RCRA Box 1475

Prepped by Candice Davis

Document Number:

44) II-I-101

Docket Number:

A-95-28

Good, pilot-scale & modeling for scale-up.

C1:(WA) 17

A-95-28

II-I-101

Presented at POWER-GEN Americas '95
Anaheim, California, December 5-7, 1995

AN EVALUATION OF PULVERIZED COAL AND COAL–WATER–SLURRY IN REBURNING NO_x CONTROL FOR UTILITY BOILERS

Roy Payne, David K. Moyeda, Robert A. Ashworth, and Bruce Li
Energy and Environmental Research Corporation
18 Mason
Irvine, California 92718

Abstract

Reburning is a NO_x reduction technique which has been demonstrated successfully on a number of coal–fired utility boilers. Although natural gas has been the reburning fuel of choice for the majority of these demonstrations any hydrocarbon fuel can be used in the process, including pulverized coal and coal–water–slurry. The use of coal however poses some considerable challenges in its application in reburning, due to factors such as: the presence of fuel–bound nitrogen, which can affect process efficiency; the volatility of the fuel, which affects the availability of hydrocarbon fragments in the reburning zone; and the oxidation of residual char in the upper regions of the boiler furnace. This paper presents the results of an evaluation in which a number of different pulverized coals and coal–water–slurries (made from recovered coal fines) have been studied with regards to their application in reburning NO_x control for coal–fired utility boilers. Experimental studies have been conducted in a pilot–scale facility designed to simulate representative boiler conditions, and have confirmed the viability of coal as a reburning fuel. The subbituminous and lignite coals tested showed the potential to achieve high levels of NO_x control, while performance with bituminous coals tended to be related to fuel nitrogen content and volatility. With all coals, reburning performance was also found to be strongly influenced by available residence time and by initial NO_x levels. Existing reburning process models and boiler performance models have been adapted to accommodate the coal and slurry reburning data, and these models have been used to extrapolate performance to specific utility boiler applications. Anticipated NO_x reduction efficiencies, carbon burn–out and potential impacts on unit thermal performance are presented and discussed.

Introduction

Throughout the world, regulations are being implemented to control acid rain precursors such as sulfur and nitrogen oxides from coal–fired utility boilers. Therefore, there is increasing interest in the development and application of cost effective technologies for controlling these emissions. Reburning is one technology which is particularly effective at controlling NO_x emissions and which can be easily retrofit to existing utility boilers. The key advantages of reburning over other NO_x control technologies are that: 1) it provides high levels of NO_x control; 2) it can be implemented without significant impacts on boiler performance or carbon in ash; 3) it produces no by–product emissions; and 4) it can be applied to all types of boilers, including tangentially fired, wall–fired, and cyclone–fired boilers.

In the reburning process, fuel is injected above the main combustion zone to provide a slightly fuel rich environment or "reburning zone" which reduces nitrogen oxides formed in the primary combustion zone to molecular nitrogen. Following the reburning zone, additional combustion air is added to the boiler to oxidize carbon monoxide and any remaining fuel fragments exiting the reburning zone. Small–scale studies have shown that any hydrocarbon fuel can be used in the process, including natural gas, fuel oil, or coal [1, 2]. In the United States, several demonstrations of the application of natural gas reburning on coal–fired utility boilers have been completed [3, 4], and have successfully validated the engineering feasibility and the ability to achieve high levels of NO_x control. As a result, reburning technology is commercially available, and is of interest for utilities needing to comply with Title I and Phase II of Title IV of the Clean Air Act Amendments of 1990. In addition, there is a considerable interest in the application of reburning technology to utility boilers throughout the world [5].

Natural gas has many advantages as a reburning fuel in that it contains no fuel nitrogen and that combustion occurs readily, making it ideal for retrofit applications with limited access and limited combustion space. However, natural gas is generally more expensive than coal, and there may be significant technical and cost benefits to using coal and coal–based fuels as the reburning fuel where this may be viable. In considering the application of coal reburning to a specific boiler, one critical issue is the way in which coal properties influence NO_x reduction levels achievable, and the impacts of coal properties on boiler performance. Understanding these effects is essential to optimizing the process for boiler applications.

Coal is a nitrogen bearing fuel, and the extent to which this factor and other coal properties are expected to impact overall reburning effectiveness will depend primarily upon fuel nitrogen content and nitrogen reactivity. In the retrofit of reburning to an existing boiler, complete combustion of the reburning fuel is always a concern because of the limited time and temperature available for reactions to occur. Because coal does not burn as readily as natural gas, coal reburning also has the potential to increase unburned carbon losses. In addition, coal ash can slag under fuel–rich conditions leading to increased deposits on the boiler walls in the reburn zone. Therefore, the use of some coals in specific boiler situations may be unacceptable from a boiler operability point of view.

In the application of coal reburning to a particular boiler, there are several fuel alternatives to consider. The coal used in the reburning process could be the same as the coal fired under normal conditions, or it could be a coal which is selected to yield improved NO_x control performance with reduced boiler impacts in comparison to the nominal plant coal. Tailoring the coal to fit site specific requirements could benefit a utility's overall compliance plan. A third reburning fuel alternative for consideration is the use of coal–water–slurry, which could be formed from the nominal plant coal, or from coal fines recovered from a coal cleaning process. Although this latter approach is very site specific, the use of coal fines in the form of coal–water–slurry could provide environmental benefits and reduce fuel and NO_x control costs [6].

This paper presents results from experimental evaluations of the feasibility of using coals of various rank, and coal–water–slurries, as reburning fuels in coal–fired utility boilers, with a primary focus on the impacts of coal properties on the effectiveness of the reburning process. Objectives of the experimental studies were: (1) to develop an experimental data base on the performance of coals and coal–water–slurries under reburning conditions; (2) to determine the operating conditions which are necessary for optimization of the use of coal–based fuels in the reburning process, with respect to maximizing NO_x reduction and carbon burnout; and (3) to assess the potential impacts of coal characteristics on performance and the resulting implications for full–scale application.

In these studies, a number of different pulverized coals and coal–water–slurries made from recovered coal fines were evaluated as potential fuels for reburning application to coal–fired utility boilers. The coals were tested in a small pilot–scale facility designed to simulate representative boiler conditions, but with sufficient flexibility to cover an effective range of process parameters. Experimental conditions were defined following a brief survey of utility boiler design and operational characteristics, where key parameters such as uncontrolled NO_x emissions, local temperatures, quench rates, and residence times were identified, relative to specific coal types.

In the following sections of this paper, the general impacts of fuel properties and process parameters on the performance of the reburn process using coal–based fuels will be described. The results of the experimental studies, their implications for full–scale application, and the application of process models for scale–up to specific applications will be discussed.

Reburning for NO_x Control

Reburning is a combustion modification technology which removes NO_x from combustion products by using fuel as a reducing agent. The fundamental principle of this technology—

that fuel fragments can react with NO to form molecular nitrogen—has been studied for over two decades. The reburn process has been extensively evaluated at bench, pilot and full scale to identify the parameters which control process performance [1, 2, 7–9]. The results of these studies have shown that the most critical parameters which impact reburning performance are: primary NO_x level; reburning zone temperature and residence time; and reburning zone stoichiometry. In general, reburning effectiveness improves with increasing primary NO_x level, and with increasing reburn zone temperature and residence time. For utility boilers, the optimal stoichiometry for the reburning zone generally corresponds to the addition of a quantity of reburn fuel equivalent to about 20 percent of the total boiler heat input. In practical applications of the process, mixing of the reburning fuel, and the overfire air, with the bulk furnace gases is also a very important consideration.

In the use of coal and coal–based fuels as reburning fuels, a significant question is the extent to which fuel bound nitrogen and other coal properties influence NO_x reduction effectiveness. Previous studies using coal as a reburning fuel have suggested that the suitability of a coal for reburning depends upon fuel volatility, nitrogen content, and nitrogen reactivity. Fuel volatility impacts the availability of fuel in the reburn zone and, hence, the evolution of radical species. As a result, fuels with a higher volatile content would be expected to attain higher levels of NO_x reduction. Fuel nitrogen can also have an impact on reburning effectiveness since the addition of reactive nitrogen species to the reburning zone can influence the final emissions levels attained. Generally, fuel nitrogen content becomes more critical at lower initial NO_x levels. The distribution of nitrogen in the volatile matter and char is also important, since nitrogen species released with the volatile matter have more opportunity to be reduced to molecular nitrogen. During burnout, nitrogen in the char can be oxidized, or it may play a role in heterogeneous NO_x reduction [10].

In application of coal reburning to utility boilers, there are also concerns about the impacts of the process on carbon burnout and slagging and fouling in the reburning zone. A key consideration is the impact of available residence time on the process performance and on carbon burnout. The impacts of coal properties on carbon burnout and slagging and fouling are expected to be coal and boiler specific. The use of computational models for predicting these impacts and for developing strategies to mitigate their influence is expected to be a key step in full–scale applications of the technology. To this end, EER is currently adapting existing reburning and boiler performance models to accommodate the data obtained in these studies and to extrapolate performance to possible utility applications.

Experimental Results

Reburning experiments were conducted in a 1.0 MMBtu/hr pilot–scale test facility, which consists of a down–fired refractory lined combustion tunnel followed by a convective pass simulator and baghouse. To facilitate evaluation of the test coals on a consistent basis, the primary fuel was natural gas which was fired at 800,000 Btu/hr with ten percent excess air.

Initial NO_x emissions from the primary flame were controlled to set levels between 200 and 1300 ppm (dry, corrected to 3%O_2) by premixing ammonia with the combustion air. The reburning fuels were all injected at an initial temperature between 2,600 and 2,700°F. Nitrogen, to simulate recirculated flue gas, or air was used as the transport carrier for the pulverized coals and as the atomization media for the coal water slurries. Burnout air was injected downstream of the reburning fuel to bring the overall furnace stoichiometry up to twenty percent excess air. The burnout air injection location was set to provide a reburn zone residence time between 200 and 1200 milliseconds. The thermal profile in the furnace was set to provide a quench rate in the reburning zone of approximately 350°F per second. Test coals were selected from a data base of coals commercially available in the United States and Canada. Ranges of selected properties are summarized in Table 1, where the coals are classified by rank.

Ten different coals were tested to evaluate reburning NO_x reduction performance over a range of reburning zone stoichiometric ratios, corresponding to reburning fuel heat input varying between 10 to 40 percent of the total heat input. Results for the pulverized coals are summarized in Figure 1. Also shown in this figure are the results of using natural gas as a reburning fuel. Generally, each of the pulverized coals exhibited an optimum NO_x reduction at a reburning fuel heat input of about 20 percent, when using an inert transport medium. At this level of heat input, the NO_x reduction achieved with pulverized coal ranged from 40 to 60 percent, with some coals displaying performance equivalent to that of natural gas under the same nominal conditions. The variation in control performance achieved in these tests illustrates the potential impact of coal properties on the process.

The NO_x control performance measured with coal–water–slurry as a reburn fuel is shown in Figure 2. This figure compares the results obtained with a bituminous coal, where the coal was introduced to the reburn zone in either pulverized or slurry form. In addition, tests were performed where water (as steam) was added to the pulverized coal prior to injection into the reburning zone. The results shown in Figure 3 indicate that there is little influence of the water addition, and suggest that the method of introducing the coal has little impact on the NO_x reduction performance. These results confirm the viability of using coal–water–slurry in the reburning process.

Figures 3 and 4 illustrate the impacts of two key process parameters, initial NO_x level and reburning zone residence time, on reburning effectiveness. In agreement with previous studies, the data shown in these figures demonstrate that the NO_x reduction performance of the reburning process increases at higher initial NO_x levels and longer reburning zone residence times. In addition, these results indicate that the actual performance which can be achieved with a specific coal is influenced by its properties. In comparison to the use of natural gas as a reburning fuel, where high NO_x reduction efficiency can be achieved at low initial NO_x levels and at reburning zone residence times as short as 200 milliseconds, the performance of coal reburning drops off significantly at initial NO_x levels below 400 ppm and at reburning zone residence times below about 500 milliseconds. For the coals and conditions investigated in these studies, the effectiveness of the reburning fuel decreases as the initial NO_x level and reburning zone residence time are reduced due to the impacts of fuel nitrogen added to the reburning zone with the coal and to the impacts of fuel volatility on the reburning process.

In the application of coal reburning to utility boilers, the selected transport medium could be air or recycled flue gas (FGR). The impact of the transport media on the performance of coal reburning is shown in Figure 5, where nitrogen was used as the inert carrier to simulate recycled flue gas. The comparison of air verses nitrogen transport shown in Figure 5 indicates that there are two important factors to consider when selecting the transport medium. First, the use of a transport media containing high levels of oxygen requires the addition of a higher percentage of the total heat input with the reburn fuel to reach the optimum level of NO_x control. Second, the presence of high levels of oxygen in the transport can reduce the optimum performance achieved with a specific fuel. Since the addition of oxygen to the transport media requires additional reburning fuel in order to consume the additional oxygen, the need to increase the reburning fuel heat input is understood; however, the factors contributing to a reduction in the effectiveness of the process appear to be coal specific and are not clear at this time. In general, all of the pulverized coals and coal water slurries tested appear to be affected in a similar fashion, but to a greater or lesser extent depending upon the fuel properties. In addition, the performance of a specific fuel appears to be more sensitive to the effects of oxygen in the transport medium as initial NO_x level and reburning zone residence time are decreased.

From the data presented above, it is clear that coal properties can have a significant impact on reburn NO_x reduction performance. Although the experimental data suggest that fuels with low nitrogen content and high volatility are better performers, NO_x reduction potential does not readily correlate with either of these parameters. In order to better account for coal composition, a ranking parameter has been developed which combines coal volatile content, fixed carbon, and fuel nitrogen, into a value which reflects the ease with which fuel nitrogen is released into the gas phase. A coal with a high ranking may, for example, be high in fuel nitrogen and low in volatile content. The use of the ranking parameter in the presentation of optimum NO_x reduction data for the different coals is illustrated in Figures 6 and 7. The figures present data for inert gas and air as the transport medium, respectively, and for combinations of different reburn zone residence times and initial NO_x values.

For the inert reburn fuel transport medium (i.e., nitrogen or FGR), Figure 6 shows that, although there is some considerable scatter in the data, there is a good preliminary indication that the general trends observed in the data are accounted for with the ranking parameter. For bituminous coals in particular, NO_x reduction performance falls off significantly with higher values of the ranking parameter. The sub–bituminous and lignitic coals tested appear, however, to be less influenced by coal properties, and NO_x reduction performance seems to reach an asymptote which is related more to local operating conditions. At higher initial NO_x levels and longer reburn zone residence times, the data in Figure 6 reflect the significant increase in NO_x reduction discussed earlier. An improvement of some 15 percentage points appears to accrue due to these more favorable operating conditions. Unfortunately, insufficient test data were obtained for the lower rank coals to determine whether performance again reached an asymptote at the higher NO_x reduction levels.

Similar trends in the data are also found when air is used as the reburn fuel transport medium, as shown in Figure 7. Again, there is some considerable scatter in the data, but the general trends established with the inert transport medium appear to hold. In comparing the results of Figures 6 and 7, it is clear that NO_x reduction performance is significantly reduced when using air to transport and inject the reburn fuel. The magnitude of this effect is equivalent to some 10 percentage points of NO_x reduction at low initial NO_x and residence time, and to about 7 percentage points at higher initial NO_x and longer times.

A further consideration in the actual application of coal reburn technology to utility boilers is carbon loss. Figure 8 shows loss on ignition results obtained for the pulverized coals which were tested. As might be expected, bituminous coals showed the highest carbon loss, while low rank coals with a higher inherent reactivity showed the lowest carbon loss. The burnout achieved with the bituminous coals appeared to be sensitive to coal volatile content, while burnout achieved with the low rank coals was not sensitive to coal volatile content over the range of parameters evaluated in this study. The data presented in Figure 8 represent a nominal utility coal grind with 70% minus 200 mesh and approximately 99% minus 50 mesh. Additional experimental studies have shown, however, that finer grinding of the coal can significantly reduce carbon loss due to the reburn fuel, with minimal impacts on NO_x reduction performance. Therefore, micronizing mills (99% < 80 mesh, 80% < 325 mesh), and the use of dynamic classifiers to eliminate the coarser particle size fraction (> 50 mesh) from conventional coals mills, are equipment requirements which must be carefully considered in utility boiler applications if increases in carbon loss are to be minimized.

Utility Boiler Feasibility

In order to scale up the results of the experimental studies to typical utility boiler systems, process models have been applied in the evaluation of NO_x reduction potential and possible boiler performance impacts. Process models employed include: reburn NO_x kinetics models; jet mixing and fluid dynamics models; boiler heat transfer and steam generation models; and coal combustion models. These models, and the methodology for their application, have been successfully validated in the design and evaluation of gas reburning installations on a number of utility and industrial boiler systems. Engineering feasibility studies for the application of coal reburning have also been carried out for a number of wall–, tangential–, and cyclone–fired utility boilers with capacities ranging up to about 1,000 MW_e.

By way of example, selected results for a 170 MW_e wall–fired unit will be presented in the following discussion. The selected unit is of a conventional wall–fired design, with coal fired through four elevations of four circular burners, and generating approximately 1,140,000 lb/hr of superheated steam at 1,000°F. The design of the unit is such that there is approximately 1.3 seconds mean residence time between the upper burner elevation and the entrance to the pendant superheat sections. Inspection of the water walls indicates adequate access for the location of reburn fuel injectors and overfire air ports, such that a mean reburn zone residence time on the order of 0.55 seconds can readily be accommodated. These parameters suggest that the unit might be an appropriate candidate for the application of coal reburn.

The coal burned on the unit is a high volatile (33%) bituminous coal with 12% ash and 1.0% nitrogen. Baseline NO_x emissions, with modified burners, are on the order of 600 ppm. The properties of the plant coal give a coal ranking parameter of 2.55 in Figures 6 and 7, which indicate a NO_x reduction potential up to about 65 percent based on initial NO_x level and available residence time. In practice, however, there are a number of factors which act to reduce the NO_x reduction potential which can be achieved in small–scale furnaces. These include local temperatures, and the degree and rate of mixing which can be achieved by the reburning fuel and the overfire air. For the specific boiler under consideration, such non–idealities are estimated to amount to a penalty of approximately 10 percent, such that a NO_x reduction level of 55 percent might be expected in practice.

Of particular interest is the potential impact of coal reburning on boiler thermal performance and the ability to generate steam at the appropriate conditions. In this evaluation, a boiler heat transfer code was applied which is based on the zone method of analysis and which allows for complex radiative heat exchange between all important surface and volume zones in the boiler furnace. The basic model has been tested extensively on a wide range of utility boiler and reburning applications, and has recently been modified to accommodate coal and slurry reburning conditions. Selected results from the thermal performance analysis are presented in Figures 9 and 10, which show, respectively, the predicted mean gas temperature profiles and heat absorption by section for different reburning scenarios. The figures compare baseline performance with predictions for coal reburning (using both air (CR/Air) and FGR (CR/FGR) as a transport/injection medium for the reburn coal), and with gas reburning without FGR (GR).

The results in Figures 9 and 10 suggest relatively small changes in thermal performance as a result of the application of reburning. In Figure 9, mean gas temperatures are predicted to increase (relative to baseline levels) in the area of the reburning zone for gas reburn and for coal reburning with air as the transport medium, and to remain the same or to show a slight decrease at the furnace exit. Such trends have generally been supported by available field data. For coal reburning with FGR transport, however, gas temperatures are expected to decrease somewhat in the reburn zone and at the furnace exit. The corresponding impacts on heat absorption are shown in Figure 10 and suggest relatively small changes except for the case of coal reburning with FGR. Here, furnace absorption is reduced while superheater and reheater absorption are increased, with a net requirement for increased attemperation flows (from 38 to 66 klb/hr in the case of superheat attemperation) in order to maintain steam conditions. In all cases, however, changes in unit performance were found to be moderate, and well within the control capabilities of the unit.

Embedded within the boiler heat transfer code employed above is a simple combustion model which describes heat release in the main and reheat zones and also predicts char burn out in ten size fractions. Char oxidation is described by a global rate equation which considers diffusion and chemical reaction rates and local oxygen concentration, and where coal specific parameters are obtained from experimental data. The application of this combustion model in the prediction of changes in carbon loss due to reburning is shown in Figure 11. Relative to baseline levels, the model predicts carbon in ash to increase as a result of all of the reburn scenarios considered. For the case of gas reburning, an increase of approximately 1% carbon in ash is predicted to occur largely due to an assumed reduction in the excess air level applied at the main burner zone. For the coal reburning cases, this effect is further compounded by carbon loss arising from the reburn coal. A finer grind of the reburn coal (80% minus 200 mesh, 99% minus 150 mesh) can however reduce carbon loss to levels typically associated with the application of gas reburn.

Conclusion

A primary objective of the studies reported above has been to determine the potential for using coal-based fuels in the application of the reburning process to coal-fired utility boilers, and to assess the factors which are expected to most influence process performance. The results of pilot-scale tests conducted with coals of different rank indicate that NO_x reductions between 40 to 60 percent should be attainable with coal reburning under typical utility boiler conditions. In addition, the results of the tests show that the coal can be introduced in pulverized or slurry form without impacting the process effectiveness. The use of coal-water-slurries made from recovered coal fines as reburning fuels is therefore expected to be a viable technique for reducing NO_x emissions.

The level of NO_x reduction performance which can be achieved with coal reburning in practice will be controlled by site specific factors such as initial NO_x level, the available reburning zone residence time, by the method with which the reburning coal is transported and injected into the furnace, and by the properties of the coal used as a reburning fuel. Coals with high inherent reactivity (such as lignites and sub-bituminous coals) were found to perform well as reburning fuels, while the NO_x reduction achievable with bituminous coals was found to depend strongly on nitrogen content and volatile matter content.

Carbon burnout, particularly for bituminous coals, was also found to depend on coal volatile content, and is likely to represent a significant issue in many full–scale applications. Modern grinding techniques (such as micronizing mills and dynamic classifiers) can however significantly improve carbon burn out, and will need to be considered in the capital equipment requirements for coal reburn retrofit applications.

Heat transfer analysis of specific coal reburn applications has suggested that the process can be applied with minimal impacts on thermal performance and steam generation, and where any changes are likely to be within the design capabilities of the unit. However, thermal performance depends upon many factors and the feasibility of a coal reburn retrofit must be evaluated on a site specific basis.

Acknowledgments

Experimental data presented in this paper was obtained in projects sponsored by the Canadian Electrical Association (CEA), and the Electric Power Research Institute–Upgraded Coal Interest Group (EPRI–UCIG), with co–funding provided by the Tennessee Valley Authority (TVA). This support is gratefully acknowledged.

References

1. Chen, S. L., et al. *NO_x Reduction by Reburning with Gas and Coal — Bench Scale Studies.* Proceedings of the 1982 Joint Symposium on Stationary Combustion NO_x Control, Volume 1: Utility Boiler Applications, EPRI Report No. CS–3182, Volume 1, Electric Power Research Institute, Palo Alto, California, July 1983.

2. Chen, S. L., et al. *Bench and Pilot Scale Process Evaluation of Reburning for In–Furnace NO_x Reduction.* Twenty–First Symposium (International) on Combustion, The Combustion Institute, pp. 1159–1169, 1986.

3. Folsom, B. A., Sommer, T. M. and R. Payne. *Demonstration of Combined NO_x and SO_2 Emission Control Technologies Involving Gas Reburning.* Presented at the AFRC/JFRC International Conference on Environmental Control of Combustion Processes, Honolulu, Hawaii, 7–10 October 1991.

4. May, T. J., et al. *Gas Reburning in Tangentially, Wall–, and Cyclone–Fired Boilers. An Introduction to Second–Generation Gas Reburning.* Presented at the Third Annual Clean Coal Technology Conference, Chicago, Illinois, 6–8 September 1994.

5. Proceedings of the Gas Research Institute/Swedish Gas Center/Danish Gas Technology Center International Gas Reburn Technology Workshop, Malmö, Sweden, 7–8 February 1995.

6. Melick, T., et al. *Co–Firing Conventional and Upgraded Coal–Water Slurry in Utility Boilers. Reduced NO_x Emissions to Increase Operating Compliance Margin.* Presented at the 20th International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, Florida, 20–23 March 1995.

7. Greene, S. B., et al. *Bench Scale Process Evaluation of Reburning for In–Furnace NO_x Reduction.* ASME Journal of Engineering for Gas Turbines and Power, Volume 108, pp. 450–454, 1986.

8. Overmoe, B. J., et al. *Pilot Scale Evaluation of NO_x Control from Pulverized Coal Combustion by Reburning.* Proceedings of the 1985 Joint Symposium on Stationary Combustion NO_x Control, Volume 1: Utility Boilers Applications, EPRI Report No. CS–4360, Volume 1, Electric Power Research Institute, Palo Alto, California, 1986.

9. Payne, R. and D. K. Moyeda. *Scale Up and Modelling of Gas Reburning.* ASME FACT–Volume 18, "Combustion Modeling, Scaling and Air Toxins", A. K. Gupta et al., editors, pp. 115–122, 1994.

10. Chen, W. Y. and T. W. Lester. *Effects of Reburning Fuel Type on NO_x Reduction.* Presented at the Eighth Annual Coal Preparation, Utilization, and Environmental Control Contractors Conference, Pittsburgh, Pennsylvania, July 27–30, 1992.

TABLE 1. PROPERTIES OF COAL–BASED REBURNING FUELS.

Coal Type	Bituminous Coals	Sub–Bituminous Coals	Lignite Coals	Coal Water Slurry Parent Coals
Proximate (wt. %):				
Moisture	1.80 – 3.39	4.83 – 6.59	10.64 – 19.34	7.07 - 7.34
Ash	5.82 – 12.45	11.47 – 18.96	14.82 – 15.97	8.33 – 12.97
Volatiles	32.93 – 35.52	29.63 – 36.8	31.26 – 43.22	25.15 – 37.00
Fixed Carbon	50.91 – 54.07	44.85 – 48.37	31.32 – 33.43	47.07 – 54.81
Nitrogen (wt. %, daf)	1.11 –1.43	0.94 – 1.29	0.92 – 1.31	1.70 – 1.77
HHV (Btu/lb)	11,661 – 14,075	9,404 – 10,111	7,495 – 9,048	12,281 – 12,477

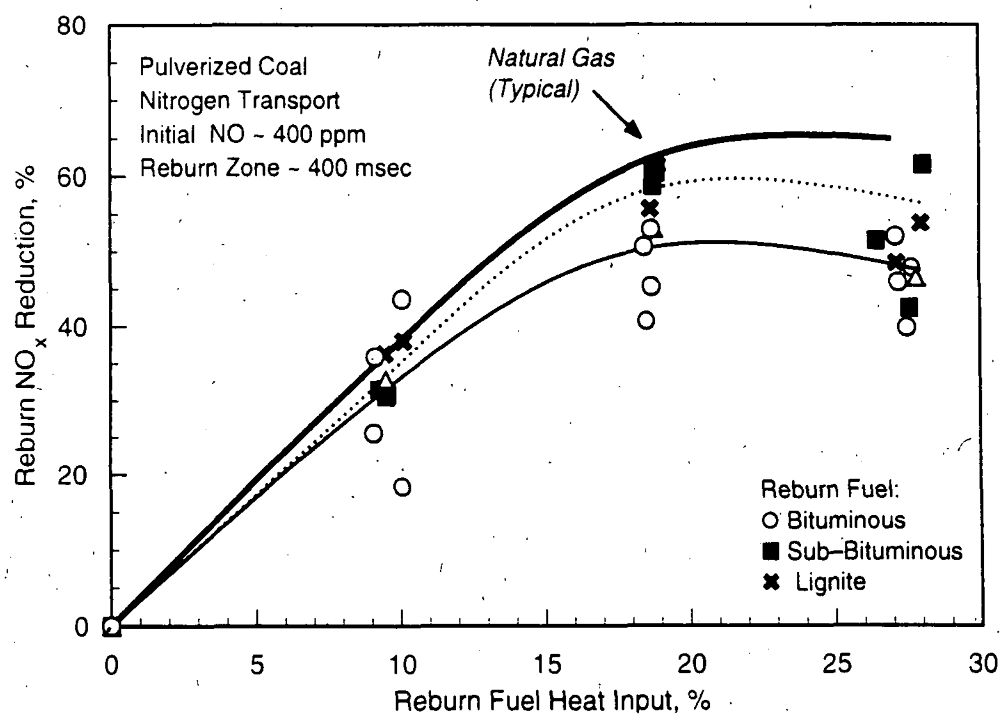

Figure 1. NO_x reduction performance of coals used as reburning fuel.

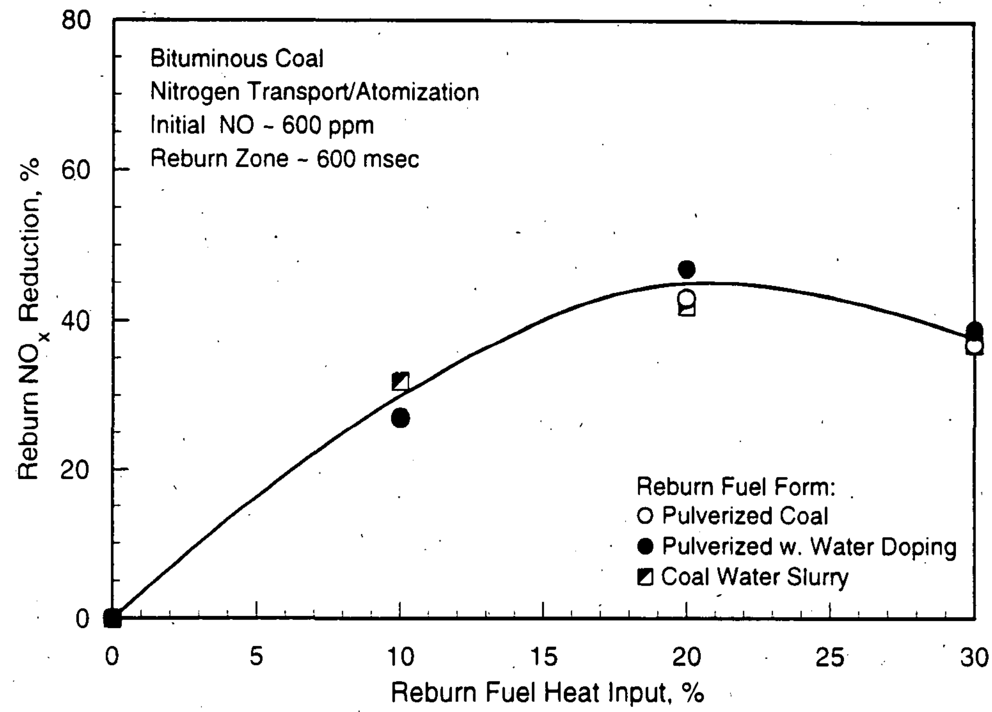

Figure 2. Performance comparison of means of injecting reburning coal.

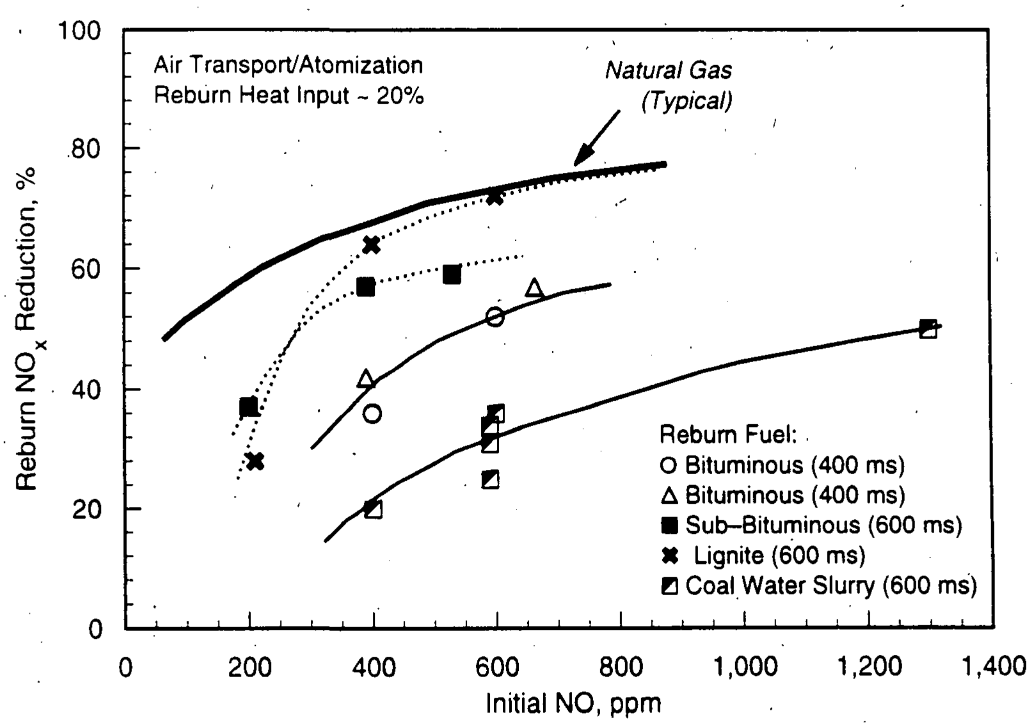

Figure 3. Impact of initial NO_x level on reburn performance.

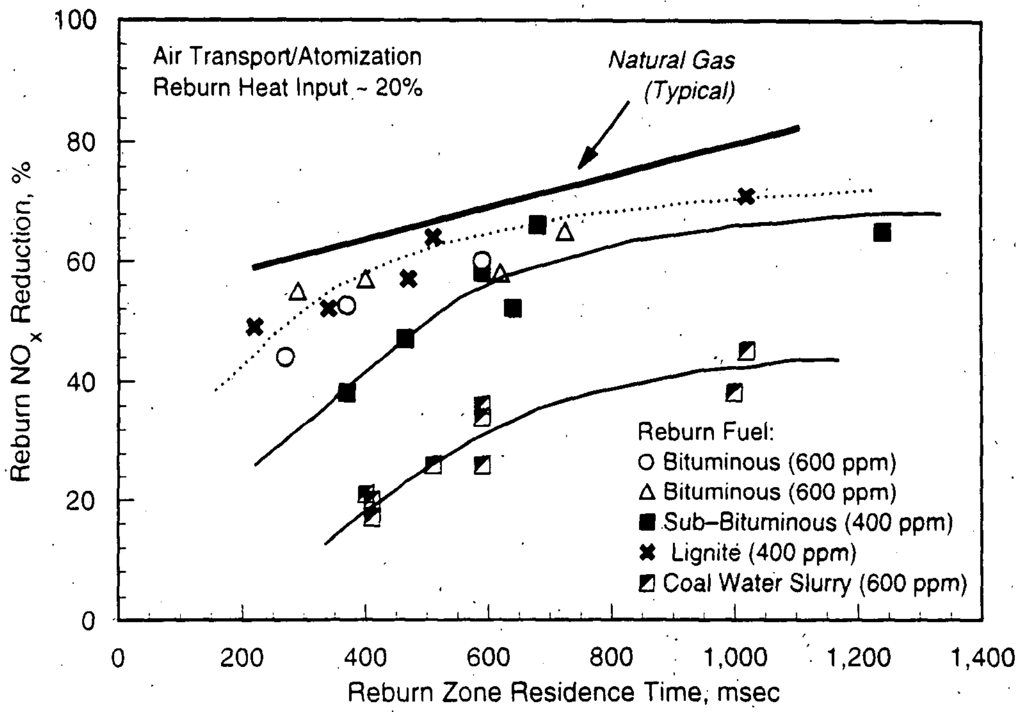

Figure 4. Impact of reburn zone residence time on reburn performance.

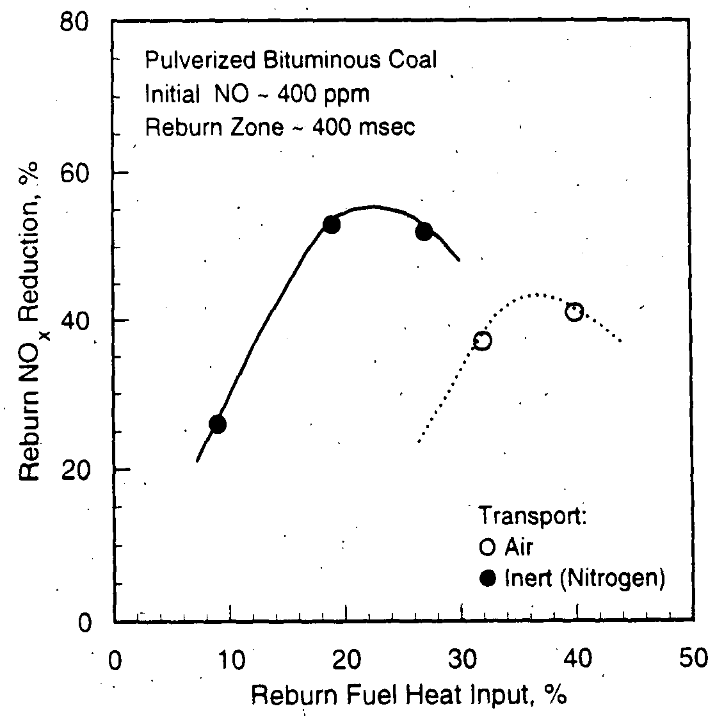

Figure 5. Impact of transport medium on coal reburn performance.

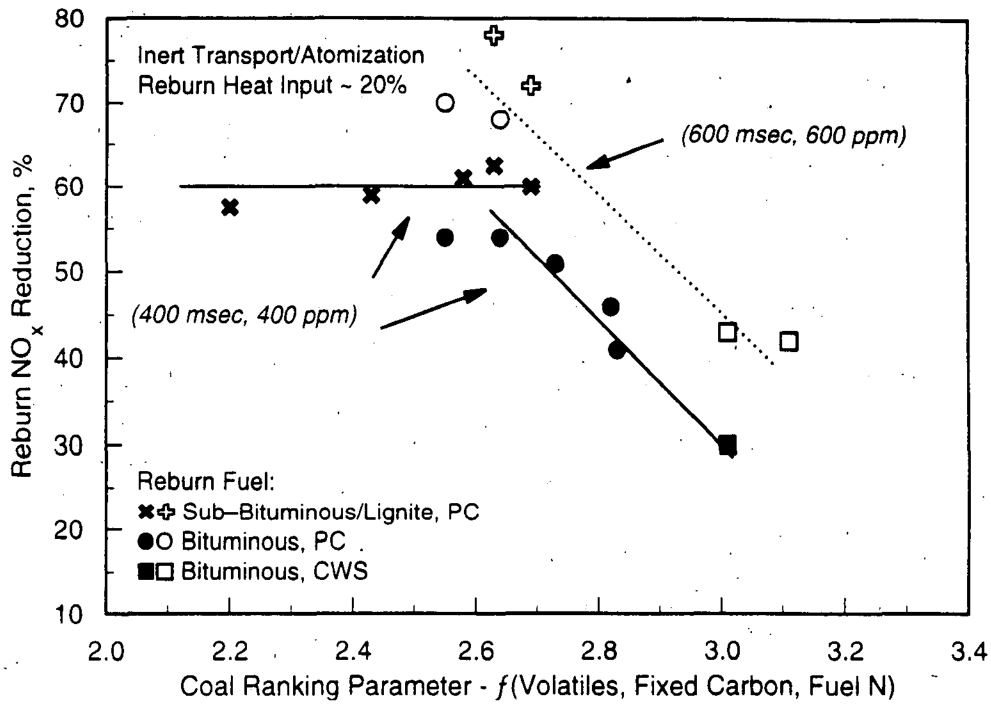

Figure 6. Correlation of coal reburn performance using inert transport.

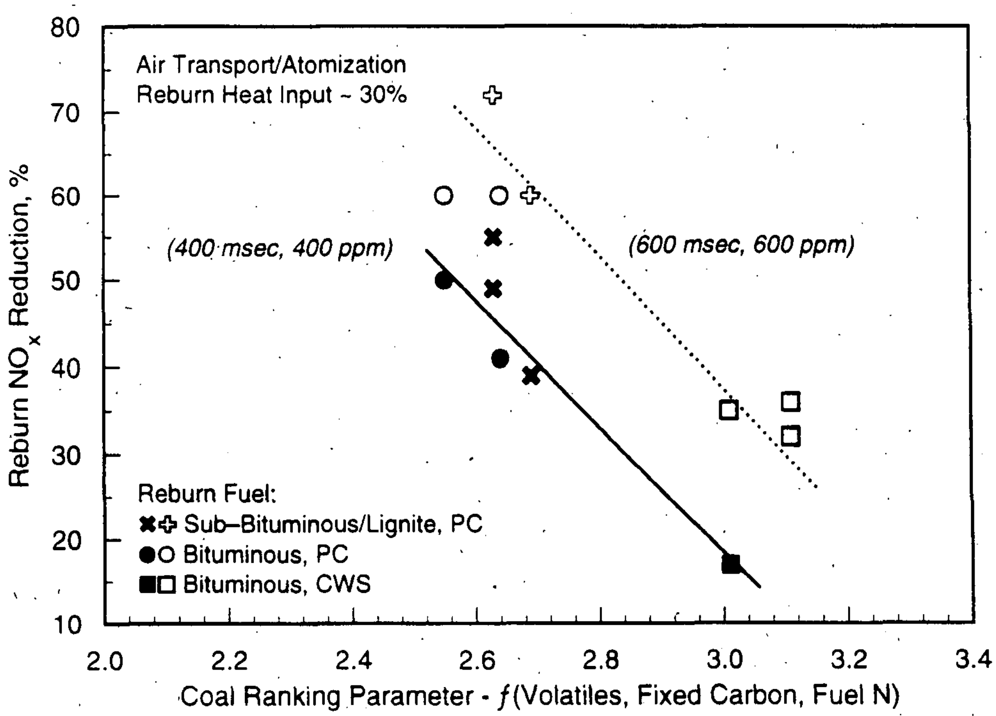

Figure 7. Correlation of coal reburn performance using air transport.

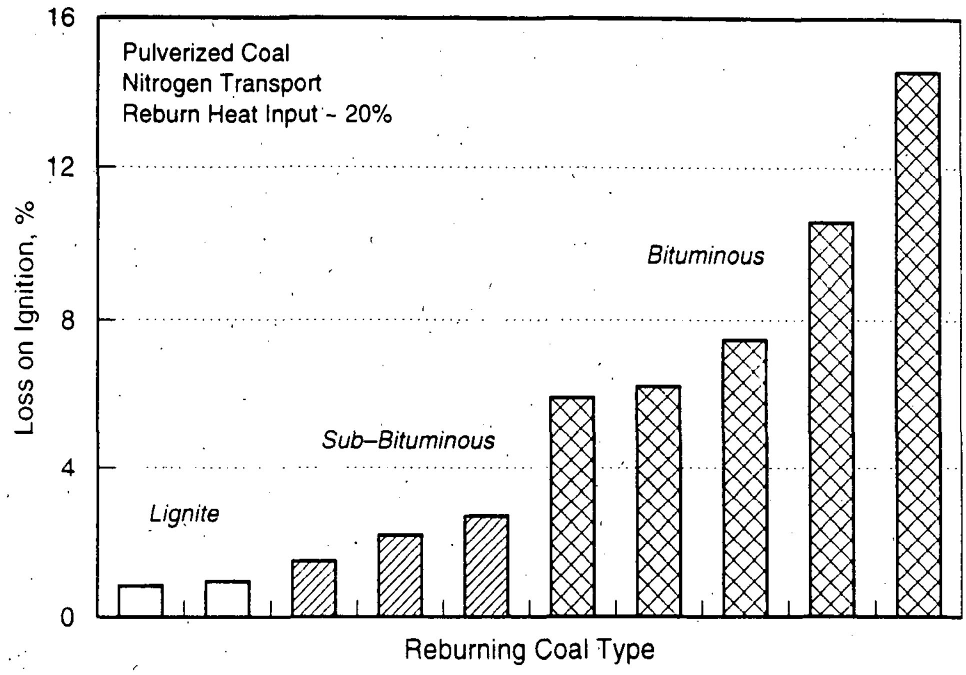

Figure 8. Carbon burnout performance of reburn coals.

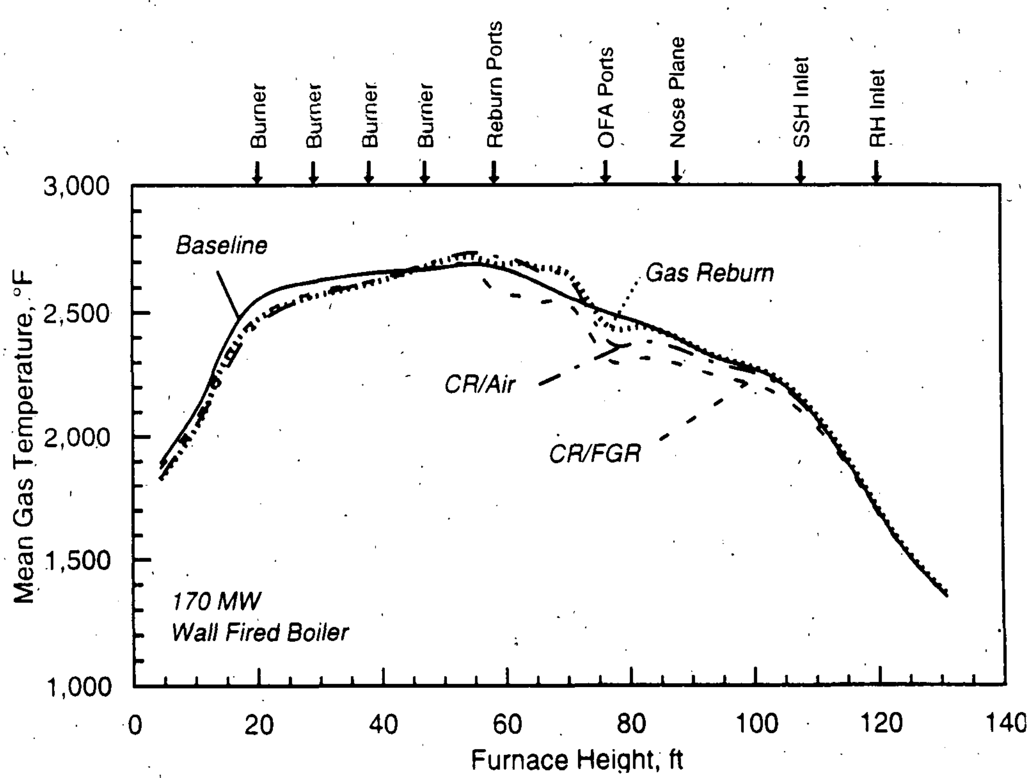

Figure 9. Predicted mean gas temperature profiles for various reburn scenarios.

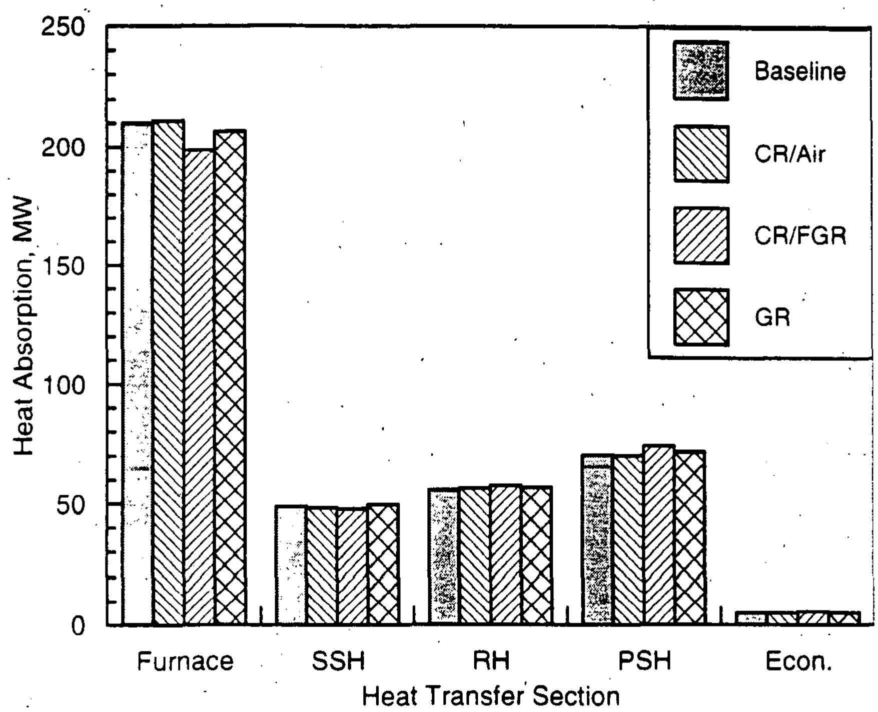

Figure 10. Predicted heat absorption by section.

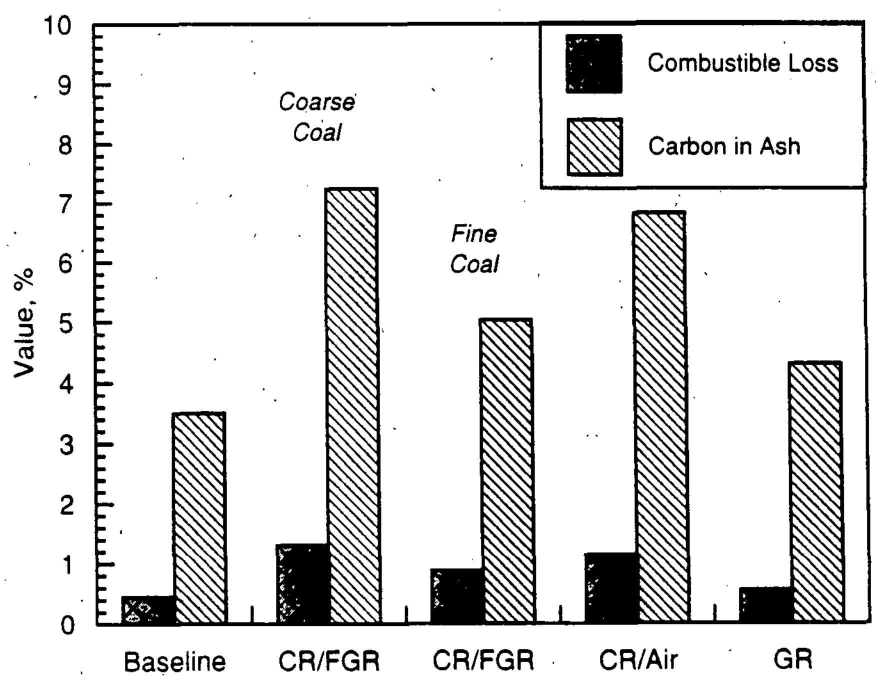

Figure 11. Predicted carbon loss.