendicular to the deposition plane

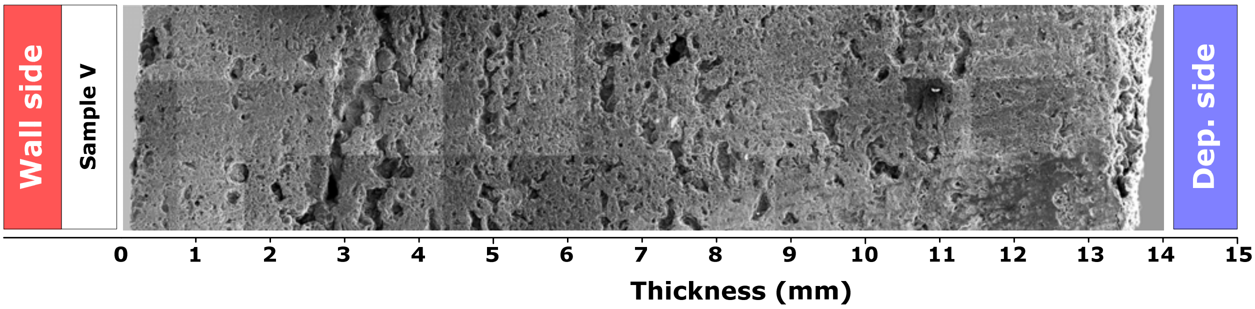


Fig. A5.7 SEM photomicrographs of carbon deposit V

Task 5.3 Effects of blend composition on deposits

Corus supplied a coal blend sample and a sample of the oil used in cokemaking, so that the effects of the addition of oil to the blend could be investigated in the UNOTT deposition rig. The composition of the coal blend charged to a coke oven has a strong influence on the nature of the volatile species and the temperature and rate of their evolution. Consequently, blend composition is an important factor in wall and roof carbon deposition. Jomoto(12) from laboratory carbonisation tests found the carbon deposition rate to be directly related to the charge volatile matter. Models incorporating terms for the gas velocity in terms of volatile matter and moisture per unit of void space per unit time established that a 1% increase by weight in volatile matter led to a 6-7% increase by weight in the carbon deposition rate.

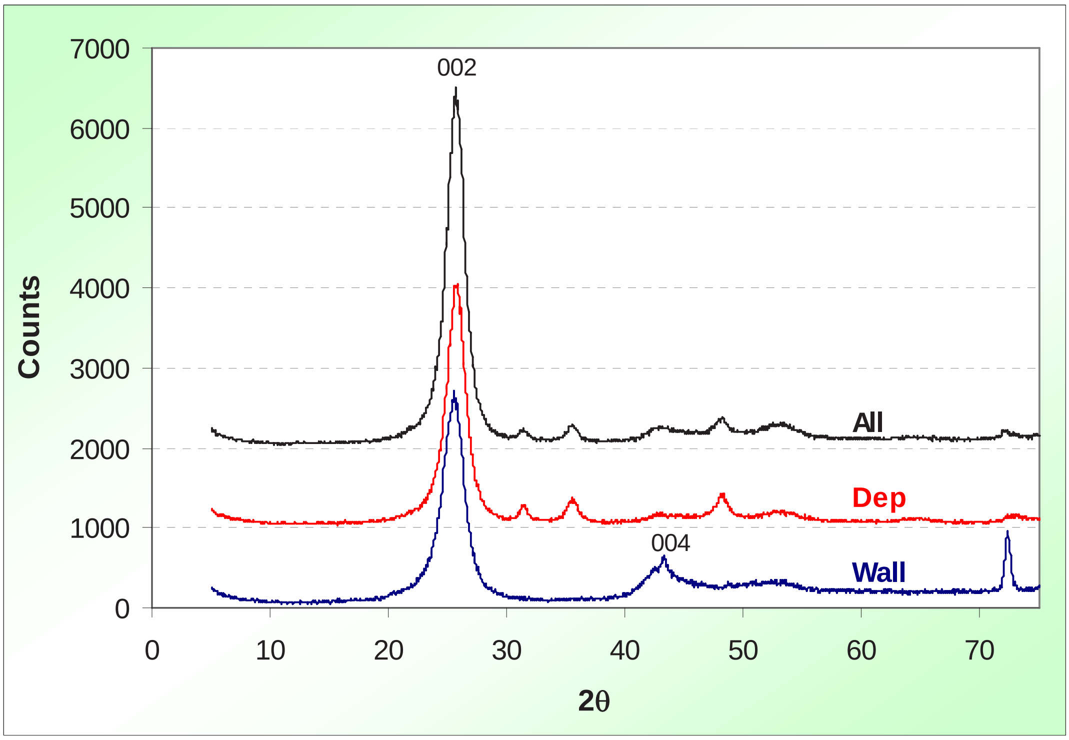


Fig. A5.8 XRD diagrams for industrial oven carbon deposit B

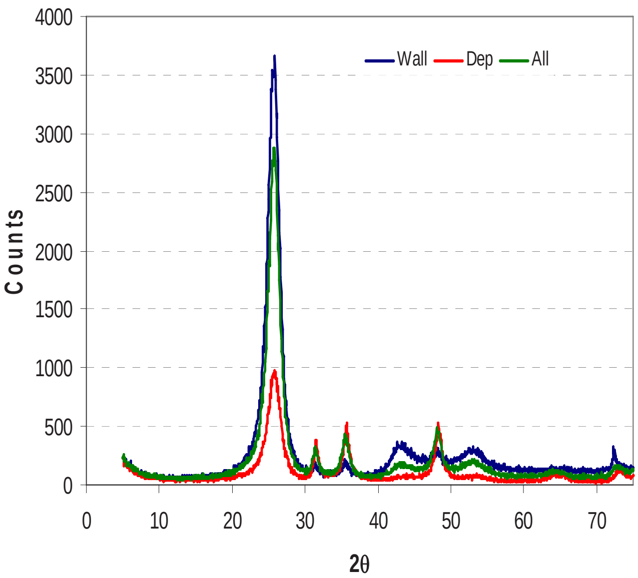


Fig. A5.9 XRD diagrams for industrial oven carbon deposit I

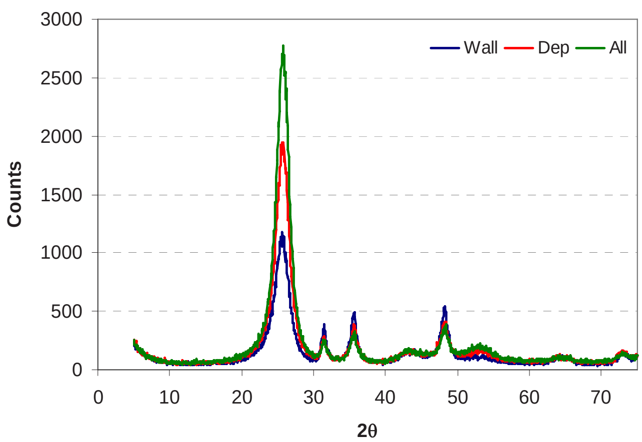
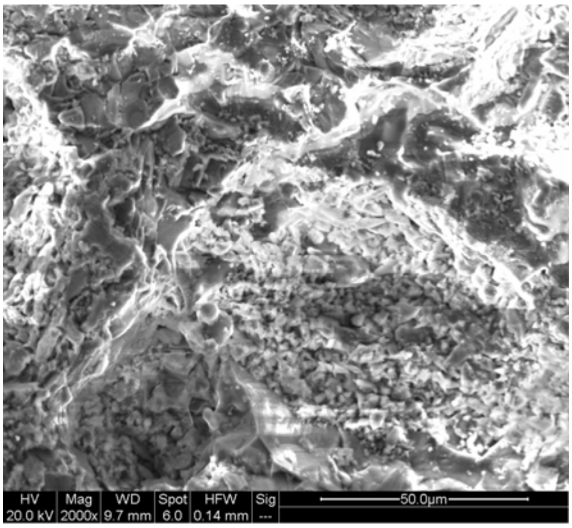


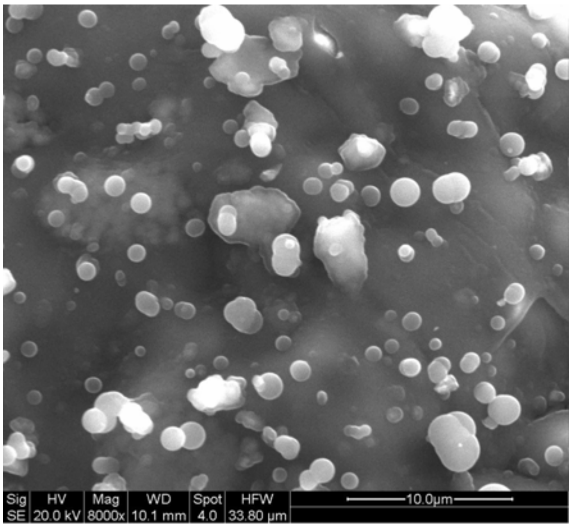
Fig. A5.10 XRD diagrams for industrial oven carbon deposit G

Krebs[7,8] also emphasised the importance of the temperature at which the released primary tars are cracked. They found deposition to increase more than five-fold as the cracking temperature increased from 850°C to 1000°C. They also identified a modifying effect of moisture on the pyrolysis tars with high moisture levels, that is above 8% by weight, encouraging the formation of oxygenated low molecular weight tars, which readily crack to form laminar carbon deposits. Lower moisture (<8% by weight) led to the production of more aromatic tars, which ultimately lead to spherulitic type carbon deposits. These effects were shown by Pajak[14] to be related to the hydrogen transfer abilities of the tars. Low ability to transfer hydrogen led to more carbon deposition during secondary cracking. Nagata[11] also reported that increased volatile matter content, as well as increased concentration of additives such as asphalt pitch and crude tar, increased carbon deposition.

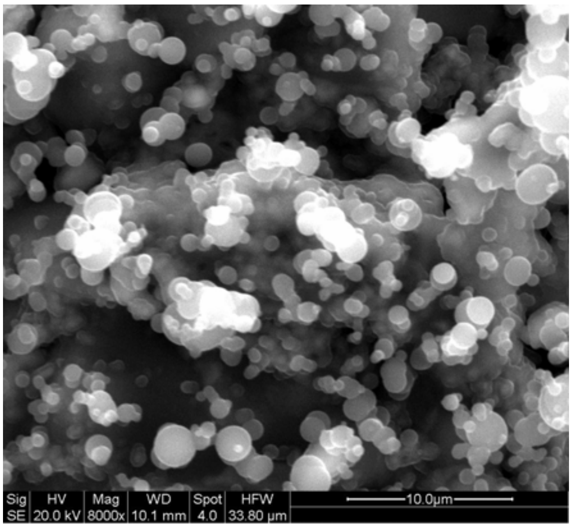
Samples of the carbon material deposited on silica slides from the carbonisation of coking coal in the laboratory-scale carbonisation rig were examined initially by SEM. The rate and extent of the deposition appeared to vary with distance from the gas source irrespective of the cracking temperatures, 700°C, 900°C or 1100°C. Figure A5.11 shows this trend for a deposit at 700°C on a 3 x 3 cm slide. It is clear that maximum deposition takes place nearer to the gas source. SEM micrographs of the carbon deposited at different temperatures, presented in Fig. A5.12, show spherulitic carbon with sphere size less than 500 nm at 700°C, four to six times larger at 900°C, and five to eight times larger at 1100°C.



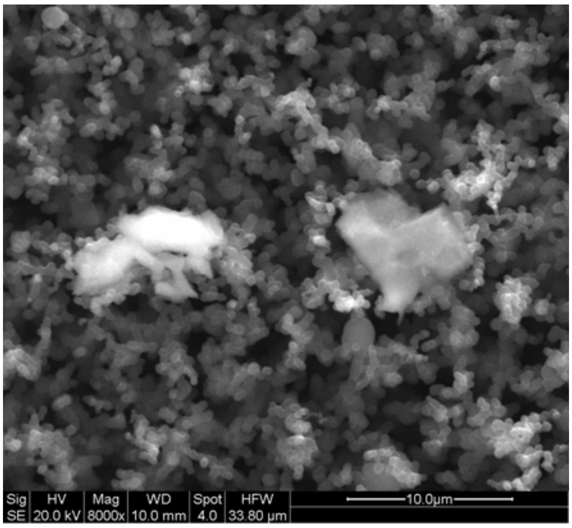
Silica brick slide before deposition



Top of the slide

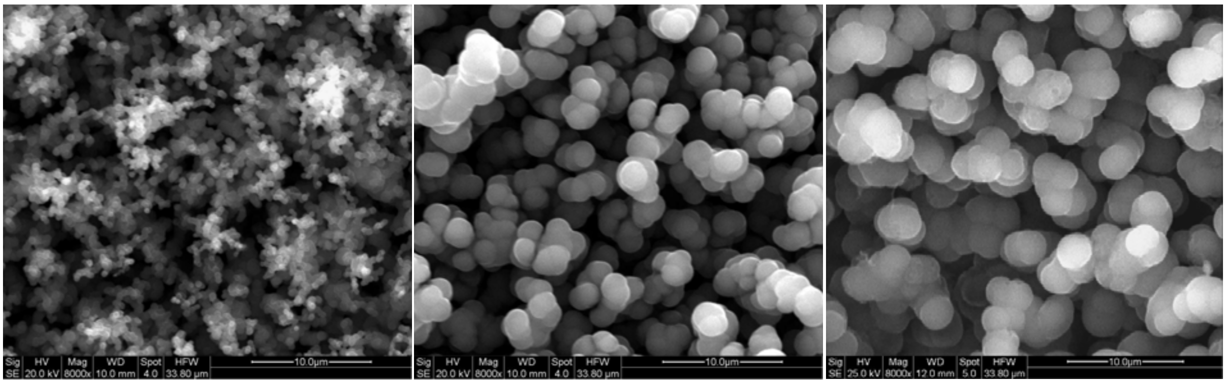


Middle of the slide



Bottom of the slide

Fig. A5.11 SEM micrographs of the surface of carbon deposited at 700°C at various positions



700°C 900°C 1100°C

Fig. A5.12 Comparison of SEM micrographs of the surface of carbon deposited at 700-1100°C

Task 5.4 Influence of charge conditions on deposits

There was insufficient time in the project to carry out all the potential laboratory trials to determine the influence of charge conditions on carbon deposition, but the literature search aided this research by revealing some of the more important effects. Generally, although carbon deposition depends primarily upon the temperature, type and concentration of the source gas, it is also influenced by the surface properties of the substrate on which the carbon is deposited. In the case of coke oven deposits, additional factors include the moisture content of the coal charge, the hydrogen transfer ability of the intermediate tars and the presence or absence of coal fines

Krebs(7) assessed the effect of moisture content and found that below 8% by weight moisture, two layers were formed, a spherulitic layer adjacent to the refractory surface and an outer layer of larger cone-shaped units of laminar carbon. As moisture content increased, the thickness of both layers decreased, and above 8% moisture only laminar carbon was deposited. Nakagawa(15) also considered moisture content, as the coal moisture control process increased the amount of roof carbon (as it reduced the moisture from 9-10% to 5-6%,). As the deposited carbon also had an increased ash content, a secondary effect of the dryness was suspected in terms of increased fines. Laboratory studies confirmed that the deposition rate was greater in the presence of coal fines. Nakagawa(15)) also found that the presence of coal fines tended to increase deposit build-up, especially at the start of carbonisation when this was enhanced by the bonding effect of the tarry material evolved. In laboratory carbonisations, Jomoto(12) found that the rate of carbon deposition could be related, not only to the coal volatile matter and the moisture content of the charge but also to temperature of the deposition surface. From modelling studies, Nagata(11) and Yoshida(17) came to the conclusion that oven temperature was the most significant effect. Notych(18) also reported that high free space temperature caused increased carbon deposition. Nagata(11) reported that gas velocity had little effect on carbon deposition. With regard to the condition of the deposition surface, Kasaoka(19) found that carbon deposition was enhanced where cracks in the oven brickwork occurred, and he concluded that smooth, defect-free surfaces inhibit the initiation of carbon deposition.

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APPENDIX 6

Work Package 6: Plant Trials

Task 6.1 Installation/testing of internal wall scanning system

The installation of the whole system on one pusher machine of the Carling and Dillingen coke plant has required the following steps:

- Manufacture and installation of the supports for the multiplexing box and the camera behind the shield
- Manufacture and installation of a by-pass and an air escape on the decarbonizing air pipe
- Installation of the rotating connection and the coaxial cable in the sheath of the decarbonizing air pipe on the pusher ram
- Installation of the camera, the multiplexing box and the control unit.

The air used to limit the temperature elevation is by-passed and cleaned (as shown in Figs. A6.1 and A6.2) before passing through the multiplexing box and the camera. It is ejected in front of the camera lens inside the hot chamber.

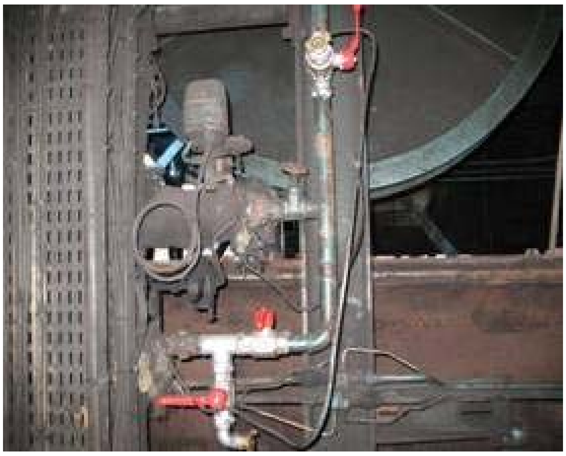


Fig. A6.1 System of air by-pass in Carling

Fig. A6.2 System of air by-pass in Dillingen

Fig. A6.3 Escape air pipe in Carling

Fig. A6.4 Device installed in Dillingen

The air pressure for decarbonizing is about 7 bar. In order to avoid the deformation of the multiplexing box, which only supports 2 bar, and to allow optimal cooling, an outlet air pipe was added downstream from the observation system (Fig. A6.3). This air escape limits not only the passage of air through the electronics of the system, but also allows fast exhausting of the heat accumulated inside the decarbonizing pipe between two pushes. The assembly of the rotating connector on the enroller of the flexible part of the decarbonising pipe required the manufacture of an adapter. This device was then equipped with spacers to facilitate the passage of the cable (in Figs. A6.5 and A6.6).

Fig. A6.5 Rotating connector and spacers in Carling

Fig. A6.6 Rotating connector and spacers in Dillingen

Fig. A6.7 Coaxial cable installation in Carling

Fig. A6.8 Coaxial cable in the decarbonising air pipe in Dillingen

Fig. A6.9 Fixture of multiplexing box

Fig. A6.10 Insulated camera head installed on the Carling pusher ram

The most complex part was obviously the installation of the coaxial cable inside the sheath of the decarbonising pipe (see Figs. A6.7 and A6.8). The camera head was fixed on its support at the backside of the shield. The insulation around the camera head was placed carefully to avoid the blockage of the camera head during its rotation. Figures A6.9 and A6.10 show the multiplexing box and the camera head connected to the multiplexing box at Carling coke plant.

Task 6.2 Installation/testing of tie-bar monitor hardware

Plant trials began with load cells installed on the top tie rods of one buckstay to monitor tie rod loads. The recording system worked satisfactorily, but problems arose when oven doors were removed for long periods (if problems occurred with pushing or charging). The best operation in preliminary experiments was load washers operating continuously for a period of six days before failure. Figure A6.11 shows the results of the last 30 hours operation with loads on the washers of 80 to 85 kN until failure occurred during pushing. This was due to excessive temperatures and mechanical damage to the cables disrupting data communications between the computer and load washer. Washers returned to the laboratory and rewired still worked, indicating that the washers could operate and survive in the hostile plant environment, but an economic solution to the cabling problem was needed.

After laboratory-based flame tests on a variety of heat-resistant materials, new load washers were constructed and tested on plant. Although trials of modified equipment had better success, their lifespan was still limited. This problem was specific to the short oven design and operation of the battery selected for initial plant trials, since the tie-bars and springs were much closer to the doors than with taller ovens. Consequently, all remaining trials took place on two taller batteries with load cells redesigned to be more sensitive to changes in load.

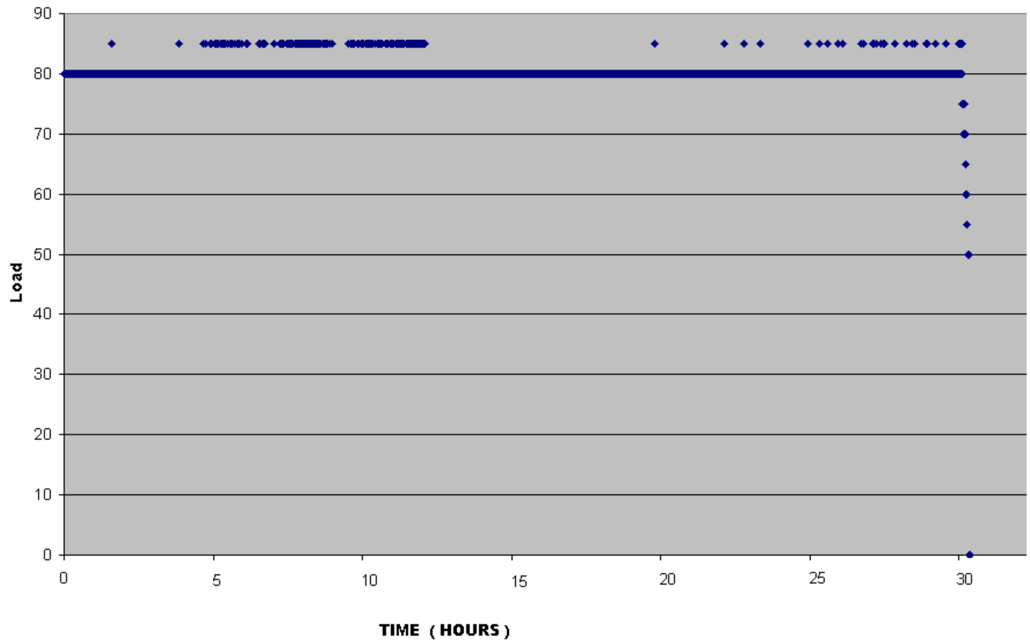


Fig. A6.11 Graph of preliminary coke oven load washer trial results, with loads of 80 to 85 kN

Two load cells of new design were installed on the left-hand and right-hand tie-bar springs of a mid-battery buckstay, covering the left-hand wall of one oven and right-hand wall of the adjacent oven. Cables ran up the battery crossover to a local data logger, which collected and stored data for periodic downloading to a laptop computer via radio communications. One of the load cells has logged data successfully for three years, responding to plant events including oven pushing and charging and plant stoppages. The other washer malfunctioned after 7 weeks, but inspection suggested that the problem was with the load cell itself rather than the logging equipment or cabling. However, its replacement still operates after 2.5 years.

These more sensitive cells detected charge car movements as well as oven pushing, as illustrated in Fig. A6.12 (left graph). During pushing and charging operations, there is an initial increase in load during a push, followed by a drop in load as the oven is filled with the cold coal, and then the load increases as the carbonisation process advances. The loads on tie-bars on the same buckstay are not usually identical. Occasionally, dramatic changes in the loads are detected by one or both sensors, which can be compared with plant logs in order to tie them to specific events. The second graph demonstrates that load cells record events elsewhere along the battery and shows on which side of the buckstay they have occurred. A reduction in load of approximately 4 t detected by the right-hand sensor (pink line) with no detected change in load on the other sensor (blue line) suggested an event took place to the right of Buckstay 75. Since it has become apparent during this study that placing a load sensor on every tie-bar on a battery would produce too much data for practical plant processing, it is useful that data from one sensor provides information about adjacent areas of the battery. In the third graph, an increase in load on the tie-bar springs of 5.5 t occurred during a planned plant maintenance period, as the battery heated up. Loads crossing and then reverting to their original loads suggest a period of torsion in the structure of that part of the battery. The load increases on one side of the oven (compressing the monitoring spring) and decreases on the other side. Besides this, Fig. A6.13 also shows the effect of a sudden increase in load, which has affected the right-hand tie-bar (pink line) more than the left-hand one (blue line), suggesting the activity was to the right of buckstay 75.

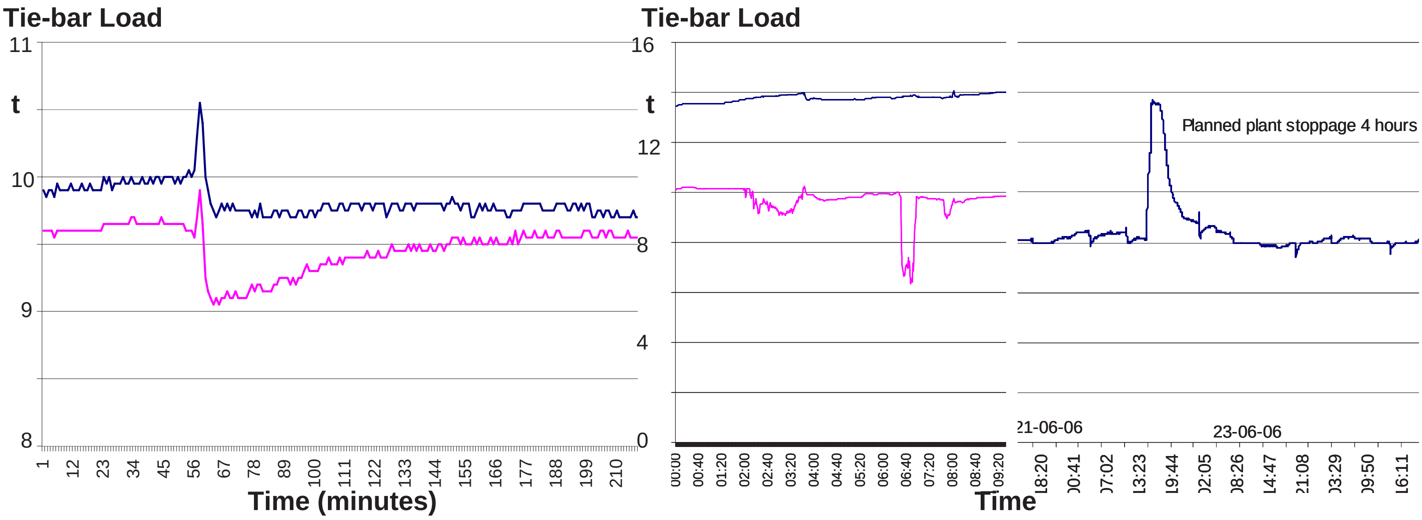


Fig. A6.12 Load cell data during pushing/charging, a problem one side of the battery, and a stoppage

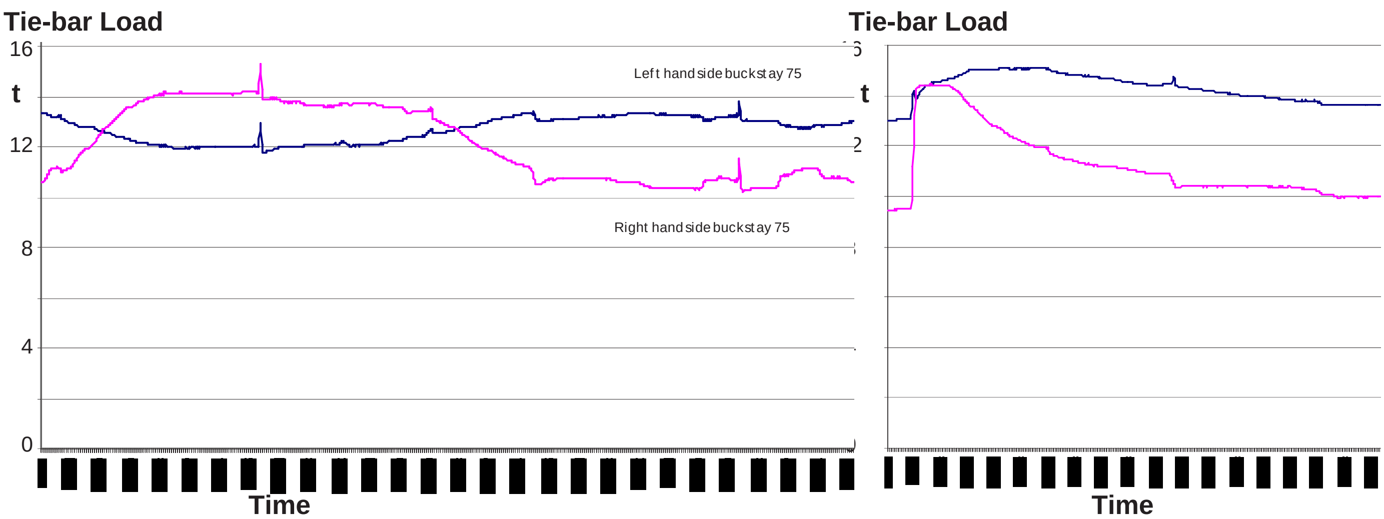


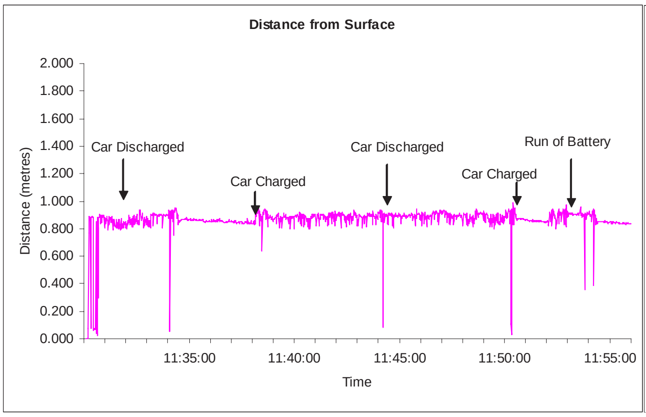
Fig. A6.13 Torsion causes tie-bar loads to cross and operational change causes a sudden load increase

After successful monitoring trials over many months of two load cells on the top tie-bars of one buckstay, six more sensors were fitted at intervals along the length of two batteries. When readings from sensors were below the aim values, investigations took place to check that the springs were set to the correct length or if there was a problem with the springs. Since problems with individual springs are apparent from the data, they can be replaced. Continuous monitoring is providing an opportunity to improve interpretation of the data, and monitoring is now permanent on those two batteries. This is particularly useful, when problems with coal supply or steel production lead to changes in battery operation, because loads on the battery structure are recorded.

Task 6.3 Installation/testing of oven top machine hardware

Preliminary plant trials began by logging output from an ultrasonic sensor attached to the coke charge car. Tests were carried out with the sensor attached in two different positions at 1 m and 2.5 m above the top of the coke oven. The charge car was then operated through two cycles of filling the charge hoppers and dispensing the coal into the oven, driven the full length of the battery and returned to the start position.

The data for the sensor position at 1 m have been plotted in Fig. A6.14, showing when the car charges and discharges, and the position of the car altering between the loaded and unloaded positions. The stable signal clearly shows when the charge car is at rest. Some conditioning of the signal was needed to filter the apparent noise. In Fig. A6.15, the signal for the 2.5 m position of the sensor has been filtered to reduce the noise, using software to simulate the 'peak picker' mode of operation. The amount of noise picked up in this position still made the signal appear unstable, as the higher the position of the sensor the more susceptible it became to noise. Unless the charge car position was logged accurately, comparisons of the readings at similar positions during the movement up and down the battery were impossible.



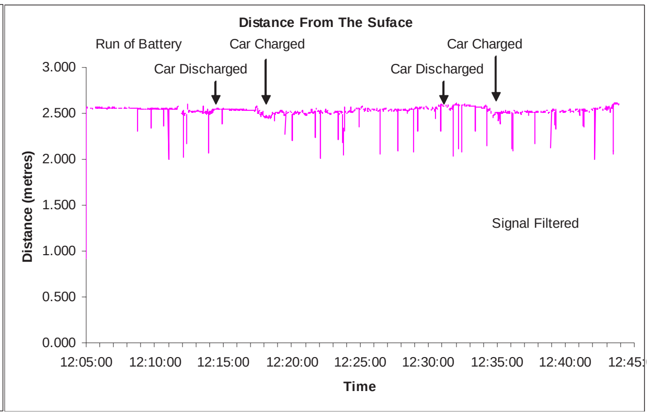


Fig. A6.14 Unfiltered signal with sensor at 1 m Fig. A6.15 Filtered signal with sensor at 2.5 m

Although attaching an array of displacement transducers to a charge car enabled continuous monitoring of the oven top, disturbance by charge car movement adversely affecting analysis of results. Consequently, all subsequent trials took place with the laser monitors attached to a beam.

Task 6.4 Survey of wall temperature distribution

Plant trials were carried out on two batteries with the automated flue temperature and vision monitor to survey flue temperature and flue wall profiles, with the aim of optimising the mean flue temperatures on individual ovens and the vertical temperature distributions in the battery. This is not possible using conventional flue temperature recording methods and is a critical factor controlling battery life, underfiring costs, carbon deposition and fugitive emissions through brickwork.

Fig. A6.16 Control system and data display with head temperature graph (on the left) and flue video (on the right)

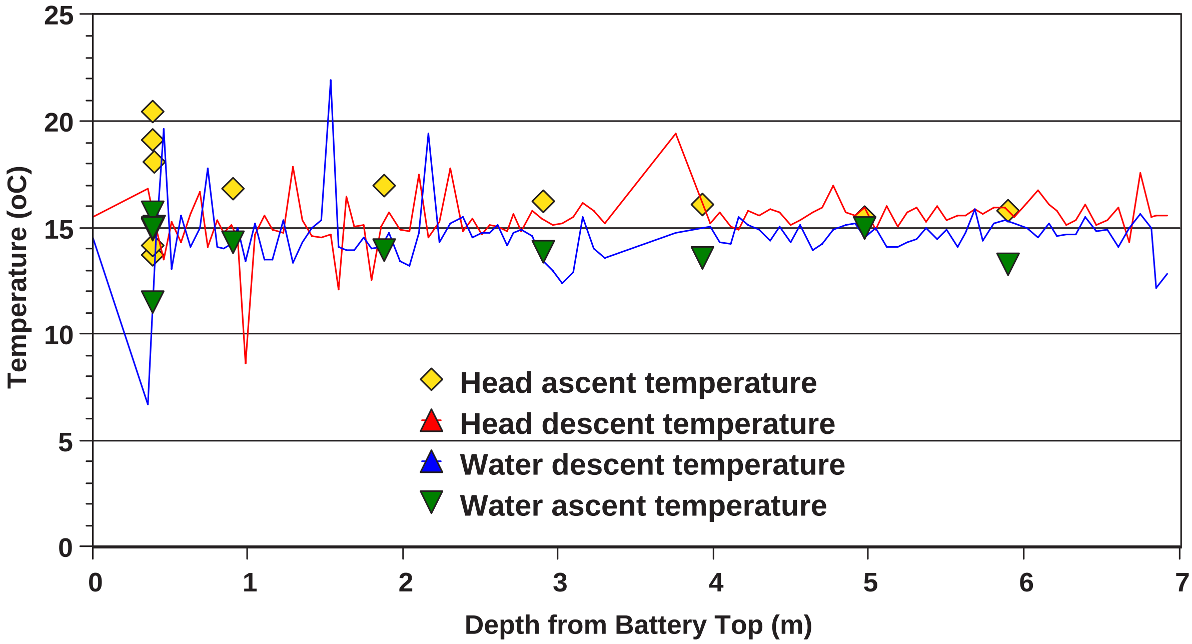


Fig. A6.17 Head and cooling water temperatures during descent and ascent of flue in Wall 55

The monitor was easy to use on plant, as temperature data and video images inside the flues were displayed in real time. Since the temperature of the camera was critical, the temperature of the head and the cooling water were observed, while the umbilical head was in the flue. Figure A6.16 shows the head temperature and the video recording of the flue on the rig. Head and cooling water temperatures were much lower than those measured in laboratory experiments (in Appendix 3) even as the umbilical was withdrawn from the flue, and averaged around 15^{o}C, as Fig. A6.17 illustrates. These good results demonstrate the effectiveness of the selected insulation and cooling systems.

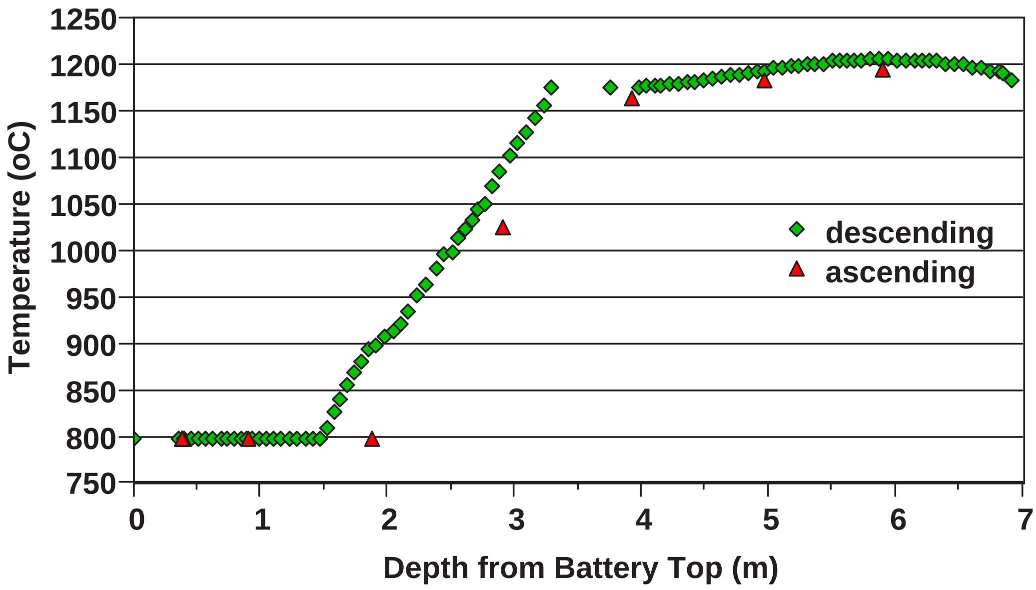


Fig. A6.18 Good repeatability of temperatures descending and ascending a flue in Wall 55

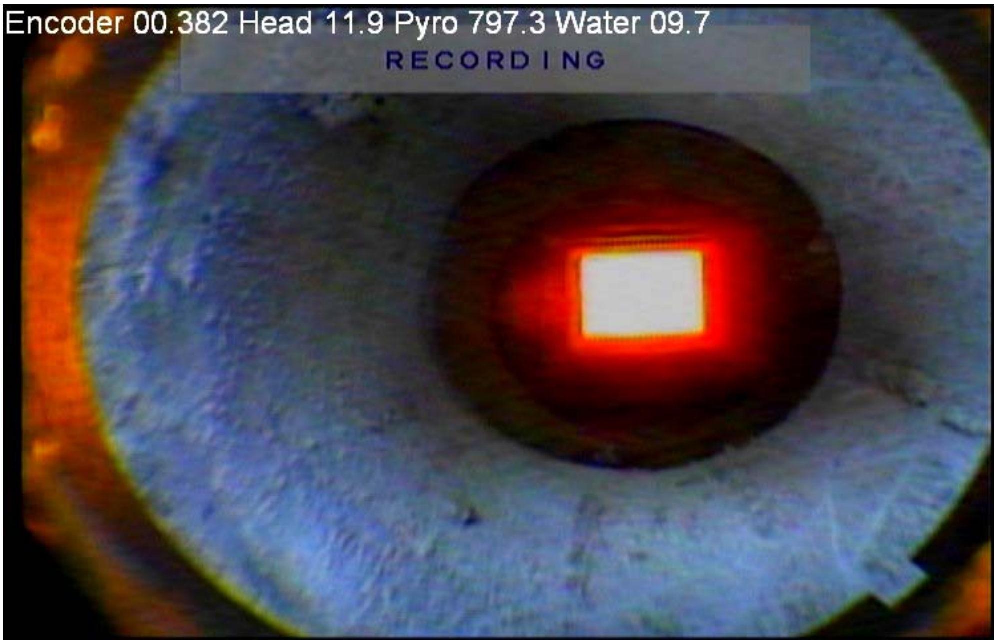


Fig. A6.19 View down a flue from the battery top

There was good repeatability of temperatures descending and ascending the flues, as Fig. A6.18 shows. When this had been confirmed, less measurements were taken during withdrawal of the head from the flue. A large number of video images (like that in Fig. A6.19) have been stored for comparison with the results from the next trial of the same flues. The videos were also useful for highlighting temperature variations between flues, as Fig. A6.20 demonstrates. In Wall 44, Flue 6 was much cooler than adjacent Flue 7 (see Fig. 34) due to some problems with the flue, and this is apparent in the photographs. Both the temperature and the vision monitoring was successful with this equipment, and it was sufficiently mobile for easy transportation on any battery.

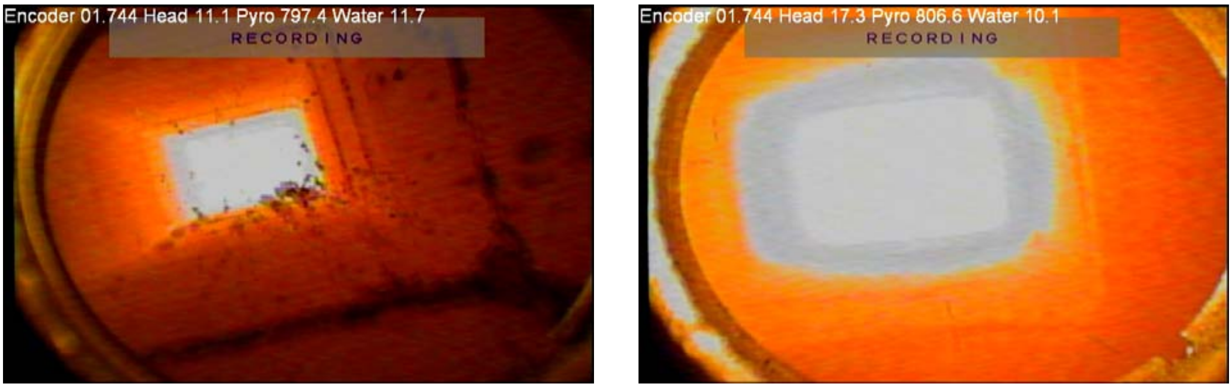


Fig. A6.20 Wall 44, Flues 6 (on the left) and 7 (on the right) 1.7 m from the battery top

Task 6.5 Application regenerator inspection/cleaning system

All plant trials were conducted at a regenerator of a German coke plant.

Prototype 1 inspection system (without cleaning equipment)

Fig. A6.21 Photographs of regenerator brickwork inspection with the Prototype 1 inspection system

Figure A6.21 showed photographs taken from the inspection of the sole flue of the coke plant at the heating flue No. 28 with the Prototype 1 inspection system, in which the position and swivelling angle of the welding mirror was adapted and controlled manually. The two photographs were shot with a standard camcorder from different positions on the movable slide and with different inclinations of the swivelling mirror. In spite of darkness, from a total of 15 slots of the single brick, 6-8 slots were made visible by light incidence from temperature radiation in upper parts of the regenerator brickwork. Small tears/breaks and deposits of dust and ceramic mortar can be identified roughly, but they were not made clearly visible with a satisfactory optical resolution. The selected welding mirror showed good resistance to thermal stresses, but only mediocre optical properties. Enhanced lighting was needed for the camcorder.

Prototype 2 inspection system with combined cleaning equipment

A radio-controlled swivelling mirror made from optical glass and a new camcorder, which could be operated with temporary additional lighting in two modes (visual/IR-mode), were used in the optimised Prototype 2 inspection system to improve the quality of optical inspection. Air nozzles were combined with the optical equipment in this system to allow cleaning of regenerator brickwork as well as inspection. Additional lighting was used to make the brickwork visible during cleaning.

Fig. A6.22 Insertion of the Prototype 2 inspection/cleaning system into the sole flue

Insertion of the Prototype 2 inspection/cleaning system into the sole flue of the coke plant is shown in the photographs of Fig. A6.22. First inspection tests were conducted without simultaneous operation of the cleaning equipment. With the radio-controlled swivelling mirror, a fast and targeted scan of the lower brickwork sections could be obtained. Photographs shot during these inspection tests are shown in Fig. A6.23 (visual mode of the camcorder) and Fig. A6.24 (IR-mode of the camcorder).

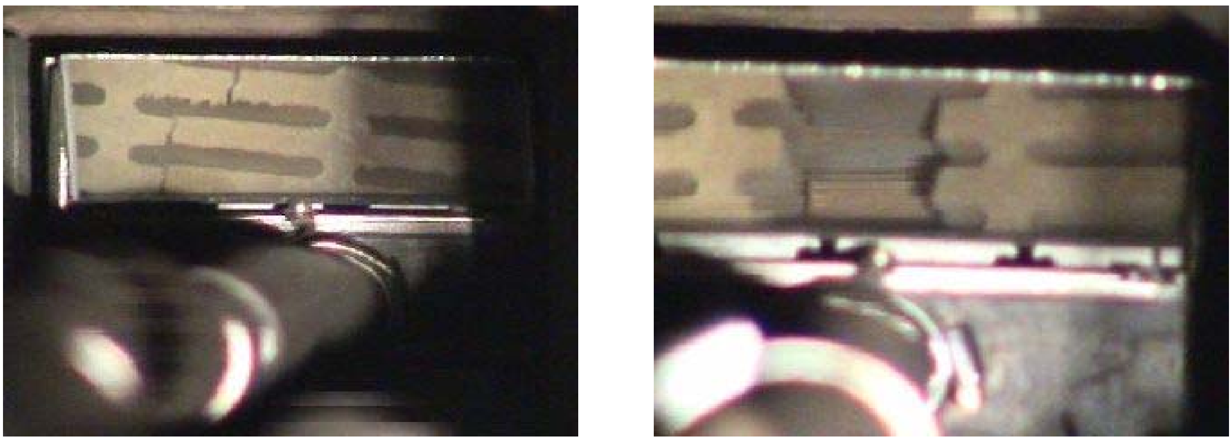


Fig. A6.23 Photographs of regenerator brickwork inspection with the Prototype 2 inspection/cleaning system without operation of the cleaning equipment (camcorder: visual mode)

Fig. A6.24 Photographs of regenerator brickwork inspection with the Prototype 2 inspection/ cleaning system without operation of the cleaning equipment (camcorder: IR-mode)

As shown in Figs. 14 and A6.23 the quality of inspection photographs shot with the improved second inspection system is excellent in the visual mode of the camcorder and much better than with the Prototype 1 inspection system, when the added cleaning equipment is not operated during inspection.

Additional inspection tests were conducted with simultaneous operation of the cleaning equipment. By running the air nozzle cleaning equipment, large quantities of dust and other deposits could be blown away from the brickwork in lower sections of the regenerator brickwork, so that good cleaning results could be achieved in these sections of the regenerator. Because the swirled dust particles are deposited again lower down in deeper sections of the sole flue, an aspiration may be necessary after some cleaning procedures. Whether cleaning effects could also be achieved in upper brickwork sections of the regenerator with the air nozzle cleaning equipment could not be evaluated exactly. However, improved cleaning with the nozzle system can be expected for these regenerator sections also, compared to the conventional method of blowing undirected compressed air into the sole flue. Photographs shot with the Prototype 2 inspection system in trials with simultaneous operation of the added cleaning equipment are shown in Fig. A6.25, before start of cleaning, at start of cleaning, during and after operation of the added cleaning equipment. From Fig. A6.25, it becomes evident that optical inspection of the regenerator brickwork is disturbed to a large extent during operation of the cleaning equipment by swirling dust, which causes backscattering of light during cleaning. Consequently, any optical recording is impossible during cleaning. For that reason, optical inspection and cleaning have to be run separately.

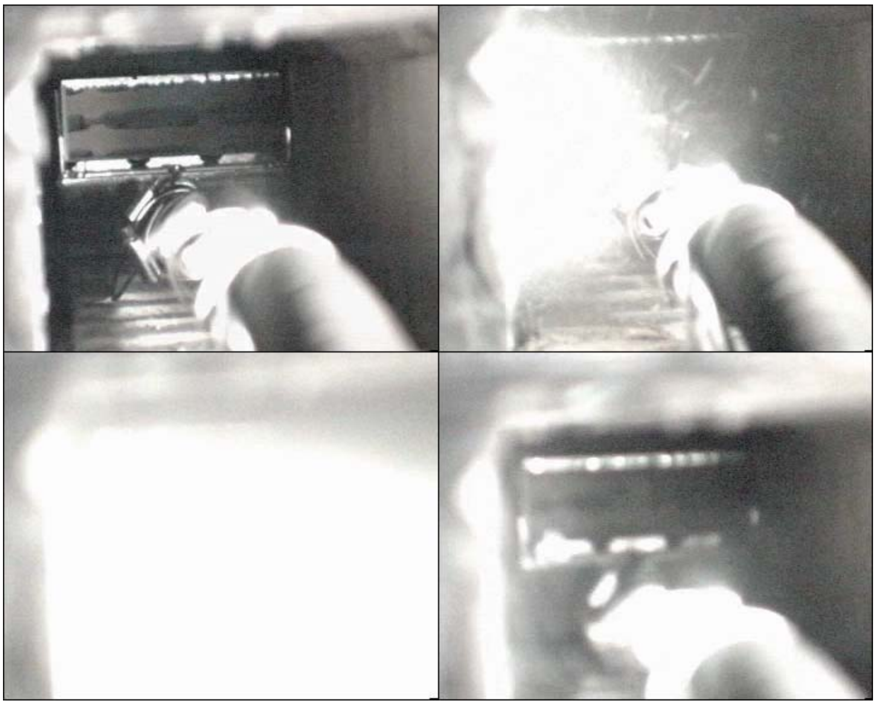


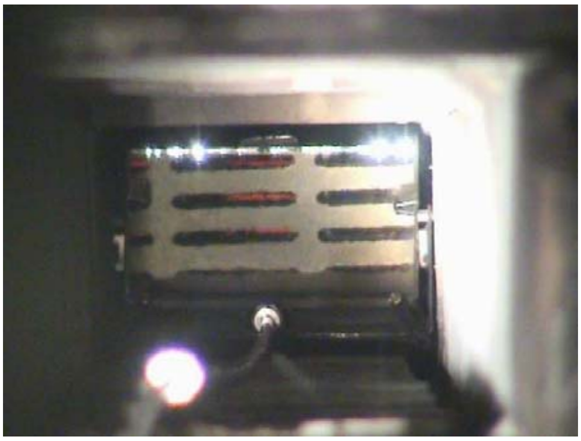
Fig. A6.25 Photos of regenerator brickwork inspection with the Prototype 2 inspection/cleaning system with simultaneous operation of the cleaning equipment
left top before start of cleaning
right top start of cleaning
left bottom during cleaning
right bottom after cleaning

Simplified Prototype 3 inspection system (without cleaning equipment)

To run optical inspection without any problems from simultaneous cleaning with a system as simple as possible, a much simplified Prototype 3 inspection system without any cleaning, heat protection and cooling devices was developed and tested in plant trials. Photographs shot with the simplified Prototype 3 inspection system during plant trials are shown in Fig. A6.26. The quality of photographs taken with simplified Prototype 3 inspection system is as excellent as that with the more complex Prototype 2 inspection system, when it is operated without the combined cleaning equipment. As shown in Fig. A6.26, by application of the Prototype 3 inspection system different types of brickwork damage can be monitored and identified with a high optical resolution.

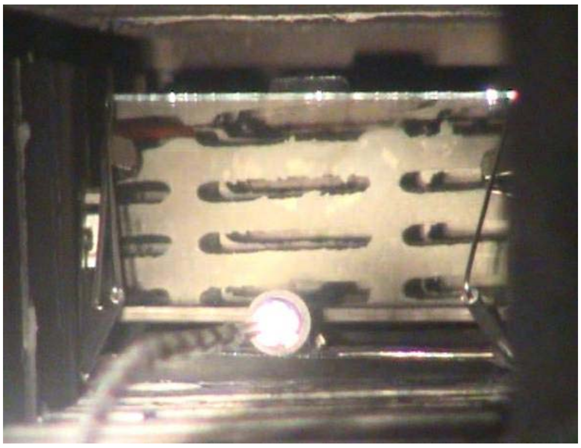
Conclusions

In plant trials, the Prototype 1 inspection system showed insufficient optical properties. Brickwork damage could only be identified very roughly, as details were only just visible with low optical resolution. The improved Prototype 2 inspection/cleaning system provided excellent inspection photographs, when the added cleaning equipment was not operated during inspection. Good cleaning results were achieved with the added air nozzle cleaning equipment in lower sections of the regenerator brickwork. However during cleaning, optical inspection was disturbed by swirling dust. With the simplified Prototype 3 inspection system without any cleaning equipment, photographs were obtained with the same high quality and optical resolution as with the more complex Prototype 2 inspection system.

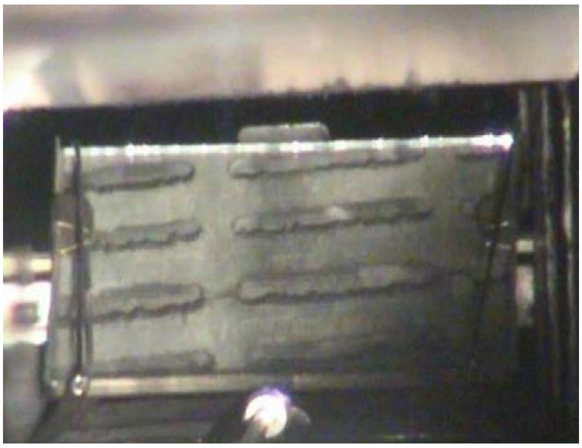


undamaged brickwork

damaged brickwork – cracks



damaged brickwork – displacement



damaged brickwork – deposits of soot

damaged brickwork – structural surface damages

Fig. A6.26 Photographs of regenerator brickwork inspection with the simplified Prototype 3 inspection system

Task 6.6 Comparative trials plant/laboratory carbon deposits
Task 6.7 Evaluation/correlation of plant data

As alterations to oven operation following the plant trials have reduced carbon growth, it was impossible to obtain further samples after the trials within the time-scale of this project. However, the total number of industrial carbon deposits was large, and the factors that reduce carbon deposits do not change their nature, according to the literature survey. Consequently, the new monitoring data have been evaluated in comparison with plant operations. The carbon deposition studies have increased knowledge of the formation of deposits to aid their reduction.

In plant trials with the newly-developed swivelling mirror/camera inspection system, some regenerator brickwork damage could be detected in the sole flue of a German coke plant. Besides deposits of soot and dust, cracks and breaks could be monitored in some parts of the regenerator brickwork. Over time, slight and medium damage of the regenerator brickwork cannot be avoided, even with best maintenance and smooth coke plant operation. Slight and medium brickwork damage often occurs due to normal thermal stresses, whereas severe damage is caused mostly by uneven heating and local overheating over long periods, which results in various problems for operators of coke plants.

- Cracks and breaks in the brickwork of the sole flue area give a risk of instability in the lower part of the oven. If damage is allowed to progress for a long time, an increasingly part of the regenerator brickwork may collapse. As a consequence, operation of many ovens has to be stopped for the period of refurbishment with losses of coke production.

- Uneven heating of the regenerator brickwork, arising from blockages of the regenerator channels and damage to the brickwork, will also cause uneven heating of the oven charge, so that parts of the oven charge cannot be carbonised fully, resulting in losses of coke quality.

- In the case of incomplete carbonisation resulting from uneven heating of the oven charge, emissions at the batteries will rise during pushing.

- Often hot spots are formed in the heating flues, caused by an uneven heating of the regenerator brickwork. In this case, higher emissions of NOx are also to be expected at the battery stacks as an additional adverse environmental effect.

The described effects have become more critical now at most older coke plants, because many of them are being operated beyond their planned 20-25 year lifespan. Until now, operators of such old coke plants have not been able to control and avoid these effects, owing to a lack of powerful and easy systems for the inspection of regenerator brickwork. With the newly-developed swivelling mirror/camera inspection equipment, a system is now available now to overcome this problem. Improved operation resulting in a longer battery life can be expected, if brickwork inspection is carried out regularly with this inspection system, so that start of brickwork damage can be detected and repaired before damage progresses to a severe stage.

Evaluation of the other new monitoring systems was described in the Scientific & Technical Section of this report.

LIST OF FIGURES IN APPENDIX 6

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