REBURN: A COLLABORATIVE APPROACH TO RESEARCH, TECHNOLOGICAL DEVELOPMENT, AND DEMONSTRATION IN EUROPE

G. HESSELMANN

Mitsui Babcock Energy Limited, Technology, Porterfield Road, Renfrew, PA4 8DJ, Scotland

The reburn process has a number of attractive features making it a technology worthy of consideration for the reduction of NO\textsubscript{x} emissions from pulverized coal plant. The process was taken from the conceptual stage to plant demonstration, supported by the European Commission (ECSC, JOULE, and THERMIE). Pilot scale testing and CFD analysis were central to establishing the optimal process conditions for reburning and ensuring good mixing of the reburn fuel and overfire air. Gas reburn was successfully demonstrated at the 600 MWe Longannet Power Station, and the demonstration of coal reburn is imminent at the 320 MWe Vado Ligure Power Station.

Keywords: Pulverized coal combustion; NO\textsubscript{x}; Reburn

INTRODUCTION

Current generation low NO\textsubscript{x} burners are capable of achieving NO\textsubscript{x} emissions of 650 mg/Nm\textsuperscript{3} at 6\% \textsubscript{O}2 (the current EC legislative limit) for a wide range of coals. Proposed EC legislation calls for a NO\textsubscript{x} emission of 200 mg/Nm\textsuperscript{3} at 6\% \textsubscript{O}2 for large (over 300 MWt) coal-fired plant, and in the USA a similar limit of 0.15 lb NO\textsubscript{x}/million Btu is to be implemented by 2003 in a number of states under Title I (ambient air quality, including ozone) of the 1990 Clean Air Act Amendments.

NO\textsubscript{x} emissions of below 650 mg/Nm\textsuperscript{3} at 6\% \textsubscript{O}2 can be achieved by combining low NO\textsubscript{x} burners with furnace air staging. In a new plant with large, generously sized furnaces, this combined technology can attain NO\textsubscript{x} emissions of below 400 mg/Nm\textsuperscript{3} at 6\% \textsubscript{O}2. However, furnace air staging carries with it the risk of increased fireside corrosion. Jones (1997) reports that water wall panels require replacement within four years when previously they lasted 12–15 years, and carbon in ash levels arising are generally higher when the technology is retrofitted.

Address all correspondence to Prof. G. Hesselman, ghesselman@mitsuibabcock.com.

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Post combustion NO\textsubscript{x} control is certainly capable of meeting the latest legislative requirements. For retrofit installations Takeshita (1995) quotes the cost of SCR to be around $100–150 per kWe, though this is dependent on the inlet NO\textsubscript{x} level, the NO\textsubscript{x} reduction required, and the complexity of the retrofit. Lower installation and operating costs are incurred for SCR when this technology is applied in conjunction with combustion-modification processes, for example, the combined cost of low NO\textsubscript{x} burners, furnace air staging, and Selective Catalytic Reduction (SCR) is only 90% of that for SCR alone (in terms of $/ton NO\textsubscript{x} removed) according to Kitto et al. (1998).

Against this background there is a clear requirement for an in-furnace NO\textsubscript{x} reduction process that is capable of lower NO\textsubscript{x} emissions, can be retrofitted to existing boiler plants, and has minimal impact on plant performance (carbon in ash, availability, maintenance requirements). Reburning represents one of the more promising of the new technologies becoming commercially available. The development of the reburn process to the point of commercial demonstration in large-utility pulverized coal-fired furnaces within Europe has been achieved by means of a collaborative approach involving plant operators, equipment suppliers, and academic institutions, supported by the European Commission DG XII and XVII through the ECSC, JOULE, and THERMIE programs.

**PROCESS DESCRIPTION**

The reburn process (shown schematically in Fig. 1) involves the staged addition of a hydrocarbon fuel to the furnace chamber to destroy NO\textsubscript{x} formed during the combustion of the main fuel. The main fuel supply (typically 80% of the thermal input to the boiler) is fired under fuel-lean conditions in the primary zone, with a stoichiometry of typically 1.10. The reburn fuel (20% heat input) is supplied

![FIGURE 1](image-url)
downstream of the main combustion zone, and under slightly fuel-rich conditions (typical reburn zone stoichiometry is 0.90). The fuel decomposes to form hydrocarbon radicals, which react with previously formed NO\(_x\), reducing it to harmless nitrogen (see Fig. 2). Finally, the combustion is completed by the addition of overfire air (OFA).

In the practical application of the reburn process to the utility-scale plant, the stoichiometry in the main combustion region is coupled directly to that in the reburn zone; Figure 3 shows the relationship. From this figure, it is seen that the main combustion occurs in an oxidizing environment with reasonably high excess

**Primary Zone Stoichiometry (-)**

**Reburn Zone Stoichiometry (-)**

**FIGURE 2** Simplified reburn chemistry.

**FIGURE 3** Interrelationship between primary and reburn zone stoichiometry.
air. Only a relatively small proportion of the furnace volume is operated under fuel-rich conditions, and this is not in the region of peak heat fluxes. As a result, the risk of high temperature corrosion and furnace slagging is considerably less than that for air-staging technologies, and the impact of the process on carbon in ash levels is also somewhat lower.

In principle, any fossil fuel can be used as the reburn fuel, though the use of natural gas has a number of attractions:

- SO$_2$ emissions are reduced in proportion to the quantity of the gas being fired
- Complete combustion of reburn gas in the burnout zone — lower unburned loss
- Reduced ash disposal
- Quick formation of species involved in NO$_x$ reducing reactions
- No fuel preparation requirements, easy handling
- Simpler to retrofit
- Lower CO$_2$ emissions

Coal can also be used as the reburn fuel, and this can be economically advantageous for sites that are remote from the natural gas transmission system or where there is a significant cost differential between natural gas and coal.

GAS OVER COAL REBURN

In many respects the use of natural gas represents the simplest option for the reburn fuel. The supply of natural gas to the furnace is straightforward and, as indicated previously, there is less likely to be significant impact upon the overall carbon in ash levels arising from the introduction of the process. For these reasons, the demonstration of gas-over-coal reburning was presented first.

Process Design

The process design conditions for reburning were largely established by pilot-scale combustion testing undertaken during two EC-sponsored projects viz:

- ECSC — "Air Staging and Reburning — Application of Pilot Scale Tests" Mitsui Babcock
- JOULE — "Effect of Coal Quality on In-Furnace NO$_x$ Reduction Efficiency" (Mitsui Babcock-coordinator, IFRF, Elsamprojekt, TUD, CSM)

A total of seven coals of varying volatile content were fired under gas-reburning test conditions in MBEL’s 160 kWt furnace-details of the test facility are
The coals tested represent the range of coals typically fired through circular burners in front or opposed wall-fired furnaces as supplied to the UK domestic and world markets, as well as a number of lower volatile coals, which would normally be supplied to downshot fired plant. The key coal properties are presented in Table I.

The combustion testing carried out by Mitsui Babcock was undertaken with the objective of establishing the underlying data required to arrive at the optimum process conditions with regard to stoichiometry, residence time in the primary and reburn zones, and reburn fuel fraction.

Figure 4 presents the effect of the reburn zone stoichiometry (and by inference the stoichiometry in the primary zone) on the NO\textsubscript{x} emissions arising from a world-traded bituminous coal (coal A) when fired with 20% reburn gas. By ensur-

<table>
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<th>Coal</th>
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<th>Fuel ratio*</th>
<th>Fuel nitrogen (% daf)</th>
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<tr>
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<td>6.19</td>
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</table>

*Fuel ratio = Fixed carbon/volatile matter.

\[
\text{NO}_x \text{ (mg/Nm}^3\text{@6}\%\text{O}_2) 
\]

![Figure 4 Gas-over-coal reburn — Effect of stoichiometry.](image)
ing that the reburn zone is fuel rich, it is found that the NO\textsubscript{x} emission is reduced to below 300 mg/Nm\textsuperscript{3} at 6% O\textsubscript{2} (this compares to the current EC requirement of 650 mg/Nm\textsuperscript{3}). It is seen that the optimum reburn zone stoichiometry would be around 0.9, here the NO\textsubscript{x} emission is no longer sensitive to further reductions in stoichiometry, and the primary zone remains fuel lean so as to maximize the burnout of the main fuel while avoiding conditions that may lead to increased furnace deposition or corrosion.

Residence time is a key consideration when establishing the process design of a gas reburn system. Some typical data (for coal A as before) is presented in Figure 5. Generally it is found that longer residence time in the primary and reburn zones leads to greater reduction in NO\textsubscript{x}. In the primary zone, the residence time must be sufficient to complete the combustion of the main fuel; there is little additional benefit in extending the zone beyond this. Similarly, the reburn zone residence time must allow for the mixing and gas phase reactions to be completed.

![Figure 5: Gas-over-coal reburn — Effect of residence time.](image)
Significant NO\textsubscript{x} reductions (55–65\%) were obtained for all of the coals tested, with final NO\textsubscript{x} emissions of 290–415 mg/Nm\textsuperscript{3} being achieved. There was a slight trend of higher final NO\textsubscript{x} levels for the lower volatile coals, for world-traded coals fired through wall-fired plant typical emissions of around 300–350 mgNm\textsuperscript{3} would be anticipated. Summary data for the coals tested is presented in Figure 6. Significantly, the reburn process is seen to be effective for coals that otherwise might be considered to be "difficult"-good NO\textsubscript{x} reductions were achieved for coals having relatively low volatile content.

**Plant Demonstration**

At the time the ECSC and JOULE projects were initiated, the underlying information available to the power utilities and equipment suppliers was insufficient to move to a plant demonstration. In this respect these EC-sponsored collaborative projects could be seen as laying the underlying technical basis for gas-over-coal reburning and were, to some extent, precompetitive. When Scottish Power decided to proceed with a THERMIE demonstration of gas-over-coal reburn technology, the basic process information was available. The host site for the demonstration was Scottish Power’s Longannet Power Station, and the partners in the project were Mitsui Babcock, BG plc, ESB, EDF, ENEL, and Ansaldo.

Longannet Power Station comprises of four 600 MWe pulverized coal-fired boilers generating steam at 568°C, 169 bar. A side elevation of the boiler is presented in Figure 7. The boiler is front-wall fired with 32 burners arranged in 4 tiers of 8; for full-load operation only 24 burners are required to be in service.
The original burners were replaced with low NO\textsubscript{x} burners at the time of the gas reburn retrofit.

Details of the Longannet project and, in particular, the design of the retrofit, have been presented elsewhere by Macphail et al. (1997). The main process conditions (viz stoichiometry and residence time) were established from the pilot-scale data obtained in Mitsui Babcock’s 160 kWt test facility, after taking due account of the existing plant constraints. CFD modeling (by ENEL and Ansaldo) was used to determine the optimum location of the reburn gas and OFA injectors, and the required injection velocities. The key design features established by the design team were as follows:

- Reburn zone stoichiometry = 0.9
- 20\% gas reburn heat input
Primary zone stoichiometry = 1.12
• 24 reburn gas injectors (8 on front wall, 16 on rear wall)
• 16 OFA injectors (12 on front wall, 2 on each side wall.

The arrangement of the reburn injectors reflects the gross flow pattern in the furnace-this is biased toward the rear wall and so there were a greater number of injectors in this location. Ideally, a number of OFA injectors would also have been located on the rear wall, but there was insufficient access to accommodate this.

After completing the installation of the gas reburn system, an extensive test program was undertaken by the THERMIE project partners to provide plant characterization. Over 200 individual tests were completed giving performance data at baseline, air staging, and reburning conditions. It should be noted that, after the gas reburn retrofit, true baseline testing could not be undertaken as a cooling air flow through the various injector nozzles was required to maintain the mechanical integrity of these components. There was, therefore, a degree of air staging at all times. This becomes evident when considering the test results.

NO\textsubscript{x} emissions from Longannet are presented in Figure 8, while the corresponding carbon in ash levels are shown in Figure 9. The figures show the effect of stoichiometry in the reducing zone—that is, the primary zone for air staging or the reburn zone.

Under baseline firing conditions, with just cooling air through the OFA ports, the measured NO\textsubscript{x} emissions were in the range of 670–760 mg/Nm\textsuperscript{3} at 6% O\textsubscript{2}. As primary zone stoichiometry is reduced (i.e., the quantity of OFA in-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Reburn performance ($\text{NO}_x$) at Longannet Power Station.}
\end{figure}
creases), the NO\textsubscript{x} emissions are seen to fall. The firing pattern is also seen to have an impact on the NO\textsubscript{x} emissions obtained.

Carbon in ash levels is typically in the range of 7–12%, with poorer burnout being observed with a low firing pattern at baseline conditions (i.e., only cooling air through the OFA ports). This apparent anomalous finding possibly arises from the finer pf size distribution to the top burner rows due to the installation of rotary classifiers. As the quantity of OFA is increased (i.e., lower stoichiometry), furnace-mixing effects diminish the impact of the firing pattern on carbon in ash.

At the design reburn zone stoichiometry of 0.9, the gas-over-coal reburn process achieves a NO\textsubscript{x} emission of 325 mg/Nm\textsuperscript{3}, and values as low as 250 mg/Nm\textsuperscript{3} were observed at lower stoichiometries. Significantly, the carbon in ash levels are in the range of 4-6% at the design condition, and this is significantly better than for furnace air staging. Previously reported data (Golland et al., 1998) showed similar levels of NO\textsubscript{x} reduction (of the order of 50–60% from the levels achieved by low NO\textsubscript{x} burners alone) with a modest increase in carbon in ash (but starting from a lower initial level). Typical carbon in ash levels from conventional pf plant are of the order of 5%.

NO\textsubscript{x} emissions were seen to reduce with stoichiometry for all firing modes, as anticipated from the initial pilot-scale testing. Under furnace air-staging conditions, the carbon in ash levels was found to be insensitive to stoichiometry, and here it is believed that the increased mixing effectiveness arising from the higher proportion of OFA is compensating for the deeper staging. Under reburn condi-

FIGURE 9  Reburn performance (burnout) at Longannet Power Station.
tions, it is observed that as reburn zone stoichiometry is reduced, the primary zone also becomes more deeply staged (see Fig. 3), while the mixing is relatively unchanged (the quantity of recycle flue gas is constant while the OFA actually increases), and, therefore, there is a worsening of the carbon in ash. However it is also noted that the combustion of the main coal occurs in an oxidizing primary zone when operating with gas-over-coal reburn, compared to reducing conditions for furnace air staging; this accounts for the improved carbon in ash levels observed.

The NO\textsubscript{x} emissions achieved at Longannet were found to be in line with expectations based on the results of the pilot-scale testing undertaken in Mitsui Babcock’s 160 kWt facility (Fig. 10). This observation is significant in that it provides confidence in the use of small-scale combustors for generating process design information for in-furnace NO\textsubscript{x} reduction technologies in general.

Boiler operation was not unduly affected by the gas reburn retrofit. Attemporator spray flows increased, but this was in line with expectations, and the capacity of the spray system was sufficient to control the final steam temperature to the desired value. The commercial operation of the boiler was in no way compromised by the retrofit.

With significant NO\textsubscript{x} reductions (of up to 60% below the levels achieved by low NO\textsubscript{x} burners alone), at worst only a marginal increase in carbon in ash, and no detrimental effects on boiler performance, the demonstration of gas-over-coal reburn was successfully achieved at the 600 MWe Longannet Power Station.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig10}
\caption{Comparison between pilot scale and plant scale reburn performance.}
\end{figure}
COAL OVER COAL REBURN

While gas is undoubtedly a convenient reburn fuel, it is not always available at an acceptable cost—indeed the proximity of a particular site to the gas distribution network can have a significant impact on the economics of a reburn retrofit. Because of this, the possibility of using pulverized coal as the reburn fuel is clearly of interest.

Process Design

As for gas-over-coal reburn, the underlying process design data was established by pilot-scale testing during two EC-sponsored projects undertaken in parallel.

- JOULE — ”Performance Prediction in Advanced Pulverized Coal Fired Utility Boilers — Project Area 3 — Advanced Coal Reburning” (Mitsui Babcock-coordinator, ENEL, University of Pisa, IFRF, TUD, IVD)
- THERMIE — ”Vado Ligure Coal Over Coal Reburn Demonstration” (ENEL-coordinator, Mitsui Babcock, Ansaldo, ESB, Powergen, IST, EDP, James Howden & Sons, EDF, IVD).

Four coals of varying volatile content were tested in the 160 kWt pilot-scale facility, with the key properties summarized in Table II.

Typical coal-over-coal reburn results are presented for coal I in Figure 11. As before it was found that NO\textsubscript{x} emissions are sensitive to the stoichiometry in the reburn zone, and a value of around 0.9 appears to be optimal. From a baseline emission in excess of 800 mg/Nm\textsuperscript{3}, the NO\textsubscript{x} was reduced to 300 mg/Nm\textsuperscript{3} by coal reburn. The figure also shows the relative effect of gas-over coal reburn versus coal-over-coal reburn. Here it is seen that gas is apparently a less effective reburn fuel than coal. At a reburn zone stoichiometry of 0.9, the NO\textsubscript{x} emission achieved is 380 mg/Nm\textsuperscript{3}. This result is initially surprising given the relatively small amount of volatile material in coal relative to natural gas. However for the low concentrations of NO\textsubscript{x} entering the reburn zone (at the ppm level), the coal can still provide an excess of hydrocarbon radicals to initiate the NO\textsubscript{x} reduction reactions. Furthermore, coal contains organically bound fuel nitrogen, which is re-

<table>
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<th>Coal</th>
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$^*$Fuel ratio = Fixed carbon/volatile matter.
**FIGURE 11** Gas- and coal-over-coal reburn — Effect of stoichiometry.

**FIGURE 12** Coal-over-coal reburn — Effect of coal quality.
leased into the reaction pool as HCN, and this may assist in promoting the NO\textsubscript{x} reduction reactions.

Figure 12 shows that, while NO\textsubscript{x} emissions are higher for lower volatile coals, the percentage reduction in NO\textsubscript{x} is independent of coal quality. For the four coals tested, NO\textsubscript{x} reductions of 49–62% were observed in the combustion test facility. These reductions are comparable to those achieved by gas-over-coal reburning (Fig. 6) and clearly demonstrate the effectiveness of coal as a reburn fuel.

**Plant Demonstration**

Coal-over-coal reburning is to be demonstrated in a large utility boiler in Italy. Vado Ligure Power Station is located close to Savona and comprises of four 320 MWe subcritical once-through boilers. Steam is generated at 538°C, 175 bar. The furnace is opposed wall fired and can generate full load with either oil or pulverized coal. Coincident with the reburn retrofit, low NO\textsubscript{x} burners are being installed. These will be arranged in three tiers of four burners per row, giving a total of 24 burners on the front and rear furnace walls.

A similar approach to the coal-over-coal reburn system design to that at Longannet was adopted. Process conditions were established from pilot-scale testing, and extensive use of CFD models was made to optimize the injector port arrangement. The main features of the design eventually adopted are as follows:

- Reburn zone stoichiometry = 0.89
- 20% heat input with reburn coal
- Primary zone stoichiometry = 1.09
- 10 reburn coal injectors (5 on front wall, 5 on rear wall)
- 10 OFA injectors (5 on each side wall)

\[\text{Figure 13  Vado Ligure Power Station — Arrangement of reburn and OFA injectors.}\]
Figure 13 presents a graphical representation of the reburn and OFA injector positioning. With a more symmetric (though still nonuniform) flue gas flow in the furnace, an equal number of reburn injectors were located in the front and rear walls. The overfire air injectors were positioned in the side walls because the Vado Ligure furnace has gas tempering for gas temperature control. These injectors were located at a similar elevation to that required for the OFA.

The retrofit of the coal-over-coal reburn system at Vado Ligure is largely complete and was undertaken in conjunction with the installation of wet FGD and SCR plant. Commissioning of the plant is ongoing. An extensive series of plant characterization tests is planned. No performance data is available at the present time. Further details of the Vado Ligure demonstration, pilot-scale testing, modeling, and system design have been presented by Bertacchi et al. (1997).

CONCLUSIONS

- Gas-over-coal reburning has been demonstrated successfully at the large (600 MWe) scale with NO$_x$ reductions of 60% being achieved. Carbon in ash and boiler operation were not adversely affected.
- Pilot-scale combustion test facilities can simulate the in-furnace NO$_x$ reduction processes to a sufficient degree that process design information can be reliably obtained.
- The retrofit of reburn to existing plant is generally constrained by a variety of site specific factors, and each unit needs to be assessed individually.
- Coal-over-coal reburn has been demonstrated at the pilot scale, and a plant demonstration (at the 320 MWe scale) is in progress.

Acknowledgments

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References


