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The Evaluation of Waste Tyre Pulverised Fuel for NO_x Reduction by Reburning

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Abstract

The combustion of coal for power generation will continue to play a major role in the future, however, this must be achieved using cleaner technologies than we use at present. Scrap tyre arisings in the UK are 400,000 tonnes per year amounting to 30 million tyres and in the EU as a whole, more than 2.5 million tonnes of tyres per year are scrapped. The recent EC Waste Landfill Directive (1999) sets a deadline for the banning of whole and shredded tyres from landfill sites by 2006. Consequently, there is an urgent need to find a mass disposal route for tyres. We describe, in this paper, a novel use for tyre rubber pulverized fuel in a NOx reburning process which may have an application in power station boilers. This method of disposal could represent a way of combining waste disposal, energy recovery and pollution control within one process. A preliminary study of micronised tyre combustion was undertaken to identify the suitable size ranges for application in NOx reduction by reburning. Tests were performed in a down-fired, pulverised fuel combustor (PFC) operating at about 80kW. Superior combustion characteristics i.e. burnout were achieved with particle sizes less than 250 µm. A South African coal was used as the primary fuel in the reburn tests and the tyre was fed pneumatically via a separate feed system. Parameters studied, were, reburn zone stoichiometry and reburn fuel fraction. Additionally, the carbon content of the ash was carefully monitored for any effect on burnout at the fuel-rich reburn stoichiometries. The NOx reductions achieved with tyres are compared with reburning with coal. NO_x reductions up to 80% were achieved with tyres at half of the reburn fuel feed rate required to achieve the same reductions by coal. The results have been evaluated within the context of other studies available in the literature on NOx reburning by bituminous coal, brown coal, gas and biomass.

Keywords
NO_x, Reburn, Tyres, review

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1 Introduction

Coal combustion for electricity generation creates significant pollutant emission problems including oxides of nitrogen (NO_x), principally from fuel-bound nitrogen. NO_x emitted to the atmosphere forms gaseous nitric acid (HNO_3) at night [1]. HNO_3 is then deposited via precipitation causing acidification to land, lakes and streams. Ground level O_3 is formed through a series of photolytic reactions between NO_x, CO (carbon monoxide), and CH_4 (methane) and is a major component of smog in urban industrialised areas and can result in impacts to human health [2].

Technologies which may be implemented for NOx reduction from power stations include, air staging, selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR) and reburning. This paper is concerned with reburning which can be defined as a three stage combustion process (Fig. 1) and consists of a primary zone, a reburn zone and a char burnout zone [3]:

- *Primary (burner) Zone:* The primary fuel (coal) is fired at a rate corresponding to 75 to 90 % of the total heat input. NO_x created in this zone is slightly lower than normal operation due to the lower heat release and the reduced excess air level.
- *Reburn Zone:* Injection of the Reburn fuel occurs down-stream of the main burner through wall ports. Hydrocarbon radicals (CH_i's, CH_2, HCCO etc.) are produced as a result of the fuel pyrolysis and partially combusted by the available oxygen which is strictly controlled to create a predominantly fuel-rich zone. The CH_i radicals react with the NO_x produced in the primary combustion zone reducing it to N_2 via the following outline reaction process:

  $$CHi + NO = HCN + O \quad (1)$$

  $$NO + NHi = N2 + H_2O \quad (2)$$

  Hydrogen cyanide produced in reaction (1) is converted to N_2 in the flame via reactions :

  $$O + HCN = NCO + H \quad (3)$$

  $$NCO + H = NH + CO \quad (4)$$

  $$NH + H = N + H_2 \quad (5)$$

  $$N + NO = N_2 + O \quad (6)$$

  Optimum NO_x reduction performance is typically achieved when the reburn zone is fuel rich (reducing conditions). A variation in the reburn fuel injection rate between 10% - 25% (total boiler heat input) is thought to produce optimum NO_x reduction [4].

- *Burnout (exit) Zone:* Oxygen (typically 20 percent of the total air flow) required to burn any remaining combustibles left over from the reburn zone is injected through overfire ports situated just downstream of the reburn zone. Optimisation of the air flow rate and injection point ensure the lowest possible levels of CO emitted and unburnt carbon in fly ash.

There are a number of reburning studies in the literature which examine the possibility of utilising waste materials and biomass. Kicherer et al. [5] examined NO_x reduction using different reburning fuels in the solid, liquid, and gaseous phase. Light fuel oil (100% volatiles), natural gas (100% volatiles) and straw (75 % volatiles) produced higher NO_x reductions to that of coal (volatiles, typically 32 %). For light fuel oil, natural gas and straw, good burnout efficiencies were observed even at extremely fuel rich conditions in the reburn zone. Temperature is also important since slow release of volatiles may impart a delay on the initiation of the reactions between CHi radicals and NO. Alzueta et al [6] established that when CH_4 and C_2H_6 individually or mixed (ratio 9:1) were used as a reburn fuel NO_x reductions of 25% – 85%, were achieved for initial concentrations of NO_x from 650 ppm – 1100 ppm. The reduction of NO by CH_i radicals proceeds via a complex reburn mechanism involving the intermediate HCN [7-9]. Maly *et al* [10] carried out reburn tests with natural gas (CH_4), biomass, orimulsion, coal, coal pond fines (CPF), and carbonised refuse derived fuel (CRDF) using CH_4 as a primary fuel. The parameters investigated, as in this present study, were reburn zone stoichiometry and initial NO_x concentrations. The resulting NO_x reductions observed for natural gas (CH_4), biomass, orimulsion, coal, CPF, and CRDF were 25% - 85%. In a reburn study performed by Nimmo *et al* [11] using calcium magnesium acetate (CMA) as a reburn fuel NO_x reductions of 80% were achieved in addition to acid gas capture by the calcium component of the additive.

In this paper we suggest that waste tyre rubber may be a potential alternative, novel reburn fuel due to the high volatile hydrocarbon content of > 60% daf. Evidence for waste tyres being an ideal source of CH_i radicals is clear from thermal treatment studies of waste tyres [12-16] and show that they are a rich source of gas phase hydrocarbons (methane (CH_4) ethane (C_2H_6), propane (C_3H_8) butane (C_4H_{10}); butene (C_4H_8)) readily producing CH_i radicals that are required in the reburning zone to generate NO_x destruction, further favouring tyres as an excellent reburn fuel. Waste shredded tyres also have low nitrogen content (<0.5% ar), low chlorine content (~0.01%), and a high calorific value (35-39 MJ/kg) [17].

2. Experimental

Tests were performed in down-fired, refractory-lined, pulverised fuel combustor (PFC), operating at $80kW_{th}$ using waste shredded tyres of different particle size ranges supplied by SRC LTD (Cheshire, UK) and pulverised South African coal (<100µm) supplied by E.On (Nottingham, UK). The rubber is recovered from the waste tyre by scrubbing followed by shredding under ambient conditions for further size reduction. The burner was housed at the top of the PFC, in circular flanged stainless steel sections. The burner could be operated in a reduced NOx mode by staging the combustion air. The main body of the PFC is structured in 8 steel box sections each of 500 mm in vertical length, with a square cross section of length 350 mm; it was also fitted with ports for sampling or injection. The inner part of the box sections is lined with low density refractory, approximately 75 mm in thickness. The overall height of the PFC is 4.5m.

The primary combustion zone air to fuel stoichiometry (SR_1) was set at 1.05 for all reburn experiments undertaken. The reburn zone stoichiometry (SR_2) et by controlling the feed rate of waste shredded tyres, coal and the primary zone oxygen levels and the residence time was 0.8s. Reburn fuel fractions (*Rff*) up to 25% were studied. Propane, when used as the primary fuel, was doped with ammonia gas to simulate fuel-NO_x formation in order to create a range of desired initial NO_x concentrations for tyre-on-gas reburn (TGR), coal-on-gas reburn (CGR). A South African coal was used as the primary fuel for tyre-on-coal reburn (TCR), and coal-on-coal reburn (CCR). Reburn waste shredded tyres and coal were metered via screw feeders (Rospen) and delivered pneumatically using nitrogen as a carrier gas. Temperature profiles at different heights within the PFC were recorded by types R and K thermocouples. Flue gas sampling was performed by extracting and quenching the gas through water-cooled or short silica probes and subsequently through traps, filters and a chiller unit. Analysis was performed online for NO_x (Chemiluminescence), CO_2, CO, SO_2 (non-dispersive infrared), and O_2 (paramagnetic). SO_2 concentrations were obtained by sampling via heated sample line and magnesium perchlorate drying system through a separate sampling probe. All gas analyser measurements and temperature data were recorded on a data logger. NOx concentrations were obtained from averaged data over a period of steady state operation at the desired condition. The results are reported with a confidence of ± 5ppm for NOx measurement which gives an uncertainty in reductions of ± 2% if the initial NOx level is 500ppm.

Particle sizing was performed using a Malvern Mastersizer and thermogravimetric analysis was performed using a Shimadzu TGA-50H with a heating rate of 25^oC/min under N_2 to110^oC (hold 10mins) then 25^oC/min to 925^oC (hold 15 mins). Then switch to air for ashing (20mins).

The aims of the study reported here are threefold, namely;

1. Assess the effect of particle size on tyre pulverised fuel (Tyres 1, 2 and 3) combustion with regard to emissions and completeness of combustion (burnout) and suitability as a fuel for NOx reburning.
2. Investigate the NOx reductions which may be achieved using Tyre 3 as a reburn fuel.

3. Compare the performance of tyre and coal from this study with the results from other literature studies. An assessment of tyre vs biomass, coal and gaseous fuel is a particular feature of the review study.

Waste tyres and pulverised coal were combusted under reburn conditions at reburn fuel fractions between 0.3 % - 13.9 % in order to determine and assess their NO_x reduction efficiencies and potential as reburn fuel. The resulting data may be used in understanding the characteristics of waste tyres, particularly the optimum reburn zone stoichiometry (SR_2), required for maximum NO_x reduction.

3.0 Results and Discussion

Pilot scale combustion tests and the effect of particle size.

A preliminary assessment of the combustion behaviour of the three tyre samples was performed by combusting the material under different furnace oxygen levels in the down-fired furnace. In these experiments the fuels were fed directly through the burner with no secondary fuel added. Particle size distributions are shown in Fig. 2. Maximum particle diameters of 1200μm, 500μm and 250μm were measured for tyre samples 1, 2 and 3 respectively with d(0.5) of 600μm, 150μm and 100μm. The South African (SA) coal included in this study had a similar top size to tyre 3 but a significantly lower smaller fraction as evidenced by a d(0.5) of 40 μm. The different tyre particle size ranges gave different levels of burnout (Fig. 3) and generally improved with increasing oxygen, however, Tyre 1 performed badly throughout the range due to the large size, up to 1200 μm. Tyre 2 performed better showing improved burnout throughout the range of stoichiometries, but still below that expected from a viable pulverized fuel. Tyre 3 (<250 μm), however, performed as well as the SA coal tested here with burnouts greater than 99.5 % at oxygen levels greater than 3%. This represents less than 1% carbon in ash. At oxygen levels in the region of 1%, typical of the primary zone stoichiometry used during reburning, the carbon in ash rose to 3.8% and 5.6% for Tyre 3 and the S.A. coal, respectively, with corresponding burnout levels of 99.4% and 98.7%. We can, therefore conclude that Tyre 3, although having a comparatively large size has shown the potential to burn out to the level of a typical coal of much smaller size and indeed shows slightly greater reactivity at lower oxygen levels. Tyres 1 and 2 were rejected as potential fuels for reburning in this study.

Further characterization of the tyre and coal fuels by TGA (Fig. 4) shows that the three tyre samples show similar DTG patterns at the slow heating rates employed in the TGA although the particle size differences are significant (Table 1). The raw data was smoothed with a 10 point moving average method. Three release peaks are observed for Tyre 3 with the onset taking place at 190°C with peaks at around 270°C, 370°C and a shoulder at 425°C. In contrast the SA coal onset is at the higher temperature of 350°C with a peak at 460°C. Significantly there is a large proportion of the volatiles still being released at temperatures greater than 500°C which is the temperature at which Tyre 3 has already completely devolatilised. Release rates are an order of magnitude higher for the tyre (1.6E-02) over the coal (3.33E-03) due to the heavier nature of the hydrocarbons.

NO Reburning using Tyre and Coal

Tyre 3 was chosen for the reburning tests since it performed well in the initial combustion tests showing excellent burnout characteristics (Fig 3). NO reduction with tyre as the reburn fuel was compared with the performance of a South African coal for furnace conditions where either propane or coal was used as the primary fuel. In the case of the propane tests the NO concentration was varied by the addition of ammonia to the primary air feed to the burner. The effect of increasing the reburn fuel fraction on NO emissions is shown in Fig. 5. The concentrations are expressed in mg/Nm^3 with the upper and lower dashed horizontal lines indicating the 2008 and 2016 NO_x (as NO_2) emission targets, respectively, as set by the Large Combustion Plant Directive (LCPD, 2001/80/EC).

Reductions in NO emission obtained with tyre 3 in the furnace employed here are shown on figure 5A with decreasing emissions with increasing reburn fuel fraction (*Rff*).

Maximum reductions with tyre 3 are achieved at an *Rff* level of 6% to 7% and are consistently below the 500mg/m^3 limit for initial NO levels up to 1500mg/m^3. However, for the lower initial NO levels, around 600mg/m^3 or less, then the NO emissions better the more stringent emission target of 200mg/m^3 at a reburn fuel fraction between 3% and 8%. In contrast, coal reburning (Fig. 5B) can only attain the same emission limits at much higher reburn fuel fractions. Levels of coal reburn fuel input in between 8% and 20% of the total thermal input are required to achieve NO emissions less than the 200mg/m^3 limit for the same range of initial NOx levels. In particular, it is apparent that coal on coal reburning is unlikely to achieve the lower limit with the current reburn configuration on this furnace.

This is partly due to the relatively high initial NO levels and partly due to the fact that char-N in the reburn coal is oxidised in the burnout zone to NO_x. However, tyre on coal reburning attains 300mg/m^3 from the same high initial levels at an *Rff* of 10%. In reality a power station with low NOx burners and over-fire air will have already attained the upper NO emission limit before the requirements for attaining the lower limit must be satisfied, therefore the results from tests with initial NO levels of 500mg/m^3, or less, will be more representative of the required performance of tyre or coal reburning.

NO reductions have been calculated and are shown in Fig 6 and includes both the tyre reburning data and the coal reburning data. The solid lines of the tyre reburning results show reductions at much lower reburn fuel fractions. Reductions in NO emission by tyre reburning can be achieved at one half the required feed rate for equivalent reductions using coal (Fig 6). NO reductions are greater when the initial levels are higher due to the dependence of the rate of CHi radical reaction with NO on the species concentrations. We have demonstrated here the superior performance of pulverised tyre over pulverised coal reburning despite the large difference in particle size (table 1).

In the following discussion TGR, CGR, TCR and GCR refer to the rig configurations which were used to obtain experimental data in this study. Having selected tyre 3 as a suitable candidate for the reburning tests, the principal objective was to characterise NO_x reduction capabilities under N-doped (propane), and coal firing conditions and compare with previously reported results for other reburn fuels. The South African coal was also included in the experimental study as a baseline study for coal. The test variables that were shown to have an impact on NO_x reduction were the type of reburn fuel used, initial NO_x concentrations and the reburn zone stoichiometry (SR_2). Volatile matter content and its rate of release are the principal fuel characteristics that have an influence on NO_x reduction. A higher NO_x reduction performance was observed with waste tyres which had a greater volatile matter (typically >60% ar) content than that of South African coal (26% ar).

Effect of stoichiometry on NOx reburning using tyres

The reburning results for TGR and TCR show comparable NO_x reduction efficiencies under NH_3-doped propane and coal as primary fuels (Figs. 7 a, b respectively). TGR gives a NO_x reduction of 79% at an SR_2 of 0.92. The same can be seen for TCR which has a similar NO_x reduction of 77% at SR_2=0.92.

The TGR shows a decrease in NO_x reduction at SR_2 = 0.78 (77%) in comparison to a lower SR_2 of 0.92 (79%). This decrease in NO_x reduction is highlighted when it is then compared to the highest NO_x reduction for TCR at an SR_2 = 0.84 (81%). This may indicate that the maximum NO_x reduction efficiency has been exceeded and that beyond an SR_2 of ~ 0.88 for TCR and TGR hydrocarbon volatiles are in excess of NO_x within the PFC.

The emissions of NO_x from tyre-on-coal reburn (TCR) in comparison to coal-on-coal reburn (CCR) are similar; however the SR_2 at which these NO_x emissions for TCG and CCR take place vary significantly as shown in Figure 7. The TCR gave NO_x emissions of 317 ppm ($SR_2 = 0.98$), 277 ppm ($SR_2 = 0.97$), and 173 ppm ($SR_2 = 0.92$) at an initial NO_x concentration of 740 ppm. This equates to respective NO_x reductions of 58%, 63% and 77%. CCR exhibits NO_x emissions of 452 ppm ($SR_2 = 0.98$), 301 ppm ($SR_2 = 0.86$), 217 ppm ($SR_2 = 0.81$) and 184 ppm ($SR_2 = 0.77$) the respective NO_x reductions being 42%, 62%, 72% and 77%. Waste tyres appear to be a superior reburning fuel to the SA coal used in this study as they produce much lower emissions of NO_x at higher stoichiometric ratios i.e. a more fuel lean environment. Fuel characteristics such as a high volatile content and rapid devolatilisation are the key attributes of waste tyre particles that provide such a high NO_x reduction performance of 77% at an SR_2 of 0.92 (slightly fuel rich) [5]. The significance of the difference in SR_2 between TCR and CCR is made apparent from the highest NO_x reduction for CCR which is 77% at an SR_2 of 0.77. A similar NO_x reduction of 77% can be achieved with TCR at an SR_2 of 0.92 which is a lot less fuel rich to that of CCR ($SR_2 = 0.77$).

Results for tyre on coal reburning suggest that an SR_2 of about 0.9 may be the optimum point for NO_x reduction efficiency. The NOx reduction efficiency of CCR showed little variation between an SR_2 of 0.81 (72%) and 0.77 (77%) indicating that an SR_2 of 0.81 may be the optimum NO_x reduction point. Exceeding an SR_2 0.92 (TCR) and 0.81 (CCR) may only lead to a poorer burnout as the majority of the reburn fuel does not have sufficient residence time in the reburn zone to undergo adequate devolatilisation and reaction. As mentioned previously a higher proportion of partially devolatilised fuel is entering the burnout zone which can lead to a higher carbon in ash content (Fig 3). The same may be said for nitrogen, which which may be partitioned between the volatile products of devolatilisation and the solid char which persists into the burnout zone where it burns with the consequence that NO_x may be slightly increased compared with the emission at slightly lower reburn fuel fractions.

As shown in the TGR and CGR experiments high initial NO_x levels exhibit the highest NO_x reduction efficiency. This trend is also observed in TCR and CCR experiments. Lower operational reburning stoichiometries for waste tyres compared to coal carry significant economic implications.

Pulverised tyre as an alternative fuel for NOx reburning

Pulverised tyre as a reburn fuel has been compared, from the available literature, with gaseous fuels and ”alternative” reburn fuel candidates such as biomass, low grade coal fuels and orimulsion. Before any comparison between the results of tyre reburning could be made with NO_x reductions of previous reburn studies the literature data was carefully analysed and presented in a standard form involving the correction to 6 % O_2, and converted from mg/m^3 to ppm as was the case for the research by Spliethoff *et al* [19]. The reburn study carried out by Maly et al [10] was reported as a function of the reburn fuel fraction (R_{ff} %). Extreme care was taken when applying the conversion procedures for the literature data so that the comparison of NOx reduction results could be made with the greatest confidence. The NO_x reduction efficiencies of previous reburn studies were grouped into high (Fig 8)and low (Fig 9) initial NO_x concentrations since it is recognised [18] that initial NOx concentration is a factor in determining the efficiency of the reduction process.

Gas, coal and biomass reburn studies [5-7, 11, 19 -22] show a similar trend to that of TCR and TGR in that NO_x emissions decrease with a lowering reburn stoichiometric ratio. Therefore, as the reburn zone becomes more fuel rich an increased NO_x reduction is measured up to a critical point. It is, however, noted that the NO_x reductions of TCR and TGR show a significantly narrower range of stoichiometry in which this occurs in comparison to some previous gas, biomass and coal reburn studies. A reburn stoichiometry of 0.92 was taken as a reference point since it corresponds to a reburn fuel fraction of around 13% which is a moderate NOx reburning condition. At this condition, TCR and TGR show a better NO_x reduction to that of gas reburning studies (Fig. 8a) at high initial NO_x concentrations carried by Spliethoff *et al* [19]; Kicherer *et al* [5] and Bilbao *et al* [23] reported as being 53%, 58% and 24%, respectively, at an SR_2 = 0.92. In order for these previous gas reburning studies to reach a performance (77% reduction) matching that for tyre reburning at SR_2 = 0.92, a more fuel rich environment of 0.82, 0.8, and 0.5, respectively, is required. It is also found that gas reburn at a low initial NO_x concentration [5] is significantly less efficient at reducing NO_x than waste tyre (Fig. 9a). A NO_x reduction of ~53% is reached at an SR_2 of 0.92 for TGR, which is lower by 21%.

Kicherer *et al* [5] looked at a series of reburn fuels including coal, the NO_x reduction performance of this coal has been compared to that of TCR and TGR (Fig. 8b). The NO_x reduction efficiencies for coal start at a slightly more fuel rich SR_2 of 0.9 which has a NO_x reduction efficiency of 43%, even when TCR and TGR are compared at this slightly higher SR_2 the NOx reduction efficiency for coal is still ~ 32% lower. Even when the reburn zone is at an extremely fuel rich ratio of 0.5 the coal is still only able to manage ~64% NO_x reduction. This high SR_2 would be unacceptable for industrial purposes resulting in high carbon in ash levels.

The performance of alternative reburn fuels (coal pond fines and orimulsion) compared with tyre on gas reburning (TGR) at lower initial NO_x concentrations are shown in Fig. 9b. Harding et al (Coal); Maly et al (orimulsion, bituminous coal) and Folsom et al (brown coal) found NO_x reduction efficiencies of 56%, 52%, 34%, and 54% at an SR_2 of 0.92 respectively. These NO_x reduction efficiencies approximate to a difference of 17%, 21%, 39%, and 19%

respectively lower than TGR. As discussed previously with gas reburn studies a more fuel rich region has to be achieved to reach NO_x reductions greater than 60%.

NO_x reduction by straw [5] shows a similar trend to that of the TCR and TGR results presented here where NO_x reduction begins in a fuel lean region (SR_2 =1.04), however at the reference SR_2 of 0.92 the NOx reduction efficiency for straw is shown to be 55% compared to 77% and 79% for TCR and TGR, respectively (Fig. 8c). It is only at moderately fuel-rich conditions (SR_2 = 0.74) that a significant NOx reduction of 75% is achieved.

The NOx reduction efficiencies of Maly et al and Harding et al, like Kicherer et al, require more fuel rich conditions (SR_2 = 0.83 and 0.84) to reach NO_x reductions of 70% and 60%, respectively. Under these conditions, NOx reduction with TGR is ~73% which is similar to the results of Maly et al. It is clear that the quality of the biomass fuel, with particular reference to the hydrocarbon content, is responsible for its lower NO_x reductions compared with waste tyres.

Biomass is composed mainly of a cellulose material therefore a high yield of oxygenated volatiles (carbon-to-oxygen bond) result from the thermal degradation of wood. This large fraction of CO and CO_2 produced diminishes the fraction of CH_i radicals essentially responsible for NO_x reduction in a reburn environment [20]. The results suggest (Figs. 8c and Fig 9c) that waste tyres could be a more efficient reburn fuel compared to biomass due to the higher portion of hydrocarbon volatiles (Carbon-to-hydrogen bond) to that of oxygenated volatiles which predominates for biomass decomposition.

4. Conclusions

The results presented in this paper have addressed the following principal objectives with regard to the novel application of waste, pulverised tyre fuel as a NOx reburning fuel;

Combustion studies of a selection of different sized tyre fuels identified a candidate for application as a reburn fuel with a particle size d(90) of 250 μm. Carbon burnout levels were found to be acceptable at >99.5% (carbon in ash about 1%) for this tyre fuel (tyre 3) and was comparable or better than typical power station coal for overall flue gas O_2 levels in the range 1%-6% (dry basis). This is despite the difference in particle size between tyre 3 and the coal tested.

The resulting data for waste shredded tyre and coal reburn with either coal or propane as primary fuels showed similar NO_x reductions between 19% - 81% but, it is noted that this occurred at significantly different reburn zone stoichiometries. TCR and TGR showed a significantly better performance of NO_x reduction at a higher SR_2 (0.92) to that of CCR and CGR. TCR and TGR show NO_x reductions at similar SR_2 (0.92) this is the same for CGR and CCR. However, good burnout under reburning conditions was not achieved, with levels in the region of 96% with carbon in ash levels of about 15% with the South African coal as primary fuel.

The optimum SR_2 for TCR and TGR showed small variation and was found to be ~ 0.92. results in the literature for a range of reactors and fuels show that The tyre reburning experiments ultimately show that much lower feed rates are required in obtaining desirable NO_x reductions that match and surpass coal reburning tests and literature reburn studies at high and low initial NO_x concentrations using gas, coal and biomass as reburn fuels.

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TABLE 1: Proximate, ultimate and size analyses of South African Coal and the 3 tyre fuels under test.

		Ultimate analysis, wt % AR					Proximate, wt % AR				Size µm	
Sample	C.V. (gross) MJ/kg	C	H	N	S	Cl	Moist	Vols	Fixed Carbon	ash	(max)	D(0.5)
tyre 1	37	79.6	7.1	0.5	2.3	-	0.1	63.4	28.1	8.4	1200	600
tyre 2	39	84.6	7.48	0.25	1.49	0.1	1	64.1	29.4	5.5	500	150
tyre 3	35	77.6	6.4	0.44	1.4	0.02	1.4	51	36.4	11.2	250	100
SA coal	27	68.4	3.8	1.53	0.63	0.01	3.1	23.5	57.6	15.8	250	40

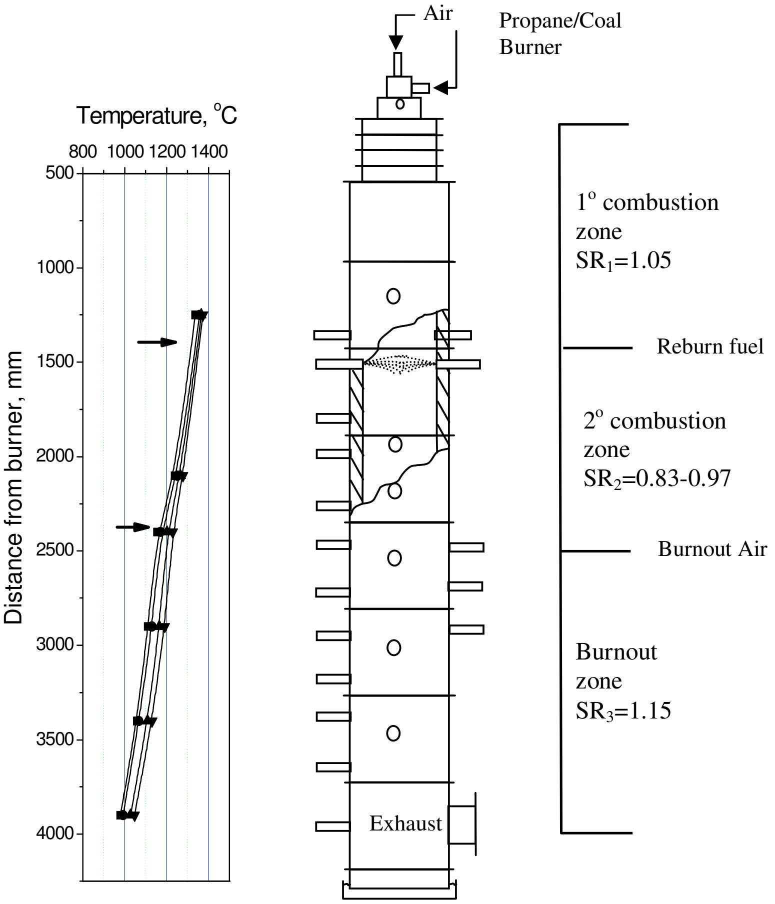

Fig. 1 Schematic diagram of PC combustor showing 3 stage reburning arrangement and typical temperature profiles for reburn fuel fractions (*Rff* thermal) of - 4% ■, 8% ● , 13% ▲ and 20% ▼.

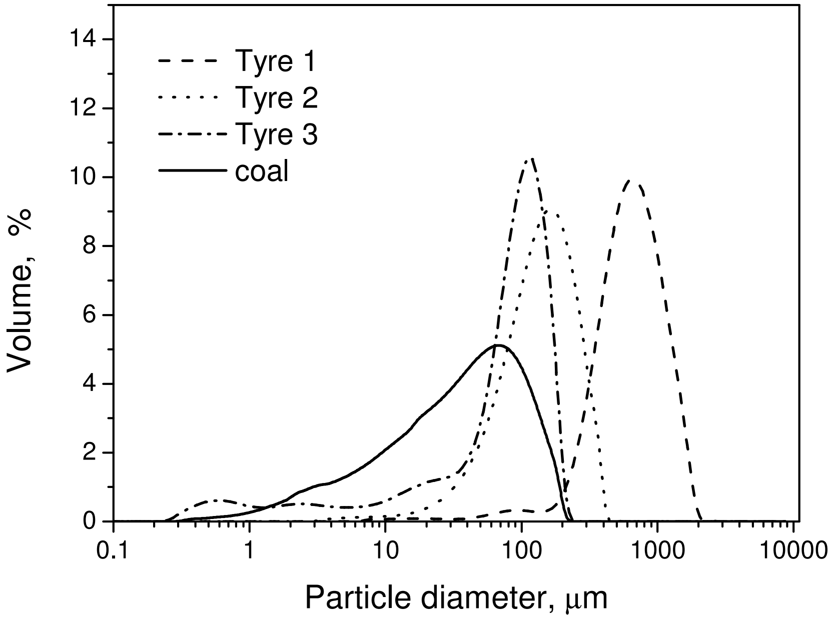

Fig. 2 Particle size analysis for tyre samples and South African coal.

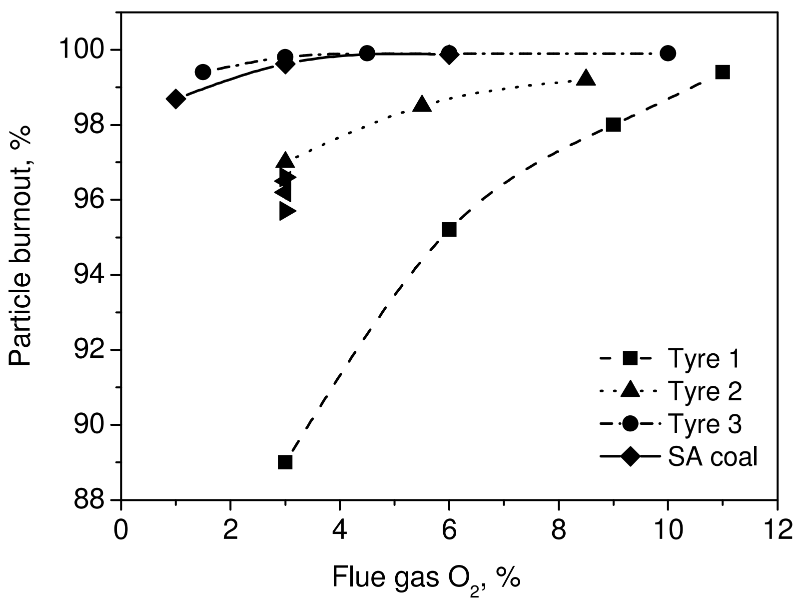

Fig. 3 Combustion efficiency of tyre and South African coal under different air to fuel ratios. Tyre 1■, Tyre 2 ▲, Tyre 3 ●, SA coal ◆, tyre on coal reburn ◀ (*Rff*=5.1% and 19.1%) , coal on coal reburn ▶ (*Rff*=3.5% and 18%).

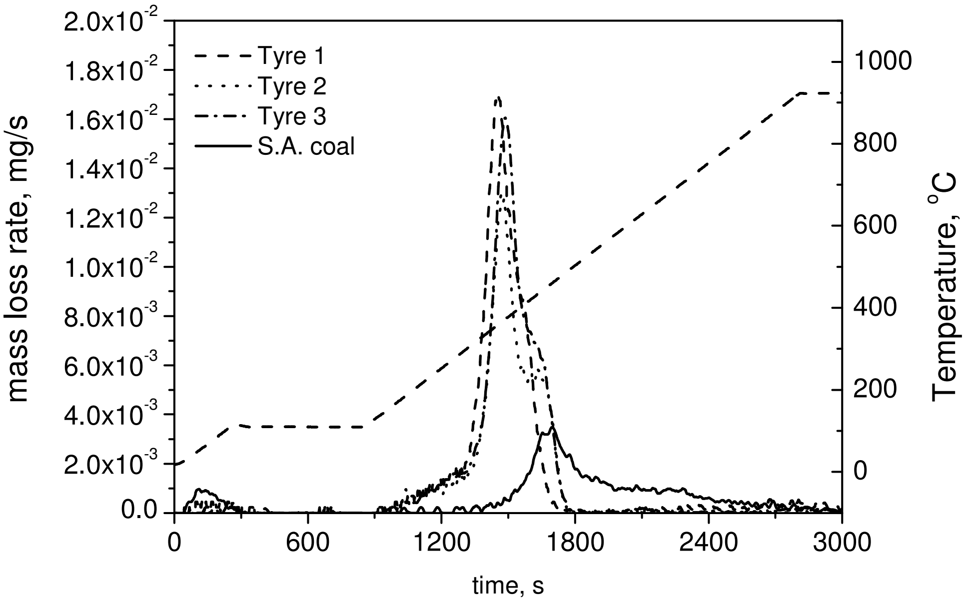

Fig. 4 Thermo-gravimetric analysis of tyre and coal. dw/dt (mg/s) and temperature are plotted vs time showing peaks of maximum rate of release of hydrocarbon volatile material.

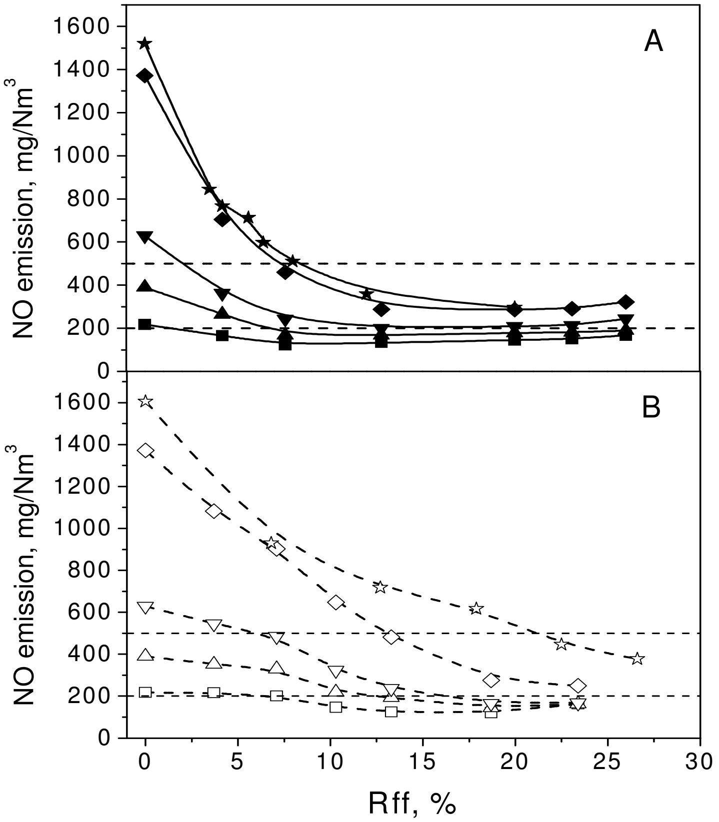

Fig. 5 NO emissions measured for a range of reburn fuel fractions (*Rff*) for different initial NO levels. A - tyre reburning; NO_i , 217 mg/Nm3 ■, 390 mg/Nm3 ▲, 629 mg/Nm3 ▼, 1372 mg/Nm3 ◆, 1520(SA coal) mg/Nm3 ★. B – coal reburning; NOi , 217 mg/Nm3 □, 390 mg/Nm3 △, 629 mg/Nm3 ▽, 1372 mg/Nm3 ◇, 1605(SA coal) mg/Nm3 ☆.

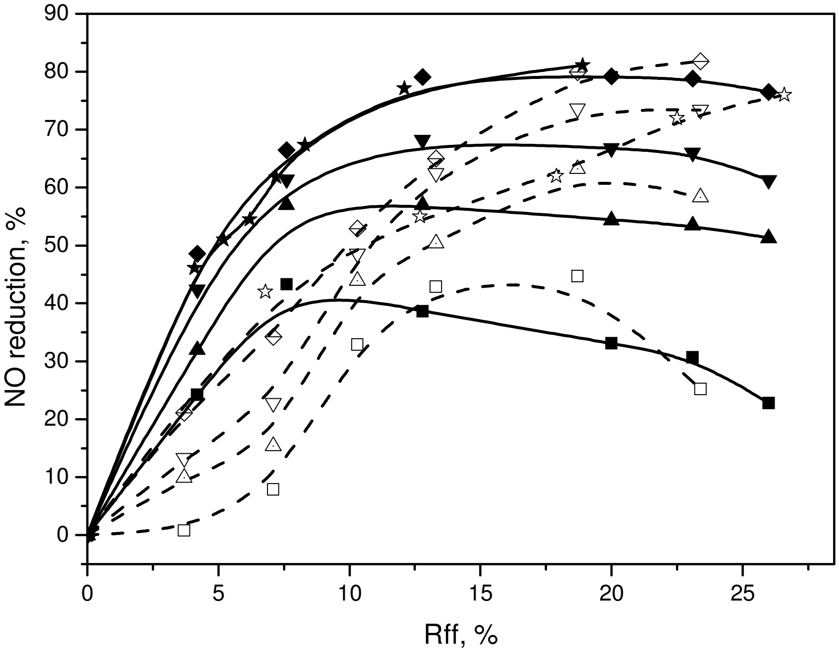

Fig 6. NO reductions measured for a range of reburn fuel fractions (*Rff*) for different initial NO levels. Tyre reburning; NO$_i$, 217 mg/Nm^3 ■, 390 mg/Nm^3 ▲, 629 mg/Nm^3 ▼, 1372 mg/Nm^3 ◆, 1520(SA coal) mg/Nm^3 ★. Coal reburning; NO$_i$, 217 mg/Nm^3 □, 390 mg/Nm^3 △, 629 mg/Nm^3 ▽, 1372 mg/Nm^3 ◇, 1605(SA coal) mg/Nm^3 ☆.

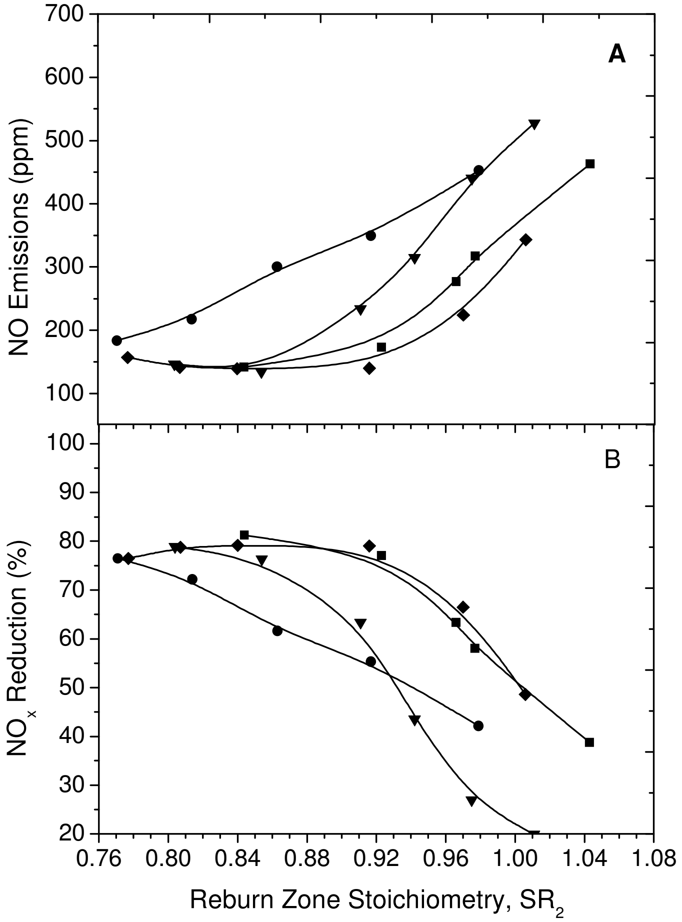

Fig. 7. A. Emissions of NO_x (ppm) at an SR_2 of 1.04 – 0.84 for tyre-on-coal reburn (TCR) ■, 0.98 – 0.77 for coal-on-coal reburn (CCR) ●, 1.01 – 0.78 for tyre-on-gas reburn (TGR) ◆ and 1.01 – 0.80 for coal-on-gas reburn (CGR) ▼. B. Percentage NO_x reductions at an SR_2 1.04 – 0.84 for tyre-on-coal reburn (TCR) ■, 0.98 – 0.77 for coal-on-coal reburn (CCR) ●, 1.01 – 0.78 for tyre-on-gas reburn (TGR) ◆ and 1.01 – 0.80 for coal-on-gas reburn (CGR) ▼. Initial NO_x concentrations were 740 ppm (1520 $mgNm^{-3}$), 782 ppm (1606 $mgNm^{-3}$), 668 ppm (1372 $mgNm^{-3}$), and 668 ppm (1372 $mgNm^{-3}$), respectively. All emission data have been corrected to 6 % O_2.

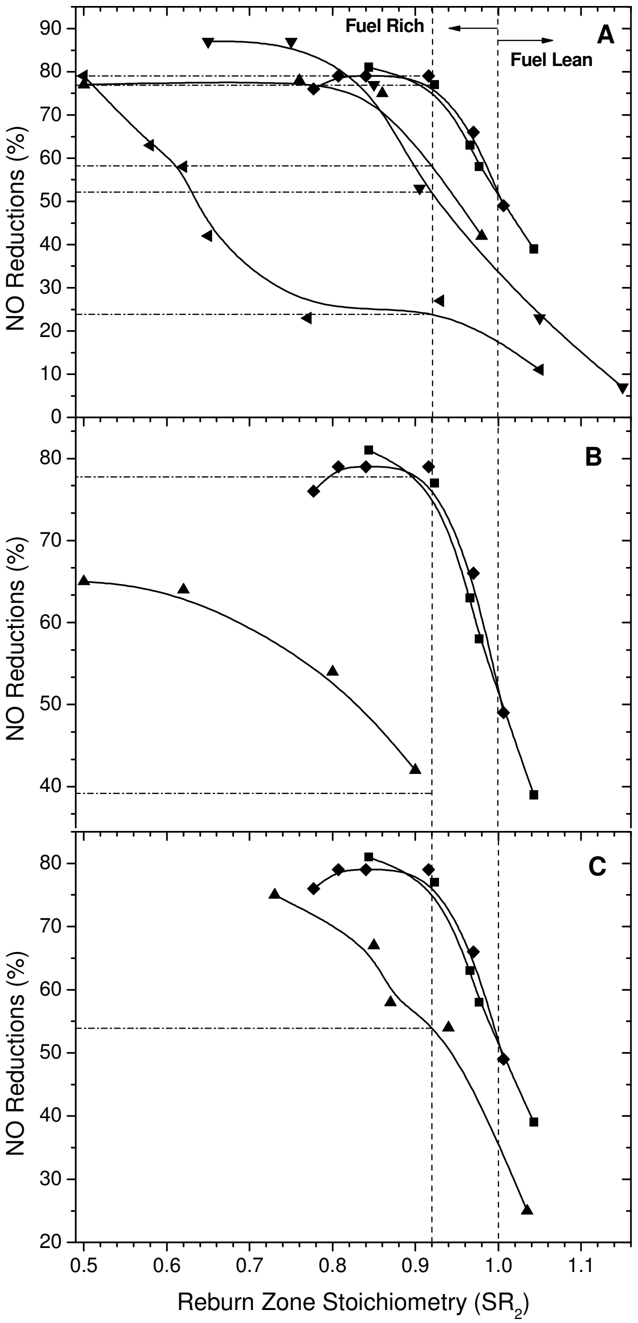

Fig. 8 A - represents NO_x reductions (%) of gas reburning studies performed by Spliethoff et al (1996) ▲, Bilbao et al (1997) ◀ and Kicherer et al (1994) ▲ in comparison to TCR ■ and TGR ◆. B - represents NO_x reductions (%) of coal reburning studies of Kicherer et al (1994) ▲ in comparison to TCR ■ and TGR ◆. C - represents NO_x reductions (%) of a straw reburning study by Kicherer et al (1994) ▲ in comparison to TCR ■ and TGR ◆. High initial NO_x concentrations being 740 ppm (1520 $mgNm^{-3}$), (TCR), 782 ppm (1606 $mgNm^{-3}$) (TGR), 1135 ppm (2736 $mgNm^{-3}$) (Spliethoff) ▼, 600 ppm (1231 $mgNm^{-3}$)(Kicherer) ▲, and 788 ppm (1616 $mgNm^{-3}$)(Bilbao) ◀. All emission data have been corrected to 6 % O_2.

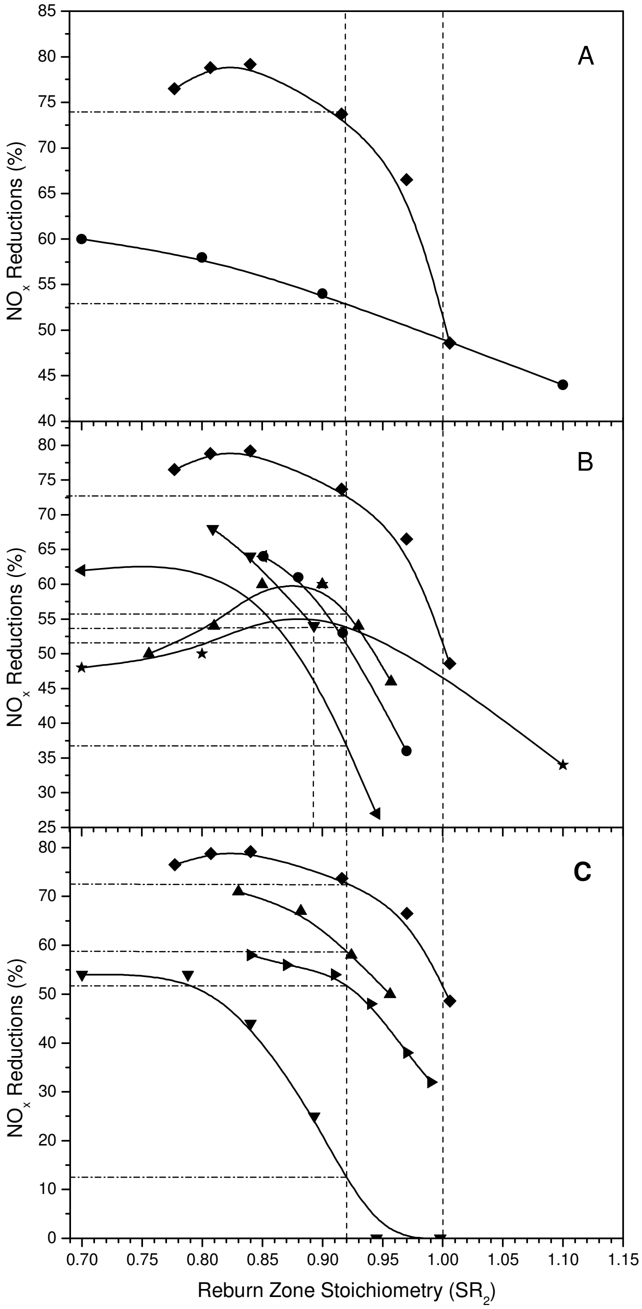

Fig. 9 A. represents NO_x reductions (%) of gas reburning studies performed by Folsom et al (1997) ● in comparison to TGR ◆. B. represents NO_x reductions (%) of coal reburning studies of Maly et al (1999) (▼coal pond fines), (orimulsion ●), (bit coal ◀), Harding (coal) et al (2000) ▲ and Folsom (brown coal) et al (1997) ✶ in comparison to TGR ◆. C. represents NO_x reductions (%) of wood reburning studies of Maly et al (1999) ▲ and Harding et al (2000) ▶ and Casaca ▼ (2005) in comparison to TGR ◆. Low initial NO_x concentrations of 427 ppm (877 $mgNm^{-3}$) (TGR), 560 ppm (1149 $mgNm^{-3}$) Maly et al, 412 ppm (846 $mgNm^{-3}$) Harding et al, 442 ppm (906 $mgNm^{-3}$) (Folsom et al) and Casaca 350ppm (1718 $mgNm^{-3}$). All emission data have been corrected to 6 % O_2.