Carbon Burnout Project – Coal Fineness Effects

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DTI 226: CARBON BURNOUT - COAL FINENESS EFFECTS FINAL PROJECT REPORT

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SUMMARY

Carbon-in-ash presents an obvious cost to coal-fired generation plant in terms of lost fuel. High levels of carbon-in-ash can also inhibit the efficiency of electrostatic precipitators, which in turn can lead to increased particulate emissions, while the potential for selling fly-ash is dependent upon the level of carbon in the ash and excessive levels can result in additional disposal costs.

Within the industry it is generally accepted that improvements in coal particle size distribution are effective in achieving enhanced combustion efficiency and stability, and considerable emphasis is placed on the optimisation and maintenance of coal pulverising equipment at utility power plant as a result. Reductions in carbon-in-ash brought about by improvements to milling plant can allow generators to reduce excess air levels which, in turn, promote reduction of NO_X emissions and improve boiler and precipitator efficiency.

There is, therefore, a requirement to broaden the understanding of the influence of coal particle size on the coal combustion processes occurring within large utility plant furnaces.

The aim of DTI project 226 has been to establish good quality plant and rig data to demonstrate the effect of changing coal fineness on carbon burnout in a controlled manner, which can then be used to support computational fluid dynamics (CFD) and engineering models of the process. The project was designed to achieve this through:

- Full-scale boiler trials
- $1MW_{th}$ combustion test facility (CTF) trials at Powergen's Power Technology Centre
- Laboratory tests of fuel and fly ash samples produced by the plant and rig trials, at Imperial College of Science, Technology and Medicine (ICSTM).

The modelling elements of the project were completed by Mitsui Babcock Energy Ltd (MBEL) and validated using the data produced by the other partners.

The full scale plant trials were successfully completed at Powergen's Kingsnorth Power Station, establishing plant data that demonstrates the effect of changing coal fineness on carbon burnout in a controlled manner. A full set of tests were also completed on Powergen's CTF, operating with four different fuel grind sizes. During these tests both carbon-in-ash and NO_X levels were seen to increase with increasing fuel particle size.

In addition to carrying out laboratory analysis of samples produced during these trials, ICSTM completed video observation of the combustion processes within the furnace during the full unit trials, the results from which contributed to the assessment and interpretation of the burnout measurements.

ICSTM's laboratory analysis of fly-ash produced during the plant and rig trials revealed that only small differences in char morphology and reactivity could be detected in samples produced under significantly different operating conditions. Thermo Gravimetric Analysis (TGA) was also undertaken on a range of PF size fractions collected from mills operating at different conditions. In these data, no significant differences were evident between corresponding size cuts for the different operating conditions.

On the basis of these analyses it has been concluded that there is no significant effect on burnout from differences in particle properties, beyond the impact of PF size distribution on the quantities of unburnt carbon produced.

To provide additional input to the MBEL's CFD modelling, Imperial College also generated chars using their High Temperature Wire Mesh (HTWM) method from three coal grinds. These chars were analysed using TGA and the analysis compared with similar results from the samples taken during the full-scale plant trials. These comparisons indicated that temperatures encountered during char formation on the plant are around 1600°C and almost certainly do not exceed 1800°C.

MBEL undertook CFD modelling on three test conditions from the matrix of tests carried out at Kingsnorth, using detailed measurements of plant conditions including coal fineness and primary air to fuel ratios as inputs. The three conditions modelled represented similar excess air levels, with the same coal under the same firing pattern, but with different grind quality, controlled on plant by the rotational speed of the dynamic classifiers. Consequently, the differences between the tests can be reliably attributed to differences in coal particle size distribution.

This analysis used the FLUENT 6.0.12 code, initially modelling a baseline case with uniform air and coal flows and uniform coal fineness. Subsequent models simulating plant test conditions indicated a sizeable bias of carbon-in-ash production from the bottom burner rows. The performance of the mills feeding these rows was such that they were fed larger coal particles.

The carbon-in-ash trends predicted by the CFD model compared favourably with the trends measured on the plant. In addition to demonstrating the considerable impact that coal particle size distribution has on carbon burnout, analysis of these results also indicated that primary air to fuel ratio has a significant impact on carbon-in-ash levels.

As well as CFD modelling, carbon-in-ash was predicted using MBEL's in-house engineering model. A total of 9 tests were analysed, covering the effects of coal particle size distribution and excess air level. The predictions replicated the observed plant trends to an acceptable level of accuracy, and it was concluded that simple carbon-in-ash models of this nature can be used to quantify the impact of plant operating parameters.

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1 INTRODUCTION

Implementation of low NO_X combustion technologies and increasingly stringent particulate emissions legislation both act to increase the requirements for improved carbon burnout in the furnaces of conventional coal-fired utility power plant.

Fuel which doesn't burn out fully represents a direct efficiency penalty for the plant, while the resultant increases in the levels of carbon in the fly ash reduce the effectiveness of electrostatic precipitators (ESP's) which can cause dust emission problems. High levels of carbon-in-ash can also affect ash sales contracts and potentially incur disposal costs.

It is generally accepted that improvements in coal particle size distribution are effective in enhancing both the efficiency and the stability of the combustion processes, reducing carbon-in-ash levels. If these reductions are large enough, they may allow the operator to reduce excess air levels, which will have beneficial impacts upon NO_X emissions, boiler efficiency and precipitator performance. There is also some evidence in the available literature that improving PF fineness will also have a direct impact on the NO_X formation processes, reducing the NO_X levels produced for a given excess oxygen level.

As a result considerable emphasis is placed on the optimisation and maintenance of coal pulverising equipment at utility power plant. However, there is still a requirement to broaden the understanding of the influence of coal particle size on the coal combustion processes occurring within large utility plant furnaces. Although the effects are clearly recognised, there is an absence of available plant data to specifically demonstrate the effect of coal particle size distribution on the combustion process. To a certain extent this is because carbon burnout in multi-burner utility furnaces is affected by a number of parameters other than coal particle size, the most significant of which are excess air level, coal quality, firing pattern (flame temperature and residence time) and PF and air distribution. To ascertain the effect of coal particle size on carbon burnout it is necessary to maintain these other factors constant.

The aim of DTI Project 226 "Carbon Burnout – Coal Fineness Effects" was to establish good quality plant and rig data to demonstrate the effect of changing coal fineness on carbon burnout in a controlled manner, which can then be used to support CFD and engineering models of the process. The project was designed to achieve this through:

- Full Scale Boiler trials at Powergen's Kingsnorth Power Station
- 1MW$_{th}$ Test Facility trials at Power Technology

- Laboratory tests of fuel and fly ash samples produced by the plant and rig trials, at Imperial College of Science, Technology and Medicine (ICSTM).

It was recognised that significant technical advances had been made in the modelling of carbon burnout within earlier projects which had also received financial support from the DTI. However, the absence of available plant data to demonstrate the effect of coal particle size distribution on carbon-in-ash had prevented full validation of this aspect of both the CFD and engineering modelling approaches that had been developed. This shortfall was addressed by DTI Project 226, the final stage of which involved the production of engineering and CFD models of the combustion processes in the test unit at Kingsnorth. This work was completed by Mitsui Babcock Energy Ltd (MBEL), who validated the models using the data produced in the earlier parts of the programme.

2 PROGRAMME OF WORK

2.1 Full-Scale Plant Trials

The full-scale plant testing represented the largest element of work on the project, and Kingsnorth Power Station was selected as the site where these trials would be carried out.

The four units at Kingsnorth are of a tangentially fired divided-furnace design manufactured by International Combustion Limited (ICL). Each unit has a gross generating capacity of 500MWe, features a tilting-nozzle-type combustion system, and has 5 coal nozzle levels (i.e. 40 nozzles in total). Full load is achieved through firing all 5 elevations. All of the units have been retrofitted with ABB C-E's Low NO_X Concentric Firing System (LNCFS) Level II, which incorporates a separate level of overfire air (SOFA).

Figure 1 shows the arrangement of the corner windboxes in Unit 3 (the test unit). Each column features 5 coal/PA compartments, 10 coal SA compartments, 4 oil burners, 6 offset air compartments, and one level of OFA (supplied through the top oil burner box). Unit 3 typically operates with 12% of the secondary air being staged. The Concentric Firing System (CFS) itself involves the staging of the primary zone combustion air. As shown schematically in Figure 2, the offset air compartments introduce a fraction of the secondary air into the furnace at a different angle (25°) to that of the burner primary and secondary air. As well as providing further staging of air to the central fireball, this firing technique also creates an oxidising atmosphere adjacent to the furnace walls thus reducing the propensity for lower furnace slagging and corrosion

Kingsnorth was selected as the test site because the milling plant there has dynamic classifiers, allowing variations in grind quality to be obtained relatively easily. As a result of previous test activities on the site, it was possible to ascertain the range of PF fineness achievable by altering the speeds of the dynamic classifiers. In this way suitable classifier speeds were selected for the plant trials, which were undertaken with a consistent mill firing pattern over a range of excess oxygen levels for each selected classifier speed. This allowed the impact of varying coal particle size distribution to be assessed in a systematic manner.

The measurements taken during the trials included:

- PF fineness from all in service coal mills using the rotor-probe method (ISO 9931).
- Isokinetic dust sampling at airheater outlet for subsequent determination of carbon content.
- Gas analysis (NO, CO, SO_2 and O_2) at ID fan exit using test instrumentation.
- Excess oxygen level at airheater inlet using test instrumentation.
- Boiler tramp air ingress determination using a methane injection technique.
- Boiler operating parameters from commercial instrumentation.
- Raw coal samples for subsequent proximate and ultimate analysis.

The test unit was also fitted with PF flowmeters on the PF distribution pipes to each burner, providing direct indications of the degree of fuel maldistribution in the furnace.

2.2 Flame Stability Assessment

The lower-volatile coals which tend to give burnout problems can also give rise to less stable combustion in the near burner region. Since this is potentially correctable by adjustments in burner operating parameters it is not a prime mechanism for unburnt carbon production. Nonetheless it was considered to be worthwhile to confirm that qualitatively stable combustion was being achieved during the full-scale plant trials to avoid confusion.

To do this, Imperial College carried out a short programme of video observations during the full-scale plant trials, using techniques and equipment developed under other DTI Projects (CC121 and 207). The resultant video images of near-burner combustion during the trials at Kingsnorth Power Station were used to assess relative combustion stability as operating parameters were varied.

Coal particle size would conventionally be expected to impinge on burnout in the later stages of combustion, when insufficient time is available to complete combustion of the large particles. It was recognised, however, that any changes occurring in PF ignition patterns at the start of combustion might also be important, principally by delaying the start of combustion and hence further reducing combustion time. The video observations allowed these possible differences in ignition/stability between test runs to be assessed relatively accurately and cheaply.

2.3 Combustion Test Facility Trials

To provide data on the influence of PF fineness on carbon burnout with perfect fuel and air distribution, Powergen undertook to perform trials on their Combustion Test Facility (CTF). The fuel used for these trials was identical to that used in the full-scale plant trials, ground to produce particle size distributions representative of those achieved on the plant.

Powergen had previously undertaken similar CTF trials with typical UK and South American coals which had been ground to produce PF fineness levels representative of those achievable from a wider range of commercially available milling/classification equipment. The results of these earlier trials were also made available as part of the project reported here.

2.4 Particle-Based Coal and Char Analysis

Unburnt carbon arises from the failure of a relatively few individual particles to burn completely. Techniques to characterise the nature of individual pulverised coal and char particles have been the subject of sustained research at Imperial College.

Recent results have shown that a very wide continuum of coal particle types exist in pulverised coals, and that individual char particle properties can be related to the composition of the original coal particle. Production of these results involved the processing of high-precision reflectance and bi-reflectance images of coal and char particles, using digital image analysis techniques to yield parameters that describe particle population statistics.

The intent of the analysis conducted under DTI Project 226 had been to utilise these techniques to determine which coal particle types at a given particle size manifest themselves as unburnt char in associated fly ash samples.

Initial optical analysis of a small number of char particles indicated that the morphology of chars generated from significantly different plant operating conditions were remarkably similar. As such, Imperial College concluded that optical analysis of additional samples (coal or char) would be of little value.

Char properties were subsequently characterised by Thermo-Gravimetric Analysis (TGA).

2.5 Coal Grinding Selectivity

It is central to changes in coal fineness whether or not it is just the amounts of the larger particles that are altered or also the types of particles, due to selectivity in grinding.

This coal grind selectivity was originally to be examined using the optical analysis techniques described in Section 2.4. However, the failure of this technique to detect any differences in particle type led to it being abandoned in favour of more sensitive TGA techniques.

Different size cuts from the pulverised fuel (PF) samples extracted during the plant trials were, therefore, characterised using TGA. The greater sensitivity of this technique meant that it was more likely to detect property differences between the coal particle size cuts than optical microscopy. It was also more suited to handling the full range of particle sizes found within PF.

2.6 Char Reactivity for Model Input and Validation

The high temperature wire mesh (HTWM) apparatus developed at Imperial College offers a unique capability for producing char samples at realistically high temperatures (≥ 1600ºC, 10,000 K/s, 1-2 s residence time) for reactivity measurements. Reactivity data from HTWM chars had previously been applied to industrial boiler design, and was identified as forming an essential CFD model input for this project.

Reactivity data was generated using TGA from a series of such experimental chars produced from the coals fired during the plant and rig trials. These could then be compared with the reactivity measurements produced by the activities described in Section 2.4 from actual unburnt char samples collected during the full-scale and test facility trials. The results of these comparisons were used to indicate the thermal history actually experienced by the chars on plant. This data forms an essential input to model validation and can be used to identify (or rule out) non-ideal effects such as particles bypassing the main combustion zones.

2.7 CFD Modelling

Mitsui Babcock set up a CFD model of the unit used for the full-scale plant and simulated a representative cross-section of the conditions tested. The resulting carbon-in-ash data were then compared against the measured data. The validity of the model predictions compared to the actual plant performance was assessed, and sensitivity studies undertaken to quantify the possible reasons for apparent discrepancies.

The model was also used to further assess the impact of larger changes in coal particle size distribution.

2.8 Engineering Model Analysis

Data from the full-scale plant trials was also assessed by means of the engineering model developed previously within the “DTI Collaborative CIA Project” and by using in-house Mitsui Babcock engineering models of burnout.

It was originally planned for additional validation data for the modelling work to be provided “in-kind” by TXU Europe Power from full-scale testing over a range of coals on plant with milling equipment of a similar design to that used for the main full-scale plant trials. However, changes in plant ownership and in the status of TXU Europe Power over the duration of the project have meant that it was not possible to complete this element of the work.

3 DISCUSSION OF RESULTS

Full details of the results produced by each of the activities described in Section 2 were given in the relevant Milestone Reports. In the following the main findings of those reports are listed and discussed.

3.1 Full-Scale Plant Trials

Full scale plant trials were successfully completed at Kingsnorth Power Station, establishing plant data that demonstrates the effect of changing coal fineness on carbon burnout in a controlled manner.

During these trials, a wide variety of measurements were taken using test instrumentation. In the majority of cases, the data was considered to be of high quality. PF grind size and carbon in dust levels have exhibited the anticipated trends (see Figures 3 and 4), with carbon in dust increasing as grind quality was reduced. NO_X levels were also seen to increase as grind quality was reduced (see Figure 5).

NO_X and CO gaseous emissions measured using test instrumentation show consistency with boiler commercial instrumentation. However, quoted tramp air ingress and PF distribution data was treated with some caution, as there were concerns about the accuracy of these results.

Two methods were used to infer tramp air levels from plant measurements. One uses the methane injection measurement technique to determine ID and FD flows, the second calculates tramp air levels from measured oxygen concentrations and the FD flow measured using the methane injection technique. Reasons for the disagreement apparent in the results reported from these two approaches were not fully understood. However, it is accepted that in any method used to establish tramp air ingress, there are large potential errors inherent in the determination procedure. Although the tramp air flows reported by both calculation methods fell within the maximum error bands associated with the measurement techniques, lower tramp air flows are more typical for this size of boiler.

The values obtained for PF distribution were extracted directly from the TR-Tech electrostatic PF Flow measurement devices installed on each burner line on Unit 3. These sensors provide a relative indication of coal flow in each pipe. It should be noted that the degree of accuracy that can be attached to these results is not known, as the devices have not been formally calibrated on every burner line.

3.2 Flame Stability Assessment

The objectives of the video observation sub-task were met successfully. The results contributed to the assessment and interpretation of burnout measurements.

Video techniques developed as part of DTI Projects CC121 and CC207 have proved to be transferable to corner fired furnaces and the results appear to be robust and reasonable.

The results suggest that PF fineness variations from a variable-speed rotary classifier (which does not change the proportions of finer PF significantly) do not have a significant effect on flame stability.

Flame stability is affected by excess air levels at the burners. Lower excess air levels, which can be expected to give poorer burnout, also give reduced flame stability near the burner. This may, therefore, be a contributing factor to poor burnout, in addition to reduced rates for heterogeneous char combustion reactions due to lower oxygen levels.

Relative flame stability may also be reduced slightly at periods of higher load.

3.3 Combustion Test Facility (CTF) Trials

A full set of tests were completed operating with four different fuel grind size distributions through Powergen's CTF at Power Technology.

Basic analysis of NO_X and carbon-in-ash data collected from the rig revealed some interesting trends. NO_X was seen to increase with both increasing O_2 level and increasing fuel particle size. In most cases carbon-in ash also increased as grind size increased. However, samples taken from certain points in the rig showed no discernible trend in carbon-in-ash and in one location the trend was actually reversed.

TGA analysis undertaken by Imperial College on the samples produced from the CTF trials allowed a more thorough consideration of these results. This indicated that the CTF chars had a higher reactivity than either the chars produced during the full-scale plant trials or from the HTWM tests. This suggests that the collected from the rig had not been exposed to the same (high) temperatures in the early stages of combustion as those from the full-scale plant. This is surprising as the furnace is designed such that coal particles experience the same time-temperature history as those on a 500MWe boiler such as Kingsnorth.

However, size analysis of the CTF samples showed almost a complete absence of larger (+125μm) particles. Analysis was therefore also conducted on +/-75μm samples. Similar to sample collected during the full-scale plant trials, the finer fractions showed higher reactivity than the coarse fraction.

It is likely that the gas flow within the CTF furnace is insufficient to maintain coarser particles in suspension. Consequently, they will fall into the furnace bottom leaving only the finer particles available for sampling. This phenomenon would produce both the increase in char reactivity along the furnace gas path and also the increase in reactivity of CTF chars relative to Kingsnorth boiler chars, apparent from the sample analysis that has been undertaken.

Results of the previous CTF testing that were also made available to this project displayed a similar insensitivity of burnout to coal grind quality.

As such, it appears that although combustion conditions on the CTF closely replicate those found at full scale, it is not possible to collect suitable samples of fly ash for the type of analysis employed in this project.

3.4 Particle-Based Coal and Char Optical Analysis

3.4.1 Optical Analysis

Chars from full scale plant tests conducted under two significantly different operating regimes were analysed optically. Essentially, the two test conditions were fine grind, high excess oxygen (expected to promote good combustion) and coarse grind, low excess oxygen (expected to promote poor combustion).

Analysis revealed that under these significantly different operating conditions, only small differences in char morphology could be detected. Imperial College have, therefore, concluded that the effect of different particle properties between different test conditions is insignificant.

3.4.2 TGA Analysis

TGA analysis of fly-ash samples taken from Kingsnorth Power Station have shown that whilst the amount of char present in the samples vary significantly, there are minimal differences in char reactivity.

Further analysis has been conducted on fine (-125μm) and coarse (+125μm) fractions of the same ash samples. The overriding conclusion is that although the coarse fractions showed lower reactivity in each test, there was little difference between the reactivities of each size cut between tests. The coarse fraction always contained a much higher proportion of char than the fine fraction, but represented only a small fraction of each ash sample.

3.5 Coal Grinding Selectivity

PF samples from the mill outlet were extracted at different classifier speeds to obtain a range of PF particle size distributions. These were separated into numerous size fractions. Each fraction was subjected to

TGA analysis. No significant differences were evident between corresponding size cuts for different mill operating conditions.

3.6 Char Reactivity for Model Input and Validation

HTWM chars were generated from three coal grinds at a peak temperature of 1600°C, and subsequently analysed using TGA. The results were provided to MBEL as an input to the CFD model.

TGA analysis of a number of HTWM chars has been compared to analysis of the Kingsnorth boiler chars. The reactivity of HTWM chars generated at 1800°C was lower than any char from Kingsnorth indicating that temperatures on plant almost certainly do not exceed 1800°C. Reactivities of HTWM chars generated at 1600°C are within range of the +125µm chars from Kingsnorth and, therefore, lower than the average values.

3.7 CFD Modelling

The commercially available Computational Fluid Dynamics (CFD) code, FLUENT 6.0.12, was used to examine operation of the furnace used for the full-scale plant trials. This code incorporates up-to-date modelling techniques and a wide range of physical models for simulating numerous types of fluid flow, heat transfer, and chemical reaction problems in complex geometries. It uses unstructured and structured meshes to discretise the model volume, which can be generated around complex shapes with relative ease.

The furnace on the test unit has a division wall, so in this case only one half of the furnace was modelled from the base of the bottom ash hopper to beyond the 7th stage superheater, prior to the back-end convective section entry. It was assumed that this model would be representative of both halves of the furnace.

Given the unit load at the time of testing, coal properties, FD fan flow and furnace in-leakage (determined by O_2 measurement), furnace coal and airflows and temperatures could be ascertained. From these boundary conditions the governing equations of mass, momentum and heat transfer were solved for each of the cells in the model.

There are a number of coal quality related issues that influence the rate at which coal will combust, such as volatile content, fixed carbon and inert ash. These can be ascertained from proximate analysis of any particular fuel, and the combustion process is then typically modelled using the following five steps:

- Heating/cooling of the particle

- Devolatilisation
- Combustion of volatiles within the gas phase
- Diffusion of O_2 to the particle surface
- Char combustion.

In this case a modification was made to account for the additional yield of volatiles due to the high heating rates and temperatures that are experienced by the coal in full-scale plant, as defined by the HTWM measurements made by Imperial College.

At each coal nozzle, a number of representative diameter particles were injected at the primary air velocity to accurately simulate the coal size distribution, with coal dispersion being accounted for via a stochastic tracking algorithm.

Furnace walls were prescribed by an external heat transfer coefficient, external sink temperature and surface emissivity. The initial values assigned were representative of typical natural circulation boilers. These were subsequently tuned to properly simulate the condition of the walls at Kingsnorth (from modelled plant performance data supplied by Power Technology).

The specific test conditions modelled included:

- **Baseline** - idealised distribution of coal, primary air and secondary air flows, uniform particle size distribution averaged from plant data.

- **Medium Fineness** - primary air to fuel ratios defined from averaged plant data, PF fineness defined from specific plant data for Test 2 of full-scale plant trial.

- **Low Fineness** - primary air to fuel ratios defined from averaged plant data, PF fineness defined from plant data for Test 8 of full-scale plant trial of full-scale plant trial.

- **High Fineness** - primary air to fuel ratios defined from averaged plant data, PF fineness defined from plant data for Test 9 of full-scale plant trial.

The PF fineness used for each of the 4 models is presented in Table 1.

During the plant trials the primary air to fuel ratio was found to vary considerably between burners, but appeared to remain constant across the range of tests carried out. To decrease the complexity of setting up the model boundary conditions, the PF/primary air ratios were averaged across the tests and applied to the three models called Medium, Low and High Fineness.

The following analysis approach was adopted for the data produced by the models:

- The models were analysed with regard to the gross flow pattern, the temperature profile and the oxygen and carbon monoxide distribution throughout the model.

- Particle tracking was undertaken to determine the burnout of individual coal particles at different burner elevations for two of the models.

- Predictions of key performance parameters (carbon-in-ash and furnace exit O_2) were compared against measured data.

The carbon-in-ash contribution of each burner was reported for each model to allow for detailed examination of the distribution of carbon-in-ash produced by particular burner-rows or columns. This information cannot be validated against plant but does provide some useful insight.

The most salient results of the CFD modelling exercise have been drawn together to aid comparison.

Figure 6 compares the performance modelling (PROATES) temperature predictions supplied by Power Technology and the equivalent FLUENT predictions for all the cases modelled. The FLUENT values compare reasonably well with those derived from the PROATES software. The FLUENT predictions indicate little variation over the test conditions examined, as might be expected.

The carbon-in-ash contribution from each mill for the tests examined is shown in Figure 7. In the baseline case, the contribution from each row is reasonably constant. This is due to the uniform primary air to fuel ratio and uniform PF grind quality supplied to each burner. In subsequent cases, which used plant data to define primary air to fuel ratios and coal particle size distributions, the predominant sources of carbon-in-ash in the system are the bottom two burner-rows. In each of the cases modelled, a bias of carbon-in-ash and carbon monoxide production is observed from burner column 1.

A comparison of the measured plant carbon-in-ash and the CFD prediction is presented in Figure 8. It can be seen that there is a good correlation between the plant values and the CFD predictions, the trends established from the plant data being well predicted by the model. The CFD values are, however, consistently higher than the plant values by about 0.5 percentage points. This may be due to an overestimation of the convective pass air in-leakage, resulting in an assumption of less air being introduced to the furnace than occurs in reality.

Figure 9 compares plant data and model predictions for the relationship between carbon-in-ash and coal particle size distribution, as represented by the % of mill product larger than 150μm. Additional CFD analysis was undertaken in the production of this graph to examine the impact of coal particle size distributions outwith the range tested on plant. This indicated that improving the coal particle size distribution further yielded little improvement in combustion efficiency. However, using a poorer coal particle size distribution than that seen on plant brought about a significant increase in carbon-in-ash.

Figure 10 summarises the more detailed analysis of the CFD modelling results, exploring the contribution provided by each mill to the overall carbon-in-ash levels measured. This indicates a relatively linear relationship between the PF grind quality produced by each mill and the associated carbon-in-ash levels. When all mills are modelled with the same PF grind quality there is some indication of an increased contribution to carbon-in-ash from mills higher in the furnace. However, and perhaps more significantly, the modelled data indicates that the measured plant relationship between LOI and grind size (see Figure 4) is also influenced by the relative grind quality produced by each mill. This is illustrated by Figure 11, where the impact of modelling the “unbalanced” PF grind quality and PA flows seen on plant is compared with the results of modelling “balanced” conditions. The “balanced” predictions (representing the baseline case and the two cases in which particle size distributions outwith the range tested on plant were modelled) assumed that the same PF grind quality would be produced by all mills.

3.8 Engineering Model Analysis

In addition to the CFD modelling described above, Mitsui Babcock’s in-house carbon-in-ash predictor was also used to estimate the burnout at Kingsnorth. The model is comparatively simple, and makes use of straightforward ‘engineering’ inputs.

The salient features of the model are that it considers the burnout from each burner elevation, but not for each individual burner. Thus, the coal flow, fineness, stoichiometry etc. are specified by burner elevation. Gas temperatures are calculated independently pf the model.

Tests 1 to 9 of the full-scale plant trials were selected for analysis. These tests cover the effect of excess air level and coal particle size distribution (or varying classifier speed). All tests were undertaken at uniform load and with the same OFA damper settings.

For the burnout prediction it was assumed that 50% of the tramp air entered via the convective pass and was ineffective in the real combustion process – it is recognised that this is a ‘typical’ value, but insufficient data was collected to allow the accurate calculation of the tramp air distribution (a major exercise in it’s own right).

Figure 12 shows how the predicted carbon-in-ash compares against the plant measurements for all 9 tests. Generally the agreement is reasonable (within +/-2% points) but there are a number of data points where the agreement is poorer. This is unsurprising given the simplicity of the model and analysis procedure, however it is encouraging that such a simple approach leads to good predictions of carbon-in-ash more often than not. For many practical appliances the running of a full combustion CFD model is inappropriate (mainly due to the very long run-times required to achieve suitably converged solutions), and the analysis undertaken here further demonstrates the value of comparatively simple carbon-in-ash predictors in engineering applications.

Figure 13 presents the measured and predicted carbon-in-ash values vs. excess O_2 for the 3 classifier speeds tested. The measured data shows that the main benefit in classifier speed arises from an increase from 50 RPM to 60 RPM, there is little effect in a further increase to 70 RPM. Higher carbon-in-ash arises from reduced excess O_2. The predictions are found to broadly follow the observed trends – there is an increased sensitivity to excess O_2, and for most of the tests, the predicted carbon-in-ash is highest for the 50 RPM case, lowest for the 70 RPM case.

It is therefore shown that even a simple model for burnout can give a reliable quantification of the effects of coal fineness and excess air level.

4 CONCLUSIONS

- Full scale plant trials to establish the impact of coal particle size on carbon in dust and NO_X formation were successfully completed at Powergen’s Kingsnorth Power Station.

- During these plant trials good quality data was extracted for the majority of measured parameters including unburnt carbon levels, PF grind quality and NO emissions. The trends established from this data indicated that both carbon in dust and NO increased as grind quality was reduced.

- The tramp air flow determinations and PF distribution data collected during the full scale plant trials should be treated with a degree of caution due to some concerns about the accuracy of the results.

- Video techniques, previously developed by Imperial College, were also used to undertake flame stability assessments during the full-scale plant trials. These indicated that excess air levels at the burners had the most significant impact on flame stability, whereas the changes in grind quality affected during the trials were observed to have little impact.

- A full set of tests were also completed operating with four different fuel grind size distributions through Powergen's Combustion Test Facility (CTF) at Power Technology. These produced data that supported the findings of the full-scale plant trials in most case showing that both carbon-in-ash and NO_X levels increased increasing fuel particle size.

- There were some anomalous results apparent in the carbon-in-ash data taken from the CTF. Samples taken from certain points in the rig showed no discernible trend in carbon-in-ash with fuel particle size and in one location the trend was actually reversed. Further analysis of these trends has led to them being attributed to the low velocity profiles required within the CTF. These ensure that the primary design intent of the facility is achieved: the development of a time-temperature throughout the rig which is representative of that encountered on full-scale plant. Unfortunately, they also lead to larger char particles falling out of the flow prior to sampling.

- In addition to providing the further analysis of the samples from the CTF, Imperial College also undertook particle based optical and Thermo-Gravimetric Analysis (TGA) of samples produced from the full-scale plant trials. These indicated that although the amount of char present in the ash samples varied significantly depending upon the operating conditions at which the tests were undertaken, there was little change in either the morphology or the reactivity of these chars.

- Imperial College's analysis of coal grind selectivity indicated that there were no significant differences between corresponding size cuts produced from samples collected at different mill operating conditions during the full-scale plant trials.

- To provide additional input to the MBEL's CFD modelling, Imperial College also generated chars using their High Temperature Wire Mesh (HTWM) method from three coal grinds. These chars were analysed using TGA and the analysis compared with similar results from the samples taken during the full-scale plant trials. These comparisons indicated that temperatures encountered during char formation on the plant are around 1600°C and almost certainly do not exceed 1800°C.

- The Computational Fluid Dynamics (CFD) Modelling undertaken by MBEL was shown to agree well with the measured combustion performance of Kingsnorth's Unit 3. The effect of PF fineness observed on plant was suitably reproduced, with good correlation between plant carbon-in-ash values and those values predicted by the CFD model. Modelling of test conditions indicated that there was a substantial bias of carbon-in-ash towards the bottom two burner-rows. This bias was as a result of reduced coal fineness and low primary air to fuel ratios for these burner-rows.

- The arch and furnace exit gas temperatures calculated using CFD compare well with those derived from Powergen's plant performance modelling software (PROATES). The CFD predictions indicate little variation over the test conditions examined.

- Predictions of furnace exit oxygen compared moderately well with those values measured on plant.

- Examination of a coal particle size distribution finer than that tested on plant indicated that improving the coal particle size distribution further yielded little improvement in combustion efficiency. Factors such as air/fuel distribution, residence time and excess air level may limit the attainable carbon-in-ash after this point.

- Examination of a coal particle size distribution coarser than that tested on plant indicated that worsening the coal particle size distribution further significantly increased the predicted carbon-in-ash.

- The Mitsui Babcock in-house carbon-in-ash predictor was able to replicate the plant trends with regard to the effect of excess air level and coal particle size distribution. Simple engineering models of this nature are therefore seen to represent a practical alternative to sophisticated CFD codes for the quantification of the effect of plant operating variables on carbon-in-ash.

5 FUTURE WORK

This project was successful in achieving its objective of establishing good quality plant data demonstrating the effect of changing coal fineness on carbon burnout. However, some of the phenomena apparent in this data, and analysis of the results of the CFD modelling it supported, suggest a number of areas worthy of further investigation.

The quality of the plant data-set produced reduced the need for further model validation using data from other tangentially-fired plant, which was originally to be brought to the project by TXU. Circumstances outside the control of the project partners meant that this data was not available when required, however, this has had no adverse impacts on the model validation work undertaken.

Data from other plant would be valuable in assessing whether the trends of carbon-in-ash with mill grind quality observed in the Kingsnorth data are repeated elsewhere, particularly on plant with different combustion configurations and milling plant.

It would also be beneficial to undertake further testing to assess how accurate some of the conclusions drawn from the CFD work are, particularly the impact that varying individual mill conditions (particularly grind quality and primary air distribution) has on overall carbon-in-ash levels.

6 ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance of staff from each of the partner organisations to this project in the preparation of this report, particularly Michael Maloney, Jon Gibbins, Peter Cooper and Richard Hill.

7 REFERENCES

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Hill R, Gibbins J R & Mann C K, (2003). STP 08/01 & 02/02 2002: DTI 226, Carbon Burnout Coal Fineness Effects – Second Milestone Report. Power Technology report PT/03/BE21/R, February 2003.

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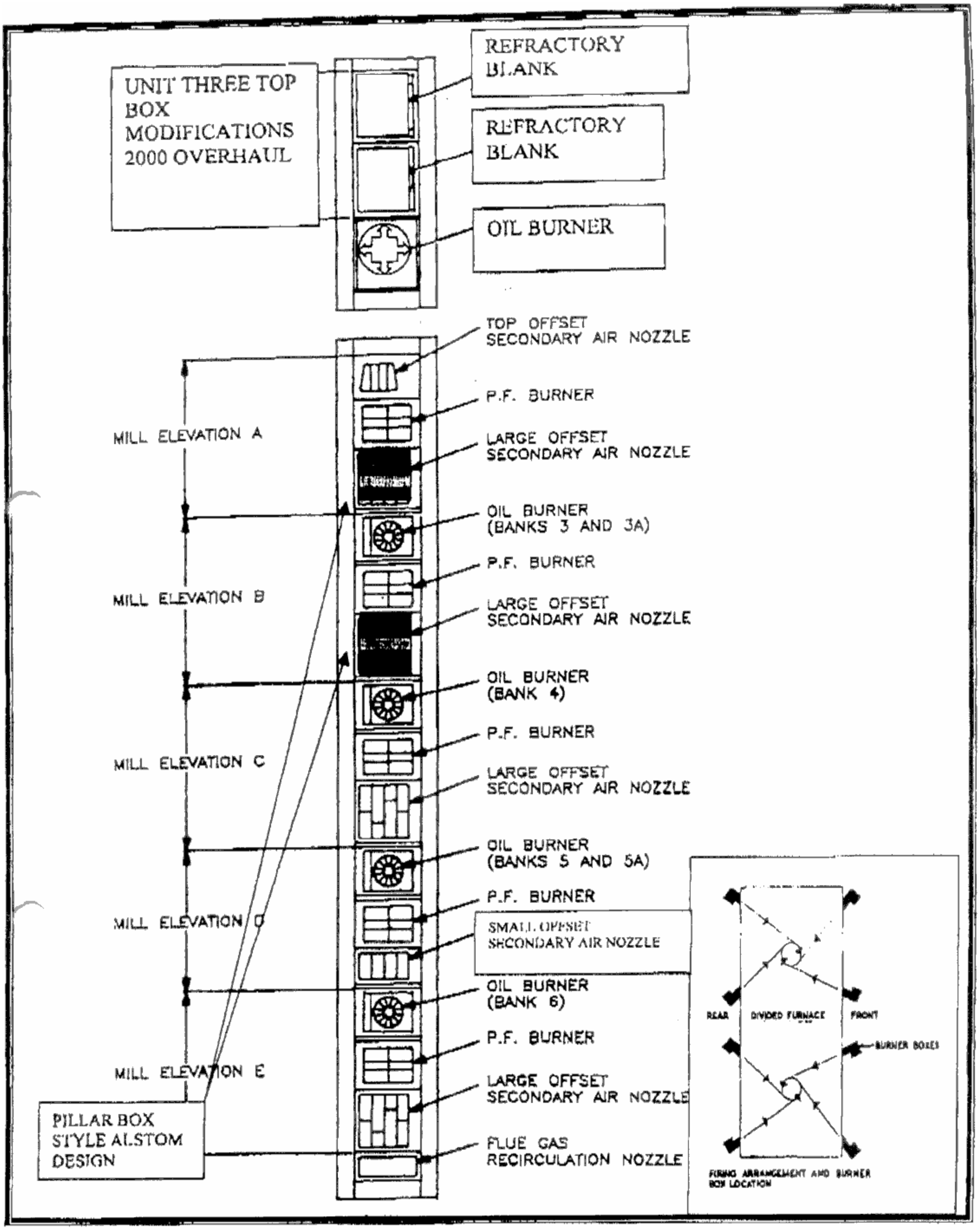
Table 1: PF finenesses data used in CFD models

Test 2	Classifier Speed (rpm)	% less than		
Mill(s)		300 μm	150 μm	75 μm
A-E	-	99.4	92.7	71.6
Test 2	**Medium Fineness**			
A (Top)	60	99.7	96.7	80.1
B	60	99.4	93.0	76.1
C	60	99.8	96.0	81.7
D	60	99.4	91.0	69.1
E (Bottom)	50	98.7	86.6	51.1
Test 8	**Low Fineness**			
A	50	99.7	96.4	74.1
B	50	99.4	93.6	79.0
C	50	99.7	95.0	73.2
D	50	98.7	87.0	63.2
E	50	98.8	87.5	60.3
Test 9	**High Fineness**			
A	70	99.8	97.2	80.9
B	66	99.6	94.6	77.8
C	70	99.8	98.0	85.5
D	70	99.6	94.0	65.2
E	55	99.2	89.3	63.6



ARRANGEMENT OF CORNER BURNER BOXES

2001 BURNER BOX RECONFIGURATION TO UNIT NO 3
LOWER TWO LARGE OFFSET SECONDARY AIR NOZZLES
REPLACED WITH ORIGINAL DESIGN PRE 1999

Figure 1: Kingsnorth burner box

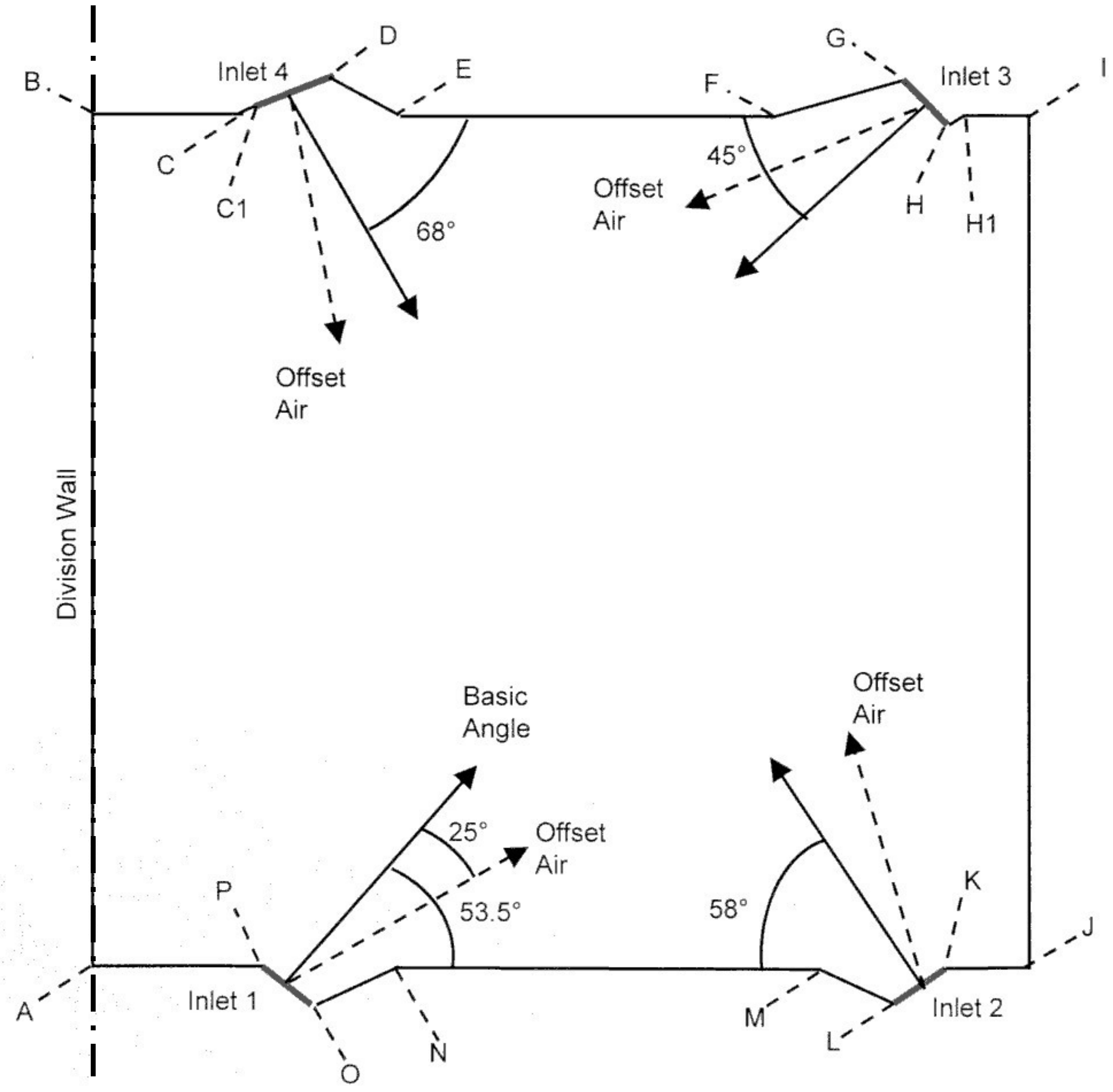


Figure 2: Furnace top view

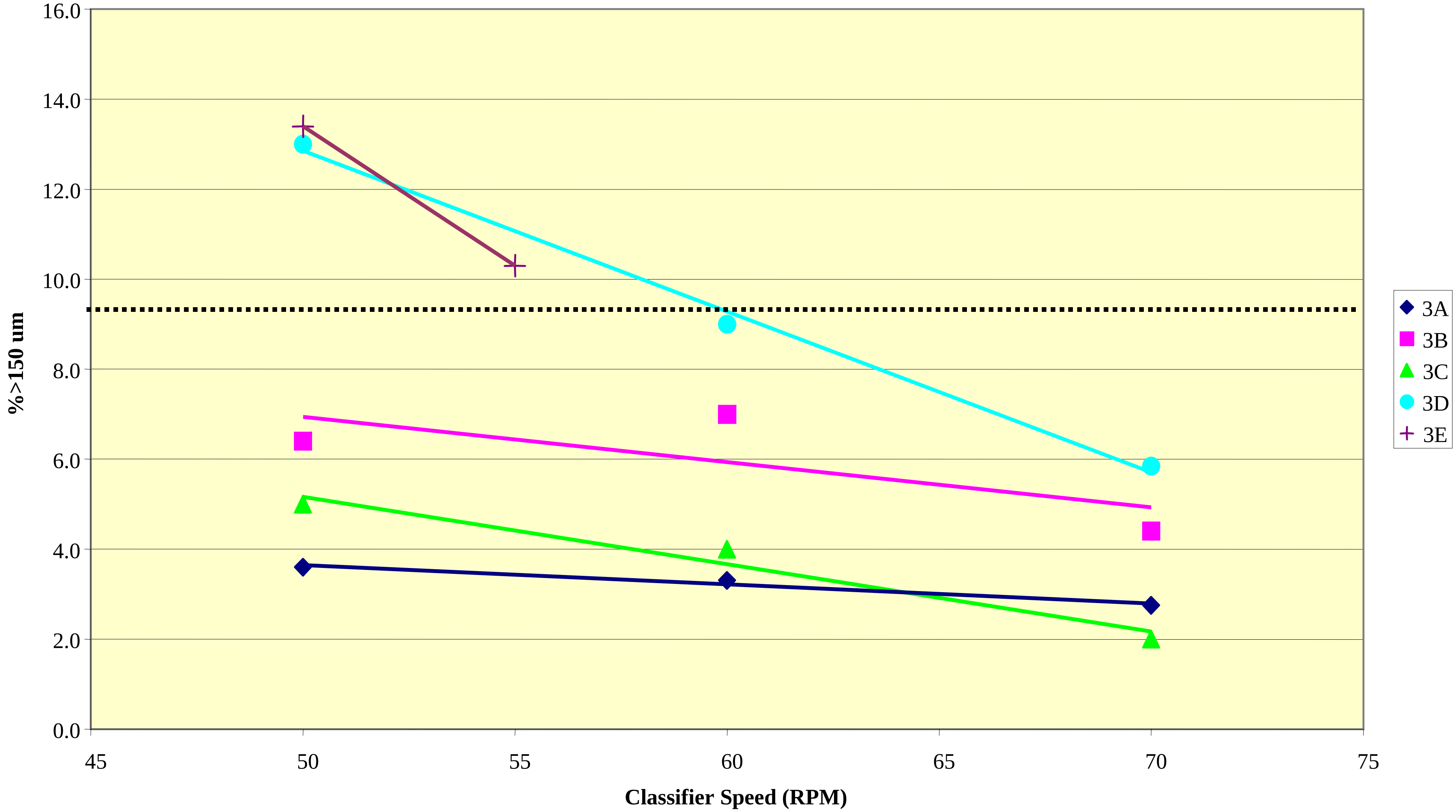


Figure 3: Grind size vs classifier speed

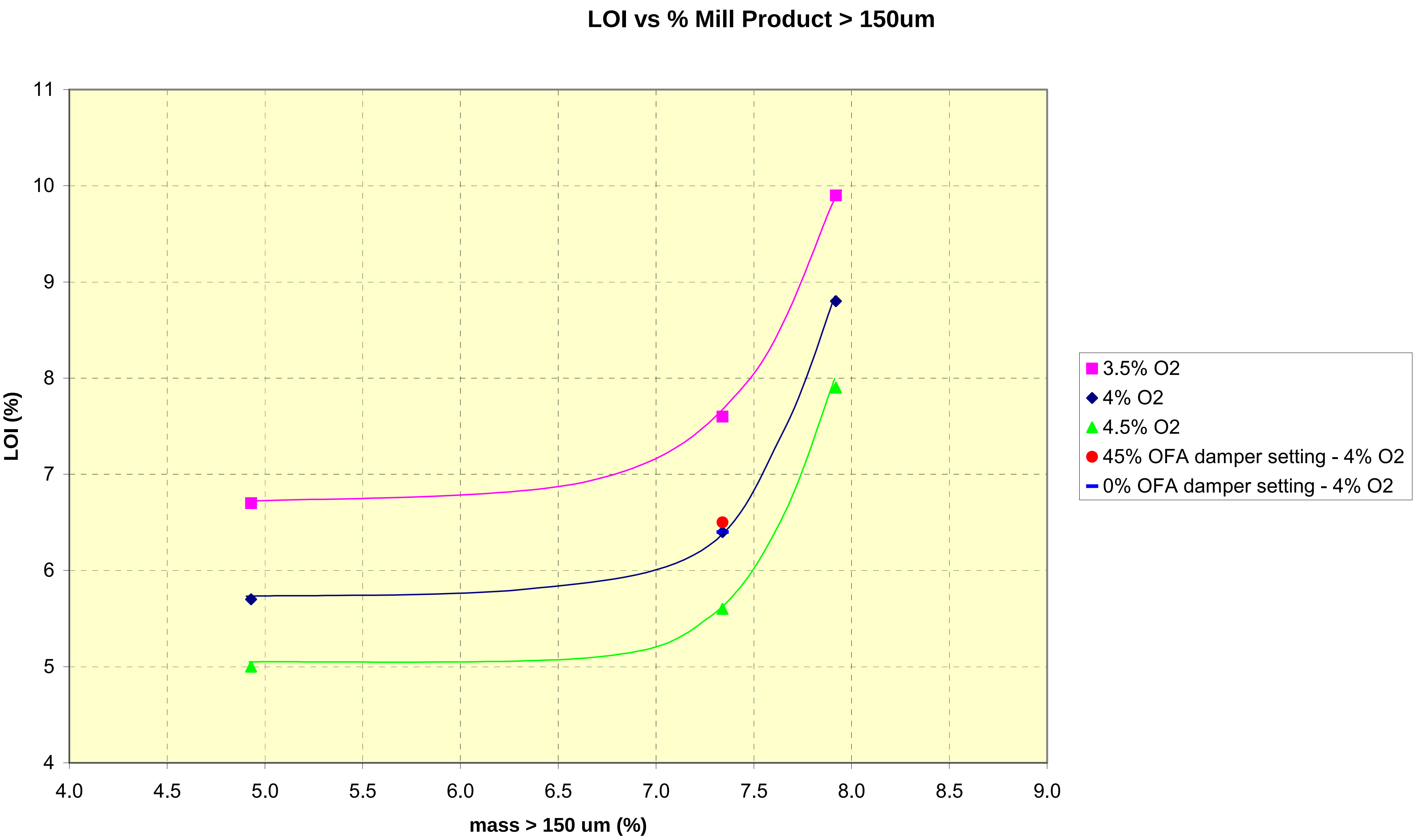


Figure 4: LOI vs Grind size

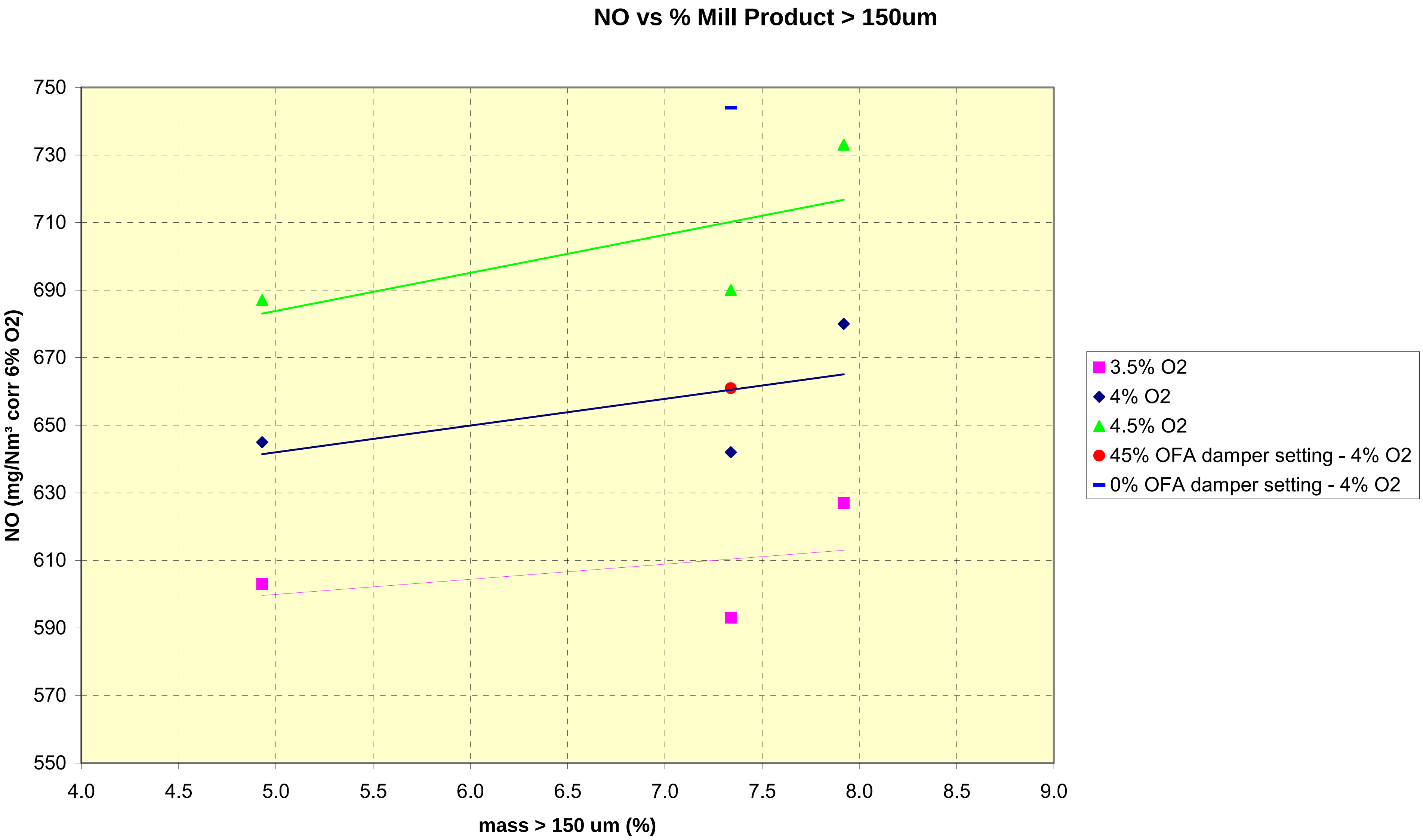

NO vs % Mill Product > 150um
750
730
710
690
670
650
630
610
590
570
550
NO (mg/Nm³ corr 6% O2)
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
mass > 150 um (%)
3.5% O2
4% O2
4.5% O2
45% OFA damper setting - 4% O2
0% OFA damper setting - 4% O2

Figure 5

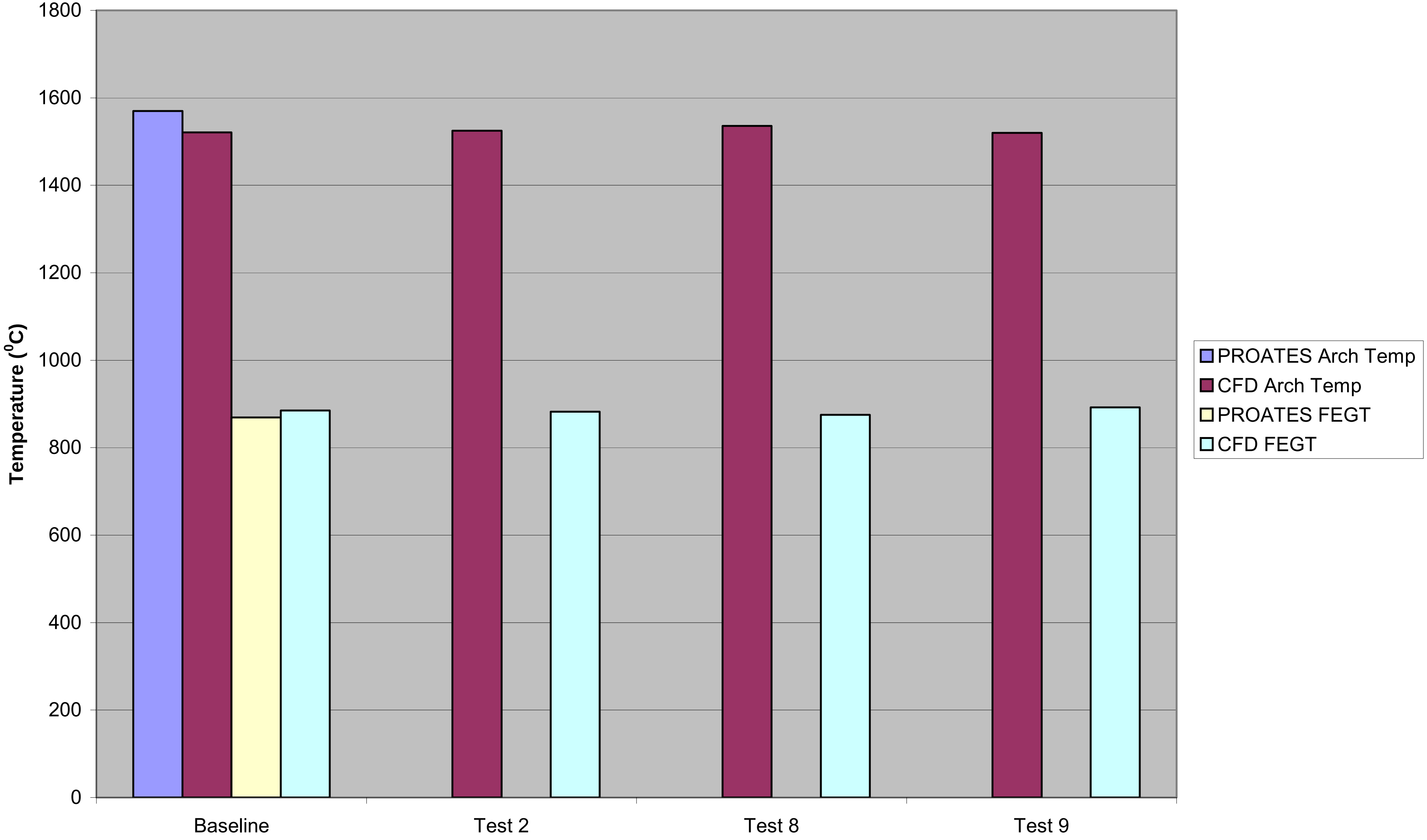


Figure 6: **Temperature Predictions – All Cases**

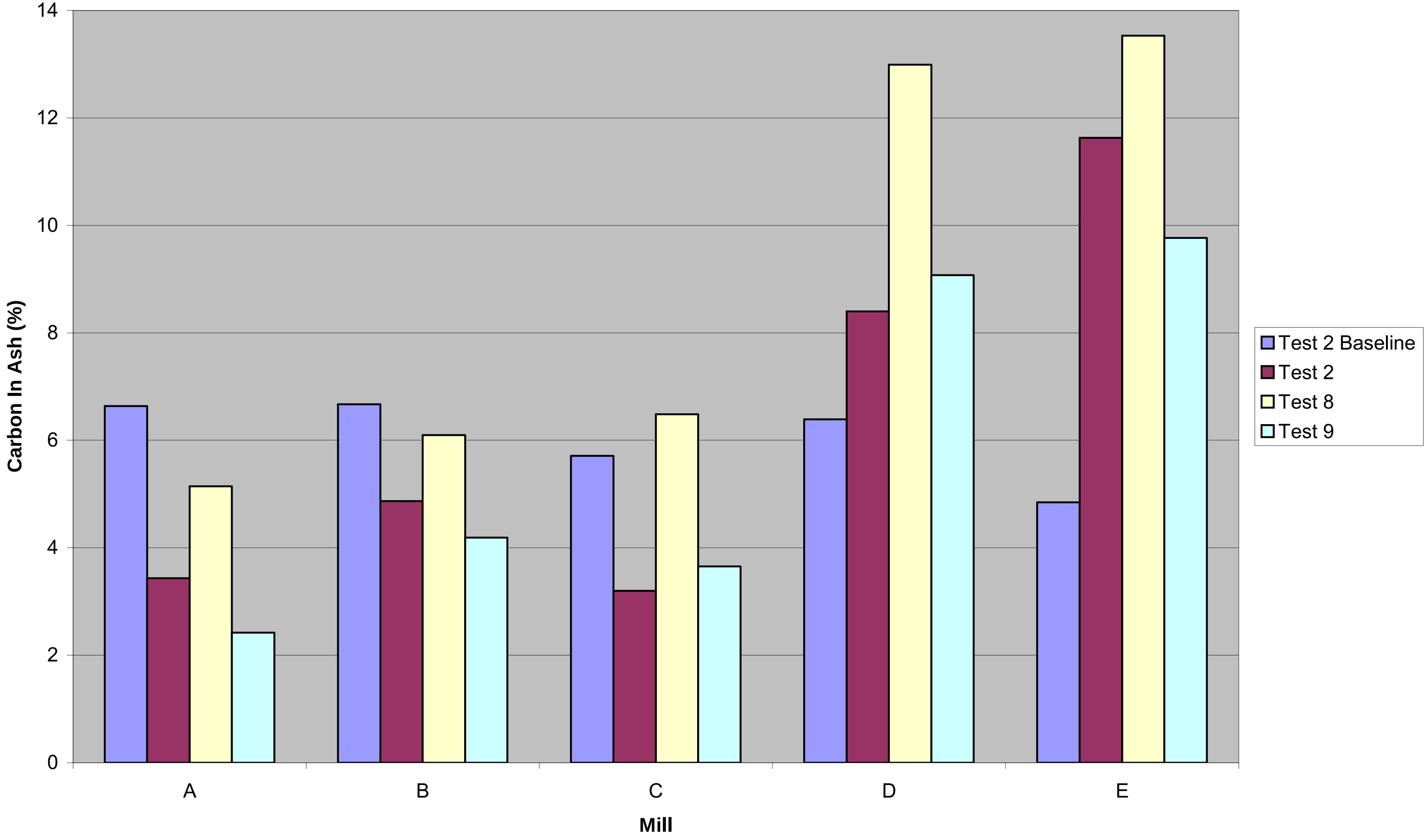


Figure 7: **CIA Contributions – All Cases**

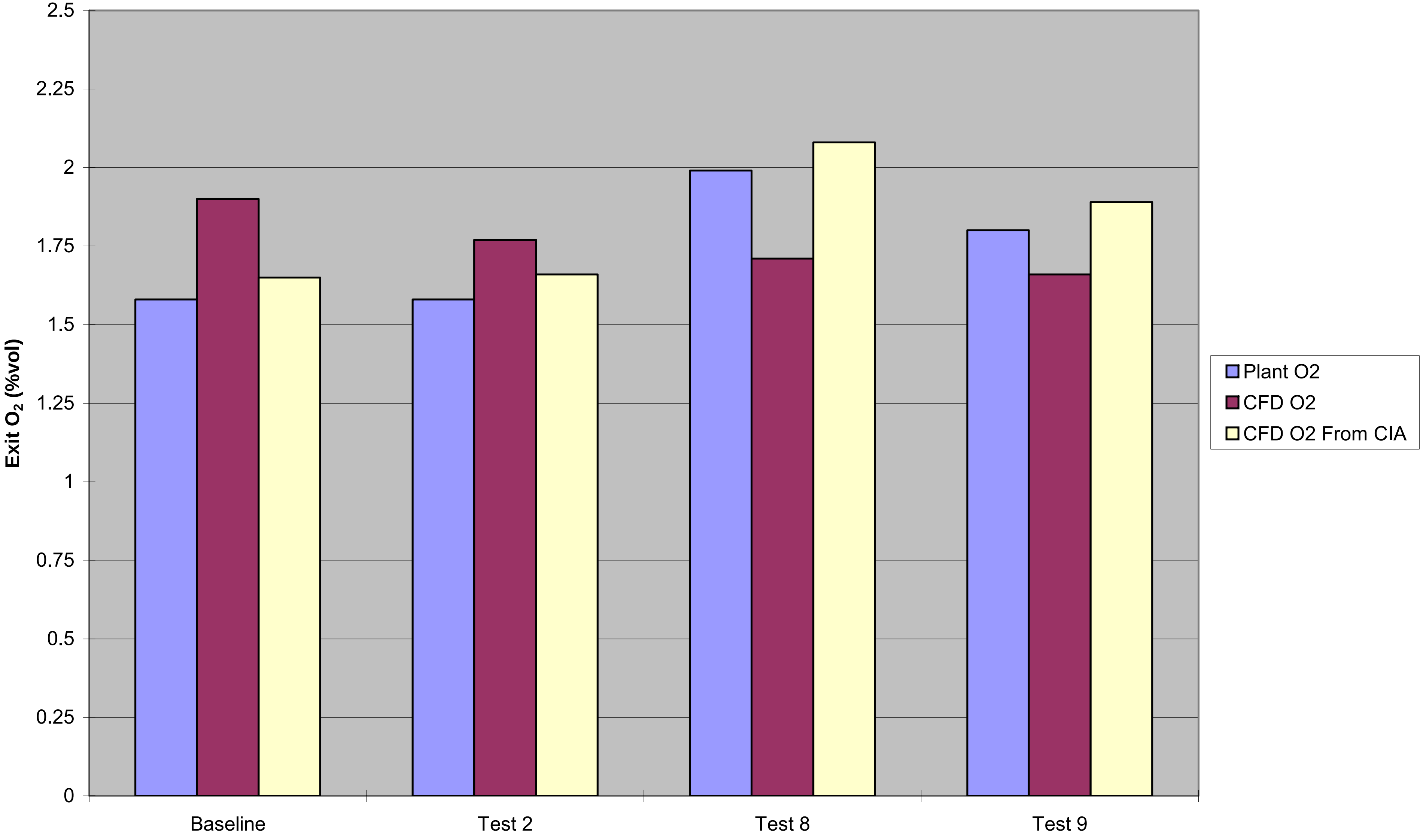


Figure 8: CIA Plant-CFD Comparison – All Cases

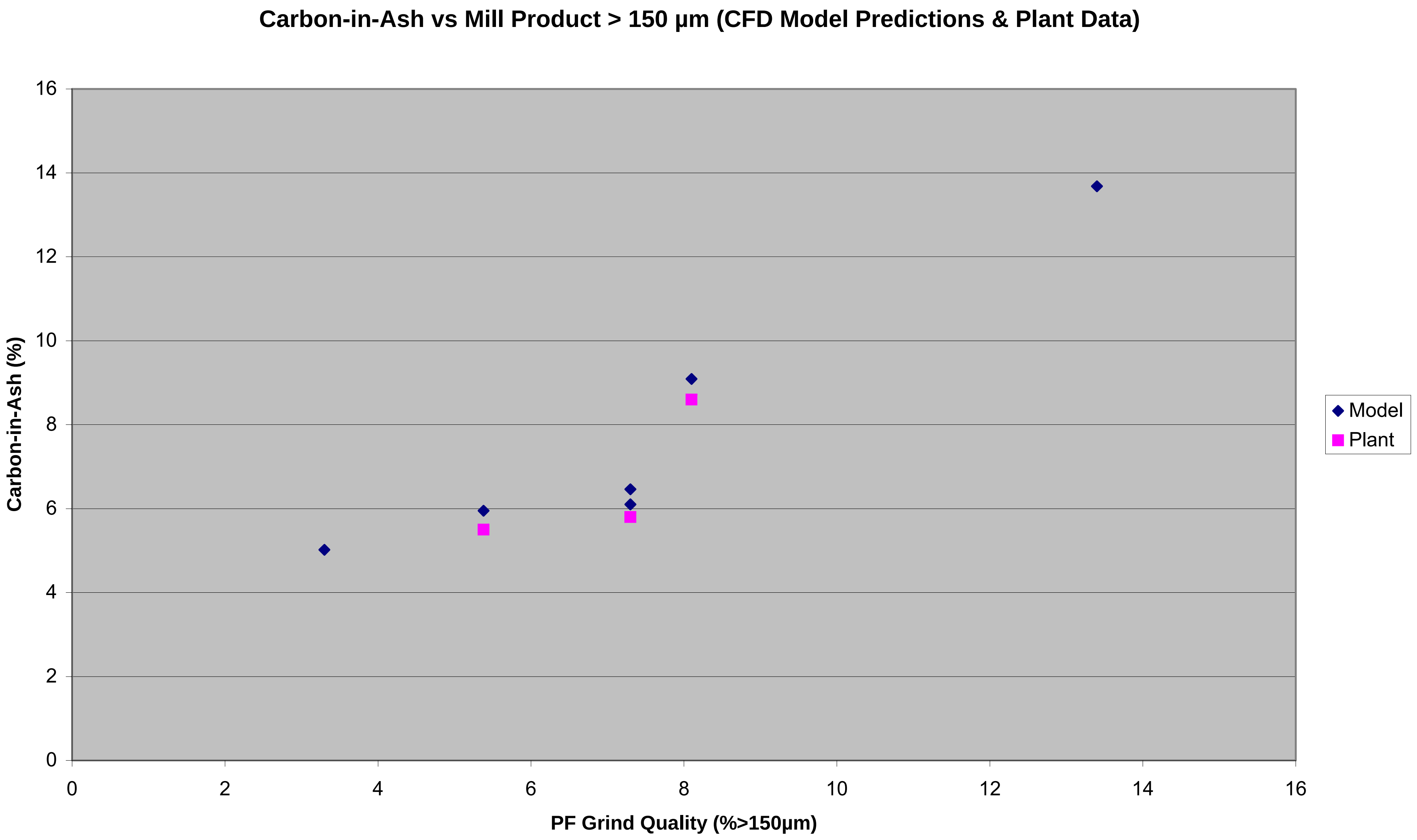


Figure 9: %LOI vs Mill Product > 150µm for CFD model predictions and plant tests 2,8, and 9

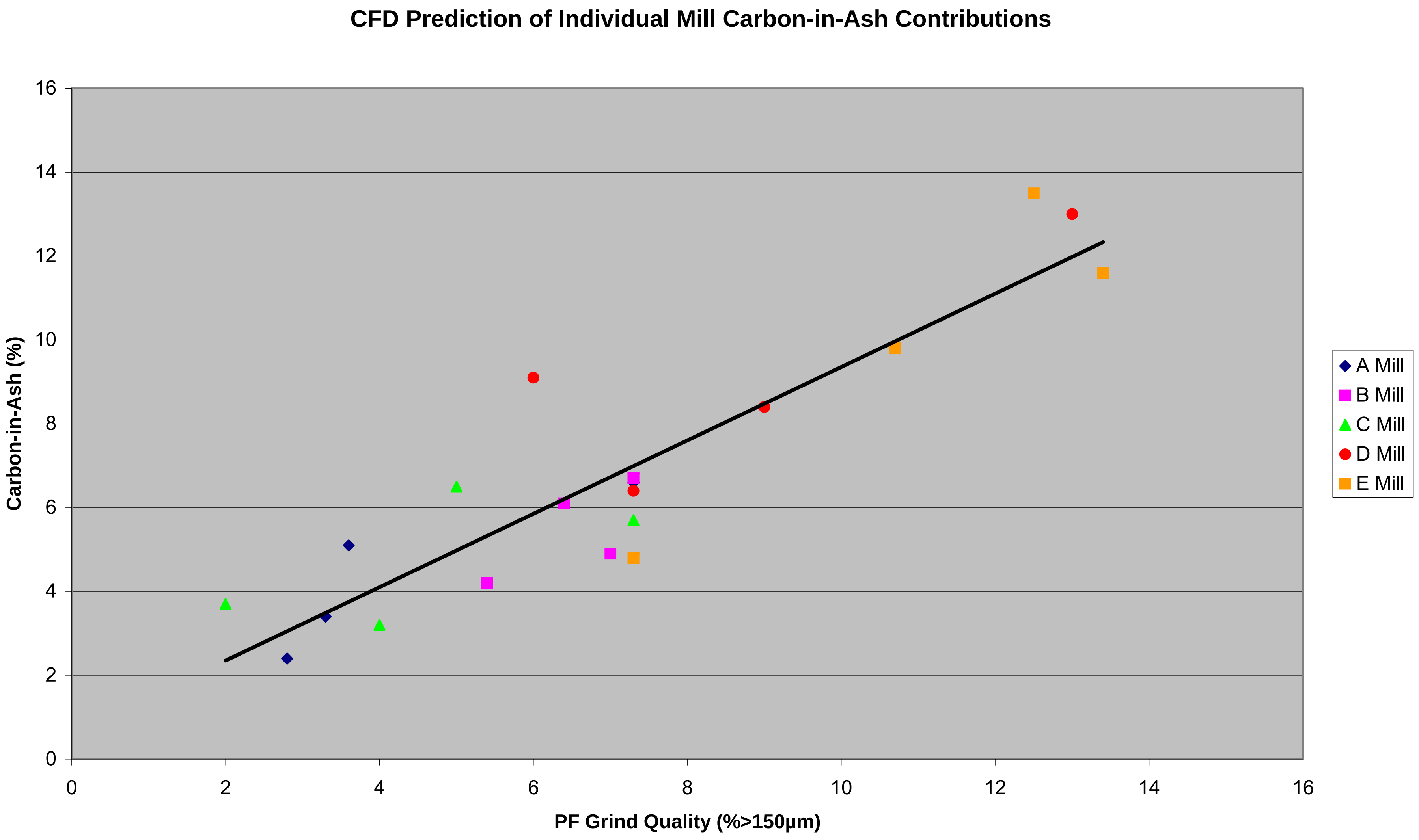


Figure 10: Carbon-in-ash contributions from each mill

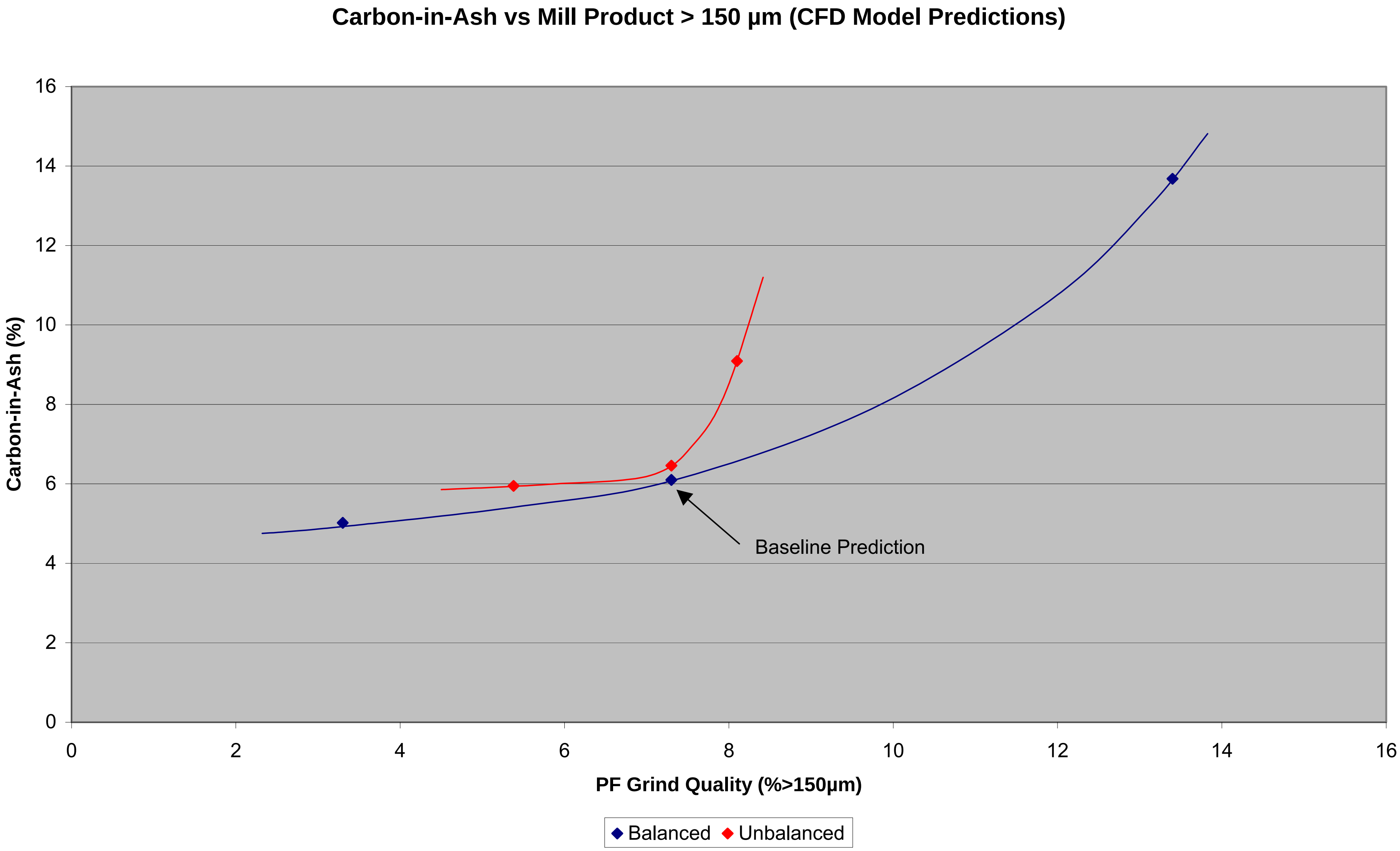


Figure 11: Repeat of figure 9 with additional lines

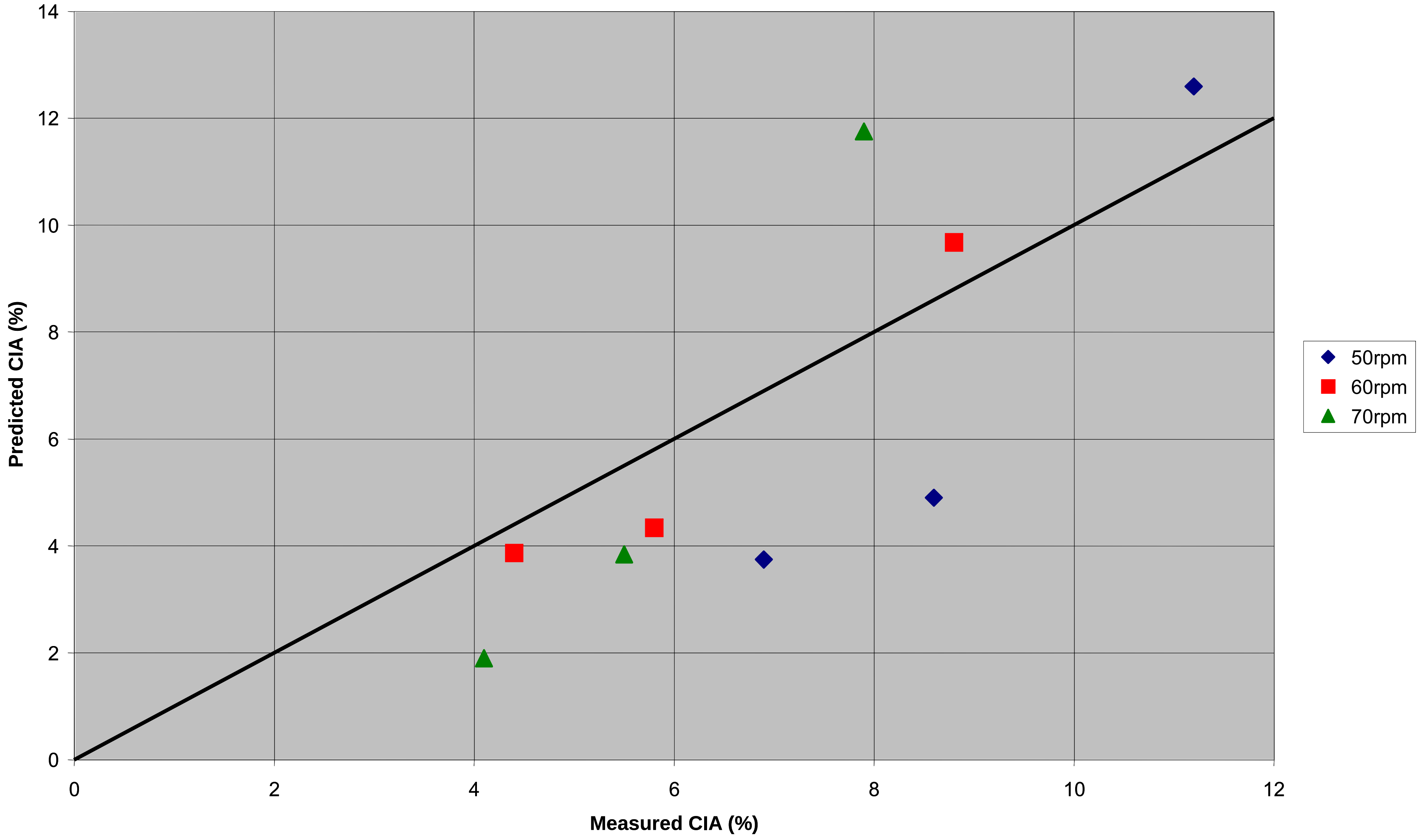


Figure 12: **Comparison of Measured CIA and HICCS Predicted CIA**

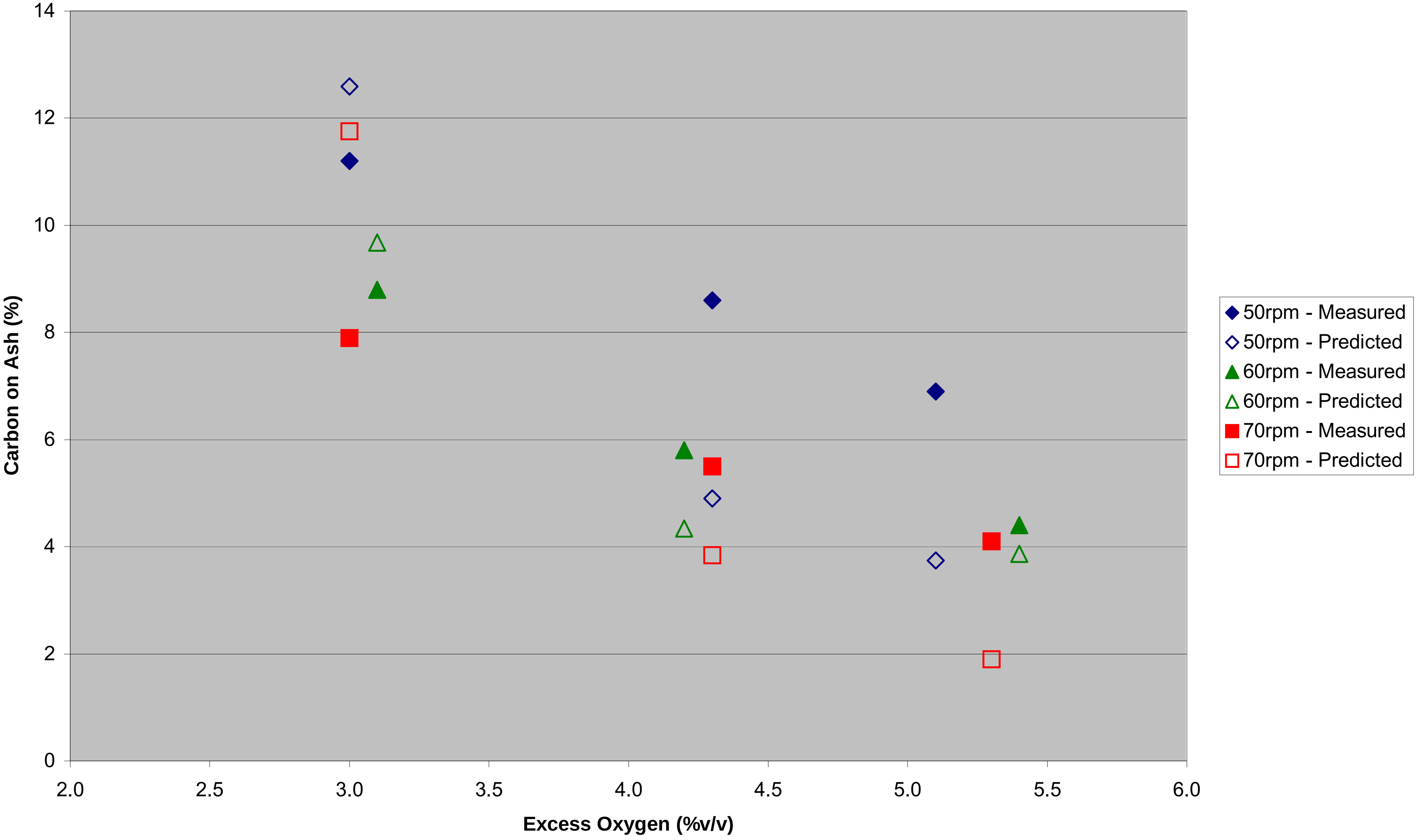


Figure 13: Effect of Excess Oxygen on Measured CIA and HICCS Predicted CIA