

Control of NO_x and particulate emissions from spreader-stokers fired with hogged wood

J. M. Munro

Associate Professor of Chemical Engineering at South Dakota School of Mines and Technology, Rapid City, S.D. 57701

F. W. Bradshaw

Engineer, U.S. Dept. of Defense, Pearl Harbor Naval Base, Hawaii

D. W. Pershing

Associate Dean of Graduate School and Professor of Chemical Engineering at the University of Utah, Salt Lake City, Utah 84112

ABSTRACT *The formation and emission of nitrogen oxides and particulate carry-over were studied from spreader-stoker combustion of hogged Douglas-fir, with a focus on optimizing the combustion conditions in each of the two distinct combustion zones, the bed phase and the suspension phase. Local oxygen availability was the controlling parameter for nitric oxide formation. Minimum nitric oxide emissions were found when local air:fuel stoichiometric ratios were held at 0.70–0.85, with emissions reduced as much as 39%. Long first-stage residence times allowed intermediate nitrogenous species to decay to molecular nitrogen, if there was sufficient oxygen for first-stage formation of nitric oxide. Entrainment of large particulates was a function of furnace gas velocities in the bed zone. Operation of the furnace at low stoichiometric ratios (fuel rich) in the bed zone reduced these gas velocities and thus reduced particulate emissions.*

KEYWORDS

Chemical analysis
Combustion
Emission
Engineering
Environmental control
Fuels
Nitrogen compounds
Particulates

The stoker-fired industrial furnace is the equipment of choice in most wood combustion processes because of its ability to handle large fuel particles. The wood residues burned in industrial boilers typically consist of bark, sawdust, planer shavings, sander dust, and trim from lumber cutting and plywood manufacture.

These wood fuels are usually hogged to reduce their size. Hogged fuels often contain as much as 50% moisture by weight. Typically, they are burned in spreader-stoker furnaces to create a burning bed phase over the entire grate in the furnace. In general, spreader-stokers are sized for heat release rates of approximately 2.4 MW/m²; however, some wood-fired units are operated at much higher

capacities, even up to 4.7 MW/m².

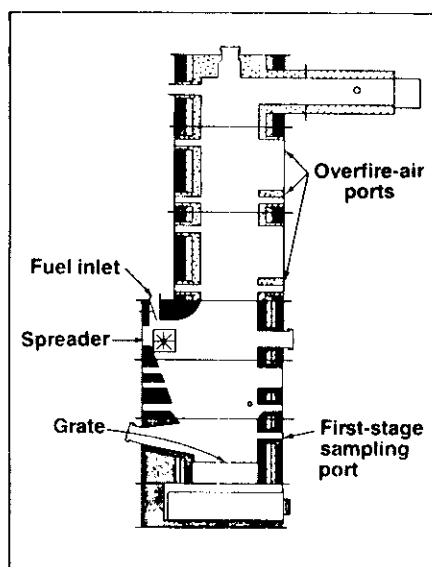
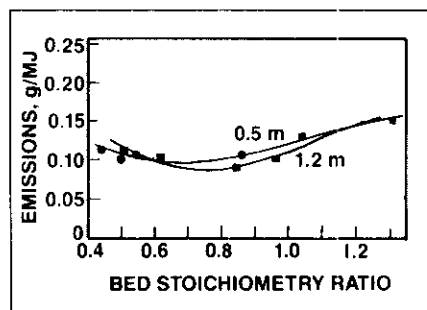
In recent years, there has been growing concern over emissions of nitrogen oxides (NO_x) from boilers fired with wood residue. Although there is considerable evidence that particulate emissions and carbon utilization are affected by changes in the combustion process which reduce NO_x emissions, no fundamental studies of this interaction have been reported.

In the field of coal combustion in stokers, the fate of fuel nitrogen is well documented (1) in a study in which the concentrations of the intermediate nitrogenous species of ammonia, hydrogen cyanide, and nitric oxide were measured under a variety of stoichiometric conditions. The NO emissions decreased as bed, or first stage, stoi-

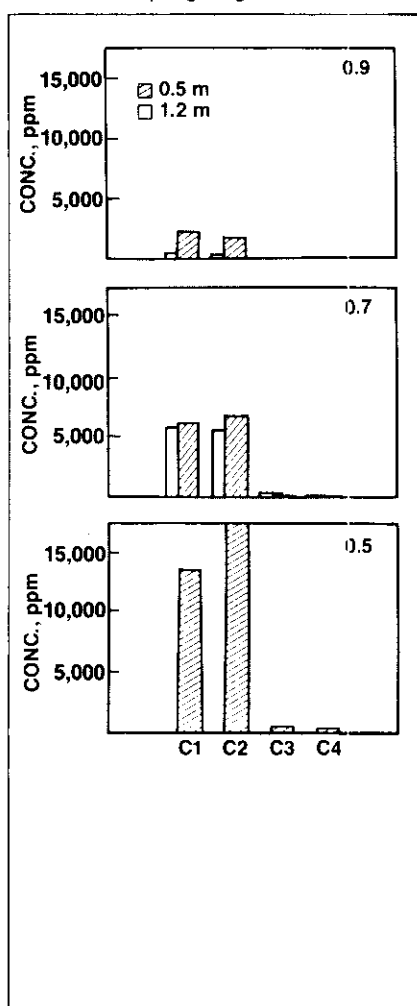
chiometries decreased, achieving a minimum at bed stoichiometries of approximately 0.65. These reductions in NO were attributed to the reduction of nitrogenous species to nitrogen in the fuel-rich first stage.

In the field of wood-fired stokers, several studies have been made on the factors which affect NO_x emissions from full-scale industrial boilers (2, 3). However, detailed and fundamental data from controlled laboratory-scale equipment have not been previously available. Kester (4) and Kester and Pilat (5) reported studies in which hogged Douglas-fir bark was burned in a 1.8-MW, pilot-scale spreader-stoker. Although the exact stoichiometry distribution in the furnace was not reported for each experiment, the

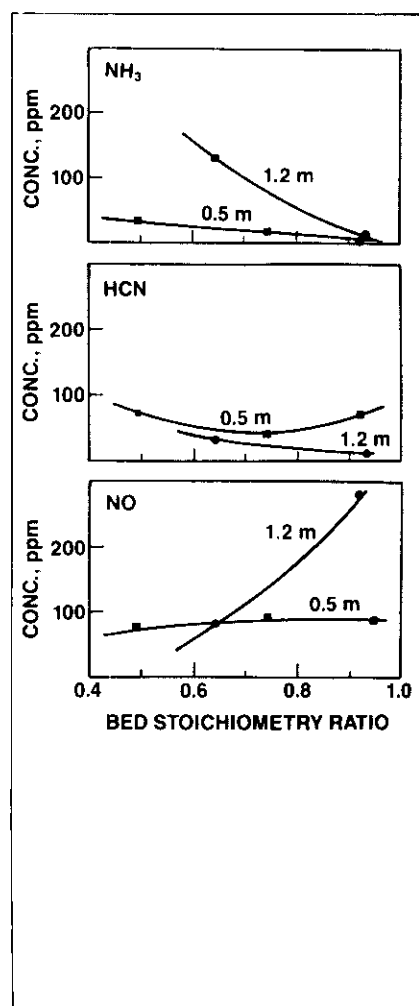
1. Model stoker furnace schematic

2. The effect of bed zone stoichiometry on NO_x emissions (Excess oxygen = 5%. Load = 1.40 MW/m².)

3. First-stage hydrocarbon concentrations for bed stoichiometric ratios of 0.9, 0.7, and 0.5 at two sampling heights



4. Concentrations of first-stage nitrogenous species



bed was operated under fuel-rich conditions, and typical NO emissions of approximately 0.052 g/MJ of NO_x (as NO₂) were measured at firing rates up to 1.90 MW/m².

The pollutant from wood combustion which has received the greatest research attention is particulate emissions. Junge (6) has itemized the factors responsible for particulate emissions, especially as related to post-combustion flue gas treatments. The key factors are high excess air concentrations (causing entrainment), transient combustion conditions, and fly ash reinjection. A model for predicting particulate emissions from wood-fired boilers has been developed by Adams (7). Adams concentrated on emissions from fuel beds in stoker systems and showed that fuel feed rate, undergrate air flow rate, and fuel particle size distribution are parameters that affect particulate carry-over.

In our studies of NO_x emissions, we focused on the formation of interme-

mediate nitrogenous species and subsequent reactions to NO. The possibility of obtaining reductions in NO emissions by tailoring the local oxygen availability in specific regions of the furnace was evaluated. Similar studies with gaseous and liquid fuels, as well as with coal-fired-stokers, have shown that large NO reductions can be achieved under optimum combustion conditions.

Nitrogen oxide formation

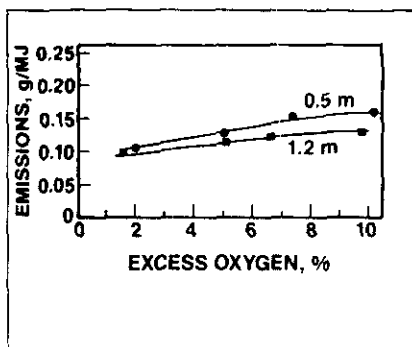
Exhaust NO_x

Extensive testing was conducted to evaluate the effects of combustion-zone parameters on emissions of NO from the experimental model stoker furnace, shown in Fig. 1. Although no specific data from full-scale boilers exist in the appropriate literature, several baseline conditions were chosen as focal points and used in all experiments except as noted. These conditions were:

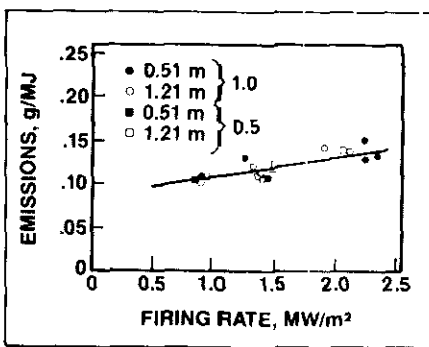
- Firing rates of approximately 1.42 MW/m²
- Fuel moisture content of 34 wt. %
- Bed air:fuel stoichiometric ratios of 0.5 and 1
- Overfire-air heights of 0.5 m and 1.2 m
- Excess oxygen concentrations of 5% and 10%.

Because previously reported experiments with coal had demonstrated the NO reductions possible with proper tailoring of the bed stoichiometries, fairly extensive experimentation was devoted to similar experiments with combustion of hogged Douglas-fir. Figure 2 shows the emissions of NO in a series of experiments in which the excess air was maintained at 31% and the firing rate was held at 1.42 MW/m². The overfire air was injected at either 1.2 m or 0.5 m above the grate. The nominal bed stoichiometry was varied

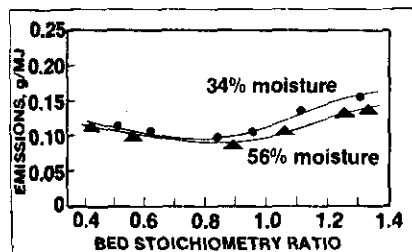
5. The effect of excess oxygen on NO_x emissions (Bed stoichiometric ratio = 1.00. Load = 1.45 MW/m².)



6. The effect of furnace load on NO_x emissions (Excess oxygen = 5%.)



7. The effect of fuel moisture content on NO_x emissions (Excess oxygen = 5.5%. Load = 1.40 MW/m². Overfire-air height = 1.2 m.)



by changing the fraction of the total air admitted as overfire air.

The emissions of NO were observed to pass through a minimum, similar to emissions during coal firing; however, the minimum was fairly shallow, with emissions ranging from 0.090 to 0.150 g/MJ. Although under excess air conditions these emission concentrations are lower than NO emissions obtained during analogous coal firing [0.150 g/MJ for wood vs. 0.220 g/MJ for coal (1)], when based on fuel nitrogen, they represent conversions of approximately 100%. This high fuel nitrogen conversion is not necessarily typical for wood-fired stokers, but it is due in part to the relatively low nitrogen content of the fuel tested.

The minimum NO emissions under wood firing were not much less than that observed with coal firing [0.090 g/MJ for wood vs. 0.110 g/MJ for coal (1)], although their respective fuel nitrogen contents vary by a factor of 10. These data indicate that under optimum staged combustion conditions, the gas-phase nitrogen chemistry may be partially equilibrated, which reduces the influence of fuel nitrogen content and speciation.

While both curves in Fig. 2 have minimums, the minimums occur at different values of bed-zone stoichiometry. This difference may have re-

sulted from the variation in fuel distribution between the suspension phase and the bed phase. When the overfire air was injected at 0.5 m above the grate (i.e., below the spreader), a larger percentage of the fuel would have been entrained in the suspension phase than when the overfire air was injected above the spreader. With lower bed-phase burning rates, the actual bed stoichiometry would have been higher than the nominally calculated bed-zone stoichiometry. Thus, although the minimum NO_x occurred at a nominal bed stoichiometry of 0.65 when the overfire-air height was 0.5 m, the actual local oxygen concentrations probably were equivalent to a higher stoichiometric ratio.

First-stage hydrocarbons

Hydrocarbon measurements were made in the fuel-rich stage to assess possible "reburning" mechanisms for NO reduction. Figure 3 shows hydrocarbon measurements at two heights above the fuel bed for three different nominal bed stoichiometries. In these experiments, the overfire air was injected at 1.8 m above the bed so that the first-stage chemistry could be studied in detail. As expected, the hydrocarbon concentrations increased markedly with decreasing stoichiometric ratio. With the bed zone stoichiometric ratio equal to 0.9, the concentrations at 1.2 m were consistently lower than those at a ratio of 0.5, which is probably a result of the reaction with oxygen as mixing becomes more complete at higher positions above the bed. In all cases, virtually all the hydrocarbon speciation occurred as one- and two-carbon molecules; only trace amounts of longer chain hydrocarbons were detected.

First-stage nitrogen speciation

In tests analogous to the hydrocarbon measurement tests, experiments were

conducted in which concentrations of NO, NH₃, and HCN were measured in the fuel-rich first stage at heights of 0.5 m and 1.2 m above the bed. Overfire air was injected at 1.8 m above the bed. The results of these tests are shown in Fig. 4. As the bed stoichiometry was decreased below unity, the concentrations of the intermediate nitrogenous species NH₃ and HCN increased, while the concentrations of NO decreased. The tendency of the intermediate species distribution at low bed stoichiometries and at the sampling location closest to the burning bed was toward HCN formation. This observation is consistent with that of Fenimore and Fraenkel (8), who observed fuel nitrogen to form HCN preferentially under fuel-rich conditions.

The concentration of NH₃ increased markedly from the 0.5-m sampling height to the 1.2-m sampling height at low bed stoichiometries. This shift in fixed nitrogen speciation is indicative of HCN reaction to form NH₃ (9, 10). The increase in NH₃ at the 1.2-m sampling position is probably due to increased evolution of nitrogen from the suspension-phase fuel, which is injected between the 0.5-m and 1.2-m sampling locations. The NH₃ thus formed may react with NO to form molecular nitrogen, or it may oxidize to form NO (9, 11). The high concentrations of both NH₃ and HCN at low (< 0.5) bed stoichiometric ratios and high sampling heights may be the cause of the increase in exhaust NO emissions seen at those bed stoichiometries in Fig. 2. The high concentrations of HCN and NH₃ would convert to high concentrations of exhaust NO when mixed with the final excess air.

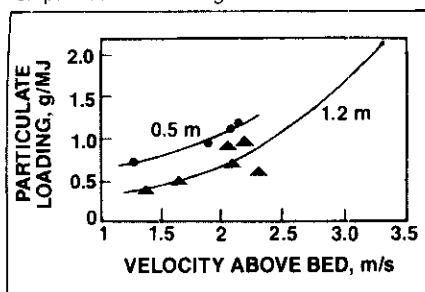
Effect of firing conditions on NO_x emissions

Excess air

The effect of total furnace stoichiometry on NO_x emissions at a fixed-bed stoichiometry is shown in Fig. 5. In these experiments, a nominal bed-zone stoichiometry of 1 was maintained, while the excess oxygen concentrations in the exhaust were varied from 1.5% to 10% (10–90% excess air).

When the overfire air was injected at 0.5 m above the bed (below the spreader), increasing the excess oxygen from 2% to 10% increased the exhaust NO by approximately 35%. This relatively large change must be associated with increased suspension-phase burning (due to the higher verti-

8. The effect of superficial gas velocities on particulate loadings



cal velocities) and perhaps with higher local temperatures. A somewhat smaller change was observed when the overfire air was at 1.2 m. In this case, the overfire air was injected above the spreader, so increases did not alter particle entrainment.

The effect of changing the overfire air height, at a constant excess O₂, from above the spreader to below the spreader was to increase NO emissions 10–20%. Winter (12) has shown that the suspension-phase conversion of fuel nitrogen in biomass fuels increases with increasing local oxygen content.

Load

The effect of furnace load was studied by varying the firing rate from 0.88 MW/m² to 2.2 MW/m². For these tests, the bed stoichiometric ratio was maintained at values of 0.5 or 1. For each condition, the overfire-air jets were positioned at either 0.5 m or 1.2 m above the grate. Emissions of NO for these tests are shown in Fig. 6. The concentrations of NO emissions increased slightly as the firing rate increased.

It would appear from these results that bed stoichiometry has virtually no effect on NO_x emissions at a given firing rate. However, the two values, 0.5 and 1, lie on either side of the optimum bed stoichiometry. Thus, while the concentrations of NO emissions at these two stoichiometries were nearly equal, the NO_x emissions would have been lower at bed stoichiometries between them, as shown in Fig. 2.

Fuel moisture content

The effect of fuel moisture content on NO_x emissions was studied by conducting comparison tests with fuel containing 56% moisture by weight. The results of these tests are shown in Fig. 7. The NO emissions for the two fuels were virtually identical for sub-stoichiometric beds. However, at excess air bed stoichiometries, the NO

emissions were slightly lower for the fuel of higher moisture content. The lower NO emissions are probably attributable to lower rates of suspension-zone volatilization, resulting from the lower furnace temperatures.

These results are consistent with those of Winter (12), who noted that the denser particles in a fuel of high moisture content tended to fall through the suspension phase without burning. The results are also consistent with those of Starley *et al.* (1), who showed that suspension-phase conversion of fuel nitrogen tended to be much greater than bed-phase conversion. While exact measurements of gas temperature were not made, thermocouples in the refractory walls indicated that furnace temperatures were cooler by approximately 60°C during the runs with the fuel of higher moisture content.

Particulate carry-over

A series of detailed experiments was conducted to evaluate particulate carry-over from the model stoker furnace under several different furnace conditions. The parameters of specific interest were bed-zone stoichiometry, firing rate, overfire-air height, overall stoichiometry, and fuel moisture content. Particulate samples were collected in the spray tank, dried, and screened to remove particles which passed through an 80-mesh screen (Tyler). Only particles larger than 80-mesh were evaluated as particulate carry-over.

The particulate carry-over loadings for these runs ranged from approximately 0.4 g/MJ to 2.2 g/MJ. The loadings of particles smaller than 0.35 mm (42-mesh), were relatively constant regardless of the firing conditions and accounted for less than 0.21 g/MJ. The loadings of particles larger than 2.4 mm (8-mesh) showed the largest deviations among the experimental runs. Total particulate loadings increased primarily as a result of increased carry-over of large particles, while small-particle emissions remained approximately constant.

To assess the fundamental principles governing particulate emissions, gas-phase furnace velocities were computed at the surface of the fuel bed. Values of the molar flow rates of the combustion gases were available from furnace material balance computations. Furnace velocities were computed using the ideal gas density, based on temperatures measured by thermo-

couples in the refractory walls. The particulate loadings as a function of superficial gas velocities above the fuel bed are shown in Fig. 8 for all of the cases studied.

While the particulate loadings were somewhat dependent upon the stoichiometry distribution, the overfire-air height and the superficial velocity above the fuel bed appeared to be the controlling parameters. Increasing the vertical velocity increased the particulate loadings. Decreasing the overfire-air height to 0.5 m (below the spreader) increased the particulate carry-over, because of the higher vertical velocity at the spreader. The influence of increasing excess oxygen was small and somewhat complex because the higher oxygen partial pressure enhanced the carbon burnout and somewhat mitigated the increased entrainment resulting from the higher volumetric flow rates of the exhaust gases. The effect of fuel moisture content on particulate emissions was negligible. Overall, the fundamental mechanism governing particulate emissions appears to be particle entrainment, particularly of particles off the surface of the fuel bed.

To evaluate the extent of carbon utilization in the suspension phase, several samples were characterized in terms of their chemical constituents. The analyses indicate that hydrogen evolution is essentially complete in all the particulates (i.e., hydrogen content < 0.35 wt. %). Carbon contents were low in the smallest particulate size range relative to the larger particulates (30% vs. 80% by weight, respectively). These data indicate that higher heating rates in the small particles outweighed the shorter combustion-zone residence times which they would have experienced. The particulate composition data show no discernible differences arising from other furnace parameters. Energy losses from the removal of incompletely burned particulates represented up to 3% of the energy input to the furnace at high gas velocities at the fuel bed.

Conclusions

Emissions of both nitrogen oxides and particulates were reduced when the fuel bed was operated under a fuel-rich condition. The controlling parameters for nitrogen oxide formation were oxygen availability and residence time in the fuel-rich first stage. Long first-stage residence times allowed decay of

the intermediate nitrogenous species to N₂, if there was sufficient oxygen for first-stage NO formation.

Particulate emissions were primarily a function of furnace gas velocities in the bed zone. These velocities decrease at low bed-zone stoichiometries, creating less entrainment of large particles and allowing less carbon carry-over into the exhaust gases. Thus, reductions in NO_x and improved combustion efficiency as a result of lower particulate losses are possible with optimized stoichiometry in hogged-wood, stoker-fired furnaces.

The results of this study should be of interest to boiler designers and operators as they strive to meet environmental regulations for emissions of nitrogen oxides. Our results indicated that such emissions can be reduced by proper creation of a fuel-rich zone within the furnace and that such a furnace operation can result in increased boiler efficiency by decreasing particle carry-over.

Experimental

The experimental facility used in this study was the model stoker furnace shown in Fig. 1. The furnace was designed to simulate the combustion environment found in a typical large-scale unit. Fuel was delivered to the furnace by means of a calibrated feeder. The fuel was directed onto a rotating spreader which projected the wood particles into an overthrow region where small particles burned in the suspension phase. The spreader was located 0.81 m above the grate, and the total furnace height was 3 m, thereby producing a vertical scaling of approximately 1:1 with the combustion zone of typical field units.

The model stoker furnace was designed to fire at 175 kW on a 930-cm² dumping grate, producing grate heat release rates that are comparable to full-scale boilers. The interior walls of the furnace consisted entirely of high-temperature castable refractories. The furnace was equipped with 175 kW natural gas burners, which were used to preheat the combustion chamber to typical operating temperatures prior to experimental runs. Air was injected into the furnace under the grate and at various heights above the grate. All air streams were at ambient temperature. The furnace chamber contained access ports for insertion of sampling probes or for injection of overfire air.

Exhaust gas samples were with-

I. Fuel analysis (dry basis)

Chemical constituent	Content, % by wt.
Carbon	52.26
Hydrogen	5.79
Nitrogen	0.08
Sulfur	0.03
Ash	1.39
Oxygen	40.45
The heating value was 20.6 kJ/g.	

drawn with a water-cooled stainless-steel probe and pumped to a continuous analysis unit that included a chemiluminescent NO_x analyzer, a paramagnet O₂ analyzer, and a nondispersive infrared analyzer for carbon monoxide and carbon dioxide. In-flame HCN samples were withdrawn through a controlled-temperature probe (120°C) and analyzed with an HP-5840® gas chromatograph containing a nitrogen phosphorus detector. Ammonia was sampled with an acid spray probe, collected in a series of bubblers, and analyzed with a gas sensing electrode. Hydrocarbon measurements were made using a gas chromatograph with a flame ionization detector and with methane as a standard.

Particulate carry-over measurements were evaluated by quenching particulate combustion in a water-spray tank followed by subsequent weighing of the collected solids of particle size greater than 0.177 mm. The experimental facility was not amenable to meaningful measurements of small-diameter particles (5–20 μm) normally associated with stack gas sampling. Rather, the purpose of the particulates collection system on the model stoker furnace was to measure the mass of relatively large particulates which represent combustion inefficiencies resulting from unburned carbon carry-over.

The fuel used in the study was hogged Douglas-fir, which is a representative wood fuel in the Pacific Northwest. The fuel was available in two separate moisture contents, with virtually identical particle size distributions. Each fuel was screened to a nominal size range of 6×25 mm. The dry-basis analysis of the fuel is shown in Table I, with the particle size distribution shown in Table II.

Furnace stoichiometries and burning rates were computed for each run from the exhaust gas compositions and known air flow rates. The bed-zone or first-stage stoichiometries were nomi-

II. Particle size distribution

Particle diameter, mm	Composition, % by wt.
<0.5	0.7
2–0.5	1.1
2–4	5.5
4–8	20.0
8–16	52.1
16–32	19.7
32–64	0.9
>64	0.0

nally computed as if all the fuel-burning processes occurred on the grate.

Literature cited

1. Starley, G.P., Slaughter, D.M., Munro, J.M., and Pershing, D.W., Nineteenth Intl. Symposium on Combustion Proceedings, The Combustion Institute, Pittsburgh, 1982, p. 1311.
2. Tidona, R.J., Carter, W.A., Buening, H.J., and Cherry, S.S., Evaluation of Combustion Modification Effects on Emissions and Efficiency of Wood-fired Industrial Boilers, EPA 600/S7-83-042 (1983).
3. Junge, D.C., 1980 Environmental Conference Proceedings, TAPPI PRESS, Atlanta, p. 23.
4. Kester, R.A., Nitrogen Oxide Emissions from a Pilot Plant Spreader Stoker Bark Fired Boiler, Ph.D. dissertation, Univ. of Washington, Seattle, 1980.
5. Kester, R.A. and Pilat, M.J., Tappi 63(2): 159(1980).
6. Junge, D.C., Research Bulletin 17, Oregon State Univ., 1975.
7. Adams, T.N., Combustion and Flame 39: 225(1980).
8. Fenimore, C.P. and Fraenkel, H.A., Eighteenth Intl. Symposium on Combustion Proceedings, The Combustion Institute, Pittsburgh, 1981, p. 143.
9. Fenimore, C.P., Combustion and Flame 26: 249(1976).
10. DeSoete, G.G., Fifteenth Intl. Symposium on Combustion Proceedings, The Combustion Institute, Pittsburgh, 1975, p. 1093.
11. Duxbury, J. and Pratt, N.H., Fifteenth Intl. Symposium on Combustion Proceedings, The Combustion Institute, Pittsburgh, 1975, p. 843.
12. Winter, R.M., Optimization of Wood Combustion and Control of NO_x Formation in the Suspension Phase of a Spreader Stoker Furnace, Ph.D. dissertation, Univ. of Utah, Salt Lake City, 1986.

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