Reduction of NO_X Emissions in a Down-Fired Boiler

Ana de Magalhães Vasconcelos de Oliveira Passos Strickrodt

A thesis submitted in partial fulfilment of the requirements of the University of Glamorgan/Prifysgol Morgannwg for the degree of Master of Philosophy

This research project was carried out in collaboration with National Power PLC, Aberthaw Power Station

April 1997

ABSTRACT

Nitrogen Oxides (NO_X) are known to be among the pollutants resulting from fossil fuel combustion with particularly harmful effects on the environment and human health. Increased concern for the effects of NO_X and other pollutants has prompted the European Community (EC) to draw up legislation on the limitation of emissions with which industrial plants have to comply.

In the context of this requirement the subject of this work is the investigation of NO_X reduction and control methodologies at Aberthaw "B" Power Station (unit 7), a coal-fired 500 MWe power plant owned by National Power PLC. Since retrofitting the latest NO_X control technology is not a viable option at Aberthaw, the specific objective of this project was to optimise the combustion process with respect to NO_X emissions using existing plant and control systems. In order to meet this objective, applicable NO_X control parameters had to be identified and a programme of plant tests had to be designed, carried out and evaluated. To complement these plant tests, a physical 3D model was designed and applied to analyse the prevailing flow patterns under some of the test conditions investigated with the real process.

Although it was not possible to relate the experiences gained from the modeling work as closely as it was envisaged with those gained from the plant experiments, the modeling was effective in showing two characteristic flow patterns (symmetric and asymmetric flow), which could be distinguished for all experimental conditions that were investigated. The potential low NO_X operating conditions were identified as: lower boiler load, reduced excess air, air staging (through damper settings), burner biasing, burners out of service (BOOS) in the furnace middle chamber, BOOS across the furnace chambers, and a combination of these techniques. Additionally, the application of oil burners in service as a NO_X control methodology (which cannot be considered at Aberthaw as the known 'reburning' effect) was discovered as an interesting NO_X control methodology. Amongst the investigated techniques, only the effect of lower boiler load and burner biasing could not be confirmed in the experiments. All other operating conditions showed to different extents reducing effects on the NO_X emissions. The optimal NO_X control methodology turned out to be a combination of oil burners in service with the reduction of excess air and air staging, yielding minimum NO_X levels between 385 and 450 ppm (at 6% O_2, dry). The particular value of this novel technique is further stressed by the low carbon in ash and CO levels, which it ensures. Based on the experiences, a concise set of operational guidelines for the power plant operators at Aberthaw was summarised in order to facilitate a permanent low NO_X operation (according to the best of current knowledge), which does not affect the boiler efficiency. Further refinements of the operational conditions might, however, be possible on the basis of the extended research programme proposed at the end of this work.

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to thank my first supervisor, Dr. M. Biffin, for his support and advice throughout the project as well as for his initiative in setting up this project. Likewise, the advice and expertise from Prof. W. G. Kaye, my second supervisor, and Prof. J. Ward, the Head of the Department of Mechanical and Manufacturing Engineering, is gratefully acknowledged.

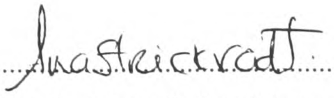
Also, I would like to thank the University of Glamorgan, in particular the Department of Mechanical and Manufacturing Engineering and its members of staff for the support and advice during the design and set-up of the boiler model. For their invaluable support I would like to thank especially Mr. M. D. Williams and Mr. A. Evans.

National Power PLC provided both the 'object of research' and the funding for the project, which is gratefully acknowledged. Furthermore, I would like to thank all staff at National Power that were involved in my project - in particular the advice from Mr. L. Moss and Mr. J. Richmond was essential and is therefore gratefully acknowledged.

Finally, I would like to thank my family and in particular my mother for all their support and understanding throughout my studies. Last but not least, I would like to thank especially my husband Matthias for his support, understanding, patience, advice and everything else.

AUTHOR'S DECLARATION

This thesis has not been nor is currently being submitted for the award of any other degree or similar qualifications.



(Ana de Magalhães Vasconcelos de Oliveira Passos Strickrodt)

NOMENCLATURE

Symbol	Description	Units
A	Area.	m^2
BFPT	Boiler feed pump turbine.	
BOOS	Burners out of service.	
B&W	Babcock & Wilcox.	
Cig	Carbon in grit.	
CinA	Carbon in ash.	
CO	Carbon monoxide.	
d	Equivalent diameter.	m
EC	European Community.	
EP	Electrostatic precipitator.	
FD	Forced draught.	
FGR	Flue gas recirculation.	
FW	Foster Wheeler.	
GCV	Gross calorific value of the fuel.	
HP	High pressure.	
ID	Induced draught.	
IFNR	In-furnace-NO_X-reduction (reburning).	
IP	Intermediate pressure.	
i/s	In Service.	
LHS	Left hand side.	
LNB(s)	Low NO_X burner(s).	
LP	Low pressure.	
M	Momentum flow rate.	N
m	Mass flow rate.	kg/s
MCR	Maximum continuous rating. MCR is the maximum load at which the turbine is designed to run at (500 MWe).	
NCV	Net calorific value of the fuel.	
OFA	Overfire air.	
OIS	Operational information system.	
o/s	Out of Service.	
PA	Primary air.	
PF	Pulverised fuel.	
PFA	Pulverised fuel ash.	
PFb	Pulverised fuel burner.	

ppm	Parts per million.	
Q	Volume flow rate.	m^3/s
Re	Reynolds number.	
RAH	Regenerative airheater.	
RHS	Right hand side.	
s	scaling factor.	
SCR	Selective catalytic reduction.	
Sett.	Setting.	
SNCR	Selective Non-catalytic reduction.	
V	Velocity.	m/s

Greek Symbols

ρ	Density.	kg/m^3
μ	Dynamic viscosity.	kg/ms

Other Symbols

$\approx$	around.
α	proportional.

Subscripts

c	Coal.
cg	Combustion gases.
m	Model.
o	Nozzle outlet.
p	Plant.
pa	Primary air.
sa	Secondary air.
sa1	Secondary air (1st stage).
sa2	Secondary air (2nd stage).
sa3	Secondary air (3rd stage).
t	Total.
TA	Total air (primary, secondary and tertiary).
ta	Tertiary air.
w	Water.

1. INTRODUCTION

Nowadays, the combustion of fossil fuels and of biomass are known to be one of the major sources of pollutants responsible for significant changes in the atmospheric composition which have detrimental effects on the environment and human health. On the basis of this knowledge, strict European environmental legislation has therefore been introduced, aiming at controlling and reducing the emissions of these pollutants. Such pollutants are particularly worrying since they travel enormous distances from the country they originate from, severely affecting other countries and populations. This long-range transport of pollutants has therefore resulted in an international call for protection of the environment. Further worries also result from the synergistic effect of the pollutants and from the new pollutants which originate from this mixture of emissions. The long atmospheric lifetime of the pollutants is of concern, too. N_2O, for example, can last up to 300 years.

This introductory chapter describes the subject of this work and the need for it, as well as the aims and the structure of the thesis.

1.1 The Subject Of This Work And The Need For It

The subject of this work is to address the problem of control and reduction of nitrogen oxides (NO_X) as one of the above mentioned pollutants at a particular coal-fired power station in the UK: Aberthaw "B" Power Station[1], unit 7. There are three major aspects of the need for this work:

- Nitrogen oxides detrimental effects: These include acid rain, photochemical smog, the greenhouse effect, stratospheric ozone depletion, ambient particulate matter and human health concerns.
- Compliance with the EC law: In order to protect both the environment and human health, the EC has introduced environmental legislation for control and reduction of NO_X emissions from power plants.
- The need for an individual NO_X investigation: A wide variety of NO_X reduction and control methods have been proposed to date, yet their effects on NO_X varies considerably not only between different boiler types but also between sister units. Many other conditions such as coal, combustion air temperature, etc., also influence the effects of the various NO_X reduction methods. Therefore, NO_X investigations must be carried out on each application.

[1] Aberthaw Power Station has in effect two plants: "A" station with 6 units which was closed in 1995 and "B" station with three units (7, 8 and 9).

The latter need for an individual NO_X investigation is further strengthened by the type of furnaces at Aberthaw: the "down-fired-furnace" (details in appendix A). This specific furnace design is required to burn the local low volatile coal (semi-anthracite), whilst ensuring a stable combustion and ignition. In the UK, Aberthaw is the only power station with this type of furnace and there are not many others in operation around the world. Because these furnaces are not very common, the information available on NO_X reduction techniques for these types of furnaces is small.

1.2 The Aims Of This Work

New power plants are purpose-built to produce a minimum of NO_X emissions, that is: they employ special technology for NO_X reduction and control. Old plants can sometimes be retrofitted with the latest NO_X control technology. This option, however, is not always available - mostly due to technological or economical reasons.

At Aberthaw, which is an older generation power plant, a retrofit is economically not viable. Thus, achieving the new plant standards, which is the aim at Aberthaw, is only possible using the "BATNEEC" approach (Best Available Techniques Not Entailing Excessive Costs). Therefore, in order to address the above needs and the aim of Aberthaw Power Station, the overall objective of this research project was to optimise the combustion process with respect to NO_X emissions using existing plant and control systems.
In order to achieve this overall objective, the following specific aims of this work were defined:

- to identify low NO_X operating conditions at Aberthaw using the existing boiler operating variables.
- to investigate the possible extent of NO_X reduction of the above identified low NO_X operating conditions, within the constraints of CO, carbon-in-ash and flame stability in plant tests.
- to observe the flow patterns in a physical model of the furnace and to correlate them to the plant results.
- to gain insight and experience with respect to the flow patterns and how they change under different conditions in a 3D model.
- to optimise low NO_X operating modes on the basis of the knowledge obtained from the correlation between the power plant and the modelling work.
- to develop operational guidelines for a low NO_X operation at Aberthaw, on the basis of the information gained from the power plant and the modelling work.

1.3 The Structure Of This Thesis

After the problem scope as well as the aim and need have been described in the previous sections, chapter 2 gives a review of the origins and types of NO_X, the reasons for concern about NO_X emissions and an introduction to the European NO_X reduction requirements.

Obviously, in the context of this thesis, it was particularly important to gain an understanding of the numerous NO_X control methodologies known to date. Chapter 3 details the various currently available NO_X control methods and briefly mentions those methods in the research and development phase. Based on this knowledge, the applicability of different techniques to the Aberthaw power plant was checked and the test program designed.

Equally important for the design and analysis of the power plant tests was the understanding of the design and combustion characteristics of down-fired furnaces, as well as the link between anthracite/semi-anthracite coals and down-fired furnaces (chapter 4).

The design and results of the power plant tests, are given in chapter 5 and 6, respectively. In chapter 7 the discussion of the results is presented.

In order to carry out the modelling work, it was first necessary to design and construct the physical model and test rig. Design details as well as other considerations such as choice of the flow medium are given in chapter 8. This is followed by chapter 9 and 10 with the results of the modelling work and discussion, respectively.

Finally, in chapter 11, the possible extensions of both modelling and power station work are detailed, and the final conclusions are drawn. Additionally, details of possible parameters affecting NO_X formation at Aberthaw as well as possible side effects of low NO_X operation are discussed.

2. NO_X AS A POLLUTANT AND ITS IMPLICATIONS

Nowadays, the combustion of fossil fuels and of biomass are known to be responsible for the significant change in the atmospheric composition with consequential detrimental effects on the environment and human health. This change in the atmospheric chemistry has resulted from the release of various compounds from combustion such as H_2O, CO_2, HC (CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_8, C_6H_6, CH_3CHO, etc.), CO, NO_X (NO, N_2O, etc.), reduced nitrogen (NH_3 and HCN), sulphur gases, (SO_2, OCS, CS_2), halocarbons (CH_3Cl and CH_3Br) and particles [1].

Specifically nitrogen oxides (NO_X) are of concern in this work, thus in the following section a brief review of their sources, formation mechanisms, reasons for concern and EC regulations is presented:

2.1 What is NO_X ?

NO_X is a generic term that covers all the oxides of nitrogen from nitric oxide (NO), nitrous oxide (N_2O), nitrogen dioxide (NO_2), nitrogen trioxide (NO_3), dinitrogen trioxide (N_2O_3), dinitrogen tetroxide (N_2O_4) and dinitrogen pentoxide (N_2O_5). However, only NO, NO_2 and N_2O are of major importance as they are stable, with the remaining oxides of nitrogen being either negligible or unstable [2].
NO_X emissions result mainly from the combustion of fossil fuels due to the high temperatures and the availability of oxygen and nitrogen from the air and/or fuel.

In the past, NO_X was ignored as it did not affect the design or thermal performance of boiler plants and of motor vehicle engines. However, due to the introduction of strict environmental legislation [3, 4, 5, 6, 7], NO_X emissions have increasingly caught attention. This is due to the fact that NO_X as well as sulphur oxides (SO_X) have been identified as contributors to acid rain, greenhouse effect, stratospheric ozone depletion, photochemical smog and human health concerns.

2.2 The Origins of NO_X

Nitrogen oxides originate from natural (biologically produced) and anthropogenic (man-made) sources, which contribute equally to the overall output. Half of the man-made contribution results from vehicles, the other half from stationary emitters [2,8].

In urban areas, NO_X emissions are particularly abundant, with NO predominating [2]. As a country, UK is the third largest source of NO_X emissions in Europe and Europe accounts for about one third of the global man-made source [2].

It has been established that NO represents of the order of 95% [9] of the three stable NO_X types (NO, NO_2 and N_2O) emitted from conventional power plants, whereas NO_2 (a subsequent oxidation of NO) represents 5% of the total NO_X [10, 11].
N_2O is usually ignored as its emissions from conventional power plants are negligible (< 5 ppm) [12, 13, 14]. However, until not long ago, stationary fossil fuel combustion was believed to be one of the major sources of N_2O emissions (25-40% of the NO_X levels) [15]. This was due to a sampling artefact used in the past, which allowed significant levels of N_2O to be produced from NO in the presence of SO_2 and water in the sample containers, leading then to erroneous conclusions [12, 13, 15, 16].
N_2O levels are, however, significantly higher from fluidised-bed combustors than from other types of combustion systems [17,18] and are increased in low NO_X burners (compared with the high NO_X burners).

Although most of the NO_X emitted from combustion is in the form of NO, it continues to oxidise to the air pollutant NO_2 as soon as it reaches the atmosphere. For monitoring purposes, the total NO_X emissions must therefore be quoted as an NO_2 equivalent [7].

2.3 Mechanisms of NO_X Formation

In conventional power plants, NO is formed by three main processes. Accordingly NO is distinguished as: Thermal-, Fuel- and Prompt-NO, with the percentage of each depending on the combustion process and fuel.

In coal-fired stations under normal boiler operation, fuel-NO represents the major component of NO formed. It can represent 75 to 90% of the total, with the remainder being thermal-NO [19, 20, 21]. This is due to the relatively low temperatures achieved by most pulverised fuel flames (with exception of the pulverised fuel-fired cement-kiln). Also, fuel nitrogen reacts to form NO more readily than atmospheric nitrogen does. This is because the organic nitrogen is bound by N-H and C-N bonds, which are much weaker than the triple bond in molecular atmospheric nitrogen and therefore more likely to take part in reactions [22].

Prompt-NO formation is usually ignored in the coal combustion process as it is believed to account for less than 5% of the NO formed [23 , 24].

In oil-fired boilers, fuel- and thermal-NO contribute roughly 50% each to the total NO [21], whereas gas-fired boilers generate solely thermal-NO [25].

Thermal-, fuel- and prompt-NO formation is now considered in more detail:

2.3.1 Thermal-NO

Thermal-NO refers to the NO formed through high temperature oxidation of the atmospheric nitrogen in the boiler furnace. An example is natural gas, a fuel that contains no chemically bound nitrogen but which forms NO upon burning.

The mechanism of thermal-NO formation was first described by Zeldovich [26]. Three main reactions have been proposed for this process [10, 26, 27, 28]:

$$N_2 + O \leftrightarrow NO + N \qquad \textbf{(Eq. 2.1)}$$

$$N + O_2 \leftrightarrow NO + O \qquad \textbf{(Eq. 2.2)}$$

$$N + OH \leftrightarrow NO + H \qquad \textbf{(Eq. 2.3)}$$

These reactions are strongly dependent on residence time, high temperature [10, 29] and fuel-lean regions within the combustion chamber [24]. Thermal-NO formation is therefore significantly reduced in fuel-rich systems, at temperatures below 1600-1800 K [30, 31] and by minimising the residence time in the region of highest temperature.

2.3.2 Fuel-NO

Unlike thermal- and prompt-NO, fuel-NO is formed by the oxidation of the nitrogen compounds in the fuel. Although the reactions are not fully known, it is understood that during combustion the nitrogen compounds in the fuel split between volatile and char structures. Fuel-NO is then formed from the homogeneous oxidation of the volatile nitrogen or from heterogeneous oxidation of the char nitrogen. A simplified overall mechanism of the fate of fuel nitrogen in coal combustion is illustrated in Fig. 2.1 (in which the reburning mechanism - c.f. chapter 3, section 3.1.1(d)) - is also integrated):

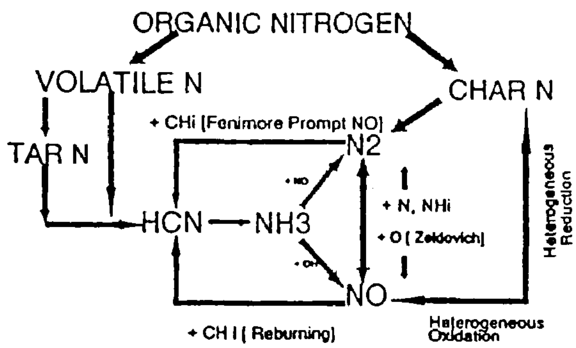


Fig. 2.1: Fate of Fuel-N in coal combustion [94].

Fuel-NO has been shown to be insensitive to flame temperatures in pulverised coal combustion over a wide range of temperatures [19, 20]. It increases with excess air and with volatile matter, thus anthracite being a low volatile fuel gives lower fuel-NO than other coals [32]. High fuel-NO levels are therefore expected in lean and stoichiometric mixtures and low levels with rich mixtures [29].

Several workers have tried to establish the proportion of volatile and char nitrogen that contribute to total fuel-NO emissions under normal and staged conditions in pulverised coal combustion: Pohl and Sarofim [33] concluded that in unstaged combustion at a furnace temperature of 1500°C, volatile nitrogen compounds are the major source of fuel-NO ranging from 60 to 80% of the total NO emissions. This agrees with other reports [19, 34]. Additionally, Lockwood and Romo-Millares [35], found that char nitrogen compounds account for 13 to 15% of the total NO produced at the exit of burners.

Under staged conditions Papadakis et al. [36], found that it is the NO due to the volatile nitrogen that is reduced and that NO reductions of as much as 60% can be achieved. This is in agreement with previous work which showed that combustion modifications through aerodynamic changes primarily influence volatile NO since volatile nitrogen is more sensitive to the early changes in burner aerodynamics (therefore sensitive to changes in the early oxygen concentration) while char is not [19, 34].

2.3.3 Prompt-NO

Prompt-NO may be considered as another source of thermal-NO since it is formed by reactions of hydrocarbon fragments with atmospheric nitrogen [10, 37, 38]. However, unlike thermal-NO, prompt-NO is weakly temperature dependent [37, 39, 40] and independent of residence time [29]. Prompt-NO was first studied by Fenimore [37] who proposed the following equations to describe its formation:

$$CH + N_2 \leftrightarrow HCN + N \qquad \textbf{(Eq. 2.4)}$$

$$N_2 + C_2 \leftrightarrow 2CN \qquad \textbf{(Eq. 2.5)}$$

Subsequently, reactions of HCN and other molecules with a single nitrogen atom with oxygen containing species could then result in NO formation [41]. The formation of prompt-NO is not fully understood, but it is believed to be generated in the front of a very rich flame, where due to the very short residence time the Zeldovich reactions are inadequate [10, 39, 42]. Since the prompt-NO mechanism requires a hydrocarbon fragment (i.e. CH, C_2, C, etc.) to initiate the attack on the molecular nitrogen, the mechanism is more efficient in fuel-rich flames. This has been demonstrated by various workers, who showed that fuel-rich flames give more prompt-NO than lean or stoichiometric flames of the same temperature [43, 44].

2.4 Concerns for NO_X

It is well established that NO_X has direct and indirect hazardous effects, both in the environment and human being. The most important aspects are discussed in the following:

2.4.1 Photochemical Smog

Photochemical smog is a brownish coloration of the troposphere, which results in plant and materials damage, eye irritation, reduced visibility and respiratory difficulties [45].
Photochemical smog consists of several compounds, some of which are ozone (O_3), nitrogen dioxide (NO_2), peroxyacetyl nitrates (PAN) and small particles [46]. These compounds result from complex photochemical reactions caused by sunlight, involving NO, NO_2, oxygen and organic compounds such as reactive hydrocarbons (HC) [2, 47]. Increases in incident sunlight, temperature and reactants are

thus expected to raise the concentrations of the photochemical smog compounds. The overall formation mechanism is shown in Fig. 2.2.

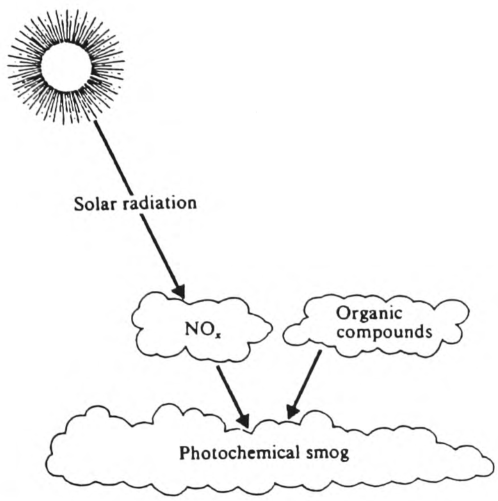


Fig. 2.2: Formation of photochemical smog [45].

The formation of ozone, for example, results from the photolysis of NO_2 by UV light, followed by the reaction between atomic and molecular oxygen [48, 49]:

$$NO_2 \xrightarrow{UVLight} NO + O^{\bullet} \qquad \textbf{(Eq. 2.6)}$$

$$O_2 + O^{\bullet} \rightarrow O_3 \qquad \textbf{(Eq. 2.7)}$$

where: "$\bullet$" is a free radical.

However the process is reversed by the reaction:

$$O_3 + NO \rightarrow O_2 + NO_2 \qquad \textbf{(Eq. 2.8)}$$

2.4.2 Acid Rain

Acid rain is blamed for causing vegetation damage or death, acidification of rivers, lakes or other water in the nature, loss of fish and other aquatic organisms, acidification of the soil and damage to historic buildings, in particular those with sandstone, limestone marble and with steel [48, 49]. Furthermore, it can represent a health threat, in the case of exposure to a higher heavy metal intake from drinking water provided in lead or copper plumbing, or from the bio-accumulation process in the aquatic food chain, particularly mercury and cadmium [8].

Acid pollution can be in wet or dry form, but in either form it affects the environment in two ways: (1) by direct mechanisms, that is the emitted pollutants interact directly with the plants, buildings, etc., or (2) by indirect mechanisms on the fauna and flora by causing a change in the soil or aquatic ecosystems [8].

NO_X as well as SO_2 are known to contribute to the formation of acid rain. Acid rain refers to rain with a pH below about 5 [48, 49]. It basically consists of a dilute solution of sulphuric acid (H_2SO_4) and nitric acid (HNO_3) plus minor contributions from carbonic and organic acids. The sulphuric and nitric acids account for over 90% of the acid rain [50].

During daylight, NO_2 forms nitric acid through the following reaction [50]:

$$NO_2 + OH + m = HNO_3 \qquad \textbf{(Eq. 2.9)}$$

where "m" is a body (N_2 or O_2) that absorbs energy. At night in the presence of ozone, NO_2 is oxidised to a nitrate radical. This then reacts with N_2, giving N_2O_5 and finally nitric acid [50].
Most acid rain control has, however, concentrated on the SO_2 contribution since SO_2 is easier to control than NO_X and because SO_2 accounts for around 2/3 of the acidity [48, 49].

2.4.3 Greenhouse Effect and the Stratospheric Ozone Depletion

The greenhouse effect, also known as global warming, results from the absorption of solar energy by certain atmospheric constituents (greenhouse gases) in the lower atmosphere (troposphere). Air pollution is responsible for the increase in these greenhouse gases.

Presently, main greenhouse gases (GHGs) of concern are CO_2, CFCs (chlorofluorocarbons), halons, CH_4, N_2O and O_3. Gases such as NO and CO do not have a direct greenhouse effect, however, they contribute indirectly through their chemical reactions with the greenhouse gases, thus affecting the concentrations of the latter. Greenhouse gases such as O_3 and CH_4 have both direct and indirect effects [47].

The problem with greenhouse gases is that some not only contribute to the greenhouse effect, but also affect the depletion of the stratospheric ozone layer. The stratospheric ozone layer, which contains about 90% of the atmospheric ozone, filters most of the ultra-violet radiation (UVR) from the sun that is below 300 nm. This protects humans from the adverse effects of UV, such as sunburn and various types of skin cancer, which increase significantly under exposure to radiation below 320 nm [48, 49].

Depletion of the stratospheric ozone therefore leads to a larger amount of UV radiation incident on the earth's surface and to an increased risk of cancers [48, 49]. Additionally, once in the lower atmosphere, the UVR also acts as an energy source for the tropospheric ozone generating process. This increasing ozone at lower levels, not only contributes to photochemical smog, but also further contributes to the greenhouse effect.

Nitrogen oxides are potential catalysts for the destruction of ozone. Nowadays, there is a growing concern for N_2O emissions as a result of its increasing levels in the atmosphere (0.2-0.4% per year) [17, 51, 52, 53]. The reason for this increase is not completely understood since N_2O is formed largely by anaerobic processes in the soil. Nevertheless its increase is believed to result from some form of disruption or intervention by man's activities through soil processes, fertiliser usage and fossil fuel combustion [2].

N_2O is not only a greenhouse gas in the troposphere but also a participant in stratospheric ozone depletion mechanisms [12, 13, 15]. In the troposphere, N_2O is a strong absorber of infrared radiation and therefore contributes to the greenhouse effect [2, 15, 17]. However, being a stable molecule (mean lifetime of 150 years in the troposphere) [17], allows N_2O to migrate into the stratosphere where it decomposes to NO, one of the main catalysts in the stratospheric ozone depletion [1, 54]:

$$N_2O + O \rightarrow 2NO \quad \textbf{(Eq. 2.10)}$$

NO then destroys ozone through the following reactions:

$$NO + O_3 \rightarrow NO_2 + O_2 \quad \textbf{(Eq. 2.11)}$$

$$NO_2 + O \rightarrow NO + O_2 \quad \textbf{(Eq. 2.12)}$$

This NO formed from N_2O, is estimated to cause up to 50-70% of global ozone depletion and the N_2O is estimated to be responsible for around 6% of the current anthropogenic contribution to the greenhouse effect [51].

2.4.4 Particulate Matter

Nitrogen oxides are also known to contribute to ambient particulate matter (or particles). Particles are made up of a variety of materials suspended in the atmosphere either as solids or as liquid droplets. They originate from natural (sea, volcanoes, etc.) and biological sources (spores, pollen, etc.). Their main sources, however, are man-made (fuel combustion and industrial processes) [55].

Like other air pollutants, particles affect the atmospheric properties and human health. The atmospheric effects consist of air pollution (with the most notorious being a reduction of visibility) and a significant influence on the weather [55, 56]. With respect to human health, particles can be harmful, either on their own or in combination with gaseous pollutants which may result in synergism. An example is the known synergistic effect between SO_X and particulate matter [55]. Additionally, there is some evidence that NO_2 in combination with particles may result in synergism, however this is still under investigation [50, 57].

2.4.5 Health Effect

As explained from sections 2.4.1 to 2.4.4, nitrogen oxides can affect the human health after contributing towards a change in the atmospheric chemistry. That is, through photochemical smog, acid rain, the greenhouse effect, the stratospheric ozone depletion and through particulate matter. This can be regarded as an indirect effect.

However, nitrogen oxides can also have a direct impact on the human health. Studies have shown that of all nitrogen oxides that occur in the atmosphere through the combustion of fossil fuels and subsequent conversion processes, NO_2 and NO are the most toxic for the human being.

NO_2, like O_3 and SO_2, has been shown to cause a decrement in pulmonary function [50]. One single exposure to high NO_2 concentrations can result in irritation of the eyes and respiratory tract bronchospasm, severe respiratory distress and finally death [58]. On the other hand, NO reduces the capacity of blood to carry oxygen, which in acute cases can also cause death [46].

Additional effects of NO and NO_2 on the human being are, however, not fully understood for two main reasons. Firstly, many experiments are carried out in animals, whose results unfortunately cannot be directly related to humans. Secondly, it is difficult to separate the individual effects of NO and NO_2

Both are normally present in the atmosphere, acting individually or together from which their action may be either additive or synergistic.

The harmful effects of NO_X are nowadays acknowledged. Therefore strict legislation has been introduced to combat and control further NO_X emissions.

2.5 European NO_X Reduction Requirements

In view of the continuous increasing levels of atmospheric pollutants and due to their harmful effects on the environment and the human health, the European Community (EC) has drawn up a series of programmes that aim at the reduction and control of pollutants from industrial plants.

There are two main EC directives of concern for this work, since they deal with the emission of pollutants into the atmosphere from industrial plants, one of which is NO_X:

1. The EC Directive "on the limitation of emissions of certain pollutants into the air from large combustion plants" (88/609/EEC), also known as LCPD (large combustion plants directive), [5].
2. The EC Directive "on the combating of air pollution from industrial plants", (84/360/EEC), [3].

Directive 88/609/EEC [5] applies only to combustion plants which are designed for production of energy and in particular to those that have a thermal input of more than 50 MW [5]. It is important to note that it does not apply to those plants which make direct use of the combustion products in manufacturing processes, such as coke battery furnaces, reactors used in the chemical industry, direct heating, etc.

The LCPD main objective is to reduce and control emissions from new and existing large combustion plants, where new plants are defined as those in place after July 1987 and existing plants as those in place before July 1987.

In the case of new plants, the directive fixes emission limit values for SO_2, NO_X and dust. For all new plants, the NO_X limitation is: 650 mg/m^3 (6% O_2, dry) for solid fuels in general, 1300 mg/m^3 (6% O_2, dry) for solid fuels with less than 10% volatile compounds, 450 mg/m^3 for liquid fuels and 350 mg/m^3 for gaseous fuels (both at 3% O_2, dry) [5].

In the case of existing combustion plants, the directive aims at a gradual and staged reduction of total annual emissions of SO_2 and NO_X. For all existing plants, the directive specifies emission targets compared with 1980 emission levels. In the case of UK, the NO_X requirement is a reduction of 30% by 1998 based upon 1980 levels. In order to achieve these low NO_X levels, the existing plants must be upgraded through a process of gradual adaptation in accordance with the criteria included in articles 4, 12 and 13 of Directive 84/360/EEC, [3].

According to article 4 in the directive, an "authorisation for the operation and substantial alteration of industrial plants which can cause air pollution" may only be issued by the competent national authorities when:

1. "all appropriate preventive measures against air pollution have been taken including the application of BATNEEC (Best Available Technology Not Entailing Excessive Costs)". However, the definition of BATNEEC as described by the EC Directive 84/360/EEC [3] has been adapted to "Best Available Techniques Not Entailing Excessive Costs" by the Environmental Act 1990 [7]. Therefore, the definition of BATNEEC as in accordance with the Environmental Protection Act 1990 is as follows [59]:

> "Best" means the most effective in preventing, minimising or rendering harmless polluting releases. There may be more than one set of techniques that achieves comparable effectiveness [59].
>
> "Available" means procurable by the operator of the process in question. It does not imply that the technique has to be in general use, but it does require general accessibility. It includes a technique which has been developed (or proven) at pilot scale, provided this allows implementation in the relevant industrial context with the necessary business confidence [59].
>
> "Techniques" involves both the plant in which the process is used and how the process is operated. It should be taken to mean the components of which it is made up and the manner in which they are connected together to make the whole. It also includes matters such as numbers and qualifications of staff, working methods, training and supervision and also the design, construction, layout and maintenance of buildings and will affect the concept and design of the process [59].
>
> "Not Entailing Excessive Costs" needs to be taken in two contexts, depending on whether it is applied to new processes or existing processes. Nevertheless, in all cases it means that best available techniques (BAT) can be modified by economic considerations when the costs of applying best available techniques would be excessive in relation to the nature of the industry and to the environmental protection to be achieved" [59].

2. "the use of plant will not cause significant air pollution..." in particular from the polluting substances listed in annex II of the directive: (i) SO_2 and other sulphur compounds, (ii) NO_X and other nitrogen compounds, (iii) CO, (iv) Organic compounds in particular hydrocarbons (except methane), (v) Heavy metals and their compounds, (vi) Dust: asbestos (suspended particles and fibres), glass and mineral fibres, (vii) Chlorine and its compounds and (viii) Fluorine and its compounds,

3. "none of the emission limits applicable will be exceeded", where emission limit values "means the concentration and/or mass of polluting substances in emissions from plants during a specified period which is not to be exceed".

4. "all the air quality limit values applicable will be taken into account", where air quality limit values "means the concentration of polluting substances in the air during a specified period which is not to be exceeded".

Articles 12 and 13 outline the responsibilities of the EC member states with respect to keeping track of new technological developments and the environmental situation. Based on the knowledge about technological and environmental matters, the member states are required to impose appropriate conditions (article 12) on plants authorised in accordance with the EC directive and to implement policies, strategies and measures for the gradual adaptation of these plants to the best available technology (article 13). These actions have to be taken with the consideration of the following aspects:

- "the plant's technical characteristics"
- "its rate of utilisation and length of its remaining life"
- "the nature and volume of polluting emissions from it"
- "the desirability of not entailing excess costs for the plant concerned having regard in particular to the economic situation of undertakings belonging to the category in question".

At the time of writing this thesis, The "UK National Air Quality Strategy" was being prepared according to the requirements of the Environment Act 1995. An outline of the "UK National Air Quality Strategy" can be found in reference [60].

3. NO_X CONTROL METHODOLOGIES

Nowadays, there are numerous NO_X control methods available. These can be grouped under two main categories: (i) Control of NO_X emissions by combustion modifications - based on the prevention of NO_X formation, or (ii) Control of NO_X emissions after combustion - based on the removal or destruction of the formed NO_X.

The main difference between the two categories is that the abatement of NO_X through combustion modifications is much less costly than that based on the flue gas treatment, primarily because of the low operating costs.

The main methods of both categories are summarised in this chapter.

3.1 Control of NO_X Emissions by Combustion Modifications

Control of NO_X emissions by combustion modifications can be achieved by: "Modification of operating conditions" (section 3.1.1), normally applied to existing boilers, and/or "Modification of design features" (section 3.1.2), mainly applied to boilers to be constructed. These are explained below:

3.1.1 Modification of Operating Conditions

(a) Low Excess Air Operation

Normally excess air is required to ensure complete combustion. Typical values of excess air operation are 20 to 30% or even higher for coal-firing [61], 2% for oil-firing and 8% for natural gas-firing [62].

Practical reduced levels of excess air operation vary considerably with the boiler specific characteristics. In the case of coal-firing, for example, practical minimum values of excess air operation can vary between 18 to 25% depending on burning characteristics of the coal types and ash slagging tendencies [63].

Given that low excess air operation requires minimal operational changes, it is a very convenient NO_X reduction method and it may even give the unit an increase in boiler efficiency [64] as it reduces the boiler flue gas loss.

Low excess air firing reduces local flame concentration of oxygen, thus reducing both fuel- and thermal-NO_X [65]. Limiting parameters to the extent of excess air reduction are flame stability, smoke, CO formation and carbon in ash. Even if smoke is not a problem, particulate emissions tend to increase at low excess air levels [66], limiting its trimming. Moreover, further quantities of excess air may occasionally be required to maintain steam temperatures at desired levels or to prevent damage to refractories or other sensitive parts [67], once more limiting the low excess air operation.

NO_X emissions from coal-fired boilers show a linear correlation with excess air. This correlation depends upon the unit design, but generally varies between 11 and 15% of NO_X reduction per 1% decrease in excess oxygen for most coal-fired units in the normal operating range [68]. On the other hand, CO and carbon-in-ash increase exponentially with decreasing oxygen levels.

(b) Staged Combustion

Staged combustion consists of burning the fuel with only a portion of the stoichiometric air in a first combustion stage, with the remaining air added later to complete combustion in a second stage. This principle is also referred to as two-stage or delayed combustion due to this "second" or "late" addition of the air. Throughout this thesis the term "staged combustion" is employed.

With the application of staged combustion, NO_X formation is restricted in two ways: (1) conversion of fuel-bound nitrogen and (2) thermal fixation of atmospheric oxygen and nitrogen. Therefore, significant reductions in both fuel- and thermal-NO_X can be achieved [65, 66]. This is due to the limitation of oxygen and lower flame temperatures in the primary combustion zone and lower temperatures in the secondary air-rich combustion zone [69].

Although staged combustion has been shown to be the most practical means of achieving reduced NO_X emissions from coal and other fuels with significant fuel nitrogen contents [70], possible corrosion effects and slagging must be considered. Also, recent work on staged combustion showed that this method is highly effective in reducing NO emissions particularly when the secondary air is injected in an established reducing atmosphere and that NO_X reduction is better with fine coal than with coarse coal [71].

Staged combustion can be accomplished in three different ways: (a) using burners out of service (BOOS) also widely known as biased-firing or off-stoichiometric combustion, (b) using overfire air (OFA) ports also known as NO_X ports and (c) by using burner biasing[1]. In coal-fired plants, NO_X reductions of 30 to 50% are possible with OFA ports or BOOS depending on design limitations [68].

(i) Burners Out Of Service (BOOS)

BOOS consists of operating some burners under fuel-rich conditions and some on air only. This is achieved by removing certain burners from service in a particular area of the furnace while continuing to supply air to that location. The original excess air level in the furnace is maintained [63].

Main limitations that often establish the degree of BOOS operation are (1) mill capacity to handle the extra coal flow to the remaining burners in service and (2) arrangement of the burners in the furnace that are associated with each mill, since it influences the choice of burner pattern (which may not be ideal for low NO_X emissions) [68]. Staged combustion by BOOS is therefore for boilers with spare mill capacity otherwise loss in generating capacity may be expected. Overloading mills when spare capacity is not available, should be avoided as it will result in burners operating outside design limits and in a degradation of the pulverised fuel quality leading to increased carbon in ash emissions.

In coal-fired boilers, NO_X reductions varying from 15 to 45% are possible depending on unit type, degree of staging and operating flexibility. For units with 24 burners or more it is possible to remove 15 to 25% of the burners from service, if the unit has spare mill capacity. This corresponds to a 20 to 30% reduction in NO_X [68]. It is important to note that BOOS efficiency is strongly dependent upon the firing pattern [68].

(ii) Overfire Air (OFA) Ports

Staged combustion can also be achieved by the use of OFA ports. In this system, typically 15 to 20% of combustion air is diverted to OFA ports normally located at a certain distance above the top burner row [68]. This results in the burners operating substoichiometrically, thus limiting NO_X formation. The possibility of diverting 20 to 40% of the air to OFA ports is being investigated for further NO_X reduction [72].

The reduction in NO_X emissions with this technique is variable, depending on the boiler type and design and the method of OFA application, but normally it varies between 10-25% [73]. However,

[1] In order to distinguish the staged combustion approaches (a) and (c) which are distinct but both referred to as "biased-firing" in the literature, the terms "BOOS" and "burner biasing" will be used for (a) and (c), respectively, in this work.

in a tangentially-fired boiler, the application of OFA ports is reported to give an average NO_X reduction of 38% for coal- and oil-fired-furnaces and 50% for natural gas [63].

The main disadvantage of OFA ports is the cost of installation, as OFA ports need to be fitted with special nozzles in order to ensure adequate mixing of the OFA in the combustion process for an adequate burnout.

(iii) Burner Biasing

In addition to BOOS and OFA ports, burner biasing has been reported as another means of staged combustion [68]. Here staged combustion is achieved by reducing the coal flow on a number of mills and by increasing coal flow through the remaining others. It is reported to be less effective than BOOS and OFA ports, giving 8% NO_X reduction for horizontally-opposed furnaces and 7% for single face-fired furnaces [68, 74].

(c) Low NO_X Burners (LNBs)

In the past coal-fired boilers were designed to save capital costs by minimising the boiler furnace volume. This was compensated by the design of highly turbulent burners in order to ensure maximum complete burnout and desired output [75]. Burners were designed with register vanes and impellers to be used as turbulisers, ensuring rapid mixing and high temperatures [76]. This resulted in the so called premixed flame which inevitably led to high NO_X emissions.

With the new NO_X legislation, new burners had to be designed in order to minimise NO_X formation whilst continuing to maximise carbon utilisation. Nowadays there is a wide variety of designs from different manufacturers for retrofit and new applications.

Babcock & Wilcox (B&W), for example, started by developing the DRB (Dual Register Burner), aiming at low NO_X emissions while continuing to maximise carbon burnout. This was followed by the DRB/Compartmented windbox, a system in which the compartmented windbox controls fuel and air flows to each burner group, providing the flexibility to operate with low excess air and maintain an oxidising atmosphere around each burner [76].

Additional B&W low NO_X burners for new and retrofit utility applications were developed. These included the enhanced ignition dual register burner (for difficult to burn fuels) and the Hitachi-NR burners (for further NO_X reduction relative to the DRB) for utility applications. For retrofit applications, the low-NO_X cell burner was created [77]. Later the XCL (aXial-Controlled-Low NO_X) burner was developed, reducing NO_X emissions about 25% below that of the earlier DRB designs [78, 79].

Other manufacturers like "Foster Wheeler" (FW) [80, 81, 82], "Hamworthy" [83] and many others also presented their own designs of low NO_X burners.

Clearly there are many different designs of LNBs, but despite the variety they all work on the same principle. LNBs reduce fuel-NO_X [72] by generating a diffusion flame. They work by delaying the mixing of air and fuel allowing the fuel to devolatilise in a fuel-rich environment and reduce the peak flame temperature [54], therefore reducing both fuel- and thermal-NO_X. This is achieved within the burner envelope by staging either the fuel (staged fuel burners) or the air (staged air burners) [84]. In the case of the air-staged burners, the combustion air is divided into a number of streams and the fuel is projected into the internal recirculation zone (IRZ). The IRZ is a reverse flow region which in a LNB has a low oxygen concentration since it is fed by the combustion products (Fig. 3.1) [85].

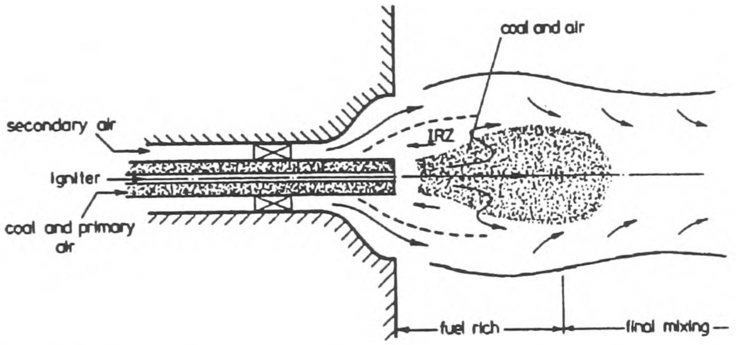


Fig. 3.1: The IRZ of an aerodynamically air-staged burner [85].

Penetration of the IRZ is possible either by increasing the fuel momentum or by adjusting the position of the coal injector [85]. Once in the IRZ the fuel devolatilises and the reaction paths from volatile nitrogen species to N_2 are favoured [86]. The fuel type is an important factor in terms of the IRZ: Generally, high volatile coals will devolatise rapidly within the IRZ. Therefore, the IRZ must be larger for low volatile coals to enable devolatilisation within that zone.

LNBs are applicable to all fuels and give a NO_X reduction of 30 to 50% [73, 87]. Additionally, they are a very attractive option since they are relatively cheap and easy to install. However, retrofitting LNBs may require certain modifications in the combustion plant which may not be possible in some cases, such as mills and windbox alterations.

(d) In-Furnace-NO_X-Reduction (IFNR)

In-furnace-NO_X reduction (IFNR) also known as fuel-staging or reburning is a very powerful NO_X reduction method. NO_X emissions with IFNR are extremely low: 15 to 40 ppm on natural gas, 40 to 60 ppm on oil and 50 to 100 ppm on coal [77].

In reburning the combustion is divided into three zones (Fig. 3.2): In the primary zone the main (or primary) fuel is burned in an oxidising or slightly reducing atmosphere producing NO_X. In the reburning (or secondary) zone, the reburning fuel (which may be different from the primary fuel), is injected in a substoichiometric atmosphere producing hydrocarbon radicals which will then react with the NO_X produced in the first combustion zone. The amount of the reburning fuel is normally 10 to 20% of the total fuel (in terms of net heat input). Finally in the tertiary zone, air is injected through OFA ports to complete burnout [72, 88, 89, 90].

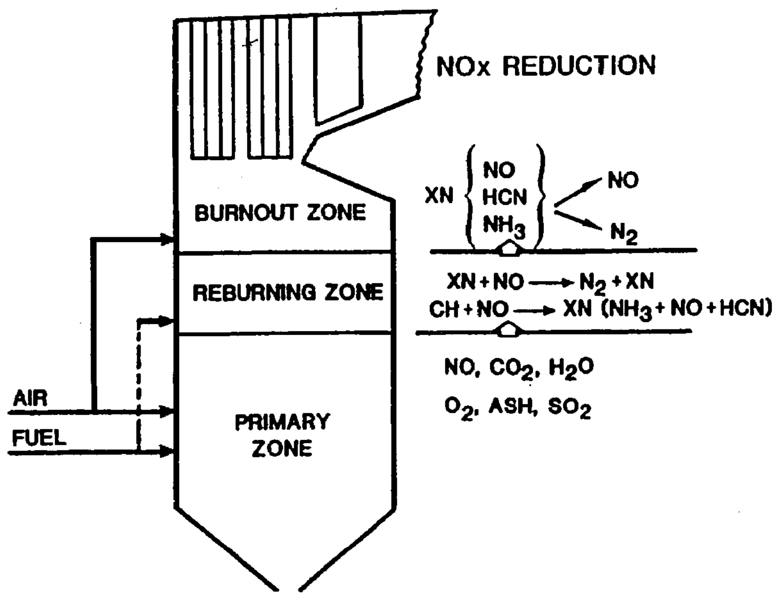


Fig. 3.2: Reburning principle [91].

There are several optimal conditions required for a successful application of reburning [89]. For example in the reburning zone a residence time of at least 400 ms is required [88, 92], whereas in the tertiary zone a residence time of 700 ms to 900 ms is necessary to complete combustion [89]. High furnace temperatures are also needed to favour molecular nitrogen formation. It is reported that the reburning fuel and reburning air must be injected at a furnace temperature of 1400 ± 50°C and 1300 ± 50°C respectively, to ensure complete burnout prior to the superheater [88]. Additional conditions required for successful application of reburning are given in [89].

IFNR can be used on all fossil fuel-fired boilers. As a reburn fuel, natural gas has been shown to give the best results in reducing the NO_X levels [89, 93]. Additionally, gas has the advantage that it is less complicated to supply to the upper parts of the boiler and of taking less time to burn-out [73]. Recent research, however, reports on a marginally better performance of heavy oil as a reburn fuel [94]. Other fuels under investigation for use as reburn fuels are coal, wood and peat [89].

IFNR requires burners to incorporate the reburn fuel, OFA ports and the corresponding furnace height above the burners. This means complex installations and high costs. Although it is a very effective technique, IFNR is currently not widespread in UK partly because UK boilers do not have the required height, since they were designed on the basis of high heat release rates resulting in boilers of small dimensions.

(e) Flue Gas Recirculation (FGR)

FGR consists of recirculating combustion gases from the economiser outlet to the windbox so that it flows through the firing burners into the primary combustion zone. Alternatively the combustion gases can be injected directly into the flame zone. It works by lowering the overall flame temperature and by diluting the oxygen in the air, affecting mainly thermal-NO_X. It has little or no influence on the control of fuel-NO_X [72, 95, 96]. FGR performance depends therefore on the type of fuel being burnt, being more effective with gas and oil than with coal [97].

The optimum amount of recirculation is around 20%. Higher amounts give little gains in NO_X reduction, increased probability in CO and hydrocarbons emissions and flame instability [98].
On coal-fired units the application of 15 to 20% of FGR is reported to reduce NO_X emissions by around 15% when applied as an individual control measure at high NO_X levels. However, its effectiveness decreases when used with staged combustion and at lower initial NO_X levels [68, 99].

FGR is not a very attractive NO_X control technique in utility boilers due to the cost of plant modification, tube erosion (in long term use), efficiency penalty of approximately 1% (due to the auxiliary load to drive the recirculating fans) and maintenance considerations [68]. Moreover, FGR requires a redistribution of the heat transfer since there is a reduction in radiant heat transfer (due to the lower temperatures) and an increase in convective heat transfer (due to the larger flow rate of flue gas) [98].

FGR has been used for many years to control the heat distribution in the boiler. Its aim was to increase convective heat available in the convective parts of the boiler, mainly superheater and reheater, at reducing firing rates. In this application, the flue gases were normally drawn from the economiser outlet and then supplied to the furnace through ports in the furnace bottom. In this case any reduction of NO_X is coincidental and not the primary purpose.

(f) Effective Sootblowing

A boiler with clean walls will tend to produce less thermal-NO_X. This can be explained by the fact that heavily fouled furnace walls result in a reduced heat transfer, therefore increasing the peak flame temperature and consequently thermal-NO_X formation. Hence, effective sootblowing is a useful way of reducing NO_X emissions.

(g) Load Reduction (or Derating)

Operating boilers at lower loads is known to reduce NO_X emissions. This overall decrease in NO_X levels is the result of two counteracting effects. On one hand, there is a decrease in the net combustion intensity (or volumetric heat release rate) as a result of the lower loads. This lowers peak flame temperatures [96] and thus thermal-NO_X [69]. On the other hand, there is an increase of fuel-NO_X emissions due to the increased availability of oxygen typical of low loads [69, 84]. Low loads require higher excess air levels than full load, in order to obtain superheat and reheat temperatures (by an increased mass air flow) and to improve combustion intensity which has been diminished by the decrease in overall temperature (see Fig. 3.3).

In general, lower loads result in reduced NO_X emissions per unit weight of fuel. The relationship between specific NO_X emissions and load is reported to be a little more than proportional to load for gas-fired units and a little less than proportional to load for coal- and oil-fired units [11]. Similar findings are reported by other workers who found that the NO_X reduction for a 25% reduction in load was 50% on gas-fired units and 25% on coal- and oil-fired units [63]. Moreover, others report that reducing load in coal-fired boilers reduced NO_X emissions by a lower percentage than the percentage reduction in load, but only for gas-firing was the percent NO_X reduction greater than the percent load reduction [69].

This difference in behaviour between fuels can be explained by the fact that fuel-NO_X is relatively load insensitive [11]. Coal- and oil-fired units produce more fuel- than thermal-NO_X. Since load reduction affects mainly thermal-NO_X, it is obvious that such a reduction will affect more significantly the gas-fired units which produce only thermal-NO_X.

Although effective, NO_X reduction by lower loads reduction is an economically unattractive method, since it carries a capital cost associated with underutilising the equipment [11]. Additionally, there is a loss of plant efficiency with lower loads which is related to the operation of the steam turbines at reduced loads [100]. Also, it is important to note that the relationship between load and NO_X emissions can vary significantly with boiler design [68, 74], as explained in section 3.1.2).

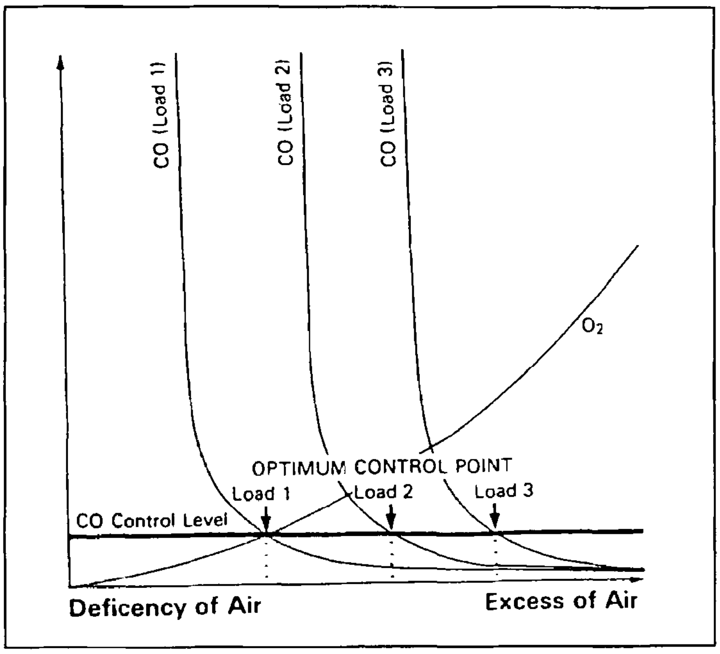


Fig. 3.3: Relationship between boiler load, CO and excess air [101].

(h) Air Preheat

In pulverised coal combustion air preheat is necessary to increase the rate of combustion. However, high preheat temperatures result in an increased flame temperature and subsequently increased NO_X emissions, mostly thermal-NO_X [11]. This is why reduced air preheat as a means of reducing NO_X, is less significant with oil- or coal-firing than with gas-firing [63].

The effect of air preheat on NO_X emissions in a coal-fired boiler, has been shown to be very much dependent on the levels of excess air [102]. Armento and Sage [102] reported that at high excess air levels, NO_X emissions increased around 260 ppm when preheated temperatures rose from 350° F to 650° F (176° C to 343° C), whereas at normal excess air levels, NO_X actually decreased (around 40 ppm) for the same temperature rise.

Air preheat as a means of NO_X control has some drawbacks. Although it has the potential to reduce NO_X emissions, a significant efficiency penalty of 1% per 40°F (1% per 4.4° C) is to be expected [87]. Additionally, in coal- or oil-firing elimination of air preheat is expected to increase particulate emissions [63]. Finally, the approach is not very practical, because the operator can usually only vary air preheat temperatures within narrow limits without upsetting the thermal balance of the system [96] and combustion rate.

(i) Steam or Water Injection Operation

Another means of controlling NO_X formation, is by injection of steam or water into the furnace. This reduces peak flame temperature and thus reduces thermal-NO_X [98]. Water is usually preferred due to its greater thermal effect and lower price [9] and it has been shown to be effective in gas-fired units, however, it is less effective with coal or oil since it primarily reduces thermal-NO_X formation [63].

Nevertheless, steam/water injection in boiler plants presents serious disadvantages such as a lower thermal efficiency, increased corrosion of equipment [9], fan power requirements for increased mass flow [87] and large quantities of water/steam.
This method is therefore mainly applied in internal combustion engines and stationary gas turbines (with NO_X reductions up to 80%) [9, 98].

(j) Combination of Combustion Modification Techniques

The application of NO_X control methods in combination is not linearly additive [68, 74, 103]. Generally, the total yield of NO_X reduction from a combination of NO_X reduction techniques varies widely with the type of fuel and with the combination itself [97, 102].

From the various combinations of NO_X reduction methods, the most powerful is the use of staged combustion in conjunction with low overall excess air for all fossil fuel types, as it affects the formation of both thermal- and fuel-NO_X [64, 69, 97].

3.1.2 Modification of Design Features

NO_X levels are not only dependent on boiler operation but also on its design. There are various boiler design features that have a great impact on NO_X formation. Modification of such features, however, are mainly considered in the design phase of new units, whereas the reconstruction of existing units is normally not feasible due to the extensive costs.

Main boiler design parameters which affect NO_X formation are: (1) the location and spacing of the burners within a multiple burner system, (2) the presence of division walls, (3) furnace volumes (4) the burner design and (5) the fuel and combustion air distribution within the furnace.

The first three parameters (1, 2 and 3) are related to the heat absorbing characteristics of the furnace. Closely spaced burners especially in the middle of multiple burner furnaces, result in a lower ability to radiate to cooling surfaces [67]; in the same way, small furnace volumes and/or the absence of furnace division walls mean reduced heat absorbing surfaces, resulting in higher flame temperatures and consequently increased thermal-NO_X formation.
Heat release rates per surface area must therefore be taken into account in the design of low NO_X boilers. There are various definitions of this "heat release rate per surface area", such as the "Burner Zone Liberation Rate (BZLR)" [104, 105, 106], the "Burning Area Heat Release (BAHR)" [107, 108] and the "Primary Burning Zone" [109]. Although these definitions differ slightly, they all contain basically the same information.

Burner design (parameter 4) also affects NO_X emissions. Fortunately, nowadays low NO_X burners present a relatively easy and cheap option (previously discussed in section 3.1.1(c)).

Finally, the fuel and combustion air distribution within the furnace (parameter 5) is another boiler design parameter which affects NO_X emissions. The manner in which the fuel and combustion air is admitted and distributed in the furnace will determine important factors for NO_X formation such as local stoichiometries and the intensity of combustion. An example is the inherently air staged combustion of the down-fired-furnace, which generates characteristically low NO_X emissions (detailed discussion in section 4.1.2).

Due to the various design parameters, different furnace types yield therefore characteristically distinct NO_X levels, as shown in Fig. 3.4:

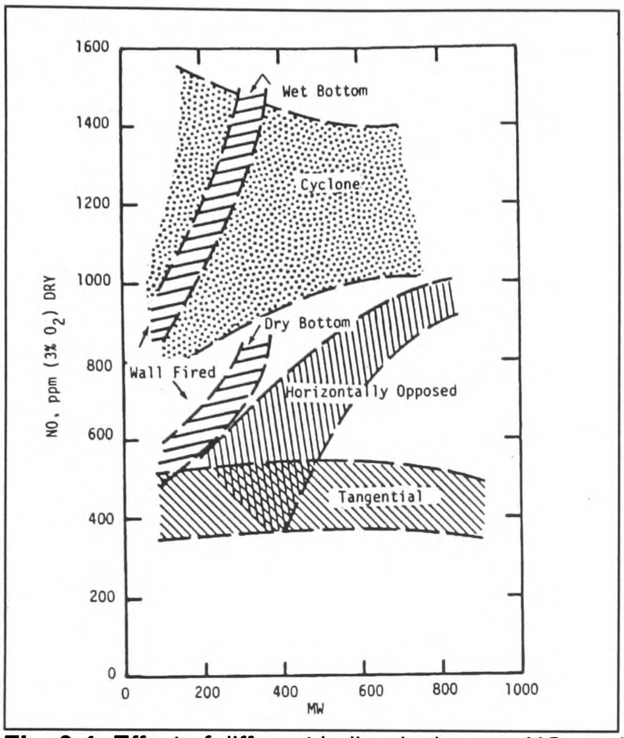


Fig. 3.4: Effect of different boiler designs on NO_X emissions [68].

3.2 Control of NO_X Emissions Post-Combustion

This section details two post-combustion NO_X control methods currently used in industry and gives an overview of the various processes for combined NO_X and SO_2 control that are still in the research and development phase.

3.2.1 Selective Catalytic Reduction (SCR)

SCR is a very effective method of NO_X reduction, capable of 80 to 90% NO_X reduction while not affecting boiler operation [110, 111]. This technology was first developed in Japan [89, 90] and is now used worldwide.

SCR consists of a heterogeneous gas phase reaction, in which ammonia (NH_3) usually diluted with air or steam is injected into the flue gas after the economiser. The resulting mixture is then passed through a fixed bed catalyst, where NO_X is selectively reduced by NH_3 and oxygen (O_2) to molecular nitrogen (N_2) and water (H_2O). There are various types of catalysts, but the main ones currently in operation for coal combustion are titanium oxide based, iron oxide based, zeolite and activated carbon/coke [72, 89].

SCR chemistry may be represented by 5 different reactions, from which the following is the dominant one [112]:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad \textbf{Eq. 3.1}$$

The optimum temperature for the reaction is about 1000°C, however, the catalyst reduces the reaction temperature to 350-400°C [113]. To obtain flue gas temperatures in this range, the catalyst is normally located between the economiser and the air preheater. This location is known as "high dust location", however, other locations are also possible such as the "low dust location" and "tail end location" [90].

One of the main concerns of SCR, is the carryover of NH_3 and the possible formation of ammonium sulphate ($(NH_4)_2SO_4$) and ammonium bisulphate (NH_4HSO_4). These will form if SO_3, NH_3 and H_2O are present in sufficient quantities and if the flue gases cool to the formation temperature [25, 112].

Both ammonium sulphates and ammonium bisulphates can deposit on the catalyst layers and downstream equipment, causing fouling, erosion, reduced heat transfer and equipment performance deterioration. Additionally they can contribute to an unacceptable flue gas since they are not completely removed by the electrostatic precipitators [25, 112].
To avoid $(NH_4)_2SO_4$ and NH_4HSO_4 formation, residual levels of ammonia are therefore kept at or below about 5 ppm [98].

A main SCR disadvantage is its high cost due to the large amounts of NH_3 needed. As an example, a 2000 MWe power station would require about 15 tonne/day [98], however, this must be compared with its main advantage - the high NO_X reduction.

3.2.2 Selective Non-Catalytic Reduction (SNCR)

There are many types of SNCR, each using a different reducing chemical [114, 115]. Two of the most commonly applied are the ammonia-based (NH_3) system, also known as Thermal DeNOx and the urea-based ($CO(NH_2)_2$) system, also known as NOxOUT [84].

SNCR consists of a homogeneous gas phase reaction [116, 117], in which NO_X is controlled through thermal reactions using the appropriate reducing chemicals. For the most common chemicals the temperature window for the reactions to take place is 900-1100°C [89].

In the ammonia-based system, for example, nitric oxide is reduced by ammonia and oxygen without the use of a catalyst. The optimum temperature for the reaction to occur is between 927 to 1028°C [25], however, this temperature can be lowered to about 740 to 760°C by injecting readily oxidisable gas such as H_2 with the NH_3 [118].

In the ammonia-based system, the overall reaction may be written as [116]:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \qquad \textbf{Eq. 3.2}$$

However, a competing oxidation reaction also occurs [116]:

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O \qquad \textbf{Eq. 3.3}$$

There is a delicate balance between these competing reactions. At the correct temperature the balance is favourable and reduction of NO_X can be achieved. At temperatures below the temperature window, ammonia can be formed whereas at higher temperatures more NO_X can be produced [116].

When compared to SCR, the SNCR technique has various disadvantages. Main disadvantages are a lower NO_X removal (40 to 60%) and a higher consumption of chemicals (NH_3:NO_X ratio of 3:1 - unlike a ratio of 1:1 as in the SCR [113]) which thereby may originate more problems with NH_4HSO_4 [118].

SNCR can also present practical difficulties when applied to large boilers. The high reaction temperature required in this process can only be achieved by injecting the NH_3 directly into the upper portion of the boiler [25]. However, during changing loads, injection points at the correct temperature for the reducing chemicals can be a problem, as well as ensuring uniform injection and mixing [89].

3.2.3 Combined SO_X and NO_X Processes

There is a wide variety of processes that have been developed for combined denitrification and desulphurisation of the flue gases. Most of them are currently under investigation. These processes can be grouped in six main categories, as follows:

(a) Solid Adsorption

Solid Adsorption processes are based on the use of a recirculating (i.e. regenerated) solid sorbent material to adsorb both NO_X and SO_2 from the flue gas. Most processes are capable of high SO_2 and NO_X removal levels. Sorbents used include activated carbon or coke, alumina-based sorbents with additives (such as copper oxide or sodium) and magnesium oxide-based sorbents [119].

In general SO_2 binds to the sorbent, and results in either sulphuric acid, sulphur or liquefied SO_2. NO_X on the other hand is reduced to nitrogen, but the technique for NO_X reduction varies with the process: NO_X can either be (i) catalytically reduced in the adsorption step by the addition of reducing agents, or (2) absorbed from the flue gas and reduced during sorbent regeneration [119]. Examples of processes in this category are various such as: the NOXSO process (anticipated to remove 90% of SO_2 and NO_2 from the flue gases [89, 120]), copper oxide process [89, 90], activated coke process [90], activated char process [119], "Nelsorbent" SO_X/NO_X control process [119] and the Bergbau Forschung GmbH and Foster Wheeler-process [118, 121, 122].

(b) Irradiation of the Flue Gas

Irradiation of the flue gas produces reactive intermediates that oxidise SO_2 and NO_X to their respective acids: ammonium sulphate or dry calcium sulphite/sulphate in the case of SO_2 and ammonium nitrate or dry calcium nitrate solids in the case of NO_X [119].

There are various processes in this category. For example, in the USA, Japan and Germany, an electron beam radiation process known as the "Electron-beam Dry Scrubber or E-beam" [121], is being developed for removal of both SO_2 and NO_X from the flue gas [118, 121]. Major disadvantages of this process include high capital and operating costs, waste disposal problems and low (< 80%) SO_2 removal [118]. In Denmark and Italy, another irradiation process using the corona effect is under development [89]. In this process an electrical pulse is used to develop a corona discharge in a reactor. Additional techniques for flue gas irradiation include the use of microwave and ultraviolet radiation [119].

(c) Catalytic Operations

The processes in this category use a fixed catalyst bed (or beds) to remove SO_2 and NO_X from the flue gas. In all processes SO_2 is converted to sulphuric acid or sulphur and NO_X reduced to nitrogen [119]. The processes for catalytic combined denitrification and desulphurisation are various, such as the Danish SNOX [123] and the German DESONOX [89]. The Danish SNOX process, for example, is a catalytic process for simultaneous removal of SO_2 and NO_X, with removal efficiencies of 95% and of 90% respectively [111, 124].
Another known process is the Hot Catalytic Scrubbing Baghouse [125], also known as SOxNOxROxBOx or SNRB. The SOxNOxROxBOx removes sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulates (ROx) emitted from fossil-fired boilers or other processes. All three removal processes are combined in a single device named high-temperature baghouse (BOx) [110] which operates according to the adsorption/desorption and the SCR principle [111, 126]. Removal efficiencies are 70-90% for sulphur, 90% for NO_X and 99% for particulates.

Other processes include the "Parsons Flue Gas Cleanup Process" and the "Lehigh University Low-temperature SCR Process" [119].

(d) Electrochemical Operations

At present only one process of this type, the "IGR/Helipump Solid-state Electrochemical Cell", is capable of both SO_2 and NO_X removal. In this process NO_X is reduced to nitrogen and SO_2 results in either sulphuric acid or sulphur.

The "IGR/Helipump Solid-state Electrochemical Cell", still in its early stages of development, uses a solid-state electrolytic cell with a ceramic electrolyte. In the cathodic zone of the cell, electrochemical reduction of SO_2 and NO_X yields sulphur, nitrogen and oxygen ions (which dissolve in the solid electrolyte), whereas in the anode, oxide ions are converted to oxygen gas. All three products (sulphur, nitrogen and oxygen) remain in the flue gas [119].

(e) Alkali Injection Operations

There are various processes, still in the development phase, that use alkali Injection for SO_2 removal from the flue gas. NO_X can also be removed if an additive containing sodium is included. In these processes nitrogen oxides are converted to nitrogen and soluble nitrates or sulphur-nitrogen compounds, whereas SO_2 results in dry calcium or sodium-based solid waste

Two main processes are currently under investigation: (i) "spray drying" [89] and (ii) dry injection of sodium compounds into the flue gas leaving the air heater, which is particularly useful for low sulphur applications. At present, these processes have relatively low NO_X removals (< 50%). Furthermore, high SO_2 removals (> 90%) may be difficult to obtain when NO_X removal is maximised. Also, both processes can result in the formation of a visible and thus undesirable brown plume, due to oxidation of NO to NO_2. Therefore, the injection of ammonia or urea with the sodium sorbent is being investigated in order to reduce the tendency for plume coloration [119].

(f) Wet Scrubbing

Wet Scrubbing processes are also known as chemical scrubbing or as wet systems [121]. They are used to absorb both SO_2 and NO_X from the flue gases: NO_X is converted to nitrates, nitrogen-sulphur salts or nitrogen and SO_2 results in calcium sulphite/sulphate or ammonium sulphate [119]. However, due to the low solubility of NO, special measures must be taken. These include:

1. the oxidation of NO to NO_2 in either gas or liquid phase before it can be absorbed into an aqueous solution (applied in the Oxidation-Absorption-Reduction-, Absorption-Oxidation- and Oxidation-Absorption-processes [118]), or
2. the use of additives to increase the solubility of NO (applied in the Absorption-Reduction-processes [118]).

These two measures allow the classification of the various processes in two groups. The first group of processes (Oxidation-Absorption-Reduction-, Absorption-Oxidation- and Oxidation-Absorption-processes) utilise an oxidant such as ozone, chlorine dioxide or hydrogen peroxide to oxidise NO to NO_2, since NO_2 is more soluble than NO in the scrubbing solution. Main disadvantages are the high cost of the oxidation procedure and the fact that the by-products contain nitrates and nitrites which gives disposal problems [121].

The second group of processes (Absorption-Reduction-processes) consists of the use of a water-soluble ferrous-chelating compound as a catalyst to aid in the absorption of the relatively insoluble NO [118]. An example of such additives is the iron EDTA (ethylene diaminetetraacetic acid) [89, 121]. Main drawbacks of this process are the requirement of extensive equipment, the need of a high gas-liquid contact time and sensitivity of the NO_X removal efficiency to flue gas composition (particularly O_2 and SO_2 concentrations) [118]. Like the Oxidation-Absorption-Reduction-processes, these processes have the potential to remove 90% of both SO_2 and NO_X [113].

4. INTER-RELATION BETWEEN DOWN-FIRED-FURNACES AND ANTHRACITE COAL

Down-fired-furnaces and anthracite/semi-anthracite coals are intimately linked. Due to capital costs and combustion efficiency, down-fired-furnaces generally only burn anthracite or semi-anthracite coals and in the same way, anthracite/semi-anthracite coals are only burnt in such furnaces. This, however, has not always been the case.
The historical development and combustion characteristics of the down-fired-furnace design and of the anthracite/semi-anthracite coals is given here, as follows:

4.1 Down-fired-furnaces

Down-fired-furnaces are known for their unique arrangement in which pulverised coal and transport air are injected downwards from an arch, with the remaining combustion air added through the furnace front- and/or rear- wall(s), i.e. wall(s) below the firing arch(es). These furnaces are also known as arch-fired-, roof-fired-, vertically-fired-, down-shot-, J- or U- or W-shape-flame- (depending on the number of arches) and as down-fired-sequential-air-addition-furnaces (DSAA furnaces). Throughout this work, however, the term "down-fired-furnace" is always employed.

4.1.1 Development of the Down-fired-furnace Concept

The concept of down-fired-furnaces developed from the first application of pulverised coal combustion to the steam generation, which was successfully demonstrated in Milwaukee in 1918, when a conventional travelling grate stoker was modified to allow pulverised coal combustion by removing the grate and extending the furnace into an ash pit [127].

Two major modifications resulted in the down-fired-furnaces of nowadays. Firstly, due to convenience and space limitations, the burners were oriented vertically in the furnace arch resulting in the U-shape flame. Secondly, a portion of the combustion air was diverted to the furnace front-wall and screen tubes were installed across the lower furnace. The second modification aimed at lowering the high temperatures within the furnace which had resulted in severe slagging and erosion along the furnace front-wall and bottom. These high temperatures were the result of the totally refractory lined furnace walls, which were typical of this period and believed to promote rapid combustion of the coal particles [70]. The resulting furnace configuration is shown below (Fig. 4.1).

These modifications therefore introduced not only the down-fired-furnace concept (due to the burners' position and front-wall air addition) but also the concept of waterwall furnace tubes which nowadays is an integral part of modern boiler designs.

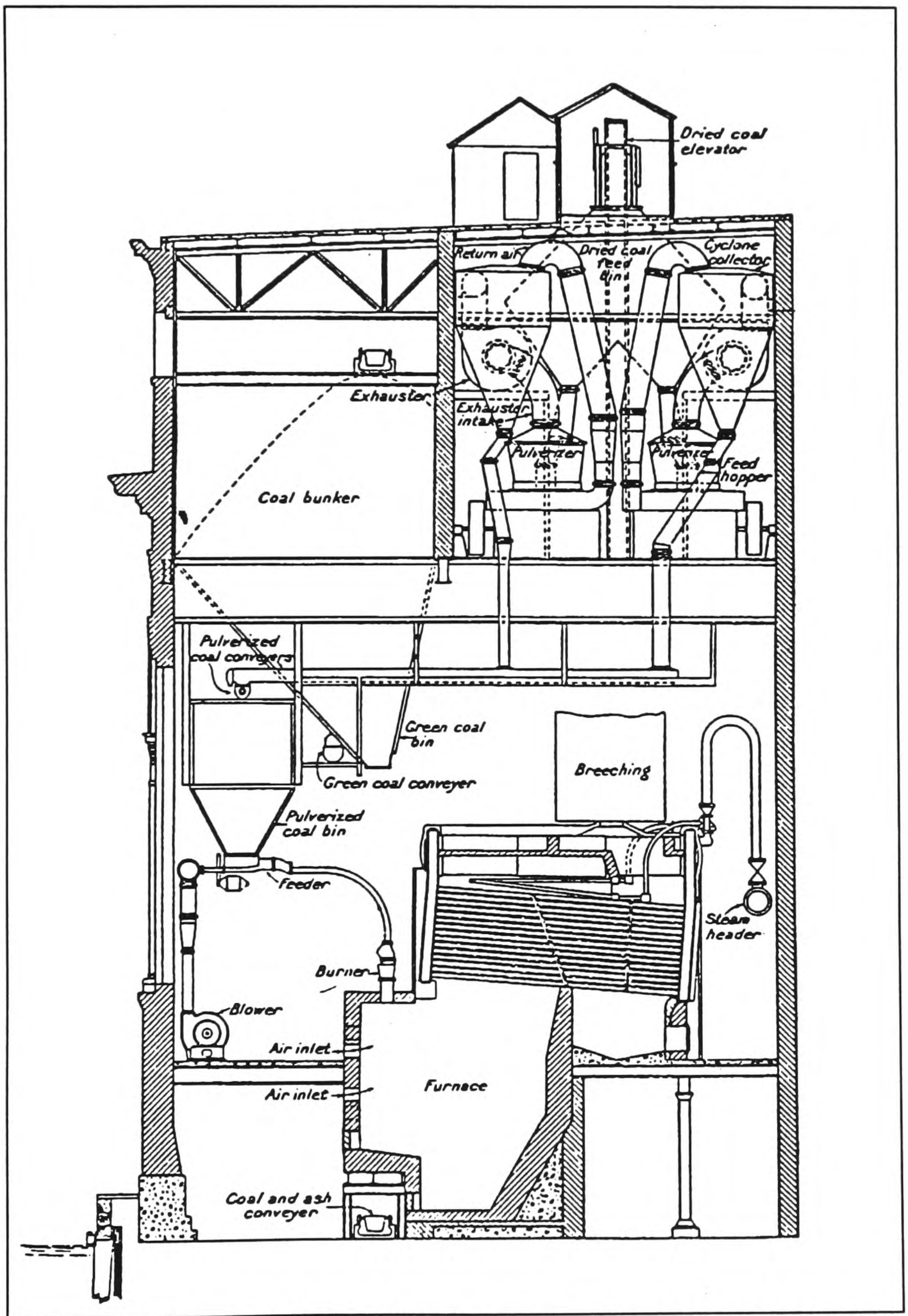


Fig. 4.1: Original application of pulverised coal combustion to steam generation [70].

Down-firing as a practical means of pulverised coal combustion for the steam generation was then promulgated and accepted [128, 129, 130] due to its ability to maintain a self-sustaining flame, which at the time was one of the major problems with the then new technology [131]. Further acceptance of the down-fired configuration was diminished by the development of the highly turbulent pulverised coal burner and of tangential-firing, which offered reduced furnace volumes for the same heat input of down-fired-furnaces, thus lowering initial capital investment [70].

Main design differences between the down-fired-furnaces are the burner design, combustion air distribution, arrangement of the burners, presence of division walls and the number of firing arches [70]. The firing arches can be either refractory lined or water cooled. When burning anthracite, however, the down-fired-furnaces normally have a refractory lined arch [131].

Nowadays down-fired-furnaces are mainly applied in the combustion of anthracite and semi-anthracite coals, but also in the combustion of other lean fuels such as high moisture or high ash content coals. This is due to cost considerations and to the specific furnace design, which enables a stable flame with such difficult to burn fuels [104, 131].

4.1.2 The Characteristic Low NO_X Emissions of Down-fired-furnaces

Unlike other furnace designs, down-fired-furnaces have characteristically low NO_X emissions. Such low NO_X emissions are due to two main design factors: (i) an inherently staged combustion and (ii) large furnace volumes as well as in some cases the presence of furnace division walls.

The inherently staged combustion results from a late and sequential addition of the front- and/or rear-wall[1] air, known as secondary air: only part of the combustion air (primary and tertiary air) is provided at the burners with the remaining air (secondary air), around 60% [132] or 80% [133] of the total combustion air, being supplied at a later stage into the flame. Lower fuel- and thermal-NO_X emissions are then achieved. This inherent staged combustion can be divided in three main regions:

(a) Near burner region: coal/air jet region, prior to any entrainment of the front- and rear-wall air. Thus, in this region the amount of NO_X formed (mainly fuel-NO_X) is very much dependent on the burner type. Simple burner designs produce a coal/air jet, which disintegrates soon after it enters the furnace, thus leading to high NO_X emissions. More complex burners maintain the integrity of the fuel-rich central core until deep in the furnace, therefore limiting NO_X production [70, 133, 134].

[1] Front- and/or rear-walls refer to those walls below the firing arches.

(b) Intermediate region: region of entrainment of the front- and rear-wall combustion air into the flame jet. It has been shown that buoyancy forces in this region tend to drive the relatively cold front- and rear-wall air down the walls, delaying mixing with the flame jet until into the lower furnace regions [133]. This not only allows the walls to be oxidised during boiler operation [104], but also creates an oxygen deficient flame that can be substoichiometric over much of its length [104], thus limiting fuel-NO_X formation. Thermal NO_X is also reduced, due to an extended heat release zone covered by the long flame path and less intense combustion.

(c) Lower furnace combustion region: final region corresponding to a complete burnout of the fuel prior to exiting the furnace [70, 133].

The second design parameter, large furnace volumes and/or furnace division walls, also contributes to lower NO_X emissions, in particular thermal-NO_X. This is due to an increased heat absorbing surface [70] and reduced heat release intensity [131], which lowers the bulk flame temperature and consequently reduces NO_X formation rates.

4.1.3 The Characteristic High Unburnt Carbon Levels of Down-fired-furnaces

In addition to the characteristic low NO_X levels, down-fired-furnaces also have consistently high unburnt carbon levels [135]. Such high levels of unburnt carbon are believed to be the result of a combination of factors: (i) combustion aerodynamics, (ii) furnace proportions and (iii) the fuel combustion properties:

With respect to combustion aerodynamics, it has been speculated that high unburnt carbon levels could be due to buoyancy forces, existent below the arches, lifting product gases and char particles out of the jet streams prior to penetration to the lower furnace regions [70]. This consequently reduces the residence time of these particles, leading to incomplete combustion.

Furnace proportions, on the other hand, have been shown to be responsible for an unbalanced combustion flow pattern in down-fired-furnaces. Inevitably, this leads to an uneven fuel residence time, thus contributing to high unburnt carbon levels [136].

Finally, fuel combustion properties can also determine unburnt carbon levels. Anthracites or semi-anthracites are coals with a difficult combustion behaviour - slow ignition and burnout and difficulty in ensuring flame stability, therefore needing high residence times in the furnace, which when shortened also lead to unburnt carbon.

In an attempt to reduce unburnt carbon levels, coal-fired boilers are usually operated with high excess air levels, which inevitably contributes to high NO_X levels. Typically excess air levels in coal-fired boilers vary between 20 and 30% or even higher [61], depending on the furnace specific characteristics. At Aberthaw, the boiler normally operates with 40% excess air.

4.2 Anthracite and Semi-Anthracite Coals

It is known that anthracites and semi-anthracites coals are typical of down-fired-furnaces. But how did they evolve as a fuel for pulverised coal combustion? Also, what are their combustion characteristics and NO_X emission levels? - Answers to these questions are discussed below.

4.2.1 Development of Anthracites/Semi-Anthracites as a Pulverised Fuel

Until about 1931-32, anthracite had been generally regarded as a refuse product due to its characteristically difficult combustion behaviour. However, developments towards an intensive use of anthracite for power generation were then initiated because of the large quantities of this fuel that were available over a long period of time [137].

From combustion studies of pulverised anthracite duff in collieries, it was concluded that combustion of pulverised anthracite required: (i) rapid ignition of the coal particles, (ii) a rich coal/air jet mixture in order to ensure a hot zone in the furnace to maintain ignition and ensure flame stability and (iii) a long flame path to ensure complete combustion [137]. These requirements clearly indicated the suitability of the down-fired-furnaces for these coals, since:

(i) In the down-fired-furnaces, rapid ignition of the coal particles is achieved by recirculation of combustion products into the burner zone (through furnace aerodynamics) and by radiation of heat into the burner zone by the use of a refractory wall.
Work with pulverised anthracite and down-fired-furnaces showed the importance of recirculating combustion products into the pre-ignition zone of the coal/air jet, in order to heat up the pulverised coal to ignition temperature [134, 138]. Additionally, this flue gas recirculation into the flame jet was shown

to be of greater importance for lean coals, since the flame front develops further downstream from the burner [134]. Furthermore the need of a closely situated refractory wall to radiate heat into the burner jet, thus ensuring a self sustaining ignition, was also demonstrated [138, 139].

(ii) A rich primary coal/air jet is essential to ensure a hot zone in the furnace in order to maintain ignition and ensure flame stability.
The rich primary coal/air mixture is normally attained by a set of cyclone-separator burners. Coal is transported to the cyclone-separator burners located on the firing-arch, where most of the primary air is separated from the coal, forming a very dense stream of coal [104].

(iii) Finally, the long flame path characteristic of down-fired-furnaces, gives the coal particles a high furnace residence time, thus maximising the carbon burnout [135].

This need of a specific type of furnace for a particular coal rank is acknowledged by Beér who stated that "...rates of combustion in pulverised fuel flames do not follow mixing as closely as in gas or oil flames and pulverised coal flames need, therefore, a mixing program to suit coal rank, fineness of the pulverised fuel, air preheat, etc." [134].

4.2.2 Combustion Characteristics of Anthracite/Semi-Anthracite Coals

Anthracites and semi-anthracites are coals with a low volatile content and with a high calorific value. They are well known for their combustion behaviour - difficulty in ignition, in ensuring flame stability and slow burnout, therefore requiring long residence times with hotter flame temperatures for complete combustion.
Many researchers have therefore concentrated on the combustion, chemical composition and structure of anthracite and semi-anthracite coals in order to understand and if possible improve their difficult combustion behaviour.

Both anthracites and semi-anthracites have been shown to have similar combustion behaviours. Work on the measurement of ignition temperatures of pulverised coal particles found that anthracites and semi-anthracites do not show ignition temperature differences between parent coal and char, unlike other coal chars which exhibit higher ignition temperatures (25 to 35 K) than their corresponding parent coals [140].

However, when compared with other coals, their combustion behaviour is quite different. Anthracites reveal a less rapid particle heat-up in the combustion process, leading to a slow ignition [141, 142] and burnout [142, 143, 144]. In a study, anthracite was shown to take 50 msec to reach the bulk gas temperature, whereas bituminous and lignites only took 5 to 10 msec [143]. Moreover, anthracites and semi-anthracites exhibit higher ignition temperatures than other coals [140].
Additionally, thermal decomposition[2] studies of pulverised coal particles have shown that whereas bituminous coals produced cloud(s) of volatiles [145, 146], anthracites did not [143].

The characteristically poor burnout of anthracites may be due not only to their low volatile content, but also to their chemical structure. Tucker [147] found that anthracite is made up from small crystals of imperfect graphite in the form of thin flat flakes. Microscopic examinations showed that like graphite the external shapes of partially burnt anthracite particles were the same as of unburnt particles, except that their interiors were eroded as if combustion had only taken place on the internal macropore surfaces. According to Tucker, this is to be expected since anthracite is of a graphitic carbon nature which tends to be chemically stable. Therefore, combustion can only start from the edges of the flakes and gradually progress towards the interior of the particle, leaving the exterior shape of the particle as before [147].
Complete burnout of anthracite particles in pulverised fuel combustion, therefore, require high residence times, as otherwise unburnt carbon will occur.

[2] During coal combustion, two distinct processes occur: thermal decomposition of the particles which produces combustible gases (or volatiles) and a slower reaction of the residual char.

5. DESIGN OF THE POWER PLANT EXPERIMENTS

This chapter will give an overview of the short-term tests[1] carried out at Aberthaw "B" Power Station, unit 7. Generally, the tests were aimed at finding out the optimum low NO_X conditions within the constraints imposed by boiler operability and safety, slagging, unburned combustible emissions and other undesirable side effects. After detailing the objectives and identifying the boiler operating variables, the design of the testing programme is described in detail. An introductory description of the boiler and pulverised fuel system of Aberthaw "B" Power Plant is given in appendix A.

5.1 Objectives of the Power Plant Testing Programme

The main objectives of the test programme carried out at Aberthaw Power Station unit 7, were:

(a) To identify low NO_X operating conditions, using the existing boiler operating variables.

(b) To investigate the possible extent of NO_X reduction of the above identified low NO_X operating conditions (objective (a)). Important constraints for the NO_X reduction experiments were : (i) retaining acceptable levels of carbon-in-ash and (ii) of CO as well as (iii) maintaining the flame stability.

(c) To develop operational guidelines for a low NO_X operation, on the basis of the information gained from objective (a) and (b).

5.2 Identification of Applicable NO_X Control Parameters at Aberthaw, Unit 7

Operating variables are specific to each boiler, which is why not all NO_X control techniques can be applied to any boiler. In order to design the experiments, it was therefore necessary to identify firstly the available NO_X affecting boiler operating variables. The available NO_X control parameters at Aberthaw power station, unit 7, were found to be:

- Load,
- Excess air,
- Air Staging (through damper settings),

[1] "Short term tests" refers in this thesis to one day tests.

- Staging firing patterns, and
- Oil burners.

As opposed to the first four parameters which are standard boiler operating parameters, oil burners are normally only applied under exceptional plant circumstances. However, the permanent operation of oil burners was discovered within this project as an interesting NO_X control parameter. All of the above operating variables are controlled from the control room (Fig. 5.1)

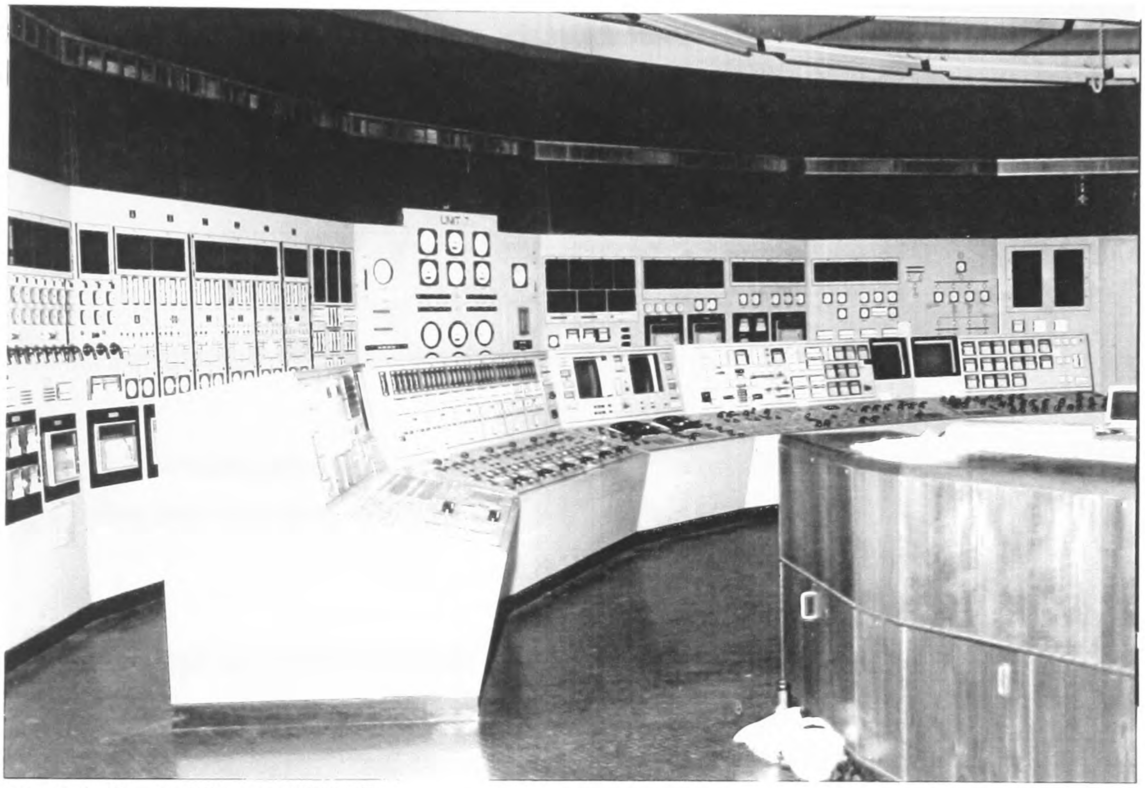


Fig. 5.1: Control Room of Unit 7.

5.3 Design of the Programme of NO_X Reduction Tests

After identification of the NO_X affecting boiler operating variables, the test programme was then designed. The testing programme essentially consisted of two parts: (5.3.1) Baseline characterisation of the boiler operating conditions and emissions typical of each particular load and (5.3.2) Combustion modification tests aiming at a reduction in NO_X emissions:

5.3.1 Baseline Operation Tests

The first step to take in the design of the low NO_X programme, was to characterise the baseline conditions (boiler operating conditions and emissions) typical of each particular load, before introduction of any combustion modification. This is known as the baseline operation test. The considered baseline conditions were:

- number of burners in service,
- preferred firing pattern (if any),
- typical emission levels, also known as "baseline-emissions" or "as-found-emissions", in particular NO_X, CO and carbon-in-ash levels,
- normal operation levels of excess air, and
- air damper settings currently favoured by the station operators.

5.3.2 Combustion Modification Tests

The combustion modification tests aimed at investigating the possible extent of NO_X reduction of the NO_X affecting boiler operating conditions (detailed in section 5.2), as follows:

(a) Load - High and Intermediate

The present testing programme was carried out at two loads: full load (500 MWe) and part load (420 MWe). Full load was chosen as it is the worst case for emissions and 420 MWe because it represents a frequent operating condition.

(b) Excess Air

The effect of excess air on NO_X emissions was investigated at two main excess air levels: (i) the normal or relatively high level and (ii) the minimum or low excess air level. The normal level corresponds to the level that the boiler normally operates at. The minimum excess air is achieved by reducing the total air flow to combustion. However, since it varies with the boiler designs, coal rank, combustion modifications, etc., it is defined as "the level in the boiler flue gases where CO is a maximum of 200 ppm with normal stack opacity" [61, 64]. At this level, the percentage of carbon-in-ash is not high when compared with its value at normal excess air levels, therefore boiler efficiency is not significantly affected.

(c) Air Staging

Air staging can be achieved by changing the damper settings. When the damper positions are changed, the overall combustion air flow is kept constant, therefore the overall combustion stoichiometry remains the same. However, new local stoichiometries are created and heat release rates altered, consequently affecting NO_X emissions.

Optimum air damper settings for staged combustion can only be established by testing various damper combinations. At Aberthaw, different damper settings affect both secondary and tertiary air flow split. There are two main sets of dampers:

1. "Secondary and Tertiary Air Dampers" - Dampers that change the split between the secondary and tertiary air flow. Indication of their position and actuation is in the control room. By varying their position, staged combustion could be achieved.
2. "Secondary Air Dampers" - Dampers that change the split of the secondary air between the top, middle and bottom stages. It is known that the discharge ports of these secondary air stages are partially slagged, with the top stage (near to the burners) being the most affected. The percentages of the secondary air flow through each stage is therefore believed to be: 16%, 31% and 53% for the first, second and third stages respectively. Since these discharge ports are partially obstructed and as they are locally operated, it was not feasible to control or adjust these dampers.

   Nevertheless, this impracticability in changing the secondary air damper settings was not considered a limitation in the testing. This is because the current flow split of these dampers contributes to an inherently staged combustion, since it delays the addition of air to the combustion: more air flows through the third stage (nearest to the furnace bottom), therefore delaying the mixing of the air with the combustion products.

Staged combustion through damper settings concentrated therefore on the "Secondary and Tertiary Air Dampers (1.)". The instruments which show the secondary and tertiary air damper settings are illustrated in Fig. 5.2.

Thus, two sets ("Set A and B") of "Secondary and Tertiary Air Damper" settings were investigated:

Air Staging Tests - "Set A":

- Secondary air set at 1/2 open and tertiary air set at 3/4 open (currently favoured by the station operators).
- Secondary air set at 7/8 open and tertiary air set at 1/2 open.

The majority of the tests performed in unit 7 investigated the above set of damper settings ("Set A"). Nevertheless, other air staging tests investigated the gradual introduction of different settings of dampers ("Set B"):

Air Staging Tests - "Set B":

- Secondary air set at 1/2 open and tertiary air set at 3/4 open (currently favoured by the station operators).
- Secondary air set at 1/2 open and tertiary air set at 5/8 open.
- Secondary air set at 1/2 open and tertiary air set at 1/2 open.
- Secondary air set at 1/2 open and tertiary air set at 3/8 open.

It was not possible to alter the primary air independently because the air/fuel ratio is a combustion control parameter:

$$\frac{PAdifferential}{MILLdifferential} \propto AIR\ /\ FUELratio$$

where "mill differential" is directly proportional to coal flow and "primary air differential" directly proportional to air flow.

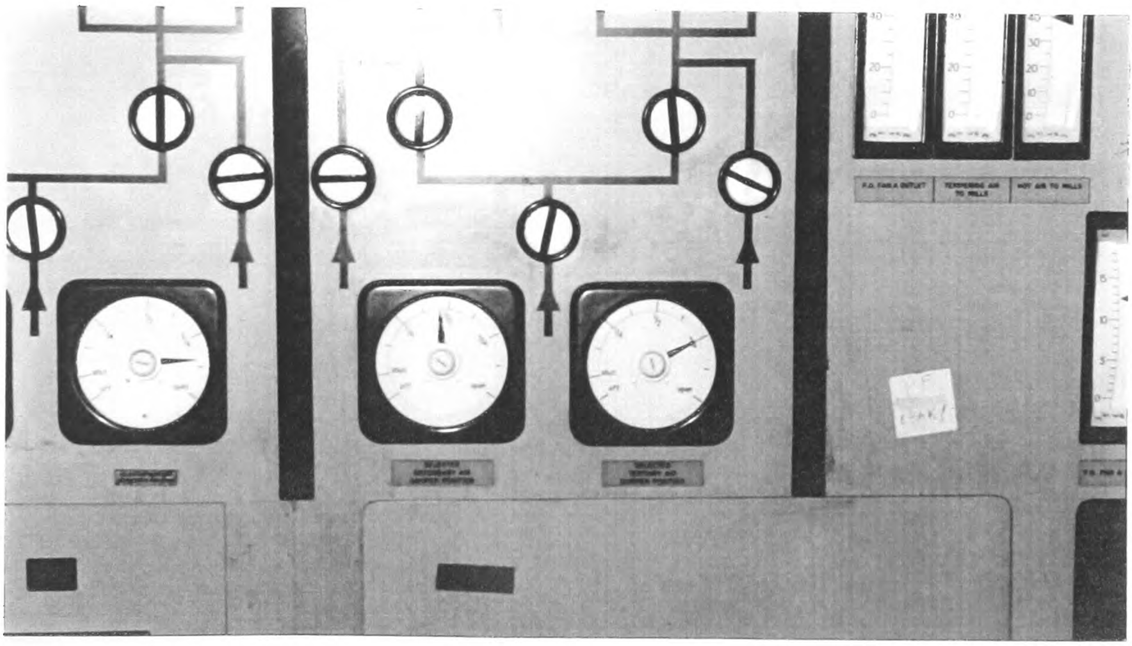


Fig. 5.2: Control room instruments for secondary and tertiary air damper settings.

(d) Staging Firing Patterns

Staging firing patterns, as the name implies, aimed at the implementation of staged combustion. At Aberthaw, staged combustion through firing patterns was implemented in two ways: (a) by burner biasing and (b) by Burners Out Of Service (BOOS). Staged combustion by means of OFA (overfire air) ports could not be carried out, since the unit does not have OFA ports. Both burner biasing and BOOS are based on the same principle, however the means to implement each of them differs. Their concept is explained as follows:

i) Burner Biasing Tests

Burner biasing involved varying the air/fuel ratio mixture to individual burners in order to create fuel-rich (substoichiometric) and fuel-lean areas within the furnace. This was achieved by reducing the coal flow on a number of mills and by increasing the coal flow through the remaining others, whilst the overall air flow remained constant. Hence fuel-rich- and fuel-lean-burners were created. A reduction in both fuel- and thermal-NO_X was therefore expected due to (1) the lower oxygen concentration of the fuel-rich burners and (2) the lower temperature operation of the fuel-rich burners due to the cooling effect of the adjacent fuel-lean burners.

Before testing, the effect of different firing patterns on NO_X emissions is unknown, therefore various combinations of burners must be tried until the optimum configuration becomes apparent. However, the set-up of specific firing patterns for investigation is dependent on the mill/burners arrangement at Aberthaw. So on the basis of the current mill/burners arrangement and in order to achieve the cooling effect described above (point (2)), two main classes of firing patterns can, theoretically, be investigated:

Class 1: The patterns in this category aim at creating lean- and rich-burners of several groups each. A representative firing pattern is:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	R	R	L	L	L									R	R	R	L	L	
R	R	R	R	L	L		R	R	R	L	L	L		R	R	L	L	L	L
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 28

Note: This is a schematic drawing of the furnace (view from the top) to illustrate the burner arrangement and firing patterns. Burners A1 to A6 are fed by mill A, burners B1 to B6 by mill B, etc. - (more detailed information is in the beginning of chapter 6).

Class 2: The patterns in this category aim at pairs of burners in which one burner is fuel-rich and the other fuel-lean. A representative firing pattern is:

					X															
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
R	L	L	R	L			R	L		L	L	R		L	L	R	L	L	R
R	L	L	R	R			R	L			R	R		L	L	R	R		
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
					X															

Total number of PF burners i/s: 29

Note: "L" - lean in fuel.
"R" - rich in fuel.
"X" - Secondary and tertiary air flows OFF.

Unfortunately class 1 of firing patterns is difficult to achieve, due to breakdowns of mills or blocked burners. Therefore the testing concentrated on class 2 firing patterns. Various class 2 patterns were investigated.

In the firing patterns investigated, both secondary- and tertiary-air flows remained "as found", so that only the effect of burner biasing on NO_X emissions could be studied.

ii) Burners Out Of Service (BOOS)

BOOS consisted of operating some burners under the fuel-rich mode, while those burners out of service operated on air only. The original excess air level in the furnace was maintained. At Aberthaw, the application of BOOS as a means of staged combustion could be investigated, since the unit had mill capacity to handle the extra coal flow to the remaining burners in service. Therefore, the lowest practical air/fuel ratios were applied to the operating burners, that is without load reduction. In general it was possible to remove around 33% of the burners from service.

BOOS efficiency in terms of NO_X reduction, is known to be strongly dependent upon the firing pattern [68], therefore for each boiler design the most effective BOOS pattern must be determined through tests. One well known optimum configuration consists of removing the fuel from the top row of burners while continuing to supply air to that location [63, 74, 99, 148]. Such pattern provides maximum separation between the fuel-rich and air-only burners in order to provide maximum cooling between primary and secondary combustion zones. Obviously, this firing pattern is only applicable to those boilers with burners placed in several rows. At Aberthaw, for example, this optimum BOOS pattern can not be applied, since down-fired furnaces have one single row of burners.

Nevertheless, when the application of the optimum BOOS configuration (BOOS on the top row) is not possible, it is reported that the application of "maximum separation between the burners firing fuel" [96] can be successfully introduced: less NO_X is formed when an increased cooling through the burners out of service is available to diminish the heat of each individual burner flame. Additionally, with respect to BOOS patterns, it is known that closely spaced burners "especially in the middle of a multiple burner installation", result in a lower ability to radiate to cooling surfaces [67], thus contributing to higher flame temperatures and consequently increased thermal NO_X formation. Based on this information, two main BOOS pattern(s) were investigated at Aberthaw: "BOOS across the Furnace Chambers" and "BOOS in the Furnace Middle Chamber".

The terminology "chambers" results from the fact that the furnace can be regarded as having three separate furnaces (or chambers), each of equal volume. The 36 burners at Aberthaw can be divided into three groups of 12 burners each, since the furnace features a spacing after every 6th burner per side. For this reason, the Aberthaw furnace is classified in this work as having three chambers: one middle chamber and two outer ones. The wider distance between every 6 burners corresponds to the location of previous division walls (indicated by the grey bars in the furnace schematics) that no longer exist. The following patterns were investigated:

- **BOOS in the Furnace Middle Chamber (BFMC)**

The "BOOS in the Furnace Middle Chamber" firing patterns are based on the fact that closely spaced burners "especially in the middle of a multiple burner installation", result in a lower ability to radiate to cooling surfaces, hence resulting in an increased thermal NO_X formation. This may well contribute to NO_X formation at Aberthaw, since there are no extra heat absorbing surfaces such as division walls in the furnace, as these were removed in the past. It is therefore likely that high temperatures occur in the furnace middle chamber. Therefore, firing patterns with air only burners in the furnace middle chamber were investigated. It is important to note, however, that in practice the set-up of a firing pattern is dependent on the problems encountered in the test set-ups (see section 5.5). A representative firing pattern is:

					X														X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*				*							*	*		*	*	
	*	*		*	*					*		*		*	*	*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X																			

PF burners o/s in the middle chamber: 9

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

As the firing pattern shows, all secondary- and tertiary-air flows are open in the burners out of service located in the middle chamber, in order to investigate the effect of "BOOS in the furnace middle chamber" on NO_X emissions.

• **BOOS across the Furnace Chambers (BAFC)**

The "BOOS across the Furnace Chambers" patterns are based on the "maximum separation between the burners firing fuel", as mentioned earlier in this section. Therefore, firing patterns with "air only" burners spread across the furnace chambers were investigated. However, as mentioned above, it is important to note that the set-up of a firing pattern is dependent on the problems encountered in the test set-ups (see section 5.5). A representative firing pattern is:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*					*	*	*	*	*	*		*	*	*	*	*	*
*			*	*	*		*			*	*						*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

PF burners o/s in the furnace: LHS (B side): 5, middle: 3, RHS (A side): 3.

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

As the firing pattern shows, both secondary- and tertiary-air flows are open in all BOOS, since the aim is to investigate the effect of BOOS across the furnace chambers on NO_X emissions.

(e) Oil Burners Effect

At Aberthaw, plant operation specifies no oil burners in service at full load. Oil burners are normally only brought into service in situations of combustion instability and for loads below 400 MWe in order to ensure combustion stability. The number of oil burners in service for loads below 400 MWe is generally around 12.

The use of oil burners in utility boilers as a means of NO_X reduction, is not reported in the literature. However, during the test programme it was observed that when oil burners were in service, the NO_X levels were generally much lower. Therefore, based on these observations, it was decided to investigate the effect of oil burners on NO_X emissions. The oil composition is given in Appendix F.

(f) Combination of Combustion Modification Techniques

The combinatorial effect of the above NO_X control methods was also investigated:

- Excess air + Air Staging ("Set A", "Set B")
- Excess air + BFMC + Air Staging ("Set A")
- Excess air + BAFC + Air Staging ("Set A")
- Excess air + Oil Burners Effect + Air Staging ("Set A")

5.4 Testing Methods and Equipment

This section deals with the methodology, equipment and considerations required during the testing programme. This includes:

5.4.1 Pre-testing Arrangements

Prior to each test, the following plant conditions had to be checked:

1. Balance in O_2 level between both sides of the furnace. This proved to be very difficult to achieve since a complete balance can only be accomplished by changing the location of the burners i/s, which subsequently alters the desired firing patterns. Therefore, a slight imbalance could not be avoided in some tests.

2. Balance in the drum level between both sides of the furnace. The drum level gives an indication of the amount of feed water and of produced steam on both sides of the boiler. When it reveals an imbalance, this can only be corrected by re-arranging the firing pattern. For example, if the rear-side of the boiler has more steam than the front-side, in order to correct this imbalance, some burners have to be taken out of service on the rear-side and/or some others added to the front-side, maintaining the same electrical output.

   It is important to note that achieving a balance in O_2 and in the drum level between both sides of the furnace was not easy, since these two conditions are also interrelated.

5.4.2 Test Measurements

An extensive log of plant data has been recorded during each test, to enable a detailed analysis of the boiler emissions and efficiency. With steady firing conditions established, the following information was logged from OIS (see glossary) at 2 minute intervals:

- NO_X levels in the stack *,
- CO levels in the furnace *♣,
- Carbon in ash levels in the furnace *♣,
- Oxygen at the economiser *,
- Oxygen at the airheaters outlet ♣, and
- Flue gas temperature at the stack ♣.

(* - denoting variables which are plotted and evaluated in the graphs in chapter 6; ♣ - denoting variables used in the boiler efficiency calculation in Appendix F).

5.4.3 Time Scales

The initial stabilisation period prior to each test lasted for thirty minutes and the duration of each test period was at least 3/4 hour.

5.4.4 Measuring Equipment

The power plant measuring equipment was used to monitor the combustion data:

1. NO_X: Infra-red NO monitor.
2. CO: Infra-red CO monitor.
3. Carbon-in-ash: Capacitive monitor.
4. Oxygen: Zirconia Cell monitor (In-situ analysers).
5. Temperature: Thermocouple.

5.5 Problems in the Test Set-ups

In practice, it was often found difficult to arrange the test set-ups with respect to the firing patterns exactly as they were planned. This is due to frequent breakdowns of the mills, burners and/or pipes blocked, making a repeat of previous test conditions or the set-up of an exact arrangement virtually impossible. Additionally, design and operating constraints have to be considered:

1. When setting up a staging firing pattern, the number and location of burners in service and of those operated on an air only basis, depend upon the mills availability and upon the pulveriser-burner configuration.
2. Also, the set-up of a BOOS pattern depends on the arrangement of the air damper controls: besides the burners with individual air damper controls, there are groups of two burners sharing one air damper control, which means that when only one burner is firing the other is on air only operation as there are no means of isolating its air supplies.
3. In a staged firing pattern, the degree of staging by the burners operated on an air only basis depends on the maximum increase of coal supply to active burners, otherwise a reduction in load can result.
4. Steam and tube metal temperatures control can limit the amount of combustion air reduction (reduced mass flow reduces superheat capacity). Additionally, they can prevent the use of ideal firing patterns. Often the operator has to exchange the burners in operation, in order to balance the steam and/or tube metal temperatures.
5. Water/steam imbalance between the furnace sides can also prevent the use of ideal firing patterns.

Uncontrollable Influences

In addition to these operating and design constraints, there were other plant factors that affected the evaluation of the effectiveness of the various NO_X control methodologies employed. Examples of the many uncontrollable influences are:

1. Non-uniform air/fuel distribution to each burner. Unfortunately, non-uniformities in the coal and air distribution to each burner are a known problem.
2. Air registers occasionally break or have non-operable mechanical linkages, resulting in maladjusted air flow.
3. Likewise, the damper adjustments are occasionally non-operable.

The above reasons make each test unique. The comparison between data from different test runs is, however, valid if similar test conditions and the stability of the plant is ensured before starting the tests.

6. PLANT EXPERIMENTS AND RESULTS

In this chapter there are a few concepts, terminologies and other generalities that need to be understood prior to looking at the power plant test results. They are described here in detail and refer to the furnace, the air dampers and the power plant tests.

The Furnace

The Aberthaw furnace has its specific terminology and as explained in chapter 5 (section 5.3.2 (d-ii)) it can be regarded as having three individual chambers. In this thesis the boiler furnace and firing pattern is defined and represented as follows:

<table>
<tr><td colspan="21">REAR SIDE</td></tr>
<tr><td colspan="7">LHS Outer Chamber</td><td></td><td colspan="6">Middle Chamber</td><td></td><td colspan="6">RHS Outer Chamber</td></tr>
<tr><td rowspan="6">A</td><td></td><td></td><td></td><td></td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td rowspan="6">B</td></tr>
<tr><td>E6</td><td>F6</td><td>F5</td><td>E5</td><td>A6</td><td>A5</td><td></td><td>E4</td><td>F4</td><td>F3</td><td>A4</td><td>A3</td><td>B3</td><td></td><td>F2</td><td>F1</td><td>B2</td><td>A2</td><td>A1</td><td>B1</td></tr>
<tr><td>*</td><td>*</td><td>*</td><td>*</td><td>*•</td><td></td><td></td><td>*</td><td>*</td><td>*</td><td>*</td><td>*</td><td>*•</td><td></td><td>*</td><td>*</td><td>*</td><td>*•</td><td>*</td><td>*</td></tr>
<tr><td>*</td><td>*</td><td></td><td>*</td><td>•</td><td></td><td></td><td>*</td><td>*</td><td></td><td></td><td></td><td>•</td><td></td><td>*</td><td>*</td><td></td><td>•</td><td></td><td></td></tr>
<tr><td>B6</td><td>D6</td><td>D5</td><td>B5</td><td>C6</td><td>C5</td><td></td><td>B4</td><td>D4</td><td>D3</td><td>C4</td><td>C3</td><td>E3</td><td></td><td>D2</td><td>D1</td><td>E2</td><td>C2</td><td>C1</td><td>E1</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>X</td><td>X</td></tr>
<tr><td colspan="7">LHS Outer Chamber</td><td></td><td colspan="6">Middle Chamber</td><td></td><td colspan="6">RHS Outer Chamber</td></tr>
<tr><td colspan="21">FRONT SIDE</td></tr>
</table>

<u>where</u>: PF burners in service (i/s) are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Oil burners i/s are marked with a bullet: •

"A" side = RHS.

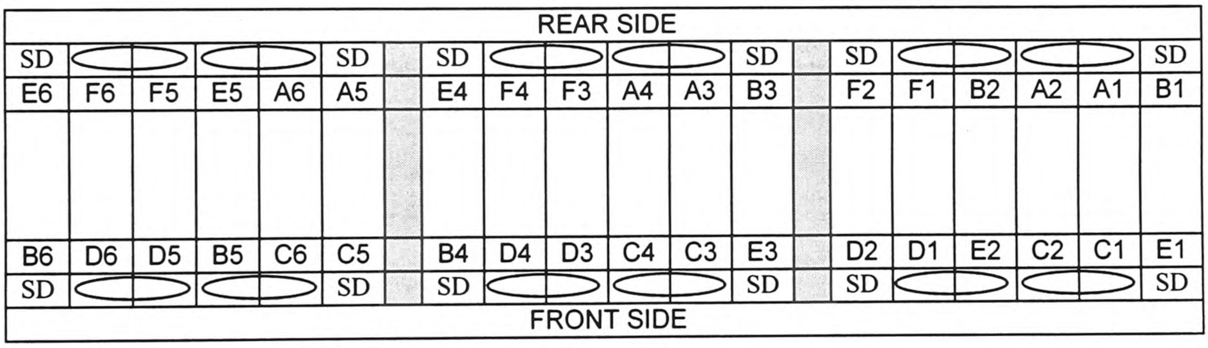
"B" side = LHS.

Air Dampers

As already mentioned in chapter 5 (section 5.3.2 (c)), there are two types of air dampers at Aberthaw. However, for the reasons previously described in that chapter, the testing was based on the "secondary and tertiary air dampers". Therefore, in this chapter the words "air dampers" refer to both "secondary and tertiary air dampers".

In the air dampers terminology, it is necessary to differentiate between "damper settings" and "damper positions". "Damper settings" means the split of air flow between the secondary and tertiary air. However, it is important to note that this split is only an indication of the flow split, due to the various uncontrollable influences that exist in a power plant (section 5.5). Different to damper settings, "damper positions" refers to whether the individual air flow (secondary and tertiary) per burner is either open (ON) or closed (OFF). To clearly make the distinction between open or closed, the terminology "ON" or "OFF", respectively, is used.

Another important consideration in the air damper terminology is their arrangement. In order to supply combustion air to the 36 burners, secondary and tertiary air is taken from 24 windboxes in the plenum chambers, 12 of which supply single burners (single windbox) with the remaining 12 supplying two burners (shared windbox). Each windbox has one single damper, therefore in a shared windbox when only one burner is firing there are no means to isolate the air supplies to the other burner. Consequently, due to this air damper arrangement, it is common to find firing patterns in which burners out of service have their air (secondary and tertiary) left ON. The Aberthaw air damper arrangement is represented schematically below:



where: "SD" means single damper.

"  " represents a shared damper. Example: burners F6 and F5.

The Power Plant Tests (and their results)

As discussed in chapter 5, the plant experiments were carried out at two main loads, 500 and 420 MWe. In general, each NO_X control methodology investigated at Aberthaw was tested three times at 500 MWe and once at 420 MWe.

With the data collected from each test, four main graphs were produced: (i) NO_X/Oxygen, (ii) CinA & CO/Oxygen, (iii) NO_X/CO and (iv) NO_X/CinA graph. Each data point in the graphs is an average of four successive measurements.

Although based on the same data the latter two graphs ((iii) and (iv)) are complementary to the first ones since they give additional insight to the relationships between the variables. However, only the first two graphs were used for reading the achievable values needed from the graphs. This specification is necessary in order to be consistent in the procedure of obtaining the results; the readings from the latter two graphs could differ slightly from those from the former two graphs due to inevitable interpolation errors.

The types of data correlation differ between the graphs (i) - (iv): In agreement with the literature [68], the NO_X/O_2 graph (i) shows a linear correlation, while CO and carbon-in-ash increase exponentially with decreasing oxygen levels (graph (ii)). Finally, the last two sets of graphs ((iii) and (iv)) demonstrated a logarithmic correlation.

As mentioned in chapter 1, the aim at Aberthaw is to achieve the new plant standards by means of BATNEEC. According to the new plant standards, the NO_X limitation is 317 ppm (650 mg/m^3 at 6% O_2, dry) for solid fuels in general [5] (see section 2.5). Thus, the graphs of the various tests show the 317 ppm[1] NO_X limit. The maximum CO limit (200 ppm) is also shown.

The majority of the tests was initiated with "as found" firing patterns and with "as found" air damper positions, for the following main reasons: (i) to understand how the boiler is normally operated by the station operators, (ii) to ensure that the values of NO_X, CO, etc., corresponded to typical operating levels, as well as (iii) to allow the investigation of any variation in emissions and (iv) to study the changes in emissions after the introduction of a NO_X control methodology. An exception was the "BOOS Across the Furnace Chambers (BAFC)" tests in which it was necessary to set the initial firing pattern as well as the air dampers position (as "OFF") already for the starting condition[2].

In general, the graphs of the various tests carried out at Aberthaw, show two main stages of work:

- Initial condition: This represents the normal boiler operation with "as found" emissions and firing patterns. No combustion modifications have been introduced in the "initial condition" of the tests. The damper settings in operation are the standard settings currently favoured by the station operators.
- Setting 1 and 2 (or (i), (ii) and (iii)): At this stage a combustion modification technique is introduced to combustion. Normally the combustion modification technique is introduced in "Setting 1" (which has the same damper settings as of the "Initial Condition"). After studying the combustion

[1] The units of the variables in the graphs are as specified in appendix B.

[2] These test conditions are further explained in chapter 7, section 7.2.4(b-ii).

modification technique in "Setting 1, another damper setting is introduced (2, (i), (ii) and (iii)) for investigation (more detailed description is in the testing procedure of each test - in this chapter).

Although the majority of the tests was carried out with the South Wales semi-anthracite coal, three tests (T5, T6 and T9[3]) were carried out with another semi-anthracite coal - "Portbury" coal[4]. During the testing period at Aberthaw, the "Portbury" coal was occasionally burnt, which is why the coal could be considered in some of the tests as an additional influence parameter. Details of the coal compositions are in Appendix F.

Finally, it is important to mention that the graphs show considerable scatter of the carbon in ash data, most likely due to the measurement instrument, which sometimes even seems to get "blocked" (e.g. in T3 and T6).

[3] For simplification reasons, when referring to a particular test an abbreviation is used (e.g. "T19", in the case of Test 19, etc.).

[4] The origins of this coal cannot be mentioned here, thus it is referred to in this thesis as "Portbury" coal.

6.1 500 MWe TESTS

6.1.1 Baseline Operation

Test 1

Aim: To investigate the boiler baseline conditions (boiler operating conditions and emissions) during normal operation of the plant at full load (500 MW) with different damper settings.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 6 mills in service (i/s).

Initial Condition: **(1.)** Boiler stable and firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners out of service (o/s) as found.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Variation of the total air flow.

The firing pattern remained the same throughout the test:

Initial Condition, Setting 1 and 2:

							X					X						
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*		*	*	*			*			*			*	*	*		*	*
*	*	*			*		*	*		*				*	*	*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
			X	X								X							X

Total number of PF burners i/s: 24

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Summary of the Results of Test 1

General Information

Initial Condition:

- NO_X ≈ 710 to 760 ppm
- Oxygen ≈ 3.7 to 3.8%
- CO ≈ 40 to 50 ppm
- CinA ≈ 10.5 to 11%

Setting 1:

- NO_X/O_2 slope ≈ 150 ppm/1% O_2

Setting 2:

- NO_X/O_2 slope ≈ 116 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO:

Setting 1:

- When CO equals 200 ppm at 3.75% oxygen:
- NO_X = 750 ppm
- CinA = 10.5%

Setting 2:

- When CO equals 200 ppm at 3.3% oxygen:
- NO_X = 580 ppm
- CinA = 12.5%

Boiler Operation Information

- Typical number of PF burners i/s at 500 MW: 24
- No specific firing pattern.
- Damper settings currently favoured by the station operators: 1/2 open on the secondary air and 3/4 open on the tertiary air.
- Secondary and tertiary air dampers open or closed on the burners o/s, due to (i) mode of operating the boiler by the operator or (ii) in the case of two burners with a shared windbox (example: burners F6 and F5), when only one burner is firing there are no means to isolate the air supplies to the other burner.

Results of Test 1

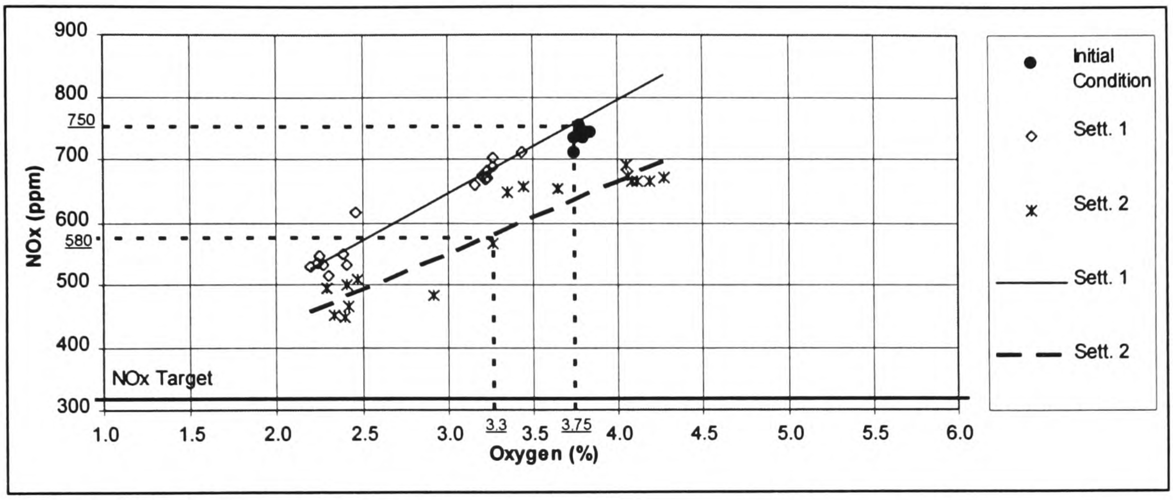


Fig. 6.1: Test 1 - NO_X versus Oxygen.

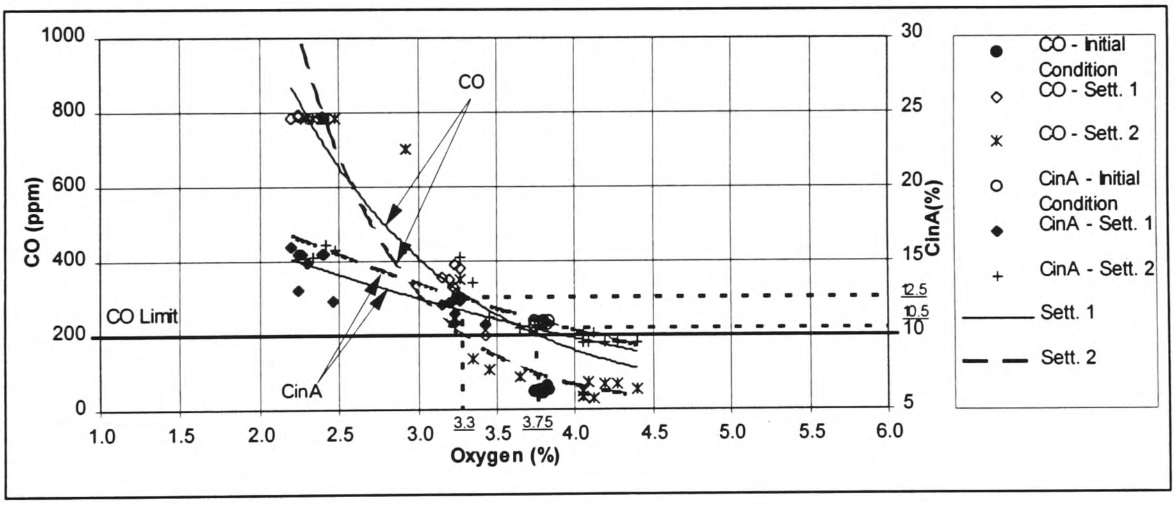


Fig. 6.2: Test 1 - CO and Carbon in ash versus Oxygen.

Results of Test 1 - cont.

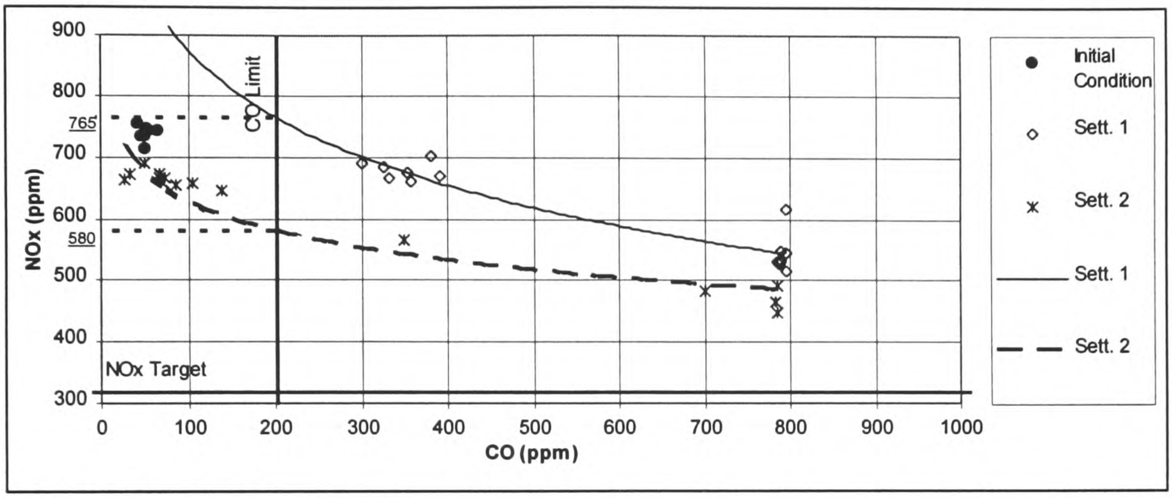


Fig. 6.3: Test 1 - NO_X versus CO.

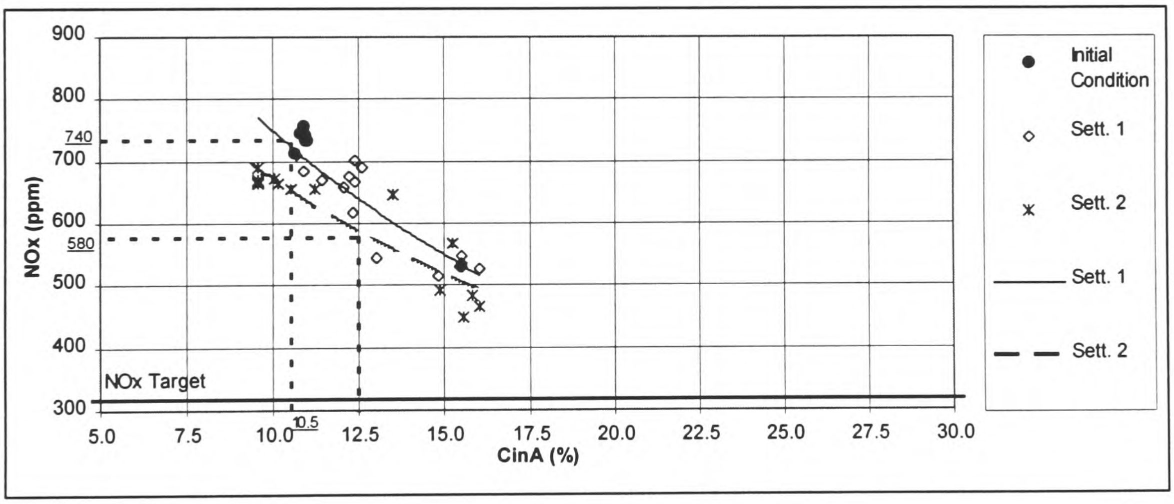


Fig. 6.4: Test 1 - NO_X versus Carbon in ash.

6.1.2 Burner Biasing

Test 2

Aim: To investigate the effect of staged combustion through burner biasing on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 6 mills in service (i/s).

1st and 2nd Initial Conditions: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Mills working at uniform pressure therefore supplying similar amounts of fuel, **(3.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(4.)** Air Damper Positions: secondary and tertiary air for burners out of service (o/s) as found.

1st Burner Biasing: **(1.)** Coal flow increased in mills B, C, E and decreased in mills A, D, F in order to achieve burner biasing, **(2.)** Total air flow remained constant.

2nd Burner Biasing: **(1.)** Coal flow increased in mills A, D, F and decreased in mills B, C, E in order to achieve burner biasing, **(2.)** Total air flow remained constant.

The firing patterns were as follows:

1st and 2nd Initial Conditions:

					X																
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1		
*	*	*	*	*			*	*	*	*	*	*		*	*	*	*	*	*		
*	*	*	*	*			*	*			(*)	*		*	*	⌈*⌋	*				
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1		
					X																

Total number of PF burners i/s: 29 (1st and 2nd). The burner marked with the symbol (*) was only running in the 1st part of the test and the burner marked with the symbol ⌈*⌋ was only running in the 2nd part of the test.

Note: PF burners i/s are marked with an asterisk: *
"X" - Secondary and tertiary air flows OFF.

1st Burner Biasing:

					X														
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
R	L	L	R	L			R	L		L	L	R		L	L	R	L	L	R
R	L	L	R	R			R	L			R	R		L	L	R	R		
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
					X														

Total number of PF burners i/s: 29 of which: 15 lean in fuel (L) and 14 rich in fuel (R).

2nd Burner Biasing:

					X														
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
L	R	R	L	R			L	R			R	L		R	R	L	R	R	L
L	R	R	L	L			L	R			L	L		R	R	L	L		
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
					X														

Total number of PF burners i/s: 28 of which: 14 lean in fuel (L) and 14 rich in fuel (R).

Summary of the Results of Test 2

- No systematic reduction in NO_X.
- The small variations during the test were only within the normal scattering of the data.

Results of Test 2

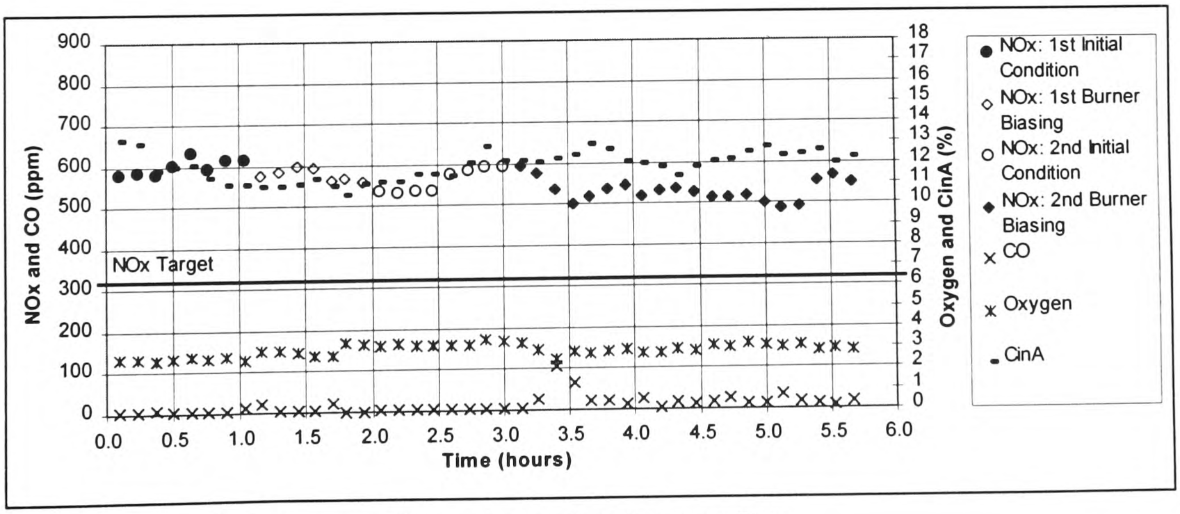


Fig. 6.5: Test 2 - NO_X Oxygen, CO and Carbon in ash versus Time.

Test 3

Aim: To investigate the effect of staged combustion through burner biasing on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 6 mills in service (i/s).

1st Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Mills working at uniform pressure therefore supplying similar amounts of fuel, **(3.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(4.)** Air Damper Positions: secondary and tertiary air for burners out of service (o/s) as found.

1st Burner Biasing: **(1.)** Coal flow increased in mills B, C, E and decreased in mills A, D, F in order to achieve burner biasing, **(2.)** Total air flow remained constant.

The firing patterns were as follows:

1st Initial Condition:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*		*	*				*			*	*				*	*	*	*
*	*	*	*	*			*	*			*	*		*		*	*		
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 23

Note: PF burners i/s are marked with an asterisk: *
"X" - Secondary and tertiary air flows OFF.

1st Burner Biasing:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
R	L		R	L				L			L	R				R	L	L	R
R	L	L	R	R			R	L			R	R		L		R		R	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 23 of which: 10 lean in fuel (L) and 13 rich in fuel (R).

Summary of the Results of Test 3

- No systematic reduction in NO_X.
- The small variations during the test were only within the normal scattering of the data.

Results of Test 3

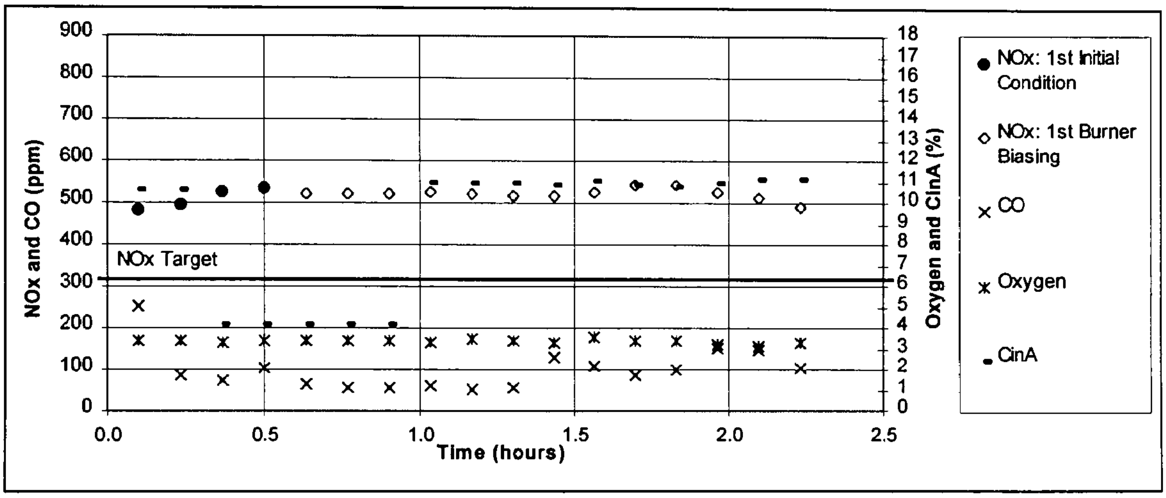


Fig. 6.6: Test 3 - NO_X Oxygen, CO and Carbon in ash versus Time.

Test 4

Aim: To investigate the effect of staged combustion through burner biasing on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - D mill out of service (o/s).

1st and 2nd Initial Conditions: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Mills working at uniform pressure therefore supplying similar amounts of fuel, **(3.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(4.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

1st Burner Biasing: **(1.)** Coal flow increased in mills B, C, F and decreased in mills A, E in order to achieve burner biasing, **(2.)** Total air flow remained constant.

2nd Burner Biasing: **(1.)** Coal flow increased in mills A, E and decreased in mills B, C, F in order to achieve burner biasing, **(2.)** Total air flow remained constant.

The firing patterns were as follows:

1st and 2nd Initial Conditions:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*		*	*	*	*
*			*		*		*			*		*				*	*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X																	

Total number of PF burners i/s: 27 (1st and 2nd).

Note: PF burners i/s are marked with an asterisk: *
"X" - Secondary and tertiary air flows OFF.

1st Burner Biasing:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
L	R	R	L	L	L		L	R	R	L	L	R		R		R	L	L	R
R			R		R		R			R		L				L	R	R	L
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X																	

Total number of PF burners i/s: 27 of which: 12 lean in fuel (L) and 15 rich in fuel (R).

2nd Burner Biasing:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
R	L		R	R	R		R	L	L	R	R	L		L		L	R	R	L
L			L		L		L			L		R				R	L	L	R
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X																	

Total number of PF burners i/s: 26 of which: 15 lean in fuel (L) and 11 rich in fuel (R).

Summary of the Results of Test 4

- No systematic reduction in NO_X.
- The small variations during the test were only within the normal scattering of the data.

Results of Test 4

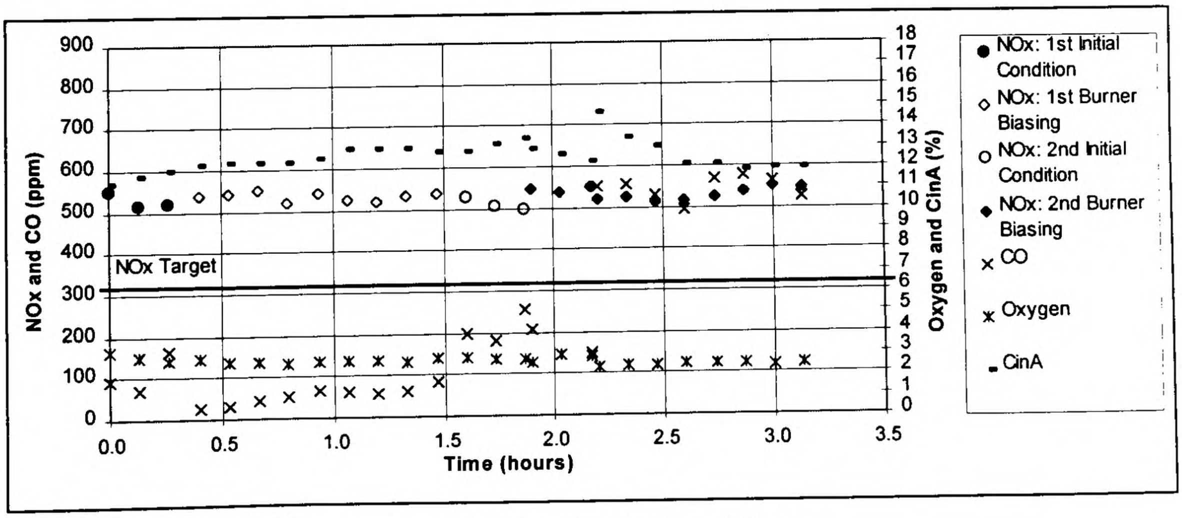


Fig. 6.7: Test 4 - NO_X Oxygen, CO and Carbon in ash versus Time.

Test 5

Aim: To investigate the effect of staged combustion through burner biasing on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** "Portbury" coal, **(3.)** 5 mills in service (i/s) - D mill out of service (o/s).

1st and 2nd Initial Conditions: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Mills working at uniform pressure therefore supplying similar amounts of fuel, **(3.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(4.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

1st Burner Biasing: **(1.)** Coal flow increased in mills B, E and decreased in mills A, C, F in order to achieve burner biasing, **(2.)** Total air flow remained constant.

2nd Burner Biasing: **(1.)** Coal flow increased in mills A, C, F and decreased in mills B, E in order to achieve burner biasing, **(2.)** Total air flow remained constant.

The firing patterns were as follows:

1st and 2nd Initial Conditions:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
*			*	(*)	*						(*)	*				*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X					X	X	X	(X)				X					X

Total number of PF burners i/s: 27 (1st) and 25 (2nd). The burners marked with an (*) were only running in the 1st part of the initial condition. The air flow marked with (X) was OFF only during the 2nd part of the initial condition.

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

1st Burner Biasing:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
R	L	L	R	L	L		R	L	L	L	L	R		L	L	R	L	L	R
R			R	L	L						L	R				R	L	L	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X					X	X	X	X				X					X

Total number of PF burners i/s: 27 of which: 17 lean in fuel (L) and 10 rich in fuel (R).

2nd Burner Biasing:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
L	R	R	L	R	R		L	R	R	R	R	L		R	R	L	R	R	L
L			L	R	R						R	L				L	R	R	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X					X	X	X	X				X					X

Total number of PF burners i/s: 27 of which: 10 lean in fuel (L) and 17 rich in fuel (R).

Summary of the Results of Test 5

- No systematic reduction in NO_X.
- The small variations during the test were only within the normal scattering of the data.

Results of Test 5

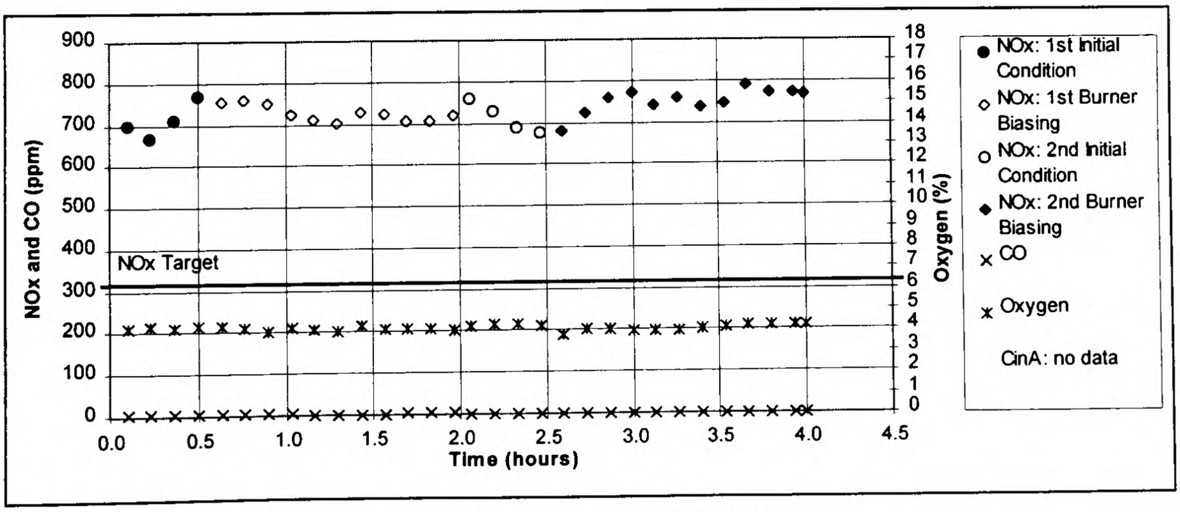


Fig. 6.8: Test 5 - NO_X Oxygen, CO and Carbon in ash versus Time.

Test 6

Aim: To investigate the effect of staged combustion through burner biasing on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** "Portbury" coal, **(3.)** 5 mills in service (i/s) - D mill out of service (o/s).

1st and 2nd Initial Conditions: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Mills working at uniform pressure therefore supplying similar amounts of fuel, **(3.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(4.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

1st Burner Biasing: **(1.)** Coal flow increased in mills B, E and decreased in mills A, C, F in order to achieve burner biasing, **(2.)** Total air flow remained constant.

2nd Burner Biasing: **(1.)** Coal flow increased in mills A, C, F and decreased in mills B, E in order to achieve burner biasing, **(2.)** Total air flow remained constant.

The firing patterns were as follows:

1st and 2nd Initial Conditions:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
			*	*	*						*	*				*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X	X	X					X	X	X					X					X

Total number of PF burners i/s: 26

Note: PF burners i/s are marked with an asterisk: *
"X" - Secondary and tertiary air flows OFF.

1st Burner Biasing:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
R	L	L	R	L	L		R	L	L	L	L	R		L	L	R	L	L	R
			R	L	L						L	R				R	L	L	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X	X	X					X	X	X					X					X

Total number of PF burners i/s: 26 of which: 17 lean in fuel (L) and 9 rich in fuel (R).

2nd Burner Biasing:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
L	R	R	L	R	R		L	R	R	R	R	L		R	R	L	R	R	L
			L	R	R						R	L				L	R		
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X	X	X					X	X	X					X					X

Total number of PF burners i/s: 25 of which: 9 lean in fuel (L) and 16 rich in fuel (R).

Summary of the Results of Test 6

- No systematic reduction in NO_X.
- The small variations during the test were only within the normal scattering of the data.

Results of Test 6

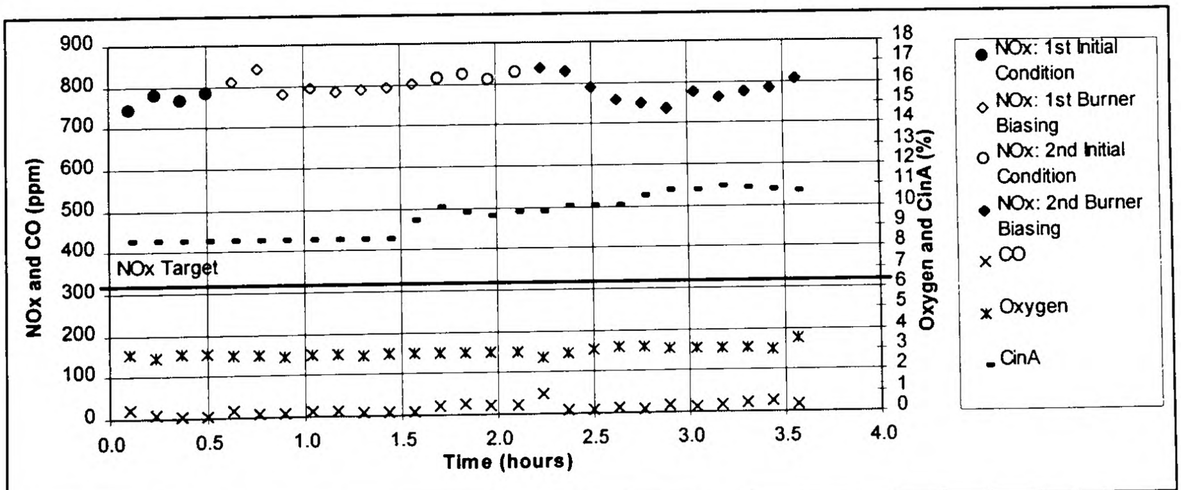


Fig. 6.9: Test 6 - NO_X Oxygen, CO and Carbon in ash versus Time.

6.1.3 Burners Out Of Service (BOOS) in the Furnace Middle Chamber

Test 7

Aim: To investigate the effect of staged combustion through burners out of service (BOOS) in the furnace middle chamber and different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - B mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

Setting 1(a): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Air Damper Positions: secondary and tertiary air ON for all burners o/s in the middle chamber.

Setting 1: **(1.)** Air Damper Settings: Secondary air 1/2 open and tertiary air 3/4 open, , **(2.)** Some burners in the middle chamber removed from service, **(3.)** Air Damper Positions: secondary and tertiary air remained ON for all burners o/s in the middle chamber (BOOS), **(4.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Air Damper Positions: secondary and tertiary air remained ON for all burners o/s in the middle chamber (BOOS), **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Initial Condition:

					X							X							X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*		*	*			*		*	*	*			*	*		*	*	
	*	*		*	*					*		*		*	*	*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X							X	X	X										

Total number of PF burners i/s: 23

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1(a):

					X														X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*		*	*			*		*	*	*			*	*		*	*	
	*	*		*	*					*		*		*	*	*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X																			

Total number of PF burners i/s: 23

PF burners o/s in the middle chamber: 6

Setting 1 and 2:

					X														X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*				*							*	*		*	*	
	*	*		*	*					*		*		*	*	*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X																			

Total number of PF burners i/s: 20

PF burners o/s in the middle chamber: 9

Summary of the Results of Test 7

General Information

Initial Condition:

- $NO_X \approx$ 740 to 810 ppm
- Oxygen $\approx$ 3 to 3.4%
- CO = 0 ppm
- CinA $\approx$ 12.7%

Setting 1(a):

- $NO_X \approx$ 620 to 690 ppm
- Oxygen $\approx$ 3.2 to 3.8%
- CO $\approx$ 15 to 60 ppm
- CinA $\approx$ 12.6 to 13.2%

Setting 1:

- NO_X/O_2 slope $\approx$ 84 ppm/1% O_2

Setting 2:

- NO_X/O_2 slope $\approx$ 67 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO, unless otherwise indicated:

Setting 1:

CO remained below 200 ppm (12-50 ppm). Lowest NO_X level achieved:

- NO_X = 520 ppm
- at CinA = 19.1%
- at Oxygen = 3.46%

Setting 2:

- When CO equals 200 ppm at 3.25% oxygen:
- NO_X = 480 ppm
- CinA = 19.1%

Results of Test 7

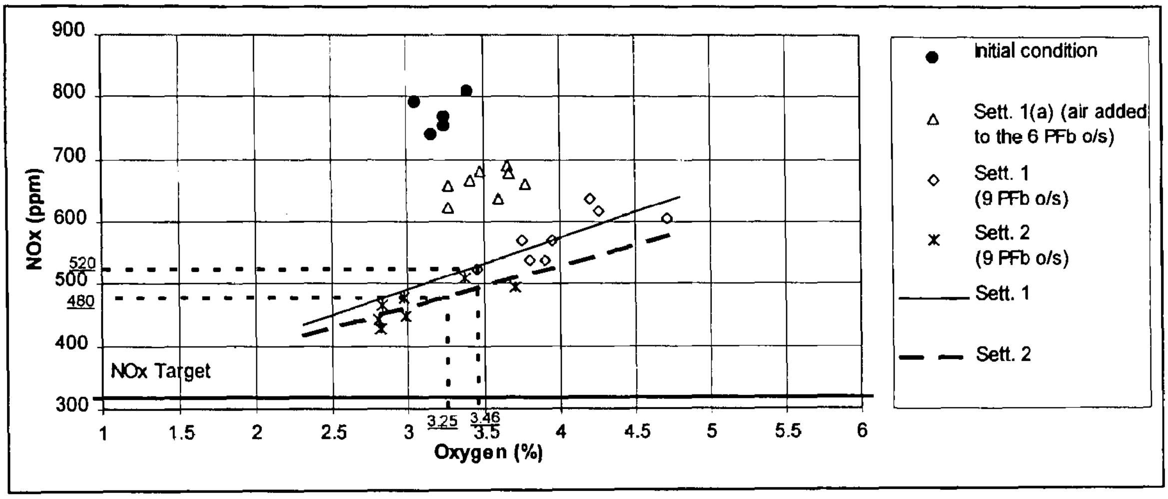


Fig. 6.10: Test 7 - NO_X versus Oxygen.

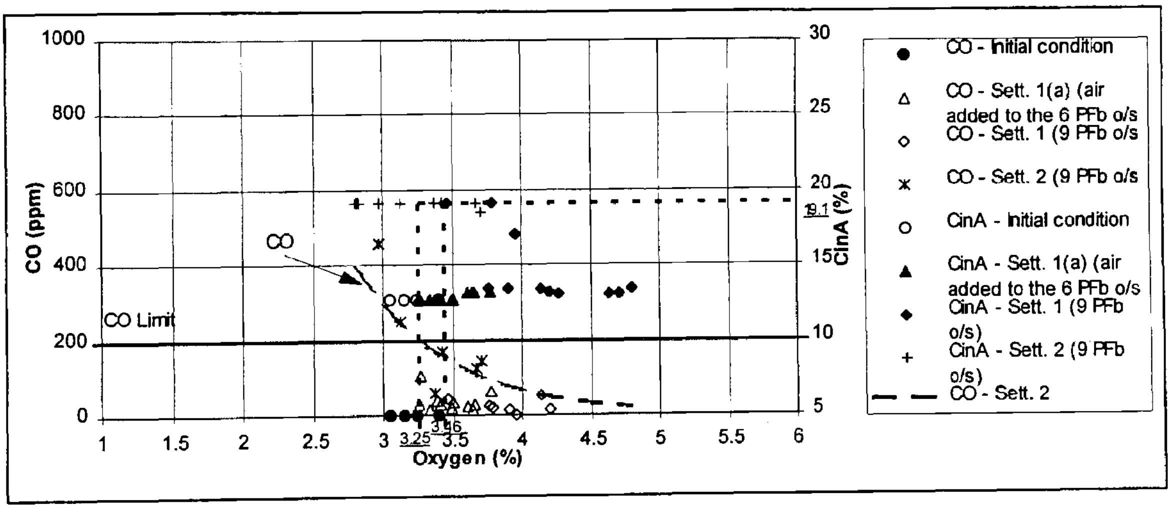


Fig. 6.11: Test 7 - CO and Carbon in ash versus Oxygen.

Results of Test 7 - cont.

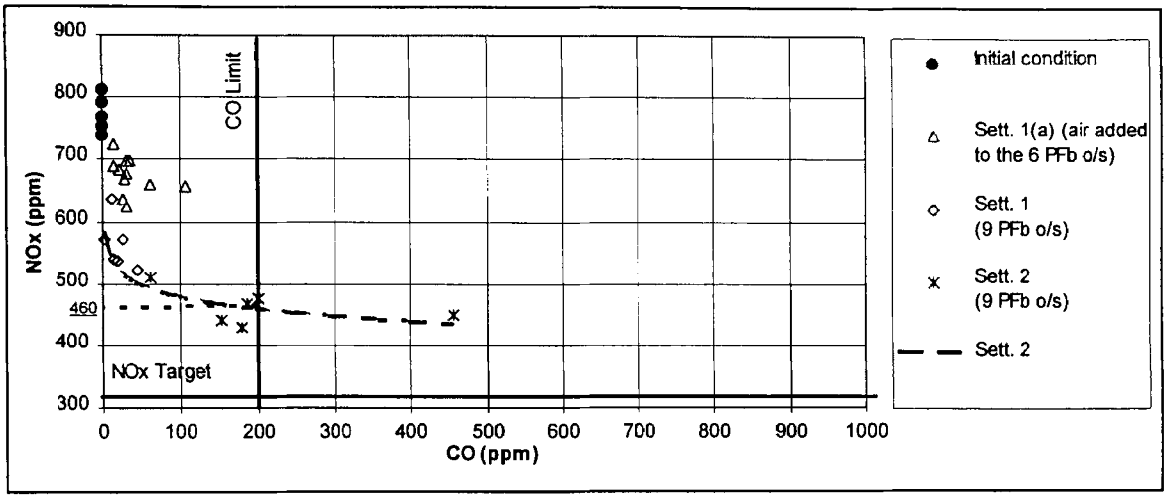


Fig. 6.12: Test 7 - NO_X versus CO.

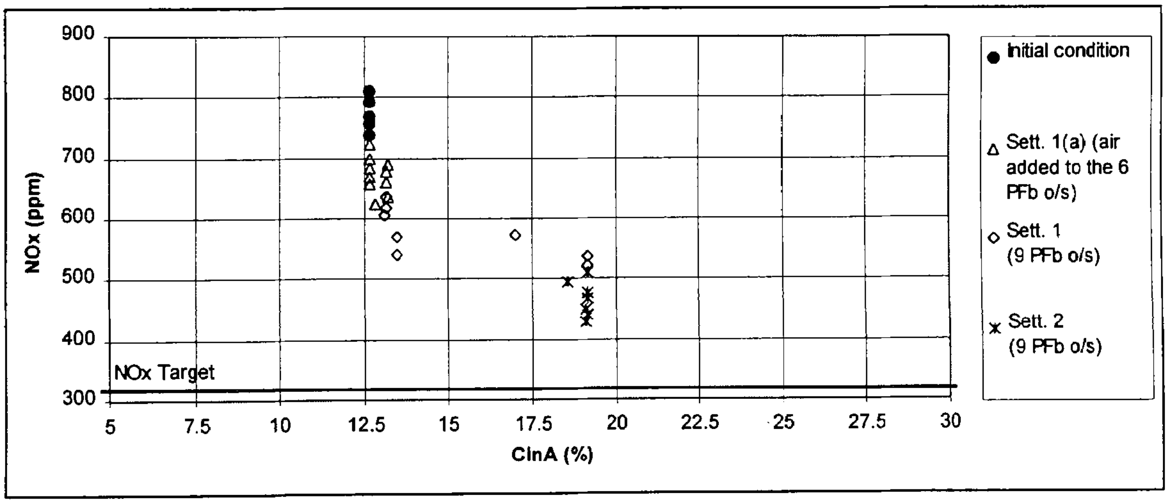


Fig. 6.13: Test 7 - NO_X versus Carbon in ash.

Test 8

Aim: To investigate the effect of staged combustion through burners out of service (BOOS) in the furnace middle chamber and different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - F mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found, **(4.)** Variation of the total air flow.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Some burners in the middle chamber removed from service, **(3.)** Air Damper Positions: secondary and tertiary air ON for all burners o/s in the middle chamber (BOOS), **(4.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Air Damper Positions: secondary and tertiary air remained ON for all burners o/s in the middle chamber (BOOS).

The firing patterns were as follows:

Initial Condition:

	X	X					X	X	X					X					
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*			*	*	*					*	*	*				*		*	*
*	*		*	*	*			*	*	*		*		*	*	*	*		*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
							X												

Total number of PF burners i/s: 24

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1 and 2:

	X	X												X					
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*			*	*	*							*				*	*	*	*
*	*	*	*	*	*							*		*	*	*	*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 22

PF burners o/s in the middle chamber: 10

Summary of the Results of Test 8

General Information

Initial Condition:

- NO_X/O_2 slope ≈ 138 ppm/1% O_2
- NO_X ≈ 730 ppm
- Oxygen ≈ 3.5%
- CO ≈ 2 to 4 ppm
- CinA: no data

Setting 1:

- NO_X/O_2 slope ≈ 60 ppm/1% O_2

Setting 2:

- No enough data to plot a line

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO:

Setting 1:

- When CO equals 200 ppm at 4.2% oxygen:
- NO_X = 430 ppm
- CinA: no data

Setting 2:

- When CO equals 200 ppm at ≈ 4.4% oxygen:
- NO_X ≈ 440 ppm
- CinA: no data

Results of Test 8

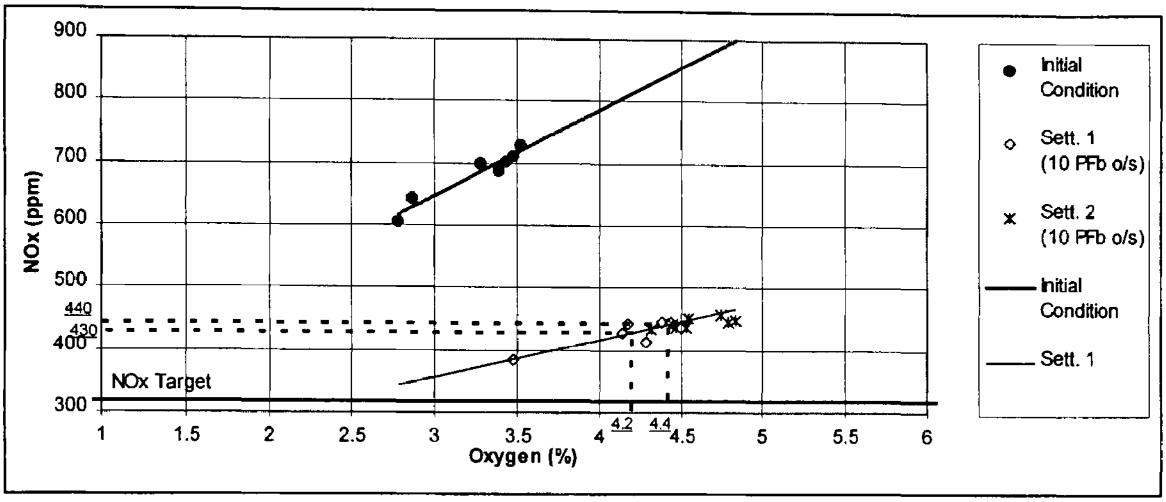


Fig. 6.14: Test 8 - NO_X versus Oxygen.

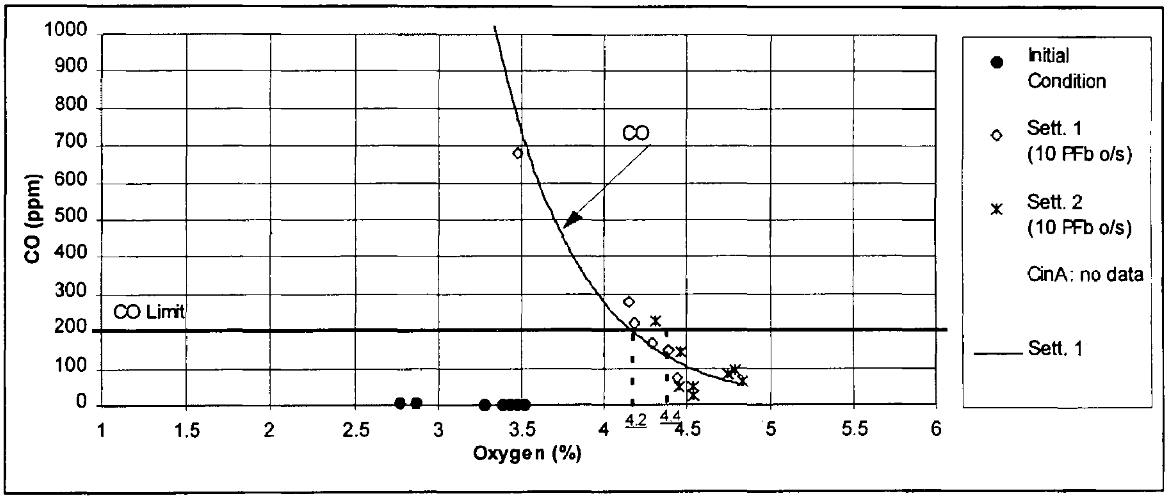


Fig. 6.15: Test 8 - CO versus Oxygen.

Results of Test 8 - cont.

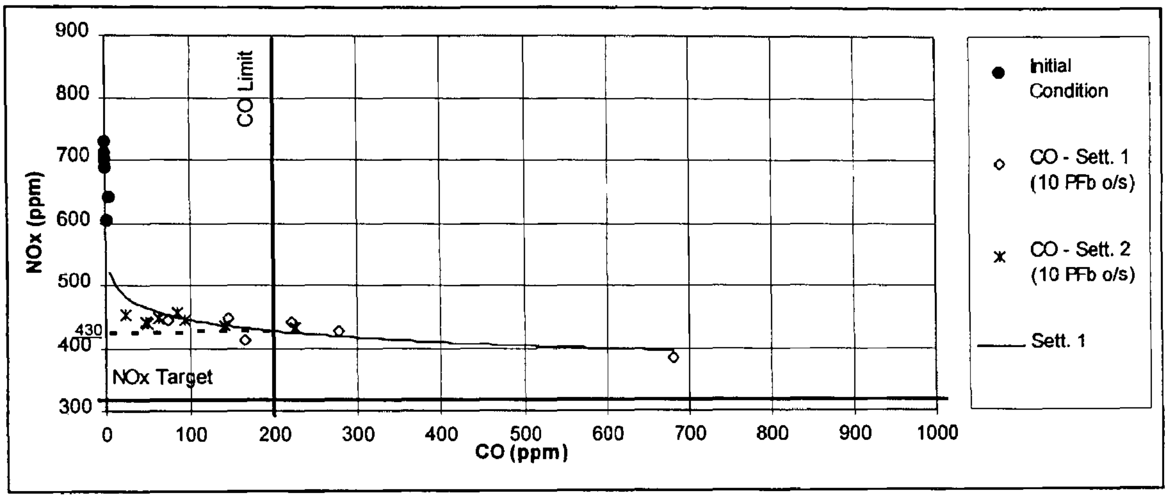


Fig. 6.16: Test 8 - NO_X versus CO.

Test 9

Aim: To investigate the effect of staged combustion through burners out of service (BOOS) in the furnace middle chamber and different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** "Portbury" coal, **(3.)** 5 mills in service (i/s) - D mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Some burners in the middle chamber removed from service, **(3.)** Air Damper Positions: secondary and tertiary air ON for all burners o/s in the middle chamber (BOOS), **(4.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Air Damper Positions: secondary and tertiary air remained ON for all burners o/s in the middle chamber (BOOS), **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Initial Condition:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*	*		*	*	*		*	*	*	*	*	*
*			*	*	*		*			*		*				*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X						X	X					X					X

Total number of PF burners i/s: 26

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1 and 2:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*	*		*	*	*		*	*	*	*	*	*
*			*	*	*		*					*				*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X												X					X

Total number of PF burners i/s: 25

PF burners o/s in the middle chamber: 5

Summary of the Results of Test 9

General Information

Initial Condition:

- NO_X ≈ 915 to 980 ppm
- Oxygen ≈ 3.2 to 3.9%
- CO ≈ 1 to 2 ppm
- CinA ≈ 10 to 10.7%

Setting 1:

- NO_X/O_2 slope ≈ 191 ppm/1% O_2

Setting 2:

- NO_X/O_2 slope ≈ 179 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO, unless otherwise indicated:

Setting 1:

CO remained below 200 ppm (1-6 ppm). Lowest NO_X level achieved:

- NO_X = 620 ppm
- at CinA = 10.8%
- at Oxygen = 2.3%

Setting 2:

- When CO equals 200 ppm at 3.3% oxygen:
- NO_X = 590 ppm
- CinA = 13.5%

Results of Test 9

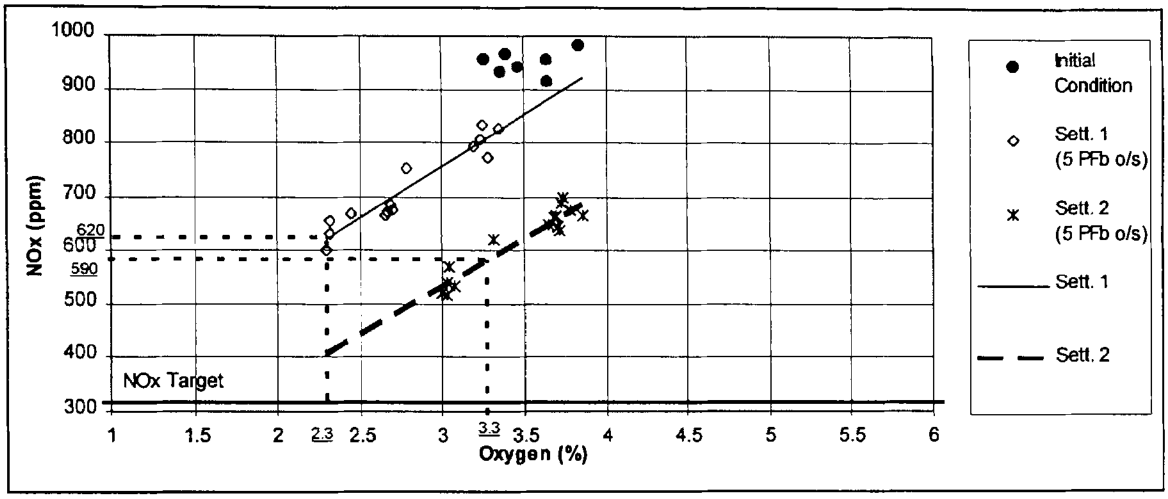


Fig. 6.17: Test 9 - NO_X versus Oxygen.

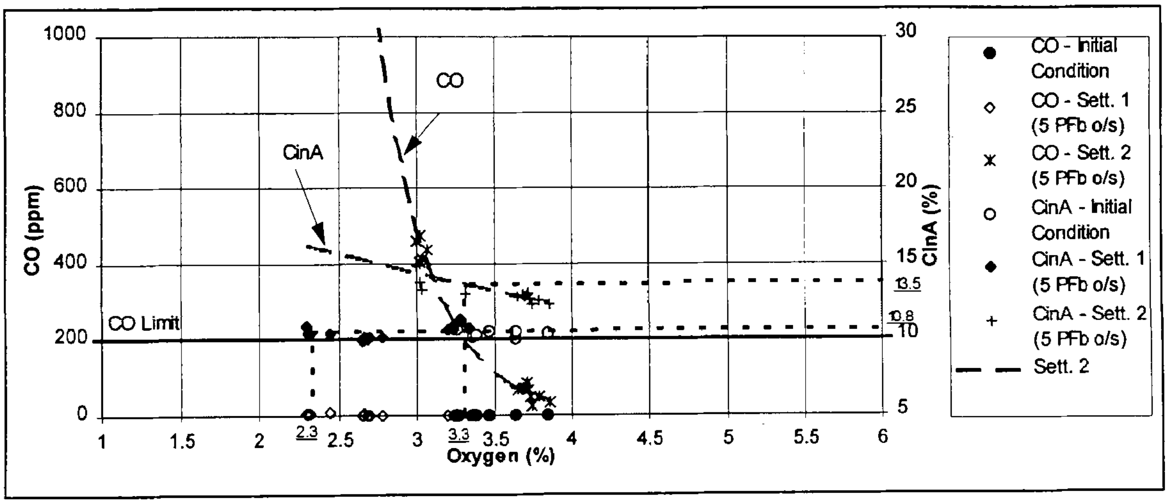


Fig. 6.18: Test 9 - CO and Carbon in ash versus Oxygen.

Results of Test 9 - cont.

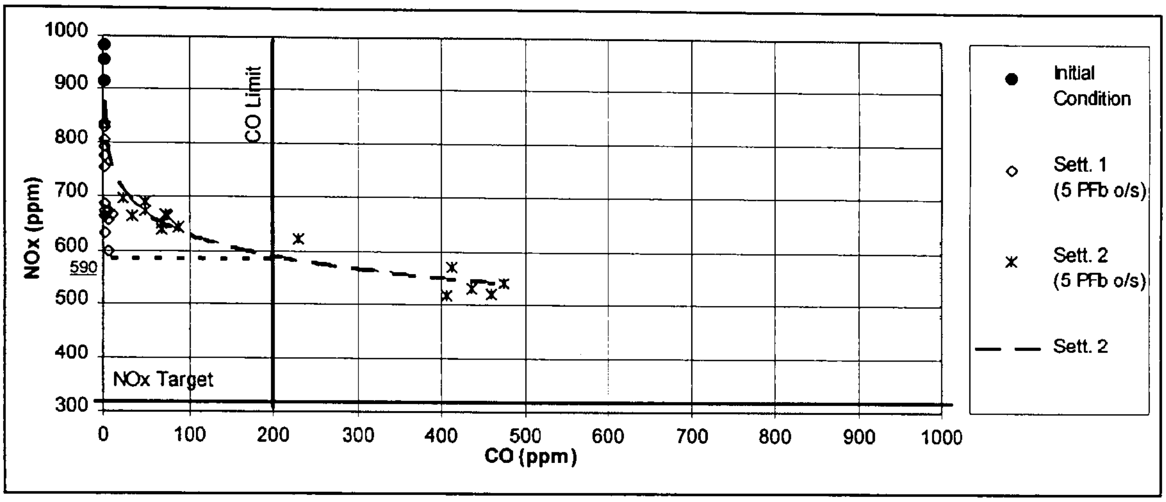


Fig. 6.19: Test 9 - NO_X versus CO.

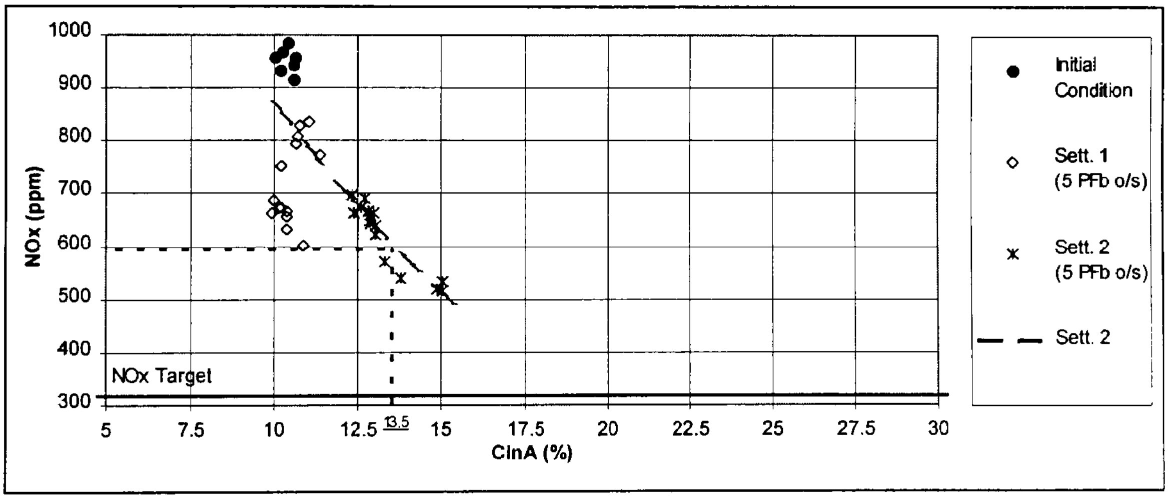


Fig. 6.20: Test 9 - NO_X versus Carbon in ash.

6.1.4 Burners Out Of Service (BOOS) across the Furnace Chambers

Test 10

Aim: To investigate the effect of staged combustion through burners out of service (BOOS) across the furnace chambers and different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - D mill out of service (o/s).

Starting Condition: **(1.)** Boiler stable and firing pattern set with burners o/s uniformly spread in the furnace, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air OFF for all burners o/s.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Air Damper Positions: secondary and tertiary air ON for all burners o/s (BOOS), **(3.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Air Damper Positions: secondary and tertiary air remained ON for all burners o/s (BOOS), **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Starting Condition:

			X	X	X														
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*					*	*	*	*	*	*		*	*	*	*	*	*
*			*	*	*		*			*	*						*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X						X	X			X		X	X	X			

Total number of PF burners i/s: 25

Note: PF burners i/s are marked with an asterisk: *
"X" - Secondary and tertiary air flows OFF.

Setting 1 and 2:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*					*	*	*	*	*	*		*	*	*	*	*	*
*			*	*	*		*			*	*						*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 25

PF burners o/s in the furnace: LHS (B side): 5, middle: 3, RHS (A side): 3.

Summary of the Results of Test 10

General Information

Starting Condition:

- $NO_X \approx$ 740 to 780 ppm
- Oxygen $\approx$ 3.2 to 3.55%
- CO $\approx$ 20 to 60 ppm
- CinA: no data

Setting 1:

- NO_X/O_2 slope $\approx$ 112 ppm/1% O_2

Setting 2:

- NO_X/O_2 slope $\approx$ 93 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO, unless otherwise indicated:

Setting 1:

CO remained below 200 ppm (30-150 ppm). Lowest NO_X level achieved:

- NO_X = 540 ppm
- at oxygen = 3.1%
- at CinA: no data

Setting 2:

CO was in general just above 200 ppm (220 to 256 ppm), for an oxygen range of 2.4 to 3.1%. Lowest NO_X level achieved was:

- NO_X = 440 ppm
- at oxygen = 2.4%
- at CinA: no data

Results of Test 10

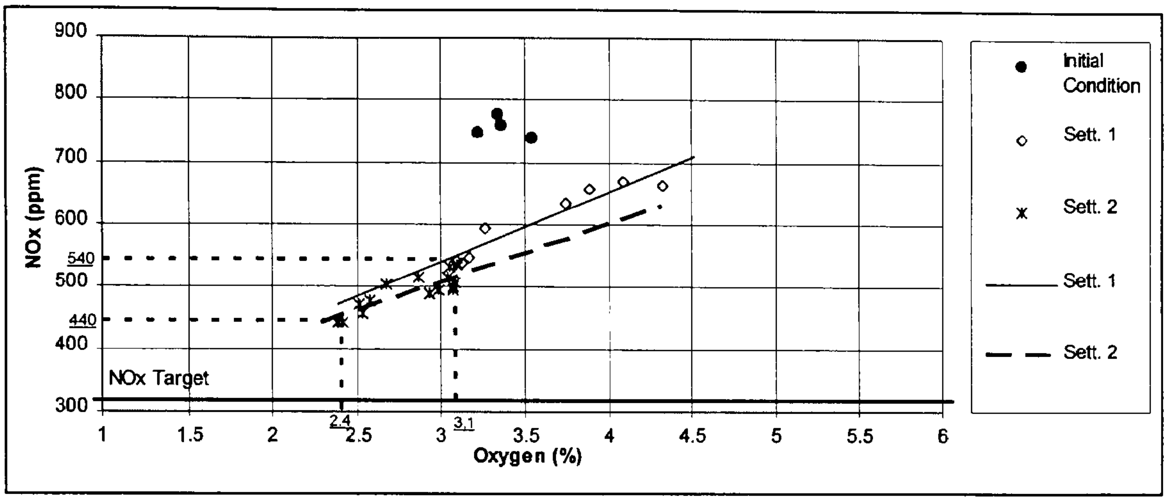


Fig. 6.21: Test 10 - NO_X versus Oxygen.

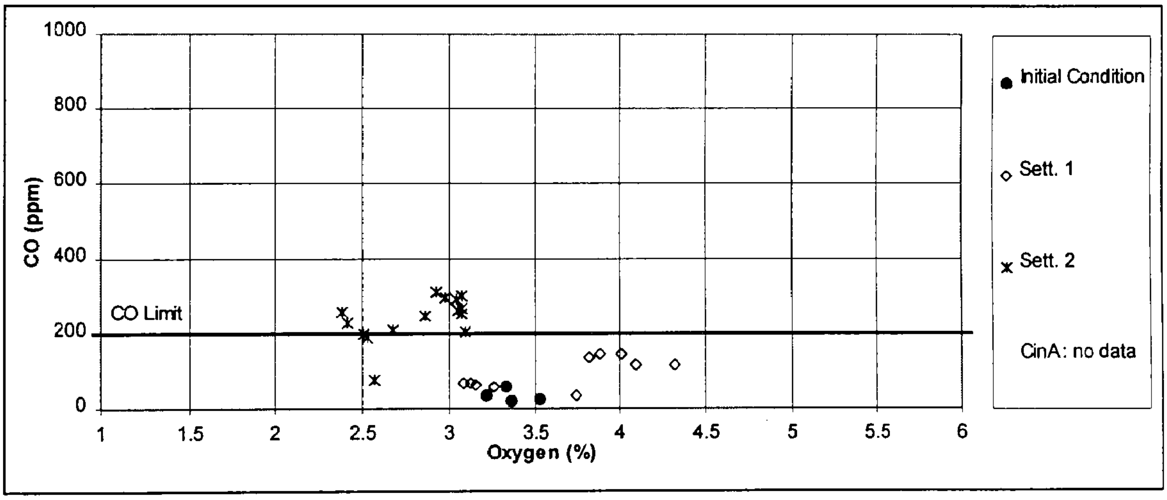


Fig. 6.22: Test 10 - CO versus Oxygen.

Results of Test 10 - cont.

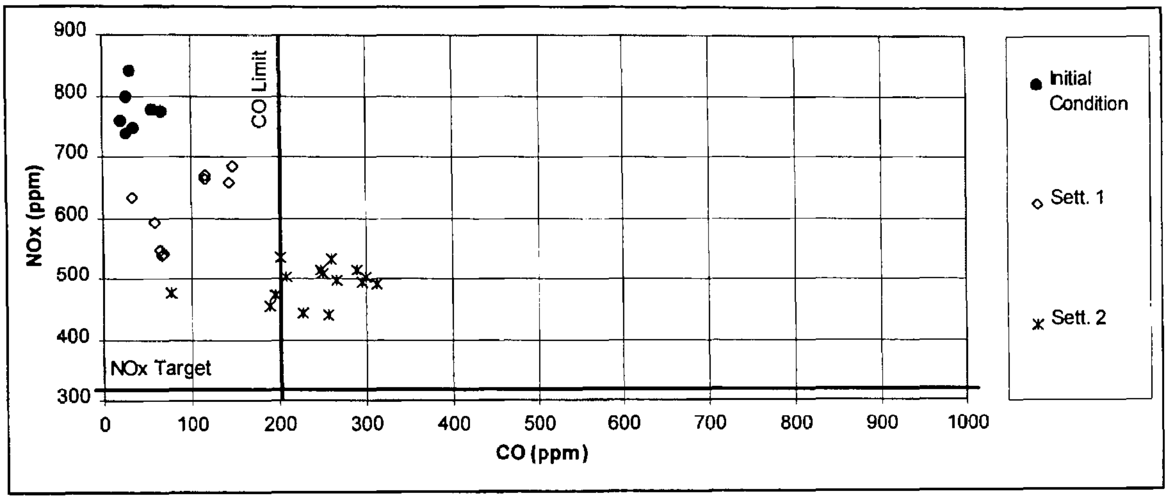


Fig. 6.23: Test 10 - NO_X versus CO.

Test 11

Aim: To investigate the effect of staged combustion through burners out of service (BOOS) across the furnace chambers and different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - D mill out of service (o/s).

Starting Condition: **(1.)** Boiler stable and firing pattern set with burners o/s uniformly spread in the furnace, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air OFF for all burners o/s.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Air Damper Positions: secondary and tertiary air ON for all burners o/s (BOOS), **(3.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Air Damper Positions: secondary and tertiary air remained ON for all burners o/s (BOOS).

The firing patterns were as follows:

Starting Condition:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
*					*		*			*	*	*							*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X	X	X				X	X					X	X	X	X	X	

Total number of PF burners i/s: 25

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1 and 2:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
*					*		*			*	*	*							*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 25

PF burners o/s in the furnace: LHS (B side): 4, middle: 2, RHS (A side): 5.

Summary of the Results of Test 11

General Information

Starting Condition:

- $NO_X \approx 660$ to 730 ppm
- Oxygen ≈ 3.7 to 4.15%
- CO ≈ 0 to 80 ppm
- CinA: no data

Setting 1:

- NO_X/O_2 slope ≈ 84 ppm/1% O_2

Setting 2:

- No enough data to plot a line

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO, unless otherwise indicated:

Setting 1:

CO remained below 200 ppm (0-80 ppm).

Lowest NO_X level achieved:

- NO_X = 520 ppm
- at oxygen = 2.9%
- at CinA: no data

Setting 2:

- No readings possible.

Results of Test 11

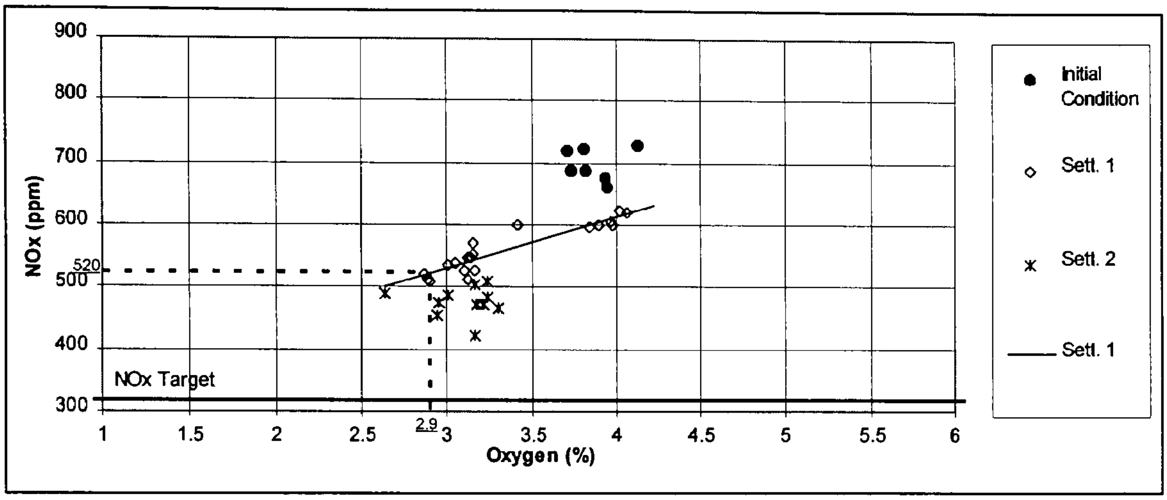


Fig. 6.24: Test 11 - NO_X versus Oxygen.

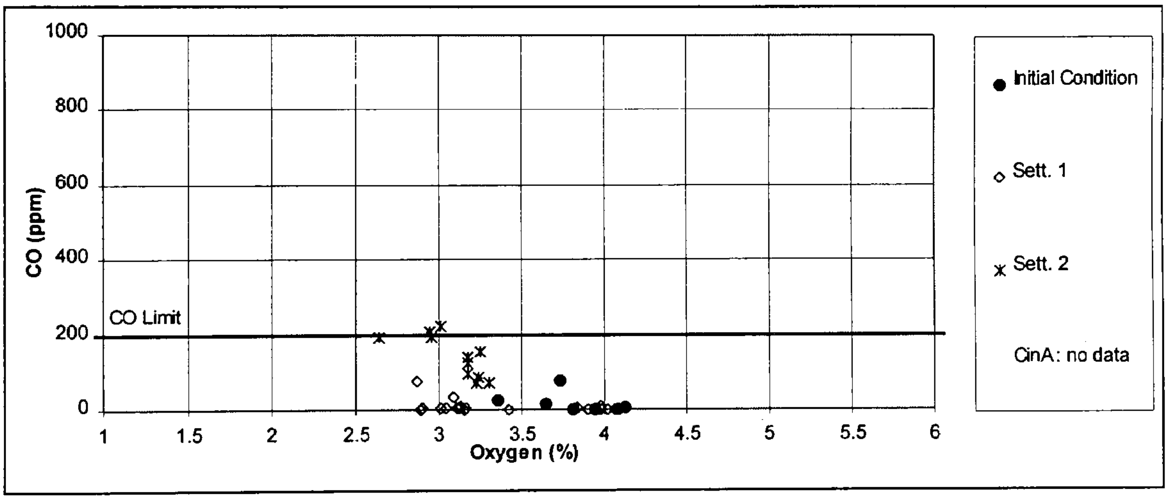


Fig. 6.25: Test 11 - CO versus Oxygen.

Results of Test 11 - cont.

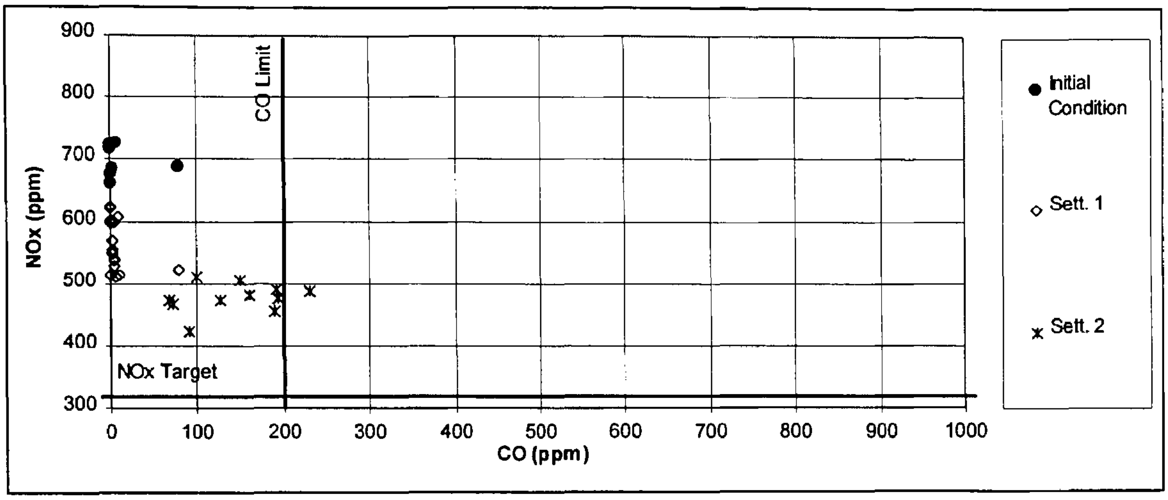


Fig. 6.26: Test 11 - NO_X versus CO.

Test 12

Aim: To investigate the effect of staged combustion through burners out of service (BOOS) across the furnace chambers and different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - D mill out of service (o/s).

Starting Condition: **(1.)** Boiler stable and firing pattern set with burners o/s uniformly spread in the furnace, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air OFF for all burners o/s.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Air Damper Positions: secondary and tertiary air ON for all burners o/s (BOOS), **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Starting Condition:

					X									X					
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*	*	*	*	*	*			*	*	*	*	*
*					*		*			*	*	*					*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X	X	X				X	X					X	X	X			

Total number of PF burners i/s: 25

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*	*	*	*	*	*			*	*	*	*	*
*					*		*			*		*					*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

PF burners o/s in the furnace: LHS (B side): 5, middle: 3, RHS (A side): 4.

<u>**Summary of the Results of Test 12**</u>

General Information

Starting Condition:

- $NO_X \approx$ 820 to 880 ppm
- Oxygen ≈ 2.7 to 3%
- CO ≈ 0 to 40 ppm
- CinA: no data

Setting 1:

- NO_X/O_2 slope ≈ 118 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO:

Setting 1:

- When CO equals 200 ppm at 2.1% oxygen:
- NO_X = 450 ppm
- CinA: no data

Results of Test 12

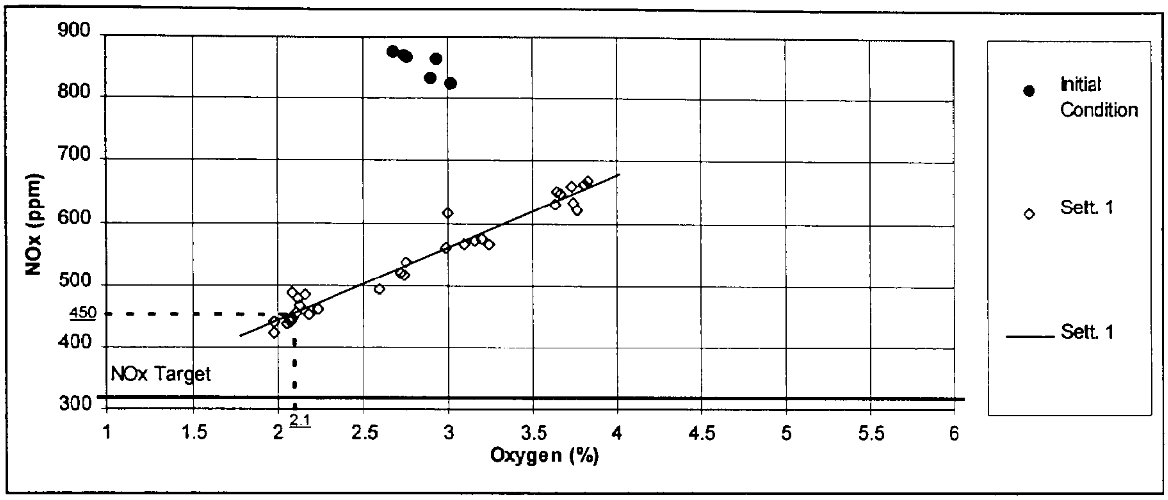


Fig. 6.27: Test 12 - NO_X versus Oxygen.

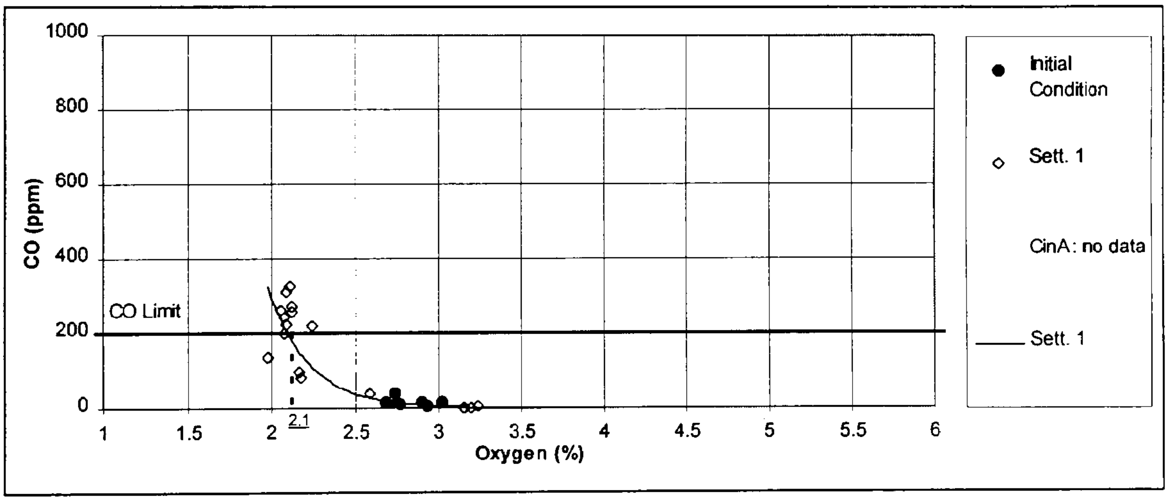


Fig. 6.28: Test 12 - CO versus Oxygen.

Results of Test 12 - cont.

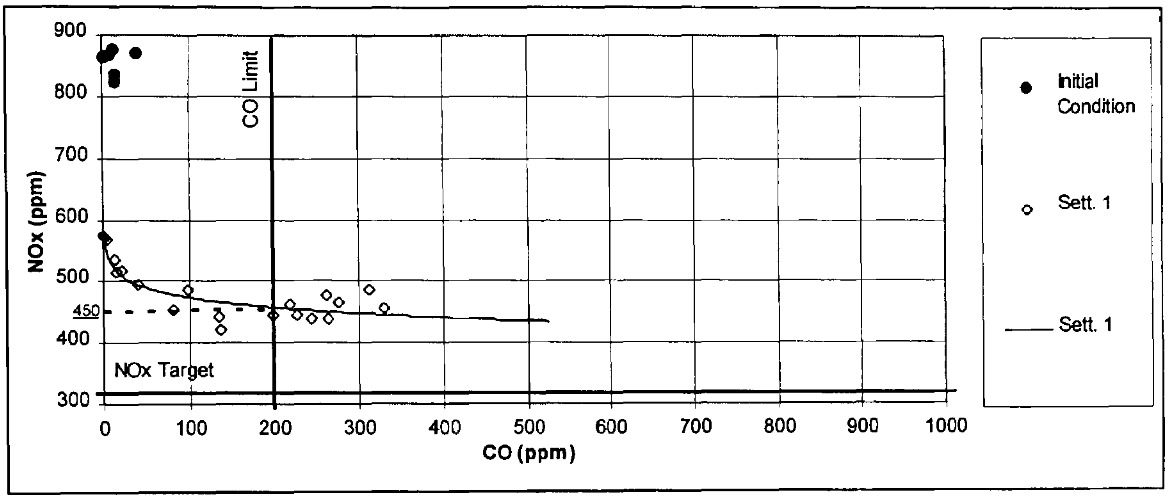


Fig. 6.29: Test 12 - NO_X versus CO.

6.1.5 Air Staging - "Set B"

Test 13

Aim: To investigate the effect of different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 6 mills in service (i/s),

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners out of service (o/s) as found.

Setting (i): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 5/8 open on about half of the burners i/s (those burners supplied by A, C and D mills only).

Setting (ii): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 1/2 open on about half of the burners i/s (those burners supplied by A, C and D mills only).

Setting (iii): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/8 open on about half of the burners i/s (those burners supplied by A, C and D mills only), **(2.)** Variation of the total air flow.

The firing pattern remained the same throughout the test:

Initial Condition, Setting (i), (ii) and (iii):

							X	X	X			X							
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*		*					*	*			*	*	*	*	*	*
	*	*	*	*	*					*				*	*	*	*		*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X							X	X	X			X							

Total number of PF burners i/s: 24

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Summary of the Results of Test 13

General Information

Initial Condition:

- NO_X ≈ 765 to 785 ppm
- Oxygen ≈ 4.1%
- CO ≈ 0 to 2 ppm
- CinA ≈ 8.7 to 9.7%

Setting (i):

- NO_X ≈ 725 to 750 ppm
- Oxygen ≈ 4%
- CO ≈ 0 to 2 ppm
- CinA ≈ 9.1 to 10%

Setting (ii):

- NO_X ≈ 670 to 700 ppm
- Oxygen ≈ 3.8 to 4%
- CO ≈ 0 to 2 ppm
- CinA ≈ 9%

Setting (iii):

- NO_X/O_2 slope ≈ 103 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO, unless otherwise indicated:

Setting (iii):

CO remained below 200 ppm (0-86 ppm).

Lowest NO_X level achieved:

- NO_X = 480 ppm
- at oxygen = 2.48%
- CinA = 10%

Results of Test 13

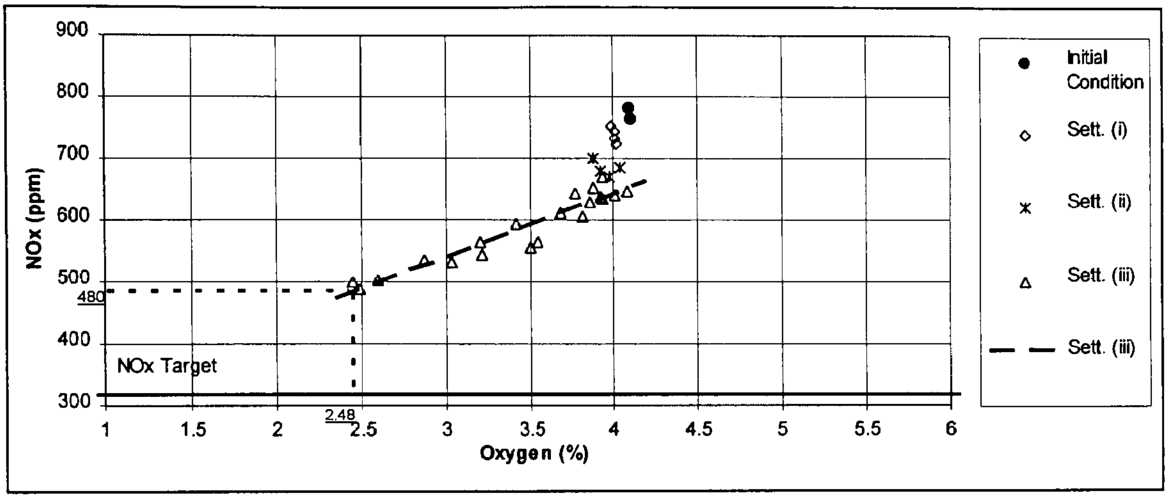


Fig. 6.30: Test 13 - NO_X versus Oxygen.

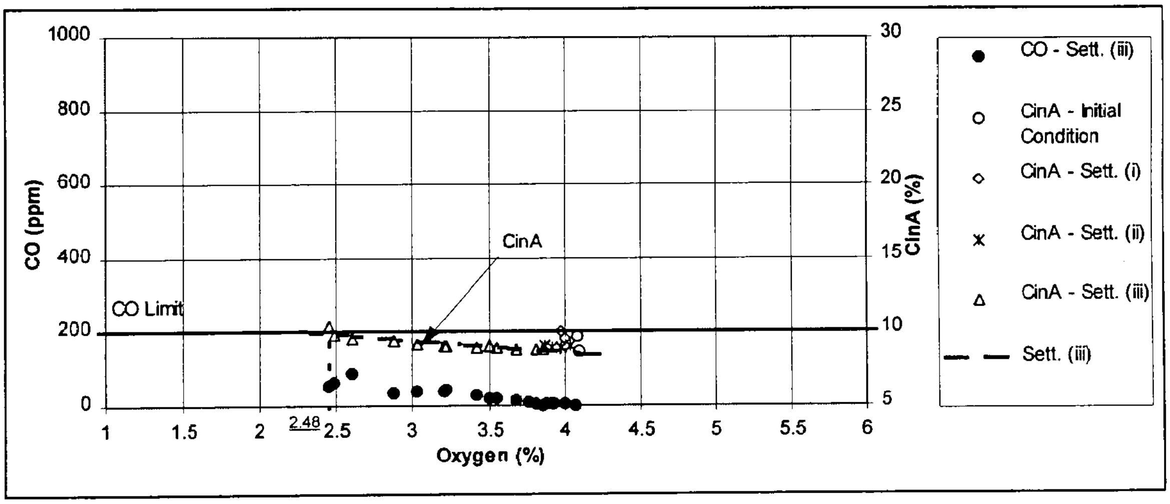


Fig. 6.31: Test 13 - CO and Carbon in ash versus Oxygen.

Note: The CO values for the "Initial Condition", "Setting (i)" and "Setting (ii)" are not plotted in the above graph (Fig. 6.31) for clarity reasons. They are, however, plotted in the next graph (NO_X versus CO) and as shown vary between 0 to 2 ppm.

Results of Test 13 - cont.

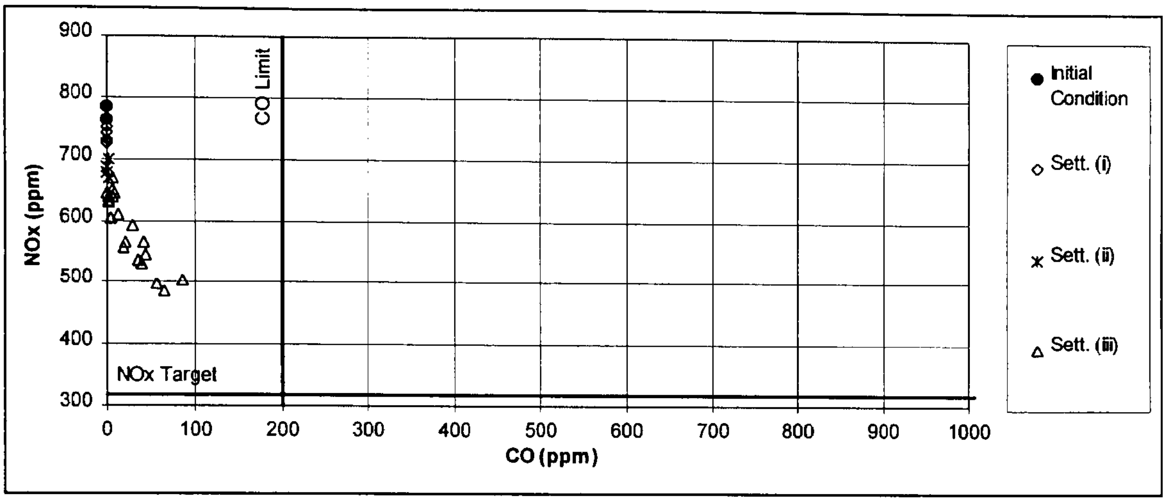


Fig. 6.32: Test 13 - NO_X versus CO.

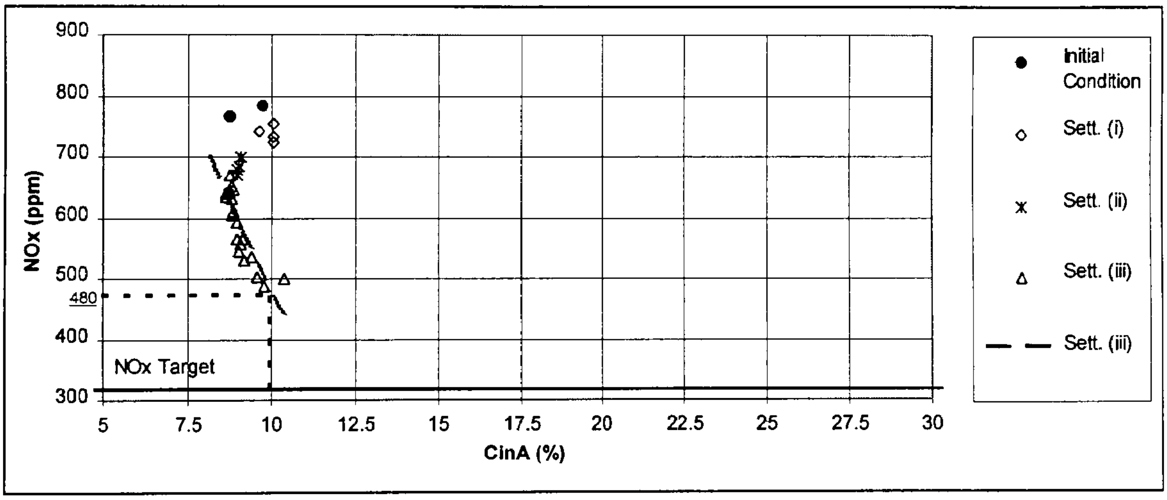


Fig. 6.33: Test 13 - NO_X versus Carbon in ash.

Test 14

Aim: To investigate the effect of different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - B mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

Setting (i): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 5/8 open on about half of the burners i/s (those burners supplied by A, C and D mills only).

Setting (ii): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 1/2 open on about half of the burners i/s (those burners supplied by A, C and D mills only).

Setting (iii): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/8 open on about half of the burners i/s (those burners supplied by A, C and D mills only), **(2.)** Variation of the total air flow.

The firing pattern remained the same throughout the test:

Initial Condition, Setting (i), (ii), and (iii):

												X							X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*			*	*			*	*		*	*	
		*			*			*	*	*		*		*	*		*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X			X	X			X												

Total number of PF burners i/s: 23

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Summary of the Results of Test 14

General Information

Initial Condition:

- NO_X ≈ 750 to 780 ppm
- Oxygen ≈ 3.9 to 4.2%
- CO ≈ 25 to 120 ppm
- CinA ≈ 10 to 10.5%

Setting (i):

- NO_X ≈ 750 ppm
- Oxygen ≈ 4 to 4.1%
- CO ≈ 88 to 95 ppm
- CinA ≈ 9.7%

Setting (ii):

- NO_X ≈ 700 to 735 ppm
- Oxygen ≈ 4 to 4.2%
- CO ≈ 50 to 90 ppm
- CinA ≈ 9.6 to 9.7%

Setting (iii):

- NO_X/O_2 slope ≈ 96 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO, unless otherwise indicated:

Setting (iii):

CO remained below 200 ppm (30-140 ppm).

Lowest NO_X level achieved:

- NO_X = 620 ppm
- at oxygen = 3.5%
- CinA ≈ 10 to 10.5%

Results of Test 14

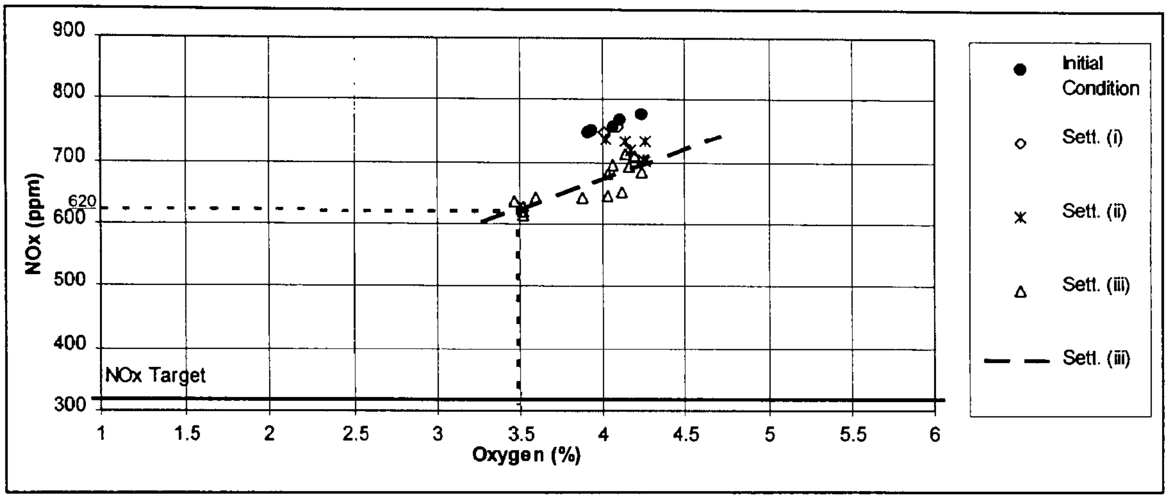


Fig. 6.34: Test 14 - NO_X versus Oxygen.

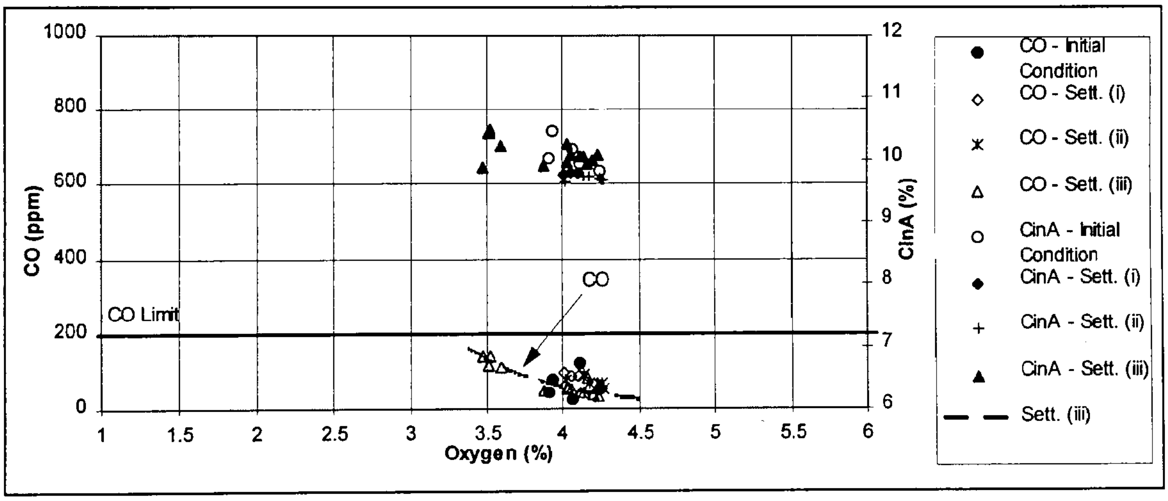


Fig. 6.35: Test 14 - CO and Carbon in ash versus Oxygen.

Results of Test 14 - cont.

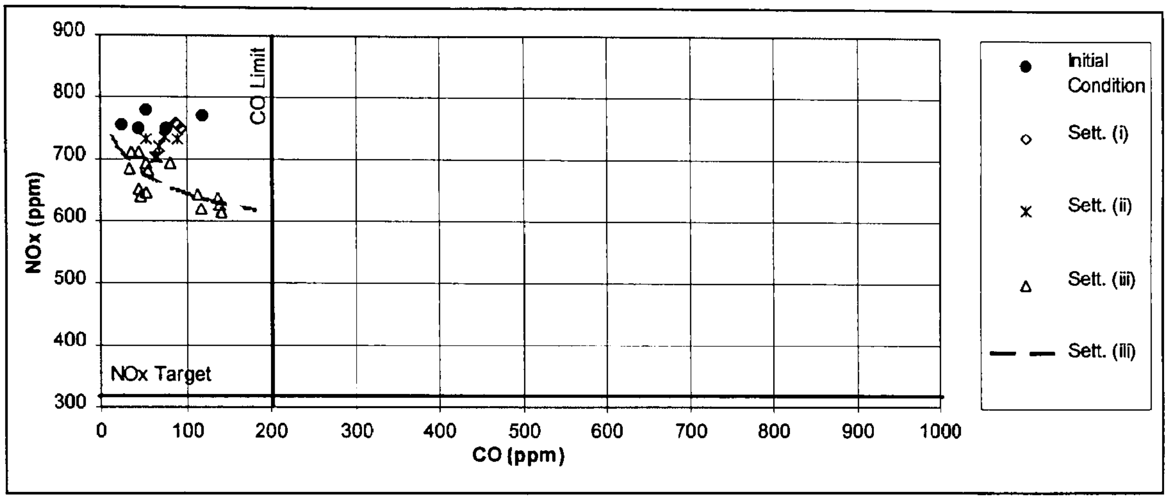


Fig. 6.36: Test 14 - NO_X versus CO.

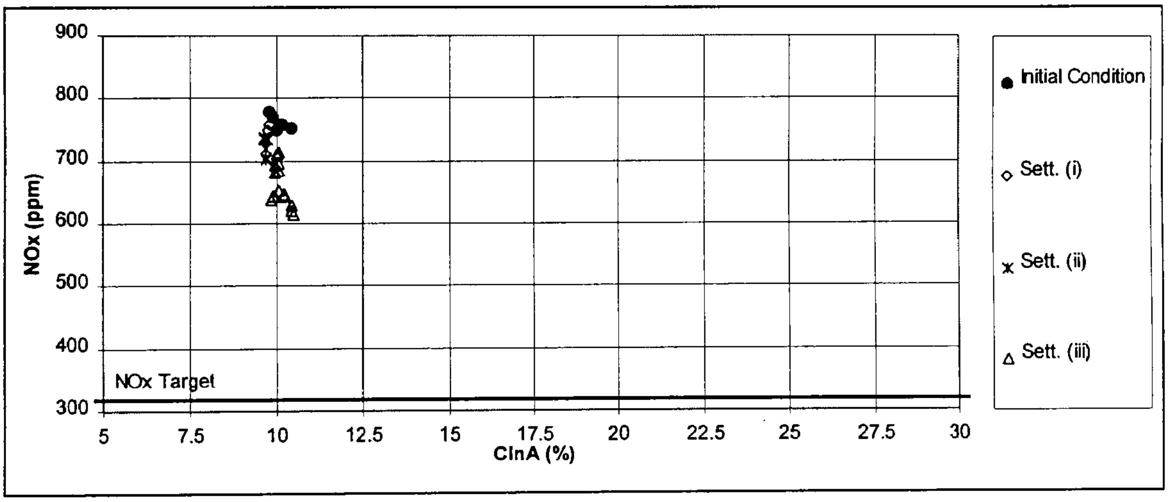


Fig. 6.37: Test 14 - NO_X versus Carbon in ash.

Test 15

Aim: To investigate the effect of different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - B mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

Setting (ii): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 1/2 open on all burners.

Setting (iii): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/8 open on all burners, **(2.)** Variation of the total air flow.

The firing pattern remained the same throughout the test:

Initial Condition, Setting (ii), and (iii):

												X							X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*			*	*			*	*		*	*	
		*			*			*	*	*		*		*	*		*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X			X	X			X												

Total number of PF burners i/s: 23

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Summary of the Results of Test 15

General Information

Initial Condition:

- $NO_X \approx$ 645 to 705 ppm
- Oxygen $\approx$ 4 to 4.1%
- CO $\approx$ 30 to 55 ppm
- CinA $\approx$ 9.7 to 10.2%

Setting (ii):

- $NO_X \approx$ 640 to 680 ppm
- Oxygen $\approx$ 4 to 4.1%
- CO $\approx$ 20 to 40 ppm
- CinA $\approx$ 9.8%

Setting (iii):

- NO_X/O_2 slope $\approx$ 102 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO, unless otherwise indicated:

Setting (iii):

CO remained below 200 ppm (30-175 ppm).

Lowest NO_X level achieved:

- NO_X = 475 ppm
- at oxygen = 2.4%
- CinA $\approx$ 12%

Results of Test 15

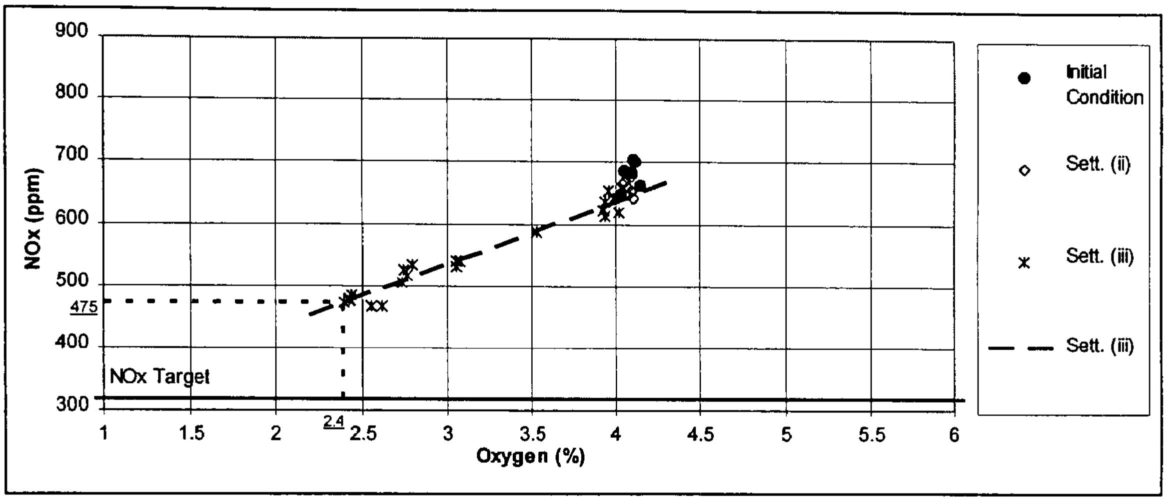


Fig. 6.38: Test 15 - NO_X versus Oxygen.

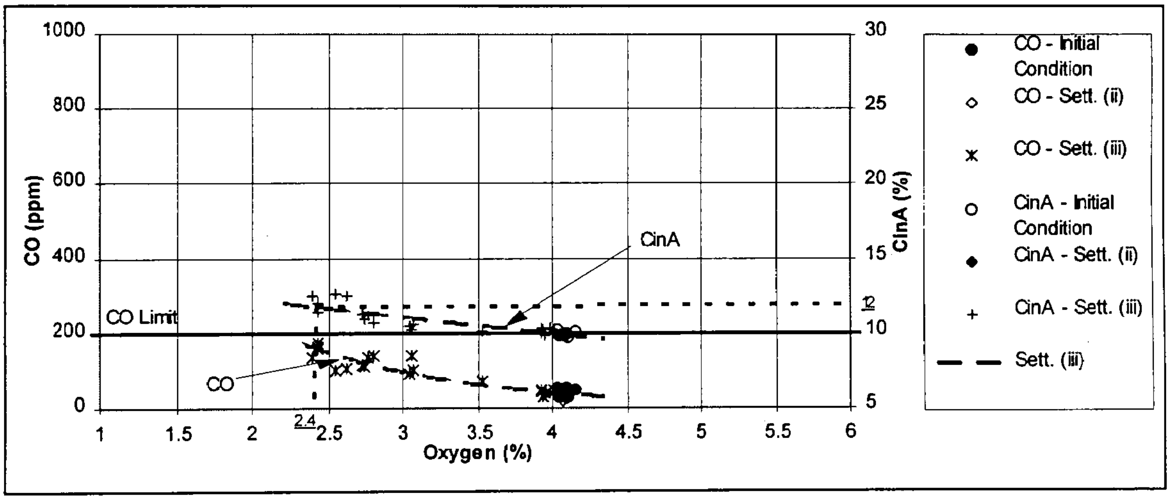


Fig. 6.39: Test 15 - CO and Carbon in ash versus Oxygen.

Results of Test 15 - cont.

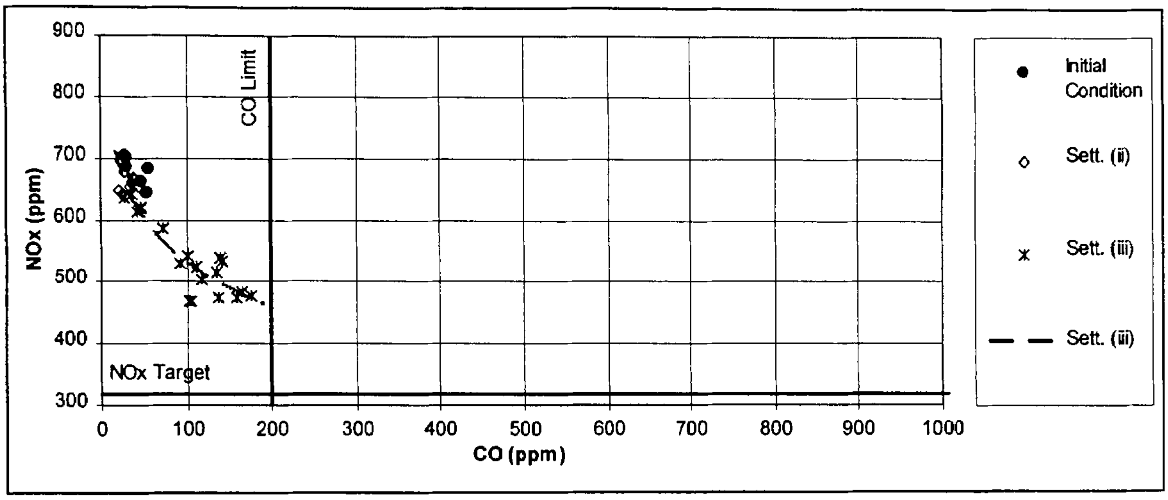


Fig. 6.40: Test 15 - NO_X versus CO.

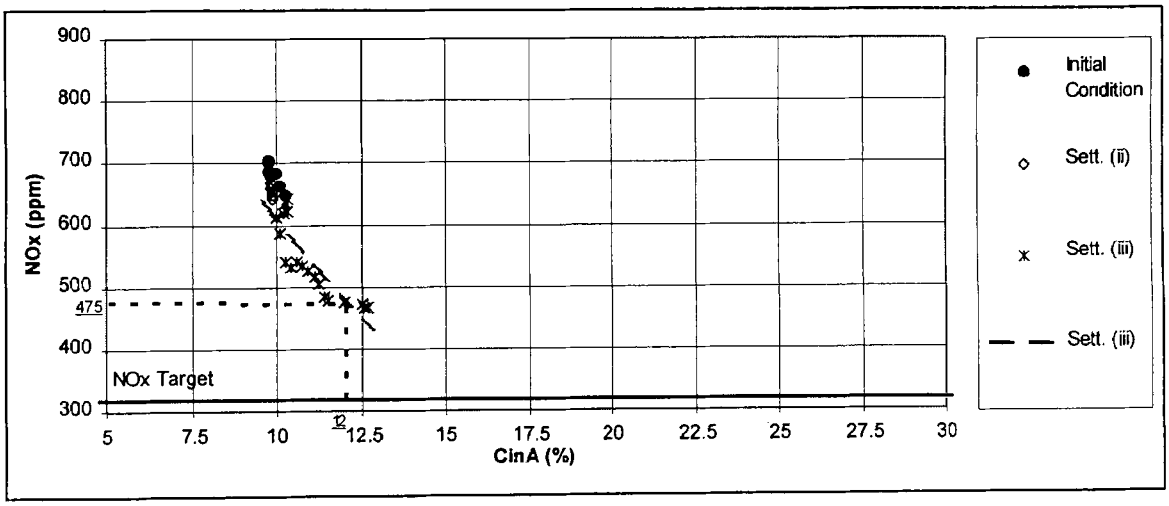


Fig. 6.41: Test 15 - NO_X versus Carbon in ash.

6.1.6 Oil Burners Effect

Test 16

Aim: To investigate the effect of oil[1] burners on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - E mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found, **(4.)** No oil burners i/s.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** 12 oil burners i/s uniformly distributed in the furnace.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** The 12 oil burners remained i/s, **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Initial Condition:

X																			X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	*			*	*			*			*	*		*	*	*	*		
	*	*	*	*	*		*				*			*	*		*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X																			X

Total number of PF burners i/s: 21

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

[1] The oil composition is given in Appendix F.

Setting 1 and 2:

X																			X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
•	*•			*	*			*	•		*•	*		*	*	*•	*	•	
	*•	*	*•	*	*		*•		•		*			*	*•		*	*•	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X																			X

Total number of PF burners i/s: 21

Total number of oil burners i/s: 12

Note: Oil burners i/s are marked with a bullet: •

Summary of the Results of Test 16

General Information

Initial Condition:

- NO_X ≈ 605 to 685 ppm
- Oxygen ≈ 4.24 to 4.7%
- CO ≈ 0 to 80 ppm
- CinA ≈ 9.6 to 11.6%

Setting 1:

- No enough data to plot a line

Setting 2:

- NO_X/O_2 slope ≈ 43 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to this 200 ppm CO, unless otherwise indicated:

Setting 1:

Oxygen level not varied. CO remained below 200 ppm (0-4 ppm). Values read:

- NO_X ≈ 460 to 500 ppm
- Oxygen ≈ 4.4 to 4.6%
- CinA ≈ 9.5 to 10%

Setting 2:

CO remained below 200 ppm (0-40 ppm). Lowest NO_X level achieved:

- NO_X = 385 ppm
- at oxygen = 3.2%
- at CinA = 11.5%

Results of Test 16

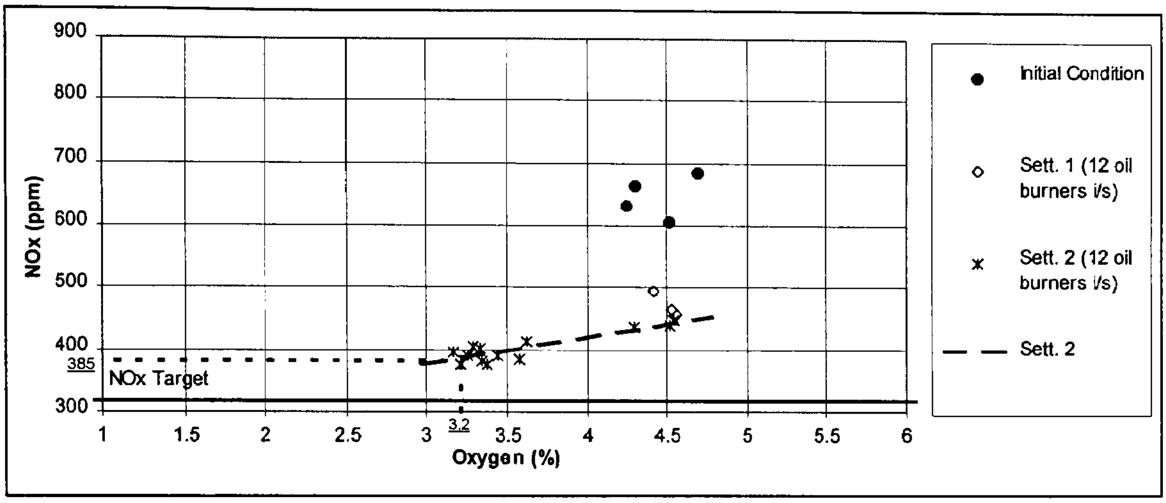


Fig. 6.42: Test 16 - NO_X versus Oxygen.

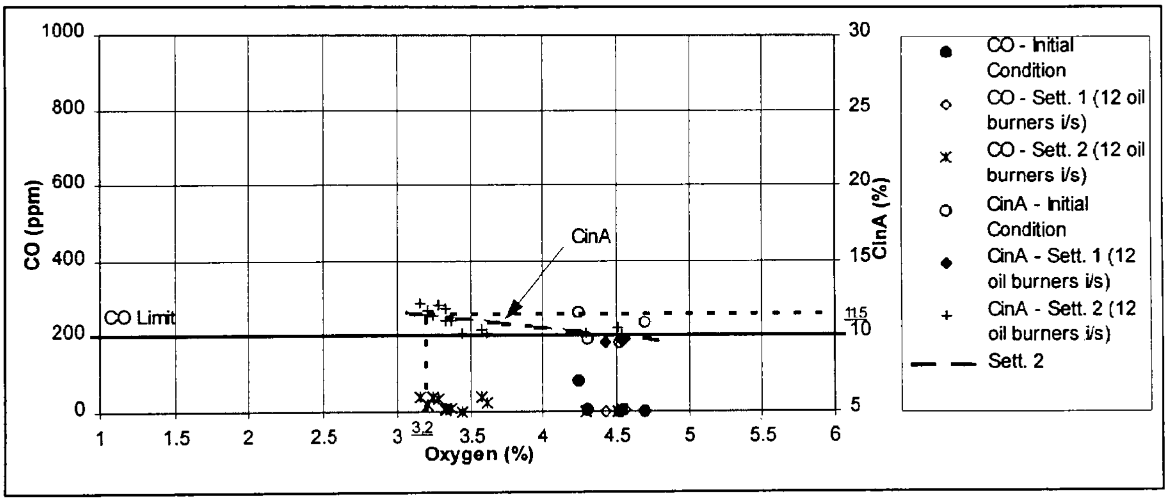


Fig. 6.43: Test 16 - CO and Carbon in ash versus Oxygen.

Results of Test 16 - cont.

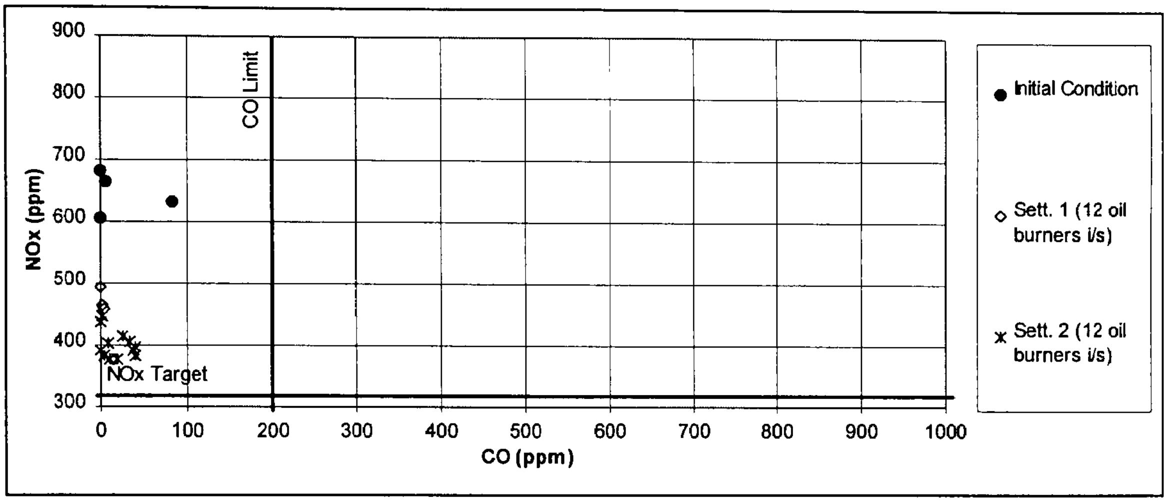


Fig. 6.44: Test 16 - NO_X versus CO.

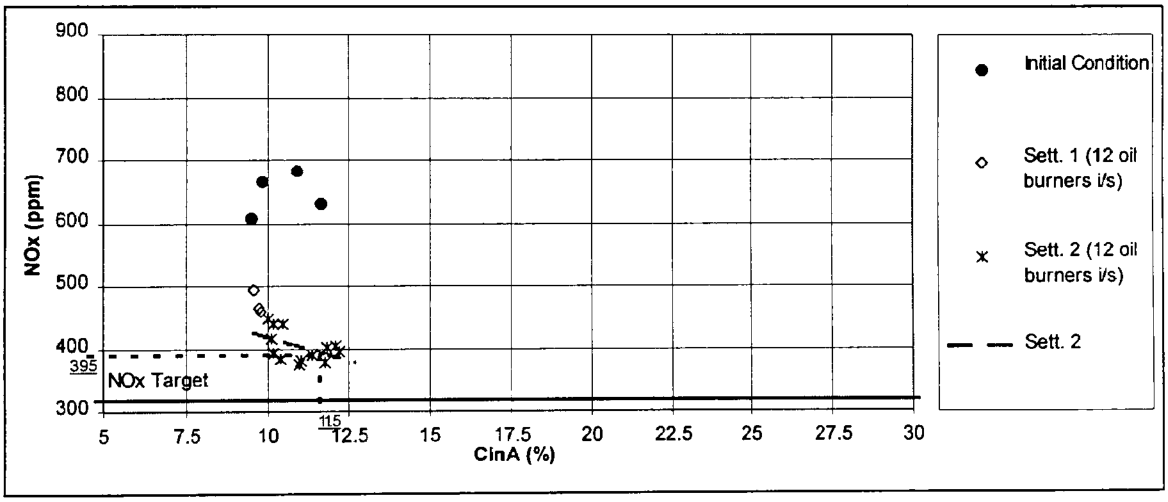


Fig. 6.45: Test 16 - NO_X versus Carbon in ash.

Test 17

Aim: To investigate the effect of oil burners on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 6 mills in service (i/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners out of service (o/s) as found, **(4.)** No oil burners i/s.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** 12 oil burners i/s uniformly distributed in the furnace.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** The 12 oil burners remained i/s, **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Initial Condition:

							X												
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*				*	*		*			*	*	*	*	*
*		*			*					*	*	*		*	*	*	*		*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
			X	X			X	X	X										

Total number of PF burners i/s: 25

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1 and 2:

							X												
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*•	*	*	*•	*				*•	*		*•			*	*•	*	*•	*
*	•	*		•	*				•	*	*•	*		*	*•	*	*	•	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
			X	X			X	X	X										

Total number of PF burners i/s: 25

Total number of oil burners i/s: 12

Note: Oil burners i/s are marked with a bullet: •

Summary of the Results of Test 17

General Information

Initial Condition:

- NO_X ≈ 540 to 590 ppm
- Oxygen ≈ 3.56 to 3.8%
- CO ≈ 100 to 170 ppm
- CinA ≈ 9.3 to 10.5%

Setting 1:

- No enough data to plot a line

Setting 2:

- NO_X/O_2 slope ≈ 37 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to this 200 ppm CO, unless otherwise indicated:

Setting 1:

Oxygen level not varied. Values read:

- NO_X ≈ 400 to 430 ppm
- Oxygen ≈ 2.65 to 2.78%
- CinA ≈ 10.7 to 11.4%
- CO ≈ 720 to 760 ppm

Setting 2:

CO remained above 200 ppm:

- NO_X = 460 ppm (for CO nearest to 200 ppm)
- at oxygen = 5%
- at CinA = 11%
- at CO = 240 ppm

Results of Test 17

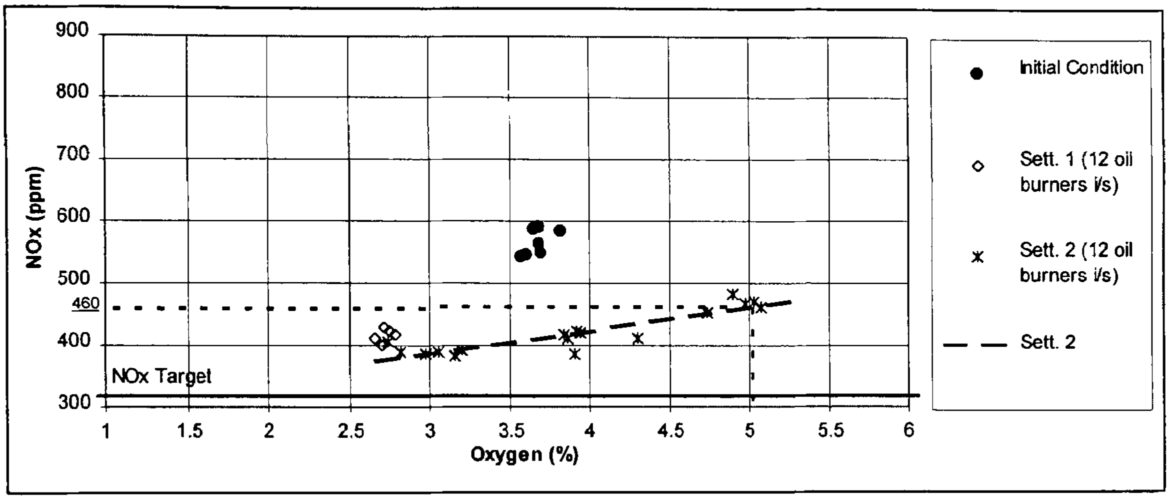


Fig. 6.46: Test 17 - NO_X versus Oxygen.

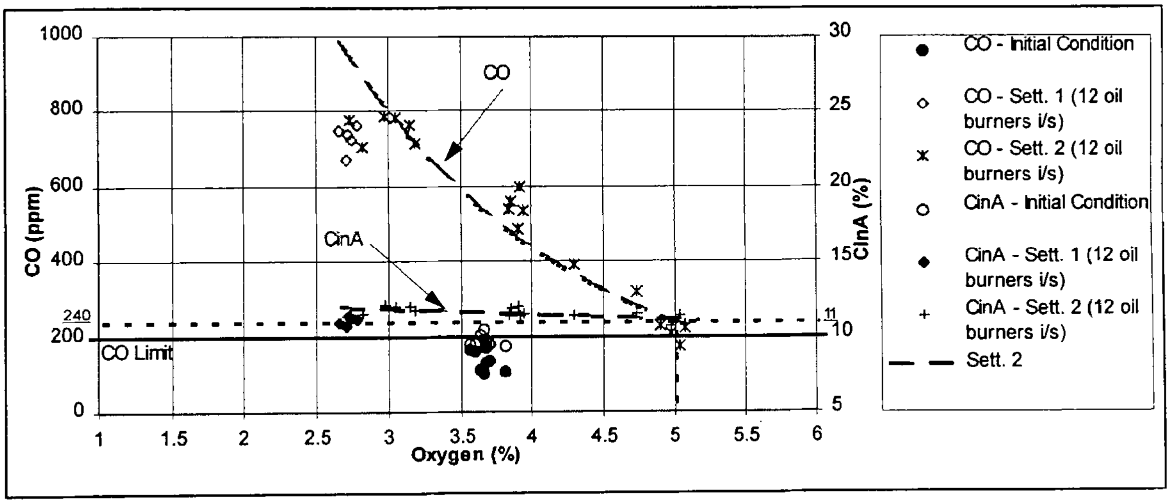


Fig. 6.47: Test 17 - CO and Carbon in ash versus Oxygen.

Results of Test 17 - cont.

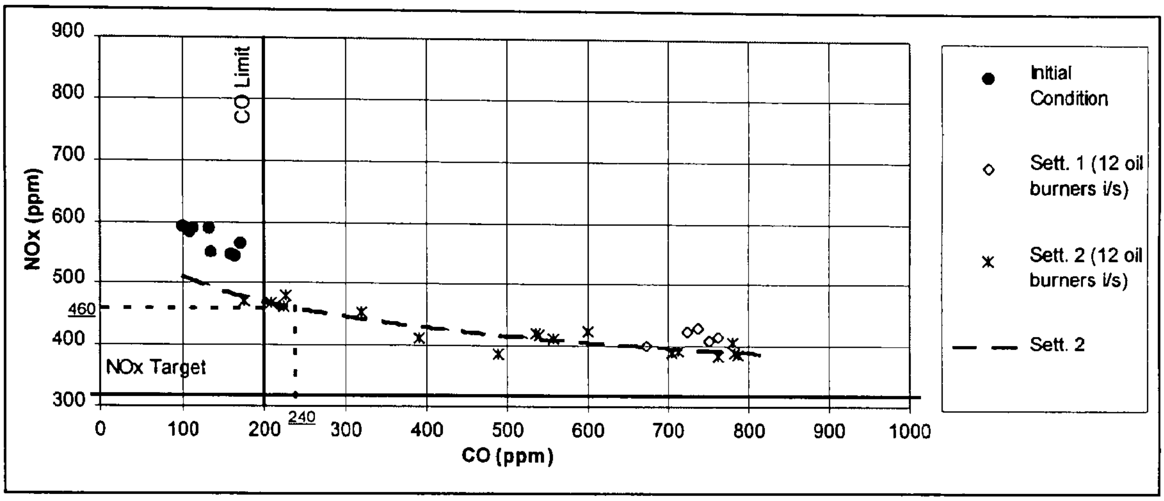


Fig. 6.48: Test 17 - NO_X versus CO.

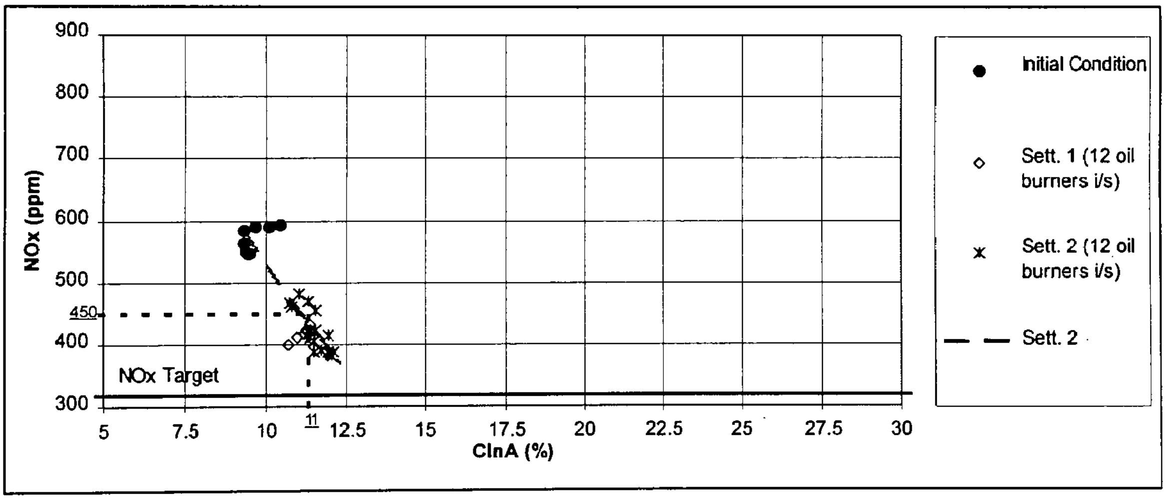


Fig. 6.49: Test 17 - NO_X versus Carbon in ash.

Test 18

Aim: To investigate the effect of oil burners on NO_X emissions.

General Test Conditions: **(1.)** Load: 500 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - F mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found, **(4.)** No oil burners i/s.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** 12 oil burners i/s uniformly distributed in the furnace.

Setting 1.1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Extra 10 oil burners i/s uniformly distributed in the furnace making a total of 22 oil burners i/s, **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Initial Condition:

X	X	X						X	X					X					
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
			*		*		*			*	*	*				*	*		*
*	*	*	*	*			*	*	*	*	*	*			*		*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
					X									X					

Total number of PF burners i/s: 24

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1:

X	X	X						X	X					X					
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
			*•		*•		*			*•	*•	*				*	*•		*•
*•	*	*•	*	*			*	*	*•	*•	*	*		•	*		*•	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
					X									X					

Total number of PF burners i/s: 24

Total number of oil burners i/s: 12

<u>Note</u>: Oil burners i/s are marked with a bullet: •

Setting 1.1:

X	X	X						X	X					X					
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	•		*•		*•		*	•		*•	*•	*•				*•	*•		*•
*•	*•	*•	*	*•			*•	*	*•	*•	*	*•		•	*		*•	*•	*•
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
					X									X					

Total number of PF burners i/s: 24

Total number of oil burners i/s: 22

<u>Summary of the Results of Test 18</u>

General Information

<u>Initial Condition</u>:

- $NO_X \approx$ 710 to 730 ppm
- Oxygen ≈ 3.9 to 4.2%
- CO ≈ 0 to 2 ppm
- CinA: no data

<u>Setting 1</u>:

- No enough data to plot a line

<u>Setting 1.1</u>:

- NO_X/O_2 slope ≈ 64 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to this 200 ppm CO, unless otherwise indicated:

Setting 1:

Oxygen level not varied. CO remained below 200 ppm (0-2 ppm). Values read:

- $NO_X \approx$ 600 to 635 ppm
- Oxygen $\approx$ 4.1 to 4.3%
- CinA: no data

Setting 1.1:

- When CO equals 200 ppm at 2.9% oxygen:
- NO_X = 395 ppm
- CinA: no data

Results of Test 18

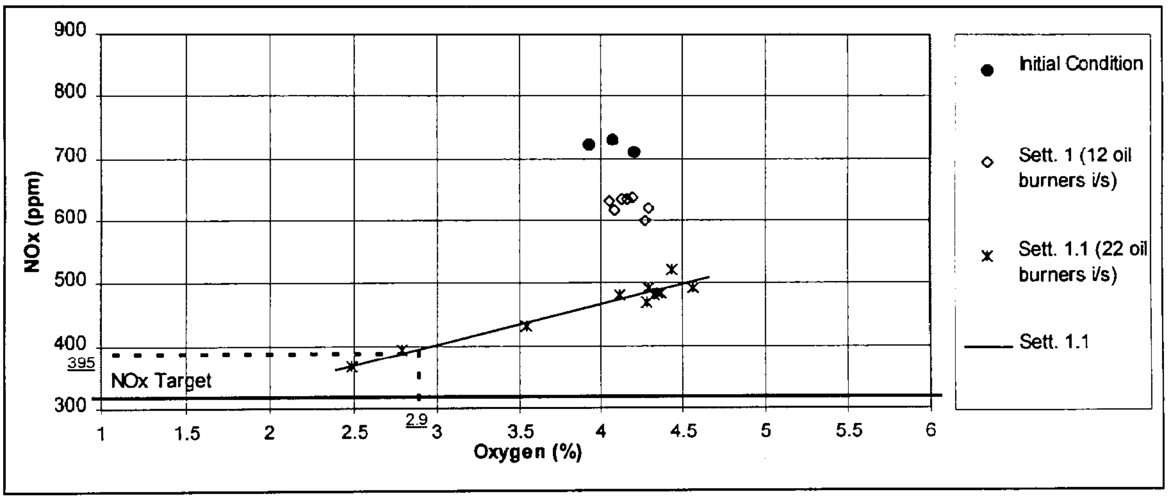


Fig. 6.50: Test 18 - NO_X versus Oxygen.

Results of Test 18 - cont.

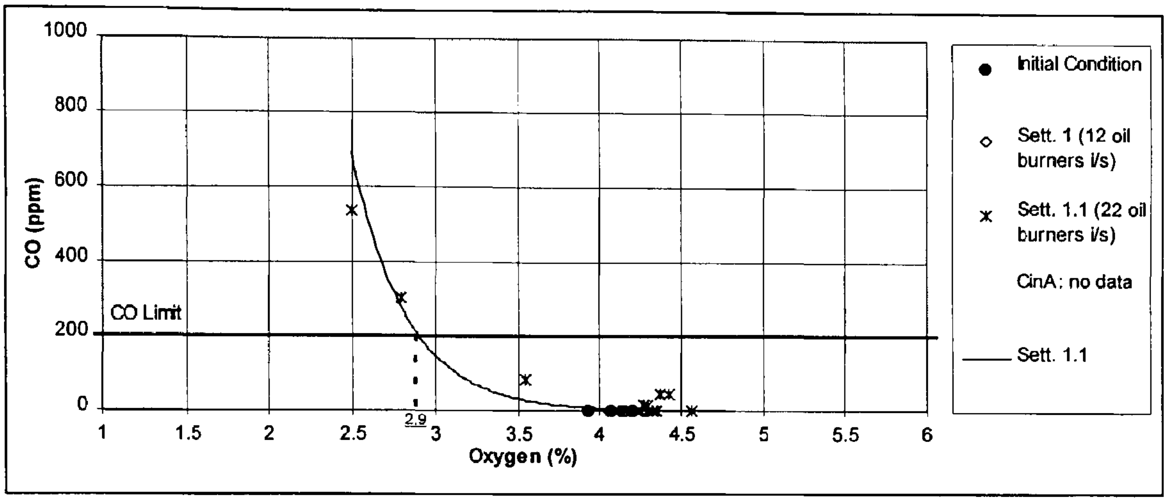


Fig. 6.51: Test 18 - CO versus Oxygen.

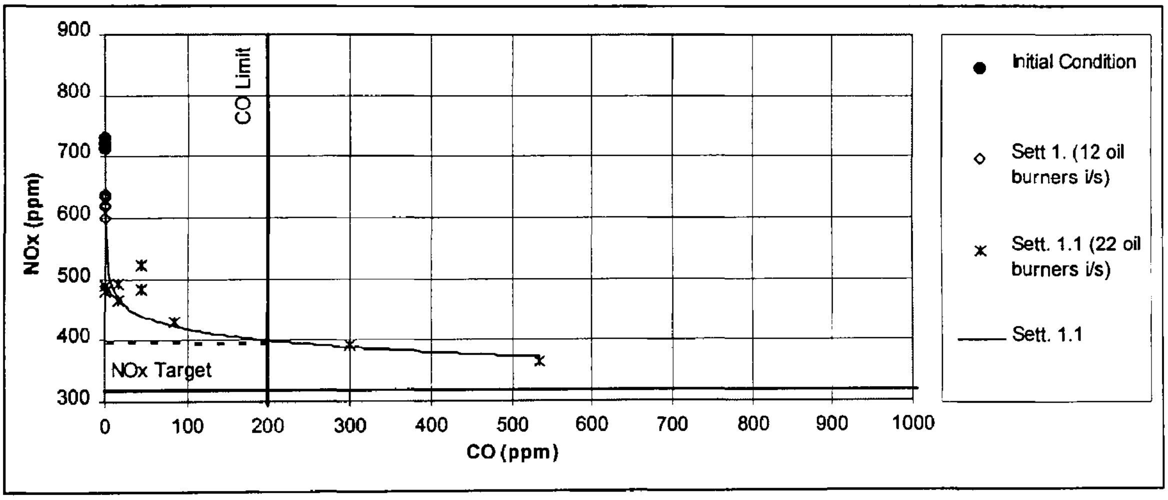


Fig. 6.52: Test 18 - NO_X versus CO.

6.2 420 MWe TESTS

6.2.1 Baseline Operation

Test 19

Aim: To investigate the boiler baseline conditions (boiler operating conditions and emissions) during normal operation of the plant at part load (420 MW) with different damper settings.

General Test Conditions: **(1.)** Load: 420 MW, **(2.)** South Wales coal, **(3.)** 4 mills in service (i/s) - E and F mills out of service (o/s).

Initial Condition: **(1.)** Boiler stable and firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Variation of the total air flow.

The firing pattern remained the same throughout the test:

Initial Condition, Setting 1 and 2:

	X	X					X	X	X										X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
				*	*					*	*	*				*	*	*	
*	*	*	*	*	*		*	*	*	*				*	*		*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
												X							X

Total number of PF burners i/s: 22

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Summary of the Results of Test 19

General Information

Initial Condition:
- $NO_X \approx$ 550 to 610 ppm
- Oxygen ≈ 3.7 to 3.8%
- CO ≈ 35 to 50 ppm
- CinA ≈ 12.5 to 13.8%

Setting 1:
- NO_X/O_2 slope ≈ 102 ppm/1% O_2

Setting 2:
- NO_X/O_2 slope ≈ 108 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to this 200 ppm CO:

Setting 1:
- When CO equals 200 ppm at 2.55% oxygen:
- NO_X = 450 ppm
- CinA = 15.5%

Setting 2:
- When CO equals 200 ppm at 2.75% oxygen:
- NO_X = 440 ppm
- CinA = 17%

Boiler Operation Information

- Typical number of PF burners i/s at 500 MW: 22
- No specific firing pattern.
- Damper settings currently favoured by the station operators: 1/2 open on the secondary air and 3/4 open on the tertiary air.
- Secondary and tertiary air dampers open or closed on the burners o/s, due to (i) mode of operating the boiler by the operator or (ii) in the case of two burners with a shared windbox (example: burners F6 and F5), when only one burner is firing there are no means to isolate the air supplies to the other burner.

Results of Test 19

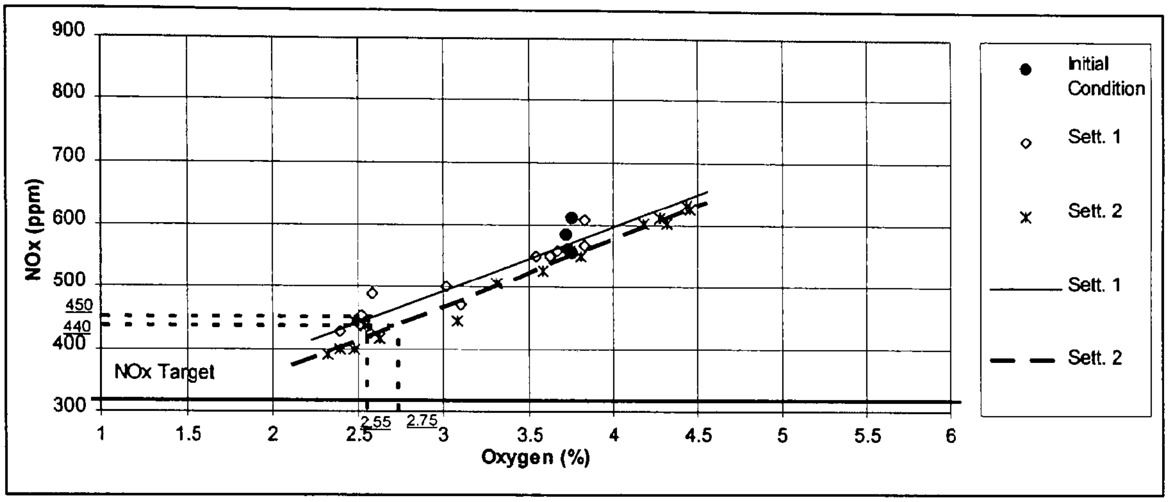


Fig. 6.53: Test 19 - NO_X versus Oxygen.

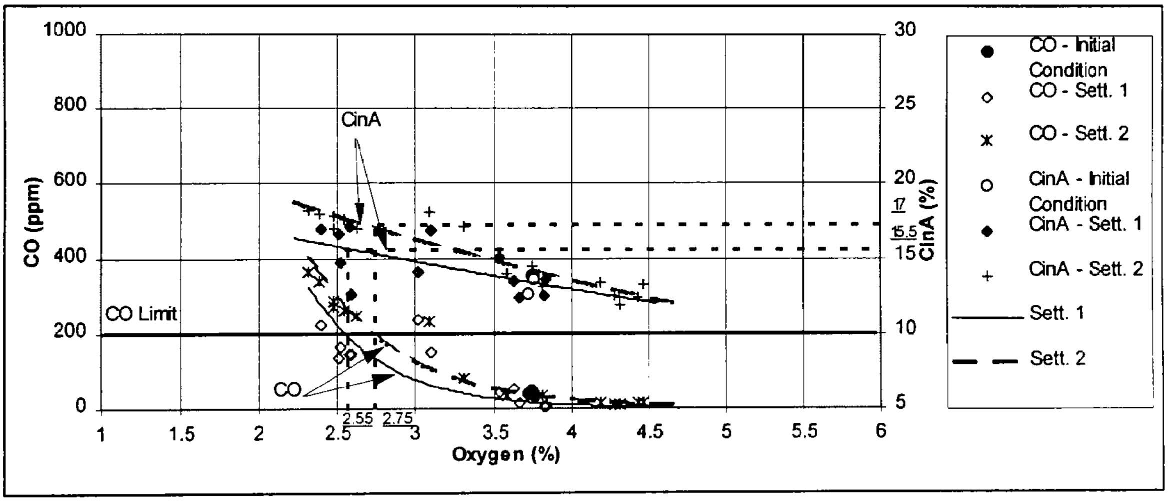


Fig. 6.54: Test 19 - CO and Carbon in ash versus Oxygen.

Results of Test 19 - cont.

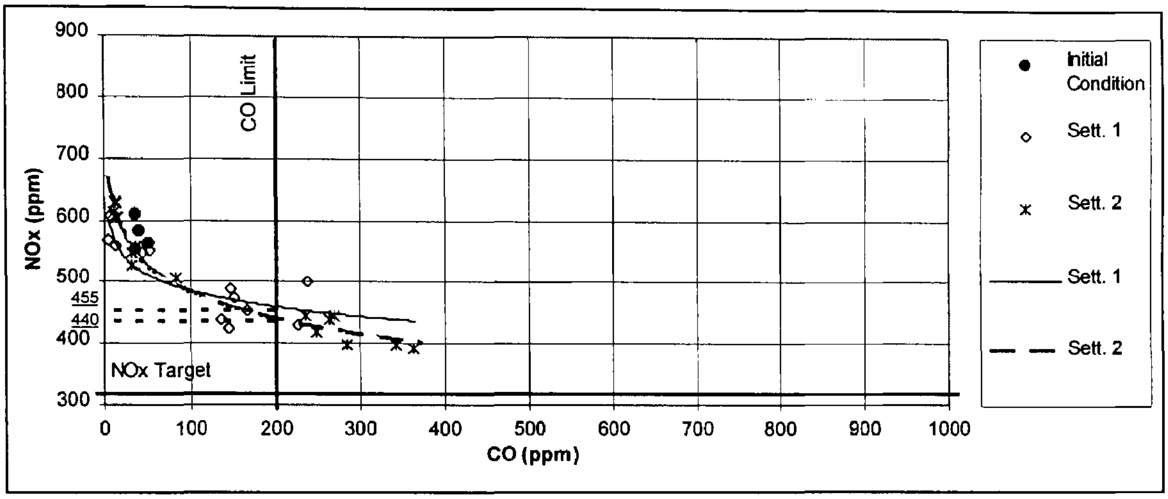


Fig. 6.55: Test 19 - NO_X versus CO.

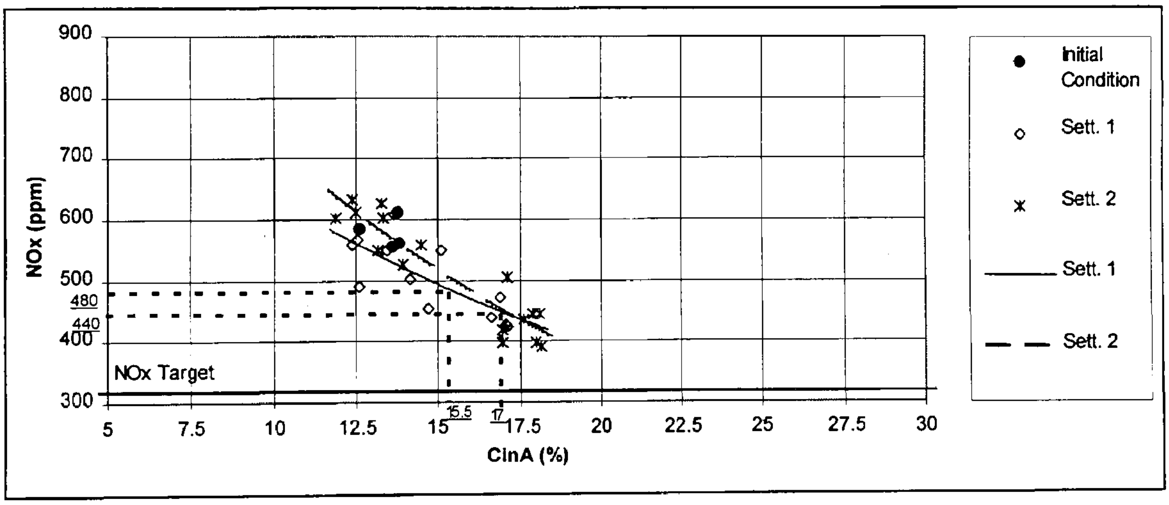


Fig. 6.56: Test 19 - NO_X versus Carbon in ash.

6.2.2 Burners Out Of Service (BOOS) in the Furnace Middle Chamber

Test 20

Aim: To investigate the effect of staged combustion through burners out of service (BOOS) in the furnace middle chamber and different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 420 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - E mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Air Damper Positions: secondary and tertiary air ON for all burners o/s in the middle chamber (BOOS), **(3.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Air Damper Positions: secondary and tertiary air remained ON for all burners o/s in the middle chamber (BOOS), **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Initial Condition:

X							X	X	X	X	X	X							
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	*	*		*										*	*	*	*	*	*
*	*	*	*	*	*					*				*	*		*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
							X	X	X			X							X

Total number of PF burners i/s: 20

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1 and 2:

X																				
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	*	*		*										*	*	*	*	*	*
*	*	*	*	*	*					*				*	*		*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
																			X

Total number of PF burners i/s: 20

PF burners o/s in the middle chamber: 11

Summary of the Results of Test 20

General Information

Initial Condition:

- NO_X ≈ 550 to 605 ppm
- Oxygen ≈ 3.2 to 3.6%
- CO ≈ 4 to 50 ppm
- CinA ≈ 10.6 to 11.8%

Setting 1:

- NO_X/O_2 slope ≈ 90 ppm/1% O_2

Setting 2:

- NO_X/O_2 slope ≈ 92 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to this 200 ppm CO:

Setting 1:

- When CO equals 200 ppm at 5.5% oxygen:
- NO_X = 660 ppm
- CinA = 15.2%

Setting 2:

- When CO equals 200 ppm at 5.25% oxygen:
- NO_X = 580 ppm
- CinA = 12.4%

Results of Test 20

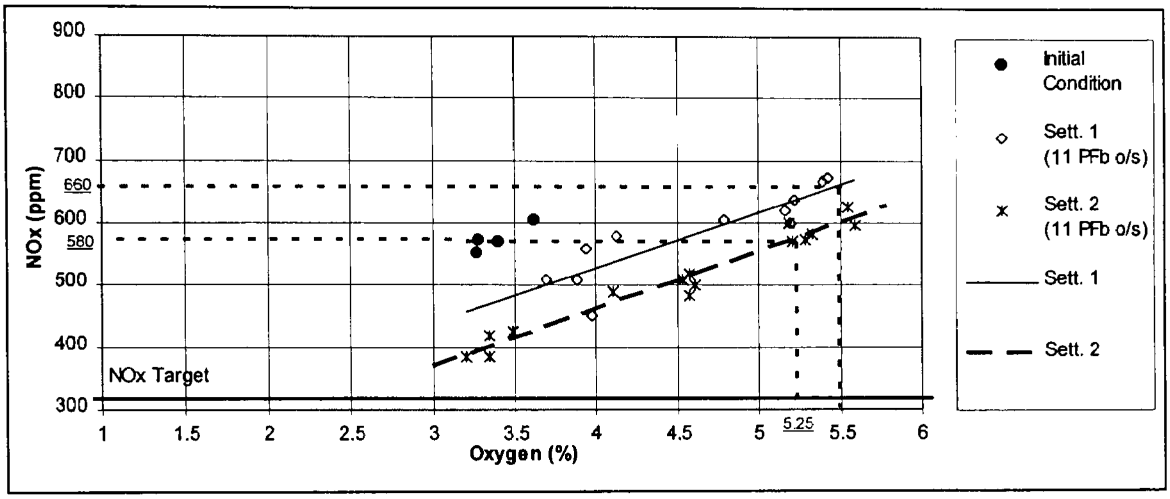


Fig. 6.57: Test 20 - NO_X versus Oxygen.

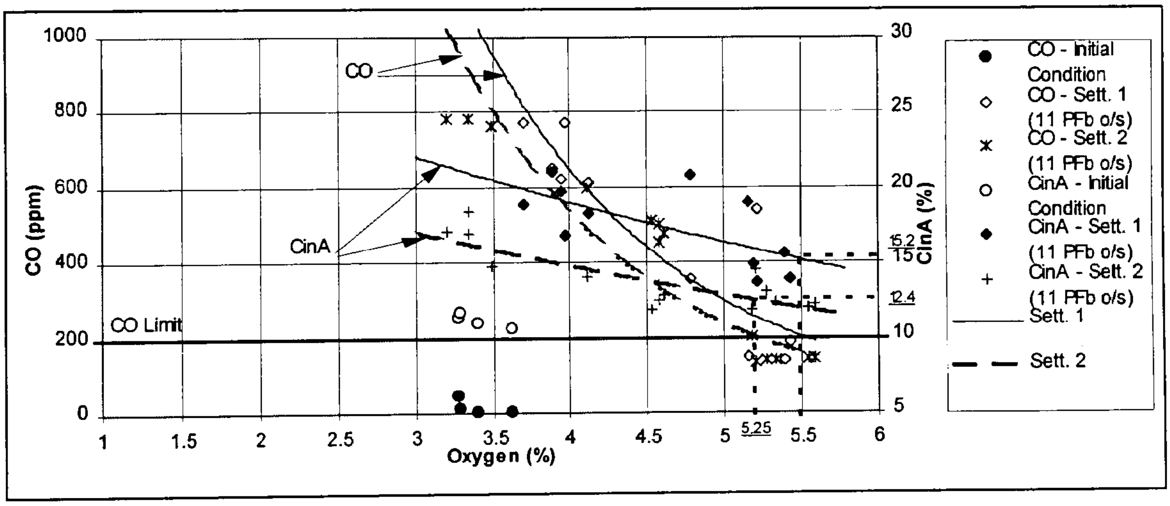


Fig. 6.58: Test 20 - NO_X and Carbon in ash versus Oxygen.

Results of Test 20 - cont.

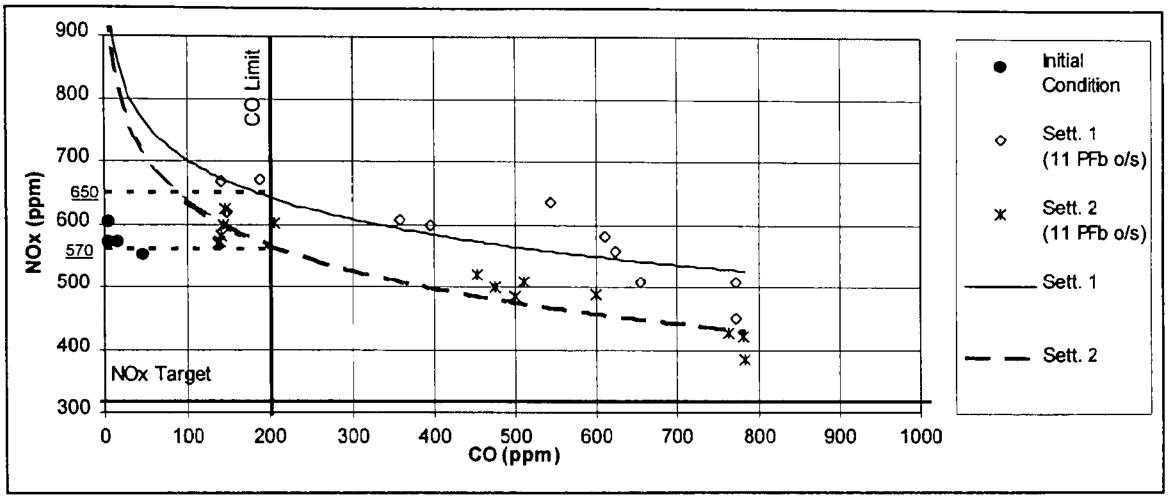


Fig. 6.59: Test 20 - NO_X versus CO.

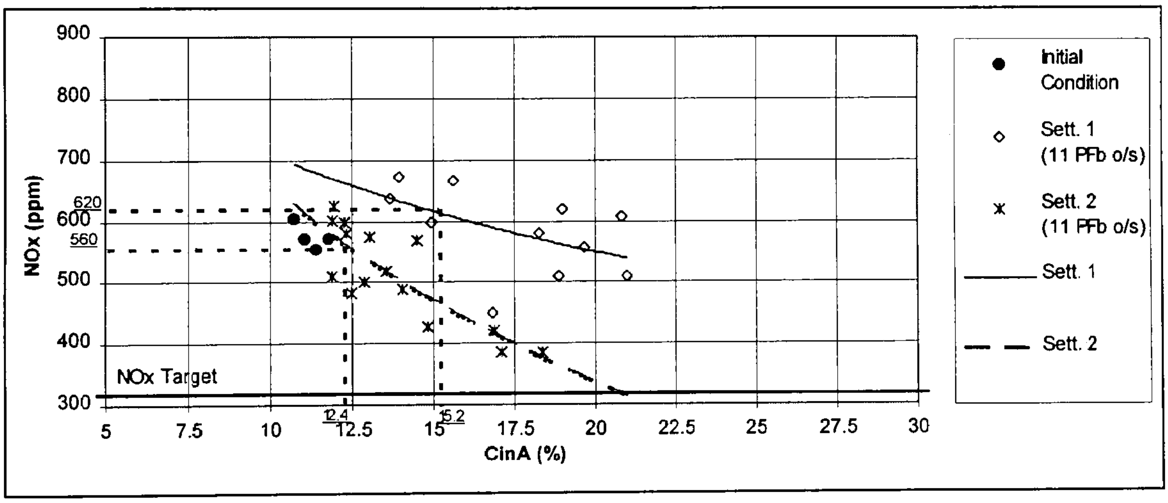


Fig. 6.60: Test 20 - NO_X versus Carbon in ash.

6.2.3 Burners Out Of Service (BOOS) across the Furnace Chambers

Test 21

Aim: To investigate the effect of staged combustion through burners out of service (BOOS) across the furnace chambers and different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 420 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - E mill out of service (o/s).

Starting Condition: **(1.)** Boiler stable and firing pattern set with burners o/s uniformly spread in the furnace, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air OFF for burners o/s, wherever possible.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** Air Damper Positions: secondary and tertiary air ON for all burners o/s (BOOS), **(3.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** Air Damper Positions: secondary and tertiary air remained ON for all burners o/s (BOOS), **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Starting Condition:

X	X	X					X												
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
				*	*			*	*	*	*	*		*	*	*	*		
	*	*	*	*	*		*	*	*	*				*			*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
X												X			X	X			X

Total number of PF burners i/s: 23

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Setting 1 and 2:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
				*	*			*	*	*	*	*		*	*	*	*		
	*	*	*	*	*		*	*	*	*				*			*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 23

PF burners o/s in the furnace: LHS (B side): 5, centre: 3, RHS (A side): 5.

Summary of the Results of Test 21

General Information

Starting Condition:

- $NO_X \approx$ 720 to 730 ppm
- Oxygen $\approx$ 3.8 to 4.2%
- CO $\approx$ 10 to 20 ppm
- CinA $\approx$ 10 to 11%

Setting 1:

- NO_X/O_2 slope $\approx$ 124 ppm/1% O_2

Setting 2:

- NO_X/O_2 slope $\approx$ 96 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to this 200 ppm CO, unless otherwise indicated:

Setting 1:

CO remained below 200 ppm (0-150 ppm). Lowest NO_X level achieved:

- NO_X = 430 ppm
- at oxygen = 2.48%
- at CinA = 13%

Setting 2:

CO remained below 200 ppm (10-180 ppm). Lowest NO_X level achieved:

- NO_X = 410 ppm
- at oxygen = 2.5%
- at CinA = 14.2%

Results of Test 21

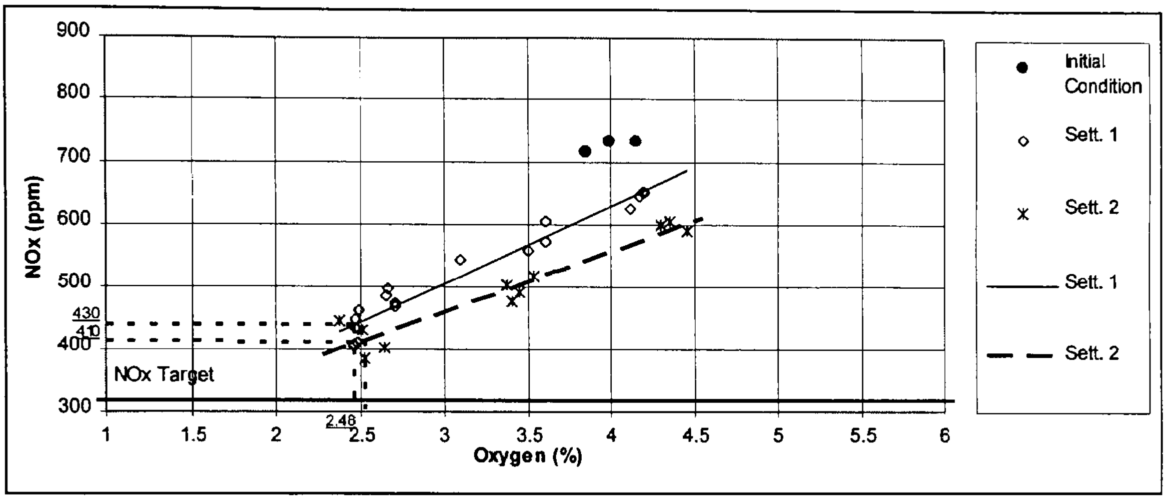


Fig. 6.61: Test 21 - NO_X versus Oxygen.

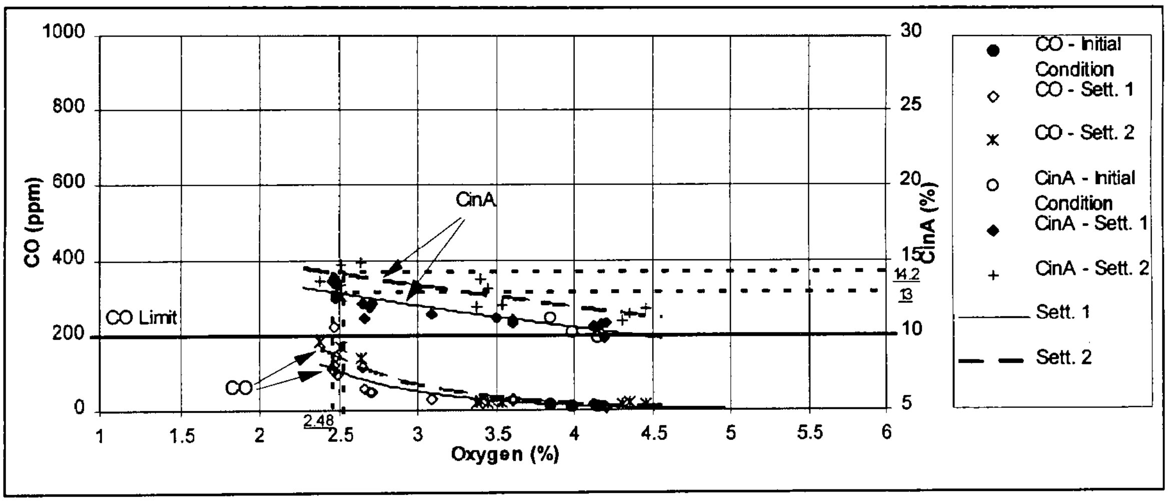


Fig. 6.62: Test 21 - CO and Carbon in ash versus Oxygen.

Results of Test 21 - cont.

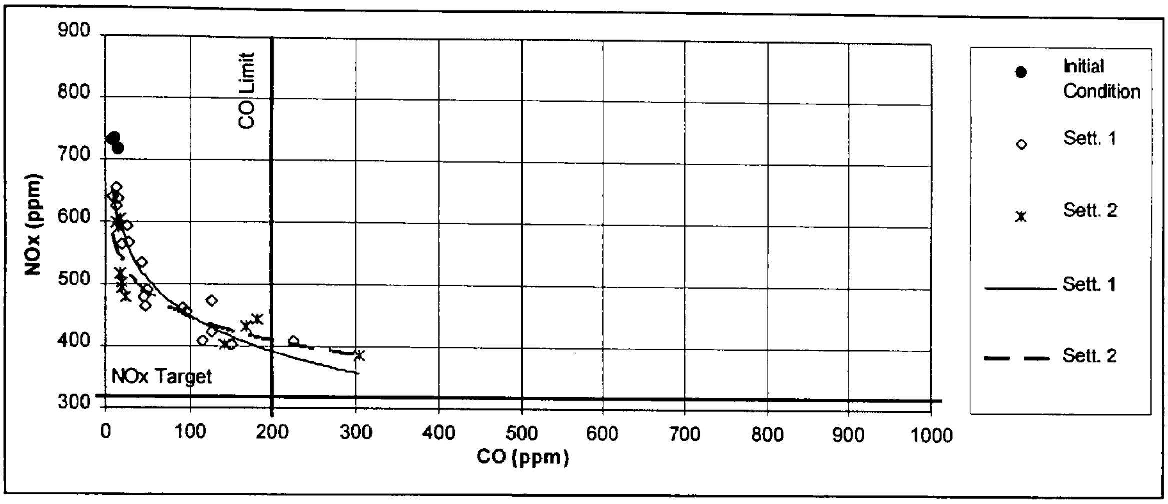


Fig. 6.63: Test 21 - NO_X versus CO.

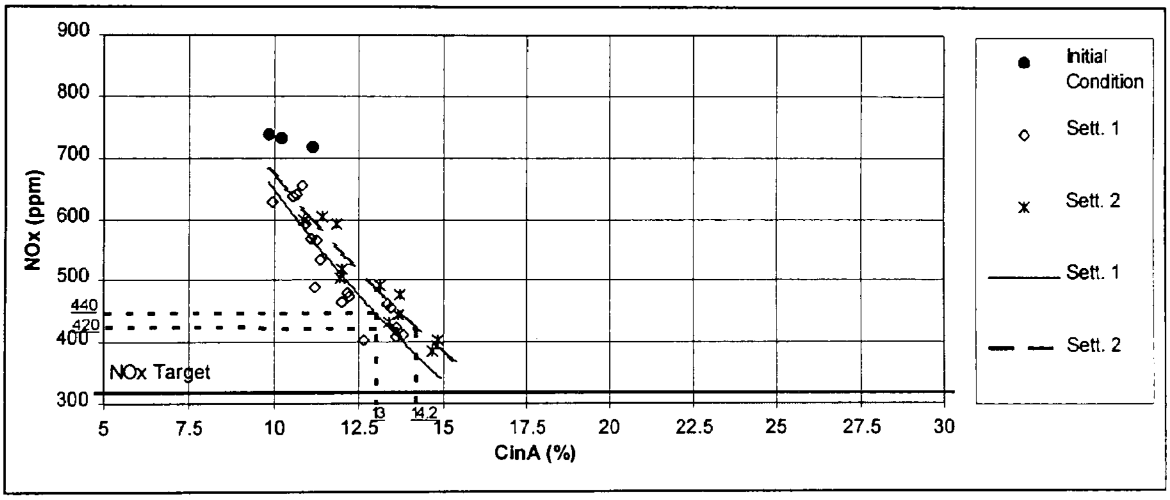


Fig. 6.64: Test 21 - NO_X versus Carbon in ash.

6.2.4 Air Staging - "Set B"

Test 22

Aim: To investigate the effect of different damper settings on NO_X emissions.

General Test Conditions: **(1.)** Load: 420 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - E mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found, **(4.)** Variation of the total air flow.

Setting (iii): **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/8 open on all burners, **(2.)** Variation of the total air flow.

The firing pattern remained the same throughout the test:

Initial Condition and Setting (iii):

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	*	*			*					*	*	*		*			*	*	*
*			*	*	*			*	*	*				*	*		*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 21

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Summary of the Results of Test 22

General Information

Initial Condition:

- NO_X/O_2 slope ≈ 123 ppm/1% O_2
- NO_X ≈ 695 to 700 ppm
- Oxygen ≈ 3.7 to 3.8%
- CO ≈ 8 to 13 ppm
- CinA ≈ 10%

Setting (iii):

- NO_X/O_2 slope ≈ 102 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to 200 ppm CO, unless otherwise indicated:

Initial Condition:

CO remained below 200 ppm (8-24 ppm). Lowest NO_X level achieved:

- NO_X = 520 ppm
- at oxygen = 2.4%
- CinA ≈ 10%

Setting (iii):

CO remained below 200 ppm (20-66 ppm). Lowest NO_X level achieved:

- NO_X = 480 ppm
- at oxygen = 2.2
- CinA ≈ 12%

Results of Test 22

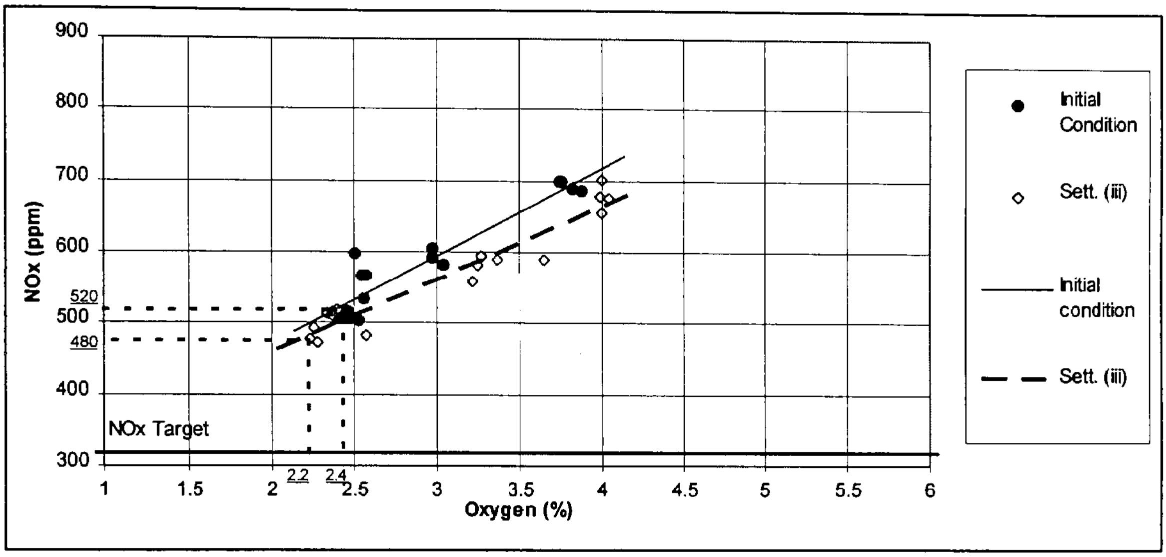


Fig. 6.65: Test 22 - NO_X versus Oxygen.

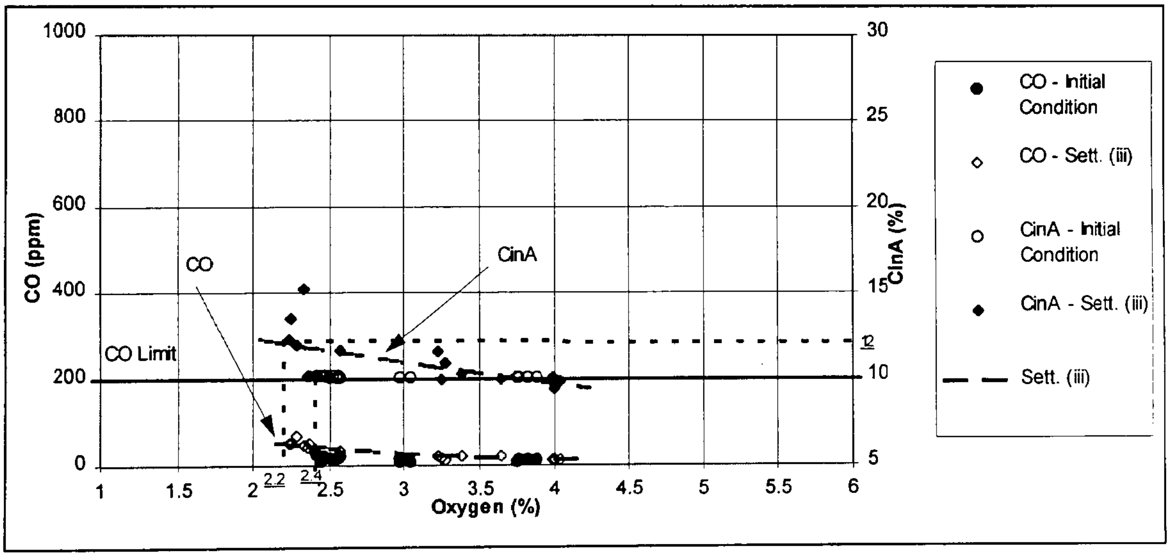


Fig. 6.66: Test 22 - CO and Carbon in ash versus Oxygen.

Results of Test 22 - cont.

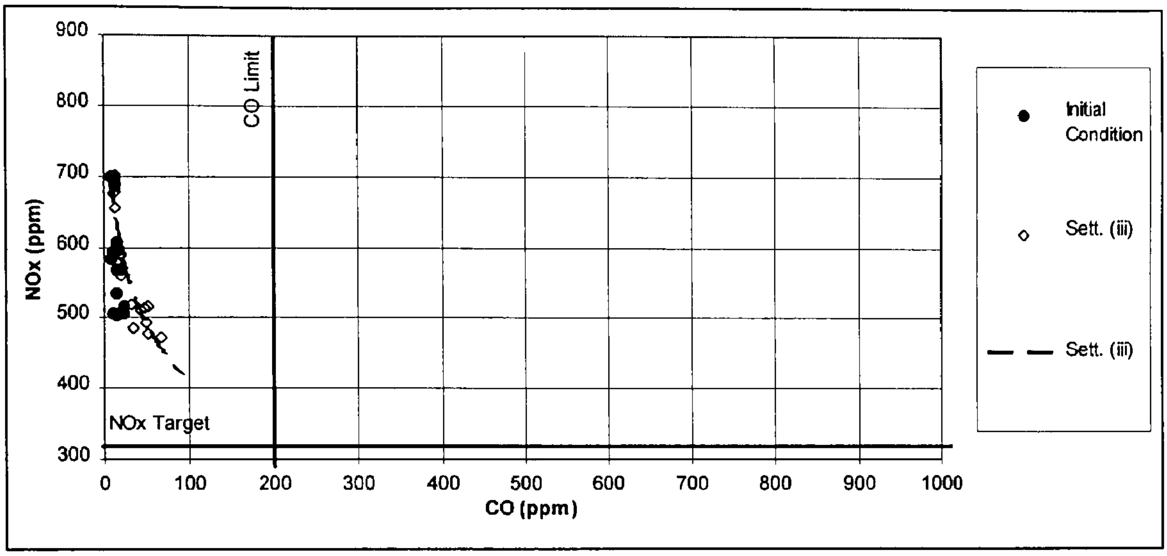


Fig. 6.67: Test 22 - NO_X versus CO.

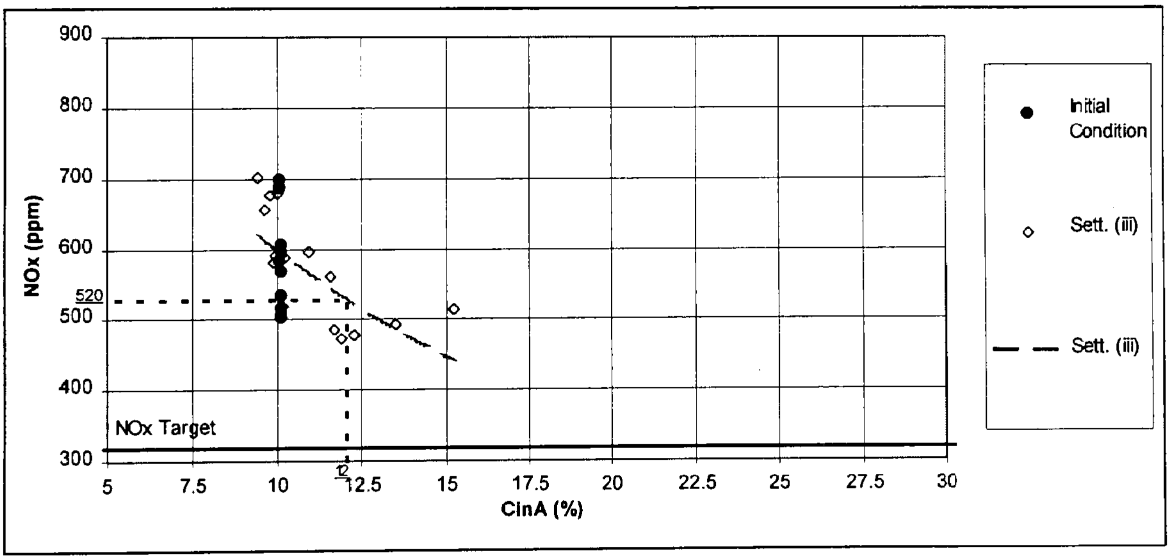


Fig. 6.68: Test 22 - NO_X versus Carbon in ash.

6.2.5 Oil Burners Effect

Test 23

Aim: To investigate the effect of oil[1] burners on NO_X emissions.

General Test Conditions: **(1.)** Load: 420 MW, **(2.)** South Wales coal, **(3.)** 5 mills in service (i/s) - E mill out of service (o/s).

Initial Condition: **(1.)** Boiler stable and initial firing pattern as found, **(2.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(3.)** Air Damper Positions: secondary and tertiary air for burners o/s as found, **(4.)** No oil burners i/s.

Setting 1: **(1.)** Air Damper Settings: secondary air 1/2 open and tertiary air 3/4 open, **(2.)** 18 oil burners i/s uniformly distributed in the furnace, **(3.)** Variation of the total air flow.

Setting 2: **(1.)** Air Damper Settings: secondary air 7/8 open and tertiary air 1/2 open, **(2.)** The 18 oil burners remained i/s, **(3.)** Variation of the total air flow.

The firing patterns were as follows:

Initial Condition:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
				*	*			*				*		*	*		*	*	*
*	*	*	*	*	*				*	*				*	*		*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 21

Note: PF burners i/s are marked with an asterisk: *
"X" - Secondary and tertiary air flows OFF.

[1] The oil composition is given in Appendix F.

Setting 1 and 2:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	•	•		*	*•			*	•	•		*•		*	•		*•	*•	*
*	*•	*•		*	*•				*•	*•		•		*	*•		*•	*•	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 19

Total number of oil burners i/s: 18

<u>Note</u>: Oil burners i/s are marked with a bullet: •

<u>Summary of the Results of Test 23</u>

General Information

<u>Initial Condition</u>:

- $NO_X \approx$ 570 to 615 ppm
- Oxygen $\approx$ 3.8 to 3.94%
- CO $\approx$ 10 to 60 ppm
- CinA $\approx$ 8.8 to 11%

<u>Setting 1</u>:

- NO_X/O_2 slope $\approx$ 60 ppm/1% O_2

<u>Setting 2</u>:

- NO_X/O_2 slope $\approx$ 52 ppm/1% O_2

Lowest NO_X levels

The maximum possible NO_X reduction is constrained by the maximum CO limit (200 ppm). Therefore, the following readings from the graphs relate to this 200 ppm CO, unless otherwise indicated:

<u>Setting 1</u>:

- When CO equals 200 ppm at 3.25% oxygen:
- NO_X = 470 ppm
- CinA $\approx$ 10.7%

<u>Setting 2</u>:

CO remained below 200 ppm (45-180 ppm). Lowest NO_X level achieved:

- NO_X = 450 ppm
- at oxygen = 3.2%
- at CinA = 11.5%

Results of Test 23

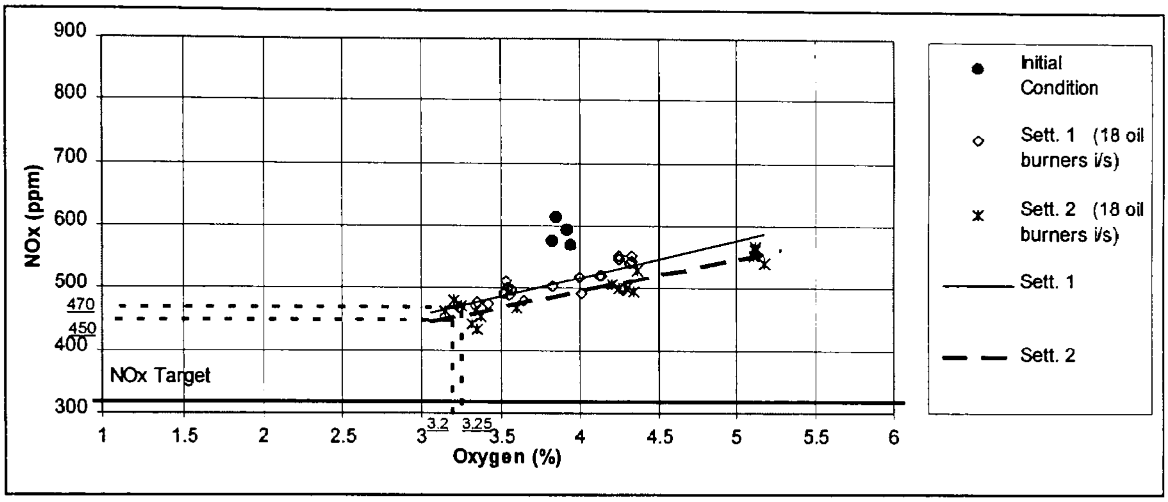


Fig. 6.69: Test 23 - NO_X versus Oxygen.

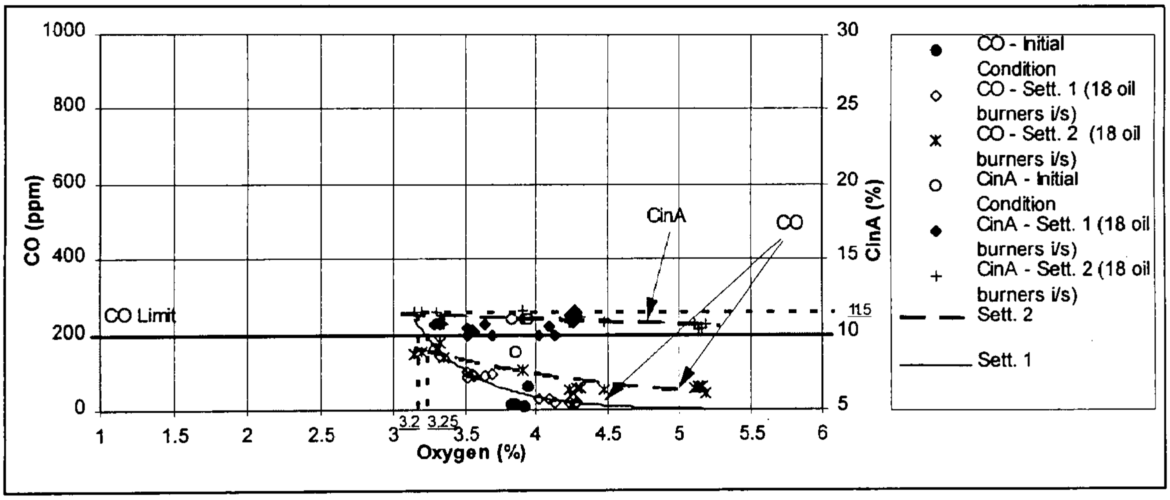


Fig. 6.70: Test 23 - CO and Carbon in ash versus Oxygen.

Results of Test 23 - cont.

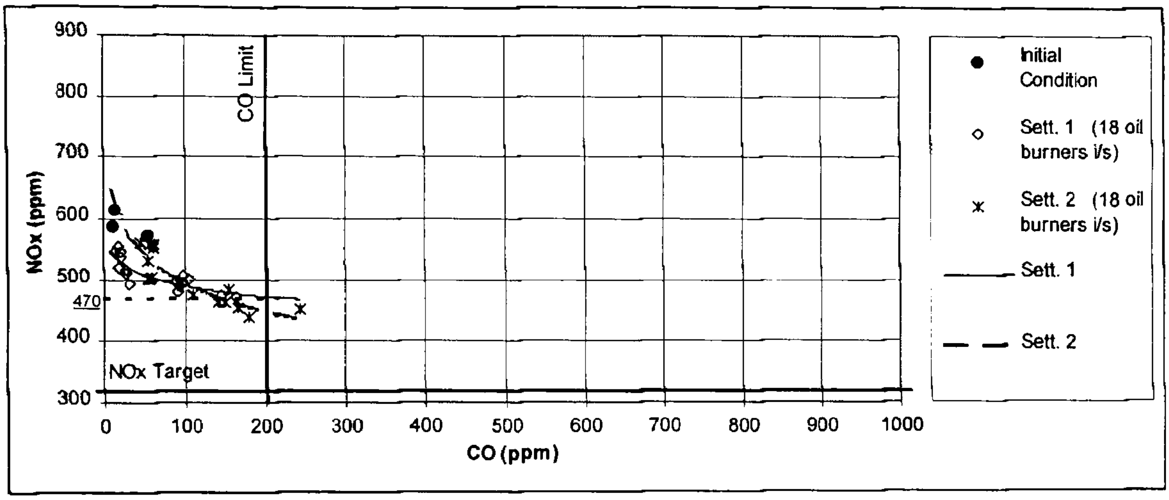


Fig. 6.71: Test 23 - NO_X versus CO.

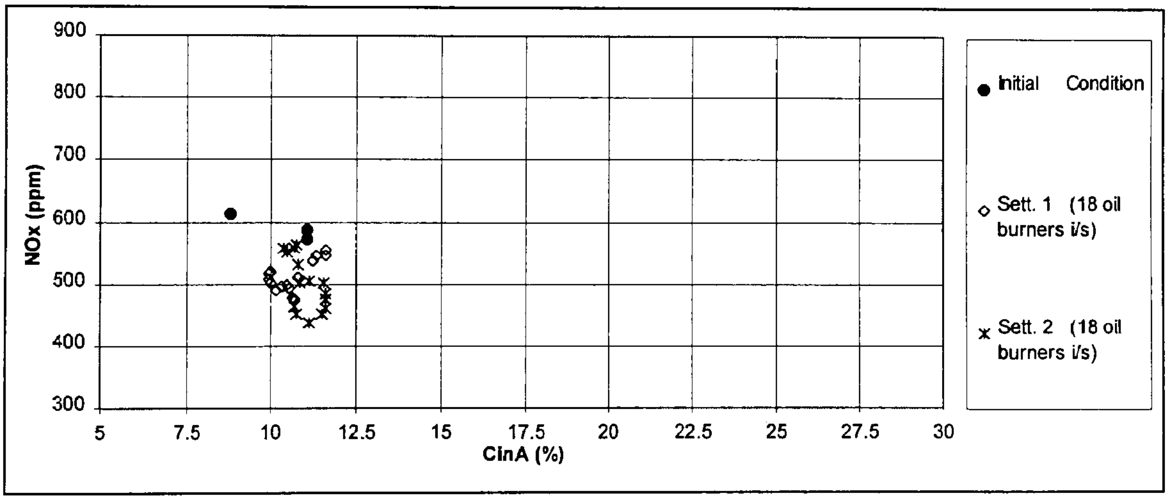


Fig. 6.72: Test 23 - NO_X versus Carbon in ash.

7. DISCUSSION OF PLANT EXPERIMENTS

In this chapter the results of the plant experiments are discussed and the specific findings are summarised. Possible further work is also indicated for each individual type of testing.

Firstly, some terminology needs to be defined to ease comprehension of the discussion: The terms "*minimum NO_X levels*", "*minimum O_2 levels*" and "*minimum carbon in ash levels*" refer to the lowest levels of these parameters that could be achieved under the defined testing conditions at the point where CO = 200 ppm.

7.1 Baseline Operation Tests

Before the introduction of any combustion modifications, it was first necessary to investigate the boiler baseline conditions typical of each load. The purpose of the baseline operation tests was mainly to determine the general boiler operating conditions and typical emissions to establish the standard with which all other tests have to be compared. Two tests were carried out: T1 (at 500 MW) and T19 (at 420 MW).

Initial Conditions:

Both tests, T1 and T19, showed that the boiler is normally operated with high levels of excess air, as the tests showed initial O_2 levels of 3.7-3.8%. NO_X emissions were also high: 710-760 ppm in T1 and 550-610 ppm in T19. With respect to CO levels, these were within typical operating levels, ranging from 35-50 ppm. Similar CO values for normal boiler operation (i.e. baseline conditions) are also mentioned in reference [61]. Regarding carbon in ash levels, these were within the normal Aberthaw operating levels (10.5-11% in T1 and 12.5-13.8% in T19). Such carbon in ash values may sound particularly high, specially when compared with the levels of other pulverised fuel power stations. Normally, pulverised fuel power stations try to operate at carbon in ash levels below 5% for an excess air level of 15-20%. However, it is important to stress that the Aberthaw carbon in ash levels are typical of this plant, since they are a result of the furnace and coal type as discussed in section 4.1.3 and 4.2.2 respectively.

The boiler operating conditions that were found to be typical of each load were described in chapter 6.

Summary

These tests showed particularly large variations in NO_X levels during the initial conditions of the tests. These variations can be due to a number of factors, such as the firing pattern, mode of operation by the operator and due to many uncontrollable influences (section 5.5). Thus, based on this data, typical operating levels of the various variables (NO_X, CO, carbon in ash and O_2) are:

- NO_X: Generally high, ranging around 550-760 ppm, (occasionally can be higher).
- CO: Within typical boiler operating levels (≈ 35-50 ppm), but in cases of poor burner performance above 100 ppm.
- Carbon in Ash: Usually between 10.5-13.8%.
- O_2: Usually between 3.7-3.8%.

7.2 Combustion Modification Tests

7.2.1 Load - High and Intermediate

Operating boilers at lower loads is known to reduce NO_X emissions (section 3.1.1(g)). Additionally, at low loads unburnt carbon is normally reduced due to: (1) increased availability of oxygen and (2) improved mill grinding performance at the lower load[1].

Thus, the question that needs to be answered here is: "Were the *minimum NO_X levels* and *minimum carbon in ash levels* at 420 MW lower than at 500 MW"?

- **Baseline Operation Tests**

The baseline tests showed that the 420 MW load contributes to lower NO_X emissions. However the 420 MW tests resulted in higher carbon in ash levels than the 500 MW tests. The latter results are against the expected trend and most likely not a systematic influence of the load reduction.

- **BOOS in the Furnace Middle Chamber (BFMC)**

With respect to the BFMC tests with 9-11 BOOS (T7, T8 and T20), a sensible comparison between loads cannot be obtained, since these tests showed poor combustion (see section 7.2.4(b-i)). Only a comparison between BFMC tests with good combustion efficiency (e.g. with 5 BOOS) will give valid information. Unfortunately, a comparison between 420 MW and 500 MW BFMC with around 5

[1] At low loads the mills are more lightly loaded. The fineness is thus improved and this may contribute to reduced NO_X production.

BOOS cannot be accomplished since no such tests have been carried out at 420 MW (see further work).

- **BOOS Across Furnace Chambers (BAFC)**

The comparison of the BAFC at 500 MW and 420 MW indicates that the 420 MW test (T21) resulted in lower *minimum NO_X levels* than the remaining tests at 500 MW. No carbon in ash data could be acquired during the 500 MW tests, hence no comparison is possible.

- **Oil Burners**

All "oil burner tests" (at 500 and 420 MW) achieved not only very low *minimum NO_X levels*, but also very low carbon in ash levels, however, a comparison between loads cannot be made due to the variations of testing conditions (see section 7.2.5).

- **Secondary Air Staging**

The *minimum carbon in ash and NO_X levels* were the same for both loads.

Summary

A systematic correlation between load and NO_X (and carbon in ash) could not be confirmed with the tests. It is therefore assumed that the carbon in ash and NO_X reduction that would be expected from the reduction of the load is relatively little and therefore within the scattering of data. The isolation of systematic effects from the scattering may however be possible on the basis of more testing data.

Further Work

In order to obtain a statistical basis for the determination of a possible correlation between load and NO_X (and carbon in ash) many more tests would have to be carried out. The value of such intensive testing, however, appears to be questionable because the influence of the load in the considered range (420 to 500 MW) seems to be quite little.

7.2.2 Excess Air

Although excess air is normally required to ensure complete combustion in coal-fired boilers, low oxygen operation is recommended for various reasons: (i) it contributes to low NO_X emissions (see section 3.1.1(a)), (ii) it results in a higher boiler efficiency, since low oxygen levels result in a decreased flue gas loss and (iii) it can lead to an increased plant efficiency[2].

The effect of excess air on NO_X emissions was investigated simultaneously to all described tests (with exception of the burner biasing tests). As a general rule, as explained in section 5.3.2 (b), the lowest level of oxygen operation is guided by the 200 ppm CO limit, thus the tests have been analysed at this CO limit.

According to the literature, NO_X emissions are known to be significantly influenced by the oxygen levels in the furnace and can decrease by 50-150 ppm for each 1% decrease in oxygen level [74]. But how much does this NO_X/O_2 slope vary between a low NO_X combustion operation and a normal operating condition (i.e. without a low NO_X combustion modification)? Does it vary with different loads, damper settings, or with any other conditions? - Answers to these questions are discussed below.

- **Baseline Operation Tests**

During normal operation of the boiler, the tests T1 (at 500 MW) and T19 (at 420 MW) showed that the NO_X/O_2 slope was similar not only for the two investigated loads but also for the different damper settings 1 and 2. This slope similarity is illustrated by T19 and setting 2 of T1 where the NO_X/O_2 slope normally varied from 102-116 ppm/1% O_2 (see Table 7.1).

These tests also demonstrated that higher initial NO_X levels give greater NO_X reductions per 1% oxygen (i.e. higher NO_X/O_2 slopes). For example, setting 1 of T1 and the initial condition of T8, both with high initial NO_X levels, gave steeper slopes (150 and 138 ppm/1% O_2 respectively) than T19 (102 and 108 ppm/1%O_2) which had lower initial NO_X levels than T1 and T8.

- **BOOS in the Furnace Middle Chamber (BFMC)**

Like the baseline operation tests, the BFMC tests (T7, T8, T9 and T20) also revealed slopes of a similar range between the two investigated loads (500 and 420 MW) and damper settings (1 and 2), provided that the test conditions were the same (i.e. similar BOOS number).

---

[2] High oxygen operation can result in high metal temperatures in the superheaters, known as hot spots, which are then cooled by an increased amount in sprayflows leading to a decreased plant efficiency.

In general, a high number of BOOS (9-11) in the middle chamber resulted in a NO_X/O_2 slope of the range of 67-92 ppm/1% O_2 (e.g. T7, setting 1 of T8 and T20). On the other hand, a lower number of BOOS, such as 5 (e.g. T9), resulted in higher NO_X/O_2 slopes of the order of 179-191 ppm/1% O_2 (Table 7.1).

The fact that a higher number of BOOS gives a lower NO_X/O_2 slope is not too surprising. As explained in section 7.2.4 (b-i), BOOS in the furnace middle chamber reduce both thermal- and fuel-NO_X through (a) the BOOS cooling effect in the middle chamber and (b) the fuel-rich combustion in the outer chambers. Hence, the higher BOOS number, the higher the NO_X reduction due to an increased effect of the two processes (a) and (b). Thus in case of a high number of BOOS, as the O_2 is reduced in order to obtain a NO_X/O_2 slope, only a small portion of NO_X is in the furnace to be reduced by air trimming (since most NO_X has already been reduced by the BOOS effect), which explains the low slope. An example of this relationship is clearly given in T8: before the introduction of BOOS, the NO_X/O_2 slope is of 138 ppm/1% O_2. However, after introduction of BOOS the slope becomes 60 ppm/1% O_2.

The influence of high initial NO_X levels on the NO_X/O_2 slope is also evidenced in these tests. T9 showed the highest NO_X levels (915-980 ppm) of the BFMC tests and thus showed higher slopes (191 and 179 ppm/1% O_2) than T7, T8 and T20. In addition to the reduced effectiveness of only 5 BOOS, which was discussed above, the results were therefore also influenced by the high initial NO_X levels.

- **BOOS across the Furnace Chambers (BAFC)**

The BAFC tests also showed NO_X/O_2 slopes of a similar range between the two investigated loads (500 and 420 MW). Different damper settings 1 and 2 showed similar NO_X/O_2 slopes.

Overall these tests resulted in NO_X/O_2 slopes in the range of around 84-124 ppm/1% O_2 (see Table 7.1). Furthermore, as in previous tests, BAFC also showed higher NO_X/O_2 slopes in the case of high initial NO_X levels. For example T10, T12 and T21 showed higher slopes (112, 118 and 124 ppm/1% O_2 respectively) than T11 (84 ppm/1% O_2) in setting 1.

When comparing the NO_X/O_2 slopes between the BAFC and BFMC tests, it is interesting to see that the slope range of the "BAFC" tests (84-124 ppm/1% O_2) is only slightly higher than that of the BFMC tests with 9-11 BOOS in the middle chamber (67-92 ppm/1% O_2). This suggests that both tests (BAFC and BFMC) ensured a similar degree of staged combustion[3], which is not too surprising since both tests had around the same number of BOOS in the furnace.

Tests	Initial NO_X Levels (ppm)	NO_X/O_2 Slopes (ppm/1% O_2)		
Baseline Operation			**Sett. 1**	**Sett. 2**
T1	710-760		150	116
T19	550-610		102	108
BOOS in the Furnace Middle Chamber		**Initial Condition**	**Sett. 1**	**Sett. 2**
T7 (9 BOOS)	740-810		67	84
T8 (10 BOOS)	730	138	60	-----
T9 (5 BOOS)	915-980		191	179
T20 (11 BOOS)	550-605		90	92
BOOS Across Furnace Chambers			**Sett. 1**	**Sett. 2**
T10 (11 BOOS)	740-780		112	93
T11 (11 BOOS)	660-730		84	-----
T12 (12 BOOS)	820-880		118	-----
T21 (13 BOOS)	720-730		124	96
Air Staging ("Set B")		**Initial Condition**	**Sett. (iii)**	
T13	765-785		103	
T14	750-780		96	
T15	645-705		102	
T22	695-700	123	102	
Oil Burners Effect		**Sett. 1.1***	**Sett. 1**	**Sett. 2**
T16	605-685		-----	43 (12 O.B.**)
T17	540-590		-----	37 (12 O.B.)
T18	710-730	64 (22 O.B.)	-----	-----
T23	570-615		60 (18 O.B.)	52 (18 O.B.)

Table 7.1: Effects of Excess Air Reduction (NO_X/O_2 Slopes in ppm/1% O_2).

* Sett. 1.1: The same damper settings as Sett. 1 but with different number of oil burners in service.

** O.B.: Oil Burners.

- **Oil Burners Effect**

It is interesting to note that the NO_X/O_2 slopes of all oil burner tests (T16, T17, T18 and T23) were very low in comparison with the slopes of the other combustion modification tests (Table 7.1). These low slopes suggest the great effectiveness of the "oil burners" on NO_X emissions. As the oil burners are introduced in the combustion process, the NO_X reduces much more than with any other NO_X control

[3] This is also indicated by the difference in NO_X levels (for the same O_2 level) between settings 1 and 2, as explained in section 7.2.3, page 162.

methodology. Consequently little NO_X is left to be reduced by O_2 trimming. Although, both settings 1 and 2 could only be tested in one of the "oil burner tests" (T23), the experience with T23 and other combustion modification tests seems to indicate that the slopes for setting 1 and 2 are generally similar.

- **Air Staging ("Set B")**

All tests showed similar slopes for 420 and 500 MW, of the order of 96-103 ppm/1% O_2. These slopes are very similar to the slopes of setting 1 and 2 of the baseline operation tests. The relatively high slopes indicate that air staging had only a limited NO_X reduction effect, while the excess air trimming played a more significant role in these tests.

Summary

Excess air reduction was shown to be an important NO_X control methodology which can be applied on its own as well as in addition to any other NO_X control methodology. In general it was found that the NO_X/O_2 slopes depend on two main parameters:

(1) The Initial NO_X Levels: Overall the tests showed that the higher the initial NO_X levels of a test, the higher the NO_X/O_2 slope and vice-versa. Examples are various, such the baseline operation tests (T1 and T19), the BFMC and BAFC tests.

(2) The Effectiveness of the Combustion Modification Techniques (in terms of NO_X reduction): The tests also indicated that the more effective the combustion modification technique in reducing NO_X emissions, the lower the NO_X/O_2 slope and vice-versa. In the BFMC tests for example, T9 (with 5 BOOS) resulted in higher slopes than the remaining BFMC tests with 9-11 BOOS (T7, T8 and T20). Additionally, T1 and T19 and the initial condition of T8 showed high slopes. This is to be expected since T1 and T19 and the initial condition of T8, had only one NO_X reduction technique in operation (O_2 trimming), unlike the remaining Aberthaw tests which had already reduced NO_X levels by means of a NO_X reduction technique (such as BOOS or oil burners effect), before decreasing O_2. Particularly noteworthy are the generally very low NO_X/O_2 slopes in the "oil burners tests", which indicate a particularly high efficiency of this NO_X reduction technique.

Further Work

The effectiveness of excess air reduction was shown - further investigations are therefore not necessary. The NO_X/O_2 slope, however, should be used in any other further tests as an indicator for the efficiency of a NO_X control methodology (point (2) above).

7.2.3 Air Staging

Air staging was achieved by changing the damper settings. As explained in section 5.3.2(c), two sets of "Secondary and Tertiary Air Damper" settings were investigated at Aberthaw, unit 7: Set A and B.

Set A: The damper test "Set A" was investigated simultaneously to the other combustion modification tests. "Set A" included two damper settings: 1 and 2. Starting from the initial boiler condition with the current standard settings of the dampers, firstly a combustion modification technique other than air staging was introduced (Setting 1). Afterwards the damper settings were changed in addition to the first combustion modification technique (Setting 2):

Initial Condition:	Normal operation of the plant (i.e. with no combustion modification techniques). Dampers: Secondary air set at 1/2 open and tertiary air set at 3/4 open, (standard setting, currently favoured by the station operators).
Setting 1:	Combustion Modification technique (other than air staging) introduced. Dampers: Secondary air set at 1/2 open and tertiary air set at 3/4 open (same as damper settings of Initial Condition).
Setting 2:	Combustion Modification technique other than air staging in operation. Dampers: Secondary air set at 7/8 open and tertiary air set at 1/2 open.

Set B: To complement the "Set A" tests, which represent the majority of air staging tests carried out, the effects of additional damper settings were investigated in "Set B". These tests were not carried out simultaneously to any other combustion modification technique - the operation of the boiler was therefore equivalent to "baseline operation".

The aim of "Set B" tests was to investigate different degrees of air staging. Another reason for the stepwise alteration of the damper settings was the unknown effect of the more "extreme" settings on the boiler stability:

Initial Condition:	Normal operation of the plant (i.e. with no combustion modification techniques). Dampers: Secondary air set at 1/2 open and tertiary air set at 3/4 open, (= standard setting in "Set A").
Setting (i):	Dampers: Secondary air set at 1/2 open and tertiary air set at 5/8 open.
Setting (ii):	Dampers: Secondary air set at 1/2 open and tertiary air set at 1/2 open.
Setting (iii):	Dampers: Secondary air set at 1/2 open and tertiary air set at 3/8 open.

The results of both "Set A" and "Set B" will now be discussed in detail:

SET A:

The various tests carried out at Aberthaw showed that setting 2 gave lower NO_X emissions than setting 1 for the same O_2 level, but at slightly higher carbon in ash levels (up to 2.7% increase).

Furthermore, the tests showed that in the cases of a very effective first NO_X reduction technique, additional NO_X reduction due to the change from setting 1 to setting 2 becomes smaller. In the case that the first combustion modification technique introduced in setting 1 leads already to a "fully staged" combustion (such as BAFC and BFMC (with 9-11 BOOS), the additional effect of air staging (setting 2) is minimal (about 20-70 ppm lower NO_X, cf. Table 7.2). In contrast, in T9 (BFMC with 5 BOOS), setting 2 gave around 220 ppm lower NO_X emissions for the same O_2 levels. Due to the low number of BOOS in T9, the staged combustion effect was not as significant as in the BAFC tests with 11-13 BOOS and BFMC tests with 9-11 BOOS.

Air Staging Tests - Set A: (combined with other NO_X control techniques)	Average NO_X reduction for the same O_2 level through staging (Setting 2 versus Setting 1):
Baseline Operation	
T1 - 500 MW	≈ 60-120 ppm
T19 - 420 MW	≈ 20-30 ppm
BOOS in the Furnace Middle Chamber	
T7 (9 BOOS)	≈ 20-50 ppm
T9 (5 BOOS)	≈ 220 ppm
T20 (11 BOOS)	≈ 70 ppm
BOOS Across Furnace Chambers	
T10 (11 BOOS)	≈ 20-60 ppm
T21 (13 BOOS)	≈ 30-75 ppm
Oil Burners Effect	
T23 (18 O.B.*)	≈ 20-30 ppm
Air Staging Tests - Set B:	Average NO_X reduction for the same O_2 level through staging (Setting (iii) versus Initial Condition):
T22 - 420 MW	≈ 15-30 ppm

Table 7.2: Average NO_X reduction for the same O_2 level through staging.

* O.B.: Oil Burners.

Overall the "Set A" tests showed that air staging appears to be a very useful complementary NO_X control methodology while it does not yield sufficient NO_X reduction on its own (cf. T1 and T19). It is interesting to note the stronger effect of air staging at the higher load, which should be confirmed in further tests.

SET B:

In order to ensure boiler stability, air staging was introduced in the first tests of "Set B" (T13 and T14) only for about half of the burners in service (supplied by 3 of 6 mills). In the remaining tests of "Set B" (T15 and T22) air staging was introduced for all burners.

Initial Conditions:

The initial conditions varied considerably with respect to NO_X and O_2 but the values were in general quite high. The carbon in ash levels were very low, between 9.1% and 10.2% and the CO levels were mostly negligible.

Minimum NO_X levels in Setting (i), (ii) and (iii):

Whilst maintaining boiler stability, T13 and T14 showed that setting (i) had hardly an effect on the NO_X levels. Setting (ii) showed slightly better results. Since the boiler was still stable, setting (iii) could finally be introduced. In setting (iii), the boiler remained stable and the O_2 was then trimmed. T15 and T22 showed that the boiler stability remained further unaffected by air staging for all burners.

The *minimum NO_X levels* achieved were satisfactory (475-480 ppm) in relation to other NO_X control methodologies, although the *minimum NO_X level* in T14 remained exceptionally high. The NO_X/O_2 charts for "Set B" (in chapter 6) indicate, however, that the major part of the NO_X reduction in these tests has been achieved through excess air reduction rather than air staging, which is confirmed by the relatively high NO_X/O_2 slopes (section 7.2.2).

Although the "Air Staging Tests - Set B" showed that setting (iii) was most effective compared with (ii) and (i), the difference in NO_X levels (for the same O_2 level) between the "initial condition" and setting (iii) was still quite small (cf. T22 in Table 7.2), which further indicates the relatively small effect of air staging "Set B". It might however be that the effectiveness of air staging is related to the load of the boiler as the baseline operation tests in "Set A" (T1 and T19) appear to indicate. To confirm this theory, more "Set B" type tests would have to be carried out at different loads.

Despite the limited effect of air staging "Set B" on the NO_X emissions, it is important to note that its contribution to the NO_X reduction is still very valuable since it adds to the effect of other NO_X control techniques (here O_2 trimming). A particularly valuable effect of these air staging tests, however, was:

- low *minimum carbon in ash levels* (10-12%) and a limited increase of up to 2% carbon in ash from the initial condition.
- low *minimum* O_2 *levels* (2.2-3.5%)
- low CO levels (< 200 ppm)

Summary

The effectiveness of air staging (both "Sets A and B") as a NO_X control methodology was shown to be limited. Similarly to "excess air", however, "air staging" appears to be a valuable and important complementary NO_X reduction technique which allows to make the best of the other NO_X control methodologies.

Therefore, the NO_X reductions achieved with air staging at Aberthaw, which are reported in [149], could not be confirmed. It is however important to note that the effects described in [149] resulted from many simultaneous variations of parameters in addition to air staging (e.g. varying boiler loads, oil burners in and out of service, different degrees of slagging and others). Furthermore, it is likely that the tests have been carried out on a sister unit and that therefore the results cannot be compared in any case.

Further Work

Setting 2 and setting (iii) were shown to be better than the current standard damper settings. Further tests should compare setting 2 and (iii), as well as other possible damper settings which result in air staging, amongst each other in order to determine the optimal damper settings.

The relationship between load and effectiveness of air staging should also be further investigated.

7.2.4 Staging Firing Patterns

This section discussed the results of (a) Burner Biasing Tests and (b) Burners Out Of Service (BOOS):

(a) Burner Biasing Tests

As mentioned in chapter 5 (section 5.3.2(d-i)) burner biasing aimed at decreasing NO_X emissions by creating fuel-rich and fuel-lean areas within the furnace, whilst the air flow remained constant.

When testing burner biasing at Aberthaw, the tests were carried out in two parts (1st and 2nd), where the second part consisted of a repetition of the first part but with an inverted pattern[4]. The aim of the inverted pattern was not only to allow the testing of another firing pattern, but also to confirm the results obtained from the first part of the test. To distinguish between the two parts of the test the graphs are accordingly labelled (1st and 2nd).

Various burner biasing firing patterns with several pairs of lean- and rich-burners (see section 5.3.2(d-i)) were investigated.

Initial Conditions:

The initial testing conditions varied significantly. Both T5 and T6 had very high initial NO_X levels of the order of 700-850 ppm (Figs. 6.8 and 6.9), whereas the remaining tests showed lower NO_X levels: T2 ($\approx$ 500-600 ppm: Fig. 6.5) and T3 and T4 ($\approx$ 500-550 ppm: Figs. 6.6 and 6.7). Such variations in NO_X emissions can be due to multiple factors, since in a process as complex as a power plant there are many uncontrollable influences affecting combustion (see section 5.5.).

On the other hand, carbon in ash and CO were generally within acceptable levels, with carbon in ash levels usually between 10.5% to 13% and CO below 200 ppm. An exception was the second part of T4, where for an unknown reason there was an increase in both carbon in ash (13 to 14.8%) and CO levels (up to 580 ppm).

Was burner biasing effective in reducing NO_X emissions?

Unfortunately, as the graphs[5] of the 500 MW tests (T2, T3, T4, T5 and T6) show, no systematic NO_X reduction was achieved, but instead NO_X variations (which are typical and within the normal scattering of the data) occurred during the tests. Because the burner biasing tests at 500 MW showed no effect on NO_X emissions, these tests were not carried out at 420 MW (at the request of the power station).

Why did the burner biasing tests have no effect on NO_X emissions?

A possible reason may have been the effectiveness of burner biasing itself. As mentioned in chapter 5 (section 5.3.2(d-i)) burner biasing, like BOOS operation, aimed at achieving fuel-rich and fuel-lean areas within the furnace in order to decrease NO_X levels. However, when comparing burner biasing with BOOS, it can be said that the BOOS procedure is more "extreme" than that of burner biasing. While burner biasing consists of increasing the fuel flow to certain burners and of reducing it to

[4] An "inverted pattern" consisted of exchanging the fuel-rich- and fuel-lean-burners between the 1st and 2nd part of the test, i.e.: the fuel-rich- and fuel-lean-burners in the 1st part of the test became in the 2nd part of the test fuel-lean- and fuel-rich-burners respectively.

[5] When carrying out these tests, in order to see the effect of burner biasing on NO_X emissions, only one change was introduced: burner biasing. Consequently the oxygen was not varied, which is why all burner biasing graphs are plotted against time.

other burners, BOOS consists of completely closing the fuel to certain burners (while leaving their air on). Apparently the staging effect of burner biasing is therefore too subtle to achieve a NO_X reduction effect in Aberthaw.

Although the burner biasing tests showed no effect on NO_X at Aberthaw, Thompson [68] reports on a small NO_X reduction with this method. So, how can his results be explained? Thompson states that burner biasing was achieved by reducing the coal flow to the upper row of burners and by decreasing the coal flow to the remaining other rows, which suggests either a horizontally-opposed-fired-furnace or a single-wall-fired-furnace. In these type of furnaces, unlike at Aberthaw, the burners fed by one mill are usually grouped together in one single row. Such mill/burner configuration facilitates the set-up of a specific firing pattern which in Thompson's case corresponded to the optimum BOOS configuration for NO_X reduction: BOOS on the top row (see section 5.3.2(d-ii)). This may therefore explain the reduction in NO_X, although small (7 and 8%), that Thompson states. The small reduction suggested that the method is generally not too effective and that, therefore, burner biasing should only be used for trimming emissions on marginally complying units.

Consequently, the fact that no decrease in NO_X was observed at Aberthaw, may have also been due to the pulveriser/burner configuration and burner location within the furnace - an optimum burner biasing pattern could no be achieved in order to provide even a small reduction in NO_X.

Summary

Burner biasing has no effect on NO_X emissions at Aberthaw.

Further Work

Further work does not appear to be sensible.

(b) Burners Out Of Service (BOOS)

As discussed in chapter 3 (section 3.1.1(b-i)), BOOS is a very effective technique in reducing both fuel- and thermal-NO_X, but its efficiency is strongly dependent upon the firing pattern. Therefore, after taking into account the configuration of the Aberthaw furnace, two main firing patterns were investigated both at 500 and 420 MW (see section 5.3.2(b-ii)): (i) BOOS in the furnace middle chamber and (ii) BOOS across the furnace chambers. The NO_X reduction effectiveness of each of these firing patterns is discussed in the next section:

(i) BOOS in the Furnace Middle Chamber (BFMC)

Before discussing the results of these tests, it is important to understand the mechanism of the NO_X reduction effect for BOOS in the furnace middle chamber: The use of BFMC at Aberthaw resulted in two main NO_X reducing effects, the first being a temperature cooling effect which reduced mainly thermal-NO_X. The second was the fuel-rich combustion in the outer chambers: with the burners in the middle chamber out of service (BOOS), more fuel had to be burnt in the outer chambers in order to maintain the same generated MW. This resulted in the substoichiometric operation of the outer chambers, decreasing both fuel- and thermal-NO_X.

Initial Conditions:

Overall, the initial conditions of the tests were within the typical Aberthaw levels, i.e. relatively high NO_X and O_2 levels, negligible CO and very low carbon in ash emissions. All 500 MW tests (T7, T8 and in particular T9) showed high initial NO_X levels (740-810, 730 and 915-980 ppm respectively), whereas the 420 MW test (T20) showed lower initial NO_X levels than at 500 MW, of the order of 550-605 ppm. The initial O_2 levels varied between 3 and 3.9% in the different tests. With respect to initial CO and carbon in ash levels, these were for all tests within normal operating levels with CO ranging from 0-50 ppm and carbon in ash from 10% to 12.7%.

Minimum NO_X levels in Setting 1 and 2:

In general, the BFMC tests showed that the higher the number of BOOS in the middle chamber, the lower the achievable NO_X levels, as illustrated by the 500 MW tests: T8 (with 10 BOOS), T7 (9 BOOS) and T9 (5 BOOS) gave the lowest NO_X levels in setting 2 at 440 ppm (with 4.4% O_2) , 480 ppm (with 3.25% O_2), and 590 ppm (with 3.3% O_2), respectively. The same gradual NO_X reduction applied in setting 1.

Although a greater number of BOOS resulted in bigger NO_X decreases, unfortunately this happened at the expense of increased carbon in ash and CO levels. As the tests show, firing patterns with 9-11 BOOS in the middle chamber (T7, T8 and T22) resulted in poor combustion. In contrast, firing patterns with 5 and 6 BOOS (T9 and setting 1(a) of T7) had a better combustion efficiency (see Appendix F for boiler efficiency). There were two main indicators which pointed at poor combustion in those tests with a high number of BOOS in the middle chamber: (i) high *minimum* O_2 *level* (i.e. at CO = 200 ppm) when compared to the normal initial O_2 levels and (ii) high carbon in ash levels at the corresponding high *minimum* O_2 *levels.*

The reason for the poor combustion is that the high number of BOOS in the middle chamber contributed to a very fuel-rich combustion in the outer furnace chambers. This very fuel-rich combustion resulted in burners operating outside design limits and in a degradation of the pulverised fuel quality leading to increased carbon in ash emissions. Thus, in order to compensate this poor burnout more O_2 was needed, explaining the high *minimum O_2 levels* in the tests. Additionally, the extent of NO_X reduction was constrained due the poor combustion.

Examples of this poor combustion are various. T7 for example, showed typical CO, O_2 and carbon in ash levels during the initial condition and setting 1(a) (with 6 BOOS). However, in setting 1 and 2 (with 9 BOOS), for a *minimum NO_X level*, carbon in ash was high (19.1%) and O_2 levels were within the range of the initial conditions of the test (Fig. 6.10). Also, in T8 (with 10 BOOS) the O_2 levels for a *minimum NO_X level* were higher in setting 1 and 2 (4.2% and 4.4% respectively) than in the initial condition of the test (≈ 3.5%) - Fig. 6.14. Test 20 (with 11 BOOS) also showed high *minimum O_2 levels* in settings 1 and 2 (5.5% and 5.25% respectively), when compared with the initial O_2 level of 3.2-3.6% (Fig. 6.57). In addition carbon in ash levels were also increased in setting 1 and 2 (15.2% and 12.4% respectively) from an initial level of 10.6-11.8% (Fig. 6.58) and NO_X emissions were at a similar level or even slightly increased (Sett. 1: 660 ppm, Sett. 2: 580 ppm) when compared with the initial condition of the test (550-605 ppm).

On the other hand, tests with fewer BOOS (5-6) showed good combustion efficiency. For example, setting 1(a) of T7 (with 6 BOOS) showed typical O_2, CO and carbon in ash levels. Also T9 (with 5 BOOS) showed for a *minimum NO_X level* not only lower O_2 levels (Sett. 1: 2.3%, Sett. 2: 3.3%) than in the beginning of the test (3.2-3.9%), but also typical carbon in ash levels (Sett. 1: 10.8%, Sett. 2: 13.5%). Thus a firing pattern with 5-6 BOOS in the middle chamber is recommended, since it reduces NO_X emissions and ensures combustion efficiency. Although the NO_X reduction in T9 (with 5 BOOS) was high (32-37% and 36-40% in setting 1 and 2 respectively) the *minimum NO_X levels* achieved were still high, which means that there was a lot of NO_X being formed in the furnace. Nevertheless it is believed that in the case of lower initial NO_X levels, a high NO_X reduction would have been observed, resulting in much lower *minimum NO_X levels* than those shown in T9. A comparison of the BFMC (5-6 BOOS) between loads was not possible since no test at 420 MW was carried out (see further work).

Summary

A high number of BOOS in the middle chamber (e.g. 9-11) results in relatively high NO_X reductions (≈ 30-41%), but at the expense of high CO and carbon in ash formation. Additionally, the poor combustion efficiency can also limit further reductions of NO_X reduction.

BOOS in the middle chamber as a means of NO_X reduction can be an effective technique at Aberthaw, provided that the right number of BOOS is chosen (e.g. 5-6 BOOS) since: (i) it reduces NO_X emissions by up to 40% and (ii) it maintains carbon in ash and CO within acceptable levels, thus boiler efficiency is not affected.

The degree of staged combustion achieved with a high number of BOOS (9-11) can still be achieved with a lower number of BOOS (5 or 6) by simply using damper setting 2 (as shown in T9 - with 5 BOOS). Setting 2 gives around 220 ppm lower NO_X emissions than setting 1 for the same O_2 level - see section 7.2.3).

Further Work

Additional tests with 5-6 BOOS in the furnace middle chamber need to be carried out at 500 MW, in order to investigate the extent of NO_X reduction in the case of lower initial NO_X levels.

Tests with 5-6 BOOS in the middle chamber at 420 MW are required in order to:

- investigate the extent of NO_X reduction at high and low initial NO_X levels.
- allow the comparison between the *minimum NO_X levels* achieved with 5-6 BOOS in the middle chamber at 500 and 420 MW.

(ii) BOOS across the Furnace Chambers (BAFC)

As the name suggests, these tests aimed at reducing NO_X emissions through a BOOS pattern in which the BOOS were spread along the furnace. Also, as mentioned in chapter 6, these tests were initiated with a set boiler firing pattern, since the aim was to start with an equal distribution of BOOS across the furnace. Additionally, the secondary and tertiary air was set OFF for all burners o/s, so that the effect of opening the air on those burners o/s could be evaluated. These tests were therefore initiated from a set condition referred to as "Starting Condition[6]".

But how did this BOOS pattern affect NO_X?; and did it reduce both fuel- and thermal-NO_X? As in the BFMC, the BAFC also contributed to a reduction in both fuel- and thermal-NO_X, as a result of the two BOOS effects: (i) temperature cooling effect and (ii) fuel-rich combustion. However, whereas in the BFMC the two effects (i and ii) were localised in two main areas (middle and outer chambers respectively), in the BAFC these two effects were spread across the furnace chambers resulting in a mixed fuel- and thermal-NO_X reduction.

For a maximum NO_X reduction, these tests (T10, T11, T12 and T21) were carried out with a maximum number of BOOS (11, 11, 12 and 13 respectively) across the furnace chambers, whilst ensuring the generated load:

[6] In the other Aberthaw tests, the term "Initial Condition" was used, which refers to "as found" conditions.

Initial Conditions:

In general all BAFC tests except from T11 showed very high initial NO_X levels: T10, T12 and T21 showed initial NO_X levels in the range of 740-780, 820-880 and 720-730 ppm respectively, whereas T11 had lower NO_X levels (660-730 ppm). The initial O_2 levels were generally also high, ranging from 3.2-4.2% between the tests. An exception was T12 which had very low initial O_2 levels (2.7-3%) but very high NO_X levels, suggesting thermal NO_X formation. CO was negligible and carbon in ash had a value of 10-11% in T21 (in the other tests the instrument failed).

Minimum NO_X levels in Setting 1 and 2:

Overall, these tests achieved very low *minimum NO_X levels* at very low O_2 levels, both at setting 1 and 2. Additionally, as the corresponding low O_2 levels suggest, combustion efficiency was good. For example T12 gave a *minimum NO_X level* of 450 ppm at 2.1% O_2 (in setting 1)[7]. Also T21 had a *minimum NO_X level* of 430 ppm at 2.4% O_2 and of 410 ppm at 2.5% O_2 (in setting 1 and 2 respectively). Thus, T12 and T21 show that with BAFC it is possible to achieve very low NO_X levels whilst ensuring combustion efficiency. However, it is important to stress that the achievement of such low NO_X levels might be at the expense of carbon burnout (T21 showed an increase in carbon in ash levels in setting 1 (13%) and 2 (14.2%) from an initial condition of 10-11%).

The remaining BAFC tests, T10 and T11, showed higher *minimum NO_X levels* (e.g. in setting 1: 540 ppm at 3.1% O_2 and 520 ppm at 2.9% O_2 respectively) than T12 and T21. Still, the *minimum NO_X levels* both in T10 and in T11 were achieved at relatively low O_2 levels[8], also indicating good combustion efficiency.

Therefore, as the tests show, BOOS across the furnace chambers not only result in low *minimum NO_X levels*, but also in a good combustion efficiency.

Minimum NO_X levels Comparison between the BFMC and BAFC

When comparing the *minimum NO_X levels* between the BFMC with 9-11 BOOS and BAFC tests, it is the latter tests which show much lower *minimum NO_X levels* at much lower O_2 levels. Additionally, the BAFC tests give good combustion efficiency, unlike the BFMC (with 9-11 BOOS).

On the other hand, the comparison between the BFMC (with 5-6 BOOS) and BAFC tests, indicates that both BFMC (with 5-6 BOOS) and BAFC provide good combustion efficiency. It seems that BAFC gives lower *minimum NO_X levels*, although more tests with 5 BOOS in the middle chamber need to be carried out in order to confirm this.

[7] Due to operational problems while testing BAFC at 500 MW, it was not possible to test setting 2 in T11 and T12 and to fully test setting 2 in T10.

[8] Due to operational problems while testing BAFC at 500 MW, it was not possible to further reduce the O_2 levels in T10 and T11 in setting 1.

Summary

A maximum number of BOOS (11-13) across the furnace chambers results in very low *minimum NO_X levels*. However, for this NO_X reduction there might be a slight worsening of the burnout.

While reducing NO_X emissions, BAFC normally ensures a good combustion efficiency.

BOOS across the furnace chambers provides lower *minimum NO_X levels* and better combustion efficiency than BFMC with 9-11 BOOS.

After comparing the BAFC tests with the BFMC (with around 5 BOOS) test it seems that the BAFC provides lower *minimum NO_X levels* than BFMC with around 5 BOOS. However, this needs to be re-assessed on the basis results obtained from the BFMC further work.

Further Work

The positive results of the BAFC tests should be confirmed in long term tests.

7.2.5 Oil Burners Effect (O.B. Effect)

As explained in chapter 5 (section 5.2 and 5.3.2 (e)), the use of oil burners in utility boilers as a means of NO_X reduction is not a known NO_X control methodology. During the testing period at Aberthaw, however, it was noticed that when the oil burners were in service under "special boiler circumstances[9]" the NO_X levels were generally lower than normal. Thus, on the basis of these observations, an investigation of the "oil burners effect" as a new NO_X control methodology was carried out.

Before testing, the effect of a different number of oil burners in service on the NO_X emissions was not known. However, since the number of oil burners in service at loads below 400 MW is generally around 12 (section 5.3.2 (e)), the tests started by investigating the effect of 12 oil burners on NO_X emissions. Additionally, as the effect of the oil burners location within the furnace was unknown, the tests were carried out with a uniform distribution of the oil burners in the furnace.

Before discussing the oil burner tests it is important to note that the aim of these tests was firstly to investigate whether the oil burners had an effect on NO_X emissions or not. Thus the tests did not aim at finding out the optimal number of oil burners in service, or the best damper settings, etc.

[9] The term "special boiler circumstances" refers to situations of boiler instability.

Initial Conditions:

In general, the values of the various variables (NO_X, CO, carbon in ash and oxygen) during the initial conditions of the "oil tests" were very similar to the initial conditions of all other combustion modification tests. With respect to NO_X and oxygen levels, these showed considerable variations between the tests. On the other hand, the CO was normally within the typical levels (i. e. negligible), except from T17 with CO levels in the order of 100-170 ppm. Carbon in ash levels were very low for all tests, varying between 8.8% and 11.6%

Minimum NO_X levels in Setting 1 and 2:

Overall, all "oil burner tests" performed at Aberthaw (T16, T17, T18 and T23) showed a NO_X reduction.

When comparing the "oil burner tests" with the remaining tests performed at Aberthaw, it can be seen that the "oil burner tests" achieved the lowest *minimum NO_X levels*. Furthermore, combustion efficiency was good, as the low *minimum O_2 levels* (between 2.9 and 3.2%) and corresponding carbon in ash levels (≈ 11.5%) suggest (e.g. T16, T18 and T23). Only T17 had poor combustion, as indicated by the high CO and high *minimum O_2 levels* (5%) in setting 2, which resulted in higher *minimum NO_X levels* than T16 and T18. Nevertheless, the poor combustion in T17 was not the result of the oil burners combustion, since the test already had high initial CO levels (100-170 ppm) before the introduction of oil burners.

Therefore, in terms of NO_X reduction effectiveness and combustion efficiency, these results indicate that the "oil burners effect" may be a very powerful and useful NO_X reduction technique.

A possible reason for no CO or carbon in ash formation at low oxygen levels may be the fact that the oil burners have their own air supply (see appendix A), providing extra air for complete burnout. With combustion complete, excess oxygen can thus be trimmed without CO and carbon in ash formation.

The "oil burner tests" were performed with a varying number of oil burners in service. In T16 and T17, only 12 oil burners were added to combustion, which was enough to give a very good decrease in NO_X levels. In T16, for example, NO_X emissions dropped from an initial level of 605-685 ppm down to 460-500 ppm (Fig. 6.42).

On the other hand, T18 investigated the effect of an increasing number of oil burners in service on NO_X emissions. Initially only 12 oil burners were introduced to combustion, however, although there was a NO_X reduction (Fig. 6.50) the NO_X levels were still high (≈ 600-640 ppm) when compared to the NO_X levels in T16 and T17 after the introduction of oil burners. Thus, a further 6 oil burners were added to combustion (Sett. 1.1), which resulted in an additional NO_X reduction. It is interesting to note that of all the oil burner tests, T18 was the one with highest initial NO_X levels (710-730 ppm). This may explain the relatively high NO_X levels after the addition of the 12 oil burners and thus the need of additional oil burners in order to further decrease the NO_X emissions.

In other occasions, it was found that 12 oil burners were insufficient to decrease NO_X emissions. For example in T23 (at 420 MW), initially only 12 oil burners were added to combustion. However, since no reduction on NO_X emissions was seen, a further 6 oil burners were added making a total of 18 oil burners, after which the NO_X levels started to decline.

But how does the use of oil burners result in a NO_X reduction?

Currently, the reasons for the NO_X reducing effect of the oil burners are not known. Therefore, at the moment, only theoretical questions can be posed such as:

- Could it be that the burning of the oil alters the coal flame shape, so that the oxygen concentration is reduced thus lowering NO_X formation?
- Does the oil somehow reduce the overall flame temperature?
- Could it be reburning?
- Could the oil burners contribute to a "dilution effect" of the NO_X levels in the furnace?

More theoretical questions could be posed here, but the latter two questions are somehow appealing. Here, each is considered in detail:

REBURNING?: Like in reburning, the use of "oil burners" as a means of NO_X reduction consisted of the introduction of another fuel and oil is also a known reburning fuel (see section 3.1.1(d)). Thus the question: Could it be a reburning effect? However, the answer to this question is most likely "No", for two main reasons:

1. The process of reburning requires three separate combustion zones, the first two of which (primary- and secondary-zone) operate largely substoichiometrically whereas the third one (tertiary-zone), is air-rich in order to ensure complete combustion. It is in the secondary-zone where the reburning fuel is normally injected and burned, whereas the primary fuel is burned in the primary zone. This reburning process is very different from the process of "oil burners" used at Aberthaw. In the Aberthaw furnace, each pulverised fuel burner is provided with an adjacent oil torch, which means that both coal- and oil-burners burn their fuel together in the same zone (unlike the two zones in reburning). Furthermore, there was no addition of air in an upper zone of the furnace (unlike reburning, where air is added in the tertiary zone).

2. Additionally, as the tests show, 12 oil burners were normally enough to decrease NO_X emissions. It is interesting to note that in terms of heat input, the 12 oil burners correspond to a value of 4.5% to 6.8% of the net heat input (depending on the capacity of the oil burners). In

contrast, reburning requires, according to the literature [89], between 10% and 20% reburn fuel in terms of net heat input.

These are the two main reasons why the effect of the "oil burners" at Aberthaw is most likely not reburning. Furthermore, the particular operational conditions which are essential for the success of reburning (such as local stoichiometries) [89] were not present at Aberthaw either. Therefore, the effect of the "oil burners" cannot be categorised as reburning in the known sense. It might however be that a "new type" of reburning is achieved with the oil burners. Amongst the advantages of the discovered oil burners effect in comparison with the normal reburning is the absence of particular requirements with respect to the furnace height.

DILUTION EFFECT?: With the introduction of oil burners to the combustion process, the coal flow was reduced accordingly so that the total power output of the power station remained the same. Assuming that the oil burners do not contribute to the NO_X emissions, this "primary" dilution effect could be responsible for an overall NO_X reduction proportional to the reduction in coal flow (between 4.5% and 6.8%). A "secondary" - more indirect - dilution effect could further result from chemical conversions: it is known that NO can be converted to N_2 if in the presence of CH_i, N, and NH_i (shown in Fig. 2.1 - chapter 2, p. 21). Certainly, some of these reactants will be present in the furnace and may or may not, in the presence of the oil burners in service, react with NO and convert it into N_2. If this is happening, then the amount of NO resulting from coal combustion would be further diluted.

Obviously, the effects of oil burners on NO_X emissions should be further investigated in more detail both in general and in particular in Aberthaw. The general investigations should also address the question whether the use of another fuel instead of oil would have a similar effect.

Summary

The "oil burners effect" results in very low *minimum NO_X levels* (lower than any other combustion modification technique carried out at Aberthaw). Additionally, whilst reducing NO_X emissions to very low levels, the oil burners effect also ensures combustion efficiency.

The oil burner tests showed that in general 12 oil burners in service were enough to reduce NO_X emissions and that further oil burners can be taken into operation as needed to achieve a certain low NO_X level.

Further Work

The effect of oil burners as a new NO_X control methodology must be researched. The specific tests to be carried out at Aberthaw include:

- Investigation of the mechanisms which lead to the positive effects of oil burners on the combustion process. This research should be supported by laboratory tests with a scaled combustion process.
- The effect of a varying number of oil burners in service.
- The best "oil burners" firing pattern.
- The best damper settings (Sett. 1 or 2) for the oil burners effect.

Due to the positive experiences, the "oil burners tests" should be carried out over a longer period.

7.2.6 Combination of Combustion Modification Techniques

Each of the individual techniques has a limited scope of NO_X reduction. For optimal NO_X reduction results it is therefore important to take advantage of the combinatorial effect of different NO_X control techniques. The tested combinations were to different degrees successful:

- **Excess air + Air Staging ("Set A", "Set B")**

Although this combination gave generally good results it is not sufficient to ensure a reliable reduction to satisfactory NO_X levels. A third technique should therefore be applied in addition to excess air and air staging.

- **Excess air + BFMC + Air Staging ("Set A")**

Due to the poor combustion, a high number of BOOS in the middle chamber (9-11) should be avoided. With a limited number of BOOS (here 5), this combination appears to be applicable, although the NO_X emissions were too high in the test. Further tests have to clarify whether the result was atypically high for this combination.

- **Excess air + BAFC + Air Staging ("Set A")**

Overall this combination resulted in a good NO_X reduction, yielding reliably low absolute levels.

- **Excess air + Oil Burners Effect + Air Staging ("Set A")**

Showing the lowest *minimum NO_X levels* of all tests (385-450 ppm), this combination proved to be the most successful approach to the reduction of NO_X emissions.

Summary

The combination of NO_X control methodologies was generally shown to be successful, although it is important to note that the NO_X reductions of the individual methods do not combine linearly to the overall NO_X reduction.

8. DESIGN OF THE PHYSICAL MODEL AND MODEL EXPERIMENTS

In the study of boiler gas flows, there is no single best modelling technique. Often it is the use of a variety of modelling techniques that gives the most accurate solution. Nevertheless, the choice of the modelling technique is normally determined by a variety of factors such as the results required, (qualitative or quantitative results), the costs involved, ease of construction, etc.

Isothermal physical flow models are generally used to study large systems which have flow patterns that are too complex for analytical solution and for which full scale experiments on operating systems are too costly [150]. It is possible to use either a hot or cold flow medium. Hot modelling has various disadvantages such as being more complicated and costly due to the need of heat resistant materials, difficult visualisation, etc. Cold modelling on the other hand, is relatively cheap and allows the direct visualisation of the flows, using transparent materials. Additionally, it is known to be a technically approved technique in the study of furnace gas flows. In this work, physical flow modelling using a cold medium was therefore used to assess the gas flow patterns in the boiler.

Further to this general decision, a variety of important aspects that had to be considered in the design and set-up of the physical model are discussed in the following sections. In addition, details of the test programme as well as the experimental settings and procedures of the modelling work are also given.

8.1 Objectives of the Modelling Work

The design of a model must be geared to the objectives of the modelling work, as it was mentioned above. The main objectives of the model experiments in this work were:

(a) To observe flow patterns and to correlate them to plant experiment results.

(b) To gain insight and experience with respect to the flow patterns and how they change under different conditions in a 3D model. Previous water modelling studies concentrated on a 2D simulation [151, 152, 153], which offers only limited information about the complex flow in a 3D furnace. Therefore, it was of particular interest to investigate the variations of the flow patterns along the furnace.

(c) Provided that sufficient knowledge could be obtained from the correlation between the power plant tests results and the associated flow patterns (objective (a)), the ultimate goal of the modelling work was the further optimisation of the firing patterns. These optimised patterns would have to be validated afterwards on the real plant where they should yield further reduced NO_X levels.

8.2 The Design of the Model

In order to investigate the combustion flow aerodynamic patterns within the down-fired-furnace, a 3D model (Fig. 8.1, 8.2, 8.3) was constructed. The overall model dimensions are to 1/48th scale, resulting in a height of 959 mm and a width of 515 mm.

The model is of modular construction (Fig. 8.4) and was made entirely of perspex with a thickness of 15 mm. It includes 36 burners, the combustion air ducting, the furnace, the rear enclosure (or heat recovery area) and the nose of the furnace. The model does not extend beyond the rear enclosure. Detailed drawings of the model are appended (Appendix C).

The shape of the boiler was represented as closely as possible, thus it may be assumed to be a true representation of the boiler in the plant. However, the burner detail and secondary air inlets had to be approximated as the exact scale reproduction was not feasible.

A typical down-fired-furnace burner arrangement is shown in Fig. 8.5. It consists of two elliptic primary air inlets surrounded by an annular tertiary air inlet. In the model this is represented by a single circular primary inlet with a concentric annular tertiary inlet as shown in Appendix C (Fig. C.4). The primary inlet area and primary/tertiary area ratio were retained. In a similar manner, the secondary air inlets in the power station (Fig. 8.6) were simplified and again a similar area ratio as the original was retained. Secondary air inlets in the model are shown in Appendix C (Fig. C.2).

8.3 Choice of Medium and Tracer

Since the aim of this work was to obtain qualitative information on the flow and mixing conditions of a down-fired-furnace design, an isothermal flow study using cold water was conducted. Water was chosen as the medium, since water models have been shown to be well suited to establish the general

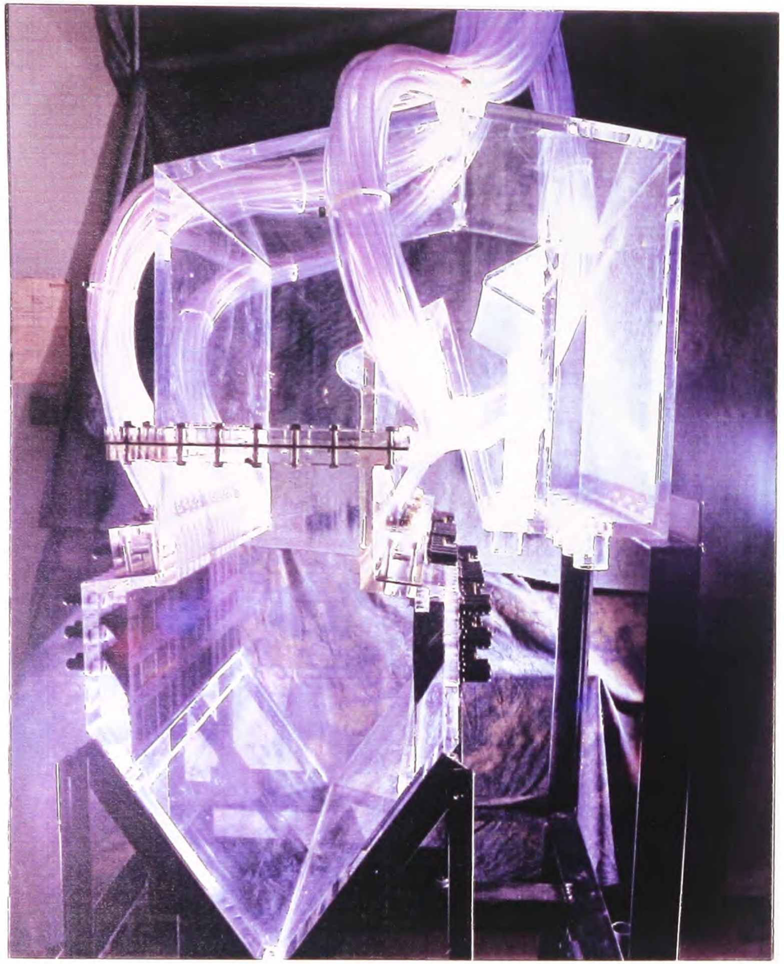


Fig. 8.1: Side view ("A" side) of the model when under assembly. Note: The classification of the boiler walls as seen on the photograph is: left: Front-wall, right: Rear-wall, front: "A" side or RHS and back: "B" side or LHS).

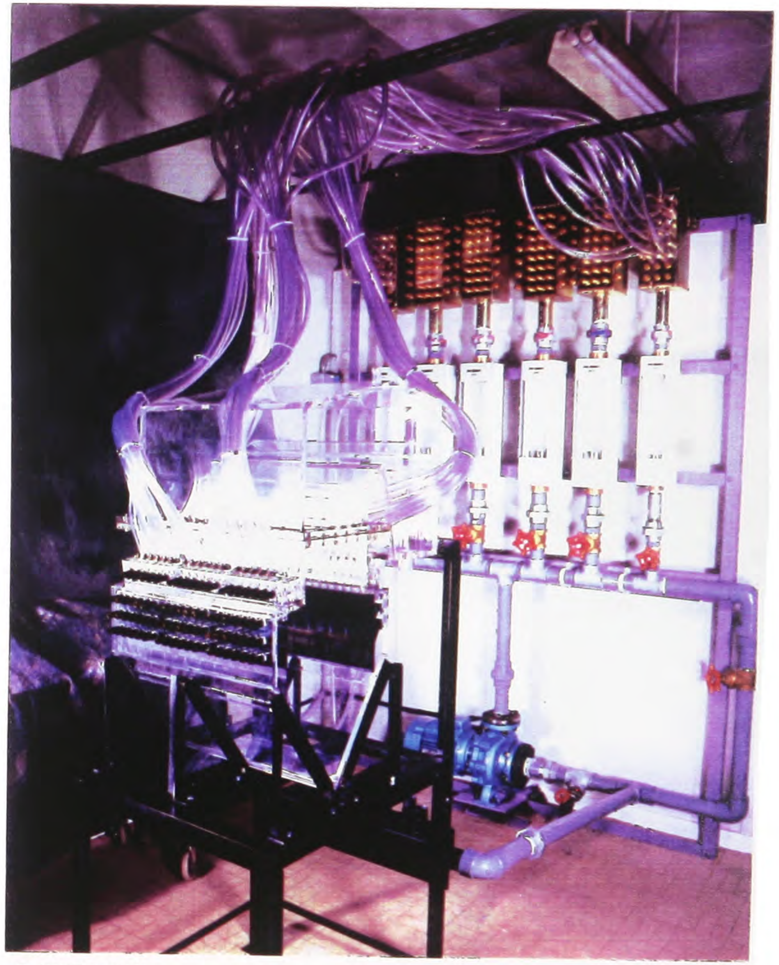


Fig. 8.2: Test rig.

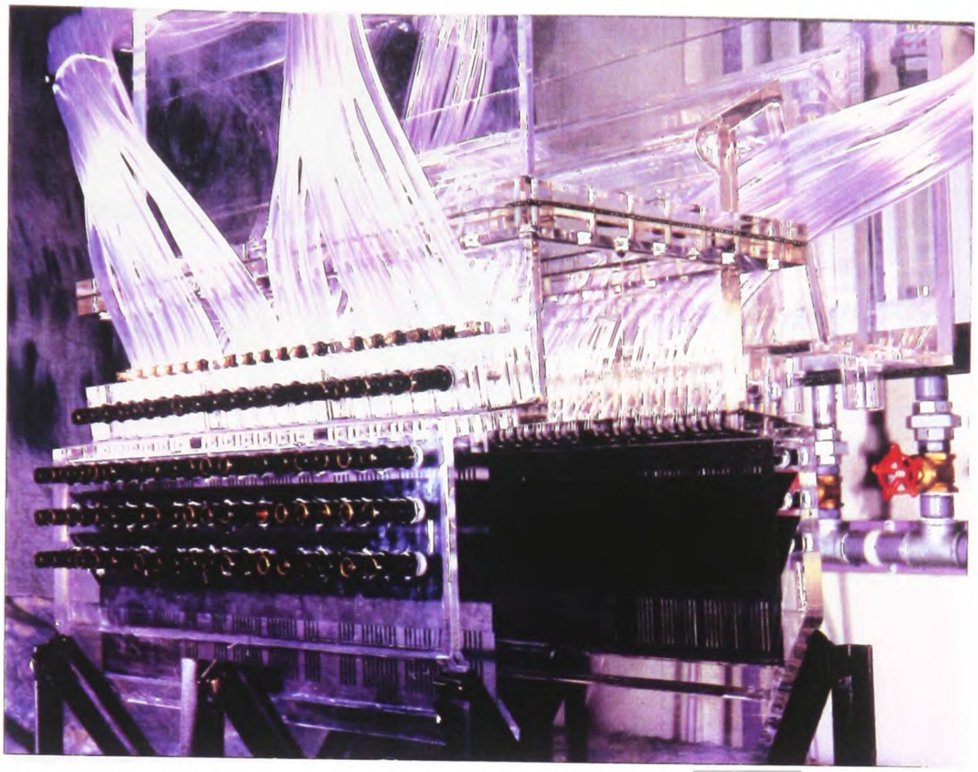


Fig. 8.3: Detail of the burner blocks and of the secondary flow stages down the furnace front-wall.

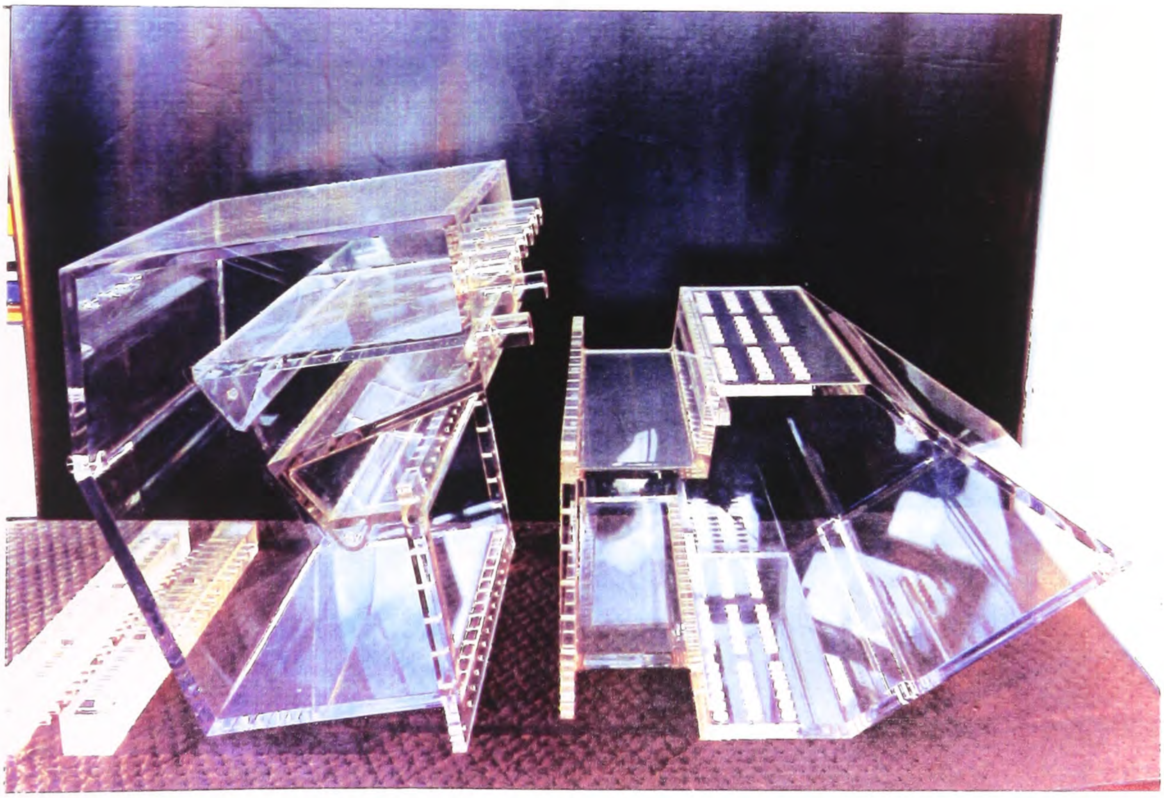


Fig. 8.4: Model modules: the burner blocks, the heat recovery area and the furnace.

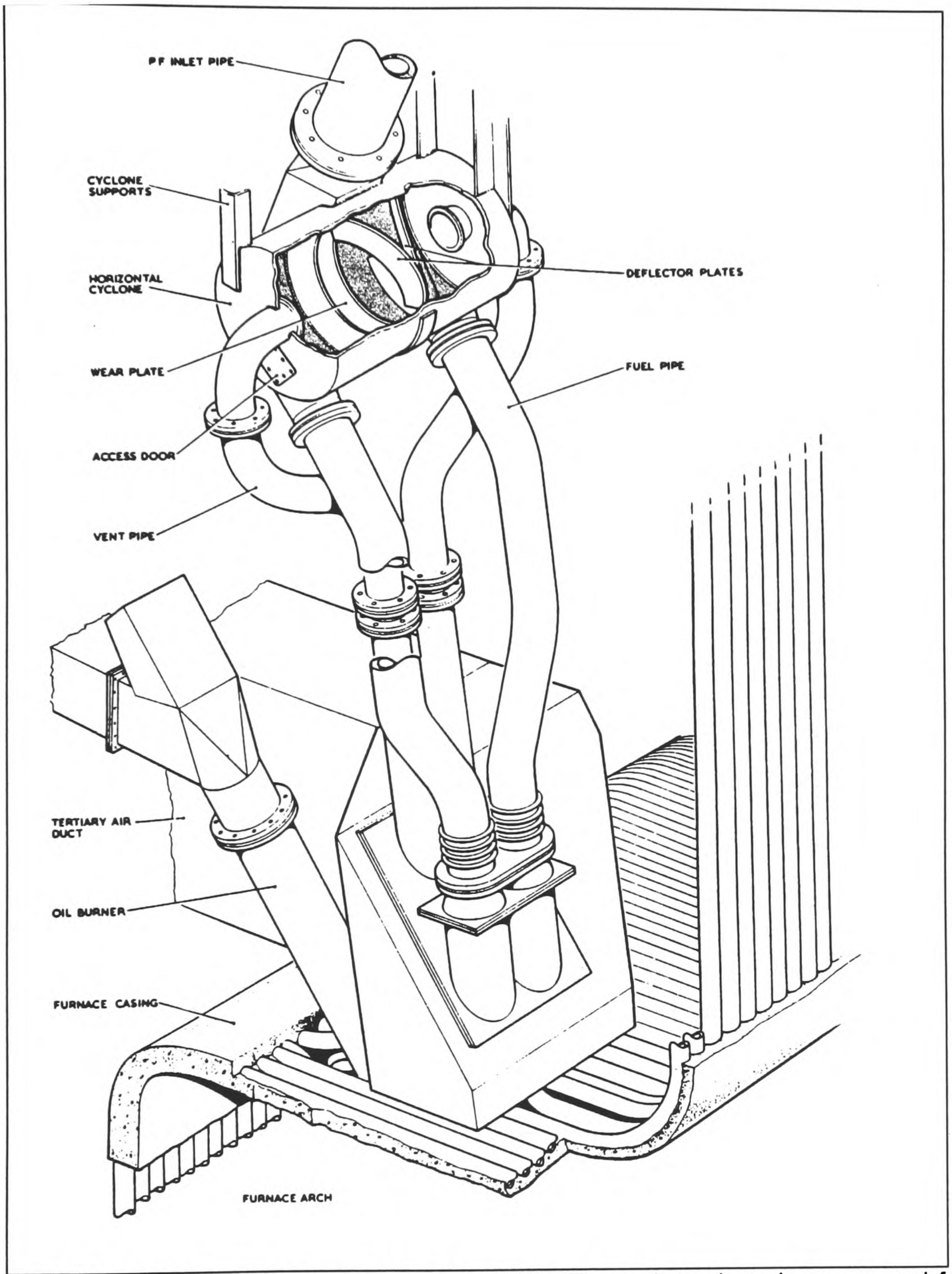


Fig. 8.5: Power station burner arrangement. (Note: The cyclones have been removed from the plant) [101].

flow patterns [154, 155]. Additionally, direct visualisation is relatively easy, due to the much lower velocities when compared with air [156].

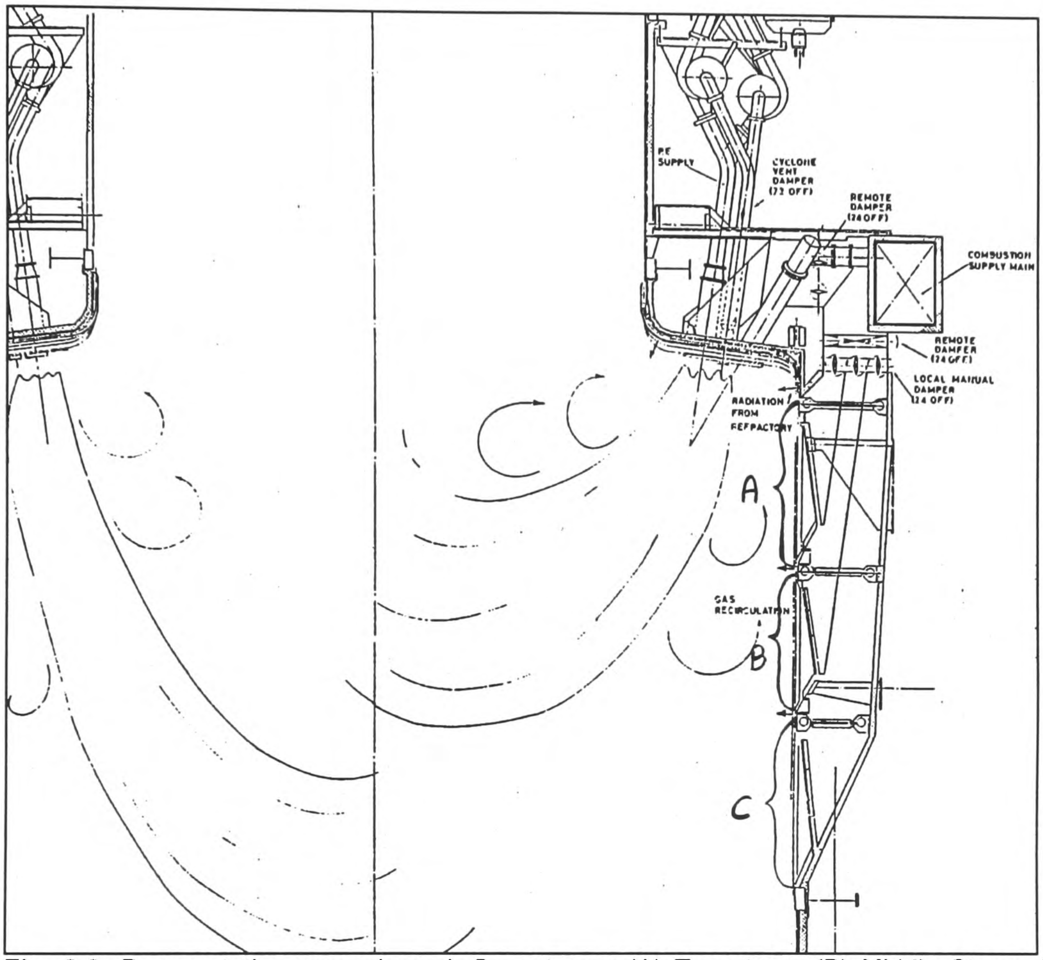


Fig. 8.6: Power station secondary air flow stages: (A) Top stage, (B) Middle Stage, (C) Bottom stage [101].

Fine silica powder (1 micron) was used as the tracer, because solid particles (such as polystyrene beads) are difficult to remove from a closed-circuit system and are potential obstructions in very small areas such as the gap between the tertiary and primary air tubes.

8.4 Scaling Criteria

In addition to maintaining exact geometric similarity between the model furnace and the real plant, there are two other main similarity criteria parameters that must be satisfied in isothermal modelling. These are: (1) equality of Reynolds number in the furnace and model [154, 156] and (2) scaling of burners in order to take into account the effects of buoyancy and of the rapid expansion of the flame gases that occur in the real furnace. These are discussed below:

8.4.1 Equality of Reynolds Number

In theory, the Reynolds number in the model should equal that of the real boiler [157]. This is, however, usually impractical or even impossible. In this study for example, a water flow rate of 12,130 l/min would have been required in order to achieve Reynolds number equality (calculations shown in Appendix E, section E.1).

Fortunately, in physical modelling, Reynolds number equality is not crucial. It has been shown that a model may be operated at a Reynolds number as low as 10^4 with little influence on the flow pattern [150, 158, 159]. Other workers also demonstrated that no significant variations occur in the flow patterns as long as the Reynolds number is within the turbulent region [154, 160].

In this work, the water model was therefore operated with a calculated water flow rate that ensured a Reynolds Number of at least 10^4. After ensuring a turbulent Reynolds Number, it was necessary to choose the basis of the water flow rate calculations - mass or volumetric flow rate - since it is impossible to satisfy the similarity requirements of both of them. As pointed out in [161], "if volumetric flow rates are at all points similar, then mass flow rates must differ and vice versa, therefore the conditions for similarity must be related to the kind of observation being made".

The mass flow rate was chosen in this work (Appendix E, section E.3), because the maintenance of equivalent momentums was considered as crucial for the observation and analysis of the flow patterns in the furnace.

The experimental work was conducted with a total water flow rate of 600 l/min, giving a Re. No. of 19,000 based on the throat of the furnace with an average upflow velocity of 0.09 m/s (Appendix E, section E.2(i)). This compares with a plant Reynolds number of 384,580 (Appendix E, section E.2(ii)) at a velocity of 12.7 m/s.

8.4.2 Scaling of the Burners

In the real furnaces, differences in temperature between the burner jet and the furnace gases, originate buoyancy forces which tend to lift the hot jet exiting from the burner port [162, 163, 164]. Furthermore, the flow pattern is affected by the expansion of the hot gases since the gas forming the flame occupies more space in the furnace than in the model [165].

The application of isothermal modelling to represent furnace flow patterns, however, presents a problem since isothermal models are not subject to the effects of buoyancy and rapid gases expansion. This may in turn affect similarity [162, 163].

Nevertheless, there are two main approaches that attempt to represent such effects: (a) the use of geometric burners with a gauze located downstream of the incoming jet at a position approximating to the flame front [161, 166], or (b) scaling of burners according to the Thring-Newby criterion [167].

The effect of inserting a gauze has been investigated by Anson [161]. Its aim is to allow the use of geometrically correct burners while producing the appropriate enlargement of the jet and to reduce the forward momentum of the jet. More details on the sizing and position of the gauze are given in [166].

However, the application of the gauze technique in the model, imposes various problems. These are: (a) in order to precisely place and size the gauze, it is necessary to know the location of the flame front and how large it should be, (b) the mechanical mounting of the gauze may prove difficult since the burners are so close together, and (c) the gauze may cause combustion simulation problems if it interferes with the combustion gas flow. Additionally in the case of work with particles as the seeding powder, it may not only interfere with the seeding system, but also distort the mixing flow study. Similar problems have been identified in [150].

Therefore, for simplicity and practical reasons, the Thring-Newby criterion was chosen to represent the effects of buoyancy and jet expansion. By applying the laws of conservation of momentum and mass to the jet, Thring and Newby showed that a change in the nozzle area would be required when representing the prototype by a physical model. This change in area is given by [158, 167]:

$$d'_o = d_o \, (\rho_o / \rho_{cg})^{0.5} \qquad \textbf{Eq. 8.1}$$

where ρ_o is the density of the air at the nozzle outlet in the actual boiler and ρ_{cg} is the density of the combustion gases in the boiler. However, the application of the Thring-Newby theorem in multiple burner systems, as in this case, is often limited [158]. In this model, the theorem was not applied as the dimensions of the nozzles would have been enlarged by a factor of two causing physical interference with adjacent burners. The air nozzles and burners therefore remained scaled to 1/48th of the original sizes.

Although simple scaling of the nozzles is acknowledged to introduce an error [158, 166], it is believed that this limitation in the modelling had little effect on the observed flow patterns. Previous work has shown that use of an isothermal model which neglects the effect of buoyancy, in general does not introduce a significant error in the flow pattern when compared with the real plant [162, 163]. Additionally, numerous investigations suggest that although no allowance is made for the expansion of gases during combustion or any buoyancy effect, the predictions from model work are in fair agreement with those existing in the actual furnace [168]. Such findings may be further justified by the work of Brais [169] which suggests that it is aerodynamics which establish the flow patterns and that combustion does not alter the pattern, but just accentuates it [170].

8.5 The Test Rig

In the test rig (as shown in Fig. 8.2), constant flow was achieved by pumping water through a closed system using a 6.5 kW pump which provided a maximum flow rate of 900 l/min at a head of 34 m. To minimise corrosion, all pipes were of plastic and most metal areas galvanised.

In the model, the flow was split into primary, secondary and tertiary flows, with the secondary flow being further split into three stages down the boiler rear and front walls. As shown in Fig. 8.7, primary, secondary and tertiary flows were measured by one, two and three rotameters, respectively. The three secondary flow rotameters allowed for the adjustment of the secondary flow stages in the furnace.

Individual burners could be isolated to simulate burners out of service. Additionally, secondary and tertiary flows associated with individual burners could also be shut.

A 2 Watt Argon-ion laser directed at a rotating mirror (2000 rpm, polygon with 8 facets) was used to produce a laser light sheet to provide illumination of various planes through the model. The thickness of the light sheet was 1 mm.

Flow patterns were recorded using a 35 mm still camera while the dynamic flow was recorded by means of a video camera. Sketches of the flow patterns were later carried out on the basis of the videotaped flow.

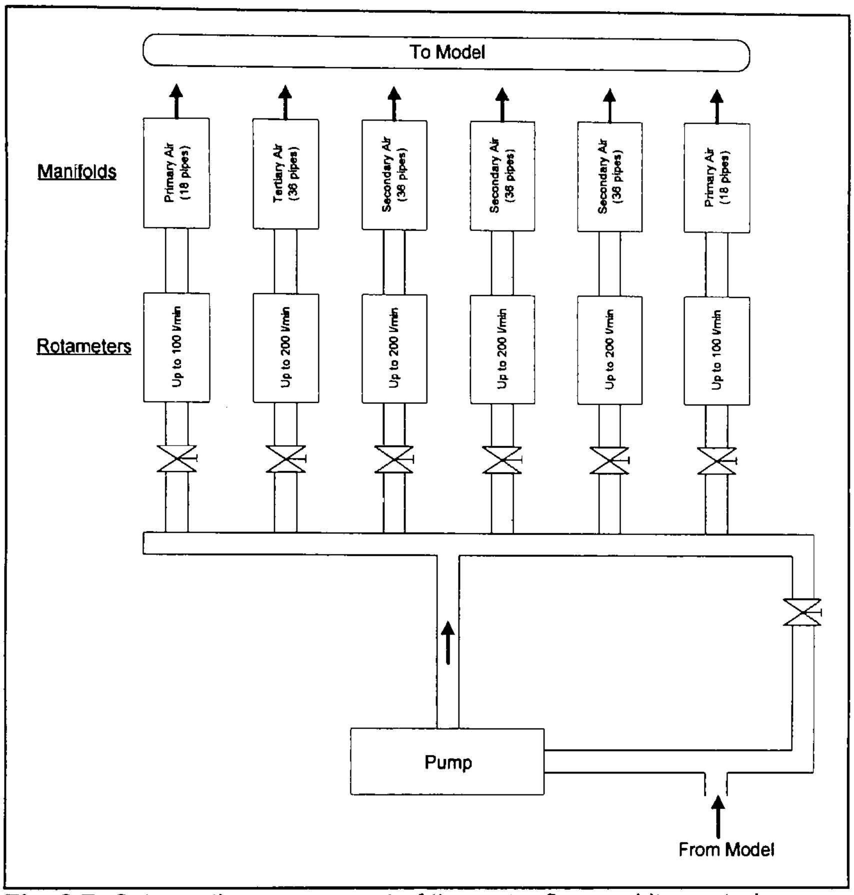


Fig. 8.7: Schematic arrangement of the water flow and its controls.

8.6 Overview of the Test Programme

In order to address the objectives of the modelling work, two groups of experiments were defined: (i) Firing patterns of typical set-ups of the tests at the real plant (section 8.6.1.a) and (ii) Theoretical firing patterns (section 8.6.1.b).

The aim of these two sets of firing patterns was firstly, to analyse and compare the flow patterns associated with the real plant tests and secondly to magnify the expected distinctions in the flow aerodynamics using the more accentuated theoretical set-ups.

Another plant experiment that could in principle be reproduced with the model is the effect of air staging. Unlike firing patterns, however, air staging cannot be exactly reproduced because its effect on the flow ratios is not known. Some general tests, based on coarse assumptions, were therefore envisaged later in the test programme but could eventually not be carried out, due to problems with the test rig.

This section further details the particular tests carried out with the model (8.6.1) and summarises those plant tests that could not be modelled for various reasons (8.6.2).

8.6.1 Modelled Tests

(a) Real Plant Firing Patterns

Different firing patterns of the following real plant tests were simulated:

- Normal operation of the plant
- BOOS in the furnace middle chamber
- BOOS across the furnace chambers

(b) Theoretical or "Extreme" Firing Patterns

Tests with more "extreme" realisations of the firing patterns of all three of the above tests which are only theoretically possible, were carried out in order to magnify the expected distinctions between the flow patterns.

The theoretical firing patterns were designed on the basis that the secondary and tertiary air flows were always open (normal operating procedure in the power plant) and 24 was chosen as the typical number of burners in service in the power plant.

8.6.2 Not Modelled Tests

For different reasons, the further NO_X reduction tests other than the BOOS and normal operation concept that were carried out at the real plant, could not be simulated with the model:

(a) Load - High and Intermediate

The difference in load has only a minor effect on the Reynolds Number (i.e. it is still turbulent). Therefore, the flow patterns in the furnace are the same for 420 and 500 MW and are both represented by the model experiments carried out in this work.

(b) Excess Air

The decrease of the excess air in these experiments is relatively little in comparison with the overall flows and has therefore a negligible effect on the flow pattern. Additionally, the Reynolds Number remains well within the turbulent range. Hence, both normal excess air and reduced excess air are represented by the same model experiments; the distinction cannot be modelled.

(c) Air Staging

As it was mentioned above, air staging which is to be reproduced by varying the flow ratios in the model remains to be done in the further work. Since the exact effect of air staging on the flow ratios is not known, these experiments can only be conducted as general studies, similar to those carried out by Tucker [151], Morris [152] and Stevens [153].

(d) Burner Biasing

Although burner biasing tests have not explicitly been reproduced in the model experiments, their effect on the flow pattern is expected to be similar to the effect of BOOS, although less distinct.

(e) Oil Burners

The use of oil burners in the furnace could not be modelled, simply because the model does not incorporate oil burners. Also, it is believed that the effect on the flow pattern would be negligible, for two main reasons: (i) a small number of oil burners (12) would be simulated as this number is normally sufficient to decrease NO_X emissions in the plant and (ii) the fuel and air flows of an oil burner are much smaller when compared to those of a pulverised fuel burner.

(f) Combinations of NO_X Reduction Techniques

A combination of the above NO_X reduction techniques could not be modelled for the reasons given in (a), (b), (c) and (e).

8.7 Experimental Settings and Procedures

8.7.1 Flow Rates

The water flow rates were calculated on the basis of mass flow proportionality with the ratio $\frac{primary + tertiary}{\sec ondary} = \frac{40}{60}$ in accordance to the literature [132]. The total water flow rate remained constant.

The water flow rates used in the model tests were as follows (calculation details in appendix E, section E.3):

Total primary air + fuel flow rate	= 128.64 l/min	(21.44%)
Total secondary air flow rate 1st stage	= 52.46 l/min	(8.74%)
Total secondary air flow rate 2nd stage	= 101.65 l/min	(16.94%)
Total secondary air flow rate 3rd stage	= 173.78 l/min	(28.96%)
Total tertiary air flow rate	= 143.46 l/min	(23.91%)
Total flow	600 l/min	(100%)

Table 8.1: Water flow rates used in the modelling tests.

8.7.2 Laser Light Sheet

Direct visualisation of the flow patterns was achieved when illuminating a slice of the model with a laser light sheet in dark surroundings.

The laser light sheet was positioned at each of the first eight burners, in order to investigate any particularities of the flow. Beyond this distance the flow pattern became indistinct due to multiple scattering from particles.

8.7.3 Photographs and Sketches

From observation of the overall flow, flow patterns were photographed and sketched. Representing such flow processes with a single sketch or photograph proved impossible. Therefore, a collection of sketched "snapshots" (Figs. 9.1-9.3) and of photographs (Figs. 9.4-9.9) illustrate the observed flows best.

9. MODEL EXPERIMENTS AND RESULTS

This chapter details the model experiments and presents the results of the modelling work.

9.1 Model Experiments

As explained in chapter 8, the model experiments aimed at the simulation of (a) real firing patterns of the tests performed in the power plant and of (b) theoretical firing patterns. For each test, three real and three theoretical patterns were simulated.

9.1.1 Normal Operation of the Plant

Firing patterns of "normal operation of the plant", refer to typical patterns normally used by the power plant operators. Many examples of these patterns are available from the power plant experiments, as most tests were initiated with "as found firing patterns". The following were simulated:

(a) Real Plant Firing Patterns

Note: The labels above the firing patterns (e.g. "Test 1"...) refer to the real plant tests.

Test 1 (1st Initial Condition):

					X														
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*	*	*	*	*	*		*	*	*	*	*	*
*	*	*	*	*			*	*			*	*		*	*		*		
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
					X														

Total number of PF burners i/s: 29

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Test 6 (Initial Condition, Setting 1 and 2):

							X					X							
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*		*	*	*			*			*			*	*	*		*	*
*	*	*			*		*	*		*				*	*	*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
			X	X								X							X

Total number of PF burners i/s: 24

Test 21 (Initial Condition, Setting 1 and 2):

	X	X					X	X	X										X
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
				*	*					*	*	*				*	*	*	
*	*	*	*	*	*		*	*	*	*				*	*		*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
												X							X

Total number of PF burners i/s: 22

(b) Theoretical or "Extreme" Firing Patterns

All burners i/s:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 36

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Symmetric Pattern:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	*	*	*	*				*	*	*	*				*	*	*	*	
	*	*	*	*				*	*	*	*				*	*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

Asymmetric Pattern:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
*			*				*			*				*			*		
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

9.1.2 Burners Out Of Service (BOOS) in the Furnace Middle Chamber

As the name suggests, firing patterns of "BOOS in the furnace middle chamber" refer to patterns with a high number of burners out of service in the furnace middle chamber. The investigated patterns were:

(a) Real Plant Firing Patterns

Note: The label above the firing patterns refer to the real plant tests.

Test 7 (Setting 1 and 2):

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*	*		*	*	*		*	*	*	*	*	*
*			*	*	*		*					*				*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
	X	X												X					X

Total number of PF burners i/s: 25

PF burners o/s in the middle chamber: 5

<u>Note</u>: PF burners i/s are marked with an asterisk: *
"X" - Secondary and tertiary air flows OFF.

Test 8 (Setting 1 and 2):

	X	X											X					
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*			*	*	*							*				*	*	*	*
*	*	*	*	*	*							*		*	*	*	*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 22

PF burners o/s in the middle chamber: 10

Test 22 (Setting 1 and 2):

X																		
E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	*	*		*										*	*	*	*	*	*
*	*	*	*	*	*					*				*	*		*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1
																		X

Total number of PF burners i/s: 20

PF burners o/s in the middle chamber: 11

(b) Theoretical or "Extreme" Firing Patterns

All burners in the furnace middle chamber out of service:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*									*	*	*	*	*	*
*	*	*	*	*	*									*	*	*	*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

PF burners o/s in the middle chamber: 12

<u>Note</u>: PF burners i/s are marked with an asterisk: *
"X" - Secondary and tertiary air flows OFF.

Symmetric Pattern:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*			*					*			*	*	*	*	*
*	*	*	*	*			*					*			*	*	*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

PF burners o/s in the middle chamber: 8

Asymmetric Pattern:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
*	*	*															*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

PF burners o/s in the middle chamber: 6

9.1.3 Burners Out Of Service (BOOS) across the Furnace Chambers

Firing patterns of "BOOS across the furnace chambers" refer to patterns with burners out of service uniformly spread in the furnace chambers. The investigated patterns were:

(a) Real Plant Firing Patterns

Note: The label above the firing patterns refer to the real plant tests.

Test 10 (Setting 1 and 2):

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*					*	*	*	*	*	*		*	*	*	*	*	*
*			*	*	*		*			*	*						*	*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 25

PF burners o/s in the furnace: LHS (B side): 5, middle: 3, RHS (A side): 3.

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Test 11 (Setting 1 and 2):

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
*					*		*			*	*	*							*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 25

PF burners o/s in the furnace: LHS (B side): 4, middle: 2, RHS (A side): 5.

Test 23 (Setting 1 and 2):

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
				*	*			*	*	*	*	*		*	*	*	*		
	*	*	*	*	*		*	*	*	*				*			*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 23

PF burners o/s in the furnace: LHS (B side): 5, middle: 3, RHS (A side): 5.

(b) Theoretical or "Extreme" Firing Patterns

BOOS spread across the furnace chambers

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*			*	*		*	*			*	*		*	*			*	*
	*	*	*	*				*	*	*	*				*	*	*	*	
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

PF burners o/s in the furnace: LHS (B side): 4, middle: 4, RHS (A side): 4.

Note: PF burners i/s are marked with an asterisk: *

"X" - Secondary and tertiary air flows OFF.

Symmetric Pattern:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
	*	*		*	*			*	*		*	*			*	*		*	*
	*	*		*	*			*	*		*	*			*	*		*	*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

PF burners o/s in the furnace: LHS (B side): 4, middle: 4, RHS (A side): 4.

Asymmetric Pattern:

E6	F6	F5	E5	A6	A5		E4	F4	F3	A4	A3	B3		F2	F1	B2	A2	A1	B1
*	*	*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*
*					*		*					*		*					*
B6	D6	D5	B5	C6	C5		B4	D4	D3	C4	C3	E3		D2	D1	E2	C2	C1	E1

Total number of PF burners i/s: 24

PF burners o/s in the furnace: LHS (B side): 4, middle: 4, RHS (A side): 4.

9.2 Modelling Results

As mentioned in section 8.7.3, the model results are presented as photographs and sketches, as follows:

9.2.1 "Snapshots" Collection of Typical Flow Patterns

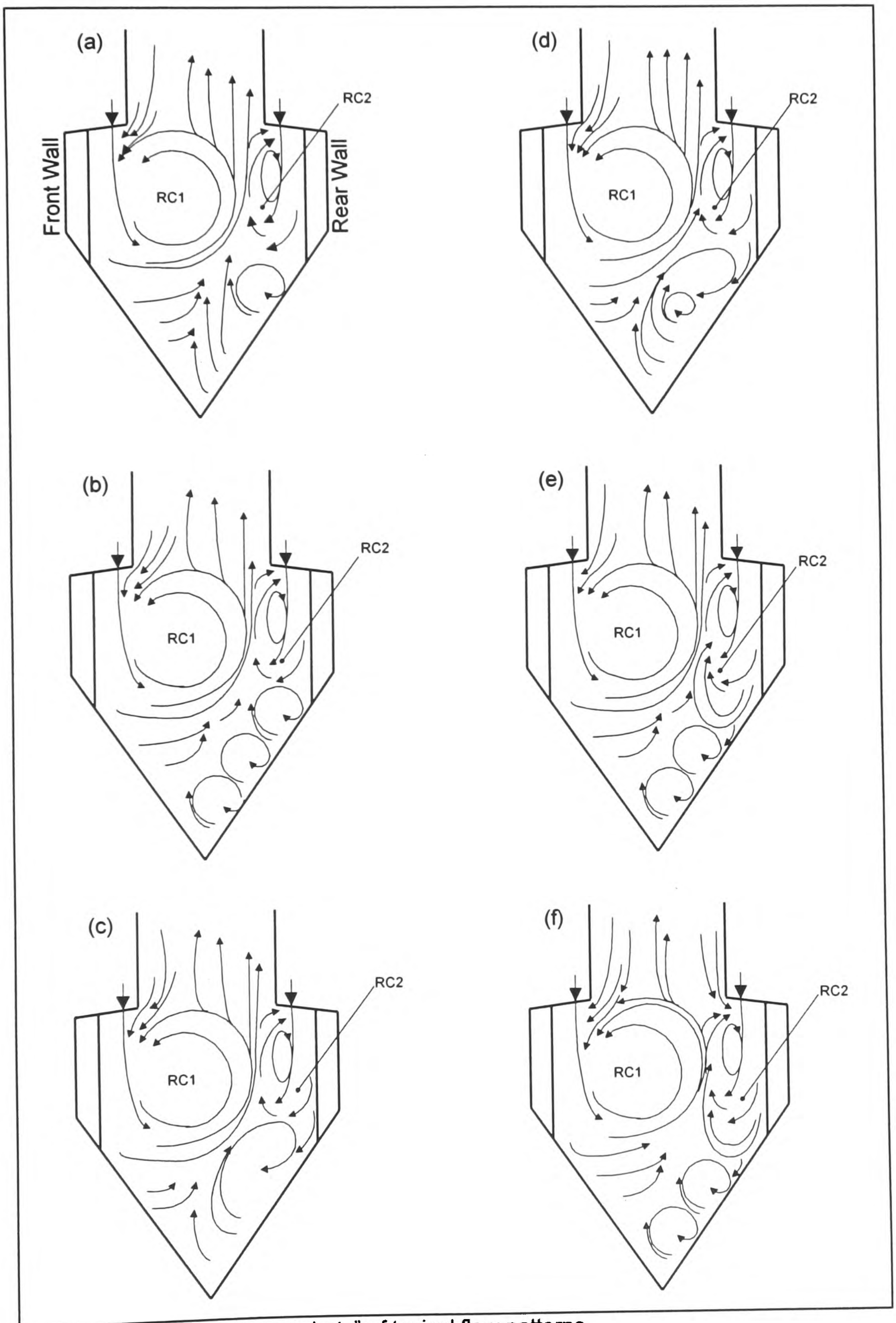


Fig. 9.1: Collection of "snapshots" of typical flow patterns.

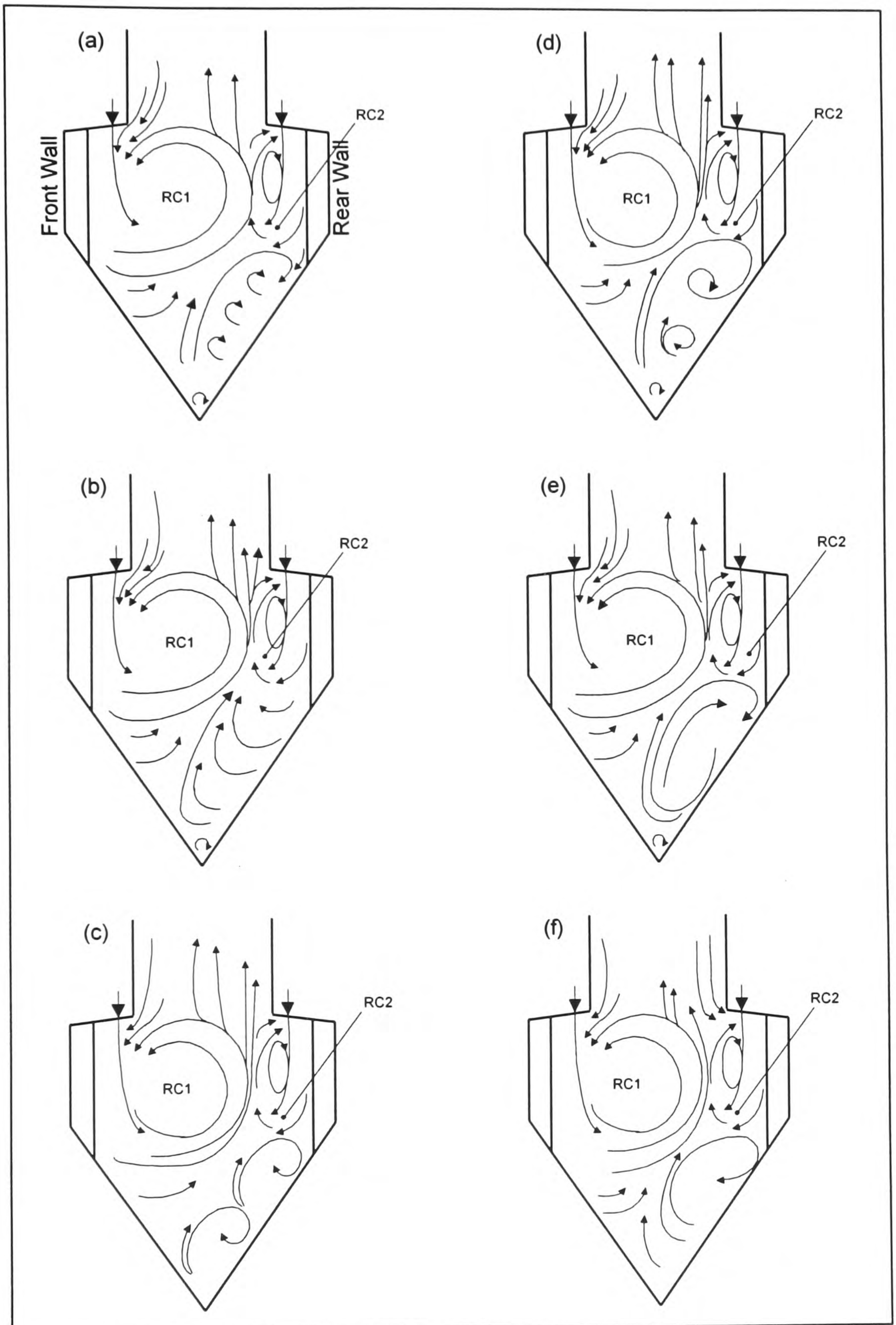


Fig. 9.2: Collection of "snapshots" of typical flow patterns.

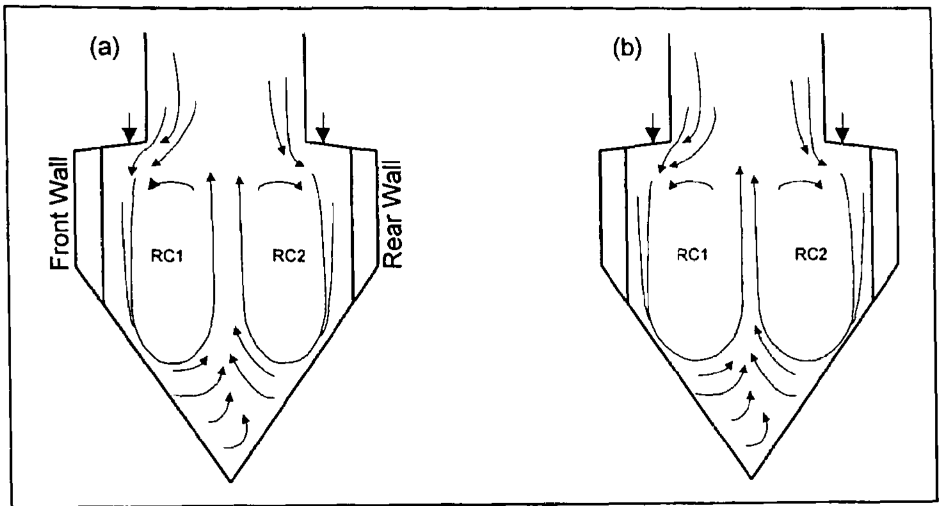


Fig. 9.3: Collection of "snapshots" of typical flow patterns.

9.2.2 Photographs

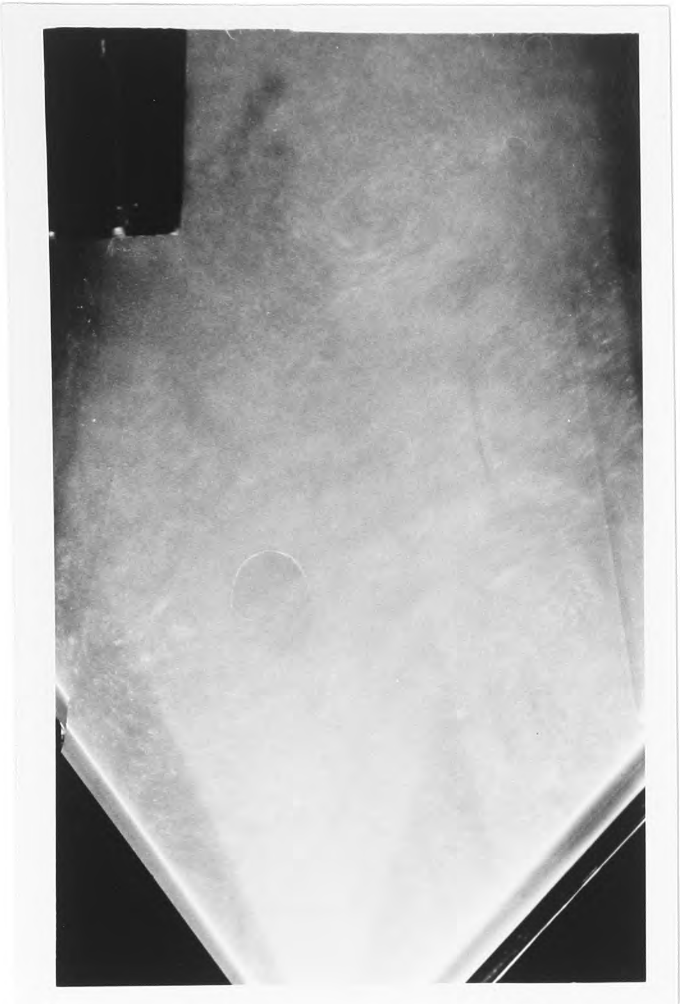


Fig. 9.4: Asymmetric flow pattern.

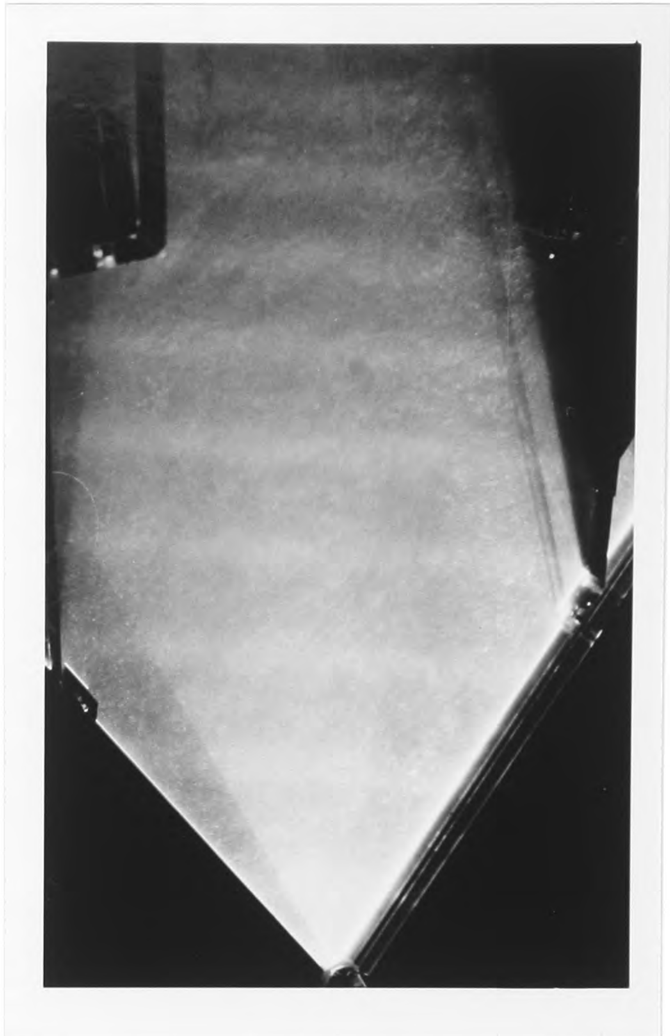


Fig. 9.5: Asymmetric flow pattern.

Fig. 9.6: Asymmetric flow pattern.

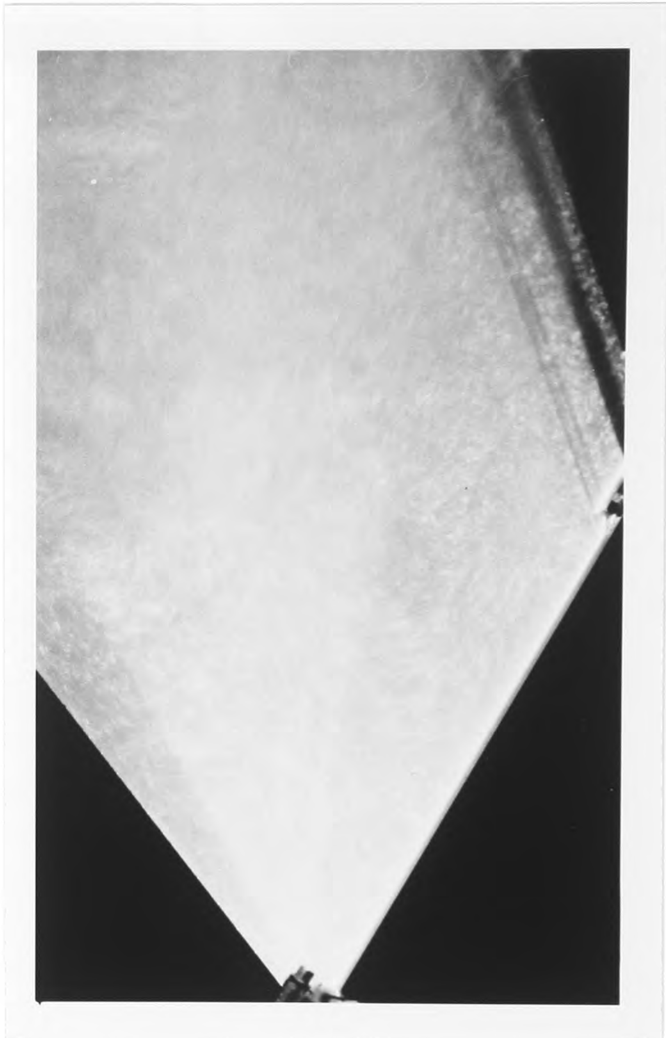


Fig. 9.7: Symmetric flow pattern.

Fig. 9.8: Turbulent flow pattern.

Fig. 9.9: Turbulent flow pattern.

10. DISCUSSION OF THE MODEL EXPERIMENTS

The analysis of the flows for the different firing patterns investigated showed no systematic variation. No difference was therefore observed in the overall furnace aerodynamics between high- (section 9.1.1) and low-NO_X (section 9.1.2 and 9.1.3) firing patterns nor between real and theoretical firing patterns. Furthermore, no differences along the furnace depth were found. Instead, all firing patterns investigated showed two main furnace flow patterns for any row of illuminated burners: a symmetric (or balanced) and an asymmetric (or unbalanced) pattern. It is therefore important to stress that both the snapshots collection (Figs. 9.1-9.3) and the photographs (Figs. 9.4-9.9) represent typical flow patterns of the various firing patterns investigated, that can occur anywhere along the furnace at varying points in time.

Predominantly the overall flow pattern was asymmetric (Figs. 9.1, 9.2, 9.4-9.6) and only occasionally for a very short period of time it became balanced or symmetric (Figs. 9.3, 9.7). Additionally, the asymmetric condition was extremely stable and showed no tendency to oscillate between the sides of the furnace.

Both symmetric and asymmetric patterns showed two distinct recirculating flows (RC1 and RC2) formed by the down-firing burner jets, one on each side of the furnace (front and rear side). Depending on the balance between these recirculating flows, the symmetry of the overall furnace flow was then determined.

In the case of the asymmetric flow pattern (Figs. 9.1, 9.2, 9.4-9.6), the front recirculating flow (labelled RC1 in the sketches) normally travelled anti-clockwise towards the centre of the furnace. Once in the centre of the furnace, part of the flow hit the rear firing arch, part exited the furnace and part returned to the front firing arch while dragging with it a small amount of flow that was already at the exit of the furnace. As a result of the last two movements, a small recirculating flow was sometimes created at the furnace exit, as shown in Fig. 9.4.
In general, the front recirculating flow was mainly located in the upper part of the furnace and did not travel towards the bottom of the furnace along the boiler front wall. On the other hand, the rear recirculating flow (labelled RC2 in the figures), normally extended from the burner jet to the bottom of the furnace. This resulted in a "curtain" of flow along the furnace rear wall, made up of various small recirculating flows. As the rear recirculating flow reached the furnace bottom, it reversed in direction and travelled upwards towards the exit of the furnace. At the exit of the furnace, most of the flow exited but part was dragged into the burner zone.

Occasionally, the two main recirculating flows (RC1 and RC2) became balanced, originating a symmetric furnace flow pattern (Figs. 9.3, 9.7). In these instances, deep penetration of the combustion flow towards the bottom of the furnace was clearly visible. Additionally, the amount of dragged flow from the exit of the furnace towards the firing arches, was well visible in both arches. This balanced pattern, however, was rare and very unstable lasting only for 3-5 seconds and finally returning to its original asymmetric state.

In other cases, the overall flow pattern was not defined being of complete turbulence (shown in Figs 9.8, 9.9). Such turbulent flow patterns corresponded to periods of transition between more stable symmetric and asymmetric patterns.

In general, both balanced and unbalanced flow fields, were in agreement with previous modelling work [136, 151, 152]. Additionally, plant tests [171] confirmed the consistently unbalanced flow patterns. Heat flux meters were installed on "B" side wall of no. 9 boiler at Aberthaw "B" power station to investigate the flame penetration within the furnace [171]. It was found that a state of unbalanced penetration existed between the front and rear burner arches at all loads. Furthermore, it was found that this asymmetric pattern did not exhibit preferential stability positions at either the front or rear of the furnace. Instead it appeared to be determined by the order in which burners were brought on load. This unbalance suggested that combustion was occurring in the upper regions of the furnace, which explained the high metal and steam temperatures being experienced at that time.

Entrainment of Recirculated Gases into the Firing Arches

Both patterns, balanced and unbalanced, illustrated a continuous entrainment of the recirculated gases into the burner jets of each firing arch. This entrainment is well documented in the literature [134, 138], being described as an essential factor in the combustion process in order to ensure ignition of the incoming coal as well as flame stability.

This recirculation of gas into the burner jets had two main origins: (i) from the two main recirculating flows, RC1 and RC2, well visible in all sketches (Figs. 9.1, 9.2, 9.3) and (ii) from the furnace exit, either on one side of the furnace only - normally the side of RC1 (Figs. 9.1(a-e), 9.2 (a-e)) or on both sides of the furnace (Figs. 9.1 (f), 9.2 (f), 9.3 (a-b)).

The Desirable Pattern

Clearly, the desirable pattern(s) would be the one(s) associated with the low NO_X tests performed on the plant. However, no difference in the flow patterns was found between the low-NO_X and high-NO_X firing patterns, as discussed above.

From the two main patterns found, the symmetric one would be the desirable pattern. This is because, it gives an even fuel residence time in the furnace, thus minimising CO and carbon in ash formation. Furthermore, it offers good furnace wall utilisation, reducing flame temperatures and consequently NO_X emissions, mainly thermal-NO_X. Unfortunately, however, such a flow pattern is difficult to maintain.

Nevertheless, solutions for a stable symmetric flow in the case of down-fired-furnaces have been presented by Anson [136] and Tucker [151]. Both authors state that better furnace proportions can ensure a stable balanced (or symmetric) pattern. Anson [136], showed that long furnace depths allow the formation of elliptic recirculating flows (as those in Figs. 9.3 and 9.7). Since these are not stable, they tend to reform and the final overall pattern becomes asymmetric (as those in Figs. 9.1, 9.2 and 9.4-9.6). Shorter furnace depths, however, allow shorter elliptic recirculating flows on each side of the furnace to be formed, thus originating a balanced pattern. Tucker [151], on the other hand, concluded from his water modelling work of an Aberthaw "B" furnace model that a wider furnace gave a deeper jet penetration than the width of the current 500 MW Aberthaw furnaces, resulting in a balanced pattern. The jets were penetrating into the ash-pit around 3 times deeper than in the narrow furnace (1.25 times narrower). According to Tucker, the narrow furnace caused an early interference between the opposing secondary flows, therefore creating unstable jet flow patterns.

11. CONCLUSIONS AND FURTHER WORK

This chapter summarises the conclusions as well as the proposed further work of the plant tests and modelling work. Additionally some overall considerations with respect to NO_X formation and low NO_X operation at Aberthaw are discussed.

11.1 Overall Considerations

The following general aspects can be concluded from the work at the power plant.

11.1.1 General NO_X Affecting Aspects to be Considered at Aberthaw

Before and during testing, a number of plant factors that possibly affect NO_X formation at Aberthaw were considered:

(a) Primary Air/ PF Ratio

The split of the output coal per mill between the burners must be as even as possible so that the correct air/PF ratio is achieved. This is because variations in the air/PF ratio can result in local thermal input unbalances as well as stoichiometric unbalances and stratification of the combustion products in the furnace. This contributes to high local CO and carbon in ash levels and finally NO_X. An even air/PF ratio is therefore required since it reduces the amount of CO and carbon in ash emissions as well as the oxygen levels required to compensate for the poor burnout. Consequently, NO_X emissions are also reduced.

As it is known, however, in coal-fired power stations the design of coal pipe systems from the mills to the burners often does not lead to uniform coal loadings at each burner. Variations of up to 50% have been documented in large units [68]. In addition to these design related problems non-uniform air/PF ratios can result from partially blocked pipes as well as from faulty or blocked burners.

Unfortunately, an even air/PF distribution is currently not achieved at Aberthaw: sudden rises in CO and carbon in ash levels were often observed when certain burners were brought into operation.

Burner performance is therefore not optimal and should be checked on a regular basis. Likewise the pipework between mills and burners ought to be checked regularly.

(b) Sootblowing

In order to fight slag, boilers are normally equipped with sootblowers in the furnace, in the superheaters and reheaters, as well as in the airheaters and sometimes in the economisers. Sootblowers keep the furnace tubes clean and by this means maintain boiler availability, lower the final flue gas temperature and consequently reduce chimney losses. This inevitably also contributes to a lower NO_X formation, in particular thermal NO_X. It is reported that changes in furnace wall conditions have been observed to produce 100 ppm difference in NO_X emissions from coal-fired boilers [64].

The boiler at Aberthaw was originally fitted with 52 sootblowers, but presently there are only four sootblowers in the furnace located near the platen superheater (top of the nose surface - cf. Fig A.1 in Appendix A), where some slag and dust deposit. Also, current operation of the plant specifies only one furnace sootblow per day. In theory, increasing the sootblowing frequency or fitting more sootblowers could be an option to reduce NO_X. Surprisingly, however, despite such low numbers of sootblowers and of sootblow operations, the boiler is reported not to be slagged. A possible reason for such a clean boiler may be that it is operated presently only during the day shift while it is normally shut down during the night shift. Most likely the slag falls off when the boiler cools down and its water and steam pipes contract. Therefore, negative effects on the NO_X emissions have to be expected if a permanent 24 hour operation should be required at some stage.

(c) Pulverised Fuel (PF) Quality

The pulverised fuel quality is not measured on-line at Aberthaw. PF quality is monitored by checking the average electrical current in the motors of the mills: if the average Ampere value drops, more steel balls are added to the tube mill.

In the past work was carried out on the mills by varying the amount of steel balls. The present operation of the mills is based on that work and is reported to be at its best. Presently the PF quality is:

- through the 200 BS mesh (75 μm): typically 78%, (according to plant specification: 91.8%).
- through the 52 BS mesh (300 μm): typically 1.5%, (according to plant specification: not greater than 0.5%).

It is important to note that an optimised PF fineness may result in lower NO_X emissions. As noted by Beer: "it is shown from experimental data that when the particle size of the pulverised fuel is reduced better use is made of the oxygen supplied by the mixing process [134]". Thus, In order to improve the pulverised fuel quality, it is recommend to use all mills to achieve as light a mill loading as possible.

(d) High Mill-Airheater Gas Inlet Temperatures

As the combustion gases exit the furnace, they enter the economiser to further heat up the feed water. They then flow into the mill- and main-airheaters to heat up the air for combustion before being discharged into the stack. However, at Aberthaw, the flue gases that flow into the mill-airheaters are bypassing the economiser, resulting in higher air temperatures to dry the coal in the mills. This flue gas bypass effect can be seen in table G.1 (in Appendix G), which shows a temperature difference of 100 K between mill- and main-airheaters gas inlet temperatures. If possible, such procedure should be avoided as higher combustion air temperatures can result in increased thermal NO_X formation.

11.1.2 Possible Side Effects of Low NO_X Operation at Aberthaw

Low NO_X operation, in particular staged combustion and/or low excess air combustion, can result in a series of potentially adverse effects to the boiler which need to be evaluated:

(a) Furnace Wall Slagging and Fireside Corrosion

Furnace slagging is of great importance not only in terms of NO_X emissions (see section 11.1.1(b)), but also in terms of boiler efficiency and availability. Under reducing (i.e. fuel-rich) conditions, the ash fusion temperature of most coals decreases by approximately 110 K [172]. Therefore, the ash melts quicker and is more fluid and sticky, fouling and slagging furnaces more easily. Fireside corrosion is then accelerated due to the increased slagging on the tube surfaces.

Fireside-corrosion, also known as fuel-ash- or high-temperature-corrosion, is the oxidation of steels by components of combustion products from fossil fuels. In an attempt to understand rates of corrosion with time, under normal firing and low NO_X combustion, short- and long-term studies have been carried out in the past [69, 172, 173, 174, 175, 176]. These studies utilised accelerated corrosion probes, corrosion test panels and ultrasonic furnace tube thickness measurement in order to estimate tube wastage. Unfortunately, the test results were inconclusive.

Therefore, the use of fuel-rich combustion at Aberthaw, in particular staged combustion, could pose a problem: will it result in reducing conditions?

It is known that the manner in which the secondary air is injected into the flame permits the walls to be oxidised during normal operating conditions [104, 133] (see section 4.1.2). Since during staged combustion the secondary air will still be injected into the flame in the same way, it is therefore likely that the walls will still be oxidised during staged combustion. This oxidisation of the walls, resembles the Foster Wheeler concept of "curtain of air" (or "boundary air system") aimed at inhibiting slagging and consequent corrosion associated with staged combustion. In the "boundary air system", boundary air enters the furnace through ports located in the furnace hopper and sidewalls, so that the walls are protected from potentially reducing conditions by a curtain of air. Additionally, this curtain of air prevents tube wastage, improves O_2 distribution which eliminates high CO concentrations in the unit, thus allowing lower O_2 operation and consequently lower NO_X emissions [80, 104, 177]. Due to these positive effects of air staging in this particular furnace design, it is therefore likely that increased furnace slagging or fireside corrosion can be avoided.

(b) Boiler Efficiency

Low NO_X operation such as staged combustion, results in a less intense combustion. This may in turn result in increased unburnt carbon levels, thus lowering boiler efficiency. On the other hand, an increase in boiler efficiency may be obtained with low excess air operation.

The boiler efficiency was calculated (see Appendix F) and the results were then used to evaluate the effects of low NO_X firing on efficiency. It was concluded that no significant changes in boiler efficiency occur when operating at low NO_X operation, as along as CO and carbon in ash are kept within the typical and acceptable limits for the Aberthaw plant (i.e. CO $\leq$ 200 ppm and carbon in ash between 10-13%).

Furthermore, previous studies have shown that boiler efficiency calculations comparing baseline and modified low NO_X operations indicate essentially no boiler efficiency penalty for the implementation of combustion modifications. This is due to fact that the increased carbon loss which results in the loss of boiler efficiency is compensated by the gain in boiler efficiency due to low excess air operation [69, 175].

(c) Particulate Emissions

Fuel-rich combustion can result in incomplete combustion, that is high CO levels and high carbon in ash emissions. This increase in CO and carbon in ash levels is then normally followed by an increase in particle emissions. In addition, the high amounts of carbon in the fly ash may in turn affect the precipitator performance, since precipitators efficiency is affected by high amounts of carbon in the fly ash. These problems, however, can be avoided as long as CO and carbon in ash are kept within acceptable limits, which for most coal-fired boilers are: CO $\leq$ 200 ppm and carbon in ash $<$ 5% for an excess air level of 15-20%[1]. As pointed out in [74], "with staged combustion and

[1] Normal carbon in ash levels at Aberthaw are however much higher, as discussed in chapter 7.

low excess air (...) carbon carryover and particulate loadings are no greater than normal operation only if the excess air is properly established and maintained (as required) for all loads, fuel types and boiler conditions".

(d) Flame Problems

Fuel-rich combustion can also result in flame stability problems. However, flame problems were not experienced during testing and on this basis are therefore not expected to occur at Aberthaw unit 7.

11.2 Conclusions

Although it was not possible to relate the experiences gained from the modelling work as closely as it was envisaged with those gained from the plant experiments, both parts of this work led to valuable results. The overall expectations and objectives of this project were therefore fulfilled as will be discussed in the following.

11.2.1 Modelling Work

The modelling results (in chapter 9) matched against the objectives, led to the following conclusions:

(a) Correlation between Plant and Model Experiments

A correlation between plant experiment results and observed flow patterns was not possible, since systematic flow variations could neither be observed for different firing patterns nor for different positions along the furnace depth.

(b) Investigation of the Flow Patterns

The modelling work was effective in showing the flow patterns and the direction of the flow. Two characteristic flow patterns could be distinguished - symmetric and asymmetric flow which occurred under all experimental conditions.

(c) Optimisation of Firing Patterns

Since no correlation between the plant experiment results and the associated flow patterns was obtained, the final objective (c), to optimise the firing pattern on the basis of the gained insights became obsolete.

As a general conclusion, the modelling work indicated that there is not a systematic flow pattern variation in the low- and high-NO_X conditions. This indicates that another mechanism other than flow patterns is responsible for the NO_X reduction. It may therefore be inferred that the NO_X reduction associated with the low NO_X patterns is due to local stoichiometry changes and/or heat release rate changes, which were not modelled in this study.

11.2.2 Plant Tests

The conclusions of the plant tests with respect to the objectives (in chapter 5) are:

(a) Identification of Low NO_X Operating Conditions

After defining the applicable boiler operating variables at Aberthaw Power Station, unit 7 (cf. section 5.2), the potential low NO_X operating conditions had been identified as:

- Lower Load
- Reduced Excess Air
- Air Staging (through damper settings)
- Burner Biasing
- BOOS in the Furnace Middle Chamber (BFMC)
- BOOS Across the Furnace Chambers (BAFC)
- Oil Burners In Service
- Combination of Combustion Modification Techniques

The expected influence of the load on NO_X emissions, however, could not be confirmed for the considered range of 420-500 MW. Likewise, the burner biasing turned out to be ineffective at Aberthaw. All other operating conditions were confirmed as having a reducing effect on NO_X.

Whereas most of the above techniques are known from literature and had to be selected and adapted according to the needs at Aberthaw, the applicability of oil burners as a NO_X control methodology emerged as a new finding of this project.

(b) Possible Extent of NO_X Reduction

The possible extent of NO_X reduction varies between the different NO_X control methodologies as it was discussed in detail in chapter 7. The optimal NO_X control methodology turned out to be a combination of oil burners with excess air and air staging, yielding *minimum NO_X levels* in the range of 385-450 ppm. This technique was particularly successful since it ensured also very low *minimum carbon in ash levels* (11-11.5%), as well as low CO levels. Hence, these results stress the importance of this novel NO_X control approach.

Despite the success of the various experiments at Aberthaw, the New Plant Standards NO_X limit of 317 ppm could not be achieved. Nevertheless, it is important to note that the volatile content of the coal burnt in Aberthaw is only just above the 10% level, for which the New Plant Standards require to comply only to a maximum limit of 634 ppm (cf. chapter 2, section 2.5).

(c) Recommended Operational Guidelines (NOx Control by Operational Adjustments)

The recommended application of the NO_X control techniques in unit 7 at Aberthaw Power Station is as follows:

Excess Air

- The boiler should be operated at low excess air levels, which must be guided by the maximum CO limit (= 200 ppm). It is important to note that low excess air operation requires careful attention by the operator in order to ensure safe operation.
- For maximum NO_X reduction, low excess air operation should be used in combination with other combustion modification techniques.

Air Staging

- Air staging is not a particularly efficient NO_X control methodology when applied on its own. For maximum NO_X reduction, however, air staging (damper setting 2 or (iii)) should be used in combination with other combustion modification techniques.

Burner Biasing

- Burner biasing has no effect on NO_X emissions and should therefore not be applied.

BOOS in the Furnace Middle Chamber (BFMC)

- The operator must operate the burners in the furnace in a such a way that both CO and carbon in ash levels are minimised (some burners tend to give a lot of CO and carbon in ash formation).
- Recommended number of BOOS in the middle chamber at 500 or 420 MW: 5-6 BOOS. This number ensures a good NO_X reduction whilst ensuring combustion efficiency.

BOOS across the Furnace Chambers (BAFC)

- As above with BFMC, the operator must operate the burners in the furnace in a such a way that both CO and carbon in ash levels are minimised.
- Recommended number of BAFC at 500 or 420 MW: a maximum number of BOOS should be used whilst ensuring that CO and carbon in ash levels are within acceptable levels and that the generated load is maintained. This number can vary from 9-11 BOOS.

Oil Burners Effect

- In general 12 oil burners in service are enough to reduce NO_X emissions significantly. Further oil burners can be taken into operation as needed to achieve a certain low NO_X level.

Combination of Combustion Modification Techniques

- Only the combination of combustion modification techniques yields satisfactory results. The most effective combinations are:
  - Excess air + Oil Burners Effect + Air Staging ("Set A")
  - Excess air + BAFC + Air Staging ("Set A")
- For the operation of the combined techniques, the individually discussed recommendations (above) should be followed.

General Guidelines

- Regular inspections of the combustion performance of each burner would contribute significantly to an effective and consistent NO_X reduction.
- It is recommend to use all mills in order to achieve as light a mill loading as possible. The optimised PF fineness may contribute to lower NO_X emissions.
- In order to reduce maldistributions of air/PF ratio to each burner, the pipework between mills and burners should be checked on a regular basis.

11.3 Further Work

Both the modelling work and the plant tests presented in this thesis show scope for various extensions:

11.3.1 Further Modelling Work

As discussed, the modelling work showed no differences in the flow fields between the various firing patterns. In practice, however, the heat release pattern would differ between the BOOS and normal operation cases. Additionally, the mixing between fuel and air would also play a significant role. Nevertheless, the 3D model may be particularly useful in providing additional information on such flow fields and mixing processes. Further work is therefore recommended in the following areas:

- During this work, the model was run in a closed loop with all the water seeded. Further work should therefore include seeding the primary flow only (primary air and fuel flow), in order to investigate the flame shape and structure, as well as the mixing between fuel and air. Provisions should be made to sieve this primary tracer in order to avoid its saturation in the water. The study of this primary flow should be carried out from a front view and longitudinal perspective, thus providing a deeper understanding of the flow and flame field.

- With the help of computer based image analysis systems, velocimetry data may be inferred from processing of photographic data. Furthermore, mixing rates can be inferred from intensity variations.

- LDA measurements can be taken to obtain mean velocity data.

- Further investigations could be conducted to determine the flow structure with:
  (a) Variation of air ratios between secondary and tertiary flows, and
  (b) Variation of secondary air split down the furnace side walls.

11.3.2 Further Plant Tests

The results of the tests showed that there are a variety of ways to reduce NO_X emissions without adversely affecting boiler operation. In order to answer the further questions which are prompted by these results, the future extensions of this work should focus on the following aspects:

1. Additional short-term tests to confirm the results obtained through this work. The individual aspects to be further investigated with respect to each of the NO_X control methodologies was detailed in the notes on further work in chapter 7.

2. Long term tests of the NO_X reducing techniques should be carried out at Aberthaw unit 7 in order to:

(i) fully explore the potential of wall corrosion and slagging.

(ii) acquire and evaluate more data on the efficiency of the NO_X control metrologies at Aberthaw found to be most effective in this project. In particular statistical analyses of the measurements could give an idea of the certainty of achieving specific NO_X levels.

3. Due to the limited data the comparison between different types of coals was inconclusive. Further tests with different coals should therefore be carried out under comparable operating conditions.

4. Detailed investigations of the novel NO_X control methodology based on oil burners in service, which was introduced in this work, ought to be carried out.

APPENDIX A - DESCRIPTION OF ABERTHAW 'B' BOILER AND PULVERISED FUEL SYSTEM

A.1) The Boiler

Aberthaw 'B' has three pulverised fuel natural circulation water-tube boilers (units 7,8, and 9), each designed to steam a 500 MWe turbo-generator. The boilers are top supported from the main boiler house steelwork, to allow for expansions. Each boiler is a single-drum reheat boiler with water wall tubes which form two box like compartments, the furnace and the rear enclosure or heat recovery area. The rear enclosure is divided into a reheater main and bypass section by a water division wall parallel with the rear wall. The boiler arrangement can be see in Fig. A.1.

(i) The Down-fired-furnace

In order to burn the local low volatile coal (semi-anthracite), the down-fired-furnace is used. Aberthaw is the only power station in UK with this type of furnace. These furnaces have a characteristic W-flame shape, which results in a long particle residence time necessary to complete combustion of the low volatile coal. Around 40% of the total air (primary and tertiary air) is provided at the burner and is projected downwards from the arch towards the furnace bottom. The remaining 60% (secondary air) is fed into the flame through multiple ports arranged in the boiler sidewall [132]. Total combustion air is drawn from the outside by FD fans (secondary and tertiary air) and PA fans (primary air).

The design of each boiler incorporates 36 burners, 18 of which are in the front arch and 18 in the rear arch. There are 6 double-end-tube-ball mills per boiler each supplying a total of 6 burners. Mills A and F groups supply burners at the rear of the boiler, C and D at the front and B and E mills are distributed diagonally across the firing arches.

(ii) Combustion Air Dampers

In order to supply combustion air to the 36 burners, secondary and tertiary air is taken from 24 windboxes in the plenum chambers, 12 of which supply single burners with the remaining 12 supplying two burners (shared windbox). This secondary and tertiary air supply is controlled by remotely operated dampers in the control room. It is important to note, however, that in a shared windbox when only one burner is firing there are no means to isolate the air supplies to the other burner. In addition

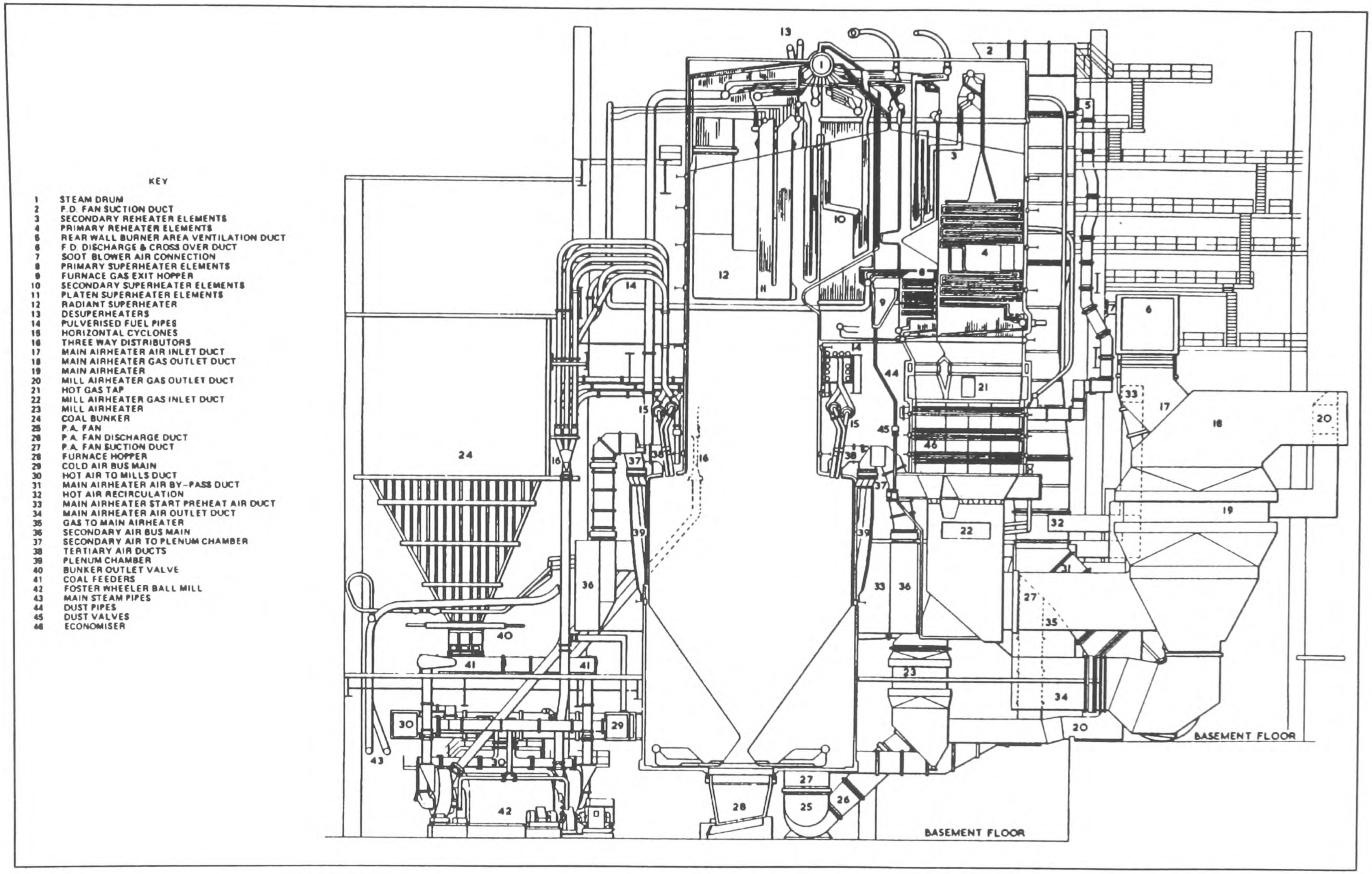


Fig. A.1: Aberthaw Boiler Arrangement [101].

to the remote dampers, there are local dampers that determine the subdivision of the secondary air between the top, middle and bottom stages in the plenum chamber.

(iii) Oil Burners

Each pulverised fuel burner is provided with an adjacent oil torch for light-up and flame support purposes (shown below Fig. A.2). At full load (500 MWe) there are no oil burners in service, however at loads below 400 MWe, there are a minimum of twelve oil burners in service as a safety precaution. Each oil burner comprises their own air supply, atomiser and igniter (by propane). The oil operating temperature at the burners ranges from 104-113°C, (heavy oil).

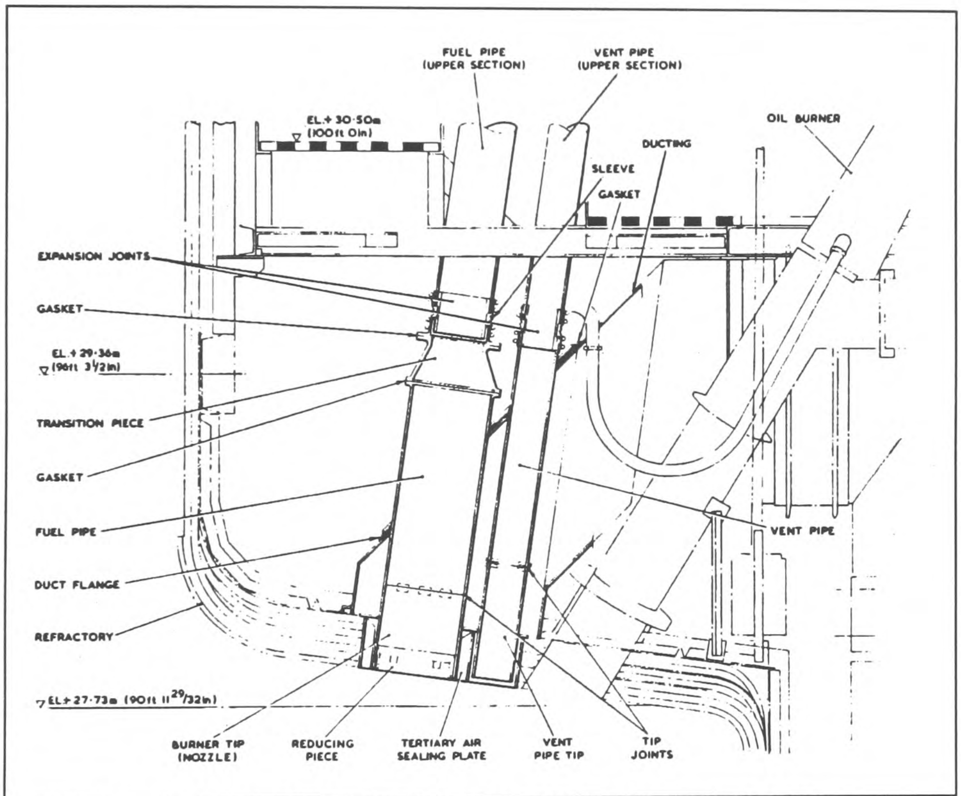


Fig. A.2: Arrangement of Pulverised Fuel and Oil Burner Nozzles [101].

(iv) Steam Temperature Controls

Control of the superheater outlet temperature is by the injection of steam atomised spray water between the platen and secondary superheater sections. Control of the reheat steam temperature is by regulating the flow gas bypassing the reheater.

(v) Airheaters

As the combustion gases leave the furnace, they flow into the economiser and pass through the two main-airheaters and two mill-airheaters to heat up the air for combustion, before being discharged to the chimney via the precipitators and ID fans.

In the main-airheaters, the combustion air supplied by the FD fans is heated and delivered to each burner as secondary and tertiary air. On the other hand, the mill-airheaters receive the air discharged by the PA fans (primary air) where it is heated, after which it is passed into the mills for drying and delivering the pulverised fuel to the PF burners at the desired temperature.

A.2) The Pulverised Fuel (PF) System

Each boiler has one PF system which consists of 6 mill groups. This system receives raw coal from the bunkers for pulverisation, to latter supply the PF burners. Each mill group supplies six burners and consists of a bunker outlet gate, two coal feeders, the mill, the classifier, dampers, the PA fan and coal/air distribution pipes. A diagram of the PF system arrangement can be see in Fig. A.3.

(i) The Mills

The mills are of the pressurised double-end-tube-ball type. Each coal feeder supplies a regulated amount of coal to its mill located below it. The coal drops from the feeder outlets and enters each end of the mill through the classifier. Each mill is a ball mill with a rotating drum within which the coal is crushed by steel balls as the drum rotates. A standby mill is supplied as full load is possible with only 5 out of the 6 mills running.

The level of coal in each mill is maintained by varying the speed of the associated pair of coal feeders. Mill output is controlled by varying the primary air flow to the mill.

(ii) Primary Air

Primary air (15% of the total combustion air) enters the mills through the classifier at each end at a controlled rate and at a temperature of 270 to 300°C. The hot primary air dries out the coal for successful grinding, and carries the ground coal particles in suspension to the classifier. After passing through the classifier, the air/coal mixture flows to the PF burners. Oversize particles rejected by the classifier are returned to the drum with the raw coal. For efficient combustion the air/coal mixture fed to the burners must be at a temperature of 93°C (by design).

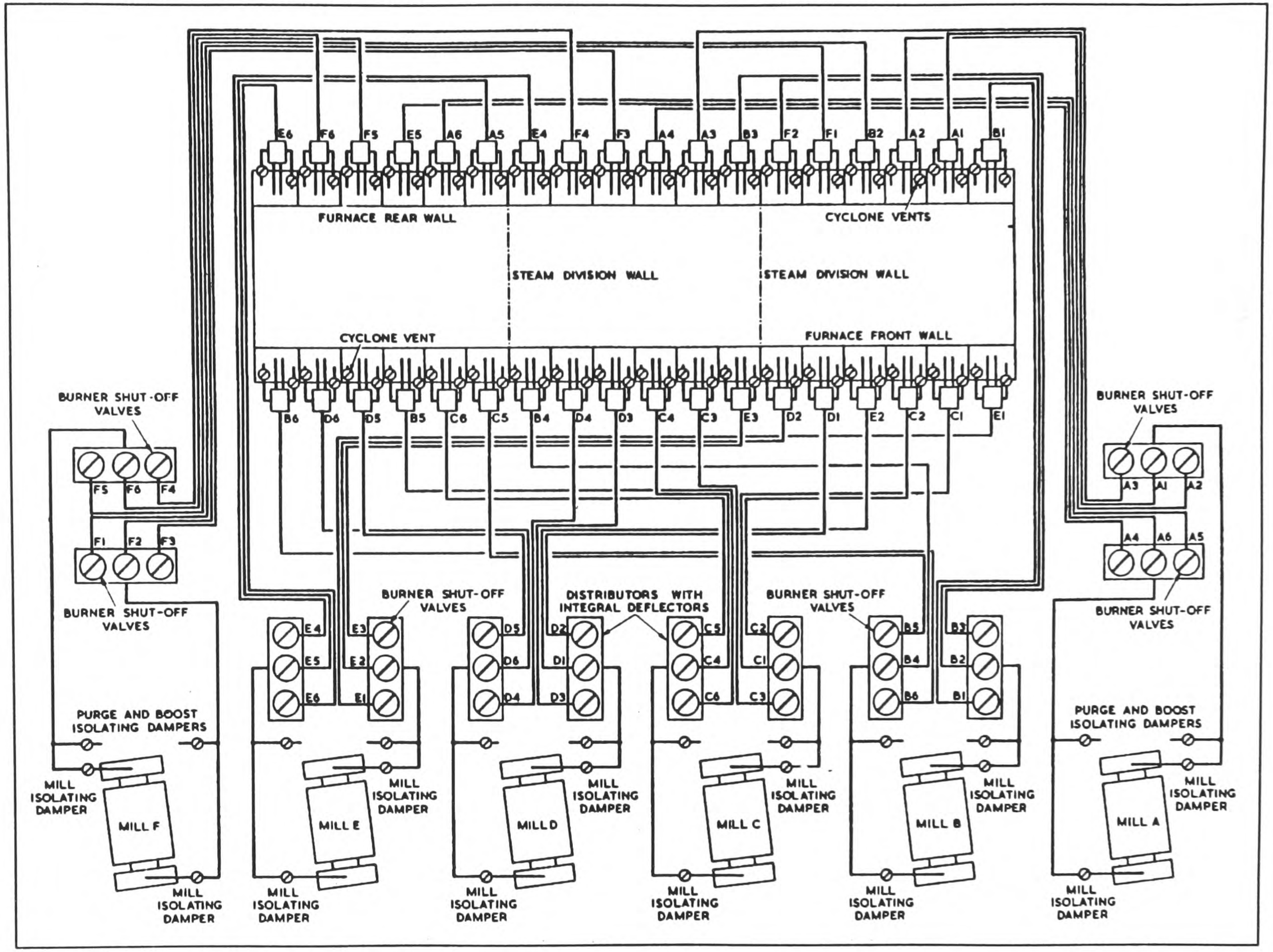


Fig. A.3: Connection Between Mills and Pulverised Fuel Burners [101].

APPENDIX B - NORMALISATION OF EMISSIONS

B.1) NO_X Emissions Normalisation

The term NO_X covers all the oxides of nitrogen. An analyser capable of monitoring all types of NO_X would be extremely complicated and costly, therefore analysers only measure NO.

According to the Environmental Protection Act [7], the NO_X value to be monitored should be the concentration of NO alone to which is then added an agreed increment (5%), to represent the appropriate proportion of NO_2. Presently the oxides of nitrogen of most concern are NO and NO_2, therefore it has been established by analysis that NO_X emissions are made up of 95% NO and 5% other oxides (mainly NO_2).

NO_X levels at the power station are measured as wet and at a varying oxygen level. According to the current legislation, NO_X emissions have to be standardised to a dry condition, 6% O_2, 273 K and 101.3 kPa. To normalise the NO_X levels the equations used were:

(i) Correction for 5% NO_2

$$ppm(corrected) = ppm(measured) \times 1.05$$ **Eq. B.1**

(ii) Correction for Water Vapour

$$ppm(dry) = \frac{100 \times ppm(wet)}{100 - \%H_2O}$$ **Eq. B.2**

Note: "% H_2O" is percentage by volume of the H_2O in the flue gases.

(iii) Correction to 6% O_2

$$ppm(corrected) = ppm(measured)\frac{20.95 - \%O_2(standard)}{20.95 - \%O_2(measured)}$$ **Eq. B.3**

Note: "%O_2 standard" is 6% for coal.

(iv) Correction for Temperature and Pressure

The instrument takes the readings at standard conditions of pressure and temperature - 101.3 kPa and 273 K.

B.2) CO, O2 and Carbon in Ash Correction

CO and oxygen are measured as wet, therefore they must be corrected for water vapour in the flue gas.

The carbon in ash value (designated carbon in grit at the power plant) obtained from the Operational information system (OIS) is not a true representation of the resultant fly and coarse ash from combustion. Since carbon in grit is only measured on one side of the boiler it does not take into account of stratification that exists in the boiler and it is only a representation of the fly ash. It must, therefore, be corrected.

Here, an assumption based on normal boiler operation has been employed to correct the value.

Given that a boiler normally produces 80% fly ash and 20% coarse ash and assuming that at Aberthaw the coarse ash is about 20%, the carbon in ash value has been corrected as follows:

$$CinA = \frac{(80\% \times cig\%) + (20\% \times 20\%)}{100} \qquad \textbf{Eq. B.4}$$

APPENDIX C - MODEL DRAWINGS

This appendix contains the drawings required for the design and construction of the 3D Aberthaw model. The drawings contained in this section are:

Fig. C.1: Aberthaw boiler model.

Fig. C.2: Sectional view of the boiler furnace.

Fig. C.3: Sectional view of the boiler upper section.

Fig. C.4: Detail of the burner blocks.

Fig. C.5: Secondary air baffle plates for secondary air split down the furnace side walls, (boiler wing plates).

Fig. C.6: Wing top hole details.

Fig. C.7: Boiler flange.

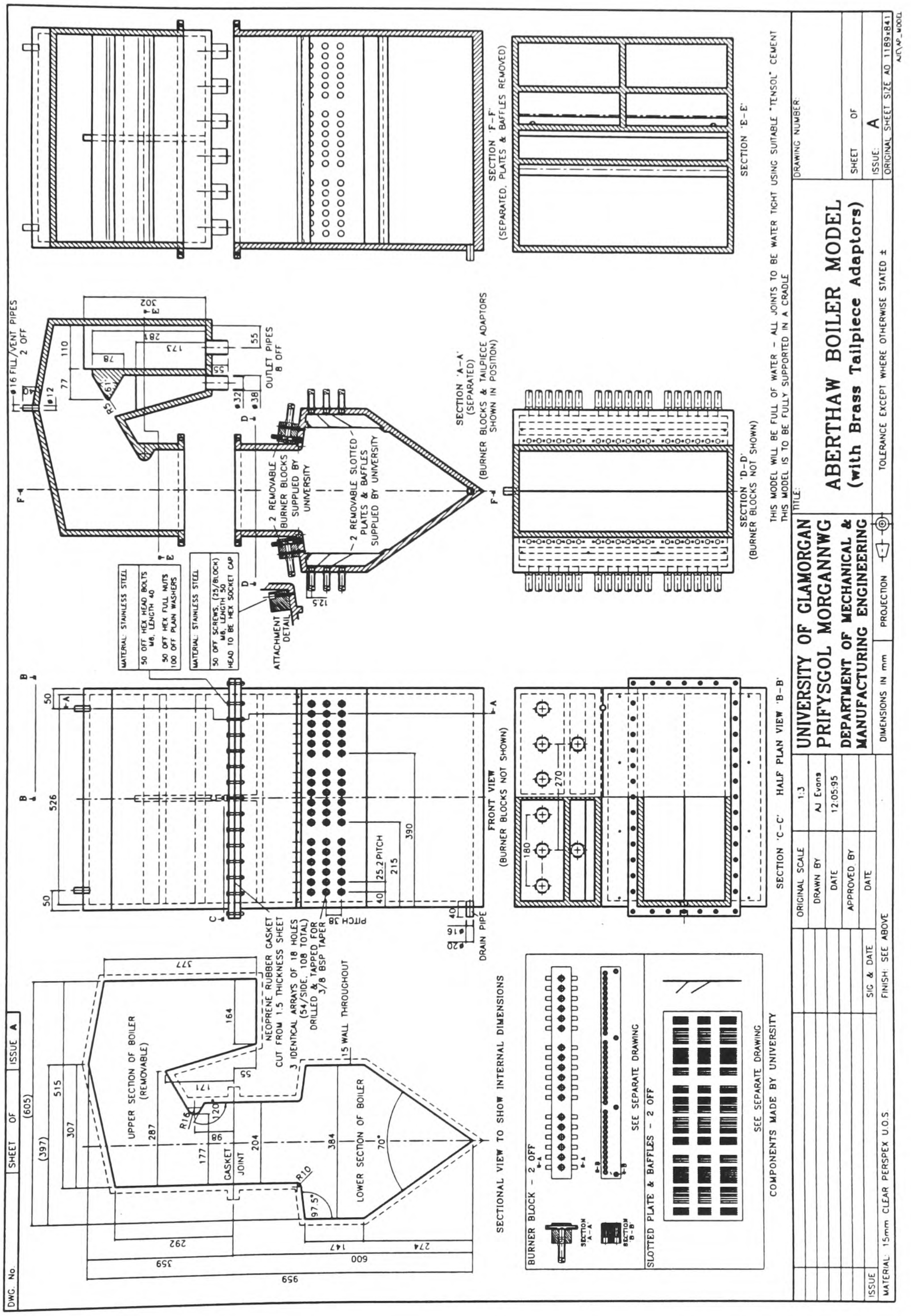


Fig. C.1: Aberthaw boiler model.

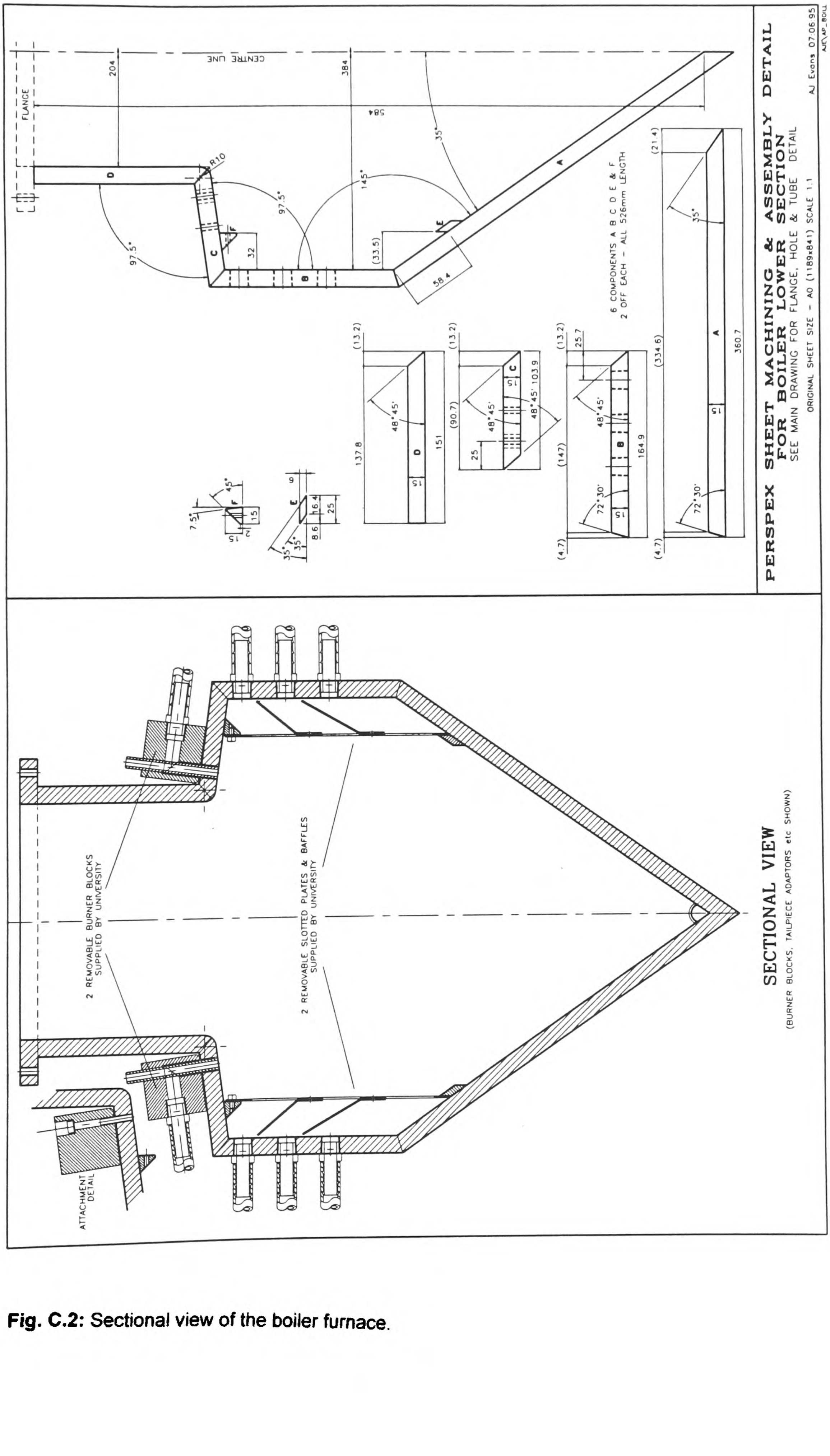


Fig. C.2: Sectional view of the boiler furnace.

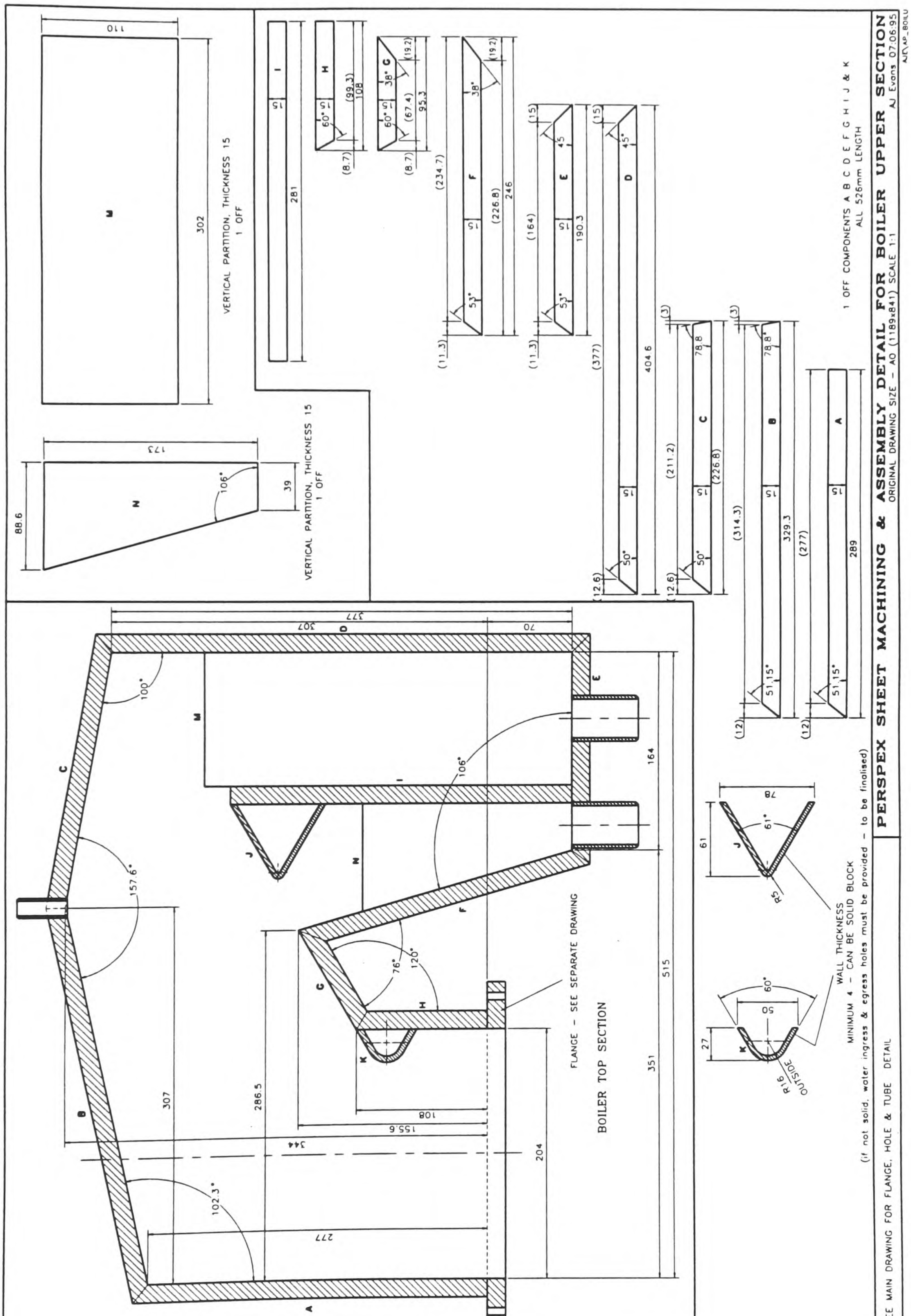


Fig. C.3: Sectional view of the boiler upper section.

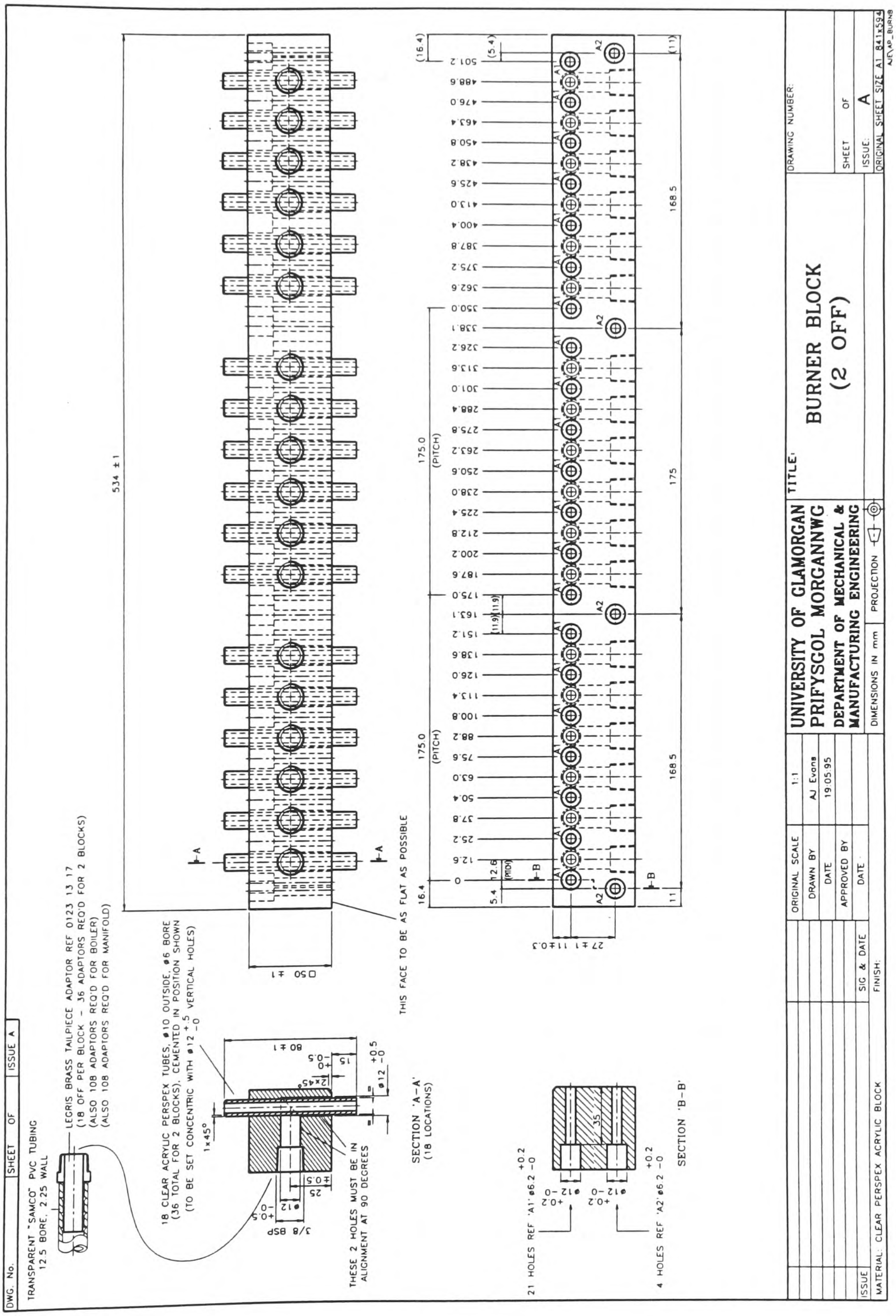


Fig. C.4: Detail of the burner blocks.

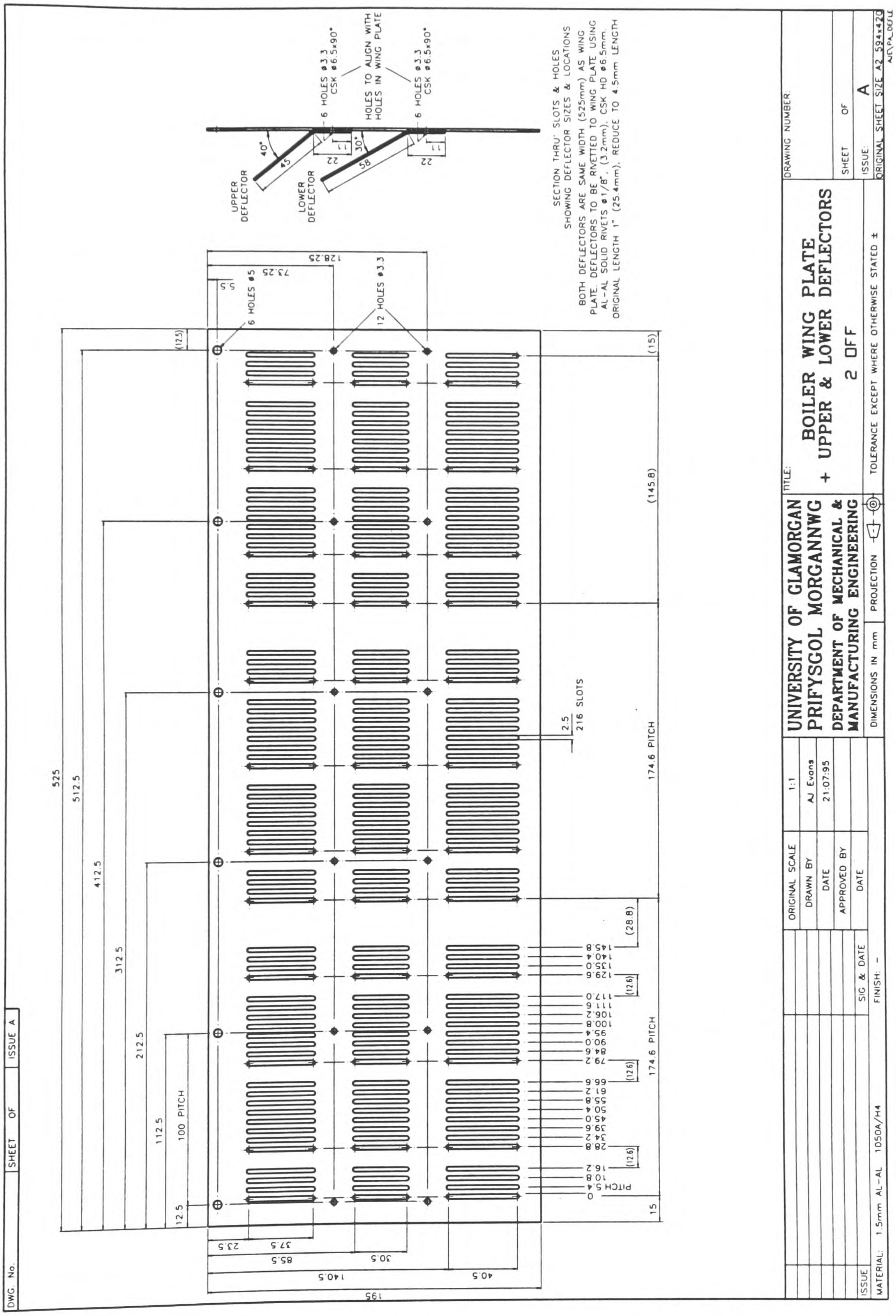


Fig. C.5: Secondary air baffle plates for secondary air split down the furnace side walls, (boiler wing plates).

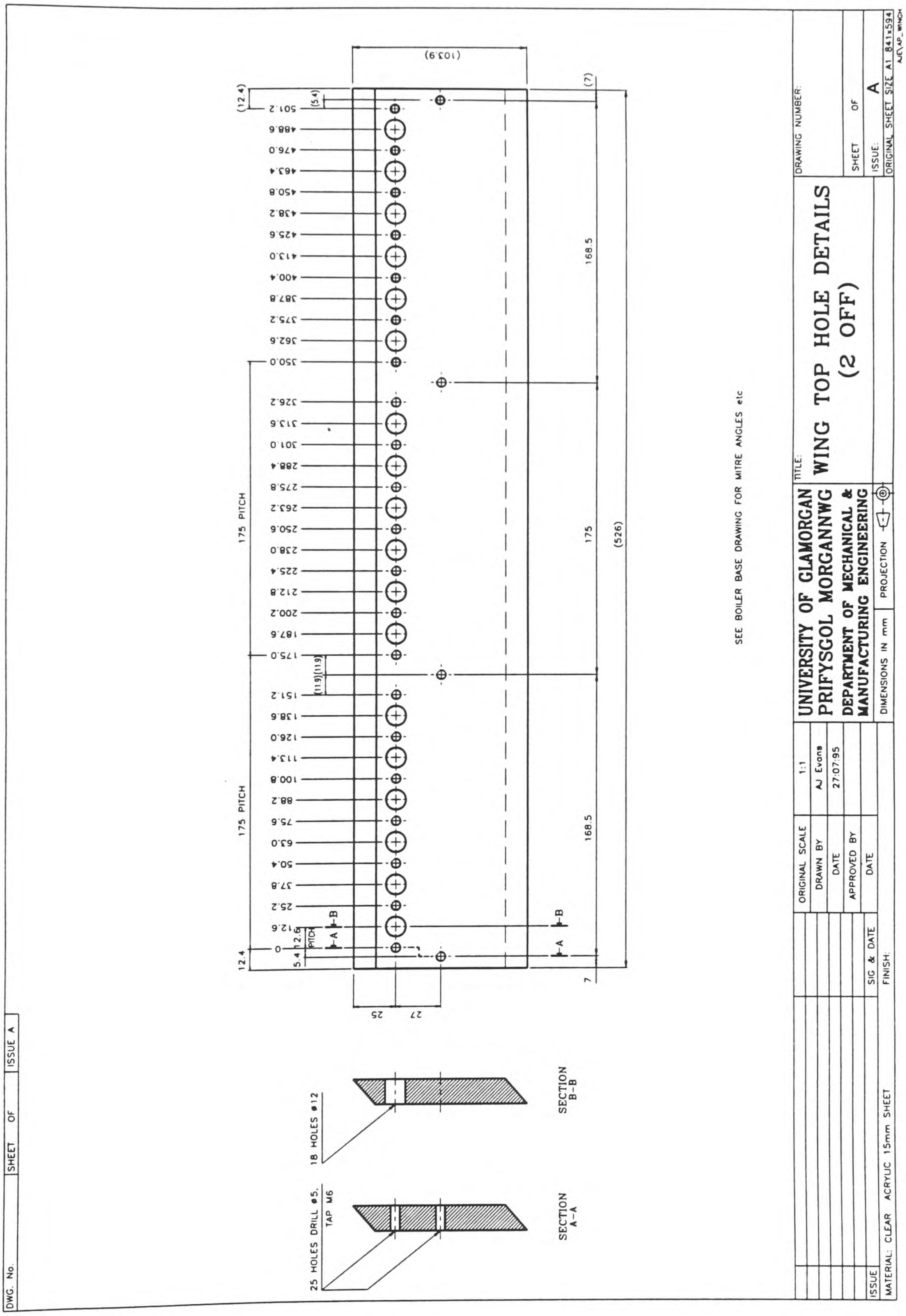


Fig. C.6: Wing top hole details.

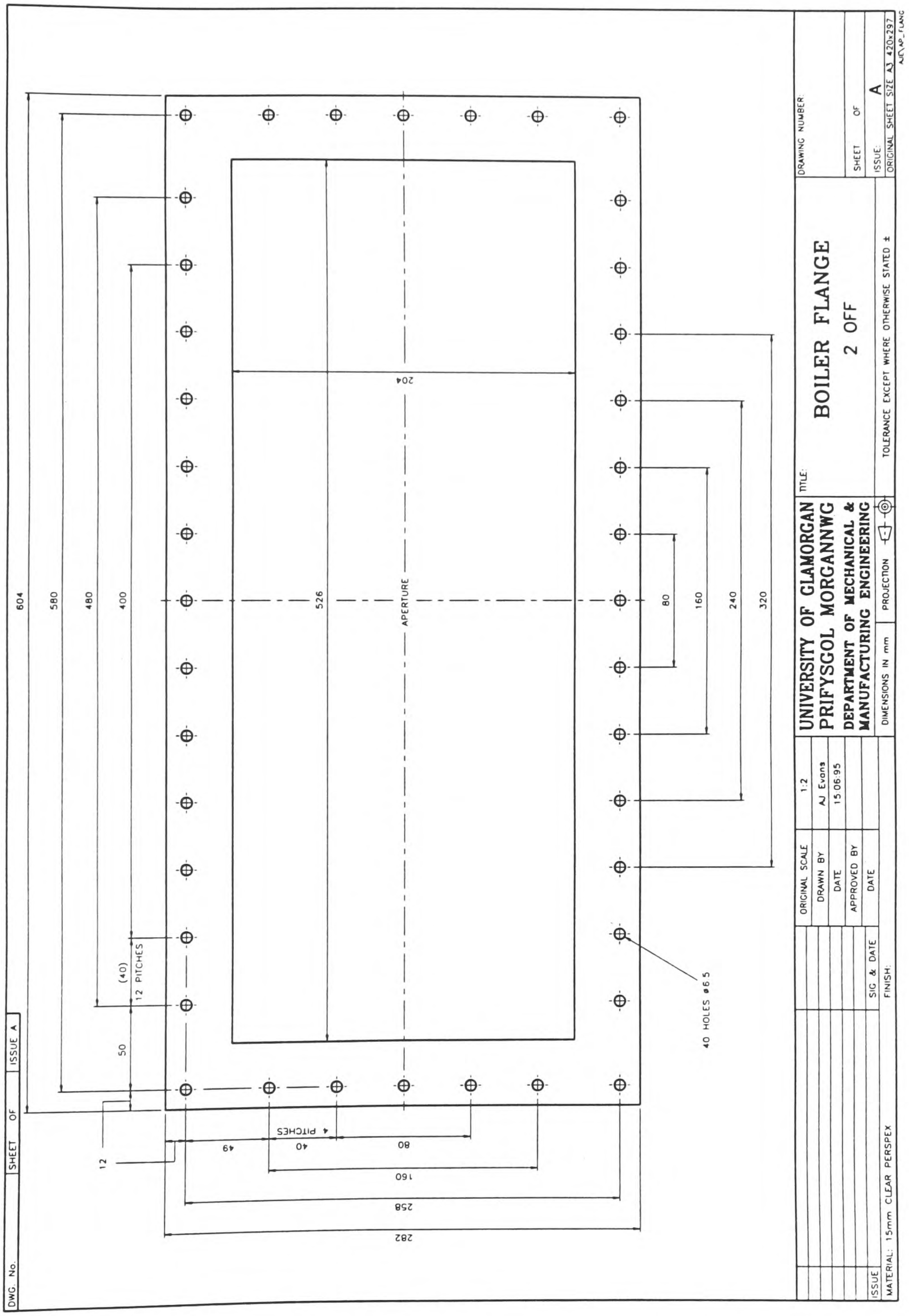


Fig. C.7: Boiler flange.

APPENDIX D - POWER PLANT AND MODEL DATA

D.1) Plant Data

(i) Combustion Air and Coal Flow Rates

From power plant data [101]:

- Coal flow rate (m_c) = 52 kg/s, at 87 °C
- Primary air flow rate (m_{pa}) = 73 kg/s, at 87 °C
- Secondary plus tertiary air flow rate (m_{sa+ta}) = 458 kg/s, at 250 °C

The air flow split between secondary and tertiary air is not known in the plant. However reference [132] states that in this boiler, 40% of the total air (primary and tertiary air) is provided at the burner with the remaining 60% (secondary air) being fed into the flame through multiple ports arranged in the boiler sidewall. With this information and with the values above from [101], the individual air flows were then calculated as follows:

- Total air flow (m_{TA}) = (458 + 73) = 531 kg/s
- Secondary air flow rate (m_{sa}) = 531 x 60% = 318.6 kg/s
- Tertiary + primary air flow rate (m_{ta+pa}) = 531 x 40% = 212.4 kg/s

but primary air flow rate (m_{pa}) equals 73 kg/s, therefore:

- Tertiary air flow rate (m_{ta}) = 212.4 - 73 = 139.4 kg/s

(ii) Properties of Combustion Gases

The calculations of density and dynamic viscosity values for the combustion gases were based on an average temperature. Although temperatures in furnaces vary considerably, a representative temperature is generally sufficient for the purpose of Reynolds number calculation in isothermal modelling [163].

Therefore, in this work the average absolute temperature at the throat of the furnace (location immediately at the exit of the combustion chamber) was assumed to be 1900 K. Furnace pressure was assumed to be atmospheric, as the normal operating pressure is near atmospheric (usually -2 to -5 mbar sub-atmospheric).

Density and dynamic viscosity values of the combustion gases were obtained from tables [178] as air. This is a reasonable assumption since the constituents of combustion gases are mainly N_2 (around 75%) and the values for air can be used with reasonable accuracy for CO, N_2 and O_2 as pointed out in [178].

The resulting density and dynamic viscosity values for combustion gases at 1 atm are:

- Density (ρ_{cp}): = 0.1858 kg/m^3
- Dynamic viscosity (μ_{cp}): = 6.008 x 10^{-5} kg/ms

(iii) Densities of Coal and Combustion Air

- Coal density (ρ_c): = 450 kg/m^3 [179]
- Primary air density (ρ_{pa}): = 0.98192 kg/m^3, calculated from [178]
- Secondary air density (ρ_{sa}): = 0.6764 kg/m^3, calculated from [178]
- Tertiary air density (ρ_{ta}): = 0.6764 kg/m^3, calculated from [178]

(iv) Areas

- Burner area (primary air + coal) per burner, (A_{pa+c}): = 6.514 x 10^{-2} m^2
- Throat area, ($A_{(throat)p}$): = 247.2 m^2
- Equivalent diameter (width of the furnace exit), (d_p): = 9.792 m
- The secondary air area varies in each of the three different stages, as shown in Appendix C (Fig. C.5). Also note that in each stage of secondary air flow there are four slots per burner, therefore the secondary air flow areas for each stage were calculated per slot and then multiplied by 4 as shown:

  Secondary air area per burner, 1st stage, (A_{sa1}): 4 x (2.2731 x 10^{-1}) m^2
  Secondary air area per burner, 2nd stage, (A_{sa2}): 4 x (1.8699 x 10^{-1}) m^2
  Secondary air area per burner, 3rd stage, (A_{sa3}): 4 x (2.4459 x 10^{-1}) m^2
- Tertiary air area per burner (A_{ta}): 7.9621 x 10^{-2} m^2

Note: This work aimed at the study of flow patterns in the furnace. Therefore the chosen equivalent diameter for the purpose of Reynolds Number calculation was the "throat" of the furnace. The "throat" of the furnace corresponds to the exit of the combustion chamber, with a width in the model of 204 mm. See Appendix C (top LHS of drawing C.1).

(v) Combustion Gases Flow Rate

The flow rate of the combustion gases can be calculated either on a mass or volumetric flow rate, as shown below. The velocity at the throat of the furnace is also shown:

Mass Flow Rate

$m_p = m_{TA} + m_c$

$m_p = (73 + 458) + 52$

$m_p = 583$ kg/s

Volumetric Flow Rates

$Q_p = (m_{TA} / \rho_{cp}) + (m_c / \rho_c)$

$Q_p = ((73 + 458) / 0.1858) + (52 / 450)$

$Q_p = 2858$ m^3/s

<u>Velocity Calculation</u>

$Q_p = (m_p / \rho_{cp}) = (583 / 0.1858) = 3137.8\ m^3/s$

$V_p = Q_p / A_{(throat)p} = (3137.8 / 247.2) = 12.7\ m/s$

<u>Velocity Calculation</u>

$V_p = Q_p / A_{(throat)p} = (2858 / 247.2) = 11.56\ m/s$

D.2) Model Data

(i) Water Properties

The water flow was assumed to be at a temperature of 20 °C, therefore:

- Density (ρ_m): = 1000 kg/m^3 [178]
- Dynamic viscosity (μ_m): = 10^{-3} kg/ms [178]

(ii) Areas

- Burner area (primary air + coal) per burner, (A_{pa+c}): = $2.8274 \times 10^{-5}\ m^2$
- Throat area ($A_{(throat)m}$): = $0.1073\ m^2$
- Equivalent diameter: = 204×10^{-3} m

APPENDIX E - MODELLING CALCULATIONS

E.1) Reynolds Number Similarity

In theory similarity between flow patterns is achieved when:

$$\mathrm{Re}(model) = \mathrm{Re}(plant) \qquad \textbf{Eq. E.1}$$

To satisfy the above equation, the model must therefore operate with a total water flow rate that gives the same Reynolds number as the hot gases in the furnace. However, as it can be seen from the following calculations, the amount of water flow rate required to satisfy Eq. E.1 is "impractical". From Eq. E.1:

$$\frac{\rho_m \times d_m \times V_m}{\mu_m} = \frac{\rho_p \times d_p \times V_p}{\mu_p} \qquad \textbf{Eq. E.2}$$

where,

ρ is the density of the fluid measured at temperature T;

d is the equivalent diameter of the section under consideration;

V is the velocity of the flow through the section under consideration;

μ is the dynamic viscosity of the fluid measured at temperature T;

(subscripts p and m refer to plant and model conditions respectively)

Rearranging Eq. E.2 gives:

$$\frac{\rho_m}{\rho_p} \times \frac{d_m}{d_p} \times \frac{V_m}{V_p} \times \frac{\mu_p}{\mu_m} = 1 \qquad \textbf{Eq. E.3}$$

but d_m/d_p = the scaling factor, s

and V = Q/A, where Q is the volume flow rate through any area A, from which:

$$\frac{V_m}{V_p} = \frac{Q_m}{A_m} \times \frac{A_p}{Q_p} = \frac{1}{s^2} \times \frac{Q_m}{Q_p}$$

Substituting into Eq. E.3, gives:

$$\frac{\rho_m}{\rho_p} \times \frac{Q_m}{Q_p} \times \frac{\mu_p}{\mu_m} \times \frac{1}{s} = 1 \qquad \textbf{Eq. E.4}$$

With the values given in Appendix D, Eq. E.4 becomes:

$$\frac{1000}{0.1858} \times \frac{Q_m}{Q_p} \times \frac{6.008 \times 10^{-5}}{10^{-3}} \times 48 = 1 \qquad \textbf{Eq. E.5}$$

Qp can have two different values (depending on the basis of the calculation) as shown in Appendix D, section v. Replacing Q_p into Eq. E.5, Q_m is calculated:

∴ Q_m = 11.048 l/m (volumetric basis) or Q_m = 12.130 l/m (mass basis) ⇒ Impractical flow rates.

E.2) Calculation of the Model and Plant Reynolds Number

(i) Model Reynolds Number:

With the Reynolds Number equation, $Re_{model} = \frac{\rho_m \times d_m \times V_m}{\mu_m}$, it was possible to calculate the model Re. No. (at the furnace exit) for a variety of flows:

Area: Throat (furnace exit)		
Q (l/min)	Re No.	V (m/s)
900	2.85×10^4	0.14
800	2.53×10^4	0.12
700	2.22×10^4	0.11
600	1.90×10^4	0.09
500	1.58×10^4	0.08
400	1.26×10^4	0.06
300	9.50×10^3	0.05

Table E.1: Model Re. No. and corresponding velocities for a variety of water flow rates.

Note: For the purpose of the modelling work, a water flow rate of 600 l/min was chosen.

(ii) Plant Reynolds Number:

The plant Reynolds Number was calculated on a mass basis as shown below:

$$Re_{plant} = \frac{\rho_p \times d_p \times V_p}{\mu_p}$$ **Eq. E.8**

Note: $V_p = Q_{(vol.)} / A$, where $Q_{(vol.)}$ is the volume flow rate through the throat area A, therefore with the values from Appendix D (section (v)), V_p = (583 (kg/s) / 0.1858 (kg/m^3)) / 247.2 (m^2) = 12.7 m/s.
Replacing the remaining values, Eq. E.8 becomes:

$$Re_{plant} = \frac{0.1858 \times 9.792 \times 12.7}{6.008 \times 10^{-5}}$$

$$\underline{Re_{plant} = 384{,}580}$$

E.3) Calculation of the Water Flow Rate for the Modelling Work

The basis of the water flow rate calculation was investigated. The tables below show the water flow rates calculated under three bases - mass, volumetric and momentum - for different secondary air splits. Mass and momentum flow rates have the same results.

Total water flow in the model: **600 l/min**	Mass flow rates, l/min (%)	Volumetric flow rates, l/min (%)	Momentum flow rates, l/min (%)
Primary flow + Coal	128.64 (21.44%)	59.44 (9.91%)	128.64 (21.44%)
Secondary flow top stage: 16%	52.46 (8.74%)	60.16 (10.03%)	52.46 (8.74%)
Secondary flow middle stage: 31%	101.65 (16.94%)	116.57 (19.43%)	101.65 (16.94%)
Secondary flow bottom stage: 53%	173.78 (28.96%)	199.30 (33.22%)	173.78 (28.96%)
Tertiary flow	143.46 (23.91%)	164.53 (27.42%)	143.46 (23.91%)
TOTAL	600 l/min (100%)	600 l/min (100%)	600 l/min (100%)

Table E.2: Flow rates for a secondary air flow split of 16, 31 and 53% for top, middle and bottom stages respectively.

The calculations of the above flow rates are shown below. Please note that the following calculations are for a secondary air flow split of 16, 31 and 53% for top, middle and bottom stages respectively. All data required to perform the following calculations is given in Appendix D.

(i) Calculation of the Model Flow Rates on a Mass Basis

Types of Flow	Plant Mass Flow Rates (kg/s)		Model Flow Rates, for a 600 l/min pump (l/min)	
Primary + Coal flow	$m_{pa+c} = m_{pa} + m_c$	= 125	m_{pa+c} x (600/m_t)	= 128.64
Secondary flow (1st stage)	m_{sa1} = 16% x m_{sa}	= 50.98	m_{sa1} x (600/m_t)	= 52.46
Secondary flow (2nd stage)	m_{sa2} = 31% x m_{sa}	= 98.77	m_{sa2} x (600/m_t)	= 101.65
Secondary flow (3rd stage)	m_{sa3} = 53% x m_{sa}	= 168.86	m_{sa3} x (600/m_t)	= 173.78
Tertiary flow	m_{ta}	= 139.4	m_{ta} x (600/m_t)	= 143.46
TOTAL	$m_t = m_{pa+c}+m_{sa1}+m_{sa2}+m_{sa3}+m_{ta}$	= 583 kg/s		600 l/min

Table E.3: Calculation of the Model Flow Rates on a Mass Basis

(ii) Calculation of the Model Flow Rates on a Volumetric Basis

Types of Flow	Plant Volumetric Flow Rates (m^3/s)		Model Flow Rates, for a 600 l/min pump (l/min)	
Primary + Coal flow	$Q_{pa+c} = (m_{pa} / \rho_{pa})+(m_c / \rho_c)$	= 74.46	Q_{pa+c} x (600/Q_t)	= 59.44
Secondary flow (1st stage)	Q_{sa1} = (16% x m_{sa}) / ρ_{sa}	= 75.36	Q_{sa1} x (600/Q_t)	= 60.16
Secondary flow (2nd stage)	Q_{sa2} = (31% x m_{sa}) / ρ_{sa}	= 146.02	Q_{sa2} x (600/Q_t)	= 116.57
Secondary flow (3rd stage)	Q_{sa3} = (53% x m_{sa}) / ρ_{sa}	= 249.64	Q_{sa3} x (600/Q_t)	= 199.30
Tertiary flow	$Q_{ta} = (m_{ta} / \rho_{ta})$	= 206.09	Q_{ta} x (600/Q_t)	= 164.53
TOTAL	$Q_t = Q_{pa+c}+Q_{sa1}+Q_{sa2}+Q_{sa3}+Q_{ta}$	= 751.57 m^3/s		600 l/min

Table E.4: Calculation of the Model Flow Rates on a Volumetric Basis

(iii) Calculation of the Model Flow Rates on a Momentum Basis

The Momentum equation is defined as:

Momentum (M) = m (kg/s) x V (m/s), from [158] **Eq. E.6**

but m (kg/s) = Q (m^3/s) x ρ (kg/m^3)

substituting into equation Eq. E.6 gives:

M (Newton) = Q (m^3/s) x ρ (kg/m^3) x V (m/s)

∴ M = ρ x Q x V **Eq. E.7**

Rearranging Eq. E.7, the flow rate can be calculated:

Q = M / (ρ x V)

In order to calculate the model flow rates, it was first necessary to determine the momentums and velocities of the plant:

- *PRIMARY AIR AND COAL:*

Primary air is responsible for the transport of the coal into the furnace. Therefore the momentum was defined as follows:

$M_{pa+c} = M_{pa} + M_c = (\rho_{pa} \times Q_{pa} \times V_{pa}) + (\rho_c \times Q_c \times V_c) = 3{,}969$ N

For the velocity calculation, it was assumed that the coal and primary air flow had the same velocity, therefore:

$V_c = V_{pa} = (Q_{pa} + Q_c) / (A_{pa+c} \times 36 \text{ burners}) = 31.75$ m/s

where: $Q_{pa} = m_{pa} / \rho_{pa}$ and $Q_c = m_c / \rho_c$

- *SECONDARY AIR:*

<u>1st Stage:</u> $M_{sa1} = \rho_{sa} \times Q_{sa1} \times V_{sa1} = 117$ N

with $Q_{sa1} = (16\% \times m_{sa}) / \rho_{sa}$

and $V_{sa1} = Q_{sa1} / (A_{sa1} \times 36 \text{ burners}) = 2.30$ m/s

<u>2nd Stage:</u> $M_{sa2} = \rho_{sa} \times Q_{sa2} \times V_{sa2} = 536$ N

with $Q_{sa2} = (31\% \times m_{sa}) / \rho_{sa}$

and $V_{sa2} = Q_{sa2} / (A_{sa2} \times 36 \text{ burners}) = 5.42$ m/s

3rd Stage: $M_{sa3} = \rho_{sa} \times Q_{sa3} \times V_{sa3} = 1,197$ N

with $Q_{sa3} = (53\% \times m_{sa}) / \rho_{sa}$

and $V_{sa3} = Q_{sa3} / (A_{sa3} \times 36$ burners$) = 7.08$ m/s

- *TERTIARY AIR:*

$M_{ta} = \rho_{ta} \times Q_{ta} \times V_{ta} = 10,023$ N

with, $Q_{ta} = m_{ta} / \rho_{ta}$

and $V_{ta} = Q_{ta} / (A_{ta} \times 36$ burners$) = 71.90$ m/s

With the above information the momentums and velocities can be calculated as a percentage to later replace in the momentum equation:

Calculation of the Plant Momentum Flow Rates				Calculation of the Plant Velocities			
calculated above (N)		as a percentage (%)		calculated above (m/s)		as a percentage (%)	
M_{pa+c}	= 3,969	$M(\%)_{pa+c} = (M_{pa+c} / M_t) \times 100$	= 25.05	V_{pa+c}	= 31.75	$V(\%)_{pa+c} = (V_{pa+c} / V_t) \times 100$	= 26.80
M_{sa1}	= 117	$M(\%)_{sa1} = (M_{sa1} / M_t) \times 100$	= 0.74	V_{sa1}	= 2.30	$V(\%)_{sa1} = (V_{sa1} / V_t) \times 100$	= 1.94
M_{sa2}	= 536	$M(\%)_{sa2} = (M_{sa2} / M_t) \times 100$	= 3.38	V_{sa2}	= 5.42	$V(\%)_{sa2} = (V_{sa2} / V_t) \times 100$	= 4.57
M_{sa3}	= 1,197	$M(\%)_{sa3} = (M_{sa3} / M_t) \times 100$	= 7.55	V_{sa3}	= 7.09	$V(\%)_{sa3} = (V_{sa3} / V_t) \times 100$	= 5.98
M_{ta}	= 10,023	$M(\%)_{ta} = (M_{ta} / M_t) \times 100$	= 63.26	V_{ta}	= 71.90	$V(\%)_{ta} = (V_{ta} / V_t) \times 100$	= 60.69
M_t (N)	15,842		100%	V_t (m/s)	118.47		100%

Table E.5: Calculation of the plant momentum flow rates and velocities as a percentage.

NOTE: where $M_t = M_{pa+c} + M_{sa1} + M_{sa2} + M_{sa3} + M_{ta}$

and $V_t = V_{pa+c} + V_{sa1} + V_{sa2} + V_{sa3} + V_{ta}$

The representation of flow mediums of different densities in a model with uniform flow medium density is an approximation. The main goal is to represent the effects of the flows with respect to the flow pattern appropriately. For this purpose, the momentums and velocities are considered proportionally in the momentum equation for the calculation of the water flow rates representing the different flows in the boiler:

$$[Qm] = M\% / (\rho_w \times V\%)$$

In this equation, the [Qm] for a particular flow is not directly a measure of the flow in the model but only a symbolic number that has to be put into context with the [Qm] for all the other flows:

$$[Qm]_{pa+c} + [Qm]_{sa1} + [Qm]_{sa2} + [Qm]_{sa3} + [Qm]_{ta} = \sum [Qm]$$

The actual flows are therefore calculated as:

$$Qm_{pa+c} = \frac{[Qm]_{pa+c}}{\Sigma[Qm]} \times 600 l / \min$$

Types of Flow	Calculation of [Qm]		Calculation of the Model Momentum Flow Rates (Qm), for a 600 l/min pump (l/min)	
Primary + Coal flow	$[Qm]_{pa+c} = M(\%)_{pa+c} / (\rho_w \times V(\%)_{pa+c})$	= 0.000935	Qm_{pa+c}	= 128.64
Secondary flow (1st stage)	$[Qm]_{sa1} = M(\%)_{sa1} / (\rho_w \times V(\%)_{sa1})$	= 0.000381	Qm_{sa1}	= 52.46
Secondary flow (2nd stage)	$[Qm]_{sa2} = M(\%)_{sa2} / (\rho_w \times V(\%)_{sa2})$	= 0.000739	Qm_{sa2}	= 101.65
Secondary flow (3rd stage)	$[Qm]_{sa3} = M(\%)_{sa3} / (\rho_w \times V(\%)_{sa3})$	= 0.001263	Qm_{sa3}	= 173.78
Tertiary flow	$[Qm]_{ta} = M(\%)_{ta} / (\rho_w \times V(\%)_{ta})$	= 0.001042	Qm_{ta}	= 143.46
TOTAL	Σ[Qm]	= 0.004386	Model Flow	= 600

Table E.6: Final calculation of the model flow rates on a momentum basis.

APPENDIX F - BOILER EFFICIENCY

When assessing the efficiency of a boiler, it is more realistic to examine the boiler losses (indirect method) than the efficiency itself (direct method - ratio of heat input to heat output). This is because the direct method requires many precise measurements that are difficult to obtain, such as the rate of coal entering the mills. For this reason the indirect method was used here.

Boiler efficiency can be expressed either in terms of the gross or in terms of the net calorific value of the fuel. In this thesis it is expressed in terms of the gross calorific value (GCV) of the fuel. The following tables F.1 and F.2 show that for the boiler efficiency at Aberthaw, based on the GCV of the fuel, about 10-13% of the heat in the fuel is dissipated as boiler losses. These can be grouped in five main categories: (1) Carbon in ash loss, (2) Dry Flue Gas Loss, (3) Moisture and Hydrogen Loss, (4) Loss due to Unburnt Gas and (5) Radiation and Unaccounted Losses. The boiler losses were calculated in accordance with the methods described in BS 2885 [180].

How much does boiler efficiency vary?

In order to see how much the combustion efficiency is affected by varying O_2 levels, flue gas temperature, unburnt carbon and CO levels, two main boiler efficiency tables are shown next: one for the Aberthaw coal and another for the "Portbury" coal.

As the results in the tables indicate, generally a CO level below 200 ppm does not significantly affect boiler efficiency. Only when CO is above 1000 ppm the boiler efficiency starts to decrease significantly. However, due to particles emissions the CO must be kept at a level $\leq$ 200 ppm. On the other hand, carbon in ash decreases boiler efficiency more severely than CO. The temperature of the flue gas and oxygen levels within the furnace can also affect the boiler efficiency significantly.

Aberthaw Coal[1]			Boiler Efficiency		% Excess Air♠
			% Gross	% Net	
% O_2 *	CO (ppm) **	% CinA***	125 °C / 130 °C♣	125 °C / 130 °C♣	
6	0	0	91.6 / 91.4	94.7 / 94.6	40
6	0	10	89.6 / 89.4	92.6 / 92.4	40
6	200	10	89.5 / 89.3	92.5 / 92.3	40
6	1000	10	89.2 /88.9	92.2 / 91.9	40
6	200	12	89.1 / 88.8	92.0 / 91.8	40
6	1000	12	88.7 / 88.5	91.7 / 91.4	40
6	200	14	88.6 / 88.4	91.6 / 91.3	40
6	1000	14	88.3 / 88.0	91.2 / 91.0	40
6	200	16	88.1 / 87.9	91.0 / 90.8	40
6	1000	16	87.8 / 87.5	90.7 / 90.4	40
6	200	18	87.6 / 87.3	90.5 / 90.3	40
6	1000	18	87.2 / 87.0	90.2 / 89.9	40
7	0	0	91.2 / 91.0	94.3 / 94.1	50
7	0	10	89.3 / 89.0	92.3 / 92.0	50
7	200	10	89.2 / 88.9	92.2 / 91.9	50
7	1000	10	88.8 / 88.6	91.8 / 91.5	50
7	200	12	88.8 / 88.5	91.7 / 91.5	50
7	1000	12	88.4 / 88.1	91.3 / 91.1	50
7	200	14	88.3 / 88.0	91.2 / 91.0	50
7	1000	14	87.9 / 87.7	90.9 / 90.6	50
7	200	16	87.8 / 87.5	90.7 / 90.5	50
7	1000	16	87.4 / 87.2	90.4 / 90.1	50
7	200	18	87.3 / 87.0	90.2 / 89.9	50
7	1000	18	86.9 / 86.7	89.8 / 89.6	50

Table F.1 : Boiler Efficiency with Aberthaw Coal.

Where: * dry at airheater outlet. ** at airheater outlet. *** Carbon in ash (%).

♣ Temperature of the flue gas at the airheater outlet. ♠ Calculated in accordance to [181].

[1] Coal analyses in the last page of this appendix.

"Portbury" Coal[2]			Boiler Efficiency		% Excess Air♠
			% Gross	% Net	
% O_2 *	CO (ppm) **	% CinA***	125 °C / 130 °C♣	125 °C / 130 °C♣	
6	0	0	91.2 / 90.9	94.4 / 94.1	40
6	0	10	89.7 / 89.5	92.9 / 92.6	40
6	200	10	89.6 / 89.4	92.8 / 92.5	40
6	1000	10	89.3 /89.0	92.4 / 92.2	40
6	200	12	89.3 / 89.0	92.4 / 92.2	40
6	1000	12	88.7 / 88.7	91.8 / 91.8	40
6	200	14	88.7 / 88.7	91.8 / 91.8	40
6	1000	14	88.6 / 88.3	91.7 / 91.5	40
6	200	16	88.6 / 88.3	91.7 / 91.5	40
6	1000	16	88.0 / 88.0	91.4 / 91.1	40
6	200	18	88.0 / 88.0	91.4 / 91.1	40
6	1000	18	87.8 / 87.6	91.0 / 90.7	40
7	0	0	90.8 / 90.6	94.1 / 93.8	50
7	0	10	89.4 / 89.1	92.6 / 92.3	50
7	200	10	89.3 / 89.0	92.5 / 92.2	50
7	1000	10	88.9 / 88.6	92.1 / 91.8	50
7	200	12	88.9 / 88.6	92.1 / 91.8	50
7	1000	12	88.6 / 88.3	91.7 / 91.4	50
7	200	14	88.6 / 88.3	91.7 / 91.4	50
7	1000	14	88.2 / 88.0	91.4 / 91.1	50
7	200	16	88.2 / 88.0	91.4 / 91.1	50
7	1000	16	87.9 / 87.6	91.0 / 90.7	50
7	200	18	87.9 / 87.6	91.0 / 90.7	50
7	1000	18	87.5 / 87.2	90.6 / 90.3	50

Table F.2: Boiler Efficiency with "Portbury" Coal.

Where: * dry at airheater outlet. ** at airheater outlet. *** Carbon in ash (%).

♣ Temperature of the flue gas at the airheater outlet. ♠ Calculated in accordance to [181].

[2] Coal analyses in the last page of this appendix.

• Coal Compositions

Aberthaw Coal					
Ultimate Analysis			**Proximate Analysis**		
	As-fired	Dry		As-fired	Dry
Total Moisture:	8%	---	Total Moisture:	0.97%	---
Ash:	15.33%	16.66%	Volatile Matter:	12.53%	12.65%
Carbon:	68.67%	74.64%	Fixed Carbon:	72.85%	73.56%
Hydrogen:	3.19%	3.47%	Ash	13.65%	13.79%
Nitrogen:	1.38%	1.5%			
Sulphur:	1.52%	1.65%			
Oxygen:	1.91%	2.08%			
Gross CV:	27.5 MJ/kg	27.5 MJ/kg			
Net CV:	26.5 MJ/kg	26.5 MJ/kg			

Table F.3: Coal analyses of the South Wales coal (semi-anthracite) [101].

"Portbury" Coal					
Ultimate Analysis			**Proximate Analysis**		
	As-fired	Dry		As-fired	Dry
Total Moisture:	7.37%	---	Total Moisture:	7.37%	---
Ash:	11.6%	12.52%	Volatile Matter:	10.1 %	10.90%
Carbon:	74.7%	80.65%	Fixed Carbon:	69.62%	75.16%
Hydrogen:	3.66%	3.95%	Ash	11.6%	12.52%
Nitrogen:	1%	1.08%	Sulphur	1.31%	1.42%
Sulphur:	1.31%	1.41%			
Oxygen:	0.36%	0.39%			
Gross CV:	28.6 MJ/kg	28.6 MJ/kg			
Net CV:	27.6 MJ/kg	27.6 MJ/kg			

Table F.4: Coal analyses of the "Portbury" coal (semi-anthracite) [101].

• Oil Composition

Typical Ultimate Analysis of a Heavy Fuel Oil		
	As-fired	Dry
Total Moisture:	0.2%	---
Ash:	0.05%	0.05 %
Carbon:	86%	86.17%
Hydrogen:	10%	10.02%
Nitrogen:	0.4%	0.4%
Sulphur:	3 %	3.01%
Oxygen:	0.35%	0.35%
Gross CV:	42.9 MJ/kg	42.9 MJ/kg
Net CV:	40.5 MJ/kg	40.5 MJ/kg

Table F.5: Typical ultimate analysis of a heavy oil [179].

APPENDIX G - HEAT DISTRIBUTION WITHIN THE BOILER

Heat discrepancies in the boiler could contribute to increased NO_X emissions. Therefore, the heat distribution of the Aberthaw unit 7 boiler was investigated. The following table (Table G.1) summarises typical results obtained from measurements on either side of the boiler at full load (500 MW).

SUPERHEATER STEAM TEMPERATURE (°C)	DESIGN	'A' SIDE	'B' SIDE
Secondary superheater inlet	--	456	444
Secondary superheater outlet	568	569	570
Platen outlet (mixing and transfer headers)	457	454	455
Platen inlet	370	373	NK
Radiant superheater inlet header	364	363	365
Primary superheater outlet header	366	361	365
Primary superheater inlet header	359	355	360
Drum saturation	357	357	355
REHEATER STEAM TEMPERATURE (°C)			
Reheater inlet	365	NK	NK
Reheater mixing and transfer header	508	NK	NK
Reheater outlet	568	569	567
FEED WATER TEMPERATURE (°C)			
Economiser inlet and desuperheater spray	254	234	228
Economiser outlet	310	295	293
Final feed water	252	226 to 235	226 to 235
AIR TEMPERATURE (°C)			
Primary air at mill-airheater outlet	274	267 to 300	284 to 300
Primary air at mill inlet	274	263	281
Primary air/PF mixture at mills (A, B, C, D, E and F) outlet	93	70 to 100 ♣	
Secondary air at main-airheater outlet	271	272	276
GAS TEMPERATURE (°C)			
Economiser outlet	340	314	305
Main-airheater inlet	--	312	316
Main-airheater outlet	124	123.8	141
Mill-airheater inlet	--	411	414
Mill-airheater outlet	120	137	136
ID fan	116	125 to 130	
Primary reheater inlet	--	NK	711
Primary reheater outlet	530	508	503
Primary superheater inlet	--	722	724
Primary superheater outlet	612	NK	585
Secondary reheater inlet	--	757	755
Secondary reheater outlet	790	NK	NK
Secondary superheater exit	961	NK	NK
Furnace outlet	1171	NK	NK

Table G.1: Boiler Temperatures.

Notes:

NK - Not Known due to bad signals.

"--" - Design figure not available on manuals.

♣ depending on the moisture of the coal.

Comments

The table shows that in general the heat distribution in the boiler seems to be within limits when compared to design.

Superheater/Reheater steam temperatures

Superheater steam temperatures are near design specification, albeit with spraywater control. Spray flows are constantly working to compensate for these high temperatures at the superheater. Reheater temperatures are also within specification; they are not controlled by spraywater but by bypass of the gas in the rear furnace as described earlier.

Air and gas temperatures

All air temperatures are near design specification. Flue gas temperatures are also generally within specification, with exception of the mill- and main-airheater gas inlet temperatures which should be the same, but differ by 100 K. The latter situation, can be explained by the fact that the gas fed into the mill-airheater is bypassing the economiser, which results in the higher temperature.

Although the idea of increasing the primary air temperature is to ensure a dried PF, it is important to note that this high temperature may be contributing to a higher NO_X level. It might therefore be advisable to consider closing the bypass of the mill-airheaters.

Feed water Temperature

Final feed water temperature shows the largest deviation from design (20° to 30°C). Low feed water temperatures make the boiler work hard resulting in higher combustion temperatures. Consequently NO_X emissions are also increased and the boiler efficiency is reduced (due to increased superheater and reheater temperatures which in turn result in increased spray flows).

The difference in feed water temperature, however, is due to the BFPT (Boiler Feed Pump Turbine): the BFPT is a turbine that drives the pump which is responsible for pumping the feed water back into the boiler. Normally the steam to drive the BFPT is obtained from the HP turbine exhaust (thus called cold reheat). However in case of operational difficulties extra steam to drive the pump is obtained from the last stage of the feed heating system (HP7 at Aberthaw). This has the drawback of lowering the final feed water temperature that flows into the boiler.

GLOSSARY

Ash: There are two types of ash:

a) Fly Ash or pulverised fuel ash (PFA): ash in the form of dust that is too light to fall out of the gas stream. It is therefore carried with the gas and mainly removed by the electrostatic precipitators.

b) Furnace Bottom ash: heavier ash which may have fused into lumps and that falls by gravity to the furnace bottom hopper. Some of this ash adheres to the furnace walls or superheater tubes and eventually falls off by gravity. At Aberthaw, the boiler is of a dry-bottom type, therefore the furnace bottom ash is removed manually.

Blended Coal: Mixture of two or more coals to achieve a more manageable coal that does not have extreme characteristics such as very high ash content, high sulphur content, etc.

Boiler: The boiler converts the chemical energy in the fuel into energy in the form of high pressure and high temperature steam. The boiler also reheats the steam after it has passed through the HP cylinder, which improves cycle efficiency. A modern power station water tube boiler consists essentially of a combustion chamber together with water tubes, headers, and steam and water drums. In addition there are superheaters, airheaters, economisers, reheaters, electrostatic precipitators, FD and ID fans and dampers.
The Aberthaw boiler is of a natural circulation type. (See definition of "natural circulation boiler" further in the glossary).

Boiler Feed Pump Turbine (BFPT): Turbine that drives the pump which is responsible for pumping the feed water back into the boiler. Normally the steam to drive the BFPT is obtained from the HP turbine exhaust (thus called cold reheat). However in case of operational difficulties extra steam to drive the pump is obtained from the last stage of the feed heating system (HP7 at Aberthaw). This has the drawback of lowering the final feed water temperature that flows into the boiler.

Bunker: A feed hopper or silo for coal. It is mounted at a fairly high level in the boiler house so that coal may be fed, to the coal mills by gravity. The bunkers normally hold sufficient coal for at least 8 hours running. This eliminates the need to run the coal conveyors continuously and hence saves power and manpower.

Calorific Value (CV) of Coal (also "Heating Value"): The CV of a coal can be defined in two ways - Gross CV (GCV, also "High Heating Value") or Net CV (NCV, also "Lower Heating Value"). The GCV is the total energy released whereas the net value discounts the latent heat of the water vapour in the products of combustion as being not available for useful heat transfer.

Char: Coal without volatiles, but still taking part in the combustion process.

Classifier: A device fitted within the coal mills that grades the coal and only lets fully ground coal to be used for combustion. Over-size particles are rejected and returned to the mill for further grinding. Classifiers may be either static or dynamic but generally rely on suddenly changing the direction of the product stream so that large particles are rejected by their centrifugal force being greater than the motive force of the product stream.

Coal: Coal is the result of decomposition of vegetation that grew millions of years ago. It contains carbon, hydrogen, oxygen, nitrogen, sulphur, and other constituents that form ash after burning. The first stage of coalification (formation of coal) involves the formation of peat, then lignite, followed by subbituminous coal, bituminous coal and finally anthracite; as coalification progresses the coal rank increases. Moisture and oxygen content of the coal fall as the rank increases and the calorific value rises, with the exception of anthracites. Loss of methane in the final stage of coalification increases the carbon content of anthracite but reduces its hydrogen content resulting in a slight fall in the inherent calorific value [182]. Anthracite coal is hard, brittle and dry; because of its low volatile content, it burns with a short blue smokeless flame. It has little or no tendency to form a coke.

Coal Analysis: Coal analysis can be either "proximate" or "ultimate". Proximate analysis determines the moisture, volatile matter, ash and fixed carbon (by difference), whereas the ultimate analysis gives the combustible constituents of the fuel along with the ash and moisture content. Both analyses are usually presented as a percentage by weight and can be reported in different ways: as-received, as-fired, dry and dry-ash-free (or dry-mineral-matter-free). The as-received and as-fired, usually only differ in the moisture content, which may vary during storage and handling. The dry analysis gives the percentage of the constituents with no moisture and the dry-ash-free gives it with no ash or moisture.

Coke: Coal remains from the combustion process, produced in certain industries. A coal has caking properties when as a result of heating it has the tendency to adhere forming a solid mass - the coke. Coke is the solid residue after liberation of the volatile constituents.
It is worth noting that the term coking coal is limited for those coals used for the manufacture of metallurgical coke [183].

Combustion Chamber or Furnace: This is the chamber in which combustion of the fuel takes place and its design details and proportions are of considerable importance to the successful operation of the boiler. Heat resulting from combustion of the fuel reaches the water in the tubes by three means of heat transfer: (a) by radiation from the combustion process into the surrounding tubes, (b) by convection due to tubes being surrounded by hot gases and (c) by conduction through refractory, insulation, walls of the tubes and any scale or deposits formed on the boiler surfaces.

Dampers: Device consisting of one or more blades fitted into air and gas ducts, fans etc. The blades interfere with the air or gas flow and so control the flow to the required rate. They may also be capable of stopping the flow completely when required.

Deaerator: A direct contact feed heater where the heating steam, drawn from the turbine, is intimately mixed with the feed water to be heated. Air and other dissolved gases are removed from the water because the water is raised to boiling point (deaeration). Therefore, the boiler water cannot contain dissolved gases. The deaerator also acts as a head tank for the boiler feed water pumps and acts as a 'buffer' to the fluctuations of condensate feedwater flow. The deaerator can also be known as the feed tank.

Down-firing: This method is used when coals of low volatile content are the main fuel. Down-fired-furnaces have therefore a characteristic W-flame shape, which results in a long particle residence time necessary to complete combustion of the low volatile coal. Around 40% of the total air (primary and tertiary air) is provided at the burner and is projected downwards from the arch towards the furnace bottom. The remaining 60% (secondary air) is fed into the flame through multiple ports arranged in the boiler sidewall [132]. The main provisions employed to obtain prompt and stable ignition are:

(1) The burners discharge a fuel rich mixture into the furnace,

(2) Back flow of some of the hot combustion gas into the ignition zone,

(3) Radiation of heat into the ignition zone (refractory walls in the burner zone),

(4) High fineness of coal pulverisation and

(5) Sufficient residence time in the furnace.

Drum: The boiler drum receives preheated water from the economiser and its function is to act as a reserve for the supply of water to the furnace wall headers and steam generating tubes, as well as forming a collecting space for the steam produced. The saturated steam then travels to the superheater system.

Economiser: When the boiler furnace gases have given up part of their heat to the water tubes and superheaters, there is still a considerable amount of heat remaining. It would be uneconomical to allow this heat to be lost to the stack. The economiser is a low temperature heat exchanger, which was added to the early boilers to lower the fuel costs, and this is how it got its name. Now, however it is an essential part of the boiler design. The economiser is located in the final downpass of the flue gases. An economiser can be considered as a feed water heater, being the final stage of reheating the condensate from the turbine before entering the boiler drum. It basically consists of a series of tubes in which feedwater passes in contra flow to the hot flue gases.

Electrostatic Precipitators (EP): PF-fired boilers must always employ special collection equipment such as electrostatic precipitators, to deal with the substantial quantities of incombustible fly ash (PFA). There are several types of precipitators, basically consisting of rows of small diameter discharge wires inserted between collector plates. The wires are energised at a high negative DC voltage, thus inducing a powerful electrostatic field and a corona discharge of electrons, which ionises molecules of flue gas passing through the zone.
Rapping is the process of periodically removing the collected dust, usually by mechanically striking the collector plate frames by rapping hammers.

Forced Draught Fans (FD Fans): Forced draught fans deliver combustion air to the furnace. At Aberthaw the FD fans supply secondary and tertiary air for the pulverised fuel burners.

Feed Heater: A heat exchanger that adds heat to the feed water by extracting steam from various stages of the turbine. There are many types of feed heaters but the most common in power stations are tubular or direct contact.

Feed System: The simplest form of a feed water system comprises a condenser, and a extraction pump, a feed tank (or deaerator), the LP feed heaters, the HP feed heaters and a boiler feed pump. The condenser condenses the steam, the extraction pump extracts the condensate from the condenser and delivers it to the LP feed heaters, feed tank (deaerator) and HP feed heaters. Finally the boiler feed pump delivers the condensate into the boiler.

Fuel-Rich Combustion: The air/fuel ratio supplied to a furnace that provides less than the theoretical minimum air required for complete combustion of the fuel. This is also known as sub-stoichiometric combustion.

Induced Draught Fans (ID Fans): The function of the ID fans is to remove the hot gases from the boiler and discharge them to the stack.

Mill or Pulveriser: Grinds damp raw coal into dry pulverised fuel (PF) so that it may be burnt readily in the furnace. The coal is transported to the furnace by the primary air.

There are two main types of mills: tube-ball- and vertical-spindle-mills. Tube-ball-mills are preferred for low volatile coals as these coals need a high degree of fineness for combustion reasons. This is better done with the tube-ball-mill than with the vertical-spindle-mill.

Natural Circulation Boiler: In a natural circulation boiler the water circulates from the drum, down the downcomers, through the bottom headers, up through the heated tubes and back to the drum. This circulation is caused by the difference in density between the water being heated and the colder water in the downcomers, hence a head difference exists and the circulation results. Another option is an assisted circulation boiler where pumps are used to assist with this circulation. Pumped circulation enables the boiler to be smaller and less high, however, the power for the pumps is considerable and an economic appraisal is required.

NO_X: There are three main forms of NO_X: Nitric oxide (NO), Nitrous oxide (N_2O) and Nitrogen dioxide (NO_2) - all known as oxides of nitrogen. NO_X produced in boiler combustion is generally about 5% NO_2 and 95% NO. N_2O is usually ignored at its emissions from conventional power plants are small. NO_X contributes significantly to worldwide pollution and its levels must be kept as low as possible. The production of NO_X is inherent in the combustion process and higher levels of NO_X generally occur when the combustion temperature is high or high levels of nitrogen are present in the fuel.

Oil: Oil is composed primarily of hydrocarbon compounds with the general formula $H_x(H_2C)_y$. In addition to carbon and hydrogen, oil also contains hydrocarbon derivatives which may contain nitrogen, oxygen or sulphur.

OIS: The Operational Information System includes all plant and processes (electricity generation) related information - power output, power consumption, plant state, process temperatures, flows, NO_X levels, etc.

Primary Air Fans (PA Fans): Primary air fans provide hot primary air to the mills. This air is of fairly high velocity. It dries the coal so that it may be milled (ground to minute particles) and then transports it to the furnace for combustion. Primary air also takes part in the combustion process.

Plenum Chambers: See windbox.

Primary Air (PA): Air heated in the mill-airheaters and supplied by the PA fans. It is responsible for the transport of the PF into the burners and furnace.

Regenerative Airheater (RAH): The regenerative airheater is normally located after the economiser in the path of the boiler gases to the stack and performs the duty of extracting still further heat from the gases. There are several types, but the most common one is a vertical shaft rotary heat exchanger in which a large diameter heat transfer matrix of metal plates is heated by rotating the matrix through the hot gas stream. The matrix rotates through the combustion air stream, thus heating the air and cooling the matrix. This heat is then transferred either to the air fed into the boiler for combustion making further economy (if originated in the main-airheaters), or it serves to dry off the wetness of the coal in the mills (when originated in the mill-airheaters).

Reheater: This is the part of the boiler which receives steam back from the turbine after it has given up some of its heat energy in the high pressure section of the turbine (HP cylinder). This helps to reduce wetness at the exhaust end of the LP cylinder. The arrangement and construction of a reheater is very similar to that of a superheater. It consists of banks of tubes at the top of the furnace, through which intermediate pressure steam passes. The tubes are surrounded by the flue gases resultant of the combustion.

Secondary Air[1] **:** Air heated in the main-airheaters and supplied by the FD fans. Secondary air is discharged into the plenum chambers. Once in the plenum chamber the secondary air flows into the furnace through the boiler front- and rear-walls being admitted along the length of the down firing part of the flame resulting in the W-shape flame.

Sootblowing: After a period of time, slag and adhesive ash starts to accumulate in the boiler walls and tube surfaces. Sootblowers spray steam into the boiler walls and tubes to remove these deposits. Steam then flashes off with the soot, and most of this mixture flows with the gas stream for ash removal in the precipitators. However, some of the deposits fall into the furnace bottom for removal. Sootblowers are generally installed in the furnace, superheaters, reheaters, airheaters and sometimes in the economisers. Its main purpose is to maintain boiler availability, lower the final flue gas temperature and by this means reduce chimney losses due to maintaining clean heat transfer surfaces This inevitably also contributes to a lower Thermal-NO_X.

Spraywater: The temperature of steam admitted to the turbine must be kept constant. In order to achieve this, water at a lower temperature than the steam, is added to the steam to regulate the steam temperature. This water is actually added to vessels called spray-desuperheaters, located between the primary and secondary superheaters. The water is sprayed into the spray-desuperheater, and as steam flashes off, the temperature is lowered. The amount of spraywater added is controlled automatically by the steam temperature control system. The amount of spraywater added generally gives an indication of the boiler condition and heat distribution. High spray flows indicating that more

[1] Secondary and tertiary air definitions are used differently between boiler manufacturers and power station staff: the definitions used in this work are as used at the power station. According to boiler manufacturers terminology, the above definition of secondary air is labelled tertiary air.

heat is being rejected from the furnace and hence being absorbed into the superheater and reheater section.

Spray-desuperheaters: See Spraywater.

Superheater: To meet the needs of a power plant, the saturated steam generated in the boiler drum must be heated still further by the furnace gases. A superheater consists of inlet and outlet headers between which are connected small diameter tubes. The superheater is generally divided into several sections or stages (primary superheater, furnace radiant superheater, spray desuperheaters and secondary superheaters). The saturated steam from the drum passes through the tubes so gaining in temperature therefore, increasing its heat content.
From the drum the steam path is via the primary superheater, furnace radiant superheater to the spray desuperheaters. After the spray desuperheater the steam passes finally to the secondary superheater.

Synergism: Increasing effect of two or more components by a greater amount than the sum of the individual effects.

Tertiary Air[2] **:** Air heated in the main-airheaters and supplied by the FD fans. Tertiary air is supplied around the burner nozzles to enable the coal to bum at a controlled rate. It also gives a momentum to the PF jet by pushing the fuel down to the bottom of the furnace. This is a typical arrangement of a low volatile coal furnace, as the fuel needs a higher residence time in the fumace.

Windbox: A plenum chamber for supplying air to the burners and furnace. It is usually large inside to reduce the air velocity and ensure uniform distribution of air to each burner or furnace area.

2 Secondary and tertiary air definitions are used differently between boiler manufacturers and power station staff: the definitions used in this work are as used at the power station. According to boiler manufacturers terminology, the above definition of tertiary air is labelled secondary air.

REFERENCES

[1] PRATHER, M.J. and LOGAN, J.A.: "Combustion's impact on the global atmosphere", *In: Proc. of the 25th Symp. (Int.) on Combust.*, The combustion Institute, 1994, 31 Jul.-5 Aug., pp. 1-23.

[2] Oxides of Nitrogen in the United Kingdom, *The second report of the United Kingdom photochemical oxidants review group*, DOE (Department of the Environment, 1990, ISBN: 0-7058-1616-8.

[3] Council Directive of 28 June 1984: "On the combating of air pollution from industrial plants", *Official Journal of the European Communities*, 1984, 84/360/EEC, no. L188.

[4] Council Directive of 7 March 1985: "On air quality standards for Nitrogen Dioxide", *Official Journal of the European Communities*, 1985, 85/203/EEC, no. L87.

[5] Council Directive of 24 November 1988: "On the limitation of certain pollutants into the air from large combustion plants", *Official Journal of the European Communities*, 1988, 88/609/EEC, no. L336.

[6] NIGEL HAIGH: *Manual of Environmental Policy: the EC and Britain*, Longman, 1992, ISBN: 0-582-08715-5.

[7] HMIP (Her Majesty's Inspectorate of Pollution): *Environmental Protection Act 1990*, Chief Inspector's Guide to Inspectors, Industry: Fuel and Power, Combustion Processes: Large boilers and furnaces 50 MW(th) and over, Process Guidance Note IPR 1/1, 1991, Apr.

[8] ENVIRONMENTAL RESOURCES LTD: *Acid Rain - A review of the phenomenon in the EEC & Europe*, Pub. by: Graham & Trotman Ltd. for the Commission of the European Communities, London, 1983, ISBN: 0-86010-501-6.

[9] CHEN, G.T.; SHANG, J.Y. and WEN, C.Y.: "NO_X emission from combustors: A state-of-the-art-review", *DOE Report*, DOE-MC-11284-166, Contract No. AM21-79MC124, DE81-026231, 90E-4-UNLTD, 1981.

[10] HAYHURST, A.N. and VINCE, I.M.: "Nitric Oxide formation from N_2 in flames: the importance of prompt NO", *Progress in Energy and Combustion Science*, 1980, vol. 6, no. 1, pp. 35-51.

[11] SAROFIM, A.F. and FLAGAN, R.C.: "NO_X control for stationary combustion sources", *Progress in Energy and Combustion Science*, 1976, vol. 2, no. 1, pp. 1-25.

[12] LINAK, W.P.; McSORLEY, J.A. and HALL, R.E.: "Nitrous Oxide emissions from fossil fuel combustion", *Journal of Geophysical Research*, 1990, May, vol. 95, no. D6, pp. 7533-7541.

[13] LINAK, W.P.; McSORLEY, J.A.; HALL, R.E.; RYAN, J.V.; SRIVASTAVA, R.K.; WENDT, J.O.L. and MEREB, J.B.: "N_2O emissions from fossil fuel combustion", *In: Proc. of the 1989 Joint EPA/EPRI Symp. on Stationary Combustion Nitrogen Oxide Control*, EPRI GS-6423, San Francisco, California, 1989, Jul., vol. 1, pp. 1(37)-1(54).

[14] SMART, J.P., ROBERTS, P.A. and DE SOETE, G.G.: "The formation of nitrous oxide in large scale pulverised coal flames", *Journal of the Institute of Energy*, 1990, Sept., pp. 131-135.

[15] MUZIO, L.J. and TEAGUE, M.E.; MONTGOMERY, T.A.; SAMUELSEN, G.S.; KRAMLICH, J.C. and LYON, R.K.: "Measurement of N_2O from combustion sources", *In: Proc. of the 1989 Joint EPA/EPRI Symp. on Stationary Combustion Nitrogen Oxide Control*, EPRI GS-6423, San Francisco, California, 1989, Jul., vol. 1, pp. 1(55)-1(72).

[16] G de SOETE, G.G.: "Formation of Nitrous Oxide from NO and SO_2 during solid fuel combustion", *In: Proc. of the 1989 Joint EPA/EPRI Symp. on Stationary Combustion Nitrogen Oxide Control*, EPRI GS-6423, San Francisco, California, 1989, Jul., vol. 2, pp. 7B(1)-7B(13).

[17] OUDE LOHUIS, J.A.; TROMP, P.J.J. and MOULIJN, J.A.: "Parametric study of N_2O formation in coal combustion", *Fuel*, 1992, Jan., vol. 71, pp. 9-14.

[18] HAKVOORT, G.: "Environmental effects of coal combustion", *Journal of Thermal Analysis*, 1992, vol. 38, no. 1-2, pp. 9-16.

[19] PERSHING, D.W. and WENDT, J.O.L.: "Pulverised coal combustion: the influence of flame temperature and coal composition on Thermal and Fuel NO_X", *In: Proc. of the 16th Symp. (Int.) on Combust.*, The Combustion Institute, 1977, pp. 389-399.

[20] PERSHING, D.W. and WENDT, J.O.L.: "Effects of coal composition on thermal and fuel NO_X production from pulverised coal combustion", *In: Proc. of the Central States Section Spring Meeting*, The Combustion Institute, Columbus, Ohio, 1976, Apr.

[21] PERSHING, D.W.; MARTIN, G.B. and BERKAU, E.E.: "Influence of design variables on the production of thermal and fuel NO from residual oil and combustion", *In: Proc. of the AIChE Symp. Series*, 1975, vol. 71, no. 148, pp. 19-29.

[22] PALMER, H.B. and SEERY, D.J.: "Chemistry of pollutant formation in flames", *Annual Review of Physical Chemistry*, 1973, vol. 24, pp. 235-262.

[23] VADAKKATH, A. and ANNAMALAI, K.: "Group effects on Fuel NO_X emissions from coal", *Heat and Mass Transfer in Fires and Combustion Systems*, ASME, 1991, vol. 176, pp. 71-77.

[24] SMOOT, L.D. and SMITH, P.J.: *Coal combustion and gasification*, Plenum Press, New York, 1985, pp. 376-377.

[25] MORRISON, G.F.: *Nitrogen Oxides from coal combustion*, IEA Coal Research, London, 1980.

[26] ZELDOVICH, T.B.: *Acta Physica U.R.S.S.*, 1946, vol. 21, no. 4,

[27] SAROFIM, A.F. and POHL, J.H.: "Kinetics of Nitric Oxide formation in premixed laminar flames", *In: Proc. of the 14th Symp. (Int.) on Combust.*, The Combustion Institute, 1973, pp. 739-754.

[28] BLAUWENS, J.; SMETS, B. and PEETERS, J.: "Mechanism of 'Prompt' NO formation in hydrocarbon flames", *In: Proc. of the 16th Symp. (Int.) on Combust.*, The Combustion Institute, 1977, pp. 1055-1064.

[29] CHIGIER, N.: *Energy, combustion and environment*, McGraw-Hill Book Company, 1981.

[30] MALTE, P.C. and PRATT, D.T.: "The role of energy-releasing kinetics in NO_X formation: fuel-lean, jet-stirred CO-air combustion", *Combustion Science and Technology*, 1974, vol. 9, pp. 221-231.

[31] MALTE, P.C. and REES, D.P.: "Mechanisms and kinetics of pollutant formation during reaction of pulverised coal", *In: Pulverised Coal Combustion and Gasification - Theory and Applications for Continuous Flow Processes*, Edited by: Smoot, L.D. and Pratt, D.T., Plenum, New York, 1979, pp. 183-215.

[32] SIPAHUTAR, R.: *NO_X formation during pulverised coal combustion*, Ph.D. Thesis, The University of Leeds, 1992.

[33] POHL, J.H. and SAROFIM, A.F.: "Devolatilisation and oxidation of coal nitrogen", *In: Proc. of the 16th Symp. (Int.) on Combust.*, The Combustion Institute, 1977, pp. 491-501.

[34] PERSHING, D.W. and WENDT, J.O.L.: "Relative contributions of volatile nitrogen and char nitrogen to NO_X emissions from pulverised coal flames", *Industrial and Engineering Chemistry Process Design and Development (Ind. Eng. Chem. Proc Des. Dev.)*, 1979, vol. 18, no. 1, pp. 60-67.

[35] LOCKWOOD, F.C. and ROMO-MILLARES, C.A.: "Mathematical modelling of fuel NO emissions from PF burners", *Journal of the Institute of Energy*, 1992, vol. 65, pp. 144-152.

[36] PAPADAKIS, G. and BERGELES, G.: "Prediction of staged coal combustion in three-dimensional furnaces", *Journal of the Institute of Energy*, 1994, Dec., vol. 67, pp. 156-167.

[37] FENIMORE, C.P.: "Formation of Nitric Oxide in premixed hydrocarbon flames", *In: Proc. of the 13th Symp. (Int.) on Combust.*, The Combustion Institute, 1971, pp. 373-380.

[38] HAYNES, B.S.; IVERACH, D. and KIROV, N.Y.: *In: Proc. of the 15th Symp. (Int.) on Combust.*, The Combustion Institute, 1975, p. 1103.

[39] HAYHURST, A.N. and VINCE, I.M.: "Production of 'prompt' nitric oxide and decomposition of hydrocarbon flames", *Nature*, 1977, Apr., vol. 266, pp. 524-525.

[40] HEBERLING, P.V.: "Prompt NO measurements at high pressures", *In: Proc. of the 16th Symp. (Int.) on Combust.*, The Combustion Institute, 1977, pp. 159-168.

[41] PERSHING, D.W. and BERKAU, E.E.: "The chemistry of nitrogen oxides and control through combustion modification", *Advances in Chemistry Series*, 1973, vol. 127, p. 218.

[42] ENGLEMEN, V.S., BARTOK, W.; LONGWELL, J.P. and EDELMAN, R.B.: "Formation of Nitric Oxide in fuel-lean and fuel-rich flames", *In: Proc. of the 14th Symp. (Int.) on Combust.*, The Combustion Institute, 1973, pp. 767-775.

[43] IVERACH, D.; KIROV, N.Y. and HAYNES, B.S.: "The formation of nitric oxide in fuel-rich flames", *Combustion Science and Technology*, 1973, vol. 8, no. 4, pp. 159-164.

[44] MORELEY, C.: "The formation and destruction of hydrogen cyanide from atmospheric and fuel nitrogen in rich atmospheric pressure vessels", *Combustion and Flame*, 1976, vol. 27, pp. 189-204.

[45] WILLIAMSON, S.J.: *Fundamentals of Air Pollution*, Addison-Wesley Publishing Company, 1973, ISBN: 0-201-08629-8.

[46] SMITH, I.: "Nitrogen oxides from coal combustion - environmental effects", *Report No. ICTIS/TR 10*, IEA Coal Research, London, 1980, Oct.

[47] WORLD HEALTH ORGANISATION: "Potential health effects of climate change", *WHO/PEP/90/10*.

[48] CLARKE, A.G.: "The air", *In: Understanding our environment*, Edited by: Hester, R.E., The Royal Society of Chemistry, London, 1986, pp. 71-118.

[49] CLARKE, A.G.: "The atmosphere", *In: Understanding our environment - An Introduction to Environmental Chemistry and Pollution*, Edited by: Harrison, R.M., 2nd ed., The Royal Society of Chemistry, London, 1992, ISBN: 0-85186-233-0.

[50] PERHAC, R.M.: "Environmental effects of nitrogen oxides", *In: Proc. of the 1989 Joint EPA/EPRI Symp. on Stationary Combustion Nitrogen Oxide Control*, EPRI GS-6423, San Francisco, California, 1989, Jul., vol. 1, pp. 1(29)-1(36).

[51] WOJTOWICZ, M.A.; PELS, J.R. and MOULIJN, J.A.: "N_2O emission control in coal combustion", *Fuel*, 1994, vol. 73, no. 9, pp. 1416-1422.

[52] WEISS, R.F.: "The temporal and spatial distribution of tropospheric Nitrous Oxide", *Journal of Geophysics Res.*, 1981, vol. 86, pp. 1785-1795.

[53] KHALIL, M.A. and RASMUSSEN, R.A.: "Increase in seasonal cycles of Nitrous Oxide in the earth's atmosphere", *Tellus*, 1983, vol. 35B, pp. 161-169.

[54] GARG, A.: "Specify better low-NO_X burners for furnaces", *Chemical Engineering Progress*, 1994, Jan., vol. 90, no. 1, pp. 46-49.

[55] MOORE, J.W. and MOORE, E.A.: *Environmental Chemistry*, Academic Press Inc. Ltd, London, 1976, ISBN: 0-12-505050-X.

[56] MANA, S.: *Environmental Chemistry*, Lewis Publishers Inc., 5th ed., 1991, ISBN: 0-87371-425-3.

[57] McELROY, M.W. and CARR, R.C.: "Relationship between NO_X and fine particles emissions", *In: Proc. of the 1980 Joint Symp. on Stationary Combustion NO_X Control*, 1981, vol. 1 , pp. 310-329.

[58] MELDRUM, M.: "Toxicology of substances in relation to major Hazards - Nitrogen Dioxide", *(HSE) Health and Safety Executive*, 1992, 22 pages.

[59] *Integrated Pollution Control: A practical guide.* Guidance issued by the Department of the Environment and the Welsh Office, London, HMSO, 1993, 32 pages, ISBN: 0-11-752750-5.

[60] DEPARTMENT OF THE ENVIRONMENT: "The United Kingdom National Air Quality Strategy", *Consultation Draft - Summary and Overview*, The Scottish Office, 1996.

[61] MANNY, E.H.: "Reducing NO_X discharges: easy as ABC", *Power*, 1980, Aug., vol. 124, no. 8, pp. 78-81.

[62] *Modern power station practice (MPSP), vol. G: Station operation and maintenance*, British Electricity International, London, Pergamon Press Plc., 3rd ed., 1991, ISBN: 0-08-040510-X (12 volume set).

[63] BUETERS, K.A. and HABELT, W.W. (Part I of the paper); BLAKESLEE, C.E. and BURBACH, H.E. (Part II of the paper): "NO_X emissions from tangentially-fired utility boilers", *In: Proc. of the AIChE Symp. Series*, 1975, vol. 71, no. 148, pp. 85-102.

[64] MANNY, E.H.: "Guidelines for NO_X Control by Combustion Modification for coal-fired utility boilers. Procedures for reduction of NO_X emissions & maximisation of boiler efficiency", *Exxon Corp. Report to EPA*, (EPA-600-8-80-027), PB-80-200595, Exxon Research and Engineering Co., Florham Park, NJ, 1980, May, 102 pages.

[65] MASON, H.B. and WATERLAND, L.R.: "Environmental assessment of stationary source NO_X combustion modification technologies", *In: Proc. of the Second Stationary Source Combustion Symp.*, New Orleans, LA, USA, PB-270-923, Washington, D.C., USA, US Environmental Protection Agency, EPA-600-7-77-073A, FLD-GP-7A, 1977, Jul., vol. 1, pp. 37-84.

[66] SIEGMUND, C.W. and TURNER, D.W.: "NO_X emissions from industrial boilers: Potential control methods", *Journal of Engineering for Power*, 1974, pp. 1-6.

[67] BARTOK, W.; CRAWFORD, A.R.; CUNNINGHAM, A.R.; HALL, H.J.; MANNY, E.H. and SKOPP, A.: "Systems study of Nitrogen Oxide control methods for stationary sources", *Esso Research and Engineering Company Final Report,* No. GR-2-NOS-69 (PB-192-789) Napca Contract No. PB-22-68-55, 1969.

[68] THOMPSON, R.E.: "Nitric Oxide controls for coal fired utility boilers from an applications viewpoint", *In: Proc. of the Second NO_X Control Technology Seminar*, EPRI FP-1109-SR, 1979, pp. 9(1)-9(27).

[69] CRAWFORD, A.R.; MANNY, E.H. and BARTOK, W.: "Field testing: Application of combustion modifications to control NO_X emissions from utility boilers", *Exxon Research and Engineering Company Report*, Linden, N.J., EPA-650-2-74-066, NTIS No. PB-237-344, GRU-1DJAF-74, Contract No. 68-02-0227, FLD-GP-13B-21B, 1974, Jun., 212 pages.

[70] SONNICHSEN, T.W.: "NO_X emissions from pulverised coal arch-fired boilers", *EPRI CS-2813 Final Report*, Contract RP-1339-1, 1982, Dec., 118 pages.

[71] CHAE, J.O. and CHUN, Y.N.: "Effect of two-stage combustion on NO_X emissions in pulverised coal combustion", *Fuel*, 1991, Jun., vol. 70, no. 6, pp. 703-707.

[72] HJALMARSSON, A.K. and SOUD, H.N.: *NO_X control installations on coal-fired plants*, IEA Coal Research, IEACR/34, London, 1991, Mar., ISBN: 92-9029-186-9.

[73] S2 1.01: "Combustion Processes: large boilers and furnaces 50 MW(th) and over", *Chief Inspector's Guidance Note, Series 2 (S2)*: Processes Subject to Integrated Pollution Control, Fuel production and combustion sector (including power generation), London: HMSO, 1995, Nov., ISBN: 0-11-7532061.

[74] "Environmental control implications of generating electric power from coal", *Technology status report*, Appendix D: Assessment of NO_X control technology for coal fired utility boilers, ANL-ECT-3, Argonne, Illinois, USA, Argonne National Laboratory, 1977, Dec.

[75] BARSIN, J.A.: "NO_X emissions controlled by design in pulverised coal burner-boiler", *Power Engineering*, 1979, Aug., vol. 83, no. 8, pp. 70-72.

[76] BARSIN, J.A.: "Pulverised coal firing NO_X control", *In: Proc. of the Second NO_X Control Technology Seminar*, EPRI FP-1109-SR, 1979, Jul., pp. 8(1)-8(22).

[77] LaRUE, D.A.; ACREE, M.A. and CIOFFI, P.L.: "Utility steam generator NO_X control update - 1985", *In: Proc. of the 1985 Joint Symp. on Stationary Combustion NO_X Control*, EPRI CS-4360, Boston, Massachusetts, 1986, Jan., vol. 1, pp 8(1)-8(9).

[78] LaRUE, A.: "NO_X reduction by combustion in PC-fired boilers", *In: Proc. of the Joint ASME/IEEE Power Generation Conference*, Boston, MA, 90-JPGC/FACT-18, 1990, Oct., pp. 1-9.

[79] LaRUE, A.: "The XCL burner - latest developments and operating experience", *In: Proc. of the 1989 Joint EPA/EPRI Symp. on Stationary Combustion Nitrogen Oxide Control*, EPRI GS-6423, San Francisco, California, 1989, Jul., vol. 1, pp. 3(93)-3(109).

[80] VATSKY, J.: "Industrial and utility boiler NO_X control", *In: Proc. of the 1985 Joint Symp. on Stationary Combustion NO_X Control*, EPRI CS-4360, Boston, Massachusetts, 1986, Jan., vol. 1, pp. 11(1)-11(28).

[81] VATSKY, J.: "Foster Wheeler's low NO_X combustion program status and developments", *In: Proc. of the 1982 Joint Symp. on Stationary Combustion NO_X Control*, EPRI CS-3182, 1983, Jul., vol. 1, pp. 5(1)-5(22).

[82] VATSKY, J.: "Field experience in over 7000 MWe of low NO_X burner retrofits", *In: Proc. of the Joint Power Generation Conference*, San Diego, CA, 1991, Oct.

[83] "Hamworthy, Combustion Systems - Low emission burners", *Company brochure*.

[84] CAMPBELL, L.M.; STONE, D.K. and SHAREEF, G.S.: "Sourcebook: NO_X Control Technology Data", EPA-600-2-91-029, *EPA Contract No. 68-02-4286*, 1991, Jul.; [prepared for Control Technology Centre US Environmental Protection Agency, 1990, Oct.],

[85] SMART, J.P. and NAKAMURA, T.: "NO_X emissions and burnout from a swirl-stabilised burner firing pulverised coal: the effects of firing coal blends", *Journal of the Institute of Energy*, 1993, Jun., vol. 66, pp. 99-105.

[86] SMART, J.P. AND WEBER, R.: "Reduction of NO_X and optimisation of burnout with an aerodynamically air staged burner and an air-staged precombustor burner", *Journal of the Institute of Energy*, 1989, vol. 62, pp. 237-245.

[87] WOOD, S.C.: "Select the right NO_X control technology", *Chemical Engineering Progress*, 1994, Jan., vol. 90, no. 1, pp. 32-38.

[88] CHEN, S.L.; McCARTHY, J.M.; CLARK, W.D.; HEAP, M.P.; SEEKER, W.R. and PERSHING, D.W.: "Bench and pilot scale process evaluation of reburning for in-furnace NO_X reduction", *In: Proc. of the 21st Symp. (Int.) on Combust.*, The Combustion Institute, 1986, pp. 1159-1169.

[89] HJALMARSSON, A.K.: *NO_X control technologies for coal combustion*, IEA Coal Research, IEACR/24, London, 1990, Jun., 102 pages, ISBN: 92-9029-177-X.

[90] HJALMARSSON, A.K.: "Control of Nitrogen Oxide emissions from coal combustion", *International Journal of Energy Research*, 1990, vol. 14, no. 8, pp. 813-820.

[91] McCARTHY, J.M.; CHEN, S.L.; SEEKER, W.R. and PERSHING, D.W.: "Pilot scale studies on the application of reburning for NO_X control" , *In: Proc. of the Joint EPRI/EPA 1987 Symp. on Stationary Combustion NO_X Control*, New Orleans, LA, USA, Mar., EPRI -CS-5361, Palo Alto, CA, USA Electric Power Research Institute, Research Reports Centre, 1987, vol. 1, pp. 11(1)-11(17).

[92] KNILL, K.J. and MORGAN, M.E.: "The effect of process variables on NO_X and nitrogen reduction in coal fuel staging", *In: Proc. of the 1989 Joint EPA/EPRI Symp. on Stationary Combustion Nitrogen Oxide Control*, EPRI GS-6423, San Francisco, California, 1989, Jul., vol. 2, pp. 6B(75)-6B(92).

[93] MEREB, J.B. and WENDT, J.O.L.: "Reburning mechanisms in a pulverised coal combustor", *In: Proc. of the 23rd Symp. (Int.) on Combust.*, The Combustion Institute, 1990, pp. 1273-1279.

[94] SMART, J.P. and MORGAN, D.J.: "The effectiveness of a multi-fuel reburning in an internally fuel-staged burner for NO_X reduction", *Fuel*, 1994, vol. 73, no. 9, pp. 1437-1442.

[95] TURNER, D.W.; ANDREWS, R.L. and SIEGMUND, C.W.: "Influence of combustion modification and fuel nitrogen content on nitrogen oxides emissions from fuel oil combustion", *In: Proc. of the AIChE Symp. Series*, 1972, vol. 68, no. 126, pp. 55-65.

[96] BARTOK, W.; CRAWFORD, A.R. and PIEGARI, G.J.: "Systematic field study of NO_X emission control methods for utility boilers", *Esso Research and Engineering CO.*, Linden, N.J., Government research Lab, GRU-4GNOS-71, OAP Contract No. CPA-70-90, PB-210-739, FLD-GP-13B-13A, 1971, 229 pages.

[97] BARTOK, W.; CRAWFORD, A.R. and PIEGARI, G.J.: "Systematic investigation of nitrogen oxide emissions and combustion control methods for power plant boilers", *In: Proc. of the AIChE Symp. Series*, 1972, vol. 68, no. 126, pp. 66-74.

[98] CLARKE, G.A. and WILLIAMS, A.: "The formation and control of NO_X emissions", *Chemistry and Industry*, 1991, Dec., vol. 24, pp. 917-920.

[99] THOMPSON, R.E.; McELROY, M.W. and CARR, R.C.: "Effectiveness of gas re-circulation and staged combustion in reducing NO_X on a 560 MW coal fired boiler", *In: Proc. of the NO_X Control Technology Seminar*, San Francisco, CA, USA, PB-253-661, Palo Alto, CA USA, Electric Power Research Institute, EPRI-SR-39, FLD/GP-07A-13B, 1976, Feb., pp. 36-70.

[100] DYKEMA, O.W.: "Analysis of NO_X control in stationary sources", *In: Proc. of the Second Stationary Source Combustion Symp.*, New Orleans, LA, USA, PB-271-756, Washington, D.C., USA, US Environmental Protection Agency, EPA-600-7-77-073B, 1977, Jul., vol. 2, pp. 41-66.

[101] Aberthaw Power Station Data.

[102] ARMENTO, W.J. and SAGE, W.L.: "The effect of design and operation variables on NO_X formation in coal fired furnaces: Status Report", *In: Proc. of the AIChE Symp. Series*, 1975, vol. 71, no. 148, pp. 63-70.

[103] BAGWELL, F.A.; ROSENTHAL, K.E.; TEIXEIRA, D.P.; BREEN, B.P.; BAYARD de VOLO, N. and KERHO, S.: "Utility boiler operating modes for reduced nitric oxide emissions", *Journal of Air Pollution Control Association*, 1971, Nov., vol. 21, no. 11, pp. 702-708.

[104] VATSKY, J.: "Experience in reducing NO_X emissions on operating steam generators", *In: Proc. of the Second NO_X Control Technology Seminar*, EPRI FP-1109-SR, 1979, Jul., pp. 7(1)-7(17).

[105] VATSKY, J. and CICHANOWICZ, J.E.: "Economic and engineering analysis of arch-fired furnaces", *In: Proc. of the 1982 Joint Symp. on Stationary Combustion NO_X Control*, EPRI CS-3182, 1983, Jul., vol. 1, pp. 13(1)-13(13).

[106] PAI, R.H.; SOMMERLAD, R.E. and WELDEN, R.P.: "Nitrogen Oxygen emission: An evaluation of test data for design", *In: Proc. of the AIChE Symp. Series*, 1975, vol. 71, no. 148, pp. 103-107.

[107] RAWDON, A.H. and JOHNSON, S.A.: "Application of NO_X control technology to power station boilers", *In: Proc. of the American Power Conference*, 1973, vol. 35, pp. 828-837.

[108] RAWDON, A.H.; LISANKAS, R.A. and ZONE, F.J.: "Design and operation of coal-fired turbo furnaces for NO_X control, *In: Proc. of the Second NO_X Control Technology Seminar*, EPRI FP-1109-SR, 1979, Jul., pp. 6(1)-6(9).

[109] RAWDON, A.H. and SADOWSKI, R.: "An experimental correlation of oxides of nitrogen from power boilers based on field data", *In: Proc. of the 93rd Winter Annual Meeting of the American Society of Mechanical Engineers*, New York, 1972, Nov. 27-30, pp. 1-6.

[110] KITTO, J.B.; LaRUE, A.D. and KULIG, J.S.: "Coal-fired NO_X emission control technologies", *In: Proc. of the 6th Annual International Pittsburgh Coal Conference*, 1989, pp. 405-414.

[111] TEMCHIN, J. and FEIBUS, H.: "Innovative coal technology NO_X control technology", *In: Proc. of the 1989 Joint EPA/EPRI Symp. on Stationary Combustion Nitrogen Oxide Control*, EPRI GS-6423, San Francisco, California, 1989, Jul., vol. 1, pp. 1(1)-1(7).

[112] CHO, S.M.: "Properly apply selective catalytic reduction for NO_X removal", *Chemical Engineering Progress*, 1994, Jan., vol. 90, no. 1, pp. 39-45.

[113] MOBLEY, J.D.: "Flue gas treatment technology for NO_X control", *In: Proc. of the Third Stationary Source Combustion Symp.*, San Francisco, CA, USA; PB-292-540; Washington, D.C., USA, US Environmental Protection Agency, EPA-600-7-79-050B, 1979, Mar., vol. 2, pp. 245-282.

[114] CATON, J.A. and SIEBERS, D.L.: "Effects of hydrogen addition on the removal of Nitric Oxide by Cyanuric acid", *In: Proc. of the 23rd Symp. (Int.) on Combust.*, The Combustion Institute, 1990, pp. 225-230.

[115] JODAL, M.; NIELSEN, C.; HULGAARD, T. and DAM-JOHANSEN, K.: "Pilot-scale experiments with ammonia and urea as reductants in selective non-catalytic reduction of Nitric Oxide", *In: Proc. of the 23rd Symp. (Int.) on Combust.*, The Combustion Institute, 1990, pp. 237-243.

[116] LYON, R.K. and LONGWELL, J.P.: "Selective non-catalytic reduction of NO_X by NH_3", *In: Proc. of the NO_X Control Technology Seminar*, San Francisco, CA, USA, PB-253-661, Palo Alto, CA USA, Electric Power Research Institute, EPRI-SR-39, FLD/GP-07A-13B, 1976, Feb., pp. 236-256.

[117] LYON, R.K.: "Thermal DeNOx: how it works", *Hydrocarbon Processing*, 1979, Oct., vol. 58, no. 10, pp. 109-112.

[118] FAUCETT, H.L.; MAXWELL, J.D. and BURNETT, T.A.: "Technical assessment of NO_X removal processes for utility application", *Final Report EPRI-AF-568*, Electric Power Research Institute, Palo Alto, CA, USA, 1978, Mar., 428 pages.

[119] DePRIEST, W.; JARVIS, J. and CICHANOWICZ, J.: "Engineering evaluation of combined NO_X/SO_2 removal processes: Interim Report", *In: Proc. of the 1989 Joint EPA/EPRI Symp. on Stationary Combustion Nitrogen Oxide Control*, EPRI GS-6423, San Francisco, California, 1989, Jul., vol. 2, pp. 7A(67)-7A(85).

[120] HASLBECK, J.L.; NEAL, L.G. and MA, W.T.: "NOXSO demonstration gives encouraging results", *Modern Power Systems*, 1988, Jul., pp. 39-43.

[121] BOSCH, H. and JANSSEN, F.: "Catalytic reduction of nitrogen oxides - A review on the fundamentals and technology", *Catalysis Today*, Elsevier, Amsterdam, 1988, Mar., vol. 2, no. 4, ISBN: 0920-5861.

[122] RICHTER, E; KNOBLAUCH, K. and WUENNENBERG, W.: "Simultaneous SO_X and NO_X removal processes gain acceptance", *Modern Power Systems*, 1989, Apr., vol. 9 , no. 4, pp. 21-25.

[123] ANDREASEN, J.; SCHOUBYE, P. and UDENGAARD, N.: "Topsoe SNOX process for flue gas cleaning", *In: Proc. of the EPRI Seminar*, Washington, DC, USA, EPRI GS-6519, 1988, Mar., pp. 11(1)-11(15).

[124] KUEHN, S.E.: "Retrofit control technology reducing NO_X emissions", *Power Engineering*, 1994, Feb., no. 1, pp. 23-27.

[125] CHU, P.; DOWNS, B. and HOLMES, B.: "Sorbent and ammonia injection at economiser temperatures upstream of a high-temperature baghouse", *Environmental Progress*, 1990, Aug., no. 3, pp. 149-155; [presented at the 1989 Spring National Meeting, AIChE, 1989, Apr.].

[126] KITTO Jr., J.B.: "The SOxNOxROxBOx uses hot catalytic scrubbers", *Modern Power Systems*, 1989, Jan., no. 1, pp. 24-25.

[127] ANDERSON, J.: "Pulverised coal under Central-Station boilers", *Power*, 1920, Mar., vol. 51, no. 9.

[128] KREISINGER, H.; BLIZARD, J.; AUGUSTINE, C.E. and CROSS, B.J.: "Tests of a large boiler fired with powdered coal (at the Lakeside Station, Milwaukee)", *Bulletin 237*, Department of the Interior, Bureau of Mines, 1925.

[129] WOLFF, J.: "Tests of pulverised fuel-fired boilers at the Lake Shore Station, Cleveland", *ASME Transactions*, 1925, vol. 47, pp. 1255-1266.

[130] MAcNAUGHTON, M.E.: *Elementary Steam Power Engineering*, New York, John Wiley and Sons, 3rd ed., 1948.

[131] CICHANOWICZ, J.E.; McELROY, M.W.; MUZIO, L.J.; SONNICHSEN, T.W. and SHIOMOTO, G.H.: "NO_X emissions characteristics of down-fired, sequential air addition furnaces", *In: Proc. of the Second NO_X Control Technology Seminar*, EPRI FP-1109-SR, 1979, Jul., pp. 12(1)-12(20).

[132] *Modern power station practice (MPSP), vol. B: Boilers and ancillary plant*, British Electricity International, London, Pergamon Press Plc., 3rd ed., 1991, ISBN: 0-08-040510-X (12 volume set).

[133] SONNICHSEN, T.W. and CICHANOWICZ, J.E.: "NO_X emissions characteristics of arch-fired furnaces", *In: Proc. of the 1980 Joint Symp. on Stationary Combustion NO_X Control*, 1981, vol. 1, pp. 237-267.

[134] BEER, J.M.: "Combustion of pulverised coal", *In: Proc. of the Conference on Flames and Industry*, Institute of fuel, London, 1962, pp. C1-C15.

[135] CUTRESS, J.O. and PEIRCE, T.J.: "Combustion of pulverised anthracite at Tir John generation station", *Journal of the Institute of Fuel*, 1965, vol. 38, pp. 54-60.

[136] ANSON, D.: "Aerodynamics in power station boiler furnaces", *Electrical Review*, 1965, May, vol. 176, no. 22, pp. 820-823.

[137] MAYER, J.: "The combustion of anthracite duff in pulverised form", *Journal of the Institute of Fuel*, 1938, Apr., pp. 305-327.

[138] CUTRESS, J.O.; PEIRCE, T.J. and TUCKER, A.C.N.: "On the ignition of pulverised anthracite", *Combustion and Flame*, 1964, vol. 8, pp. 289-298.

[139] GREY DE, M.A.: "Les expériences sur les poussières de houille et la combustion du charbon pulvérisé", *Rev. Metall*, 1922, vol. 19, pp. 645-655, (in French).

[140] FUERTES, A.B.; HAMPARTSOUMIAN, E. and WILLIAMS, A.: "Direct measurements of ignition temperatures of pulverised coal particles", *Fuel*, 1995, vol. 72, no. 9, pp. 1287-1291.

[141] HERTZBERG, M.: "Autoignition temperatures for coal particles dispersed in air", *Fuel*, 1991, Oct., vol. 70, no. 10, pp. 1115-1123.

[142] MIRONOV, S.N.: "Experimental investigation of the combustion of pulverised anthracite", *Thermal Engineering*, 1965, vol. 12, pp. 93-99.

[143] SEEKER, W.R.; SAMUELSEN, G.S.; HEAP, M.P. and TROLINGER, J.D.: "The thermal decomposition of pulverised coal particles", *In: Proc. of the 18th Symp. (Int.) on Combust.*, The Combustion Institute, 1981, pp. 1213-1226.

[144] KREMER, H. and SCHULZ, W.: "Influence of temperature on the formation of NO_X during pulverised coal combustion", *In: Proc. of the 21st Symp. (Int.) on Combust.*, The Combustion Institute, 1986, pp. 1217-1222.

[145] McLEAN, W.J.; HARDESTY, D.R. and POHL, J.H.: "Direct observations of devolatilising pulverised coal particles in a combustion environment", *In: Proc. of the 18th Symp. (Int.) on Combust.*, The Combustion Institute, 1981, pp. 1239-1248.

[146] CHEN, J.C.; MASAYUKI, T. and KAZUYUKI, I.: "Observation of laser ignition and combustion PF pulverised coals", *Fuel*, 1995, vol. 74, no. 3, pp. 323-330.

[147] TUCKER, A.C.N.: "Internal surface burning in anthracite p.f. particles", *Fuel - The Journal of Fuel Science*, 1969, Apr., vol. 48, no. 2, pp. 105-119.

[148] DYKEMA, O.W.: "Analysis test data for NO_X control in coal-fired utility boilers", *EPA-600-2-76-274*, National Technical Information Service no: PB-261-066, US Environmental Protection Agency Research Triangle Park, North Carolina, FLD-GP-13B-21B, 1976, Oct.

[149] BURDETT, N.A.: "The effects of air staging on NO_X emissions from a 500 MW (e) down-fired boiler", *Journal of the Institute of Energy*, 1987, Sept., vol. 60, no. 444, pp .103-107.

[150] BIANCA, J.D.; BAUVER II, W.P. and McGOWAN, J.G.: "An aerodynamic study of an operating tangential fired furnace", *In: Proc. of the Fluids Engineering Conference*, Boulder, CO, 1981, pp. 51-63.

[151] TUCKER, A.C.N.: *Predicted combustion performance for Aberthaw "B" Power Station and investigation into possible modifications*, (Ex-University Thesis), Classification No. SSD/SW/R94; CEGB, South Western Region, 1969, Aug.

[152] MORRIS, A.W.L.: "Velocities in Aberthaw "B" furnace water model (measurement of velocity profiles in a water model of Aberthaw "B" furnace using a miniature current flow meter)", *Report no. RD/SW/R.47*, CEGB, South Western Region, 1966, Apr.

[153] STEVENS, A.E.: "Gas side flow visualisation on a 1/32nd scale model of the furnace of the Aberthaw "B" 500 MW boiler", *R.N.L.120*, Research and Development Department, Foster Wheeler Ltd., 1964, Jan.

[154] BACON, N.P.: "Experiments with furnace models", *In: Proc. of the Joint Symp. on Scaling-up of Chemical Plant and Processes*, Pub. by: The Institution of Chemical Engineers, 1957, pp. 99-108.

[155] CLARKE, A.E.; GERRARD, A.J. and HOLLIDAY, L.A.: "Some experiences in gas turbine combustion chamber practice using water flow visualisation techniques", *In: Proc. of the 9th Symp. (Int.) on Combust.*, The Combustion Institute, 1963, pp. 878-891.

[156] WINTER, E.F. and DETERDING, J.H.: "Apparatus and techniques for the application of water flow system to the study of aerodynamic systems", *British Journal of Applied Physics*, 1956, Feb., vol. 7, pp. 247-260.

[157] JONHSTONE, R.E. and THRING, M.W.: *Pilot plants, models and scale-up methods in Chemical Engineering*, McGraw-Hill Book Company, 1957.

[158] RHINE, J.M. and TUCKER, R.J.: *Modelling of gas fired furnaces and boilers and other industrial heating processes*, Pub. by: McGraw-Hill Book Company, In association with British Gas PLC, 1991, ISBN: 0-07-707305-3.

[159] SPALDING, D.B.: "The art of partial modelling", *In: Proc. of the 9th Symp. (Int.) on Combust.*, The Combustion Institute, 1963, pp. 833-843.

[160] PATTERSON, R.C. and ABRAHAMSEN, R.F.: "Flow modelling of furnaces and ducts", *Combustion*, 1962, no. 33-34, pp. 47-55.

[161] ANSON, D.: "Modelling experience with large boilers", *Journal of the Institute of Fuel*, 1967, Jan., vol. 40, pp. 20-25.

[162] GRAY, F.A. and ROBERTSON, A.D.: "The deflection of hot jets due to buoyancy", *Journal of the Institute of Fuel*, 1956, pp. 424-427.

[163] GRAY, F.A. and ROBERTSON, A.D.: "The investigation of fluid flow problems by model techniques", *Journal of the Institute of Fuel*, 1956, Oct., pp. 428-437.

[164] HORN, G. and THRING, M.W.: "The buoyancy effects in furnaces and boilers", *Journal of the Institute of Fuel*, 1956, vol. 29, pp. 437-440.

[165] COLLINS, R.D. and TYLER, J.D.: "Experiments on gaseous mixing in open-earth furnace models", *Journal of the Iron and Steel Institute*, 1949, Aug., vol. 162, pp. 457-466.

[166] DAVIDSON, F.J.: "Nozzle scaling in isothermal furnace models", *Journal of the Institute of Fuel*, 1968, Dec., no. 41, pp. 470-475.

[167] THRING, M.W. and NEWBY, M.P.: "Combustion length of enclosed turbulent jet flames", *In: Proc. of the 4th Symp. (Int.) on Combust.*, Baltimore: Williams and Wilkins Co., 1953, pp. 789-796.

[168] HULSE, C; McINERNEY, M.J. and SARKER, S.N.: "Comparison of tests on small scale models and full scale furnaces", Section VIII, pp. 37-58; CHESTERS, J.H.; PEARSON, S.W. and THRING, M.W: "General conclusions", Section XI, pp. 71-74; *Iron and Steel Institute Special Report no. 59*, 1956.

[169] BRAIS, N.: "Technique de la combustion a bas exces d'air et equipments de haute performances", *Seminar on the Application of Natural Gas in the Pulp and Paper Industry*, Trois Rivieres, 1987, Jun., (in French).

[170] BLACKWELL, B.; OLIVER, R. and BRISCOE, B.: "Physical flow modelling of a vintage combustion engineering kraft recovery boiler", *Pulp & Paper Canada*, 1991, vol. 92, pp. 67-75.

[171] KING, D.J.: "Interim report of flame penetration measurements no. 9 boiler Aberthaw "B" Power Station". *Report No. SSD/SW/M.571*, Job. No. 16/12; CEGB, 1973, Dec.

[172] CRAWFORD, A.R.; MANNY, E.H. and BARTOK, W.: "Field testing: application of combustion modification to power generating combustion sources", *In: Proc. of the Second Stationary*

Source Combustion Symp., New Orleans, LA, USA, PB-271-756, Washington, D.C., USA, US Environmental Protection Agency, EPA-600-7-77-073B, 1977, Jul., vol. 2, pp. 3-40.

[173] CRAWFORD, A.R.; MANNY, E.H.; BARTOK, W. and HALL, R.E.: "NO_X emission control for coal-fired utility boilers", *In: Proc. of the AIChE Symp. Series*, 1975, vol. 71, no. 148, pp. 75-84.

[174] MANNY, E.H. and NATANSON, P.S.: "Fireside corrosion and NO_X emission tests on coal-fired utility boilers", *In: Proc. of the Joint Symp. on Stationary Combustion NO_X Control*, EPRI-WS-79-220, 1981, May., vol. 1, pp. 186-236.

[175] MANNY, E.H.; CRAWFORD, A.R.; and BARTOK, W.: "Field testing of utility boilers and gas turbines for emission reduction", *In: Proc. of the Third Stationary Source Combustion Symp.*, San Francisco, CA, USA; PB-292-539; Washington, D.C., USA, US Environmental Protection Agency, EPA-600-7-79-050A, 1979, Mar., vol. 1, pp. 157-198.

[176] CRAWFORD, A.R.; MANNY, E.H. and BARTOK, W.: "NO_X emission control for coal-fired utility boilers", *In: Proc. of the Coal Combustion Seminar*, Research Triangle Park, NC, USA; PB-224-210; Washington, DC, USA, US Environmental Protection Agency, FLD/GP-21B-10B, EPA-650-2-73-021, 1973, Jun., pp. 215-286.

[177] FRIEDRICH, J.L. and PAI, R.H.: "Nitrogen Oxides reduction", *In: Proc. of the NO_X Control Technology Seminar*, San Francisco, CA, USA, PB-253-661; Palo Alto, CA USA, Electric Power Research Institute, EPRI-SR-39, FLD/GP-07A-13B, 1976, Feb., pp. 135-161.

[178] ROGERS, G.F.C. and MAYHEW, Y.R.: *Thermodynamic and transport properties of fluids: SI units*, Basil Blackwell, 4th ed., 1988, ISBN: 0-631-90265-1.

[179] ROSE, J.W. and COOPER, J.R.: *Technical data on fuel*, Pub. by The British National Committee, 7th ed., 1977, ISBN: 0 7073 0129 7.

[180] BS 2885: Acceptance tests on stationary steam generators of the power station type, 1974.

[181] ASME PTC 4.1: Steam Generating Units - Power Test Codes, Dec., 1964.

[182] *Modern power station practice (MPSP), vol. E: Chemistry and metallurgy*, British Electricity International, London, Pergamon Press Plc., 3rd ed., 1991, ISBN: 0-08-040510-X (12 volume set).

[183] BRAME, J.S.S. and KING, J.G.: *Fuel: Solid, Liquid and Gaseous*, Pub. by: Arnold, London, 5th ed., 1955.