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# Overview of the Regulatory Baseline, Technical Basis, and Alternative Control Levels for Nitrogen Oxides ($NO_x$) Emission Standards for Small Steam Generating Units

NSPS

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# OVERVIEW OF THE REGULATORY BASELINE, TECHNICAL BASIS, AND ALTERNATIVE CONTROL LEVELS FOR NITROGEN OXIDES ($NO_X$) EMISSION STANDARDS FOR SMALL STEAM GENERATING UNITS

Emission Standards Division

U.S. Environmental Protection Agency
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# 1.0 INTRODUCTION

This report provides an overview of the emission data and technical basis for nitrogen oxides ($NO_x$) new source performance standards (NSPS) for small boilers. Small boilers are defined as industrial-commercial-institutional steam generating units having a heat input capacity of 29 MW (100 million Btu/hour) or less.

A number of $NO_x$ control techniques were considered for the purpose of evaluating alternative $NO_x$ emission standards for small boilers. Detailed discussions of the design and operating principles of each of these control techniques can be found in: Technology Assessment Report For Industrial Boiler Applications: $NO_x$ Combustion Modification (i.e., $NO_x$ ITAR).[1]

This report is organized according to the major fossil fuel types combusted in small boilers. A summary of key assumptions and conclusions is presented in Section 2.0. Available $NO_x$ emissions data and the results of the technical analyses for natural gas-fired boilers are presented in Section 3.0. Sections 4.0, 5.0, and 6.0 contain similar discussions for distillate oil, residual oil, and coal combustion, respectively.

## 2.0 SUMMARY

Only a small number of State and local agencies currently regulate $NO_x$ emissions from small boilers.[2] Consequently, the regulatory baseline emission level for small boilers is represented by $NO_x$ emissions from boilers operating without any $NO_x$ controls.

Available $NO_x$ test data on small boilers show that $NO_x$ emissions vary considerably for these boilers operating with or without $NO_x$ control. However, in many cases, these data are insufficient to analyze or explain the reasons for this variability. Where sufficient data were available, regression analysis was employed to develop equations predicting $NO_x$ emissions as a function of key operating parameters affecting $NO_x$ emissions (e.g., boiler load, excess $O_2$ level, combustion air temperature, and fuel-bound nitrogen content). These regression equations, however, do not explain the high degree of scatter in the data and, as a result, do not predict $NO_x$ emissions with any degree of accuracy. Consequently, neither controlled nor uncontrolled $NO_x$ emission levels can be determined for small boilers. As a result, an insufficient technical basis is available for developing an NSPS.

# 3.0 NATURAL GAS $NO_x$ EMISSIONS AND CONTROL TECHNIQUES

The $NO_x$ control techniques for which data are available include low excess air (LEA), flue gas recirculation (FGR), overfire air ports (OFA), and staged combustion burners (SCBs). These controls represent the techniques considered to be both commercially available and applicable to small boilers. Two other $NO_x$ control techniques having limited applicability to small boilers are selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR or ammonia injection). These technologies have been applied to some small boilers operating in California to meet stringent $NO_x$ emission limits in that State. Cost analyses, however, indicate that both SCR and SNCR technologies are expensive control options for small boilers (i.e., in excess of $4,000/ton).[3,4] Thus, these two technologies were not considered further.

## 3.1 REGULATORY BASELINE EMISSION LEVELS

The regulatory baseline is defined as the uncontrolled $NO_x$ emission level because of the virtual absence of State and local regulation of $NO_x$ emissions from small natural gas-fired boilers. Regulatory baseline $NO_x$ emission data from tests conducted on 14 small natural gas-fired boilers ranging in heat input capacity from 2.3 to 26 MW (8 to 88 million Btu/hour) can be found in Table 3-1. In addition to the $NO_x$ emission data, this table presents boiler data for each boiler tested.

As shown by this table, baseline $NO_x$ emissions from these boilers were highly scattered, ranging from 30.5 to 132 ng/J (0.071 to 0.307 lb/million Btu). In an attempt to reduce this scatter, regression analysis was employed to explain the variability in $NO_x$ emissions as a function of boiler load (i.e., heat release rate), excess $O_2$ level, and combustion air temperature.[7] To evaluate the adequacy of these regression equations for predicting $NO_x$ emissions from small boilers, the actual baseline $NO_x$ emission data in Table 3-1 were compared to the baseline $NO_x$ emissions predicted by the regression equations. This comparison of actual and predicted baseline $NO_x$ emission values is presented in Table 3-2.

TABLE 3-1. $NO_x$ EMISSION DATA ON NATURAL GAS-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE AND LOW EXCESS AIR CONDITIONS

| Boiler Data | | | | Test Data | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, MW ($10^6$ Btu/hr) heat input | Average test load, percent | Stack $O_2$, percent baseline/controlled | Combustion air temperature, °C (°F) | $NO_x$ emissions, lb/$10^6$ Btu baseline/controlled[b] | NOx reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/controlled | Boiler efficiency, percent baseline/control | Reference[f] |
| 3-2 | FT | 479 (152) | 3.8 (13) | 50 | 8.0/3.6 | Amb[c] | 0.122/0.080 | 34 | 13/0 | NR/84 | 5 |
| 4-4 | FT | 743 (236) | 7.3 (25) | 70 | 6.8/4.8 | Amb | 0.132/0.111 | 16 | NR/NR[e] | 80/NR | 5 |
| 5-248-1 | FT | 479 (152) | 2.9 (10) | 80 | 11.0/5.5 | Amb | 0.076/0.072 | 5 | 0/145 | NR/NR | 5 |
| 26-1 | FT | 340 (108) | 6.7 (23) | 96 | 7.2/2.7 | Amb | 0.071/0.093 | (31)[d] | 15/59 | 82/84 | 5 |
| Site 6 | FT | NR (NR) | 2.3 ( 8) | 33 | 8.3/7.2 | Amb | 0.105/0.072 | 31 | 28/117 | NR/NR | 6 |
| 1-1 | WT, PKG | 214 (68) | 11 (36) | 80 | 4.5/1.9 | Amb | 0.101/0.079 | 22 | 6/114 | NR/NR | 5 |
| 1-2 | WT, PKG | 214 (68) | 11 (36) | 59 | 4.7/2.2 | Amb | 0.101/0.095 | 6 | 10/67 | NR/79 | 5 |
| 1-3 | WT, PKG | 230 (73) | 11 (38) | 80 | 4.5/2.7 | Amb | 0.117/0.094 | 19 | 0/0 | 78/79 | 5 |
| 5-716-3 | WT, PKG | NR (NR) | 9.1 (31) | 65 | 5.8/4.1 | Amb | 0.097/0.079 | 19 | 0/0 | NR/NR | 5 |
| 10-4 | WT, PKG | 290 (92) | 22 (75) | 82 | 5.2/3.9 | Amb | 0.127/0.132 | (4)[d] | 0/42 | 80/NR | 5 |
| 19-2 | WT, PKG | 211 (67) | 6.5 (22) | 93 | 3.2/2.0 | Amb | 0.075/0.066 | 12 | 10/71 | 80/NR | 5 |
| 9-BC-1 | WT, PKG | 221 (70) | 22 (75) | 79 | 3.3/2.6 | 204 (400) | 0.307/0.294 | 4 | 0/20 | NR/79 | 5 |
| 28-1 | WT, PKG | 246 (78) | 26 (88) | 41 | 5.7/3.7 | 168 (335) | 0.257/0.202 | 21 | 0/21 | 83/85 | 5 |
| 38-2 | WT, PKG | 265 (84) | 16 (56) | 89 | 3.2/1.9 | 288 (550) | 0.268/0.222 | 17 | 0/0 | 81/82 | 5 |

[a] FT = firetube; WT = watertube; and PKG = packaged.
[b] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours) except at Site 6. 30-day tests were performed on the boiler at Site 6. To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.
[c] Amb = ambient temperature [assume 27°C (80°F)].
[d] Numbers in parenthesis indicate a $NO_x$ emission increase from baseline using LEA.
[e] NR = not reported.
[f] Test results from Reference 5 also reported in Reference 1.

TABLE 3-2. COMPARISON OF ACTUAL AND PREDICTED $NO_X$ EMISSIONS FOR UNCONTROLLED NATURAL GAS-FIRED SMALL BOILERS

| Boiler I.D. | $NO_x$ emissions (lb/million Btu) | | Percent deviation[a] |
|---|---|---|---|
| | Actual | Predicted | |
| 3-2 | 0.122 | 0.151 | -24 |
| 4-4 | 0.132 | 0.178 | -35 |
| 5-248-1 | 0.076 | 0.177 | -133 |
| 26-1 | 0.071 | 0.161 | -126 |
| 1-1 | 0.101 | 0.128 | -27 |
| 1-2 | 0.101 | 0.120 | -19 |
| 1-3 | 0.117 | 0.131 | -12 |
| 10-4 | 0.127 | 0.142 | -12 |
| 19-2 | 0.075 | 0.127 | -69 |
| 9-BC-1 | 0.307 | 0.204 | 33 |
| 28-1 | 0.257 | 0.178 | 31 |
| 38-2 | 0.268 | 0.261 | 3 |

[a]Percent deviation = (actual - predicted $NO_x$ emissions) * 100/actual $NO_x$ emissions.

As shown in Table 3-2, the deviation between the actual and the predicted baseline $NO_x$ emission levels ranges from 33 to -133 percent. These large deviations indicate that, even after the regression equations are employed, a great deal of scatter remains. As a result, these regression equations cannot be used to predict baseline $NO_x$ emissions from small natural gas-fired boilers with any degree of accuracy. Consequently, it is not possible to establish a $NO_x$ emission level representative of small natural gas-fired boilers under baseline (i.e., uncontrolled) conditions.

## 3.2 LOW EXCESS AIR (LEA)

With LEA, the combustion air flow to the boiler is reduced to near the minimum amount needed for complete combustion. The level to which the excess air can be lowered is usually limited by the onset of excessive carbon monoxide (CO) and smoke formation due to incomplete combustion. As discussed in the $NO_x$ ITAR, LEA primarily reduces thermal $NO_x$ emissions.[8] For this reason, LEA is most effective in reducing $NO_x$ emissions from the combustion of low nitrogen bearing fuels such as natural gas and distillate oil.

Two general approaches are used for LEA control. One uses an $O_2$ trim system on a conventional burner/boiler unit; the other uses an LEA-designed burner along with an $O_2$ trim device. Natural gas-fired boilers can typically operate using either LEA control system at excess air levels near 10 percent (2 percent $O_2$ in the flue gas) while maintaining safe boiler operation and satisfactory combustion conditions.

Low excess air controls can be applied to all small boilers equipped with forced draft burners. For boilers equipped with atmospheric burners, LEA cannot be used since excess air levels cannot be controlled; boilers containing these burners are typically cast-iron units. However, some larger cast-iron boilers can be equipped with forced draft burners and, therefore, could use the LEA control technique.

Emission test data from application of LEA control on small natural gas-fired boilers may also be found in Table 3-1 for the same 14 small natural gas-fired boilers discussed in Section 3.1. Like the uncontrolled $NO_x$ emission data, LEA-controlled $NO_x$ emissions from these boilers were highly scattered, ranging from 28.4 to 126 ng/J (0.066 to 0.294 lb/million Btu). The negative $NO_x$ reductions for two boilers presented in Table 3-1 indicate the LEA-controlled $NO_x$ emissions for these two units were actually higher than the uncontrolled $NO_x$ emissions.

Regression analysis was employed to explain the variability introduced into these data by operation of these boilers under different conditions. A comparison of actual and predicted $NO_x$ emissions using the regression equations developed for this analysis is presented in Table 3-3. As shown in the table, the deviation between the actual and predicted $NO_x$ emissions ranges from 33 to -123 percent. As explained above, these large deviations between the actual and predicted $NO_x$ emission levels indicate that the regression equations are not reliable predictors of LEA-controlled $NO_x$ emissions from these boilers. As a result, it is not possible to establish $NO_x$ emission levels representative of LEA-controlled small natural gas-fired boilers, nor is it possible to predict the $NO_x$ reduction performance of LEA on these boilers.

## 3.3 OTHER $NO_x$ CONTROLS

### 3.3.1 Flue Gas Recirculation (FGR)

In an FGR system, a portion of the flue gas is recycled from the stack to the burner windbox. Upon entering the windbox, the gas is mixed with the combustion air prior to being fed to the burner. For this reason, FGR has been applied primarily to boilers firing low nitrogen bearing fuels (i.e., natural gas and distillate oil).

Flue gas recirculation systems are commercially available for small boilers ranging between 1.5 and 29 MW (5 and 100 million Btu/hour) heat input capacity, although no FGR systems have been installed to date on cast-iron boilers.

Table 3-4 presents $NO_x$ emissions data from nine short-term tests conducted on five natural gas-fired boilers, operating both with and without FGR, ranging from 6.5 to 16 MW (22 to 56 million Btu/hour) heat input capacity. This table also provides boiler data for each boiler tested.

TABLE 3-3. COMPARISON OF ACTUAL AND PREDICTED $NO_x$ EMISSIONS FOR THE NATURAL GAS-FIRED SMALL BOILERS USING LEA

| Boiler I.D. | $NO_x$ emissions (lb/million Btu) Actual | Predicted | Percent deviation[a] |
|---|---|---|---|
| 3-2 | 0.080 | 0.135 | -69 |
| 4-4 | 0.111 | 0.169 | -53 |
| 5-248-1 | 0.072 | 0.161 | -123 |
| 26-1 | 0.093 | 0.140 | -50 |
| 1-1 | 0.079 | 0.114 | -44 |
| 1-2 | 0.095 | 0.108 | -14 |
| 1-3 | 0.094 | 0.122 | -29 |
| 10-4 | 0.132 | 0.136 | -3 |
| 19-2 | 0.066 | 0.119 | -80 |
| 9-BC-1 | 0.294 | 0.197 | 33 |
| 28-1 | 0.202 | 0.167 | 17 |
| 38-2 | 0.222 | 0.242 | -9 |

[a]Percent deviation = (actual - predicted $NO_x$ emissions) * 100/actual $NO_x$ emissions.

TABLE 3-4. $NO_x$ EMISSION DATA ON SMALL NATURAL GAS-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) HEAT INPUT OR LESS OPERATING WITH AND WITHOUT FLUE GAS RECIRCULATION (FGR)

| Boiler Data | | | | Test Data | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ Btu/$ft^2$-hr) | Boiler capacity, $10^6$ Btu/hr heat input | Percent FGR[c] | Average test load, percent | Stack $O_2$, percent baseline/ controlled | Combustion air temperature, °F | $NO_x$ emissions, lb/$10^6$ Btu baseline/ controlled[e] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/ controlled | Boiler efficiency, percent baseline/ controlled | Reference[f] |
| #3 | WT, PKG | NR (NR) | 13 (43) | 12 | 93 | 2.1/2.0 | Amb[d] | 0.102/0.036 | 65 | 0/57 | 84/84 | 10,11 |
| #5 | WT, PKG | 299 (95) | 16 (56) | 16 | 60 | 3.6/3.1 | Amb | 0.078/0.027 | 65 | 182/85 | NR/NR | 12 |
| [b] #6 | WT, PKG | 287 (91) | 13 (45) | 10 | 100 | 2.3/1.7 | Amb | 0.079/0.040 | 49 | NR/NR | 84/84 | 10,13 |
| #6 | WT, PKG | 287 (91) | 13 (45) | 14 | 100 | 2.3/1.5 | Amb | 0.079/0.030 | 62 | NR/NR | 84/84 | 10,13 |
| ECCC | WT, PKG | NR (NR) | 9.1 (31) | 22 | 39 | 3.1/2.6 | Amb | 0.056/0.022 | 61 | 20/20 | NR/NR | 14 |
| ECCC | WT, PKG | NR (NR) | 9.1 (31) | 26 | 30 | 3.5/1.2 | Amb | 0.069/0.016 | 77 | 10/55 | NR/NR | 14 |
| Loc.19 | WT, PKG | 211 (67) | 6.5 (22) | 17 | 79 | 3.2/3.3 | Amb | 0.110/0.032 | 71 | 19/16 | 78/79 | 15 |
| Loc.19 | WT, PKG | 211 (67) | 6.5 (22) | 20 | 80 | 3.2/3.2 | Amb | 0.110/0.029 | 74 | 19/20 | 78/79 | 15 |
| Loc.19 | WT, PKG | 211 (67) | 6.5 (22) | 20 | 83 | 3.2/2.5 | Amb | 0.110/0.027 | 75 | 19/16 | 78/78 | 15 |

[a] WT = watertube; PKG = packaged.

[b] Brackets indicate that tests were conducted on same boiler but at different operating conditions.

[c] Mass percent of flue gas recirculated to boiler.

[d] NR = not reported; and Amb = ambient temperature [assume 27°C (80°F)].

[e] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer; all tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[f] Test results from References 14 and 15 are also presented in Reference 1.

Table 3-4 shows that the five boilers were operated at a variety of loads and excess $O_2$ levels and that they have varying amounts of flue gas recirculated to the boiler. This resulted in $NO_x$ emission reductions ranging from 49 to 75 percent and FGR-controlled $NO_x$ emissions ranging from 6.9 to 17 ng/J (0.016 to 0.040 lb/million Btu). Regression analysis, employed to explain the variability in these data by operation of these boilers under different conditions was unsuccessful. Thus, it was not possible to develop equations from these data to predict $NO_x$ emissions from small natural gas-fired boilers using FGR. Further, it is not possible to establish $NO_x$ emission levels representative of small natural gas-fired boilers using FGR, nor is it possible to predict the $NO_x$ reduction performance of FGR on these boilers.

### 3.3.2 Overfire Air Ports (OFA)

With OFA, conventional burners are used to introduce the fuel and sub-stoichiometric quantities of combustion air (known as primary air) into the boiler. The remaining combustion air (known as secondary air) is introduced downstream of the burners approximately one-third of the length of the furnace through overfire air ports. As discussed in the $NO_x$ ITAR, both thermal and fuel $NO_x$ emissions are reduced using this technique.[1] For this reason, this technique is effective in reducing $NO_x$ emissions from boilers firing any fossil fuel.

Overfire air systems are commercially available for boilers with heat input capacities greater than about 7.3 MW (25 million Btu/hour); they are generally not commercially available for smaller size boilers.

Table 3-5 presents $NO_x$ emissions data from short-term $NO_x$ tests conducted on three small natural gas-fired boilers operating with and without OFA systems. These boilers, rated from 6.5 to 16 MW (22 to 56 million Btu/hour) heat input capacity, operated at different loads and excess $O_2$ levels. OFA-controlled $NO_x$ emissions ranged from 31 to 61 ng/J (0.073 to 0.142 lb/million Btu) and the $NO_x$ emission reduction achieved by OFA ranged from 13 to 31 percent for the three boilers.

Such a limited data base does not permit regression analysis to be used to develop equations predicting $NO_x$ emissions. Consequently, it is not

TABLE 3-5. $NO_x$ EMISSION DATA FROM NATURAL GAS-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS OPERATING WITH AND WITHOUT OVERFIRE AIR PORTS (OFA)

| Boiler Data | | | | Test Data | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, MW ($10^6$ Btu/hr) heat input | Average test load, percent | Stack $O_2$, percent baseline/ controlled | Combustion air temperature, °C (°F) | $NO_x$ emissions, lb/$10^6$ Btu baseline/ controlled[b] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/ controlled | Boiler efficiency, percent baseline/ controlled | Reference[e] |
| 19-2 | WT, PKG | 211 (67) | 6.5 (22) | 83 | 3.2/1.5 | Amb[c] | 0.084/0.073 | 13 | 0/185 | NR/NR | 5 |
| 38-2 | WT, PKG | 265 (84) | 16 (56) | 89 | 1.9/3.2 | NR[c] | 0.268/0.073 | 73 | 0/28 | 82/80 | 5 |
| Loc. 38 | WT, PKG | 265 (84) | 16 (56) | 88 | 1.6/3.2 | NR | 0.206[d]/0.142[d] | 31 | 140/122 | 81/81 | 15 |

[a]WT = watertube; PKG = packaged.

[b]$NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[c]Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

[d]Estimate only, only $NO_x$ values assume $NO_2$ is 5% of the total (only NO was measured).

[e]Test results from References 5 and 15 are also presented in Reference 1.

possible to establish $NO_x$ emission levels representative of small natural gas-fired boilers using OFA, nor is it possible to predict the $NO_x$ reduction performance of OFA on these boilers.

### 3.3.3 Staged Combustion Burners (SCBs)

As the name implies, staged combustion burners, also known as "low $NO_x$ burners," reduce $NO_x$ formation by allowing combustion in stages. The staging technique is similar to that of the OFA system except that the combustion staging is achieved by the burner rather than through the use of OFA ports. One type of SCB stages the fuel, others stage the combustion air to achieve staged combustion.[16] The $NO_x$ ITAR describes the various types of SCBs available for small boilers.[17] As with OFA, both thermal and fuel $NO_x$ emissions are reduced using SCBs. For this reason, this technique is effective in reducing $NO_x$ emissions from boilers firing any fossil fuel.

Staged combustion burners are commercially available in the small boiler size category for boilers with heat input capacities greater than 7.3 MW (25 million Btu/hour). Another type of SCB, called the radiant or ceramic fiber burner, emits low $NO_x$ emissions by combusting gaseous fuels without flame. Ceramic fiber burners for very small natural gas-fired firetube boilers are currently available at the 1.5 MW (5 million Btu/hour) size or less.[18]

Table 3-6 presents $NO_x$ emission data from short-term tests conducted on three natural gas-fired boilers using SCBs, rated between 18 and 31 MW (63 to 106 million Btu/hour) heat input capacity. Nitrogen oxides emissions ranged from 30 to 39 ng/J (0.07 to 0.09 lb/million Btu). Baseline test data were not available for these boilers without combustion staging. Consequently, the reduction in $NO_x$ emissions achieved by SCBs on each of those boilers cannot be determined. As mentioned above for OFA, such a limited data base does not permit the use of regression analysis. Thus, equations predicting $NO_x$ emissions from small natural gas-fired boilers using SCBs could not be developed. Further, it is not possible to establish $NO_x$ emission levels representative of small natural gas-fired boilers using SCBs, nor is it possible to predict the $NO_x$ reduction performance of SCBs on these boilers.

TABLE 3-6. $NO_x$ EMISSION DATA FROM NATURAL GAS-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS USING STAGED COMBUSTION BURNERS (SCB)

| Boiler Data | | | | Test Data | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, MW ($10^6$ Btu/hr) heat input | Average test load, percent | Stack $O_2$, percent baseline/ controlled | Combustion air temperature, °C (°F) | $NO_x$ emissions, lb/$10^6$ Btu baseline/ controlled[b] | CO emissions, ppm @ 3% $O_2$ baseline/ controlled | Boiler efficiency, percent baseline/ controlled | Reference |
| CA | WT, PKG | NR (NR) | 18 (63) | 40 | NA[c]/4.0 | Amb[c] | NA/0.090 | NA/NR[c] | NR/NR | 19 |
| #3 | WT, PKG | 227 (72) | 22 (75) | 86 | NA/4.3 | Amb | NA/0.070 | NA/744[d] | NA/NR | 20 |
| Site 5 | WT, PKG | NR (NR) | 31 (106) | 44 | NA/5.8 | Amb | NA/0.089 | NA/82 | NA/NR | 21 |

[a] WT = watertube; PKG = packaged.

[b] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (≤3 hours) except for Site 5. Thirty nine day continuous emissions testing was performed at Site 5. To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[c] NA = not available; Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

[d] This test was demonstrated intentionally at the lowest possible $NO_x$ emissions for this boiler. However, this CO emissions level met the CO regulation of the county's air pollution control district.

# 4.0 DISTILLATE OIL $NO_x$ EMISSIONS AND CONTROL TECHNIQUES

The $NO_x$ controls for which emission data are available include LEA, FGR, OFA, and SCBs. The operating principles, applicability, and commercial availability of these techniques for distillate oil-fired boilers are the same as for natural gas-fired boilers discussed above.

## 4.1 REGULATORY BASELINE EMISSION LEVELS

The regulatory baseline is defined as the uncontrolled $NO_x$ emission level because of the virtual absence of State and local regulation of $NO_x$ emissions from small oil-fired boilers. Regulatory baseline $NO_x$ emission data from tests conducted on six small distillate oil-fired boilers, ranging in heat input capacity from 3.8 to 11 MW (13 to 38 million Btu/hour), can be found in Table 4-1. Emission data were collected from one boiler using three different oil atomization techniques. Table 4-1 also presents boiler data for each boiler tested.

Table 4-1 shows that uncontrolled $NO_x$ emissions from the boilers were highly scattered, ranging from 42.1 to 96.3 ng/J (0.098 to 0.224 lb/million Btu). In an attempt to reduce this scatter in the data, regression analysis was employed to explain the variability in $NO_x$ emissions as a function of boiler load (i.e., heat release rate), excess $O_2$ level, combustion air temperature, and nitrogen content of the oil.[22] The boilers at sites #3-2 and #4-4 were deleted from the analysis due to lack of data on fuel nitrogen content.

A comparison of actual $NO_x$ emissions and predicted $NO_x$ emissions using the regression equations developed from this analysis is presented in Table 4-2. As shown in the table, the deviation between the actual and the predicted $NO_x$ emissions ranges from 26 to -47 percent. These large deviations indicate that, even after the regression equations are employed, a great deal of scatter remains in the data. As a result, these regression equations cannot be used to predict $NO_x$ emissions from these boilers with any degree of accuracy. Further, it is not possible to establish a regulatory baseline $NO_x$ emission level representative of small distillate oil-fired boilers.

TABLE 4-1. $NO_x$ EMISSIONS DATA FROM DISTILLATE OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE AND LOW EXCESS AIR CONDITIONS

| Boiler Data | | | | | Test Data | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D | Boiler type[b] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, $10^6$ Btu/hr heat input | Fuel nitrogen, percent | Average test load, percent | Stack $O_2$, percent baseline/controlled | Combustion air temperature, °C (°F) | $NO_x$ emissions, lb/$10^6$ Btu baseline/controlled[c] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/controlled | PM emissions, lb/$10^6$ Btu baseline controlled[e] | Boiler efficiency, percent baseline/controlled | Reference[f] |
| 3-2 | FT | 479 (152) | 3.8 (13) | NA[d] | 50 | 5.6/3.6 | Amb[d] | 0.221/0.197 | 11 | 0/0[d] | 0.04/NR | NR/86 | 5 |
| 4-4 | FT | 743 (236) | 7.3 (25) | NA | 47 | 5.2/2.7 | Amb | 0.224/0.186 | 17 | NR/NR | 0.03/NR | 85/NR | 5 |
| 1-2 | WT, PKG | 214 (68) | 11 (36) | 0.045 | 50 | 8.2/5.1 | Amb | 0.136/0.118 | 13 | NR/NR | NR/NR | NR/NR | 5 |
| 19-1 (Steam)[a] | WT, PKG | 211 (67) | 6.4 (22) | 0.006 | 80 | 4.3/3.6 | Amb | 0.098/0.088 | 10 | 0/49 | NR/0.04 | NR/85 | 5 |
| 19-1 (Air)[a] | WT, PKG | 211 (67) | 6.4 (22) | 0.006 | 80 | 4.3/2.5 | Amb | 0.134/0.125 | 7 | 0/0 | NR/NR | 84/NR | 5 |
| 19-1 (Mech)[a] | WT, PKG | 211 (67) | 6.4 (22) | 0.006 | 66 | 6.2/3.7 | Amb | 0.107/0.105 | 2 | 0/0 | NR/NR | NR/86 | 5 |
| Loc. 19 | WT, PKG | 211 (67) | 6.4 (22) | 0.004 | 83 | 3.2/1.1 | Amb | 0.154/0.125 | 19 | 4/181 | 0.06/0.04 | 82/83 | 15 |
| 1-3 | WT, PKG | 230 (73) | 11 (38) | 0.045 | 79 | 5.9/2.8 | 177 (350) | 0.158/0.134 | 15 | 0/17 | 0.4/NR | 81/83 | 5 |

[a] Emission tests were conducted on the same boiler operating with three types of oil atomization (i.e., steam, air, and mechanical).

[b] FT = firetube; WT = watertube; PKG = package.

[c] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[d] NA = not available; NR = not reported; Amb = ambient temperature [assume 27°C (80°F)].

[e] To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[f] Test results from References 5 and 15 are also presented in Reference 1.

TABLE 4-2. COMPARISON OF ACTUAL AND PREDICTED $NO_x$ EMISSIONS FOR UNCONTROLLED DISTILLATE OIL-FIRED SMALL BOILERS

| Boiler I.D. | $NO_x$ emissions (lb/million Btu) | | Percent deviation[b] |
|---|---|---|---|
| | Actual | Predicted | |
| 1-2 | 0.136 | 0.161 | -18 |
| 19-1 (Steam)[a] | 0.098 | 0.126 | -29 |
| 19-1 (Air)[a] | 0.134 | 0.126 | 6 |
| 19-1 (Mech)[a] | 0.107 | 0.130 | -22 |
| Loc. 19 | 0.154 | 0.114 | 26 |
| 1-3 | 0.158 | 0.232 | -47 |

[a]Indicates type of oil atomization. Mech = mechanical.

[b]Percent deviation = (actual - predicted $NO_x$ emissions) * 100/actual $NO_x$ emissions.

## 4.2 LOW EXCESS AIR (LEA)

Emission test data from application of LEA control on small distillate oil-fired boilers may also be found in Table 4-1 for the same six small distillate oil-fired boilers discussed in Section 4.1. Like the uncontrolled $NO_x$ emission data, LEA-controlled $NO_x$ emissions were highly scattered, ranging from 37.8 to 84.7 ng/J (0.088 to 0.197 lb/million Btu). The $NO_x$ emission reductions also varied considerably (from 2 to 19 percent).

As with the uncontrolled $NO_x$ emission data, regression analysis was employed to explain the variability introduced into the data by operation of these boilers under different conditions.[23] A comparison of actual $NO_x$ emissions and predicted $NO_x$ emissions using the regression equations developed from this analysis is summarized in Table 4-3. As shown in the table, the deviation between the actual and the predicted $NO_x$ emissions ranges from 36 to -40 percent. These large deviations between the actual and predicted $NO_x$ emissions indicate that the regression equations are not reliable predictors of LEA-controlled emissions from these boilers. As a result, it is not possible to establish $NO_x$ emission levels which are representative of small distillate oil-fired boilers using LEA, nor is it possible to predict the $NO_x$ reduction performance of LEA on these boilers.

## 4.3 OTHER $NO_x$ CONTROLS

### 4.3.1 Flue Gas Recirculation (FGR)

Nitrogen oxides emissions data from tests conducted on two distillate oil-fired boilers operating with and without FGR are summarized in Table 4-4. One boiler was rated at 7.3 MW (25 million Btu/hour) heat input capacity and the other boiler was rated at 16.4 MW (56 million Btu/hour) heat input capacity. This table also provides boiler data for each boiler tested.

Table 4-4 shows that the two boilers were operated at different loads and excess $O_2$ levels and that they have different amounts of flue gas recirculated to the boilers. This resulted in FGR-controlled $NO_x$ emissions ranging from 17.6 to 65.4 ng/J (0.041 to 0.152 lb/million Btu). Such a

TABLE 4-3. COMPARISON OF ACTUAL AND PREDICTED $NO_x$ EMISSIONS FOR THE DISTILLATE OIL-FIRED SMALL BOILERS USING LEA

| Boiler I.D. | $NO_x$ emissions (lb/million Btu) Actual | Predicted | Percent deviation[b] |
|---|---|---|---|
| 1-2 | 0.118 | 0.142 | -20 |
| 19-1 (Steam)[a] | 0.088 | 0.119 | -35 |
| 19-1 (Air)[a] | 0.125 | 0.106 | 16 |
| 19-1 (Mech)[a] | 0.105 | 0.110 | -5 |
| Loc. 19 | 0.125 | 0.080 | 36 |
| 1-3 | 0.134 | 0.187 | -40 |

[a]Indicates type of oil atomization. Mech = mechanical.

[b]Percent deviation = (actual - predicted $NO_x$ emissions) * 100/actual $NO_x$ emissions.

TABLE 4-4. $NO_x$ EMISSIONS DATA FROM DISTILLATE OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) HEAT INPUT OR LESS OPERATING WITH AND WITHOUT FLUE GAS RECIRCULATION (FGR)

| Boiler Data | | | | | Test Data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, MW ($10^6$ Btu/hr) heat input | Fuel nitrogen, percent | Percent FGR[b] | Average test load, percent | Stack $O_2$, percent baseline/controlled | Combustion air temperature, °F | $NO_x$ emissions, lb/$10^6$ Btu baseline/controlled[c] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/controlled | PM emissions, lb/$10^6$ Btu percent baseline/controlled[e] | Boiler efficiency percent baseline/controlled | Reference[f] |
| #5 | WT, PKG | 299 (95) | 16 (56) | NA[d] | 10 | 100 | 3.5/3.4 | Amb[d] | 0.185/0.152 | 18 | 20/24 | NR/NR[d] | NR/NR | 12 |
| Loc. 19 | WT, PKG | 211 (67) | 6.5 (22) | 0.004 | 28 | 83 | 3.2/0.8 | Amb | 0.154/0.041 | 73 | 4/46 | 0.06/0.01 | 82/82 | 15 |

[a] WT = watertube; PKG = packaged.

[b] Percent of flue gas mass recirculated to boiler.

[c] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[d] NA = not available; Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

[e] To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[f] Test results from Reference 15 are also presented in Reference 1.

limited data base does not permit the use of regression analysis to develop equations predicting $NO_x$ emissions from small distillate oil-fired boilers using FGR. Consequently, it is not possible to establish $NO_x$ emission levels representative of small distillate oil-fired boilers using FGR, nor is it possible to predict the $NO_x$ reduction performance of FGR on these boilers.

### 4.3.2 Overfire Air Ports (OFA)

Table 4-5 presents $NO_x$ emission data from tests conducted on one small distillate oil-fired boiler operating with and without OFA and rated at 6.5 MW (22 million Btu/hour) heat input capacity. This table also provides boiler data for this boiler. This boiler emitted 53.8 ng/J (0.125 lb/million Btu) of $NO_x$ during OFA operation and 66.2 ng/J (0.154 lb/million Btu) of $NO_x$ during baseline testing, resulting in a 19 percent reduction in $NO_x$ emissions over baseline. As mentioned above for FGR, such a limited data base does not permit the use of regression analysis. Thus, equations predicting $NO_x$ emissions and $NO_x$ emission reductions from small distillate oil-fired boilers using OFA cannot be developed. Further, it is not possible to establish $NO_x$ emission levels representative of small distillate oil-fired boilers using OFA, nor is it possible to predict the $NO_x$ emission reduction performance of OFA on these boilers.

### 4.3.3 Staged Combustion Burners (SCBs)

The results of a single $NO_x$ test on one small distillate oil-fired boiler rated at 22 MW (75 million Btu/hour) heat input capacity using a staged combustion burner are presented in Table 4-6. Emissions of $NO_x$ measured from this boiler were 47.3 ng/J (0.110 lb/million Btu) during low $NO_x$ operation. Baseline test data were not available for this boiler operating without combustion staging. Consequently, the reduction in $NO_x$ emissions achieved by SCBs on this boiler cannot be determined. As mentioned above for both FGR and OFA, such a limited data base does not permit the use of regression analysis. Thus, equations predicting $NO_x$ emissions from small distillate oil-fired boilers using SCBs could not be developed. As a result,

TABLE 4-5. $NO_x$ EMISSIONS DATA FROM DISTILLATE OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) HEAT INPUT OR LESS OPERATING WITH AND WITHOUT OVERFIRE AIR PORTS (OFA)

| Boiler Data | | | | | Test Data | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, MW ($10^6$ Btu/hr) heat input | Fuel nitrogen, percent | Average test load, percent | Stack $O_2$, percent baseline/ controlled | Combustion air temperature, °C (°F) | $NO_x$ emissions, lb/$10^6$ Btu baseline/ controlled[b] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/ controlled | PM emissions, lb/$10^6$ Btu baseline/ controlled[d] | Boiler efficiency, percent baseline/ controlled | Reference[e] |
| Loc. 19 | WT, PKG | 211 (67) | 6.5 (22) | 0.004 | 83 | 3.2/3.1 | Amb[c] | 0.154/0.125 | 19 | 4/29 | 0.06/0.03 | 82/83 | 15 |

[a] WT = watertube; PKG = packaged.
[b] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emi in lb/$10^6$ Btu by 430.
[c] Amb = ambient temperature [assume 27 °C (80 °F)].
[d] To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.
[e] Test results from Reference 15 are presented in Reference 1.

TABLE 4-6. $NO_x$ EMISSIONS DATA FROM DISTILLATE OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS USING STAGED COMBUSTION BURNERS (SCB)

| Boiler Data | | | | Test Data | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, MW ($10^6$ Btu/hr) heat input | Average test load, percent | Stack $O_2$, percent baseline/controlled | Combustion air temperature, °F | $NO_x$ emissions, lb/$10^6$ Btu baseline/controlled[b] | CO emissions, ppm @ 3% $O_2$ baseline/controlled | Boiler efficiency, percent baseline/controlled | Reference |
| #3 | WT, PKG | 227 (72) | 22 (75) | 84 | NA[c]/1.9 | Amb[c] | NA/0.110 | NA/91 | NR/NR[c] | 24 |

[a] WT = watertube; PKG = packaged.

[b] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[c] NA = not available; Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

it is not possible to establish $NO_x$ emission levels representative of small distillate oil-fired boilers using SCBs, nor is it possible to predict the $NO_x$ emission reduction performance of SCBs on these boilers.

# 5.0 RESIDUAL OIL $NO_x$ EMISSIONS AND CONTROL TECHNIQUES

The $NO_x$ controls for which emission data are available include LEA, FGR, and OFA. No emission data are available for SCBs operating on these boilers. The operating principles, applicability, and commercial availability of these techniques for residual oil-fired boilers are the same as for both natural gas and distillate oil-fired boilers discussed above.

## 5.1 REGULATORY BASELINE EMISSION LEVELS

The regulatory baseline is defined as the uncontrolled $NO_x$ emission level because of the virtual absence of State and local regulation of $NO_x$ emissions from small residual oil-fired boilers. Regulatory baseline $NO_x$ emission data from tests conducted on 14 residual oil-fired boilers, ranging in heat input capacity from 2.6 to 29 MW (9 to 100 million Btu/hour) can be found in Table 5-1. This table also presents boiler data for each boiler tested.

Table 5-1 shows that uncontrolled $NO_x$ emissions from these boilers were highly scattered, ranging from 86 to 276 ng/J (0.2 to 0.64 lb/million Btu). In an attempt to reduce this scatter, regression analysis was employed to explain the variability in $NO_x$ emissions as a function of boiler load (i.e., heat release rate), excess $O_2$ level, combustion air temperature, and nitrogen content of the oil.[25] Three boilers (#24-TV, ECCC, and #28-1) were deleted from the analysis because of lack of data on either heat release rate or fuel nitrogen content.

A comparison of actual $NO_x$ emissions in Table 5-1 and predicted $NO_x$ emissions using the $NO_x$ regression equations developed from this analysis is summarized in Table 5-2. As shown, the deviation between actual and the predicted $NO_x$ emissions ranges from 38 to -58 percent. As with other fuels, these large deviations indicate that, even after the regression equations are employed, a great deal of scatter remains in the data. As a result, these regression equations cannot be used to predict $NO_x$ emissions from these boilers with any degree of accuracy. Consequently, it is not possible to establish a baseline, or uncontrolled, $NO_x$ emission level which is representative of small residual oil-fired boilers.

TABLE 5-1. $NO_x$ EMISSIONS DATA FROM RESIDUAL OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE AND LOW EXCESS AIR CONDITIONS

| Boiler Data | | | | | Test Data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[b] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, $10^6$ Btu/hr heat input | Fuel nitrogen, percent | Average test load, percent | Stack $O_2$, percent baseline/ controlled | Combustion air temperature, °C (°F) | $NO_x$ emissions, lb/$10^6$ Btu baseline/ controlled[c] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/ controlled | PM emissions, lb/$10^6$ Btu baseline controlled[f] | Boiler efficiency, percent baseline/ controlled | Reference[g] |
| 23-1 | FT | 419 (133) | 2.6 (9) | 0.27 | 96 | 5.4/3.9 | Amb[d] | 0.389/0.328 | 16 | 21/26 | NR/NR | 88/NR | 5 |
| 24-TV | FT | NR[d] (NR) | 3.8 (13) | 1.30 | 104 | 3.2/1.9 | Amb | 0.239/0.227 | 5 | 0/113 | 0.09/NR | 85/NR | 5 |
| 26-1 | FT | 340 (108) | 6.7 (23) | 0.03 | 94 | 6.9/3.8 | Amb | 0.213/0.201 | 6 | 13/21 | 0.08/NR | 86/87 | 5 |
| 2-4 | WT, FE | 183 (58) | 24 (81) | 0.38 | 80 | 5.7/3.4 | Amb | 0.641/0.572 | 11 | 0/0 | NR/NR | NR/81 | 5 |
| 16-2 | WT, PKG | 183 (85) | 24 (81) | 0.29 | 83 | 4.9/3.7 | Amb | 0.256/0.236 | 8 | 0/0 | NR/NR | 85/88 | 5 |
| Loc. 19 | WT, PKG | 211 (67) | 6.5 (22) | 0.25 | 80 | 2.9/1.6 | Amb | 0.278/0.193 | 31 | 4/183 | 0.08/0.07 | 83/84 | 15 |
| 19-1 (Steam)[a] | WT, PKG | 211 (67) | 6.5 (22) | 0.44 | 83 | 4.0/2.6 | Amb | 0.439/0.438 | 5 | 0/90 | 0.03/NR | 84/85 | 5 |
| 19-1 (Air)[a] | WT, PKG | 211 (67) | 6.5 (22) | 0.44 | 83 | 4.4/2.8 | Amb | 0.436/0.368 | 16 | 0/NR | NR/NR | 85/85 | 5 |
| 19-2 | WT, PKG | 211 (67) | 6.5 (22) | 0.14 | 81 | 3.1/0.9 | Amb | 0.217/0.159 | 27 | 19/58 | NR/0.15 | 8586 | 5 |
| 20-4 | WT, PKG | 432 (137) | 29 (100) | 0.37 | 64 | 5.7/4.0 | Amb | 0.398/0.356 | 11 | 0/82 | 0.09/NR | 80/NR | 5 |
| ECCC | WT, PKG | NR (NR) | 9.1 (31) | 0.19 | 78 | 5.5/3.6 | Amb | 0.200/0.145 | 28 | <10/<10 | NR/NR | NR/NR | 14 |
| 28-1 | WT, PKG | 246 (78) | 26 (88) | NR | 41 | 5.3/4.9 | 174 (345) | 0.263/0.231 | 12 | 0/45 | NR/NR | 86/87 | 5 |
| 37-2 | WT, PKG | 318 (101) | 15 (50) | 0.30 | 81 | 4.3/3.8 | 110 (230) | 0.251/0.230 | 8 | 0/0 | 0.14/NR | 85/NR | 5 |
| Loc. 38 | WT, PKG | 265 (84) | 16 (56) | 0.14 | 85 | 3.1/0.9 | 138 (280) | 0.386[e]/0.305[e] | 21 | 22/65 | 0.15/0.11 | 85/86 | 15 |
| 38-2 | WT, PKG | 265 (84) | 16 (56) | 0.49 | 81 | 3.0/1.6 | 157 (315) | 0.419/0.312 | 26 | 0/120 | 0.11/NR | 87/87 | 5 |

[a] Emission tests were conducted on the same boiler operating with two types of oil atomization systems (i.e., steam and air).

[b] FT = firetube; WT = watertube; PKG = packaged; and FE = field erected.

[c] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[d] NR = not reported; Amb = ambient temperature [assume 27°C (80°F)].

[e] Estimate only. $NO_x$ values assume $NO_2$ is 5% of the total (only NO was measured).

[f] To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[g] Test results from References 5, 14, and 15 are also presented in Reference 1.

TABLE 5-2. COMPARISON OF ACTUAL AND PREDICTED $NO_x$ EMISSIONS FOR UNCONTROLLED RESIDUAL OIL-FIRED SMALL BOILERS

| Boiler I.D.[a] | $NO_x$ Emissions (lb/million Btu) | | Percent deviation[b] |
|---|---|---|---|
| | Actual | Predicted | |
| 23-1 | 0.389 | 0.392 | -1 |
| 26-1 | 0.213 | 0.217 | -2 |
| 2-4 | 0.641 | 0.395 | 38 |
| 16-2 | 0.256 | 0.355 | -39 |
| Loc. 19 | 0.278 | 0.290 | -4 |
| 19-1 (Steam)[a] | 0.459 | 0.429 | 6 |
| 19-1 (Air)[a] | 0.436 | 0.433 | 1 |
| 19-2 | 0.217 | 0.217 | 0 |
| 20-4 | 0.398 | 0.431 | -8 |
| 37-2 | 0.251 | 0.397 | -58 |
| Loc. 38 | 0.386 | 0.266 | 31 |
| 38-2 | 0.419 | 0.500 | -19 |

[a]Indicates type of oil atomization.

[b]Percent deviation = (actual - predicted $NO_x$ emissions) * 100/actual $NO_x$ emissions.

## 5.2 LOW EXCESS AIR (LEA)

Emission test data from application of LEA control on small residual oil-fired boilers may also be found in Table 5-1 for the same 14 small residual oil-fired boilers discussed in Section 5-1. Like the uncontrolled $NO_x$ emission data, LEA-controlled $NO_x$ emissions were highly scattered, ranging from 62.4 to 246 ng/J (0.145 to 0.572 lb/million Btu). The $NO_x$ emission reductions also varied considerably (from 5 to 28 percent).

As with the uncontrolled $NO_x$ emission data, regression analysis was employed to explain the variability introduced into the data by operation of these boilers under different conditions.[26] A comparison of actual $NO_x$ emissions and predicted $NO_x$ emissions using the regression equations developed from this analysis is summarized in Table 5-3. As shown in Table 5-3, the deviation between the actual and the predicted $NO_x$ emissions ranges from 35 to -69 percent. As explained above, these large deviations between actual and predicted $NO_x$ emissions indicate that the regression equations are not reliable predictors of LEA-controlled $NO_x$ emissions from these boilers. As a result, it is not possible to establish $NO_x$ emission levels representative of small residual oil-fired boilers using LEA, nor is it possible to predict the $NO_x$ reduction performance of LEA on these boilers.

## 5.3 OTHER $NO_x$ CONTROLS

### 5.3.1 Flue Gas Recirculation (FGR)

Nitrogen oxides emissions data from tests conducted on two residual oil-fired watertube boilers, one operating with, and the other without FGR are summarized in Table 5-4. One boiler was rated at 9.1 MW (31 million Btu/hour) heat input capacity while the other boiler was rated at 6.5 MW (22 million Btu/hour) heat input capacity. Table 5-4 also provides boiler data for both boilers.

Table 5-4 shows that the two boilers operated at different loads and excess $O_2$ levels and that they have varying amounts of flue gas being recirculated to the boilers. This resulted in FGR-controlled $NO_x$ emissions ranging from 48 to 83 ng/J (0.112 to 0.193 lb/million Btu). Such a limited

TABLE 5-3. COMPARISON OF ACTUAL AND PREDICTED $NO_x$ EMISSIONS FOR THE RESIDUAL OIL-FIRED SMALL BOILERS USING LEA

| Boiler I.D.[a] | $NO_x$ Emissions (lb/million Btu) Actual | Predicted | Percent deviation[b] |
|---|---|---|---|
| 23-1 | 0.328 | 0.372 | -13 |
| 26-1 | 0.201 | 0.181 | 10 |
| 2-4 | 0.572 | 0.374 | 35 |
| 16-2 | 0.236 | 0.342 | -45 |
| Loc. 19 | 0.193 | 0.270 | -40 |
| 19-1 (Steam)[a] | 0.438 | 0.413 | 6 |
| 19-1 (Air)[a] | 0.368 | 0.415 | -13 |
| 19-2 | 0.159 | 0.179 | -13 |
| 20-4 | 0.356 | 0.412 | -16 |
| 37-2 | 0.230 | 0.389 | -69 |
| Loc. 38 | 0.305 | 0.211 | 31 |
| 38-2 | 0.312 | 0.469 | -50 |

[a]Indicates type of oil atomization.

[b]Percent deviation = (actual - predicted $NO_x$ emissions) * 100/actual $NO_x$ emissions.

TABLE 5-4. $NO_x$ EMISSION DATA FROM RESIDUAL OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) HEAT INPUT OR LESS OPERATING WITH AND WITHOUT FLUE GAS RECIRCULATION (FGR)

| Boiler Data | | | | Test Data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, MW ($10^6$ Btu/hr) heat input | Fuel nitrogen, percent | Percent FGR[c] | Average test load, percent | Stack $O_2$, percent baseline/controlled | Combustion air temperature, °C (°F) | $NO_x$ emissions, lb/$10^6$ Btu baseline/controlled[d] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/controlled | PM emissions, lb/$10^6$ Btu baseline/controlled[f] | Boiler efficiency, percent baseline/controlled | Reference[g] |
| ECCC[b] | WT,PKG | NR[e] (NR) | 9.1 (31) | 0.19 | 7 | 67 | 4.4/4.5 | Amb[e] | 0.161/0.157 | 3 | 20/20 | NR/NR | NR/NR | 14 |
| ECCC[b] | WT,PKG | NR (NR) | 9.1 (31) | 0.19 | 19 | 67 | 4.4/2.0 | Amb | 0.161/0.112 | 30 | 10/145 | NR/NR | NR/NR | 14 |
| Loc. 19 | WT,PKG | 211 (67) | 6.5 (22) | 0.25 | 25 | 81 | 3.1/1.8 | Amb | 0.278/0.193 | 31 | 4/90 | 0.08/0.08 | 83/82 | 15 |

[a]WT = watertube, PKG = packaged.

[b]Multiple tests were conducted on the same boiler but at different operating conditions.

[c]Percent of flue gas mass recirculated to boiler.

[d]$NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[e]NR = not reported; Amb = ambient temperature [assume 27°C (80°F)].

[f]To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[g]Test results from Reference 14 and 15 are also presented in Reference 1.

data base does not permit the use of regression analysis to develop equations predicting $NO_x$ emissions from residual oil-fired small boilers using FGR. Consequently, it is not possible to establish $NO_x$ emission levels representative of small residual oil-fired boilers using FGR, nor is it possible to predict $NO_x$ reduction performance of FGR on these boilers.

5.3.2 Overfire Air Ports (OFA)

Table 5-5 presents $NO_x$ emission data from tests conducted on four small residual oil-fired boilers operating with and without OFA and ranging in heat input capacity from 6.5 to 16 MW (22 to 56 million Btu/hour).

Table 5-5 shows that OFA-controlled $NO_x$ emissions were also highly scattered, ranging from 60.6 to 105 ng/J (0.141 to 0.245 lb/million Btu). Furthermore, reductions in $NO_x$ emissions ranged considerably, from 24 to 47 percent. As mentioned above for FGR, such a limited data base does not permit the use of regression analysis. Thus, equations predicting $NO_x$ emissions and $NO_x$ emission reductions from small residual oil-fired boilers using OFA cannot be developed. Consequently, it is not possible to establish $NO_x$ emission levels representative of small residual oil-fired boilers using OFA, nor is it possible to predict the $NO_x$ emission reduction performance of OFA for these boilers.

TABLE 5-5. $NO_X$ EMISSIONS DATA FROM RESIDUAL OIL-FIRED STEAM GENERATORS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS OPERATING WITH AND WITHOUT OVERFIRE AIR PORTS (OFA)

| Boiler Data | | | | | Test Data | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[a] | Full load heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, MW ($10^6$ Btu/hr) heat input | Fuel nitrogen, percent | Average test load, percent | Stack $O_2$, percent baseline/ controlled | Combustion air temperature, °C (°F) | $NO_x$ emissions, lb/$10^6$ Btu baseline/ controlled[c] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/ controlled | PM emissions, lb/$10^6$ Btu baseline/ controlled[f] | Boiler efficiency, percent baseline/ controlled | Reference[g] |
| 19-2[b] | WT,PKG | 211 (67) | 6.5 (22) | 0.14 | 80 | 3.1/3.1 | Amb[d], | 0.217/0.166 | 24 | 0/0 | 0.03/NR[d] | 84/82 | 5 |
| 19-2[b] | WT,PKG | 211 (67) | 6.5 (22) | 0.44 | 80 | 3.1/2.4 | Amb | 0.217/0.141 | 35 | 0/190 | 0.03/NR | 84/82 | 5 |
| Loc. 19 | WT,PKG | 211 (67) | 6.5 (22) | 0.44 | 79 | 3.1/2.4 | Amb | 0.278/0.194 | 30 | 4/24 | 0.08/0.07 | 83/83 | 15 |
| 38-2 | WT,PKG | 265 (84) | 16 (56) | 0.49 | 80 | 3.0/2.9 | 157 (315) | 0.419/0.222 | 47 | 0/55 | 0.11/0.14 | 87/87 | 5 |
| Loc. 38 | WT,PKG | 265 (84) | 16 (56) | 0.31 | 85 | 2.9/3.3 | 138 (280) | 0.386[e]/0.245[e] | 37 | 22/62 | 0.15/0.12 | 85/85 | 15 |

[a] WT = watertube, PKG = packaged.

[b] Multiple tests were conducted on the same boiler but at different operating conditions.

[c] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[d] Amb = ambient temperature [assume 27°C (80°F)]; NR = not reported.

[e] Estimate only, $NO_x$ values assume $NO_2$ is 5% of the total (only NO was measured).

[f] To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.

[g] Test results from Reference 5 and 15 are also presented in Reference 1.

## 6.0 COAL $NO_x$ EMISSIONS AND CONTROL TECHNIQUES

The $NO_x$ controls for which emission data are available include LEA and OFA. Except where noted, the operating principles, applicability, and commercial availability of these control techniques are the same as those discussed above for natural gas- and oil-fired boilers.

### 6.1 REGULATORY BASELINE EMISSION LEVELS

The regulatory baseline is defined as the uncontrolled $NO_x$ emission level because of the virtual absence of State and local regulation of $NO_x$ emissions from small coal-fired boilers. Regulatory baseline $NO_x$ emission data from tests conducted on 11 small coal-fired boilers, ranging in heat input capacity from 16 to 29 MW (56 to 100 million Btu/hour), can be found in Table 6-1. Spreader, underfeed, overfeed, and vibrating grate stokers are represented. In addition to presenting $NO_x$ emission data, this table presents data for each boiler tested.

As shown in this table, $NO_x$ emissions from these boilers were highly scattered, ranging from 98 to 273 ng/J (0.229 to 0.635 lb/million Btu). Regression analysis, employed to explain the variability in the data caused by operation of these boilers under different operating conditions (i.e., boiler load, grate heat release rate, excess air level, and fuel moisture and nitrogen contents), was unsuccessful.[33,34] Thus, regression equations relating $NO_x$ emissions from small coal-fired boilers to various boiler operating conditions could not be developed and, as a result, it is not possible to establish an uncontrolled $NO_x$ emission level representative of small coal-fired stoker boilers.

Table 6-2 presents uncontrolled $NO_x$ emission data from tests conducted on three Fluidized Bed Combustion (FBC) boilers, ranging in heat input capacity from 14.7 to 28.4 MW (50 to 97 million Btu/hour). As shown in Table 6-2, $NO_x$ emissions from FBC boilers varied as much as those from the spreader stoker boilers, ranging from 181 to 327 ng/J (0.42 to 0.76 lb/million Btu). Regression analysis, employed to explain the variability in the data caused

TABLE 6-1. $NO_X$ EMISSION DATA FROM COAL-FIRED BOILERS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE AND LOW EXCESS AIR CONDITIONS[a]

| Boiler Data | | | | | | Test Data | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler I.D. | Boiler type[c] | Full load grate heat release rate, $kJ/m^2$-sec ($10^3$ $Btu/ft^2$-hr) | Boiler capacity, ($10^6$ Btu/hr) heat input | Moisture in fuel, weight percent | Fuel nitrogen, percent | Average test load, percent | Stack $O_2$, percent baseline/controlled | $NO_x$ emissions lb/$10^6$ Btu baseline/controlled[d,g] | $NO_x$ reduction, percent | CO emissions, ppm @ 3% $O_2$ baseline/controlled | PM emissions lb/$10^6$ Btu baseline/controlled | Reference[i] |
| #21-2 | SS | 1,484 (471) | 18 (63) | 2.1 | 1.5 | 81 | 8.0/5.8 | 0.635/0.452 | 29 | 35/42 | NR/0.55 | 5 |
| #21-3 | SS | 1,421 (451) | 28 (94) | 1.6 | 1.4 | 84 | 7.8/5.5 | 0.634/0.491 | 23 | 122/104 | 0.24/NR | 5 |
| Site G | SS | 2,249 (714) | 29 (99) | 4.3 | 1.0 | 99 | 7.2/5.0 | 0.540/0.412 | 24 | NR/NR | 6.3[h]/NR | 27 |
| Site G | SS | 2,249 (714) | 29 (99) | 4.8 | 1.0 | 99 | 7.5/4.0 | 0.572/0.401 | 30 | NR/NR | 4.8[h]/NR | 27 |
| Site F | SS | 2,167 (688) | 29 (98) | 3.3 | 1.2 | 75 | 8.9/7.8 | 0.468/0.443 | 5 | 146/137 | NR/NR | 28 |
| Site F | SS | 2,167 (688) | 29 (98) | 4.7 | 1.1 | 75 | 9.9/6.2 | 0.454/0.312 | 31 | 139/96 | NR/NR | 28 |
| Fairmont #3 | SS | NR (NR)[e] | 29 (100) | 7.3 | 1.1 | 75 | 8.0/6.5 | 0.506[f]/0.405[f] | 20 | 47/155 | 1.8[h]/2.6[h] | 29 |
| Fairmont #3 | SS | NR (NR) | 29 (100) | 14.2 | 0.5 | 76 | 8.0/7.0 | 0.483[f]/0.418[f] | 13 | 83/75 | 2.8[h]/2.6[h] | 29 |
| 15-32-10 | UFS | 1,449 (460) | 22 (75) | 10.5 | 1.4 | 77 | 6.6/4.9 | 0.364/0.263 | 28 | 0/0 | NR/NR | 5 |
| 15-32-13 | UFS | 1,449 (460) | 22 (75) | 10.5 | 1.4 | 77 | 10.3/8.0 | 0.433/0.361 | 17 | 0/0 | 1.3[h]/NR | 5 |
| Site I | OFS | 1,188 (377) | 28 (95) | 3.1 | 1.8 | 104 | 8.3/5.0 | 0.400/0.283 | 29 | NR/NR | 1.0[h]/NR | 30 |
| Site I | OFS | 1,188 (377) | 28 (95) | 2.3 | 1.4 | 102 | 7.7/5.9 | 0.229/0.211 | 8 | NR/NR | 1.4[h]/NR | 30 |
| Site J | OFS | 1,244 (395) | 23 (77) | 3.1 | 1.7 | 100 | 9.1/7.5 | 0.353/0.316 | 10 | NR/NR | NR/NR | 31 |
| Site K | OFS | 1,276 (405) | 18 (63) | 6.5 | 1.6 | 101 | 7.9/7.0 | 0.324/0.310 | 4 | 139/138 | 0.71[h]/0.69[h] | 32 |
| UW-Stout #2 | VGS | NR (NR) | 16 (56) | 21.5 | 0.9 | 57 | 9.3/5.2 | 0.277/0.209 | 25 | 30/111 | 0.72/0.56 | 29 |

[a] All boilers used no air preheat.
[b] Brackets indicate multiple parametric tests were conducted on each boiler.
[c] SS = spreader stoker; UFS = underfeed stoker; OFS = overfeed stoker; and VGS = vibrating grate stoker.
[d] $NO_x$ emissions were measured by Thermo Electron Chemiluminescent Analyzer. All tests were short-term (<3 hours). To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.
[e] NR = not reported.
[f] Estimate only; $NO_x$ values assume $NO_2$ is 5% of the total (only NO was measured).
[g] To convert to ng/J, multiply emissions in lb/$10^6$ Btu by 430.
[h] PM emissions were taken from inlet to the PM control device (uncontrolled emissions).
[i] Test results from References 5 and 27 to 30 are also presented in Reference 1.

TABLE 6-2. $NO_X$ EMISSION DATA FROM COAL-FIRED FLUIDIZED BED COMBUSTION (FBC) BOILERS RATED AT 29 MW (100 MILLION BTU/HOUR) OR LESS AT BASELINE CONDITIONS

| Boiler I.D. | Boiler Type[b] | Boiler size, MW ($10^6$ Btu/hour) heat input | Weight percent nitrogen in coal | Coal moisture, weight percent | Average test load, percent | Stack $O_2$, percent | $NO_x$ emissions, lb/$10^6$ Btu[c] | CO emissions, ppm | PM emissions, lb/$10^6$ Btu[c] | Emission test method (test duration)[d] | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [a] A[e] | Pkg. Sb | 26.4 (90) | NA[f] | NA | 59 | 6.0[g] | 0.76 | 585 | NA | CEM (16) | 35 |
| A | Pkg. Sb | 26.4 (90) | NA | NA | 70 | 6.7[g] | 0.42 | 160 | NA | CEM (8) | 35 |
| B | Pkg. Bb | 28.4 (97) | NA | NA | 72 | 6.7 | 0.56 | NA | 0.02 | $NO_x$: EPA-7 (3 hrs)<br>PM: EPA-5 (3 hrs) | 36 |
| C | Pkg. Bb | 14.7 (50) | 1.06 | 6.4 | 72 | 10.5 | 0.62 | 453 | NA | CEM (7.5) | 37,38 |
| C | Pkg. Bb | 14.7 (50) | 0.97 | 6.8 | 66 | 11.1 | 0.60 | 507 | NA | CEM (15 hrs) | 37,38 |
| C | Pkg. Bb | 14.7 (50) | NA | NA | 56 | 11.6 | 0.70 | 1,007 | NA | CEM (5 hrs) | 37,38 |

[a] Brackets indicate multiple parametric tests were conducted on each boiler.

[b] Pkg. Sb = packaged staged bed; and Pkg. Bb = packaged bubbling bed.

[c] Multiply emissions by 430 to convert to ng/J.

[d] CEM = certified continuous emission monitor; and EPA = EPA reference methods. The number in parenthesis represent the number of days unless otherwise specified.

[e] Excluded emission data on staged combustion test.

[f] NA = not available.

[g] Excess $O_2$ measured at the inlet of the baghouse.

by operation of these boilers under different conditions, was also unsuccessful. Consequently, it is not possible to establish an uncontrolled $NO_x$ emission level representative of small FBC boilers.

## 6.2 LOW EXCESS AIR (LEA)

The operating principles of LEA are the same as those discussed in Section 3.2 for natural gas-fired small boilers. For small coal-fired boilers, LEA is achieved by design and adjustment of the combustion air delivery system. Typical stack $O_2$ levels for small stoker boilers without LEA are about 6 percent $O_2$ (40 percent excess air) on newer units and about 5 percent $O_2$ (30 percent excess air) when LEA is applied.[39,40] Small FBC boilers are typically designed to operate at minimum excess $O_2$ levels ranging from 3 to 4.5 percent $O_2$ (15 to 25 percent excess air).[41]

Small coal-fired boilers are generally balanced draft units, with both forced draft (FD) and induced draft (ID) fans. Often, these units control combustion air flow based on furnace pressure. The FD fan damper automatically adjusts to changes in furnace pressure, and the ID fan tracks the FD signal. By including an $O_2$ trim system, better $O_2$ control can be obtained in the boiler under extreme load variations.

Emission test data from application of LEA control on small coal-fired stoker boilers may also be found in Table 6-1 for the same 11 small coal-fired stoker boilers discussed in Section 6.1. Like the uncontrolled $NO_x$ emission data, LEA-controlled $NO_x$ emissions were highly scattered, ranging from 90 to 211 ng/J (0.209 to 0.491 lb/million Btu). The $NO_x$ emission reduction achieved by LEA also varied substantially, ranging from 4 to 31 percent.

As with the uncontrolled $NO_x$ emission data, regression analysis, employed to explain the variability in the data caused by operation of these boilers under different conditions was unsuccessful. Consequently, it is not possible to establish $NO_x$ emission levels which are representative of small coal-fired stokers using LEA.

Emission data are not available on small coal-fired FBC boilers using LEA. Consequently, $NO_x$ emission levels cannot be established for small FBC boilers using LEA.

## 6.3 OVERFIRE AIR PORTS (OFA)

The mechanism by which $NO_x$ emissions are reduced using OFA is the same for coal-fired boilers as that discussed earlier for natural gas- and oil-fired boilers. Coal-fired stoker boilers achieve partial staged combustion by the nature of their design. Part of the fuel is combusted on the grate while the rest is burned in suspension above the grate. Combustion air can be split and introduced both below the grate and above the grate through OFA ports. Many stoker boilers have OFA ports as smoke control devices. Therefore, the location of the OFA ports in the boiler may not be at the optimum location to achieve the greatest $NO_x$ reductions.

Nitrogen oxides emissions from FBC boilers can also be reduced further by staging of the combustion air. A substoichiometric amount of air is introduced through the fluidizing air (primary air) injection point. The balance of the air needed to achieve adequate combustion efficiency is added above the bed. This allows combustion to be completed in the freeboard zone (i.e., space between the top of the fluidized bed and boiler outlet).

Performance data on $NO_x$ emissions are not available on small coal-fired stoker boilers using OFA. However, $NO_x$ emission data are available from the FBC boiler at site A reported in Table 6-2 using OFA. During a 2-day OFA test, $NO_x$ emissions averaged 258 ng/J (0.6 lb/million Btu). This compares with average $NO_x$ emissions of 378 ng/J (0.88 lb/million Btu) obtained for this boiler during 2 days of operation without OFA immediately following the staged combustion test.[42]

Because OFA emissions testing was conducted on only one boiler, such a limited data base does not permit the use of regression analysis to develop equations predicting $NO_x$ emissions from small FBC boilers using OFA. Consequently, it is not possible to establish $NO_x$ emission levels representative of small coal-fired boilers using OFA, nor is it possible to predict the $NO_x$ reduction performance of OFA on these boilers.

## 7.0 REFERENCES

1. Lim, K.J., et al. (Acurex Corporation). Technology Assessment Report for Industrial Boiler Applications: $NO_x$ Combustion Modification. Prepared for the U.S. Environmental Protection Agency. Research Triangle Park, NC. Publication No. EPA-600/7-79-178f. December 1979. 497 p.

2. Memorandum from Stackhouse, C.W., Radian Corporation, to Small Boiler Docket. August 18, 1987. 58 p. State and Local Regulatory Practices for Small Boilers.

3. Jones, G.D. and K.L. Johnson (Radian Corporation). Technology Assessment Report for Industrial Boiler Applications: $NO_x$ Flue Gas Treatment. Prepared for the U.S. Environmental Protection Agency. Washington, DC. Publication No. EPA-600/7-79-178g. December 1979. pp. 4-1 to 4-35.

4. Statewide Technical Review Group. Technical Support Document for Suggested Control Measures for the Control of Emissions of Oxides of Nitrogen from Industrial, Institutional, and Commercial Boilers, Steam Generators, and Process Heaters (Draft). California Air Resources Board and the South Coast Air Quality Management District. Sacramento, CA. March 1987. pp. 102 to 104, and 105 to 108.

5. Hunter, S.C., et al. (KVB Engineering Incorporated). Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase I and II (Data Supplement). Prepared for the U.S. Environmental Protection Agency. Research Triangle Park, NC. Publication No. EPA-600/2-77-122. June 1977. 643 p.

6. Carter, W.A. and H.J. Buening (KVB Engineering Incorporated). Thirty-Day Field Tests of Industrial Boilers. Site 6: Gas-Fired Firetube Boiler. Prepared for the U.S. Environmental Protection Agency. Washington, DC. Publication No. EPA-600/7-81-095b. May 1981. pp. 3, 12, 13.

7. Memorandum from Wertz, K. and K. Johnson, Radian Corporation, to Stevenson, W.H., EPA:SDB. May 19, 1986. 13 p. Natural Gas Regression Analysis.

8. Reference 1. pp. 2-3 and 2-4.

9. Reference 1. pp. 2-43 to 2-47.

10. Buening, H.J. (KVB Engineering Incorporated). Testing of Low-$NO_x$ Combustion Retrofit - Boiler No. 3. Prepared for IBM, Incorporated. San Jose, CA. Report No. KVB71-60451-2008. January 1985. pp. 3 and 4.

11. Memorandum from Copland, R., EPA:SDB, to Stevenson, W.H., EPA:SDB. July 30, 1986. Technical note summarizing $NO_x$ test for IBM boilers No. 3 and No. 6 with flue gas recirculation (FGR) systems.

12. Letter and attachments from Finker, R.A., Energy Systems Associates, to Wisinski, F., Cleaver-Brooks. November 26, 1984. Results from Performance Test California Milk Producers Boiler No. 5, October 30-31, 1984.

13. Letter and attachments from Carter, W.A., KVB Engineering Incorporated, to Gary M., IBM. September 1, 1983. Results from performance test after retrofitting boiler No. 6 with flue gas recirculation.

14. Cichanowicz, J.E. and M.D. Heap (Ultrasystems, Incorporated). Pollutant Control Techniques for Package Boilers: Phase I Hardware Modifications and Alternate Fuels. Prepared for the U.S. Environmental Protection Agency. Research Triangle Park, NC. Contract No. 68-02-1498. November 1976. p. 35.

15. Carter, W.A., et al. (KVB Engineering Incorporated). Emission Reduction on Two Industrial Boilers with Major Combustion Modifications. Prepared for the U.S. Environmental Protection Agency. Research Triangle Park, NC. Publication No. EPA-600/7-78-099a. June 1978. 167 p.

16. Waibel, R. and D. Nickeson. Staged Fuel Burners for $NO_x$ Control. John Zink Company. Tulsa, OK. (Presented at the International Flame Research Foundation 8th Members Conference. Noordwijkhout, the Netherlands. May 28-30, 1986.)

17. Reference 1. pp. 2-49 to 2-60.

18. Kesselring, J.P. and W.V. Krill (Alzeta Corporation). Firetube Boiler Fiber Burner Development Program - Phase I. Prepared for the Gas Research Institute. Chicago, IL. GRI Contract No. 5082-231-0684. November 1984. p. 76.

19. Letter and attachments from Jones, L., EPA:SDB, to Durkee, K., EPA:ISB. February 23, 1983. Tests of Low $NO_x$ Burner Performance.

20. Crosby, K.J. (Chemecology Corporation). Field Data Source Test on Boiler #3. Prepared for San Joaquin County Air Pollution Control District, San Joaquin County, CA. Report No. 1880. July 16, 1984.

21. Carter, W.A. and H.J. Buening (KVB Engineering Incorporated). Thirty-Day Field Tests of Industrial Boilers. Site 5: Gas-Fired Low $NO_x$ Burner. Prepared for the U.S. Environmental Protection Agency. Washington, DC. Publication No. EPA-600/7-81-095a. May 1981. pp. 3, 12 to 14.

22. Memorandum from Wertz, K. and K. Johnson, Radian Corporation, to Stevenson, W.H., EPA:SDB. May 19, 1986. 26 p. Fuel Oil Regression Analysis.

23. Reference 22.

24. Crosby, K.J. (Chemecology Corporation). Field Data Source Test on Boiler #3. Prepared for San Joaquin Air Pollution Control District, San Joaquin County, CA. Report No. 1880. July 16, 1984.

25. Reference 22.

26. Reference 22.

27. Langsjoen, P.L., et al. (KVB Engineering, Inc.). Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site G. Prepared for the U.S. Environmental Protection Agency, U.S. Department of Energy, and the American Boiler Manufacturers Association. Washington, DC. Publication No. EPA-600/7-80-082a. April 1980. pp. 10, 11, 13.

28. Langsjoen, P.L., et al. (KVB Engineering, Inc.). Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site F. Prepared for the U.S. Environmental Protection Agency, U.S. Department of Energy, and the American Boiler Manufacturers Association. Washington, DC. Publication No. EPA-600/7-80-065a. March 1980. pp. 8, 9, 11.

29. Maloney, K.L., et al. (KVB Engineering, Inc.). Low-Sulfur Western Coal Use in Existing Small and Intermediate Size Boilers. Prepared for U.S. Environmental Protection Agency. Washington, DC. Publication No. EPA-600/7-78-153a. July 1978. pp. 106, 111, 113, 224, 230, 231, 242.

30. Industrial Environmental Research Laboratory - RTP, Office of Research and Development. Problem-Oriented Report: Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site I. U.S. Environmental Protection Agency, Research Triangle Park, NC. Publication No. IERL-RTP-1069. May 1980. pp. 8 to 10.

31. Industrial Environmental Research Laboratory - RTP, Office of Research and Development. Problem-Oriented Report: Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site J. U.S. Environmental Protection Agency. Research Triangle Park, NC. Publication No. IERL-RTP-1070. May 1980. pp. 8 to 10.

32. Industrial Environmental Research Laboratory - RTP, Office of Research and Development. Problem-Oriented Report: Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site K. U.S. Environmental Protection Agency. Research Triangle Park, NC. Publication No. IERL-RTP-1071. May 1980. pp. 9, 11, 12.

33. Keller, L.E., et al. (Radian Corporation). Regressions for $NO_x$ Emissions from Coal-Fired Spreader Stoker Industrial Boilers. Prepared for the U.S. Environmental Protection Agency. Research Triangle Park, NC. Contract No. 68-02-3058. August 31, 1982. 118 p.

34. Memorandum from Kwapil, W.D., Radian Corporation, to Stevenson, W.H., EPA:SDB. June 1, 1983. 8 p. Regression Analyses of Mass-Feed Boiler $NO_x$ Emission Data.

35. Peduto, E.F., Jr., et al. (GCA Corporation). Continuous Monitoring of Wormser Fluidized Bed Combustor. Prepared for the U.S. Environmental Protection Agency. Research Triangle Park, NC. EPA Contract No. 68-02-2693. June 1984. 184 p.

36. Interpoll, Inc. Results of the November 13, 1985, Particulate, $SO_2$, $NO_x$ and CO Emission Compliance Test on the Fluidized Bed Boiler at the SOHIO Refinery in Lima, OH. Report Number 5-2121. November 27, 1985. 7 p.

37. U.S. Environmental Protection Agency. Statistical Analysis of Emission Test Data From Fluidized Bed Combustion Boiler at Prince Edward Island, Canada. Publication No. EPA-450/3-86-015. December 1986. pp. 3-1 to 3-10.

38. U.S. Environmental Protection Agency. Fluidized Bed Boiler Emission Test Report, Canadian Forces Base, Summerside, Prince Edward Island, Canada. EMB No. 86-SPB-2. May 1987. Appendix B.

39. Burklin, C.E. and G.D. Jones (Radian Corporation). $NO_x$ Emission Control Technology Update. Prepared for U.S. Environmental Protection Agency. Washington, DC. EPA Contract No. 68-01-6558 WA 31. January 20, 1984. p. 5-21.

40. Reference 1. pp. 2-27 to 2-29.

41. Young, C.W., et al. (GCA Corporation). Technology Assessment Report for Industrial Boiler Applications: Fluidized-bed Combustion. Prepared for the U.S. Environmental Protection Agency. Washington, DC. Publication No. EPA-600/7-79-178e. November 1979. p. 88 and 175.

42. Reference 35. p. 1.

43. U.S. Environmental Protection Agency. Background Information Document for Small Boilers (BID): Publication No. EPA 450/3-86.

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16. ABSTRACT

This report provides a summary of the technical data used in developing proposed new source performance standards (NSPS) for small industrial-commercial-institutional steam generating units (small boilers). The report focuses on nitrogen oxides ($NO_x$) emissions from boilers firing coal, oil, and gas with heat input capacities of 100 million Btu/hour or less. Conclusions are drawn from the data regarding the performance of technologies available to reduce $NO_x$ emissions. Alternative control levels are then chosen based on the conclusions drawn from the data.

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