CHAPTER 1
INTRODUCTION

1. INTRODUCTION

1.1 BACKGROUND AND DEFICIENCY IDENTIFICATION

The initiation of this project originated with the request for a steam flow - air flow curve by the Lethabo Power Station Operations department (1988). Required was a guideline to indicate the correct quantity of combustion air to the coal quantity, which is anticipated to be proportional to the boiler load (steam flow), since the coal quality is normally in a sufficiently narrow band concerning quality and consistency. This had been the normal practice at power stations with tied collieries, but at Lethabo the boiler manufacturer did not supply this guideline due to reasons concerning the unique coal quality at Lethabo, namely high ash and low volatile content.

This led to the investigation of the combustion air flow requirement for Lethabo coal. Various tests were conducted to establish more definitive guidelines at Lethabo in general, such as the Furnace Characterisation and the Lean Coal tests(3) (1988), but none were aimed at the specific optimisation thereof. The matter became urgent when Lethabo suffered a furnace explosion(13) on Boiler 3 in 1988.

The first optimisation attempts regarding the Lethabo combustion air flow quantity, were the Excess Air Reduction tests(5) conducted by the ESKOM Technology Research and Investigation group (TRI) and the Lethabo Plant Efficiency and Optimisation (PEO) section. The title of the tests suggest that the conventional wisdom of the "least air flow theory" was the target criterion, which was also the method followed internationally. That states that the lower the air flow quantity, the higher the efficiency, but in most of the cases a CO monitor determines the optimum even before the apex in the efficiency curve is reached. Many discrepancies were identified in those tests, such as:

- The poor state of plant.
- Too few tests conducted to obtain smooth curves.
- The total air flow panel readings produced peculiar values.
- The back calculated coal flow seemed improbable for the load, etc.

These and other reasons made it impossible for the results to be implemented. The tests were repeated by the author and the PEO section in 1992[2], attempting to eliminate all the problems experienced previously. The total air flow measurement was first corrected more accurately after a computational fluid dynamics (CFD) study[19], and was subsequently established as a routine activity by procedure[20] (see Appendix A.2 for the method). A new approach was formulated during the research for a M.Eng. dissertation[2] to eliminate the previous discrepancies. Some of the factors derived included:

- Carrying out more tests to obtain smooth curves (6 air flows at five loads each, totalling 30 tests).
- The testing of the whole unit including the turbine and not only the boiler.

- Using the Station Thermal Efficiency Performance (STEP) computer program which utilises the direct and indirect losses method of calculation with sliding targets.
- Allowing the maximum efficiency to emerge at any air flow in the whole spectrum, since there were indications that the "least air flow theory" might not necessarily be correct for optimising the combustion air flow, etc.

Despite these attempts a positive result could not be achieved. The main reasons for this were that some of the STEP targets proved to be incorrect and more importantly, no correlation between combustion air flow and efficiency could be derived to produce a smooth curve, despite the many sets of data. It was found after investigation of all the variables that the blended coal supplied during the tests, although of nominally specified or guarantee (spec.) calorific value (CV), had greatly varying volatile content. The volatiles in coal showed a trend with unburnt carbon in ash which was as significant as the combustion air. It was thus deduced that the impact of coal quality upon the optimum combustion air had to be investigated. It was possible that the optimum air flow was a function of not only the load, but the coal quality as well, complicating the derivation of a simple steam flow - air flow curve.

The title of the project was hence formulated to be: "A Macroscopic Determination of the Impact of Lethabo Coal Quality upon the Optimum Combustion Air Quantity". The term "macroscopic" was introduced and was intended to have the same meaning as in the study of the subject of thermodynamics. This was to measure the test parameters holistically on the full scale plant and then calculate the process magnitude (in this case the efficiency), as in typical plant performance testing. No attempt was made to perform microscopic experimentation such as laboratory/pilot scale drop tube furnace (DTF) combustion tests, since many such tests had already been performed on Lethabo coal and the results were available.

1.2 STATUS PRIOR TO TEST PROGRAMME

Although a steam flow - air flow curve was not initially supplied as an operational guideline, the boiler manufacturer did however supply an economiser outlet oxygen (O_2) curve, giving the design percentage in flue gas guideline against units generated, to comply with the Eskom statutory requirements. This Code of Practise for Pulverised Fuel (Pf) fired Boilers[8] originally stated these O_2 % limits as 3 to 9%. The original design values for the Lethabo boilers corresponded approximately to these figures. In the late 1980's there was increasing pressure in South Africa regarding particulate emission constraints. Lethabo thus had a precipitator enhancement project in progress. This process had resulted in the practice of running the boilers at reduced excess air flows, which favors precipitation and has spin-off benefits such as reduced erosion and auxiliary power.

Also, after the Boiler 3 furnace explosion, the minimum primary air (PA) flow through the mills were revised and increased to 24 kg/s from 21 kg/s. This led to the adoption of revised total air flow values. These considerations led to negotiations with ESKOM's corporate bodies to re-evaluate the Pf Code of Practice[8] for Lethabo and limits were set at 2 to 9 % O_2. This was however not based on extensive testing, but rather operational experience and calculations.

The lack of a properly defined criterion for optimum thermal efficiency still prevented the tests to produce a steam flow - air flow curve. The Pf Code of Practice was replaced by the Regulation for the Prevention of Explosions in Pf fired Boilers[35]. Section 1 made provision for the excess O_2 limits being enforced as "minimum requirements" in the "absence of test data". The norm at Lethabo since the late 1980's was thus to operate the boilers above 2 % O_2 with little attention given to the exact values at lower than maximum load, except as response to the normal reaction of the automatic controls.

There were additional operationally orientated problems at Lethabo. The tube mill enhancement project, which had been in progress since 1987, established a ball charge 10 tons greater than the original 88 tons. This overcame a lack of performance due to excessive coal moisture and lower coal quality (CV and ash). The mill performance also deteriorated with the seasoning of the ball charge. This, together with the new minimum of 24 kg/s PA flow mentioned above, had an impact on the total air via the automatic control system.

The primary air heater at Lethabo also proved to have been underdesigned regarding its heat transfer surface area. The frequently encountered higher moisture in coal showed the mills to lack drying power during the grinding process. All these factors complicated the air flow optimisation process due to these additional dependant variables being related to total combustion air flow. Most of these aspects could also not be resolved since the total combustion air flow proved to be an independent variable in relation to PA flow, mill by-pass damper setting, the ratio of PA to secondary air (SA) through the air heaters, etc.

Lethabo also suffered frequent metal temperature excursions above design limits in the final superheater region. The total air flow and the gas velocity is definitely one of the key factors in determining the superheater temperatures. The differing coal qualities as well as a poorly controlled sootblowing regime contributed as variables to these problems and had to be taken into account during the exercise (see pages 5 - 12 to 5 - 19 for detailed explanation). In practise, the excess air was often the control variable changed to improve the superheater metal temperature situation and that did not always satisfy the precipitator opacity limit, the milling combination or load in addition to the different coal quality variables (volatile content, CV or moisture).

The principal boiler and turbine performance data, obtained during independent contractual acceptance tests, had also been supplied separately. It was accepted that the maximum efficiency occurred at full load of the turbine. There was no related boiler efficiency curve, so a combined unit efficiency curve was needed.

The coal supplied to Lethabo, is via a blending stockyard, as coal in the pit has too great a variance for the combustion limits and has to be blended to a more consistent quality. Circumstances such as emergency generation periods require the stockyard to be bypassed without blending of the coal. Problems with the combustion have then been experienced, compounded by the lack of air flow guidelines, as well as the lack of knowledge of the coal quality. Due to the variability of the Lethabo coal volatile content, an on-line coal analyser had not proved to operate successfully. Proper coal classification regarding the quality limits and batch characteristics were needed. The Lethabo coal was however blended only according to specified CV values, disregarding its volatile content, thus degrading the process to "mixing" rather than blending.

During the routine efficiency calculation process evidence had been found that the CV of the coal was not representative of the actual combustion process. The bomb calorimeter process had also to be evaluated in this exercise, since CV is of utmost importance in efficiency calculation.

1.3 THE NEED OF AIR FLOW OPTIMISATION RELATIVE TO COAL QUALITY

It is a primary requirement to optimise the total combustion air flow, since it directly influences the value of parameters that are controlled by legal requirements (as explained in section 1.2). Combustion air flow quantity is also the most common root cause in the case history of flame-out and furnace explosion situations. There is thus a legal and safety aspect coupled to combustion air flow that enforces responsibility.

Secondly, even if the combustion air flow is controlled in such a way that the legal requirements are met, it is not necessarily true that this is the optimum air flow that will maximise all other criteria such as plant reliability and efficiency. The legal requirements only prescribe an envelope within which the parameters should be controlled and not a specific optimum value that would also cater for other criteria.

Into those categories also fall the aspects of air quality and its associated legislation that, can directly affect the availability of the plant, since precipitator performance is adversely effected by excess air flow. The combustion air flow also influences global aspects via the formation of CO_2 and NO_x, etc.

Many of the above mentioned requirements make opposing demands on optimum air flow. The lower the air flow, the better the flue gas opacity, and the lower is plant erosion and certain efficiency parameters such as dry flue gas loss. This reduction of excess air at certain loads can result in the reheat and final feed water temperatures being affected negatively, with accompanying turbine blade erosion, as has been proved in previous tests[2, 38]. The greater the air flow the better the unburnt carbon in ash, rear gas pass heat transfer affecting the reheat steam temperature and thus the turbine side.

The combustion air flow quantity has thus been demonstrated to influence the whole plant, both the boiler and the turbine. Also, from other enhancement activities such as mill performance, air heater design review, lean coal tests, precipitator clean air flow distribution tests, etc., it can be said that the total combustion air flow is the most independent variable. The total combustion air flow is less affected by these aspects than it can affect them. These other items should actually only be optimised after the air flow had been established to avoid a moving baseline. The combustion air flow can also be identified as the most controllable loss parameter after the plant has been designed. A listing and discussion of design considerations and constraints, controllable and uncontrollable factors appear in Appendix I.2.

The final aspect dictating the need to optimise the combustion air flow is the coal quality. This has been found to influence the optimum air flow significantly with load thus introducing a third variable.

1.4 NEW APPROACH AND HYPOTHESIS

In section 1.3 the need to optimise the total combustion air flow relative to the load and the coal quality has been stated. From those considerations it was obvious that the air flow should thus be optimised in such a way that all the losses were minimised in their accumulative total. The air flow was thus not to be optimised for one aspect such as low NO_x production only. Key criteria had thus to be defined against which the air flow could be optimised to achieve these goals.

1.4.1 The main criterion according to which the total combustion air flow had to be optimised was the thermal efficiency. It was postulated that with thermal efficiency as main criterion, most of the other requirements would be satisfied in the accumulative total.

1.4.2 The overall efficiency of the whole unit had to be evaluated simultaneously, not just the boiler in isolation.

1.4.3 The full operating range was tested in five intervals of load.

1.4.4 At each load the air flow was varied from the maximum to the minimum, to enable the optimum air flow to emanate at the maximum efficiency. This was thus not to be a minimum excess air flow criterion exercise. The optimum air flows at maximum efficiencies at each load were thus expected to be higher than that of the conventional wisdom.

1.4.5 The optimum air flow at maximum thermal efficiency was also to be determined for different coal qualities at each load. It was postulated that there should be different optima for different coal qualities.

1.4.6 A methodology had to be devised to calculate the direct side efficiency as well. The indirect losses method also did not cater for the unit as whole.

1.4.7 The STEP computer program was to be used in this exercise, with the anticipation of proving it as not only a monitoring but an optimising tool as well. It utilises the method of balancing the direct and indirect losses method and the minimising of the unaccountable losses. STEP contains polynomials that enable the sliding of targets, which also needed to be customised for Lethabo.

1.4.8 The tests were to be performed on a unit where a high state of plant health could be ensured, to eliminate discrepancies mentioned previously.

1.4.9 The total air flow was to be measured accurately and representatively, since it was the main parameter to be optimised and operational guidelines were to be derived from it. It was also postulated that the air flow remains a more comprehensive parameter to refer to in the legislation than O_2.

1.5 LIMITS OF THE STUDY

The study was initially intended for Eskom's Lethabo Power Station, due to the unique quality of its coal. The applicability of the results on other power stations and other coal qualities would depend on the nature of the findings. The extremes of the coal qualities to be tested depended on the plant design parameters, such as burners and furnace heat flux as well as previous test data. This had to be determined in advance and was one of the most important aspects of the project and future Lethabo operation (see Chapter 4 and appendices C, D and E). In contrast to the previous testing[2, 5], the coal was not to be blended. Other variables that could affect combustion conditions but not intended for this study, such as pf fineness, were to be identified and methods devised for them to be kept as constant as possible during the phase of this research.

Since evidence exists that reheat steam temperatures are affected by combustion air flow at certain loads, the test results are provisionally limited to combined boiler-turbine units and exclude range stations without reheat systems that use a common steam manifold. No limitation can be placed regarding drum or Benson type boilers, the type of mills (tube or vertical spindle), burners and firing configuration, the feed pump or turbine cylinder configuration as well as the feed heating plant. Specific variables such as feadheaters in service and the feed pump configuration and type were to be kept constant throughout the tests, or compensated for by calculation.

The anticipated load range for testing was to be the original base load design for Lethabo (400 to 600 MW). The testing for the initial optimum air flow guidelines was to be done at steady load. Starting up and other transient conditions such as mill changes were not intended for the initial determination of the test parameters. Once successfully proven, the obtained results could be tested practically for implementation as such.

The point of departure for these test criteria was only a First Law of Thermodynamics analysis. That means no deliberate attempts were made to change basic design criteria. However, since certain items of process and plant had been proven to have deficiencies (such as the mills and the air flow) provision was made for potential Second Law type modifications. Many of the mentioned deficiencies evolved from anomalies in the coal quality stated in the original coal contract[10] compared to that actually received. The plant was originally designed for other contract values of coal qualities. It was indeed these altered parameters of coal quality and combustion air flow that were to be investigated.

1.6 THESIS STRUCTURE

The characteristics of the plant, the nature of the topic and the magnitude of the tests and calculations caused this document to be an involved piece. Due to the practical application of statutory enforcement, the different academic levels and facets of engineering application (practical vs theoretical), etc., it was written for more than one audience. The interlinking of the theories and the processes involved as well as the cross referencing amongst the chapters, made it preferable that the topics be treated in one document. The reader is therefore requested not to neglect the holistic picture but to select what is applicable. The thesis has been divided into two volumes:

Volume I: The list of contents for both volumes and seven chapters.

Volume II: Eleven appendices, containing the supporting documentation.

Volume 1:

Chapter 1: INTRODUCTION

A statement of the problem to be investigated is made. This covers the identification of the deficiency, the status prior to the test programme, through to the new approach and the offered hypothesis with the limitations.

Chapter 2: LITERATURE SURVEY AND EXISTING TECHNOLOGY

This covers the survey carried out on the topic to ensure uniqueness and ground breaking work. It includes other international air flow optimisation criteria, computer programs and previous test data that is available.

Chapter 3: RESEARCH FACILITIES

The layout and specifications of the applicable plant and process are given with general technical information including characterisation of testing in five levels. The unit and Rankine cycle description, equivalent Carnot efficiency and First Law analysis values are supplied. Overall unit, turbine and boiler design figures, as well as plant and process parameters and properties are given. The control system philosophy applicable to this project is explained. Instrumentation and monitoring equipment is treated in order to distinguish between what was automatically monitored by the Sicomp plant computer and parameters where additional accuracy and test equipment was needed. Computer software and efficiency programs are briefly mentioned. Coal and the blending stockyard is explained to illustrate the uniqueness of Lethabo coal with comparisons with other international coals. The electrostatic precipitators are explained and ash analyses are given.

Chapter 4: TEST PREPARATION

This chapter treats the test coal selection and its limit calculation, the unit pre-test outage repairs, the milling plant enhancement and modifications and unit optimisation, monitoring and general arrangements, the unit loading and control setup and special calibrations and settings.

Chapter 5: TEST EXECUTION

Pre-test actions, principles and common routine activities are explained with special attention to mill load lines and grinding media level, Pf sampling, total air flow and oxygen corrections, the new sootblowing philosophy, control system setting and how the air flow was varied. The actual performing of the tests and the operation of the unit are described. The chapter concludes with practical aspects during testing for the operationally inclined reader.

Chapter 6: CALCULATION AND INTERPRETATION OF RESULTS

The devised direct efficiency calculation method is described by means of three levels of data files iterating to obtain the efficiencies and proving validation. Interpretations of the results in over thirty five graphical presentations are given. The results are evaluated which finally leads to coal characterisation and the STEP program customisation.

Chapter 7: IMPLEMENTATION OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

This describes how the results achieved were tested practically and implemented. It covers the statutory requirements and how the findings were confirmed and being made the minimum requirements for Lethabo Power Station. Some cost benefit calculations are shown and finally conclusions were drawn and in retrospection the previous objectives were measured. The thesis is concluded with recommendations for future projects emanating from this one.

Volume II: See the Table of Contents.