HRL Technology | HRL

The energy experts

Prepared for
Brown Coal Innovation Australia

LASER O2 AND CO MONITORING PROJECT
FINAL PROJECT REPORT

Report No: HLC/2015/213

August 2015

by

Thomas Cooper and Tim Bolger

HRL Technology Pty Ltd
ABN 95 062 076 199
The energy experts
Part of the HRL group of companies
www.hrlt.com.au
info@hrl.com.au

*ISO 9001 Quality Management certified by BSI under certificate number FS605116

Mulgrave (Head Office)*, VIC
Level 1, Unit 9
677 Springvale Rd
Mulgrave 3170
Australia
Tel +61 3 9565 9888
Fax +61 3 9565 9879

Coopers Plains*, QLD
Unit 2
33 - 37 Rosedale St
Coopers Plains 4108
Australia
Tel +61 7 3423 4300
Fax +61 7 3345 5937

Perth, WA
Level 1
100 Havelock St
West Perth 6005
Australia
Tel +61 8 6160 6003

Morwell*, VIC
Tramway Rd
Private Bag No. 1
Morwell 3840
Australia
Tel +61 3 5132 1500
Fax +61 3 5132 1580

Prepared for:

Brown Coal Innovation Australia

David McManus

HRL Report Archive
File: 71142070

Revision Details

Revision	Date	Reviewed by	Approved by	Comments
Initial Release	7/8/15	Andrew James Scott Salter	Scott Salter	Approved for release
Rev 1	7/8/15	Tom Cooper	Tom Cooper	Added legend to Figure 22

Disclaimer
HRL Technology (HRL) grants to Brown Coal Innovation Australia Limited (BCIA) a permanent, irrevocable, royalty-free, non-exclusive licence to use, reproduce and publish information contained in this report, which is provided under the agreement dated 7th March 2014, between Brown Coal Innovation Australia Limited and HRL Technology Pty Ltd, Research Project Agreement, Project Title: Laser based O2 and CO monitoring (Agreement).

HRL does not owe or accept any duty or responsibility to unauthorised recipients of this Report. This Report is issued to the BCIA on the basis of information, materials and/or samples provided by, or on behalf of, the BCIA who is solely responsible for acting as it sees fit on the basis of this Report. HRL is not liable to the BCIA in respect of any loss, damage, cost or expense suffered as a result of reliance on the information contained in this Report or any actions taken or not taken on the basis of this Report, except in accordance with the Agreement.

QA 720E

Copyright © 2015 HRL Limited

Executive Summary

HRL Technology (HRLT), in conjunction with Brown Coal Innovation Australia (BCIA) and EnergyAustralia Yallourn, have investigated the latest in-situ laser based flue gas analysis instrumentation for the purpose of improving combustion efficiency using more representative and accurate data on the products of combustion, specifically O_2 and CO.

For the project, two laser instruments were supplied by Siemens, one for measuring O_2 and one for measuring CO. These instruments were installed and commissioned at the Air Heater #1 Inlet on Unit 3 of Yallourn W Power Station in July 2014. The laser instruments were operated between July 2014 and May 2015 with validation checks undertaken monthly using flue gas samples taken from a grid pattern in the air heater duct. From the validation tests, the following key outcomes were obtained;

- Overall, both the CO and O_2 laser instruments were shown to have good agreement with the grid-based flue gas measurements and did not appear to deteriorate over time, providing accurate and repeatable results, as shown in the detailed report.
- In order to prevent ash build up on the optics of the laser instruments, purge gas is required to be used that is free of the target species CO and O_2. Specifically, nitrogen is the recommended purge gas for these instruments.
- Trials with station air as the purge gas showed that the CO laser could be successfully used with this readily available gas. This is a significant and practical finding as a continuous supply of nitrogen as the purge gas is not practical at most current generation power station sites.
- The O_2 laser with station air resulted in the need for correction factors (derived by HRLT as part of this work) to overcome the O_2 in the air significantly affecting the laser O_2 reading. These factors potentially allow O_2 lasers to be used in future applications.

After the successful validation of the instruments, HRL Technology were able to reduce the excess air supply to the boiler using the laser CO instrument to monitor concentration levels of CO as an indicator of incomplete combustion. An optimum between excess air and CO was achieved at around 3.3% O_2 (wet basis) and 200-300 ppm CO. The reduction in excess air is expected to deliver the following benefits to Yallourn W Power Station per unit;

- 0.1% improvement in boiler thermal efficiency, which equates to a fuel reduction of approximately 15,100 tonne/annum
- CO_2 emission reduction of approximately 12,000 tonne/annum
- 350 kWh auxiliary power saving (mostly fans and mills) – potential increase of $57,000/year in power sales.

As boiler heat rates vary between different stations, depending upon specific combustion characteristics, and generally increase during its life, different savings may be available elsewhere. ERF funding can further optimise a specific projects viability, where possible.

For a current generation plant, HRL Technology believe that the CO laser can be readily implemented as an addition to the current flue gas monitoring system and controls. The ideal location for the CO instrument installation would be in the stack to replace the current CO monitors. The current CO monitors can be unreliable, whilst the lasers are very reliable and require very little maintenance. Additionally, in this location the lasers can be used for emissions monitoring requirements as well as providing input to the operators to reduce the air demand for the unit.

Table of Contents

List of Tables

List of Figures

1 Introduction

HRL Technology (HRLT), in conjunction with Brown Coal Innovation Australia (BCIA) and EnergyAustralia Yallourn, investigated if the latest in-situ laser based flue gas analysis instrumentation offered more representative and more accurate data on O_2 and CO concentrations in comparison to traditional analysers.

The overall scope of the project was as follows:

- HRLT assessed the technology offerings from equipment manufacturers and then selected one of the manufacturers to be used in the trial, subject to appropriate support and availability of suitable equipment from the respective suppliers. (Complete – Siemens SITRANS SL selected for use)

- Initial flue gas composition survey at trial power station using HRLT's Multi Point Horiba Gas Analysis System (MPHGAS) and based upon the results of the gas survey, selected the most suitable location for the installation of the trial instrumentation. (Complete – March 2014)

- HRLT supervised the installation of selected technology at recommended locations. (Complete- August 2014)

- Initial monitoring of installed technology was conducted using HRLT's MPHGAS. This included readings being conducted at different plant configurations (i.e. low load operation, different mill configurations and different O_2 set points) to check the accuracy and response of the system. Comparisons were made between the MPHGAS readings, the laser O_2 system and the station's installed O_2 probes. These tests were conducted over several days. (Complete- August 2014)

- Monthly monitoring (for 9 months) of the installed technology, being compared with the MPHGAS, looking for long term accuracy and reliability of the technology. After approximately 6 months of use, if the system is responding well, HRLT conducted a small boiler combustion optimisation test by using the CO and O_2 sensors to reduce the air consumption by the boiler. This was compared with the MPHGAS data to determine how useful the new instrumentation is in setting the boiler air demand (Complete- May 2015).

The data obtained from the tests at Yallourn W Power Station were used to determine the initial viability of the instruments for brown coal power stations. This also gave indicative information regarding their viability for Australian black coal power stations.

2 Project Description

Traditionally, power station boiler excess air is controlled using zirconia oxygen probes installed in the flue gas stream at the boiler economiser outlet. These probes are able to measure the oxygen concentration only at one point in the duct, that being the tip of the probe.

Over many years of conducting Boiler Performance Tests and Combustion Tuning for many power stations within Australia, HRL Technology has observed that the gas composition distribution is highly stratified and the distribution pattern changes with unit load and mill configuration. This changing pattern makes it hard to get a representative sample and therefore hard to accurately control the excess air load within the plant.

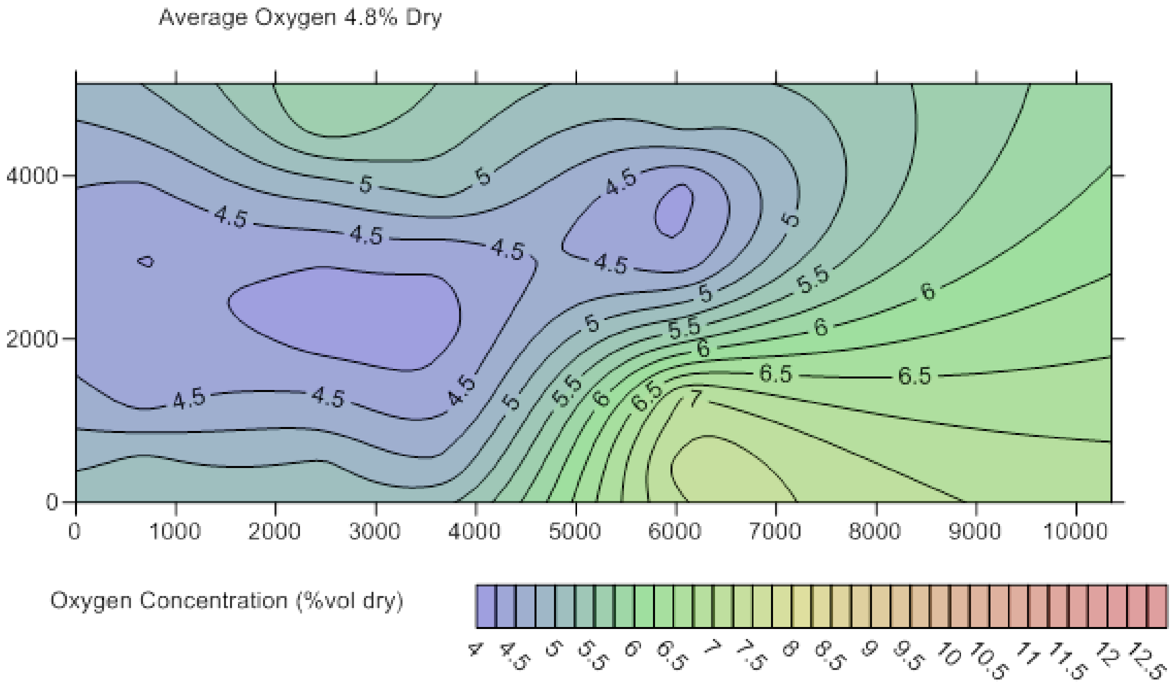

Figure 1 - Example of Oxygen Distribution in Flue Gas from in a brown coal fired power station duct (x and y axis are distances in mm)

The existing probes can only measure single spot readings rather than duct average, which can lead to inaccurate readings of the true oxygen concentration within the duct.

High oxygen concentrations directly impacts the efficiency of the boiler, leading to higher power consumption by the boiler draft fans, which need to deal with larger air flows, and increasing the coal demand to produce the same amount of power at the generator.

These issues are seen in both black and brown coal fired power stations.

The concentration of carbon monoxide (CO) in the boiler is an indication of the quality of the combustion of the fuel being used. High levels of CO indicate that there is not enough air being supplied to the system resulting in fuel being not completely combusted. This can result in an increased risk of fireside corrosion in the boiler. Conversely, the lack of CO in the flue gas may indicate that too much air is being supplied to the boiler, resulting in increased fuel requirements as this extra air needs to be heated to maintain the desired generator output.

Unfortunately, CO measurement is currently seen as unreliable, based upon feedback from several different power station operators, with the sensors typically being either ignored for station control purposes or decommissioned. Continuous Emission Monitoring Systems (CEMS) are often used to measure the carbon monoxide concentration as the flue gas leaves the stack for emissions regulatory requirements; however even these systems have been known to have reliability issues and can have trouble taking representative readings of the flue gas.

By accurately measuring the oxygen and carbon monoxide concentrations in the boiler, the combustion of coal in the boiler can be optimised such that the coal demand is reduced, the draft fan power consumption is reduced, therefore improving the efficiency of the boiler. This will lead directly to a reduction in carbon dioxide being produced in the boiler.

HRL Technology proposed to trial Tuneable Laser Diode Spectroscopy (TLDS) instrumentation for the measurement of oxygen (O_2) and carbon monoxide (CO) in the flue gas from a brown coal fired power station.

Absorption spectroscopy has long been used in analytical chemistry to determine the species present and their concentration in samples. This is based upon the ability of molecules to absorb different light wavelengths depending on their species.

Recent advances in tuneable lasers, which are able to be "tuned" to specific light wavelengths have enabled the cost of this technology to reduce and enabled its use outside the chemistry laboratory. These instruments have been successfully used in the oil and gas industry and are beginning to be used in the power industry abroad. Currently, there is no application of the laser sensors in Australian power stations, despite interest in the technology.

These instruments allow for more representative readings compared with the traditional spot point readings, as shown in Figure 2.

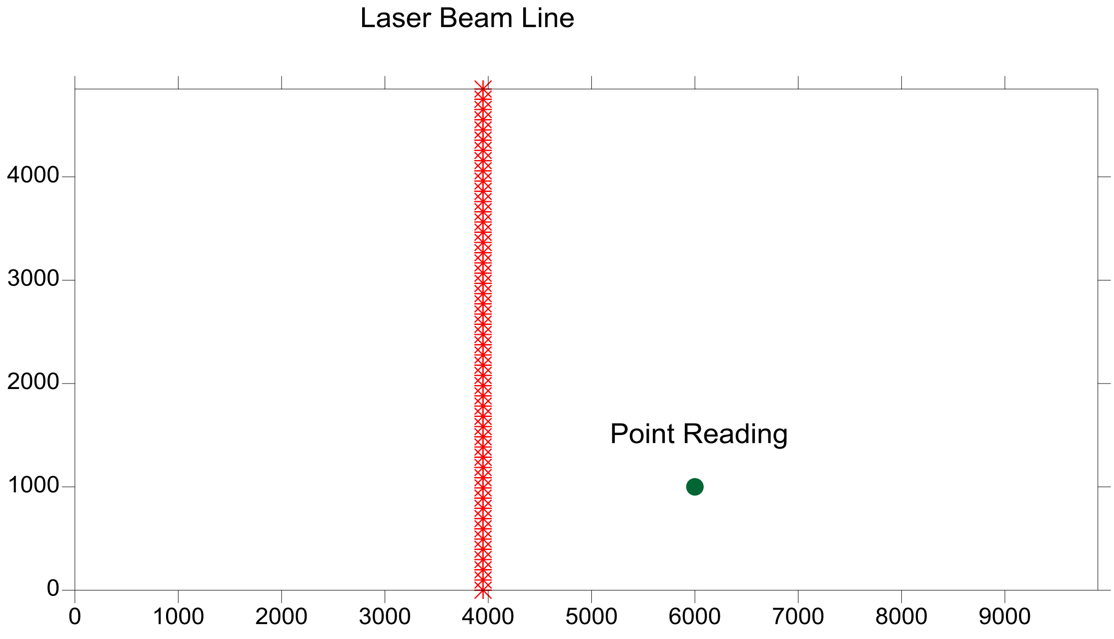

Figure 2 - Comparison between laser reading and spot point reading

One of the challenges for this technology is dealing with the large duct sizes found in Australian brown coal power stations. The receiving sensor must be able to collect a minimum amount of light emitted by the source. The amount of light that can be collected is primarily a function of the duct size and the dust (fly ash) burden in the gas stream.

Case studies from a few manufacturers of the instruments show that the instruments have been successfully used in black coal fired power stations overseas, which have high dust loadings. However, these power stations also have the advantage of having significantly smaller duct sizes compared with the Latrobe Valley Stations. The impact from the high moisture content in the flue gas and ash fouling in Australian brown coal power stations is currently unknown on the performance and reliability of the laser analysers.

3 Project Objectives

At the beginning of the project, the following objectives were defined.

1) **Select Best Location for the Installation of the O_2 and CO Sensors**
   - Determine most suitable location for installation of test equipment based upon plant configurations
   - Determine the flue gas O_2 and CO distribution profile at the test location
   - Select location for the positioning of the O_2 and CO instruments

2) **Confirm the Long Term Accuracy and Reliability of the Sensors**
   - Determine the flue gas O_2 and CO distribution profile at the test location at monthly intervals for nine (9) months
   - Compare system results with measured distribution profile
   - Compare new system readings with the existing O_2 sensors being used by the system
   - Monitor the system for instrument alarms and warnings

3) **Optimise Boiler Combustion Using the Sensors**
   - Conduct boiler tuning exercise to reduce the air demand of the boiler using the new instrumentation
   - Compare results of the tuning exercise with HRL Technology's dedicated boiler multi-point analyser

The following sections will demonstrate how these objectives were met.

4 Objective 1 - Select Best Location for the Installation of the O_2 and CO Sensors

4.1 Determine the most suitable test location

Brown Coal Innovation Australia (BCIA), EnergyAustralia, Siemens Ltd., two other instrument providers and HRL Technology (HRLT) held an initial meeting on 15 January 2014 at EnergyAustralia's Yallourn W Power Station.

The purpose of the meeting was to choose a site for the trial of the instrumentation and to set some key dates for the project.

Unit 3 at Yallourn W PS was nominated as the unit for the trial to be conducted. It had test ports installed previously for HRLT's Multipoint Combustion Diagnostic Analyser (MCDA) or Multipoint Horiba Gas Analyser System (MPHGAS) at the Air Heater Inlet. These systems would be used in determining the accuracy of the laser system.

Unit 3 also had an outage scheduled for early March 2014, where additional ports for instrumentation could be installed.

Three locations, from the boiler exit to the Air Heater Inlet on Unit 3 were investigated as potential test locations, specifically the common boiler exit duct (1), the transition duct before the bifurcation (2) and Rotary Air Heater No 1 Inlet Duct (3). These locations can be seen in Figure 3 below and a list of advantages and disadvantages for each location are shown in Table 1, Table 2 and Table 3.

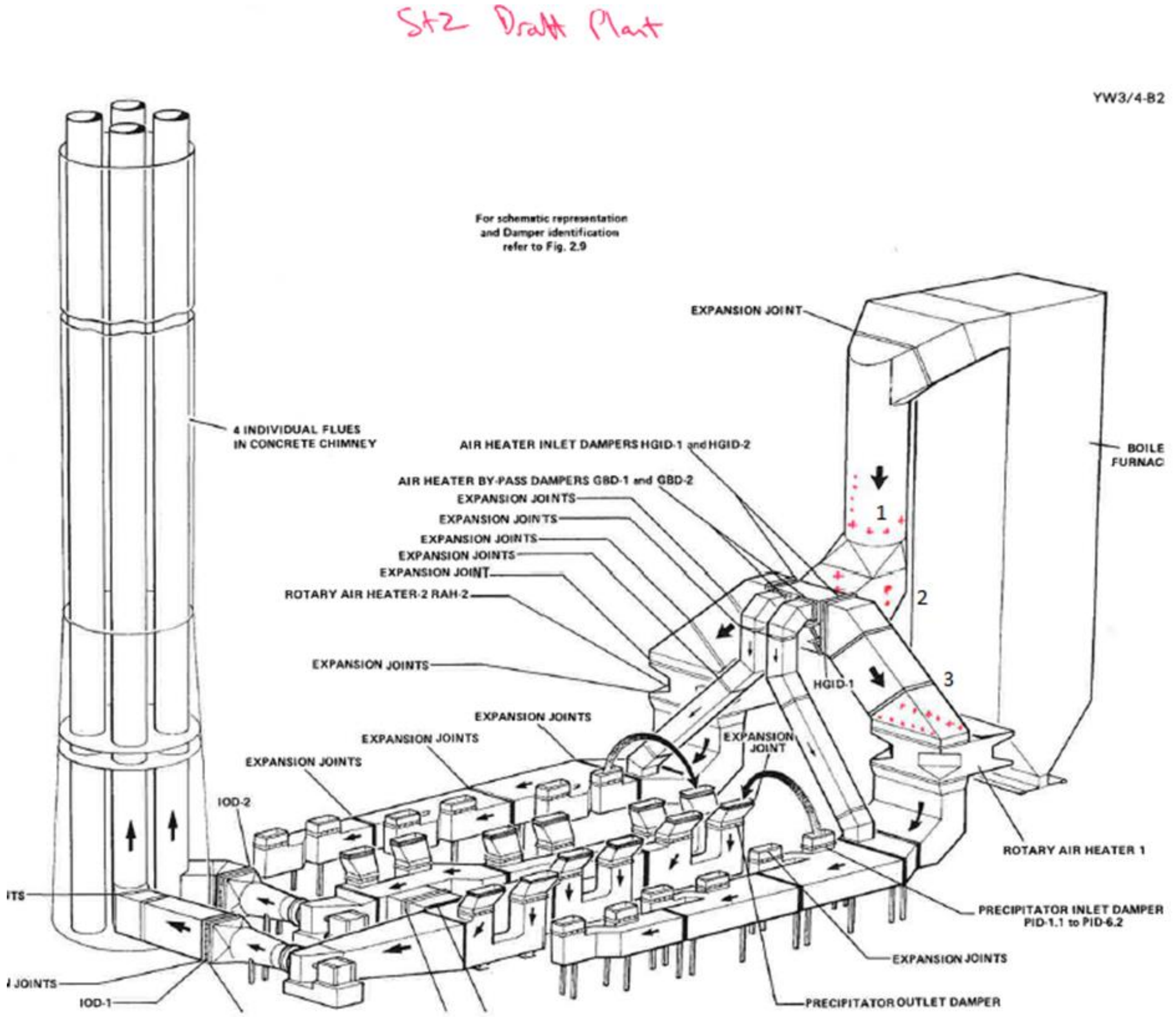

Figure 3- Potential Test Locations

Figure 4- Circular Common Duct

Location 1 – Circular Common Duct	
Advantages	Disadvantages
• Common Duct – can get representative sample of all flue gas • Able to be accessed from one floor (roof of building) • Less physical obstructions than other locations • Cooler for instruments • Less external interference (boiler clean etc.) • Could be used in the future if the technology works	• No close DCS connections • Needs a platform to be designed and built (temp or permanent) to allow for access as the roof is unsafe for walking on • Will need to run nitrogen up from the concrete floor (two floors down) • Exposed to the weather • Need a design review to cut ports into duct as it is a structural component • Will not be able to meet March deadline for port installation due to Stage 1 Major Outage

Table 1- Location 1- Circular Common Duct Assessment

Figure 5- Transition Duct

Location 2 – Transition Duct Before Split – Location of current O_2 probes	
Advantages	Disadvantages
• Close to existing O_2 sensors • DCS access is nearby	• Bad access for testing • Needs scaffolding • Restricted access

Table 2- Location 2- Transition Duct Assessment

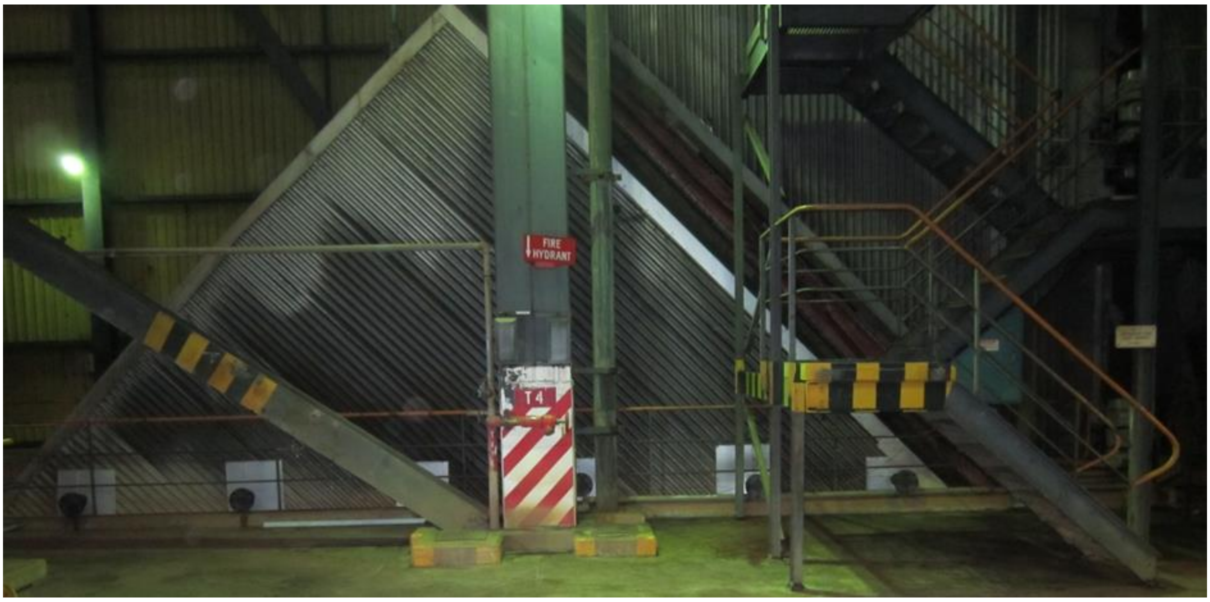

Figure 6- Air Heater 1 Inlet Duct

Location 3 – Air Heater Inlet Duct	
Advantages	Disadvantages
• Easiest access for DCS • Air Conditioned Room for analysis equipment if required • Existing test ports	• Flue Gas distribution is uncertain • Poor access to some test ports (ducts/beams may be in the way) • Will only be testing on one duct – not seeing whole picture of flue gas composition – will not allow for true combustion optimisation during the trial

Table 3- Location 3- Air Heater 1 Inlet Duct

While the group decided that the best location for the instruments would be on the circular common duct if these instruments were to be used for boiler control, this would have required significant engineering work from EnergyAustralia. EnergyAustralia would be required to design a walkway to the duct as the roof was unsafe for access, and an investigation into the structural integrity of the duct would have been required if the test ports were to be installed.

As the major scope of the test was to determine if the instruments are suitable for use in Australian Power Stations, it was decided that Location 3 would be used for the tests as there were already test points available and easy access for all extra equipment.

4.2 Determine the flue gas O_2 and CO distribution profile at the test location

In order to have the ports installed for the trial instrumentation at the outage scheduled for March 2014, characterisation of the test duct was conducted at Yallourn W PS on the 25th and 26th of February 2014.

A total of 6 tests were conducted to determine the characteristics of the flue gas at the test location, including H_2O, O_2, CO, SO_2, NO_X and CO_2 concentrations, flue gas velocities and dust measurements.

An example of the O_2 and CO gas concentration plots and velocity distributions from the Preliminary Tests are shown in Figure 7.

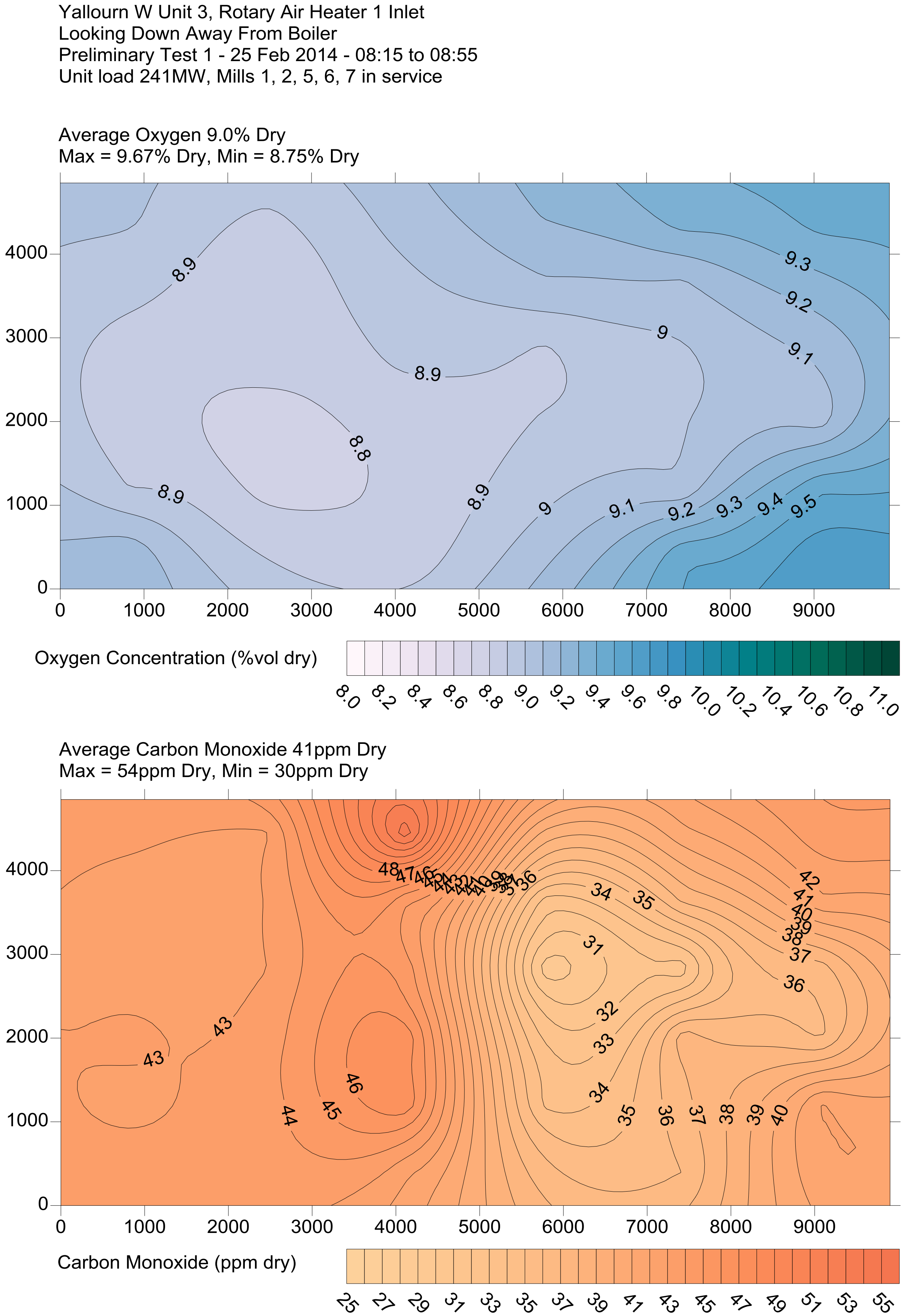

Figure 7- Preliminary Test 1 MPHGAS Gas Plots

The flue gas profiles showed some key features on the distribution of oxygen and carbon monoxide in the test duct which went into determining the preferred installation points for the laser instruments.

Oxygen Profile

Low oxygen is generally seen on the Unit 2 and Precipitator (left and top on diagrams) side of the duct, as illustrated in Figure 8 below, which shows the results of tests conducted on two different days using different mill firing patterns.

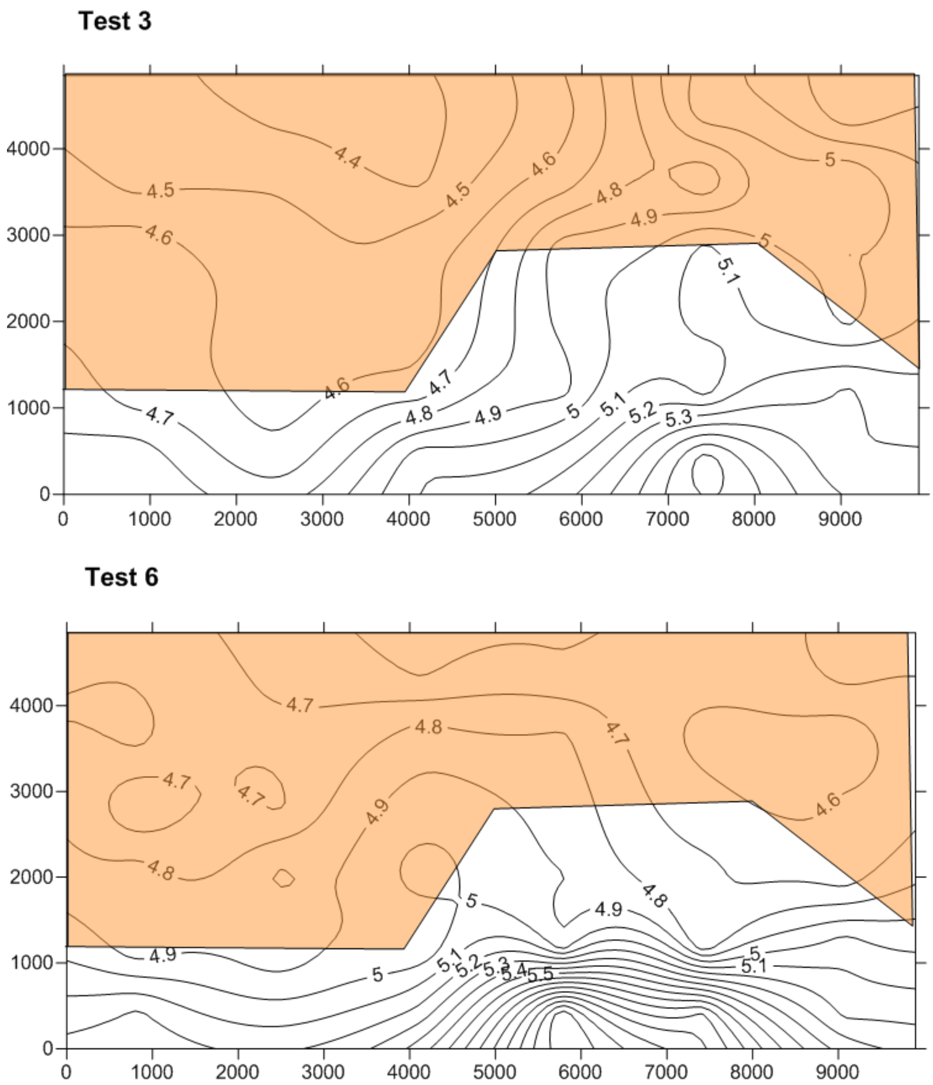

Figure 8- Common O2 Profile Features

This profile appears to be independent of both mill firing pattern and boiler load.

Carbon Monoxide

Carbon Monoxide concentrations are low at 60% and 80% boiler loads, at less than 50ppm, and then increase to a maximum of approximately 310ppm when the boiler is at high load. There is a high variation in carbon monoxide concentrations across the duct at high load, Figure 9.

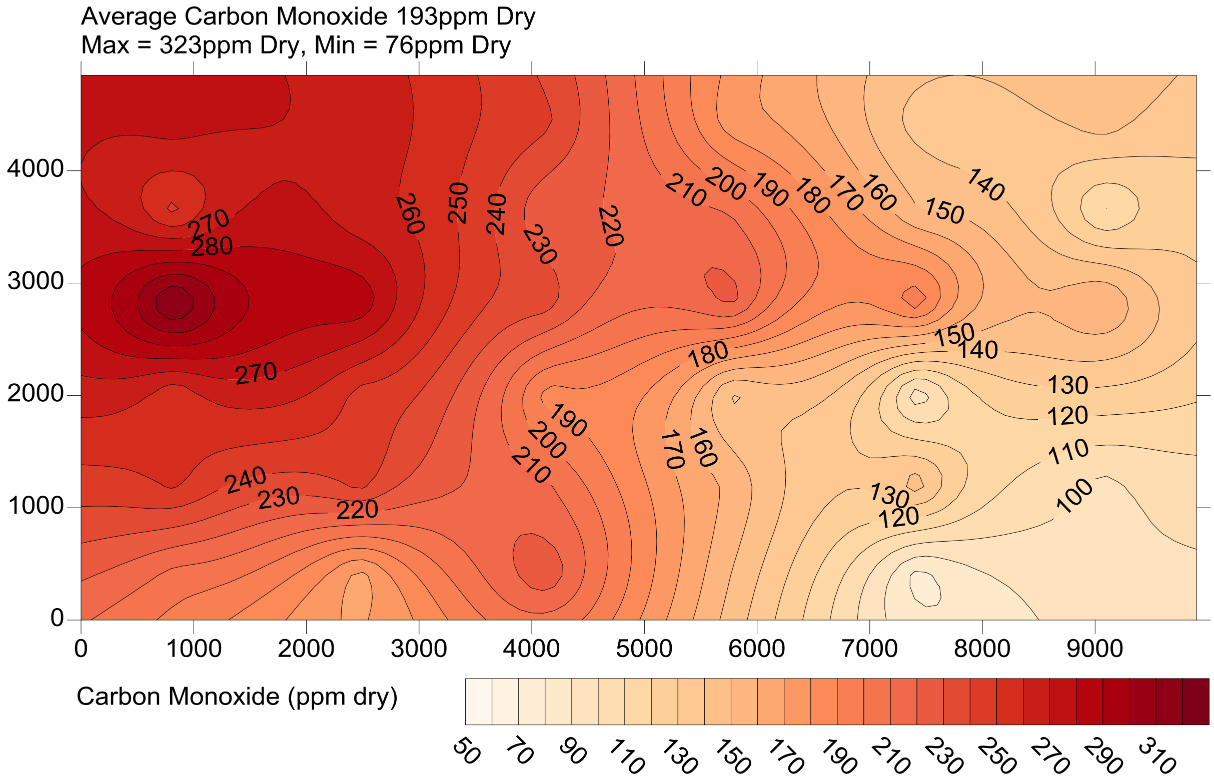

Figure 9 - CO Distribution at Full Load

Velocity Profile

Flue gas velocity was measured for all tests to determine if there is any significant stratification in flue gas flow in the duct.

The velocity was only measured in 5 of the 6 available ports. Due to port access restrictions around the test duct, the port on the Unit 2 side (left hand side on profiles) could not be measured. As such, the velocity profile of the duct is not drawn for that port.

The velocity profile in the duct, Figure 10, shows high velocities around the Unit 4 side (right hand side) and the precipitator side (top) of the duct. This corresponds with the low oxygen readings found in the duct.

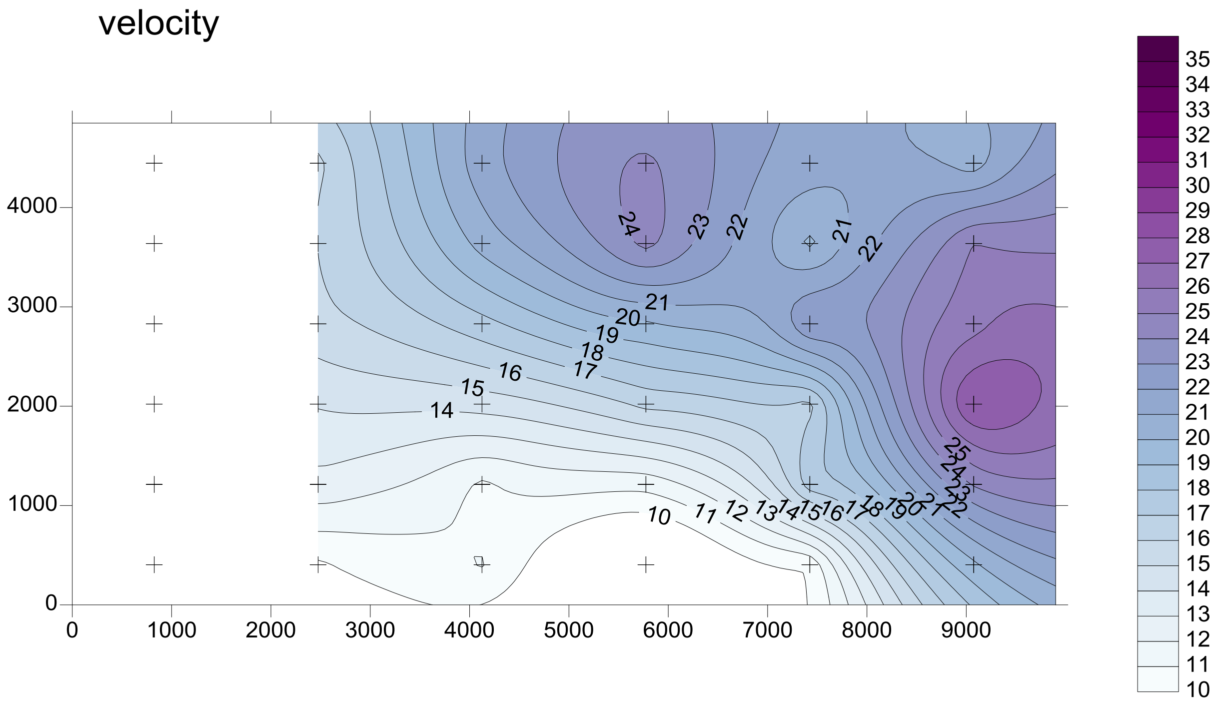

Figure 10 – Velocity Profile at Full Load

4.3 Select location for the positioning of the O_2 and CO instruments

At the conclusion of the preliminary tests, HRLT and EnergyAustralia held a meeting to discuss where to install the instruments for the trial. Based upon the results of the tests, it was decided that the ideal location for the O_2 laser would be along the Unit 2 side of the duct (left hand side on plots) as this was where the lower O_2 readings were situated which are close to the duct average. Ideally the instrument would be installed between ports 2 and 4 and translated along the side of the duct.

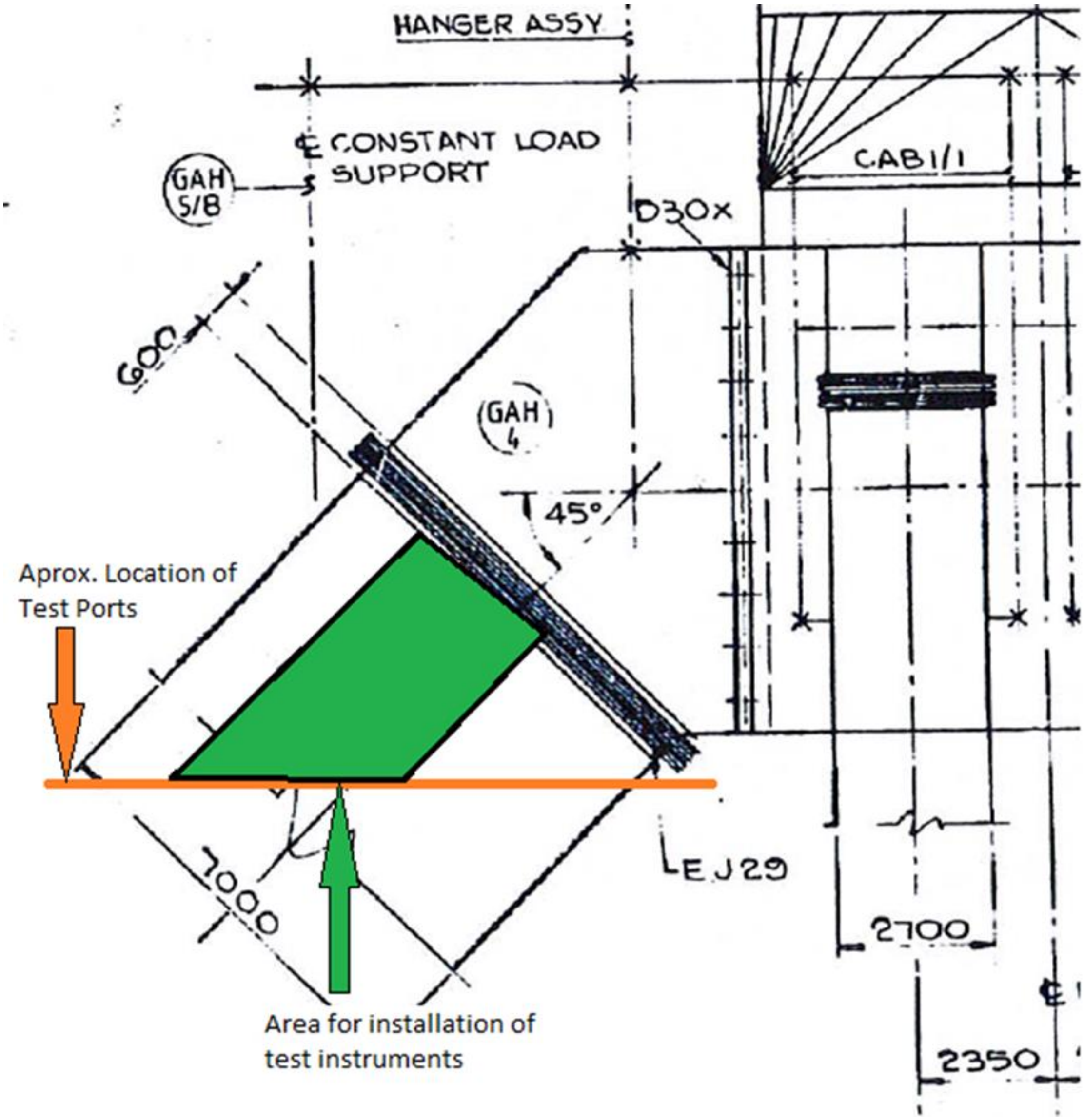

Figure 11- Preferred Area for Installation

Additionally, due to the construction of the duct, this side of the duct ensured that the instruments were installed away from any bends and expansion joints in the duct work.

It was also decided to place the CO sensor close to the O2 sensor on the same side of the duct work as this was where the largest CO concentration was observed.

A site inspection was held to look at the area surrounding the preferred area and identify any plant in the way of the proposed instrument location.

The instrumentation has a transmitter head and receiver head that need to be within 1° of alignment across the duct. Therefore ports need to be installed on both sides of the duct in the same location without interference from the plant work.

Based upon information from Siemens regarding the size of the units and their accessibility requirements, and the physical arrangement of the ductwork and its surroundings, the following location was selected.

Figure 12- Unit 2 Side of Duct showing Surrounding Items and Existing Test Ports

Figure 13- Preferred Location of Instruments, Turbine Side of Duct (end of arrows)

Figure 14- Preferred Location of Instruments- Precipitator Side of Duct

The selected location for the test instruments was approximately 1m above the third port from the Unit 2 side of the duct and then 0.5m either side of this point.

EnergyAustralia then prepared the new ports for the instruments to be installed

Figure 15 - Completed Port Installation

5 Objective 2 - Confirm the Long Term Accuracy and Reliability of the Sensors

5.1 Determine the flue gas O_2 and CO distribution profile at the test location at monthly intervals over nine (9) months

Validation tests were conducted at roughly monthly intervals to determine the flue gas O_2 and CO distribution profile at the test location and to see how the instruments change over the long term. A summary of when these tests occurred is shown in Table 4 below.

Test Type and Numbers	**Dates**	**Air Purge Gas Tests**	**Nitrogen Purge Gas Tests**
Laser Commissioning Tests (CT1 – 7)	6th – 7th August 2014	CT1, 3 - 7	CT 2
Monthly Validation Tests 1 - 12	23rd - 25th September 2014	1-6, 8-12	7
Monthly Validation Tests 13 - 22	22nd - 24th October 2014	13–18, 21-22	19-20
Monthly Validation Tests 23 - 30	25th – 26th November 2014	23-26	27–30
Monthly Validation Tests 31 - 45	10th – 11th February 2015	31–37	38-45
Monthly Validation Tests 46 - 57	22nd – 23rd April 2015	-	46-57
Monthly Validation Tests 58 - 65	20th – 21st May 2015	-	58-65

Table 4- Validation Test Times

To create the flue gas distribution profile, HRL Technology took 36 discrete flue gas measurements in a grid pattern across the duct.

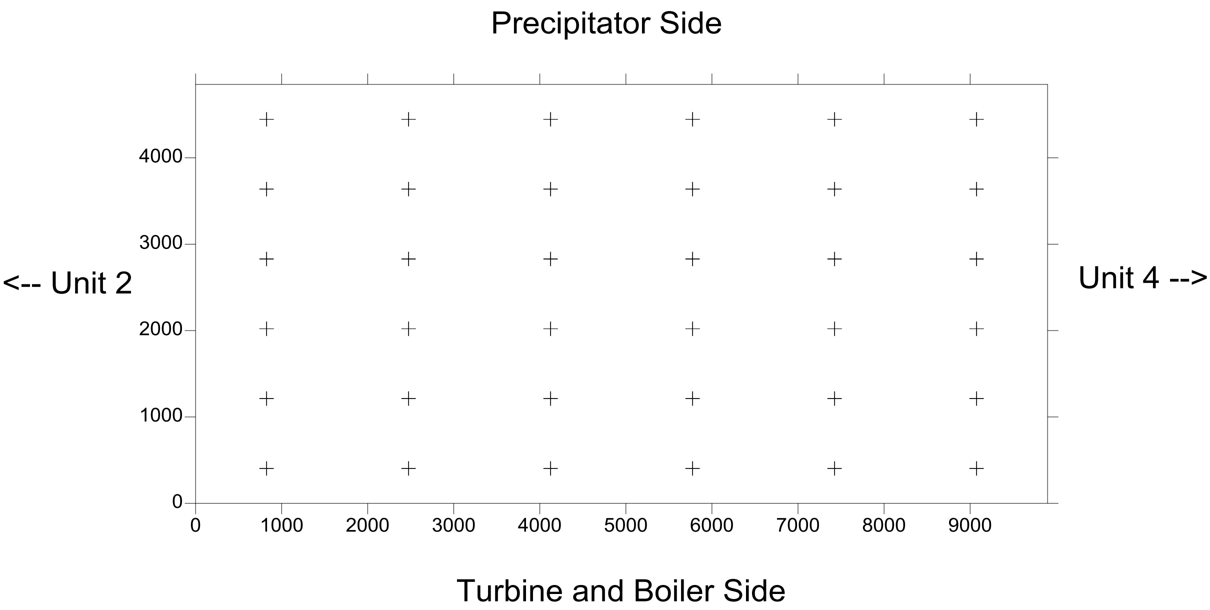

Figure 16 - HRLT Measurement Grid

These measurements are used to create a profile of the flue gas distribution in the duct

An example of HRLT's MPHGAS plots from the monthly validation tests is shown in Figure 17.

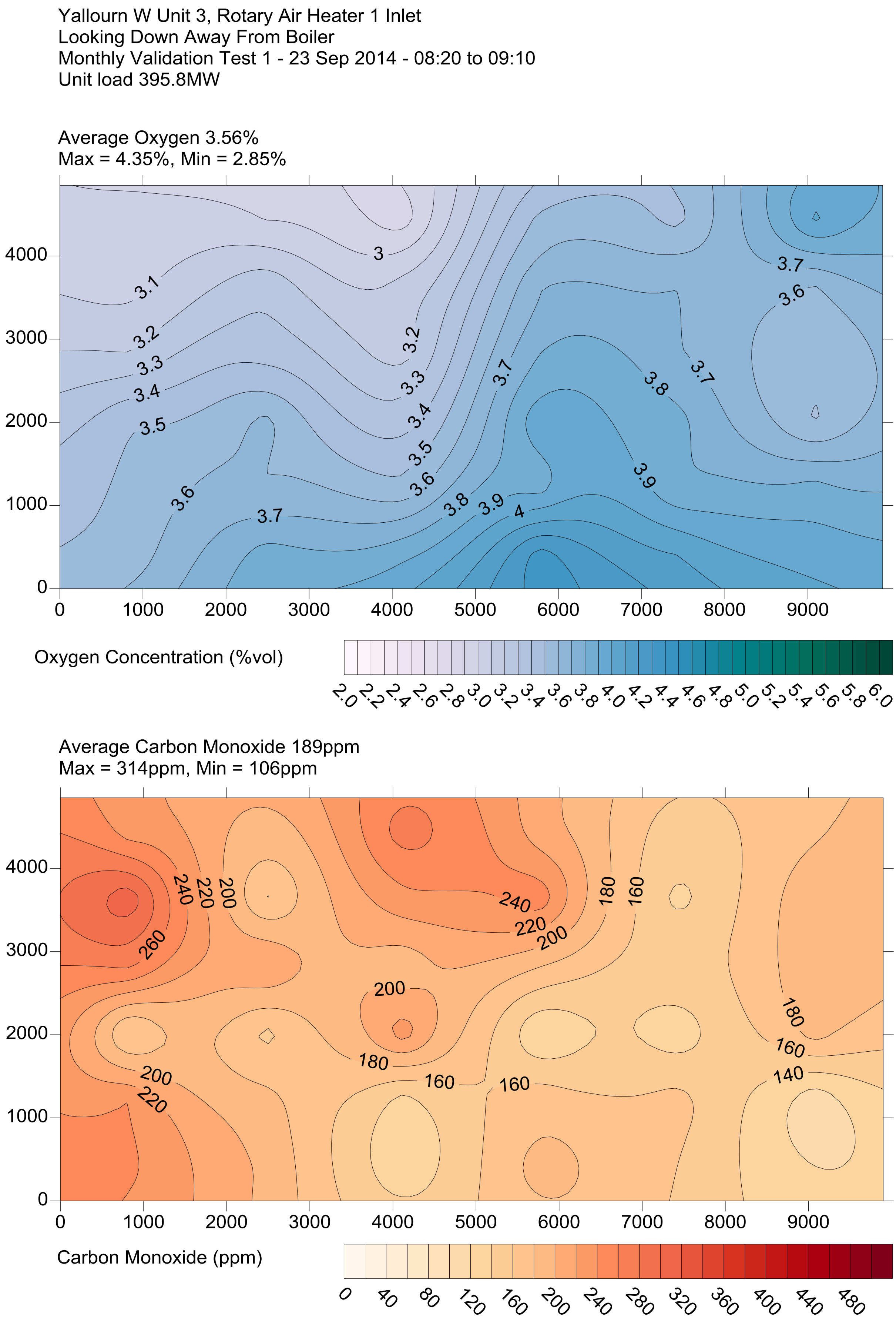

Figure 17- Monthly Validation Test 1 MPHGAS Gas Plots (O2 Purge Gas)

5.2 Compare system results with measured distribution profile

To enable comparison between the laser instruments and HRLT's measured distribution profile an average concentration along the laser beam line was calculated by using a cross section of the distribution profile where the lasers were located, as shown in Figure 18 and Figure 19.

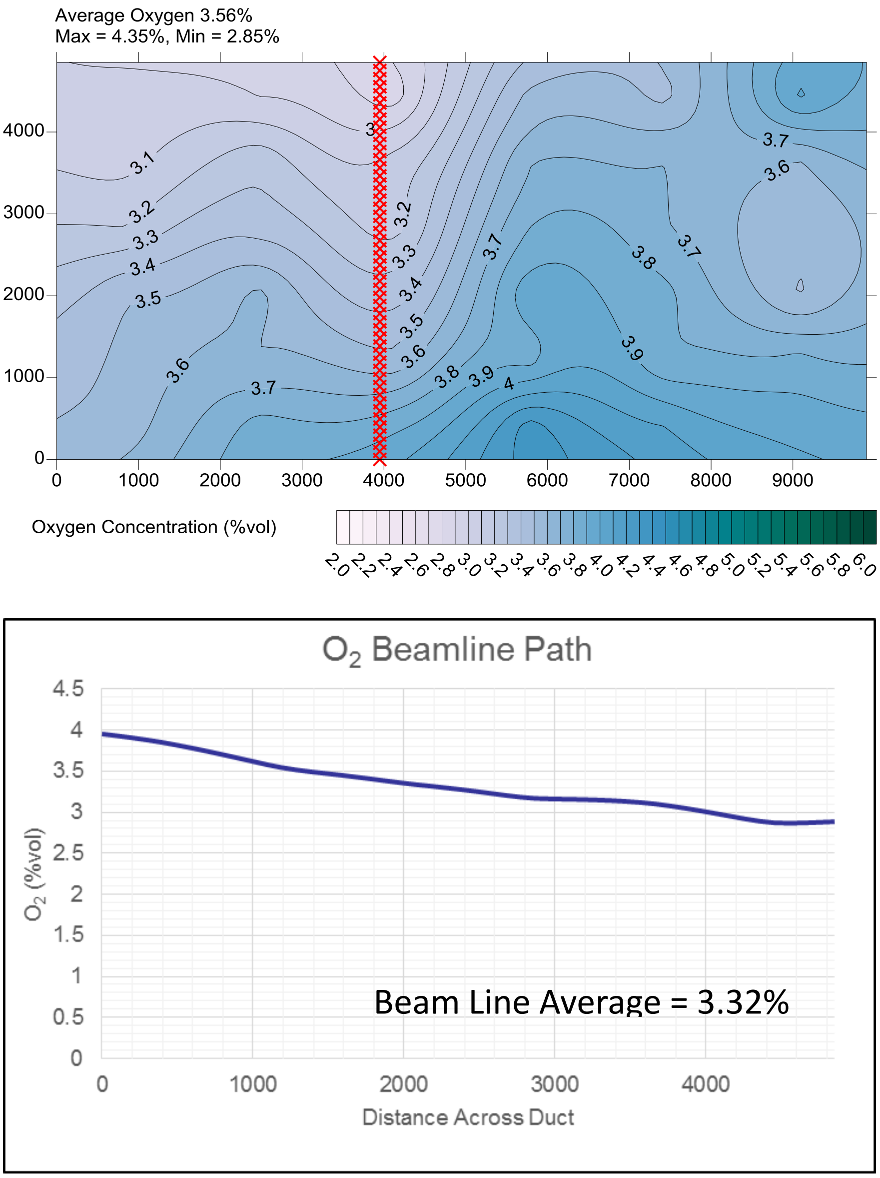

Figure 18 - Calculating the Laser Beamline Concentration for O_2 laser

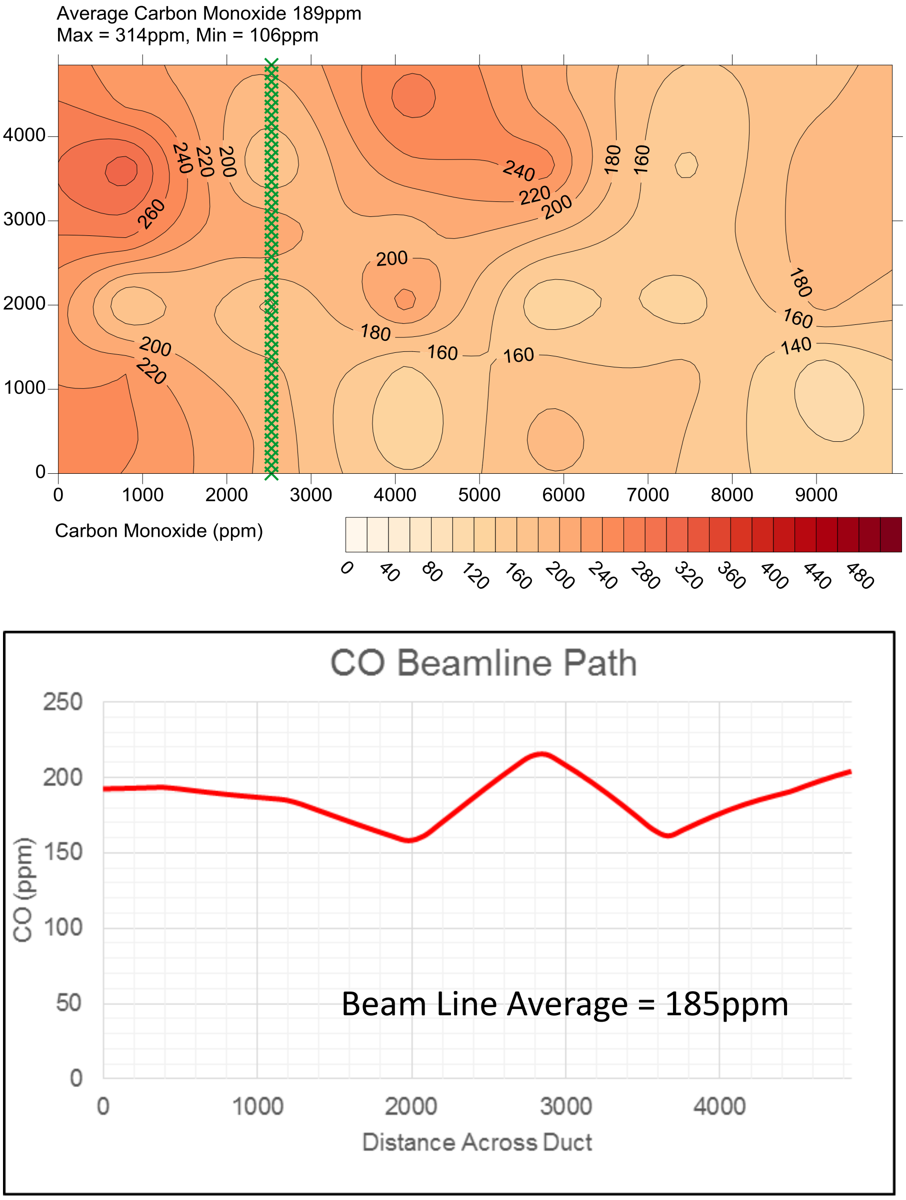

Figure 19 – Calculating the Laser Beamiline Concentration for the CO laser

These calculated values were used to compare with the results for the laser system.

It is important to note that to avoid condensation and dust build up on the instrument optics and in the test ports, purge gas is required. It is a Siemens requirement that the purging gas not contain any concentrations of the measurement target species, as this will influence the measurement. For the CO instrument, instrument air is able to be used as a purge gas as long as it is dry and oil free. However, for the O_2 instrument it is recommended that Nitrogen gas is used as the purge gas.

As many power stations in Australia do not have a large continuous Nitrogen supply available, HRLT also investigated if the instrument air could be used as the purge gas for the Oxygen Laser. A correction equation was developed to determine the corrected oxygen concentration when station air was used as the purge gas.

Through the on-site testing, it was found that the oxygen concentration results obtained using nitrogen as the purge gas were more accurate than the results obtained when station air was used as the purge gas. The nitrogen purge also provided more stable results.

Month by month comparisons for the O_2 and CO lasers are shown in Figure 20 and Figure 21 respectively. In Figure 20 it is evident that there is no significant drift in the accuracy of the O_2 laser over time, as the laser showed close agreement with the expected response each month. The results from the April testing showed the least agreement with the ideal response, which may be due to a calibration error with HRLT's test equipment. It is important to note that during this month the average transmission of the O_2 laser was just 7.4% in comparison to 27.5% for the other months. This suggests that the decline in accuracy may be due to laser misalignment rather than the laser's performance declining with time, especially with May's results being back on target.

Figure 21 shows the CO laser maintained close agreement with the ideal response over the months tested, with the only outliers occurring in February.

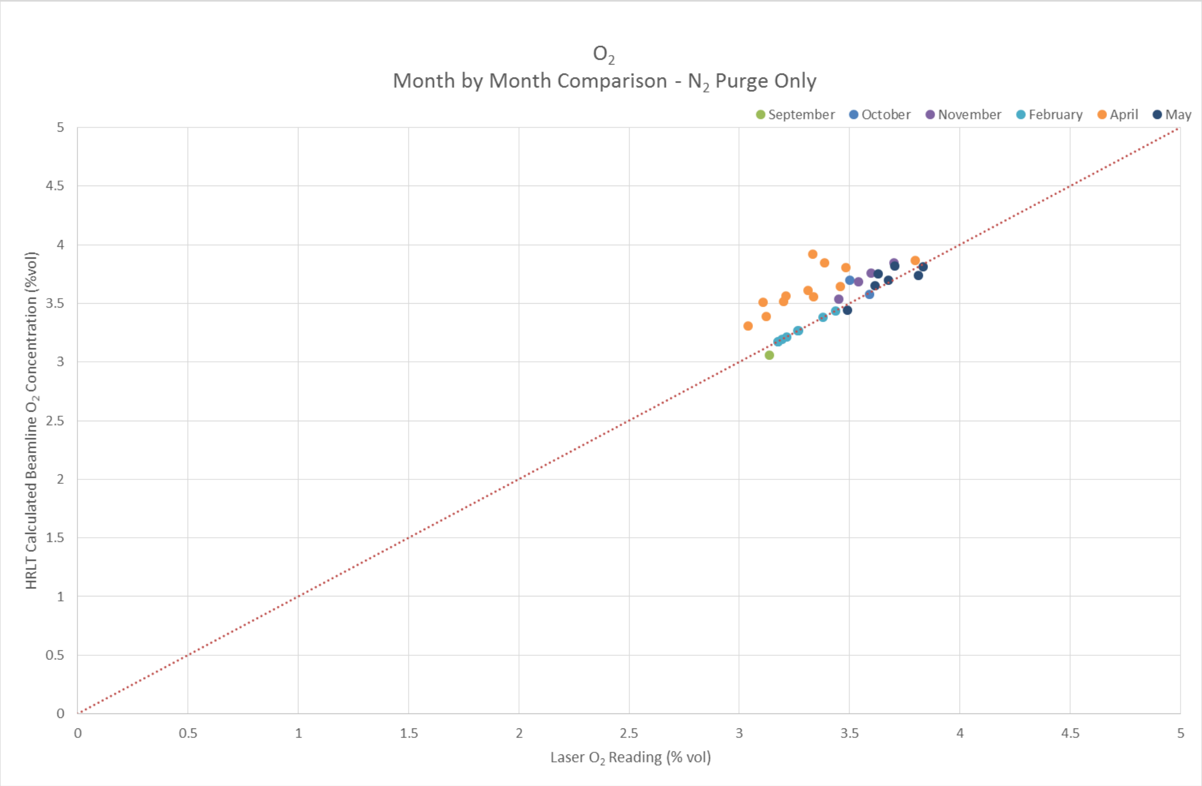

Figure 20- Monthly Laser O_2 Reading Comparison with HRLT Beamline and Expected Response

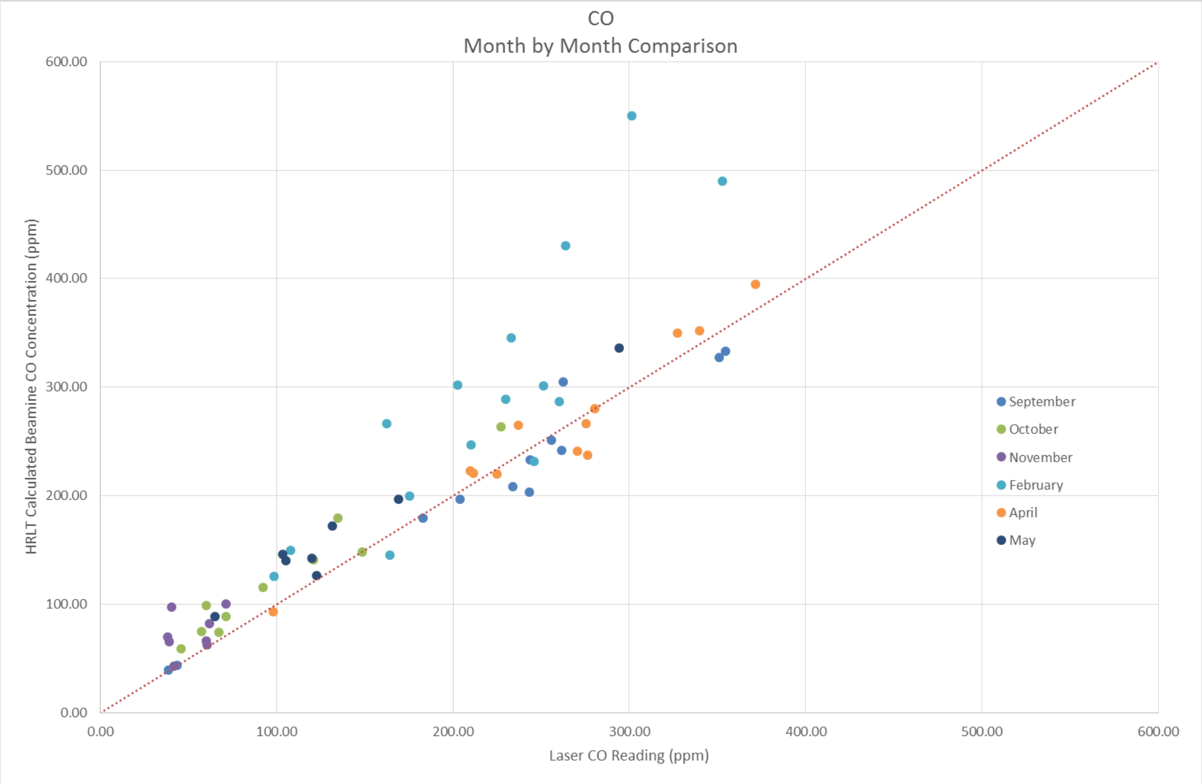

Figure 21- Monthly Laser CO Reading Comparison with HRLT Beamline and Expected Response

5.3 Compare new system readings with the existing O_2 sensors being used by the system

A comparison can be made between the new system (laser O_2) and the existing O_2 sensors from the monthly validations tests. A selection of these results when Nitrogen Purge was being used can be found in Figure 22 below.

In general, it was found that the new laser O_2 values were more closely aligned with the results obtained with HRLT's MPHGAS than the results from the existing O_2 probes, suggesting the laser O_2 system is more representative of actual conditions in the duct.

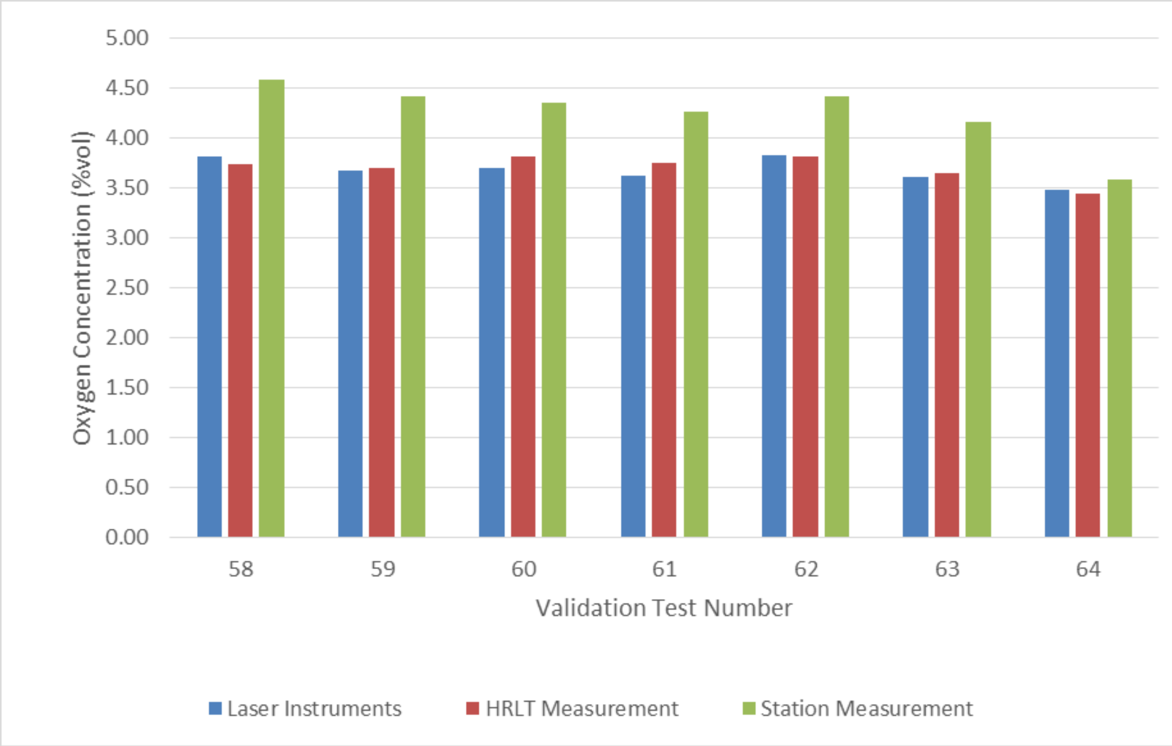

Figure 22 – Comparison of existing O_2 and Laser O_2 sensors

5.4 Monitor the system for instrument alarms and warnings

The Laser O_2 and CO systems transmission values were monitored to ensure tha t there was sufficient transmission to provide accurate results throughout the testing. The average transmission values from the validation tests was 24% and 32% for the O_2 and CO laser respectively, indicating that the lasers provided sufficient transmission throughout the testing to provide accurate results.

The instruments operated without any problems or requiring any maintenance during the project, with realignment of the instruments conducted only once due to project requirements (attempt to observe the boiler start after an outage).

6 Objective 3 - Optimise Boiler Combustion Using the Sensors

The purpose of the boiler oxygen tests were two fold, firstly to subject the laser instrumentation to different boiler conditions and secondly to determine if these sensors can find the most efficient operating point for the boiler.

6.1 Impact of Oxygen Reduction on Boiler Efficiency

ASME Performance Test Code 4 – 2008 – Fired Steam Generators (ASME PTC 4 – 2008) defines boiler efficiency as the ratio of energy output by the boiler to the fuel energy input.

$$\eta_{Boiler} = \frac{Energy\ to\ Steam}{Fuel\ Energy} \qquad \text{Equation 1}$$

To accurately determine the boiler efficiency using equation 1, the fuel flow rate must be accurately determined. ASME PTC 4 – 2008 uses the energy balance or losses method for accurately determining the boiler efficiency. This method has the advantage of providing the lowest uncertainty as well as providing a means at identifying each loss to determine if potential improvements could be made.

ASME PTC 4 – 2008 sets the boundary of the system to determine the boiler efficiency. This system boundary is shown in Figure 23. This figure shows all streams that could be adding or removing energy from the boiler. The code defines four types of energy streams, those being Input, Output, Losses and Credits

Input – Total chemical energy input to the boiler

Output – Energy absorbed by the working fluid

Credits – Energy entering the steam generator system other than the fuel

Losses – Energy departing the steam generator system that is not absorbed by the working fluid

From those definitions, the boiler efficiency can be calculated by Equation 2.

$$\eta_{Boiler} = 100 - \frac{Losses + Credits}{HHV_{fuel}} \qquad \text{Equation 2}$$

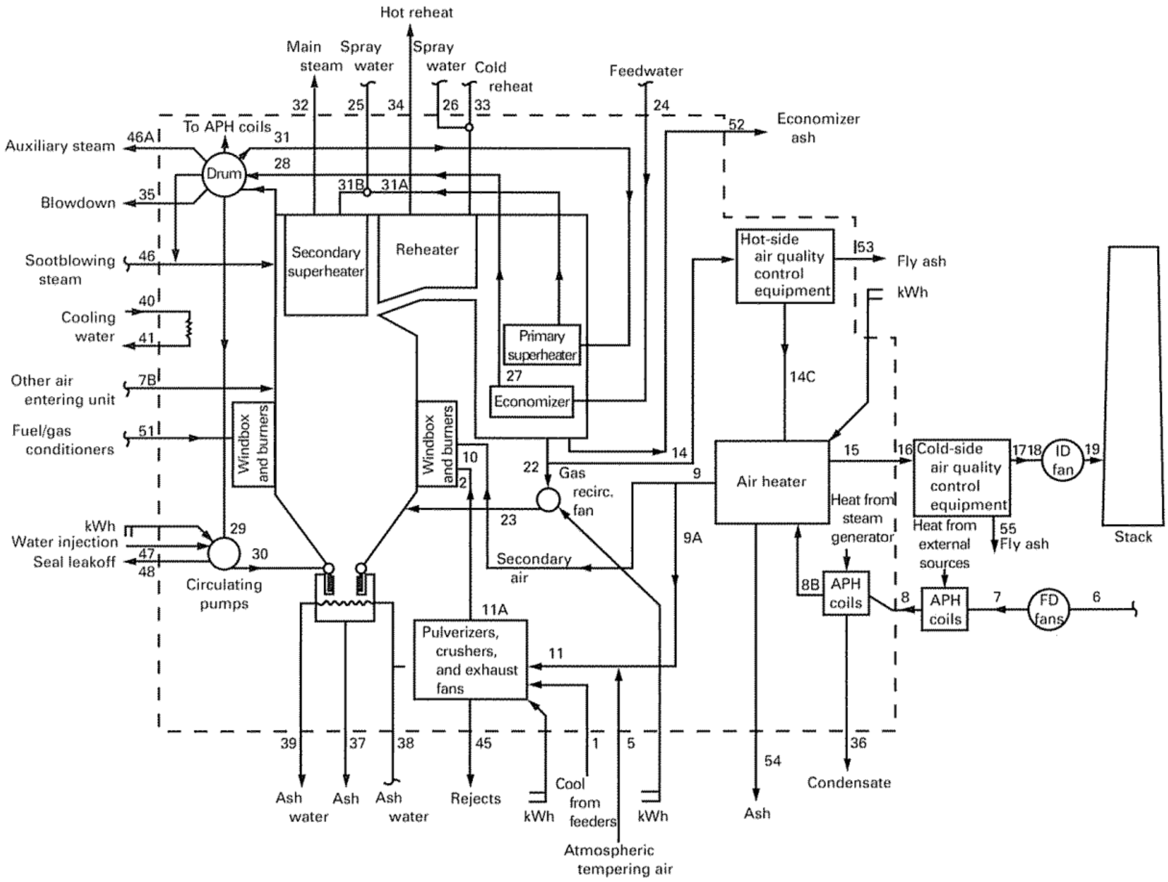

Figure 23- ASME PTC4 2008 - Boiler Efficiency System Boundary – Source ASME PTC 4 2008 – Fired Steam Generators, Page 6

When calculating boiler efficiency for a coal fired power station, HRLT considers the following credits and losses

- Heat credit from auxiliary power use in mills, circulation pumps etc.
- Heat credit from entering dry air – This is air entering the air heater from the FD fans and as the reference temperature used is 25°C, this may be negative and hence a loss to the system
- Heat credit from entering moisture in air
- Loss due to sensible heat in dry flue gas
- Loss due to moisture in fuel
- Loss due to moisture from burning of hydrogen
- Loss due to moisture in air
- Loss due to unburnt carbon in ash
- Loss due to unburnt gas (Carbon Monoxide)
- Loss due to sensible heat in Residue
- Loss due to surface radiation and convection

Further information on calculating boiler efficiency can be found in ASME PTC 4 – 2008.

By reducing the oxygen in the boiler, the impacts on boiler efficiency are realised as follows

- *Loss due to sensible heat in dry flue gas and Loss due to moisture in air*

Lower oxygen levels lead to less air that needs to be supplied and heated by the boiler. This means less fuel is required and hence the total amount of flue gas produced is lower. This has a positive impact on boiler efficiency.

- *Loss due to unburnt gas (Carbon Monoxide)*

Reducing the boiler oxygen adjusts the combustion characteristics of the boiler. As the oxygen is reduced, the concentration of carbon monoxide can increase due to less air in the combustion zone in the boiler. This is energy that is not able to be used by the boiler and therefore has a negative impact on boiler efficiency.

- *Heat Credit from Auxiliary Power Use*

Heat credit from Auxiliary Power Use typically has a very small impact on boiler efficiency as the majority of the auxiliary power use impacted by the oxygen reduction in the boiler, such as the ID and FD fans, sits outside of the system boundary when calculating the boiler efficiency. A small reduction in mill power may be observed as the fuel flow decreases.

It will however have a much larger impact on plant efficiency as the reduced load on the ID and FD fans means that the total auxiliary power demand is lower, which provides additional power to be sold on the grid for the same generator load.

Overall, the effect of reducing boiler oxygen on boiler efficiency is a balancing act between the loss due to sensible heat in the flue gas and the loss due to the presence of CO. As the boiler oxygen is reduced, there is a point where the increased loss due to the presence of CO becomes larger than the savings made in the loss due to sensible heat. This point is known as the 'knee point' and is the point of maximum efficiency in the boiler, as shown in Figure 24.

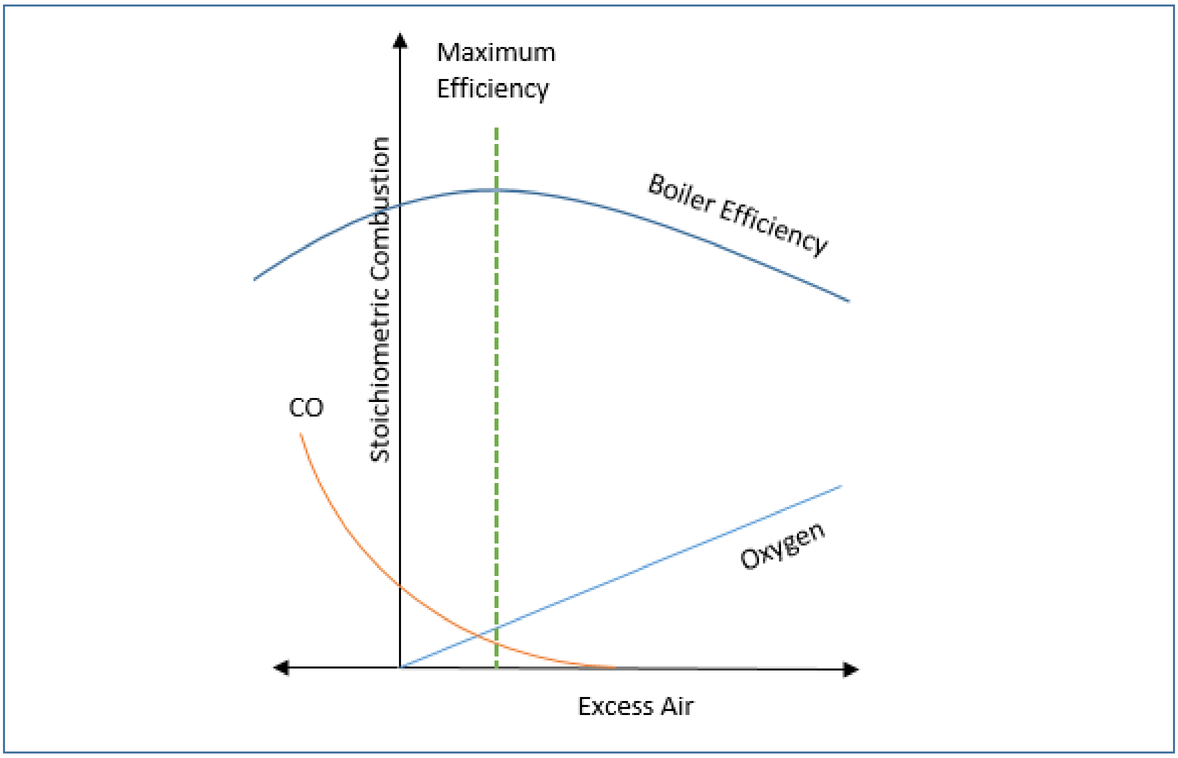

Figure 24 – Impact of reducing Excess Air on Boiler Efficiency

6.2 Conduct boiler tuning exercise to reduce the air demand of the boiler using the new instrumentation

During the February monthly validation tests, boiler oxygen reduction tests were conducted. The objective of these tests was to simulate a boiler tuning exercise that could be achieved by using the laser instrumentation being trialled.

The details of the tests are as shown in Table 5.

Overall Test Numbers	Test Period	Station Instrument Oxygen Range	Purge Gas Used
31 - 37	10th February 2015	3.8% to 3.2%	Air
38 - 45	11th February 2015	3.6% to 3.2%	Nitrogen

Table 5- Boiler Oxygen Reduction Test Details

The following methodology was used when conducting the boiler oxygen reduction tests (from the test procedure).

During the test period, HRLT will request changes to the boiler oxygen level. These changes will be determined by the measured CO levels detected in the flue gas by both the laser CO instrument and the HRLT flue gas measurements. The objective of the changes is to find the 'knee point' where the CO concentration rapidly rises, as just before this point is theoretically the most efficient place to operate the boiler.

The first test of each day is be to determine how the boiler is operating as a baseline before any changes are made, after which the boiler Oxygen set point to be reduced by approximately 0.1% at a time until the 'knee point' is found. For example, if the oxygen set point under normal conditions is 3.5% and the CO reading observed is 100ppm, at the conclusion of this test, HRLT would request a reduction in boiler O_2 *to 3.4% for the next point and so on, until the operational limit of 3.0% is reached or the CO levels exceed the limit of 1000ppm.*

Once a stable oxygen reading is recorded at the requested set point, HRLT will take a set of flue gas measurements to confirm the boiler flue gas concentrations and then make an assessment for the next step.

6.3 Compare results of the tuning exercise with HRL Technology's dedicated boiler multi-point analyser

HRLT calculated the boiler thermal efficiency for all tests based upon the average measured oxygen and carbon monoxide concentrations in the Air Heater #1 inlet duct.

During the two day period the boiler oxygen was reduced so that the boiler efficiency could be improved. The results are shown in Figure 25 and Figure 26 below.

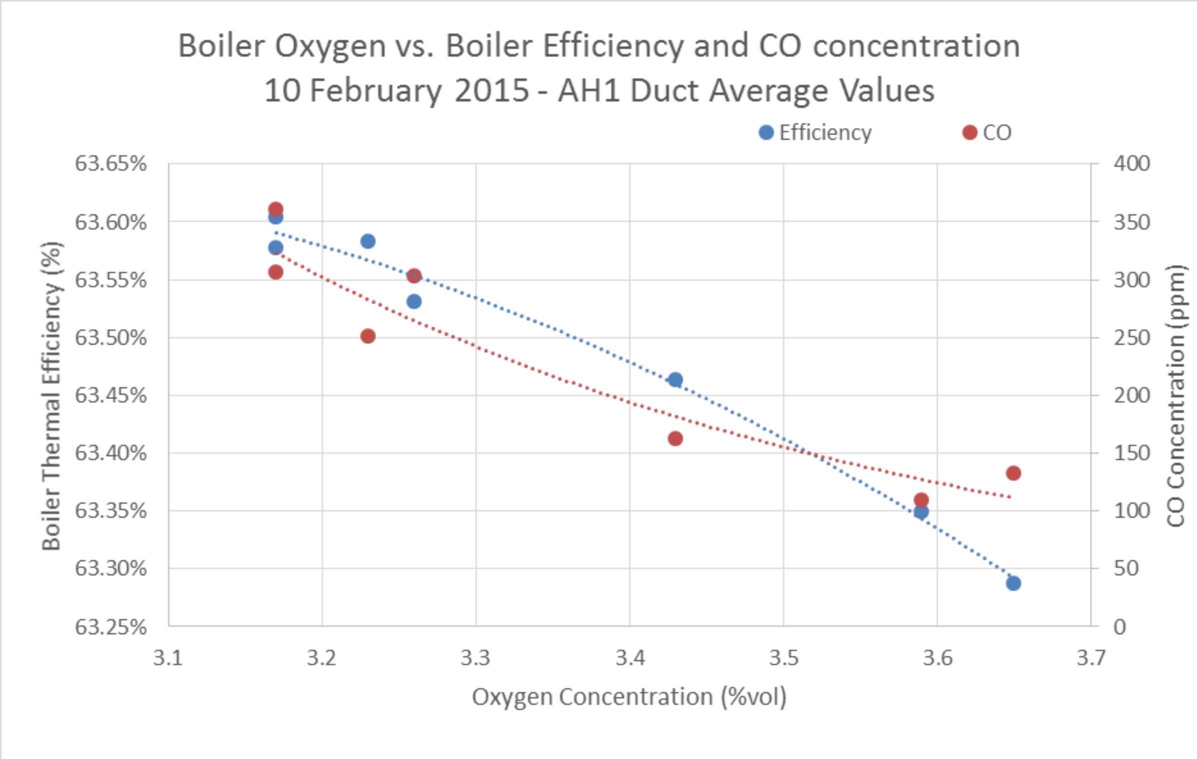

Figure 25- Boiler Oxygen vs. Boiler Efficiency and CO concentration – 10 February 2015

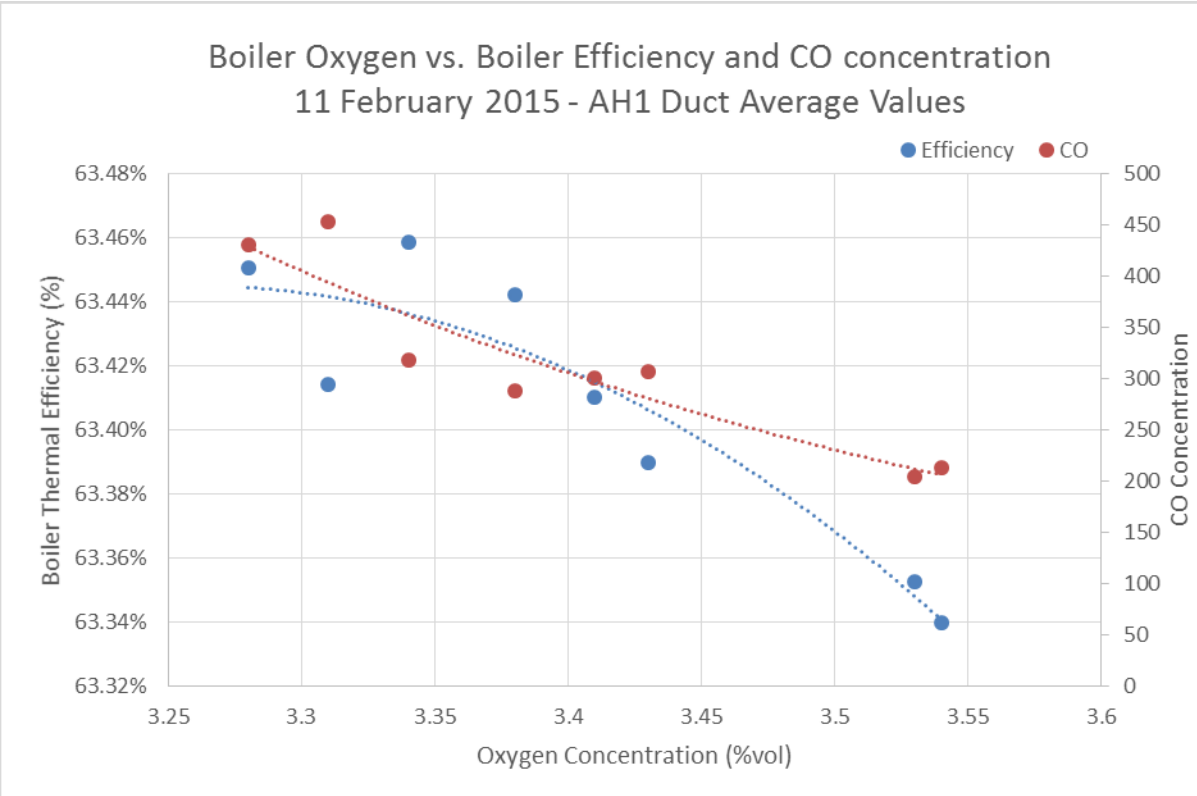

Figure 26- Boiler Oxygen vs. Boiler Efficiency and CO concentration – 11 February 2015

HRLT found reducing the boiler oxygen until the CO levels reach 300ppm will improve the boiler efficiency between 0.1 % pts and 0.25% pts. The results from the thermal model used for the boiler efficiency calculations suggests a corresponding reduction in Auxiliary Load by between 300kW and 600kW for a constant generator output based on the results observed during the tests.

Assuming a 300kW reduction in auxiliary load can be maintained over the course of one year and directly sold to the grid, a 90% plant availability and an average electricity price of $30.33/MWh with a market factor of 0.8, additional sales of approximately $57,400 can be achieved.

7 Conclusion

HRL Technology, together with EnergyAustralia and Siemens, were able to successfully install and commission the laser oxygen and carbon monoxide flue gas analysis instruments. The instruments passed the validation tests and operated for several months to determine their stability in the long term.

HRLT concludes that while the correction using air as a purge gas gives a good indication of the oxygen content in the duct, it is not recommended that air is used as the purge gas if the laser instruments are to be used for the control of the boiler. However, it is important to note that HRLT still believes that the laser O_2 can provide more representative results than the current galvanic O_2 instruments that are used in Australian Power Stations.

From the results obtained, HRLT concludes that the laser O_2 and CO instruments showed strong alignment with the ideal response when nitrogen was used as the purge gas. This indicates that the instruments would be suitable for use in brown coal fired power stations; however, a supply of ample nitrogen for instrument purging is not common in Australian brown coal fired power stations. This makes installing the CO instrument and purging it with air the most feasible option presented.

HRLT believe that a future plant that is designed to have a source of purge gas that is free of oxygen, being either Nitrogen from an Air Separation Plant or Carbon Dioxide from a Carbon Capture Plant, it would be advantageous to use these laser instruments rather than the current galvanic systems.

For a current generation plant, HRLT believe that there is a use for the CO laser by itself as an addition to the current flue gas monitoring system and controls. The ideal location for the CO instrument installation would be in the stack to replace the current CO monitors. The current CO monitors in the stack fail often, whilst the lasers are very reliable and require very little maintenance. Additionally, in this location the lasers can be used for emissions monitoring requirements as well as providing input to the operators to reduce the air demand for the unit. It was also evident that the laser instruments performance remained constant over the monitoring period, with no apparent deterioration over time. Also, extreme heat experienced during the summer months appeared to have no impact on the performance of the laser instruments.

Additionally, HRLT have also reduced the boiler oxygen at Yallourn and have been able to calculate that the most efficient operating point occurs with a CO concentration of 300ppm.

The total estimated cost of a full system setup at Yallourn (with two CO sensors i.e. one per flue) is $225,218. With the reduced excess air demand to the boiler that is achieved with the CO sensors, it is estimated that the payback period for the CO laser installation would be nearly 4 years.

The viability of installing these laser instruments on other operating power station units may be similar or much better, dependent upon the current combustion condition of that specific plant.

8 Acknowledgements

The Plant Performance and Evaluation Division of HRL Technology Pty Ltd would like to acknowledge the efforts of the EnergyAustralia Yallourn staff for their assistance and co-operation with this project, specifically with conducting the required plant modifications to accommodate the new instruments, assisting with the installation and commissioning of the test instruments and achieving and maintaining steady conditions for the duration of each test.

HRL Technology would also like to acknowledge the efforts of Siemens staff for their assistance and co-operation with this project, specifically with the air purge trials and the supply, installation and commissioning of the two laser instruments.

HRL Technology wish to acknowledge the financial assistance provided by Brown Coal Innovation Australia Limited, a private member-based company with funding contracts through Australian National Low Emissions Coal Research and Development Ltd (ANLEC R&D) and the Victorian State Government

HRL Technology wish to acknowledge the financial assistance provided by the project supporting participants:

- Alinta Energy
- AGL Loy Yang
- AGL Macquarie
- CS Energy
- GDF Suez Hazelwood
- GDF Suez Mitsui – Loy Yang B
- Millmerran Operating Company
- Origin Eraring