4.4 Results of Combustion Tests

The meanings of the terminology used in describing the results of the combustion tests are explained below:

The NOx concentration: NOx concentration in exhaust gas at oxygen concentration of 5% calculated by the following formula:
(Measured NOx concentration) x (21 - 5)/(21 - Measured O_2 in %)

The oxygen concentration: Residual oxygen concentration in the exhaust gas.

Limit oxygen concentration: Oxygen concentration below which carbon monoxide (CO) or visible smoke (Bacharach smoke meter scale 4 or higher) is produced.

The NOx emission standard: The NOx concentration of 110 ppm to be effected as the emission standard in January, 1998.

4.4.1 Results of the Tests Using Standard Oil Burner

Figures 4.4.1 through 4.4.4 show the relationships between the NOx concentration and the oxygen concentration by atomizing medium, fuel type and fuel load.

(1) Effects of Atomizing Medium on NOx Concentration

The NOx concentration levels in combustion with steam atomization were lower than those with air atomization for both of diesel oil and gas oil. In the case of diesel oil combustion at a load of 160 ℓ/h, the level with the steam atomization was about a half of that with the air atomization when the oxygen concentration was low. As the oxygen concentration increased, the difference decreased to less than 10%. In the case of gas oil, the difference increased to 35 to 41% in the intermediate range of the oxygen concentration.

This is because the steam, as an atomizing medium, lowered the flame temperature in comparison with the air. In some cases of gas oil combustion with air atomization, the NOx emission standard of 110 ppm was exceeded.

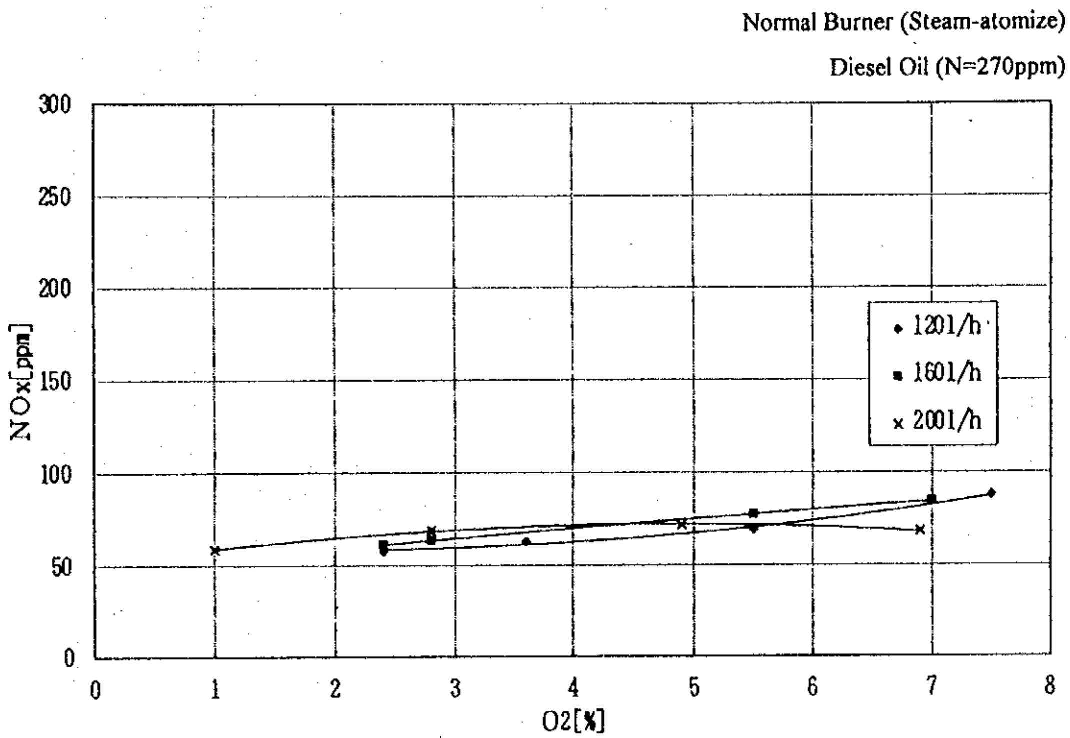


Figure 4.4.1 O_2 Concentration vs. NOx Concentration in Combustion of Diesel Oil by Steam-atomized Normal Burner

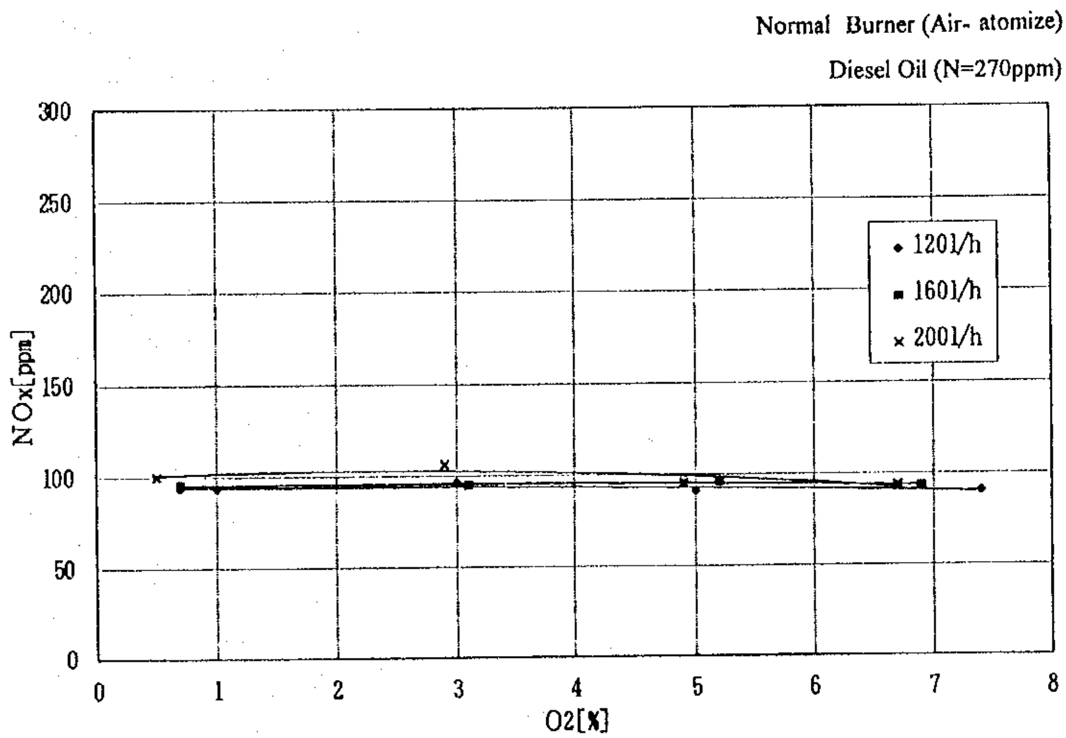


Figure 4.4.2 O_2 Concentration vs. NOx Concentration in Combustion of Diesel Oil by Air-atomized Normal Burner

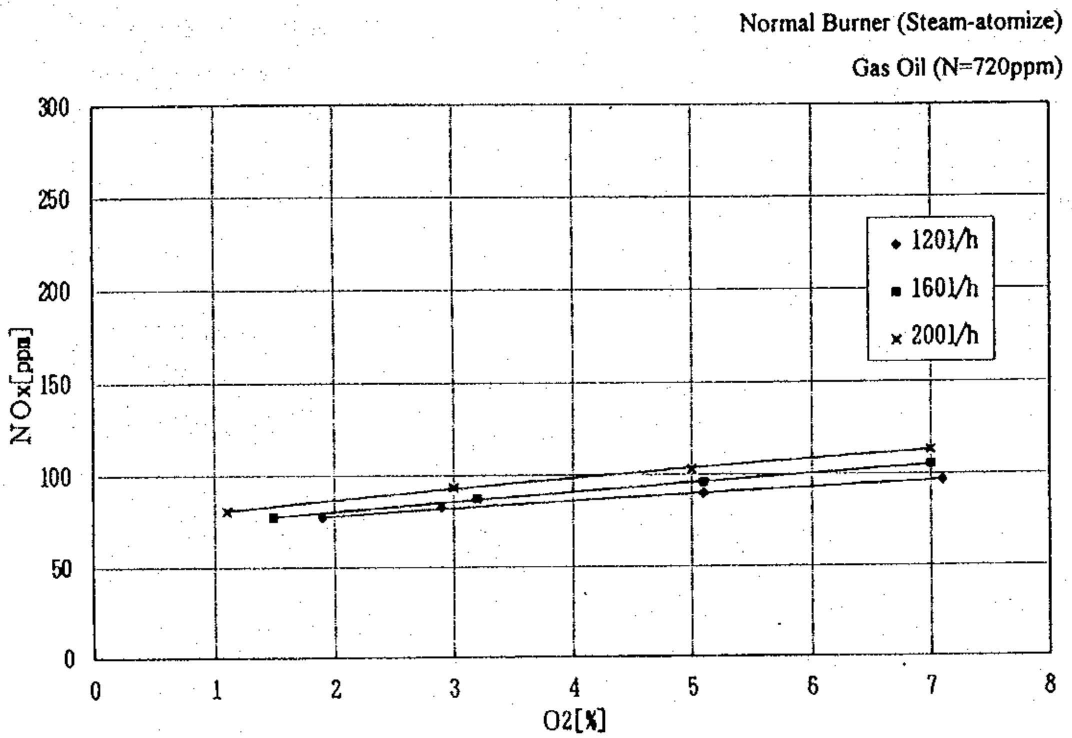


Figure 4.4.3 O_2 Concentration vs. NOx Concentration in Combustion of Gas Oil by Steam-atomized Normal Burner

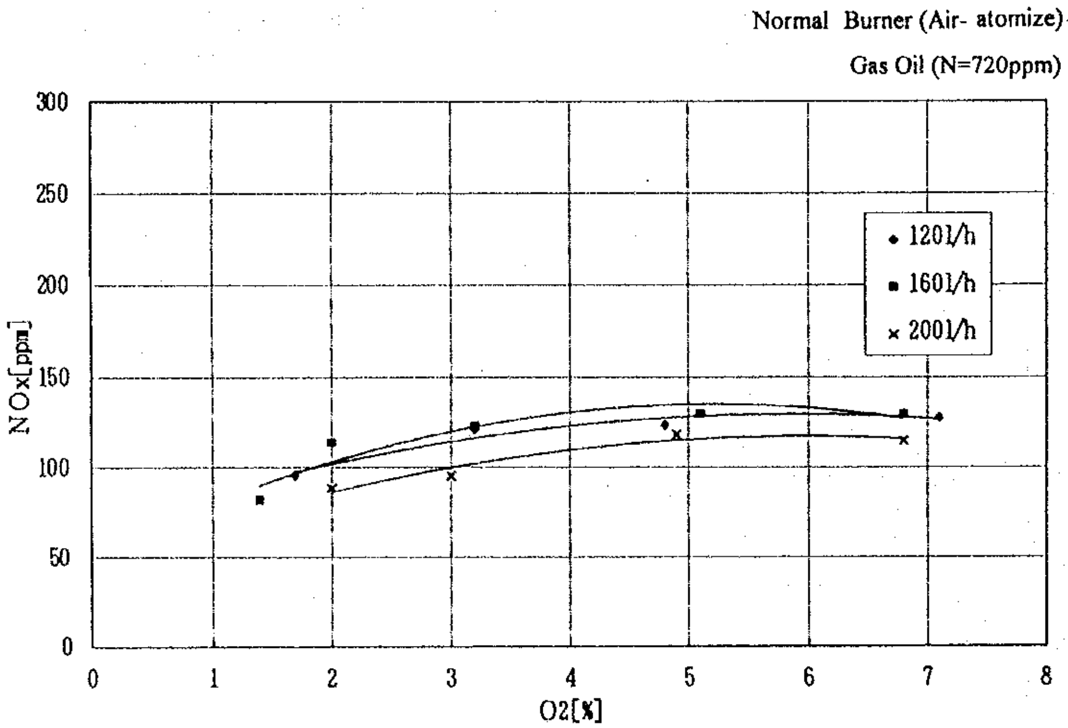


Figure 4.4.4 O_2 Concentration vs. NOx Concentration in Combustion of Gas Oil by Air-atomized Normal Burner

(2) Effects of Oxygen Concentration on NOx Concentration

Steam atomization clearly caused the NOx concentration to decrease as the oxygen concentration decreased. With the air atomization, however, this tendency is not clear.

(3) Effects of Combustion Load on NOx Concentration

The difference in the NOx concentration due to combustion load was not clear, and it was especially small with low excess air ratio combustion.

(4) Effects of Combustion Air Temperature on NOx Concentration

Combustion air was preheated by the air heater which uses produced steam as the heat source. The relationships between the preheating temperature and the NOx concentration for diesel and gas oil are shown in Figure 4.4.5.

For both fuels, the NOx concentration increased linearly as the combustion air temperature increased. It increased by 15 to 20% when the air was preheated to 136°C, as compared with that at the normal temperature.

The air heater is effective as a technique for energy saving, but the NOx emission standard is exceeded depending on the preheating temperature.

(5) Effects of Burner Nozzle Angle on NOx Concentration

Generally, several types of burner nozzles are prepared, differing with respect to the number of nozzle holes, the hole diameter and the opening angle of the nozzle, in order to select an optimal one. These nozzles produce short, long and flat flames, and that which brings about a flame shape most suitable for a particular furnace is generally selected.

In many cases, if the flame shape does not match the furnace shape, the flame contacts the wall or the rear of the furnace, thereby lowering the energy efficiency or greatly affecting the NOx concentration.

A test was made to find the relation between the burner nozzle angle and the NOx concentration using gas oil. The result is shown in Figure 4.4.6.

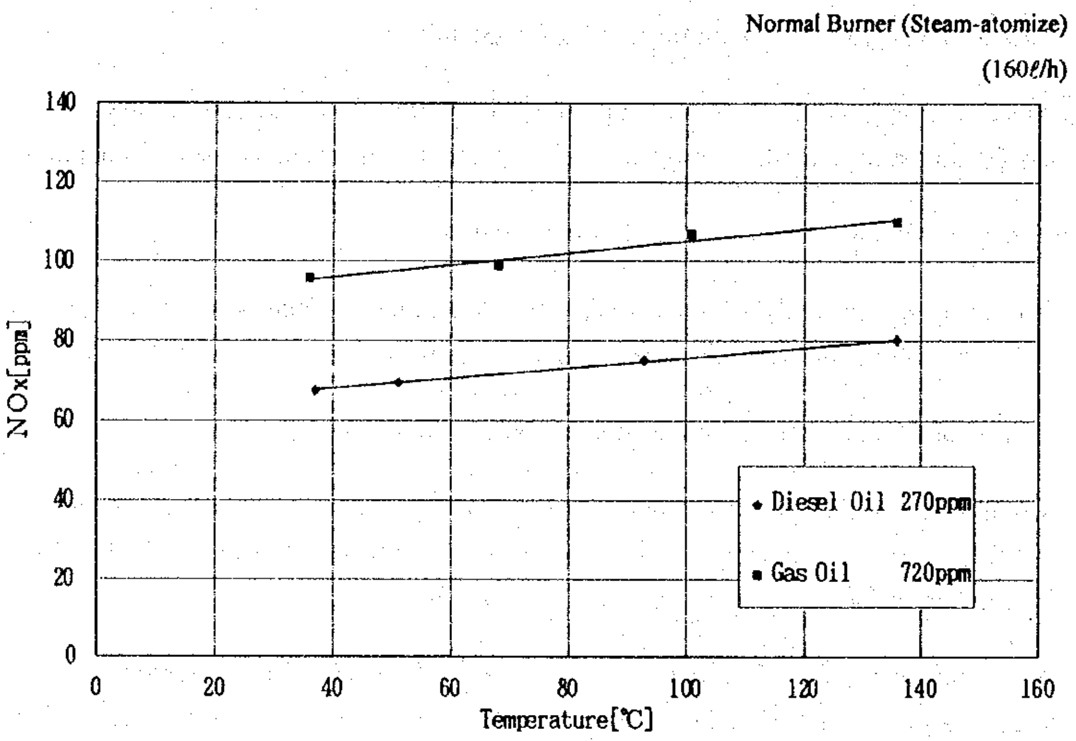


Figure 4.4.5 **Pre-heated Air Temperature vs. NOx Concentration**

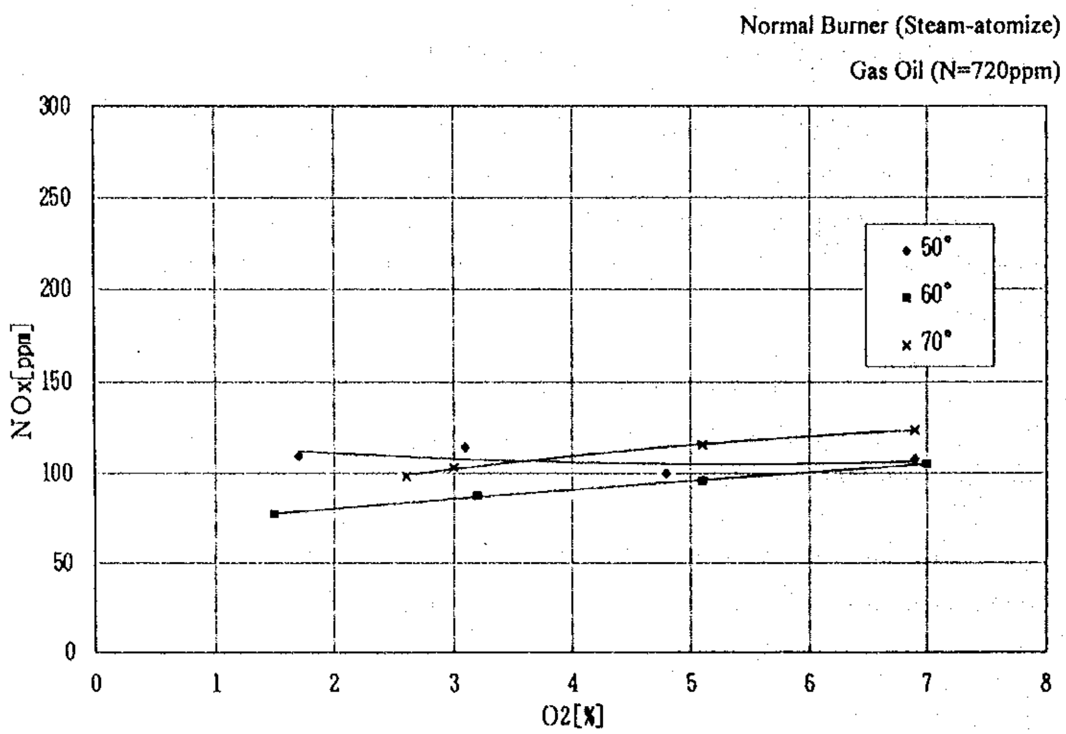


Figure 4.4.6 O_2 Concentration vs. NOx Concentration by Burner Tip Angles

The NOx concentration with the nozzle tip having a large spray angle of 70° was high in the upper range of the oxygen concentration. The NOx concentration with the nozzle tip having a small spray angle of 50° was high in the lower range of the oxygen concentration. The NOx concentration with the nozzle tip having a spray angle of 60° was low in the entire range of oxygen concentration, indicating that this nozzle tip is most suitable to the boiler.

(6) Effects of Exhaust Gas Recirculation (EGR) on NOx Concentration

EGR is effective in reducing the generation of thermal NOx since some portion of the exhaust gas is recirculated into the combustion air to lower the oxygen concentration.

Figures 4.4.7 and 4.4.8 show the relationship between the ratio of exhaust gas recirculation and the NOx concentration for diesel and gas oil, respectively. The NOx concentrations of both fuels clearly decreased in parallel with the increase in the EGR ratio, indicating that the technique was effective in lowering the NOx level.

The oxygen concentration of the combustion air was 16.0% when the EGR ratio was 28% and the Bacharach smoke number of the exhaust gas was 0 or 1.

In calculating the EGR ratio, the gas flow rate in the exhaust gas recirculation duct was measured and compared with the supply rate of the combustion air.

(7) Position of Burner Nozzle and NOx Concentration

Effects of the position of the burner nozzle on the NOx concentration in the combustion of diesel and gas oil were studied.

Figure 4.4.9 shows the NOx concentration when the nozzle was at an appropriate position and when it was moved backward by 100mm from the appropriate position.

The NOx concentration in the latter case increased by about 20% as rapid and spreading combustion resulted and part of the flame contacted the burner tile. This result shows that very minute control would be needed to reduce the amount of NOx emission.

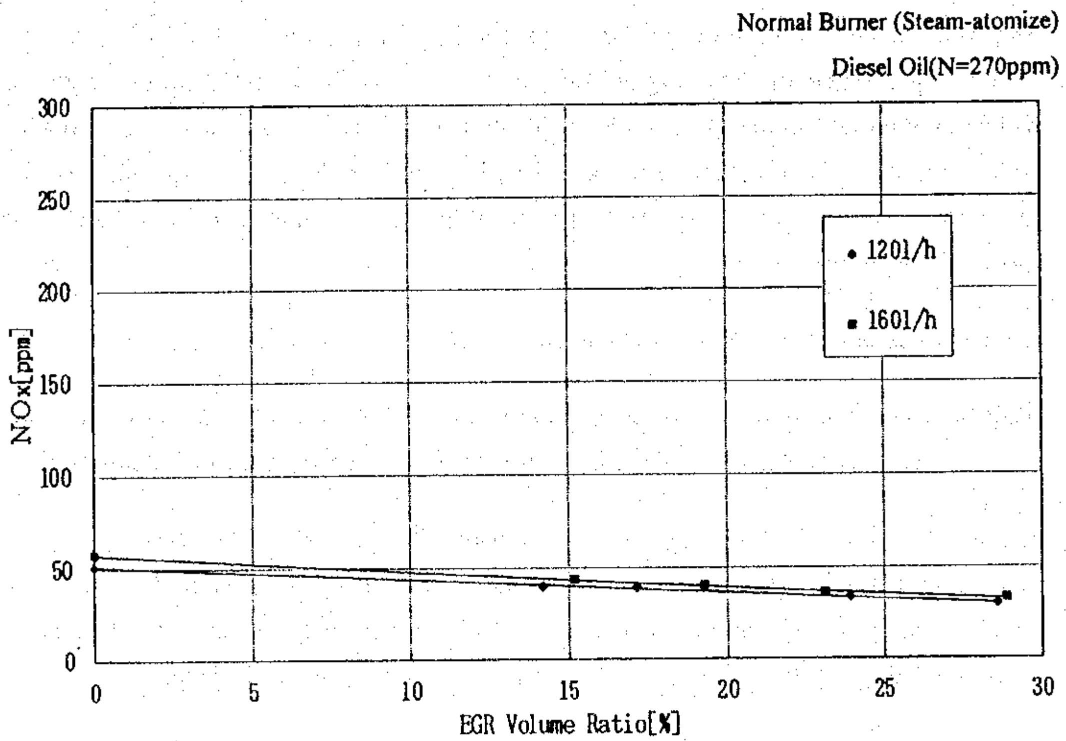


Figure 4.4.7 EGR Volume Ratio vs. NOx Concentration in Combustion of Diesel Oil by Steam-atomized Normal Burner

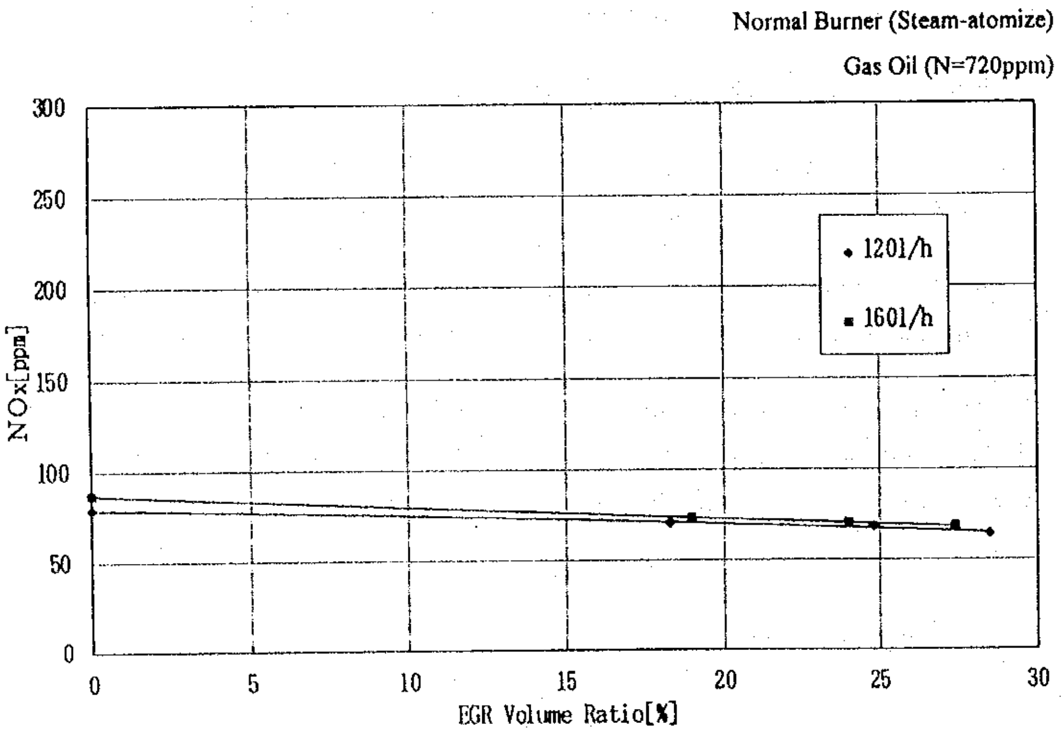


Figure 4.4.8 EGR Volume Ratio vs. NOx Concentration in Combustion of Gas Oil by Steam-atomized Normal Burner

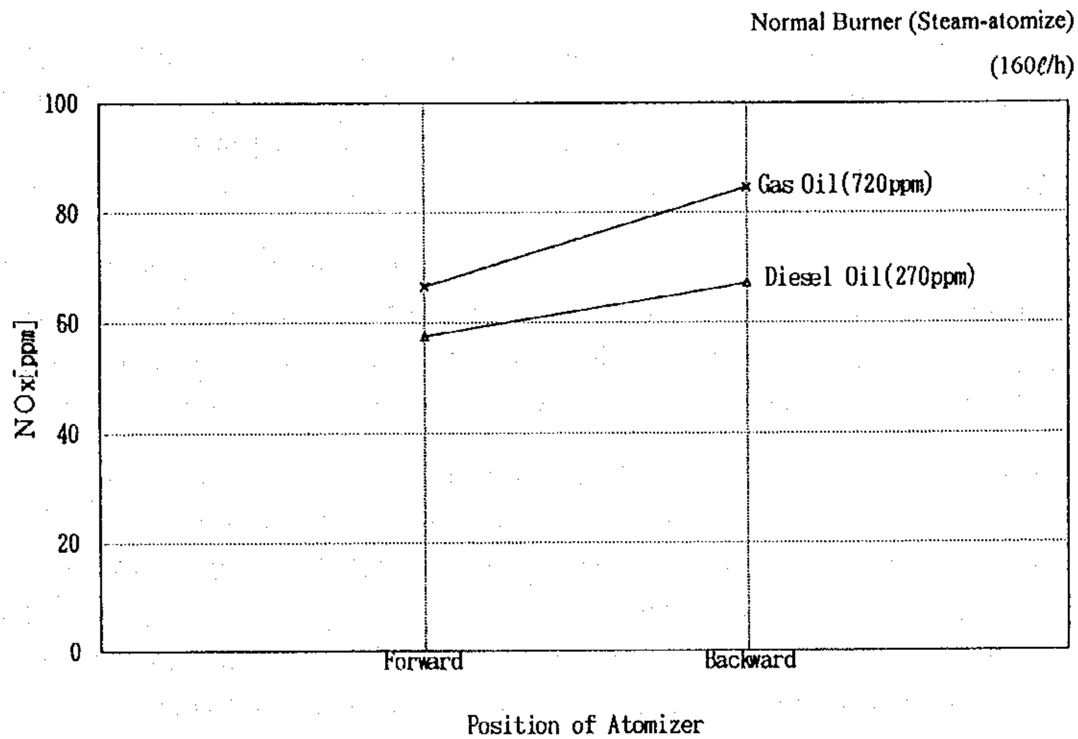


Figure 4.4.9 Influence of the Position of Burner Nozzle on NOx Concentration

(8) Influence of Mixing Method and Atomizing Steam Pressure on NOx Concentration

NOx concentrations, as well as soot and dust concentrations, were compared between two types of atomizer : the inner-mixing type and the outer-mixing type, both of which are typical atomizer types and widely used in ZMCM. The comparison was made by changing the atomizing steam pressure and the oxygen concentration.

Figures 4.4.10 and 4.4.11 show the results in diesel combustion with the inner-mixing and outer-mixing types, respectively. Similarly, the results for the inner-mixing and outer-mixing types with gas oil are shown in Figures 4.4.12 and 4.4.13, respectively. The numeric values in the figures indicate the Bacharach number.

The atomizing steam pressure hardly changed the NOx concentration with the inner-mixing type. The NOx concentration when the outer-mixing type is used tends to increase as the atomizing steam pressure increases in the lower range of the oxygen concentration. When the NOx concentrations with the outer-mixing with the Bacharach number being 4 or less are compared between the atomizing steam pressures of 1 kgf/cm^2 and 2 kgf/cm^2, the latter was higher by about 30% with both fuels.

According to the diagnostic survey of factories, boilers in ZMCM are normally operated at a substantially high atomizing steam pressure. Therefore, NOx generation by these boilers can be reduced by finding an appropriate atomizing steam pressure.

Generally, the NOx concentration decreases as the oxygen concentration decreases. However, large amounts of soot would be produced if the oxygen concentration is lowered beyond a certain limit. Smoke would become slightly visible when the Bacharach number is 4. Smoke can be viewed clearly by the eye when the Bacharach number reaches 8. This is the reason why the oxygen concentration is required to be maintained at an appropriate level so that the Bacharach number is maintained below 4.

4.4.2 Results of the Tests Using Low-NOx Oil Burner (1)

Figures 4.4.14 through 4.4.17 show the relationship between the NOx concentration and the oxygen concentration according to atomizing medium, fuel type and fuel load in the tests with the low-NOx oil burner (1).

(1) Effects of Atomizing Medium on NOx Concentration

Similarly with the standard burner, the NOx concentration level was lower with steam atomization than that with air atomization. Under the fuel load of 160 ℓ/h, the NOx concentration level with steam atomization was lower by 15 to 25% with diesel oil and 3 to 20% with gas oil in comparison to that with air atomization.

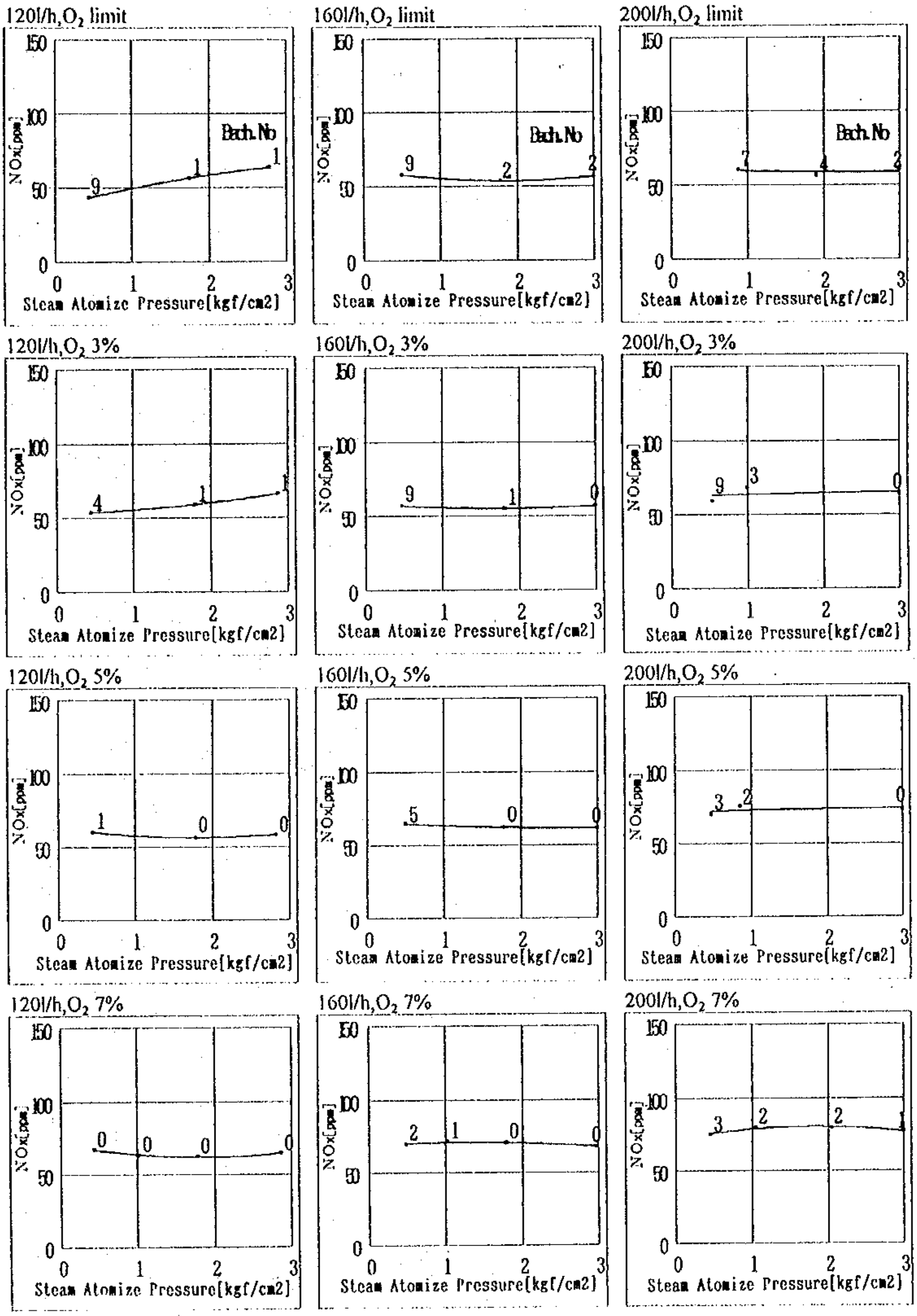


Figure 4.4.10 Atomizing Steam Pressure vs. NOx Concentration (Combustion of Diesel Oil with Inner Mixing Atomizer)

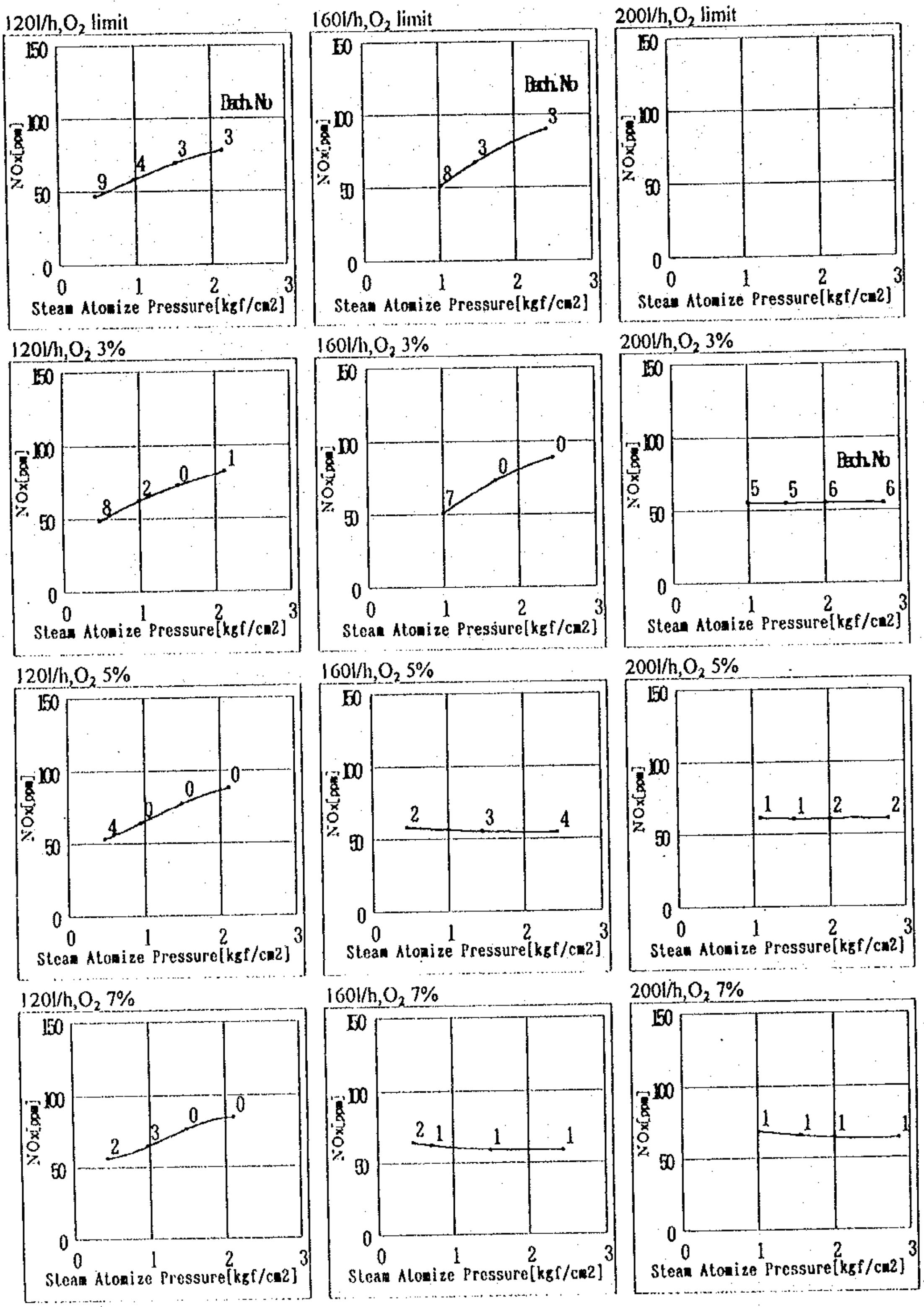


Figure 4.4.11 Atomizing Steam Pressure vs. NOx Concentration
(Combustion of Diesel Oil with Outer Mixing Atomizer)

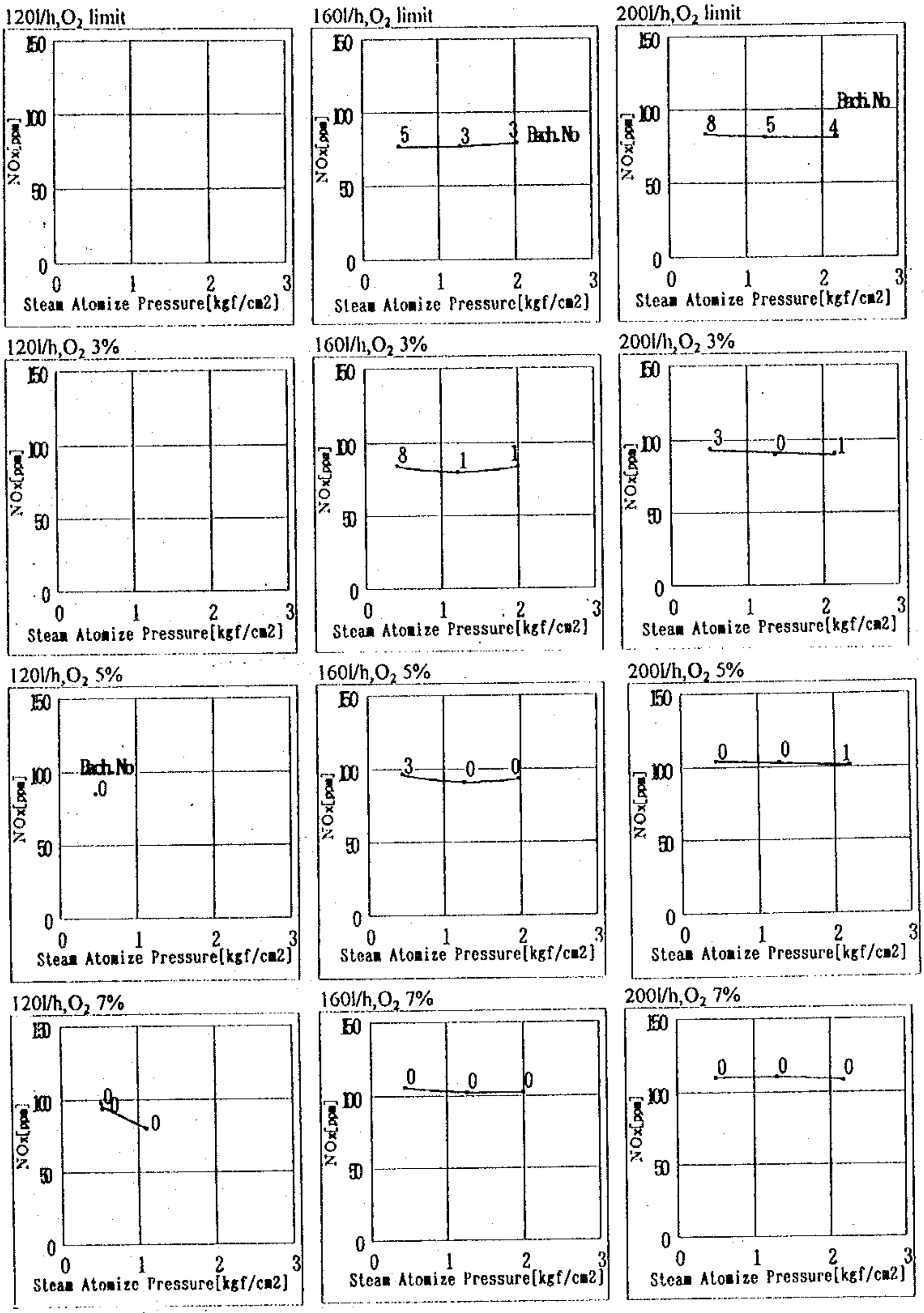


Figure 4.4.12 Atomizing Steam Pressure vs. NOx Concentration (Combustion of Gas Oil with Inner Mixing Atomizer)

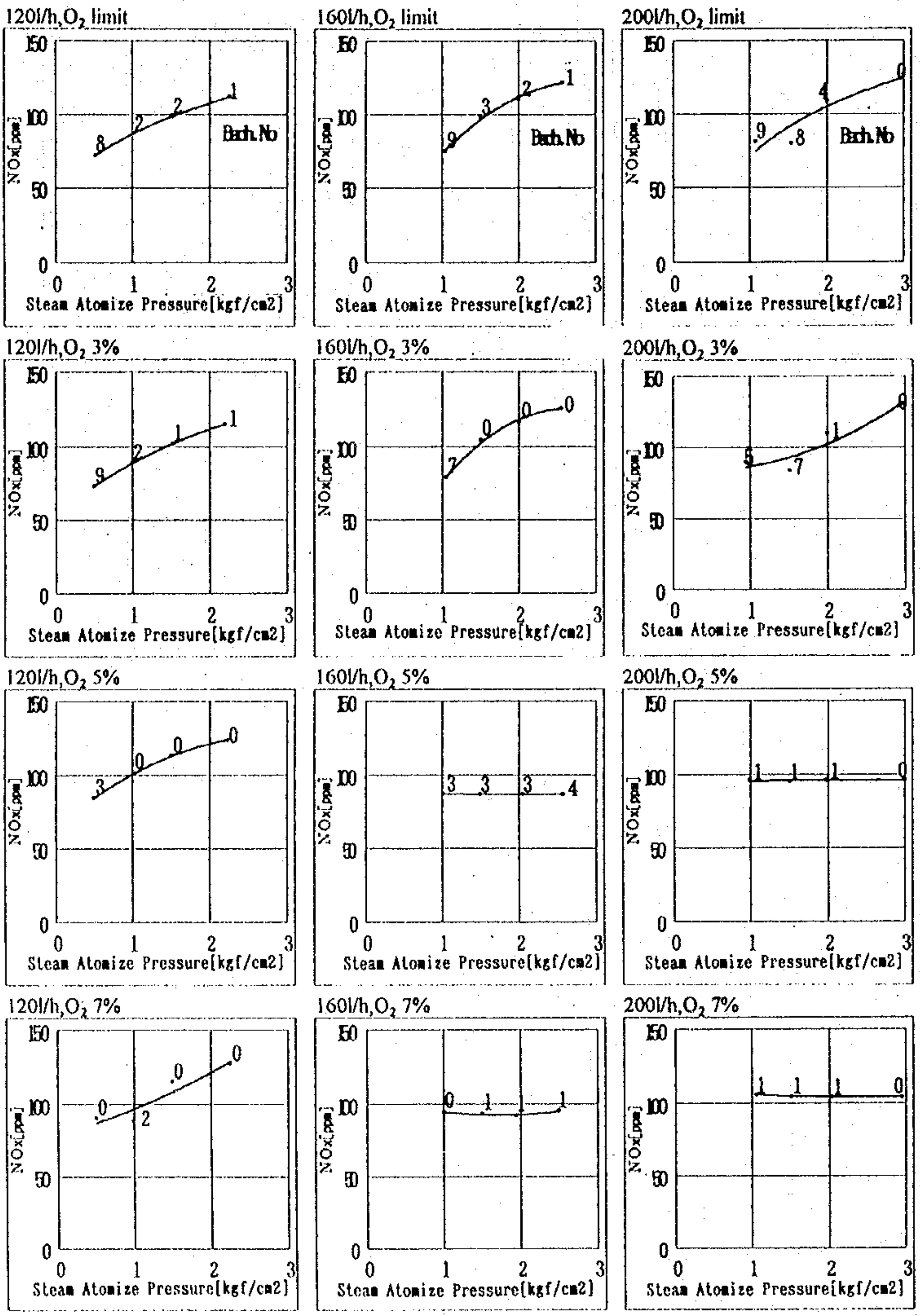


Figure 4.4.13 Atomizing Steam Pressure vs. NOx Concentration
(Combustion of Gas Oil with Outer Mixing Atomizer)

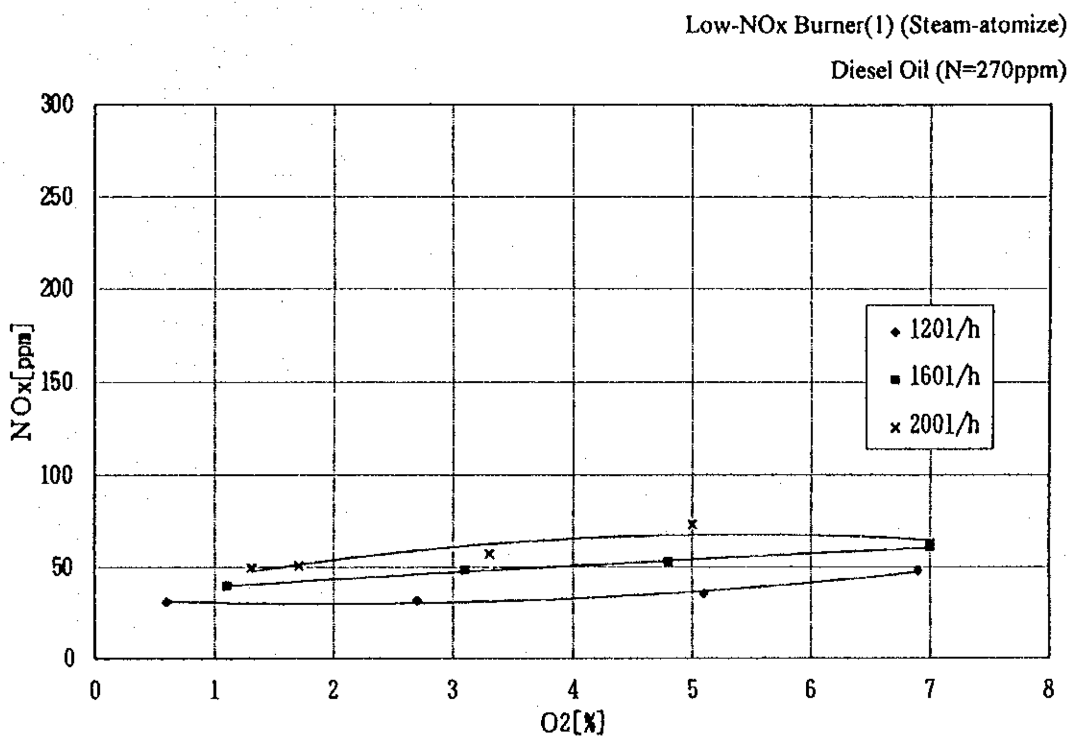


Figure 4.4.14 O_2 Concentration vs. NOx Concentration in Combustion of Diesel Oil by Steam-atomized Low-NOx Burner (1)

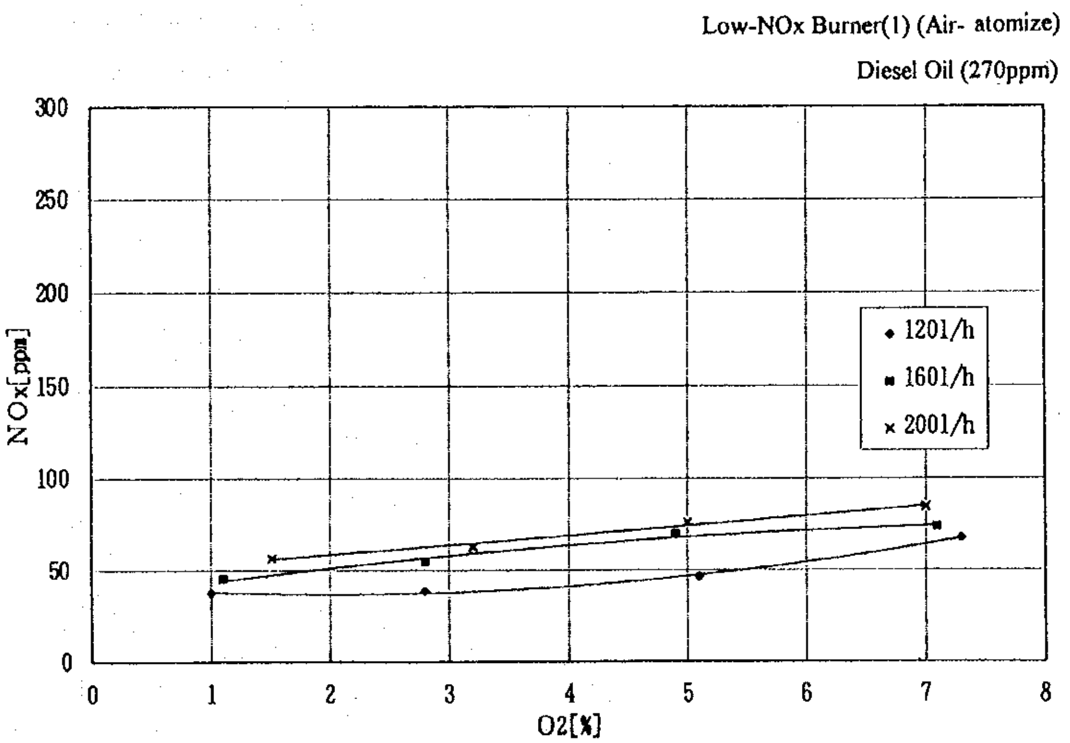


Figure 4.4.15 O_2 Concentration vs. NOx Concentration in Combustion of Diesel Oil by Air-atomized Low-NOx Burner (1)

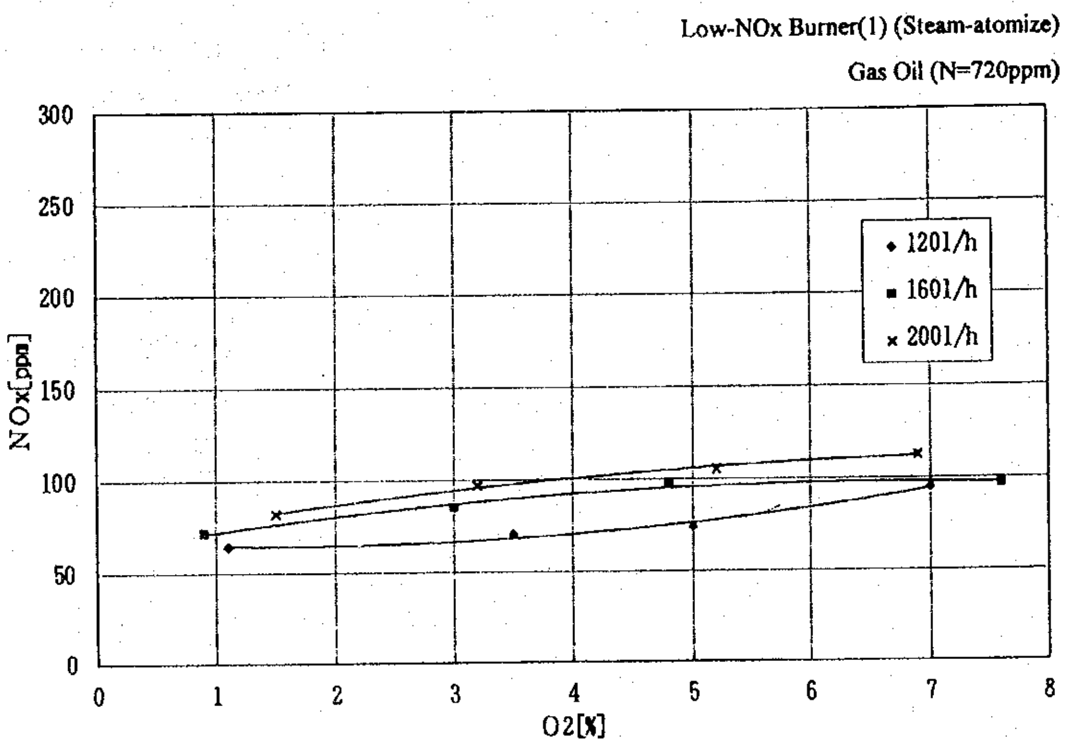


Figure 4.4.16 O_2 Concentration vs. NOx Concentration in Combustion of Gasoil by Steam-atomized Low-NOx Burner (1)

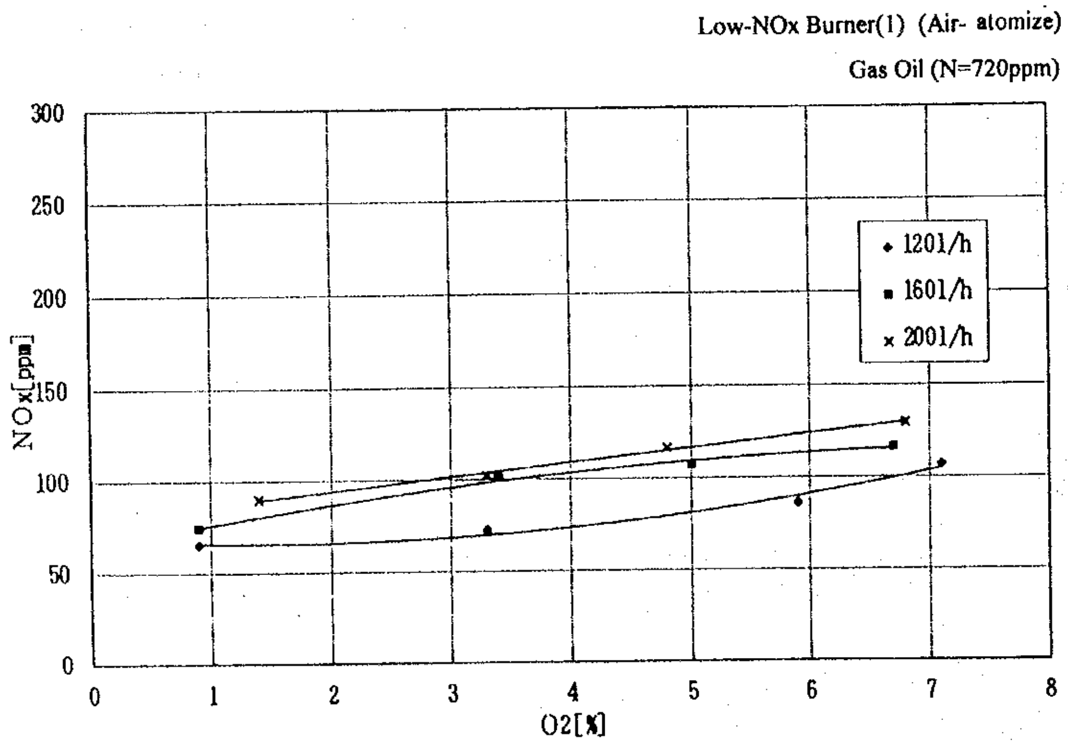


Figure 4.4.17 O_2 Concentration vs. NOx Concentration in Combustion of Gas Oil by Air-atomized Low-NOx Burner (1)

(2) Effects of Oxygen Concentration on NOx Concentration

The NOx concentration decreased almost linearly at the fuel loads of 200 and 160 ℓ/h as the oxygen concentration decreased. At a fuel load of 120 ℓ/h, the NOx concentration with the oxygen concentration range below 5% decreased only slightly with the decrease of the oxygen concentration.

In the combustion of diesel oil at 160 ℓ/h, the NOx concentration at limit oxygen concentration was 39ppm with steam atomization, and 45ppm with air atomization. Similarly, in the case of gas oil, the concentrations were 72 and 74ppm, respectively.

(3) Effects of Fuel Load on NOx Concentration

The NOx concentration decreased as the fuel load decreased in all cases. The reductions were relatively large in the range of the oxygen concentration at 3 to 5% under the fuel load of 120 ℓ/h and 200 ℓ/h.

4.4.3 Results of the Tests Using Low-NOx Oil Burner (2)

This burner combines self recirculation and two-stage combustion, and the NOx concentration changes in accordance with the ratio of the primary air in the combustion air.

(1) Relationship Between Primary Air and NOx Concentration

Figure 4.4.18 shows the relationship between the ratio of primary air and the NOx concentration in the combustion of gas oil at 160 ℓ/h.

The NOx concentration is shown to become lowest when the primary air ratio is in the range of 0.5 and 0.6 at each oxygen concentration. The lowest NOx concentration was 76ppm when the primary air ratio was 0.52 and the oxygen concentration was 3%.

(2) Relationship Between Oxygen Concentration and NOx Concentration

Figure 4.4.19 shows the relationship between the oxygen concentration and the NOx concentration by fuel load when gas oil was used.

The minimum NOx concentration for each oxygen concentration is plotted in the figure based on the relationship between the primary air ratio and the NOx concentration. The NOx concentrations at the oxygen concentrations of 3% and 7% were 76 ppm and 87 ppm, respectively, and there were no differences by fuel load.

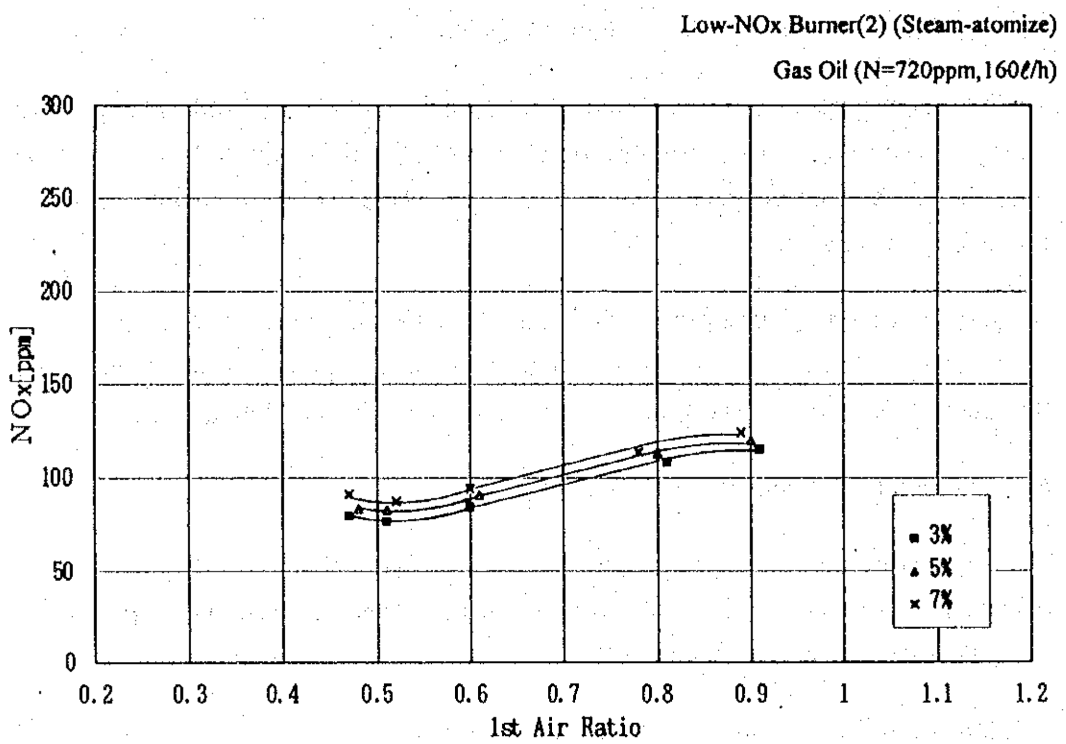


Figure 4.4.18 **Primary Air Ratio vs. NOx Concentration in Combustion of Gas Oil by Steam-atomized Low-NOx Burner (2)**

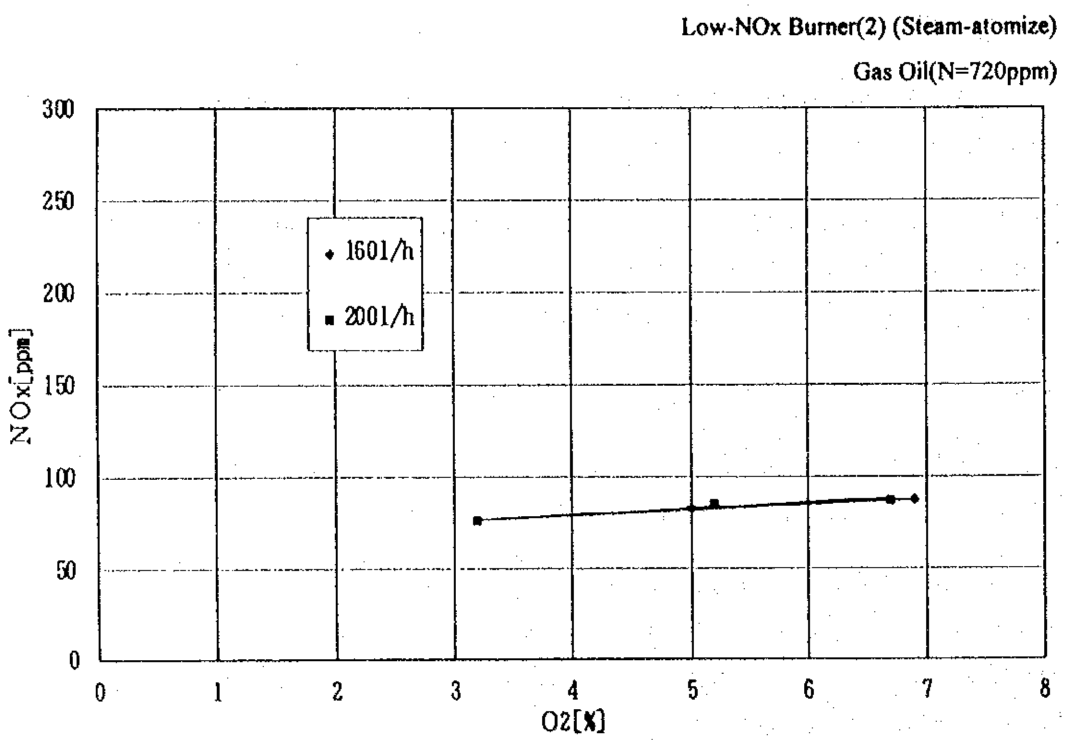


Figure 4.4.19 **O_2 Concentration vs. NOx Concentration at Optimum Primary Air Ratio in Combustion of Gas Oil by Steam-atomized Low-NOx Burner (2)**

(3) Effect of Steam Injection on NOx Concentration

Steam injection is used mainly in gas combustion facilities for lowering generation of thermal NOx. A test with natural gas was not possible, and therefore the effect of steam injection was examined using gas oil added with a nitrogen source.

Table 4.4.1 presents the result at a fuel load of 160 ℓ/h using the low-NOx oil burner (2).

Table 4.4.1 Steam Injection and NOx Concentration

	NOx Concentration (ppm)		
	Case 1	Case 2	Case 3
Stem Injection OFF	139	137	118
Stem Injection ON	138	135	117

The result shows that the effect of steam injection is not clear and it is not effective as a low NOx technique in oil combustion.

In actual examples in Japan for natural gas combustion in boilers, reductions of NOx by 20 to 30% have been reported. It appears that the low-NOx technique of steam injection is effective for some fuels. However, care should be taken because there is a tendency to produce CO in the low range of the excess air ratio.

4.4.4 Results of the Tests Using Low-NOx Oil Burner (3)

This burner uses two-stage combustion as the principle for reducing NOx generation. Similar to the low-NOx oil burner (2), the NOx concentration varied with the ratio of the primary air in the combustion air.

(1) Relationship Between Primary Air and NOx Concentration

The relationships between the primary air ratio and the NOx concentration in the combustion of diesel and gas oil are shown in Figures 4.4.20 and 4.4.21, respectively. The NOx concentrations are shown to be minimal when the primary air ratio was around 0.6.

(2) Relationship Between Oxygen Concentration and NOx Concentration

Figures 4.4.22 and 4.4.23 show the relationship between the oxygen concentration and the NOx concentration according to fuel load in the combustion of diesel and gas oil, respectively.

The minimum NOx concentration for each oxygen concentration was plotted based on the relationship between the primary air ratio and the NOx concentration.

Differences according to fuel load were small. The NOx concentration at an oxygen concentration of 3% was 45ppm with diesel oil, and 71ppm with gas oil.

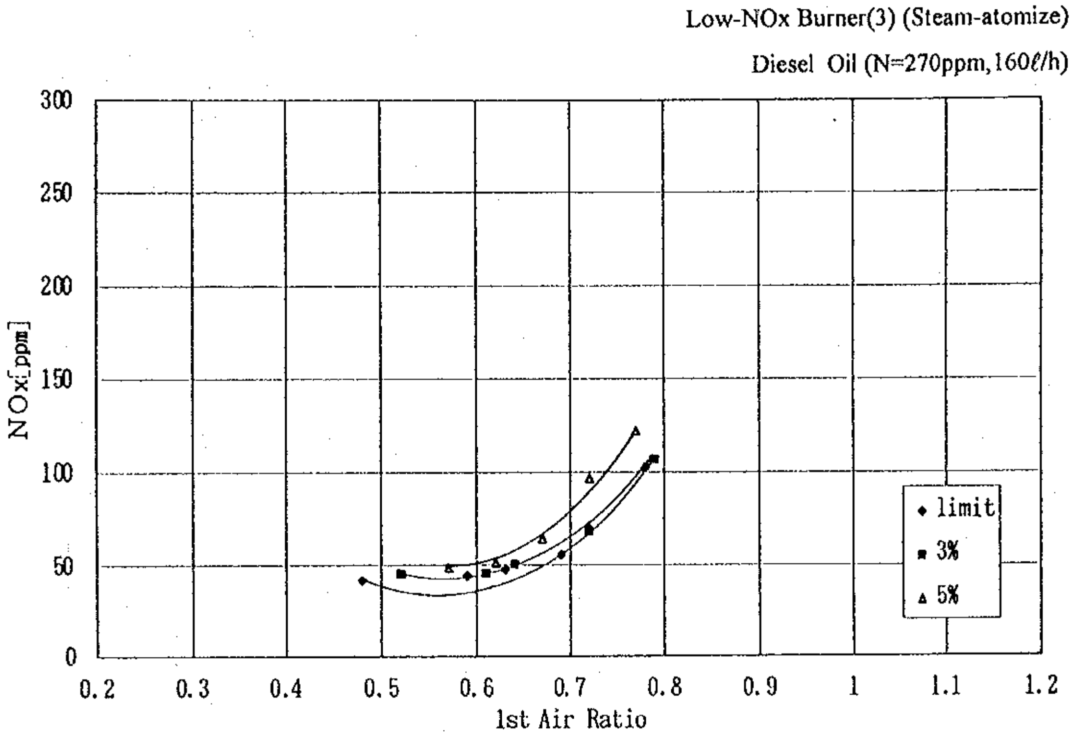


Figure 4.4.20 Primary Air Ratio vs. NOx Concentration in Combustion of Diesel Oil by Steam-atomized Low-NOx Burner (3)

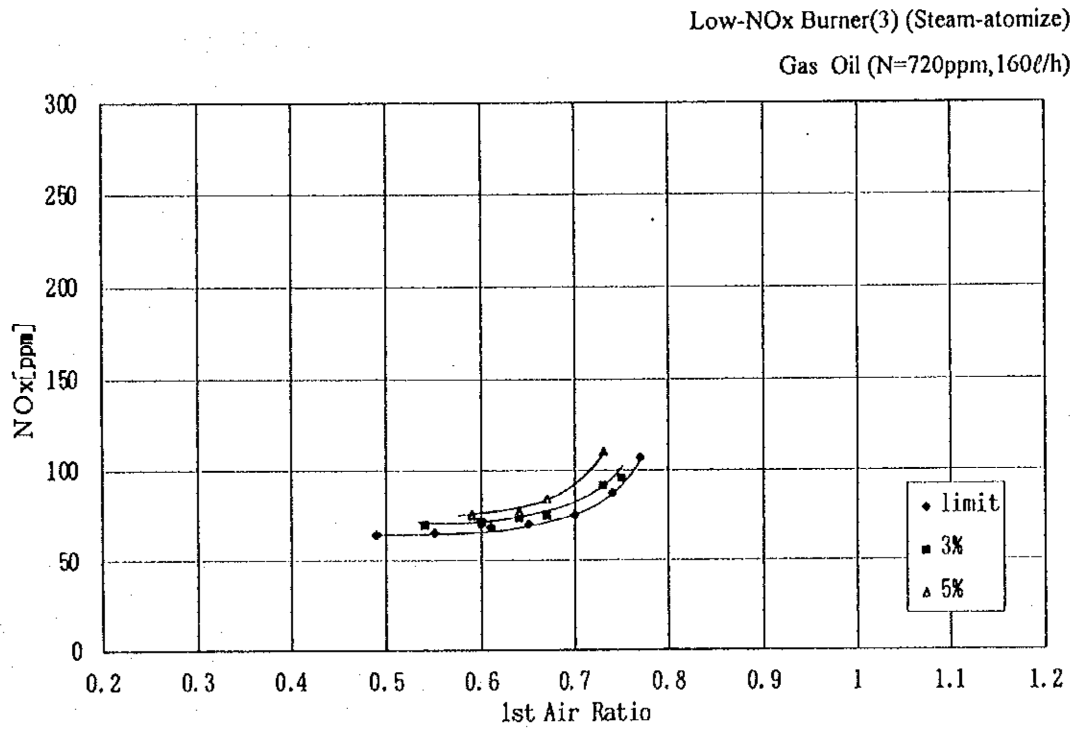


Figure 4.4.21 Primary Air Ratio vs. NOx Concentration in Combustion of Gas Oil by Steam-atomized Low-NOx Burner (3)

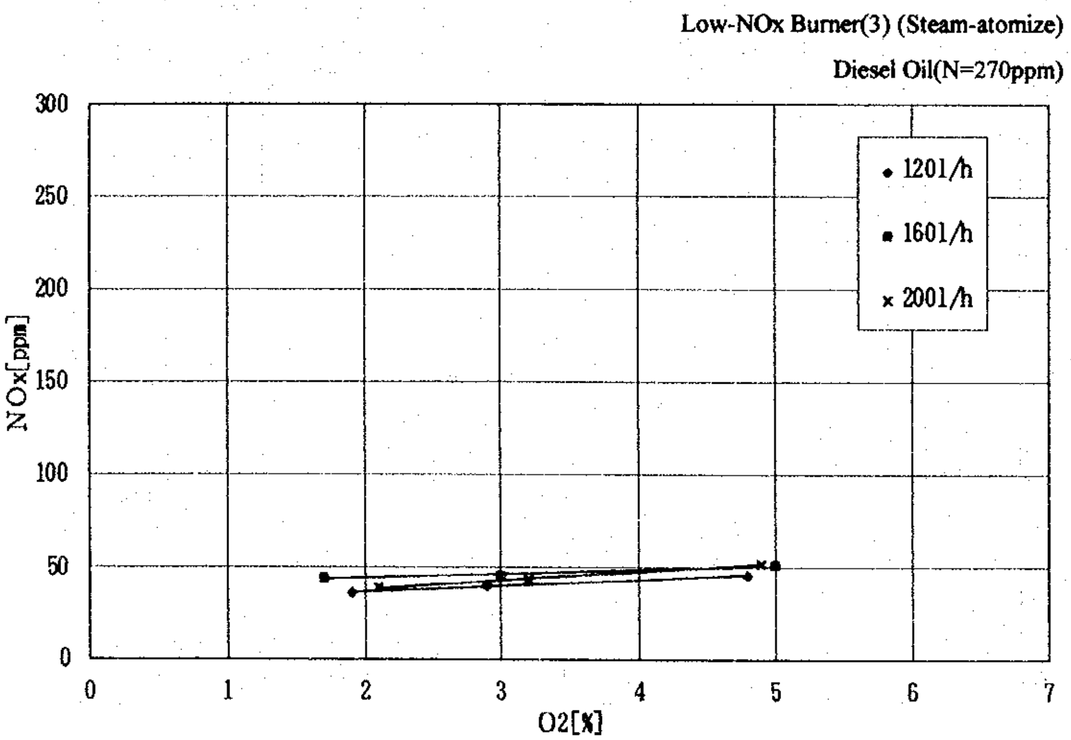


Figure 4.4.22 O_2 Concentration vs. NOx Concentration at Optimum Primary Air Ratio in Combustion of Diesel Oil by Steam-atomized Low-NOx Burner (3)

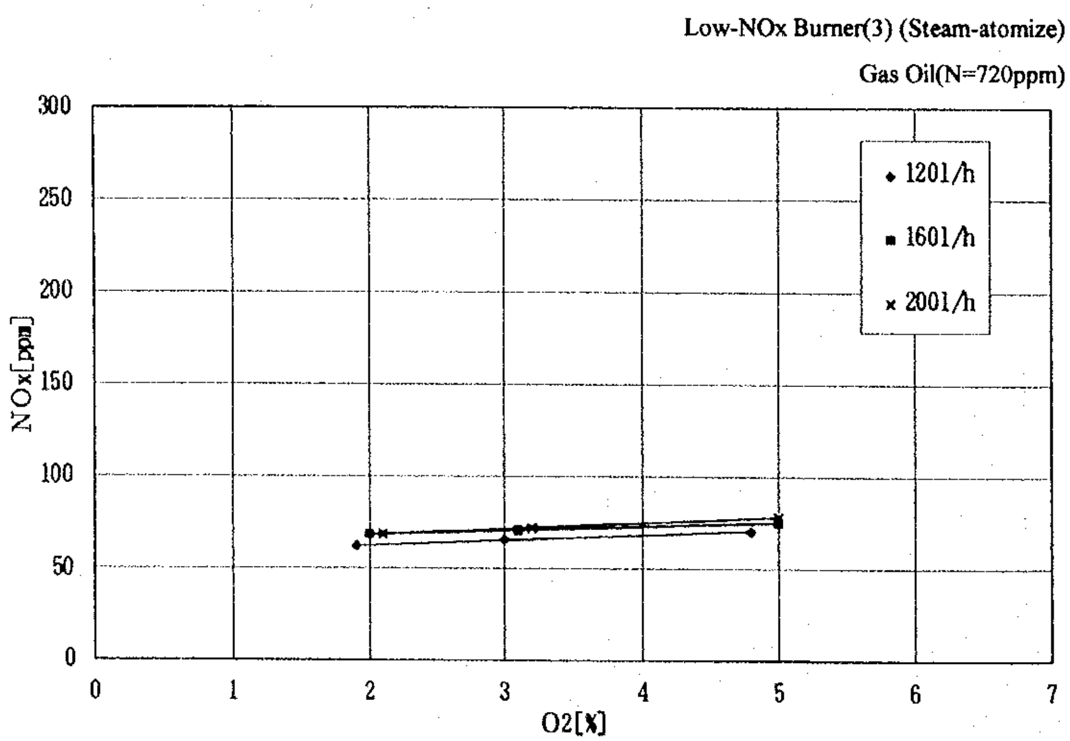


Figure 4.4.23 O_2 Concentration vs. NOx Concentration at Optimum Primary Air Ratio in Combustion of Gas Oil by Steam-atomized Low-NOx Burner (3)

4.4.5 Results of Fuel Analysis

The diesel and gas oil used in the combustion test were transported from Tula Refinery of PEMEX in a tank lorry. The specific gravity, kinematic viscosity, residual carbon, and total nitrogen were analyzed for each lot by the Study Team.

(1) Method of Analysis

• Specific gravity	JIS K 2249	Testing methods for density of crude oil and petroleum products, and petroleum measurement tables based on a reference temperature of 15 °C. (I type floating balance method)
• Kinematic viscosity	Type B viscometer method	
• Residual carbon	JIS K 2270	Crude petroleum and petroleum products - determination of carbon residue (Conradson's carbon test)
• Total nitrogen	JIS K 2609	Crude petroleum and petroleum products - determination of nitrogen content (Semi-micro Kjeldahl method)

(2) Results of Analysis

Tables 4.4.2 and 4.4.3 present the results of analyses of diesel and gas oil, respectively.

Differences in analytical values between the lots are small, and the fuel quality is considered to be uniform over the lots.

Table 4.4.4 presents the results of analysis of the nitrogen content in gas oil samples with an added nitrogen source.

(3) Comparison of Results of Nitrogen Analyses by IMP and the Study Team and Problems in Analytical Method

Table 4.4.5 compares analytical results of nitrogen in a standard fuel sample obtained by IMP and the Study Team through their respective methods of analysis. The values obtained by the two methods greatly differ.

Table 4.4.6 shows the reproducibility of the analysis of nitrogen by IMP, and Table 4.4.7 shows a comparison of the analytical values of IMP and the Study Team in the analysis of nitrogen in gas oil samples in which various amounts of a nitrogen source (triethylene tetramine : TETA) are added.

Table 4.4.2 Result of Analysis of Diesel Oil

Item	Unit	Analysis Data		
		Lot.1	Lot.2	Lot.3
Specific Gravity 15°C/4°C	-	0.8394	0.8494	0.8413
Viscosity 40°C	cSt	3.99	4.28	4.09
Conradson Carbon	%wt	0.04	0.02	0.03
Total Nitrogen	ppm	267	267	290
Total Sulfur	%wt	0.58	0.60	0.56

Table 4.4.3 Result of Analysis of Gas Oil

Item	Unit	Analysis Data		
		Lot.1	Lot.2	Lot.3
Specific Gravity 15°C/4°C	-	0.8858	0.8740	0.8775
Viscosity 40°C	cSt	9.87	8.57	9.56
Conradson Carbon	%wt	0.25	0.19	0.22
Total Nitrogen	ppm	715	724	732
Total Sulfur	%wt	1.81	1.65	1.76

Table 4.4.4 Result of Analysis of N Content in Gas Oil Added with Nitrogen

Test Date	Analysis Data (ppm)	Test Date	Analysis Data (ppm)
Aug.31	1,501	Oct.10	2,123
Sept.1	2,388	Oct.11	2,608
Sept.5	1,084	Oct.13	3,768
Sept.6	1,697	Oct.21	1,786
Sept.21	1,858	Oct.21	2,193
Sept.23	1,495	Oct.24	1,874
Sept.23	1,756	Dec.1	3,240
Sept.26	1,840	Dec.1	3,270
Sept.26	2,071	Dec.2	2,412
Oct.4	1,270	Dec.2	2,481
Oct.5	1,625	Dec.3	1,485
Oct.7	2,243	-	-

Table 4.4.5 Result of Nitrogen Analysis of Standard Fuel Sample

Standard Value (ppm)	IMP Analysis (ppm)	JICA Analysis (ppm)
5,890	2,998	5,940

Note : The standard sample used in the analysis is the one which has been certified by the Japan Petroleum Institute as a standard for analysis of nitrogen in heavy oil, and has been widely used among petroleum related companies and organizations as a most reliable sample. The certificate of this sample by the Japan Petroleum Institute is included in Data Book.

Table 4.4.6 Repeated Analysis of Nitrogen in Fuel by IMP

Calculation Data (ppm)	1st Analysis (ppm)	2nd Analysis (ppm)
4,000	2,036	3,127

Table 4.4.7 Comparison of Nitrogen Analysis in Fuels by IMP and Study Team

Calculated Data (ppm)	IMP Analysis by Chemiluminescence (ppm)	JICA Analysis by Kjeltec Method (ppm)
2,500	1,507	2,243
3,000	1,580	2,608
2,000	1,126	1,501
3,000	1,877	2,388
1,500	957	1,084
2,500	1,242	1,697
2,000	1,081	1,495
Diesel-Oil	270	267
Gas-Oil	622	724

Note : The "calculated data" in the table were calculated based on the supplier's reported values of the nitrogen content in TETA which was added to gas oil as a nitrogen source. The nitrogen content of TETA was first reported as 38.3%, and then reported as 36.3% on October 6, 1994. The uppermost 2 values in the table were calculated assuming the percentage being 36.3%, and the rest assuming the percentage being 38.3%. As a result of cross-check by IMP by mechanical analysis of the Kjeltec method in November 7, 1994, the nitrogen content of TETA was evaluated to be 31.25546%. This suggests that the quality of reagents reported by suppliers should be cross-checked every time when they are used.

The Study Team used the Kjeldahl method and IMP used the chemiluminescent method. In the latter method, the values tend to decrease as the concentration of nitrogen in fuel increases.

The chemiluminescent method adopted by IMP is applicable for the determination of the trace total nitrogen naturally found in liquid hydrocarbons with a boiling point in the range from approximately 50°C to 400°C, and uses standard samples as per ASTM Method D4629. Accordingly, this method has limitations in the nitrogen analysis of fuel samples containing high concentration of nitrogen, and its applicability has to be examined carefully in advance.

For improvement of this method by using a single nitrogen compound as a standard substance, a reference method is presented in Data book (Ref. E6).

In addition, an improved method of chemiluminescence for determination of nitrogen in standard samples of heavy oil nitrogen that has been proposed in Japan as a result of recent studies is presented in Data Book (Ref. E7).

4.4.6 Combustion Efficiency

Using a portable combustion efficiency meter, the combustion efficiency was measured in each test. The combustion efficiency can be defined by the following equation and is calculated automatically:

$$\text{Combustion efficiency} = 100 - K3 - K1 \times T/(K2 \times (1 - O_2/21))$$

T : Exhaust gas temperature (°C)
O_2 : Oxygen concentration in exhaust gas (%)

K1 : Coefficient determined by composition of hydrocarbon in fuel
K2 : Maximum theoretical concentration of CO_2 in exhaust gas

K3 : Latent heat by moisture content in exhaust gas

Coefficients K1 to K3 are determined as follows for each fuel.

	K1	K2	K3
Natural gas	0.38	11.8	11.0
No.2 oil (light oil)	0.56	15.6	5.0
No.6 oil (heavy oil)	0.60	15.6	5.0

Table 4.4.8 presents one example of the measurement results for combustion efficiency with gas oil at a fuel load of 160 ℓ/h. The combustion efficiency did not vary with differences in the burner structure.

Table 4.4.8 Combustion Efficiency by Burner Type

Burner	Combustion Efficiency (%)			
	7 % O_2	5 % O_2	3 % O_2	Limit O_2
Normal	83	85	85	86
Low NOx (1)	81	83	84	86
Low NOx (2)	80	83	84	85
Low NOx (3)	-	83	85	85

4.5 Evaluation of the Test Results

4.5.1 Pollutant Reduction Effects of Various Combustion Methods and Techniques

(1) Combustion Methods and Techniques

The methods and techniques for reducing NOx generation used in the tests are summarized below.

a) Low-NOx burners
- Self recirculation
- Two-stage combustion
- Self recirculation + Two-stage combustion

b) Energy saving
- Low-oxygen combustion
- Air preheating
- Heat recovery by economizer

c) Exhaust gas recirculation and steam injection

d) Optimal spraying conditions
- Burner nozzle angle
- Burner position
- Atomizing medium
- Mixing method and atomizing steam pressure

Effects of these combustion methods, technologies and techniques in reducing NOx generation are discussed in the following. The discussions are made mainly on the basis of the fuel load at 160 ℓ/h and the oxygen concentration at 3 to 5%.

(2) Low-NOx Burners

Figures 4.5.1 through 4.5.6 show the relationship between the NOx concentration and the nitrogen content in fuels at oxygen concentrations of 3 and 5% for the standard burner and low-NOx burners (1), (2) and (3). In these figures, the fuel with the nitrogen content of 270 ppm is diesel oil, that of 720 ppm is gas oil, and those with the nitrogen content greater than 720 ppm are gas oil samples prepared by adding a nitrogen source by varying amount.

Table 4.5.1 shows NOx reduction ratios of the tested low-NOx burners in reference to the standard burner at a fuel load of 160 ℓ/h. In each column of the table, the upper figure is the NOx concentration and the lower figure is the NOx reduction ratio.

Table 4.5.1 NOx Reduction Ratios of Various Burners in Reference to Normal Burner

Type of Burner	O_2 Conc. 3 %		O_2 Conc. 5 %	
	Diesel oil	Gas oil	Diesel oil	Gas oil
Normal	60 ppm -	92 ppm -	64 ppm -	103 ppm -
Low NOx (1)	47 ppm 22 %	84 ppm 9 %	55 ppm 14 %	96 ppm 7 %
Low NOx (2)	-	75 ppm 18 %	-	83 ppm 19 %
Low NOx (3)	44 ppm 27 %	68 ppm 26 %	51 ppm 20 %	72 ppm 30 %

Note: Fuel load : 160 ℓ/h
Upper figure : NOx Concentration
Lower figure : NOx reduction ratio in reference to the normal burner

The table shows that the following reductions would be possible:

Low-NOx burner (1) : 14 to 22% with diesel oil, 7 to 9% with gas oil.
Low-NOx burner (2) : 18 to 19% with gas oil.
Low-NOx burner (3) : 20 to 27% with diesel oil, 26 to 30% with gas oil.

The low-NOx burner (3), using the principle of two-stage combustion, showed the highest NOx reduction effect. All the burners including the standard burner are possible to satisfy the new NOx emission standard of 110ppm. As shown in Figure 4.5.6, for the normal burner at a combustion load of 200 ℓ/h, cares should be taken by lowering the oxygen concentration not to exceed the NOx emission standard.

(Steam-atomize)
(120ℓ/h)
(O2 Conc. in Exhaust Gas : 3%)

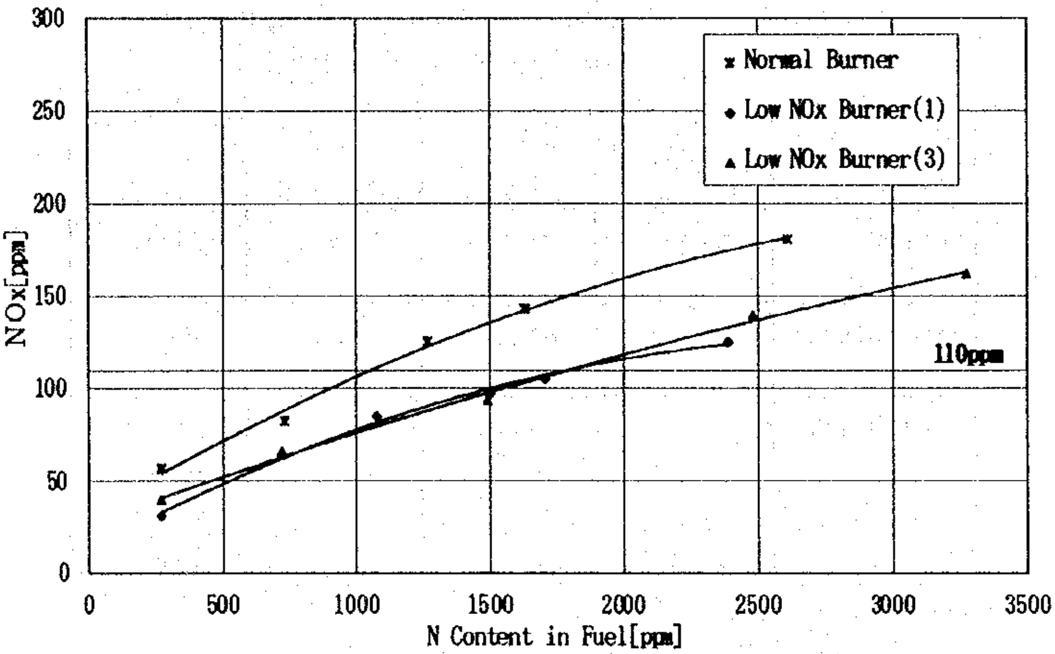


Figure 4.5.1 N Content in Fuel and NOx Concentration (at 3% O_2, fuel load 120 ℓ/h)

(Steam-atomize)
(120ℓ/h)
(O2 Conc. in Exhaust Gas : 5%)

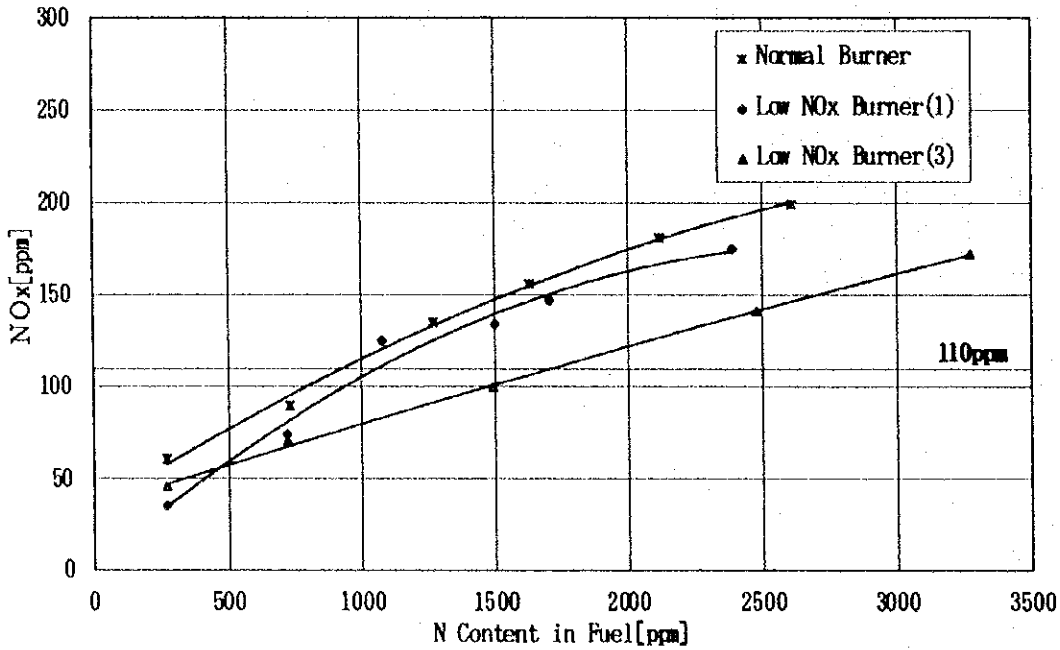


Figure 4.5.2 N Content in Fuel and NOx Concentration (at 5% O_2, fuel load 120 ℓ/h)

(Steam-atomize)

(160ℓ/h)

(O2 Conc. in Exhaust Gas : 3%)

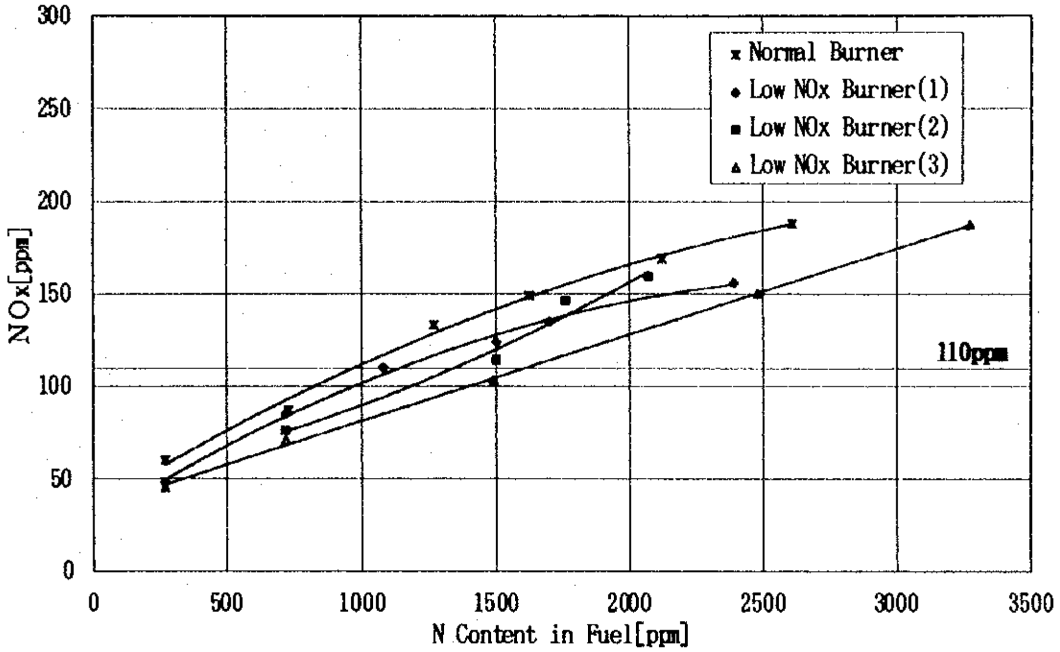


Figure 4.5.3 N Content in Fuel and NOx Concentration (at 3% O_2, fuel load 160 ℓ/h)

(Steam-atomize)

(160ℓ/h)

(O2 Conc. in Exhaust Gas : 5%)

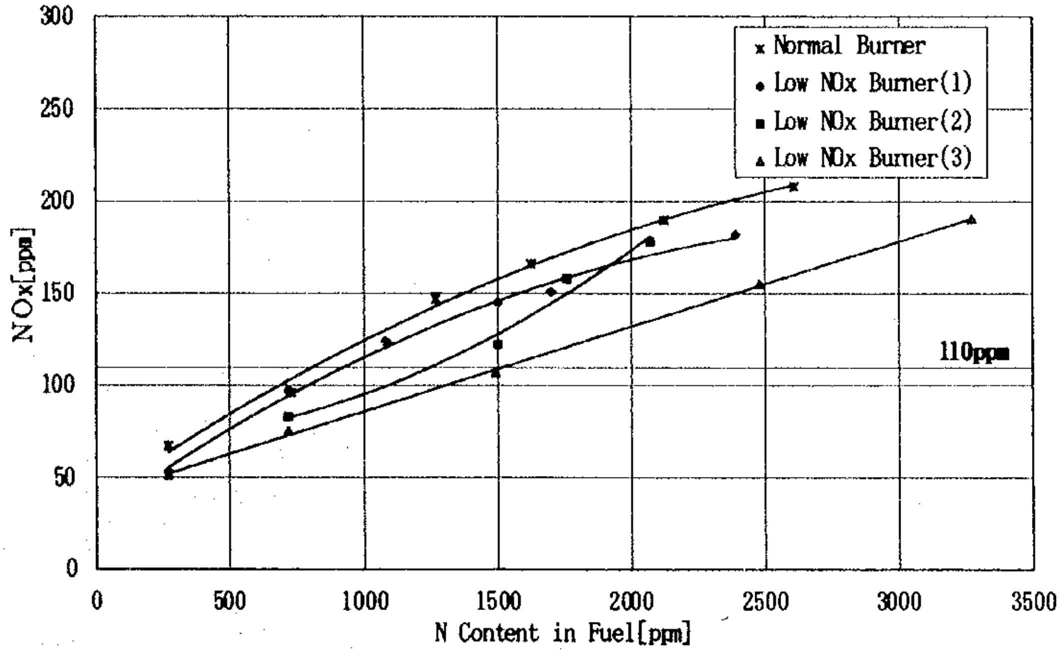


Figure 4.5.4 N Content in Fuel and NOx Concentration (at 5% O_2, fuel load 160 ℓ/h)

(Steam-atomize)

(200ℓ/h)

(O2 Conc. in Exhaust Gas : 3%)

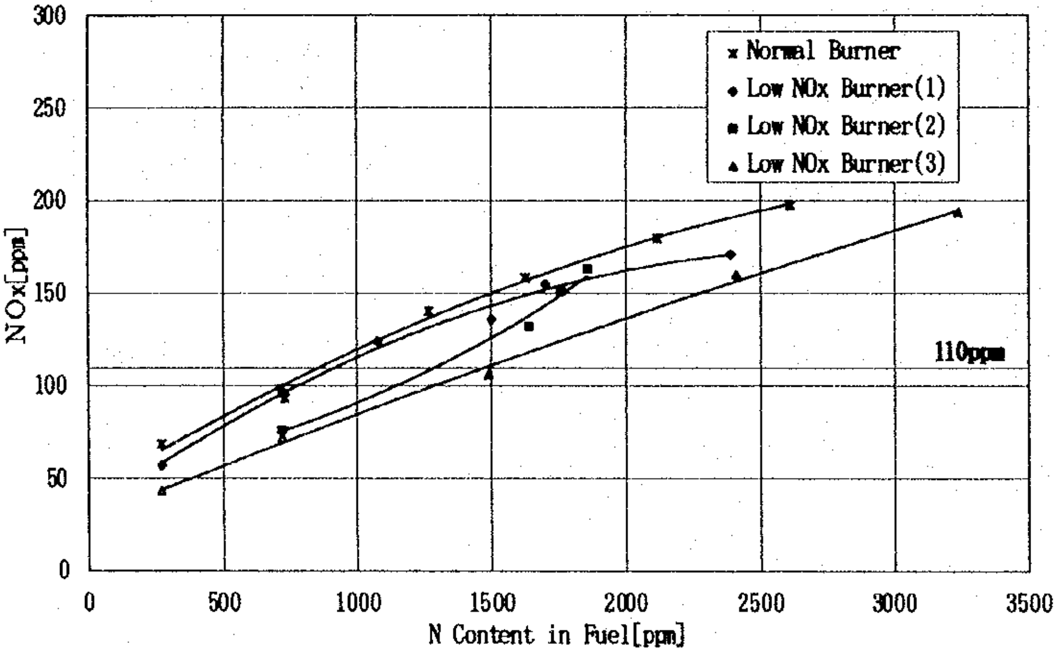


Figure 4.5.5 N Content in Fuel and NOx Concentration (at 3% O_2, fuel load 200 ℓ/h)

(Steam-atomize)

(200ℓ/h)

(O2 Conc. in Exhaust Gas : 5%)

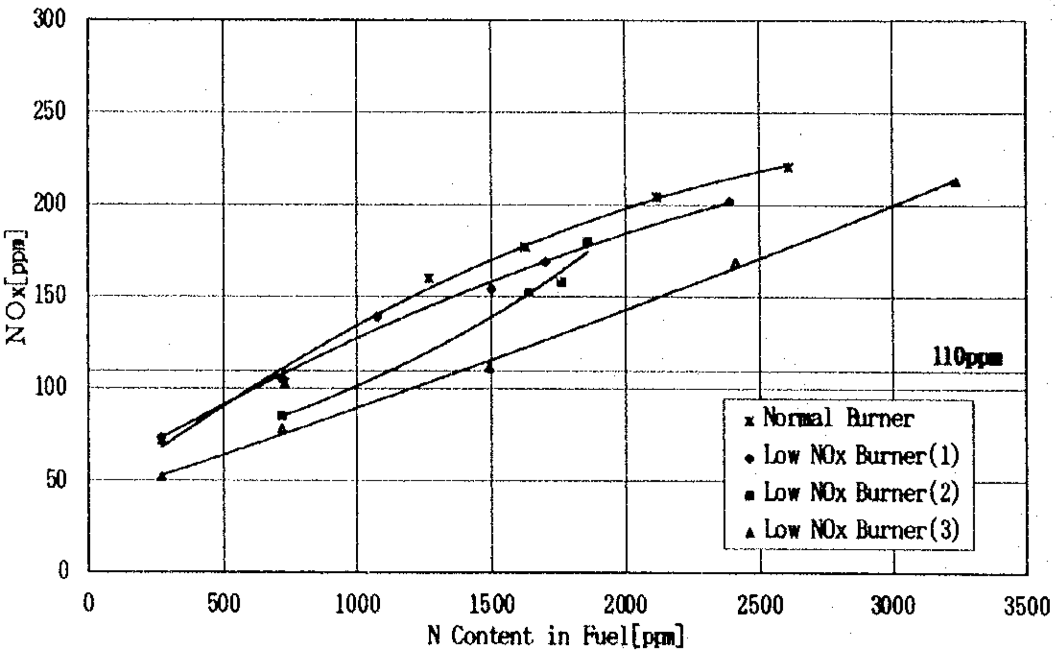


Figure 4.5.6 N Content in Fuel and NOx Concentration (at 5% O_2, fuel load 200 ℓ/h)

(3) Effects of Oxygen Concentration in Exhaust Gas

Figures 4.5.7 through 4.5.12 show the relationship between the NOx concentration and the oxygen concentration for each burner in the combustion of diesel and gas oil at fuel loads of 120 ℓ/h, 160 ℓ/h, and 200 ℓ/h.

Table 4.5.2 shows the ratio of NOx reduction when the oxygen concentration is reduced from the reference concentration of 5% at a combustion load of 160 ℓ/h.

Table 4.5.2 Ratio of NOx Reduction by Lowering Oxygen Concentration (In Reference to the NOx Concentration at 5% O_2)

unit:%

Burner	Diesel Oil		Gas Oil	
	3% O_2	Limit O_2	3% O_2	Limit O_2
Normal	14	20	11	22
Low NOx (1)	13	28	10	26
Low NOx (2)	-	-	10	-
Low NOx (3)	10	16	5	9

Fuel load : 160 ℓ/h

The NOx concentration could be reduced as follows by reducing the oxygen concentration from 5% to 3%:

Standard burner : 14% with diesel oil, 11% with gas oil.
Low-NOx burner (1) : 13% with diesel oil, 10% with gas oil.
Low-NOx burner (2) : 10% with gas oil.
Low-NOx burner (3) : 10% with diesel oil, 5% with gas oil.

In reference to the NOx concentration with the normal burner at the oxygen concentration of 5%, the NOx reductions achieved by the use of low-NOx burners with the reduce oxygen concentration of 3% are as follows:

Low-NOx burner (1) : 38% with diesel oil, 12% with gas oil.
Low-NOx burner (2) : 21% with gas oil.
Low-NOx burner (3) : 39% with diesel oil, 27% with gas oil.

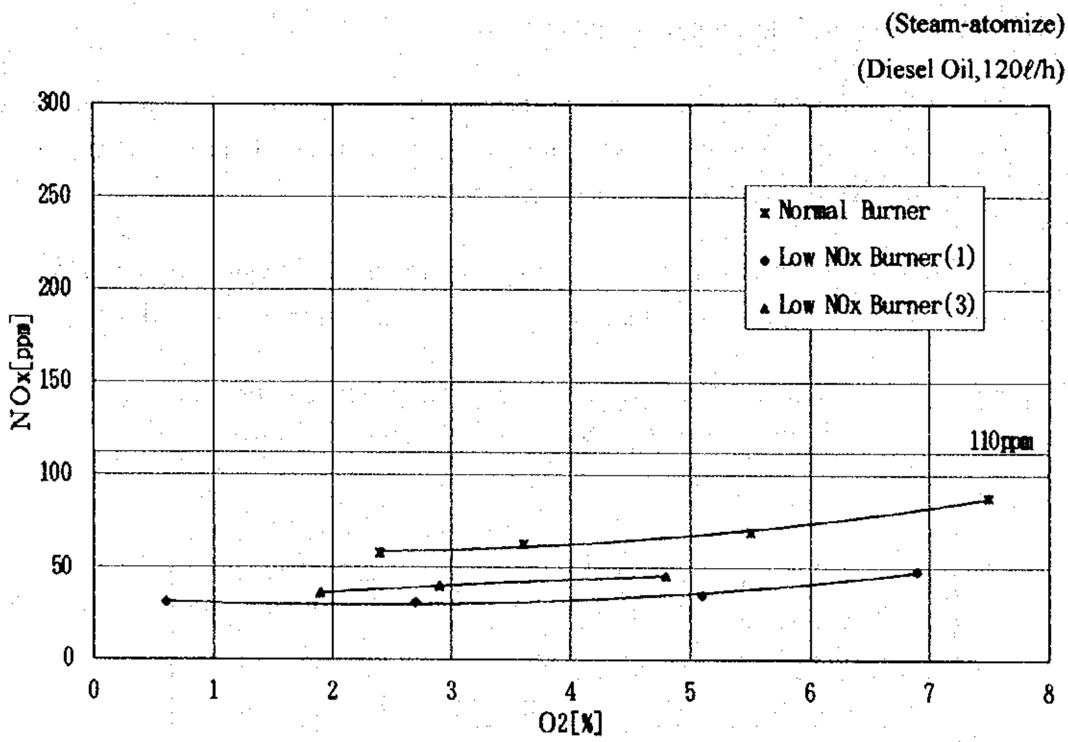


Figure 4.5.7 O_2 Concentration vs. NOx Concentration in Diesel Oil Combustion (Fuel load : 120 ℓ/h)

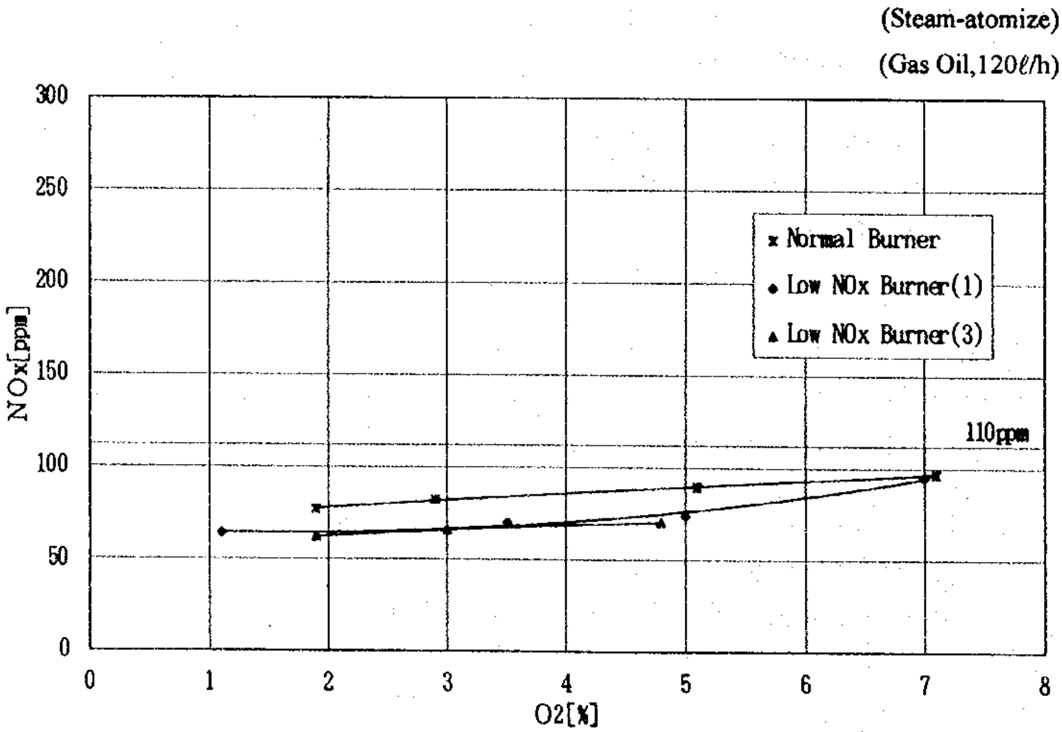


Figure 4.5.8 O_2 Concentration vs. NOx Concentration in Gas Oil Combustion (Fuel load : 120 ℓ/h)

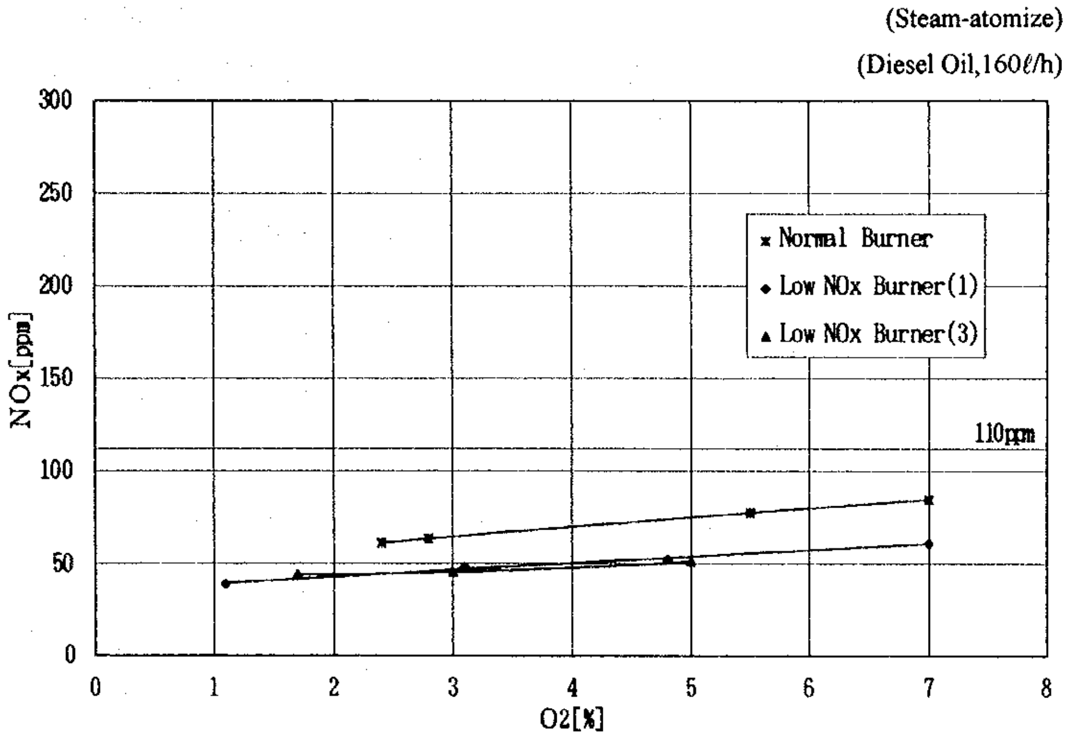


Figure 4.5.9 O_2 Concentration vs. NOx Concentration in Diesel Oil Combustion (Fuel load : 160 ℓ/h)

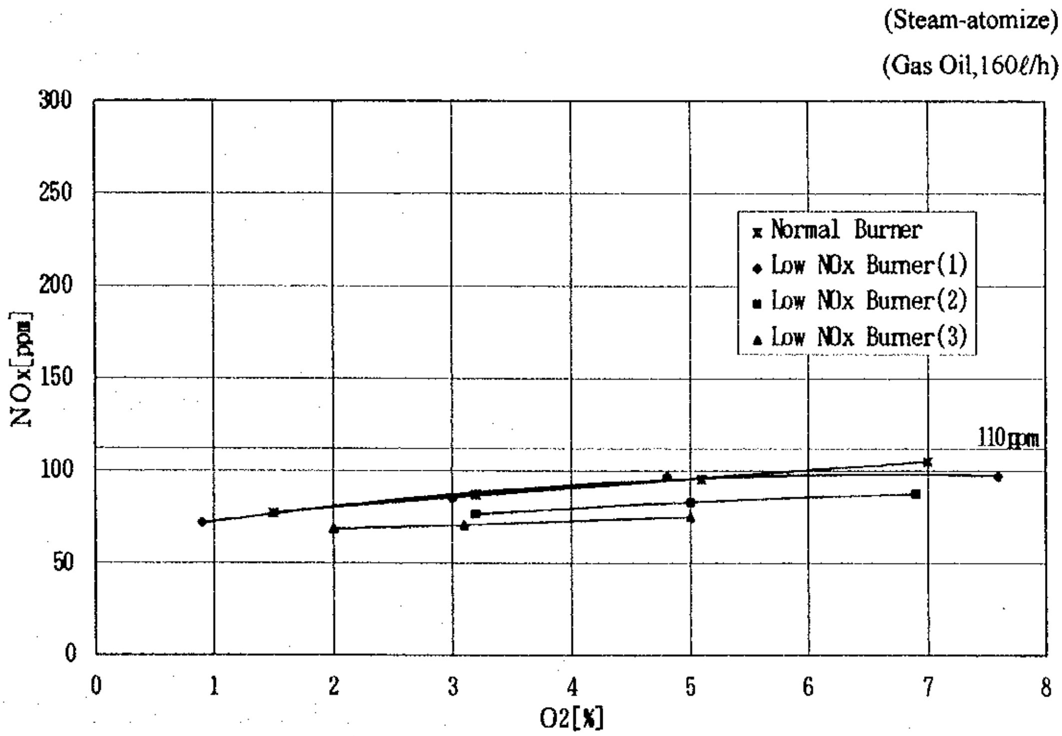


Figure 4.5.10 O_2 Concentration vs. NOx Concentration in Gas Oil Combustion (Fuel load : 160 ℓ/h)

(Steam-atomize)
(Diesel Oil,200ℓ/h)

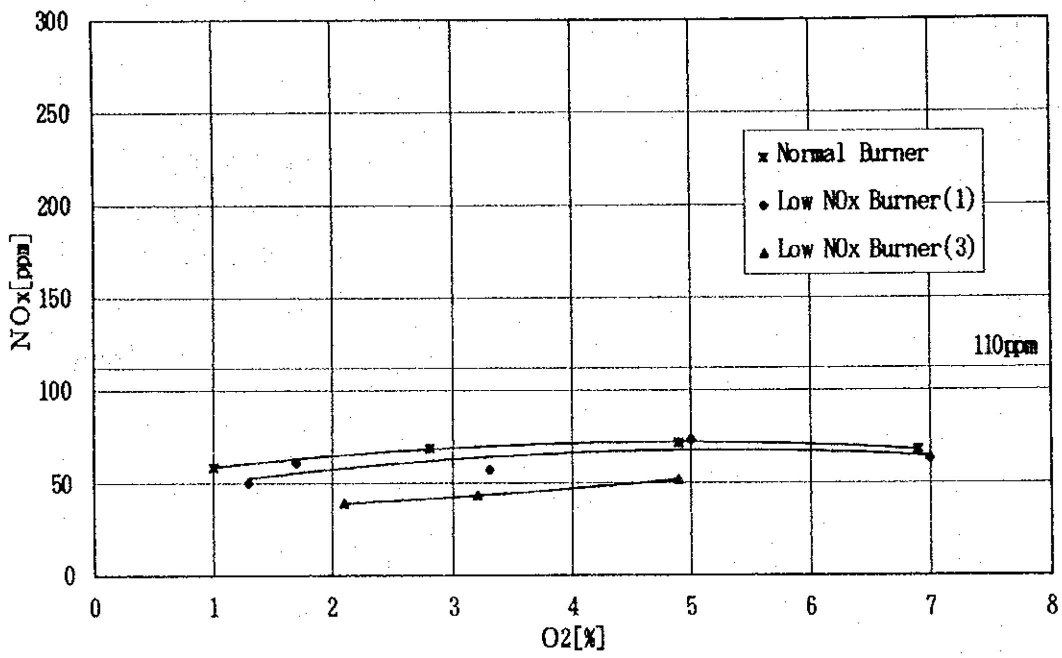


Figure 4.5.11 O_2 Concentration vs. NOx Concentration in Diesel Oil Combustion (Fuel load : 200 ℓ/h)

(Steam-atomize)
(Gas Oil,200ℓ/h)

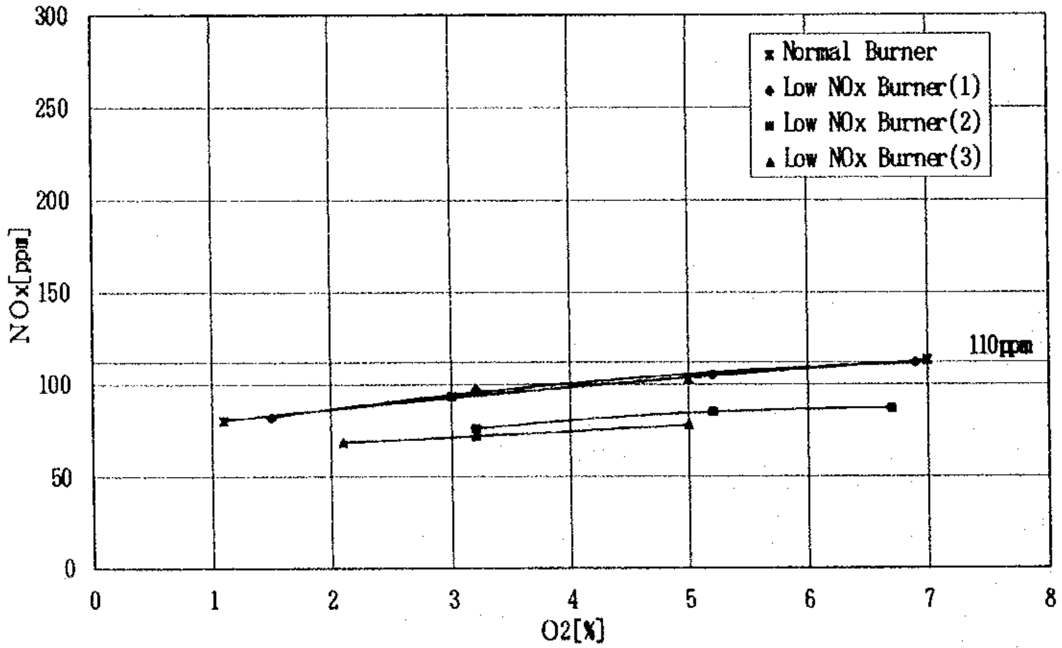


Figure 4.5.12 O_2 Concentration vs. NOx Concentration in Gas Oil Combustion (Fuel load : 200 ℓ/h)

(4) Effect of Exhaust Gas Recirculation

Figures 4.5.13 and 4.5.14 show the relationship between the ratio of exhaust gas recirculation and the ratio of NOx reduction. Table 4.5.3 shows the same at a combustion load of 160 ℓ/h.

Table 4.5.3 Relationship Between EGR Ratio and NOx Reduction Ratio

EGR Volume Ratio (%)		15	20	25	28
NOx Reduction Ratio (%)	Diesel oil	24	31	38	42
	Gas oil	12	16	20	22

Normal Burner, 160ℓ/h

A NOx reduction ratio of 42% was achieved with diesel oil at a EGR ratio of 28%, but it was 22% with gas oil. It has been shown that the effect of EGR is low for fuel NOx originating from nitrogen in fuel.

(5) Effect of Steam Injection Method

In the combustion tests, effects of the steam injection method as a low-NOx technique for liquid fuels have not been confirmed.

(6) Optimal Spraying Conditions

It is important to find optimal fuel spraying conditions for low NOx generation suitable for the volume and the shape of the combustion chamber.

1) Burner nozzle angle

The optimal nozzle angle for the boiler used in the test is 60°. Table 4.5.4 shows the variation of the NOx concentration when the angle was increased or reduced by 10° from the reference angle of 60°.

Table 4.5.4 Increase of NOx Emission by Burner Nozzle Angle

unit : %

Nozzle angle	3 % O_2	5 % O_2
50°	27	12
70°	20	23

Note: 1) Gas oil combustion at 160 ℓ/h
2) Increase of NOx emission in reference to the nozzle angle of 60°

Normal Burner (Steam-atomize)

(120ℓ/h)

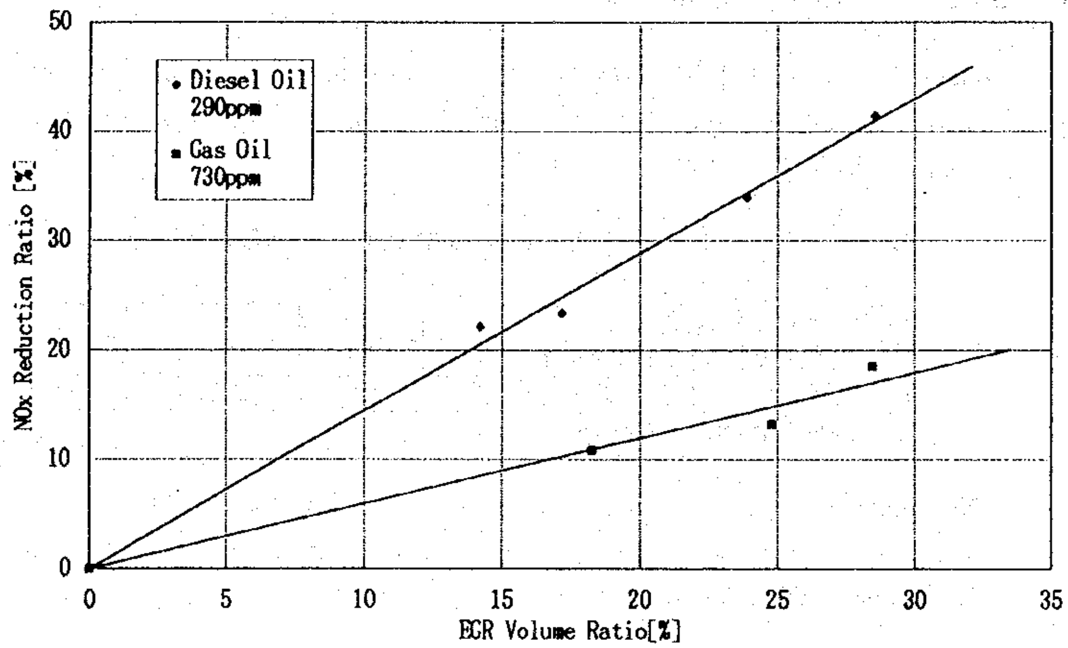


Figure 4.5.13 Effect of EGR on NOx Reduction by N Content of Fuel (Fuel load : 120 ℓ/h)

Normal Burner (Steam-atomize)

(160ℓ/h)

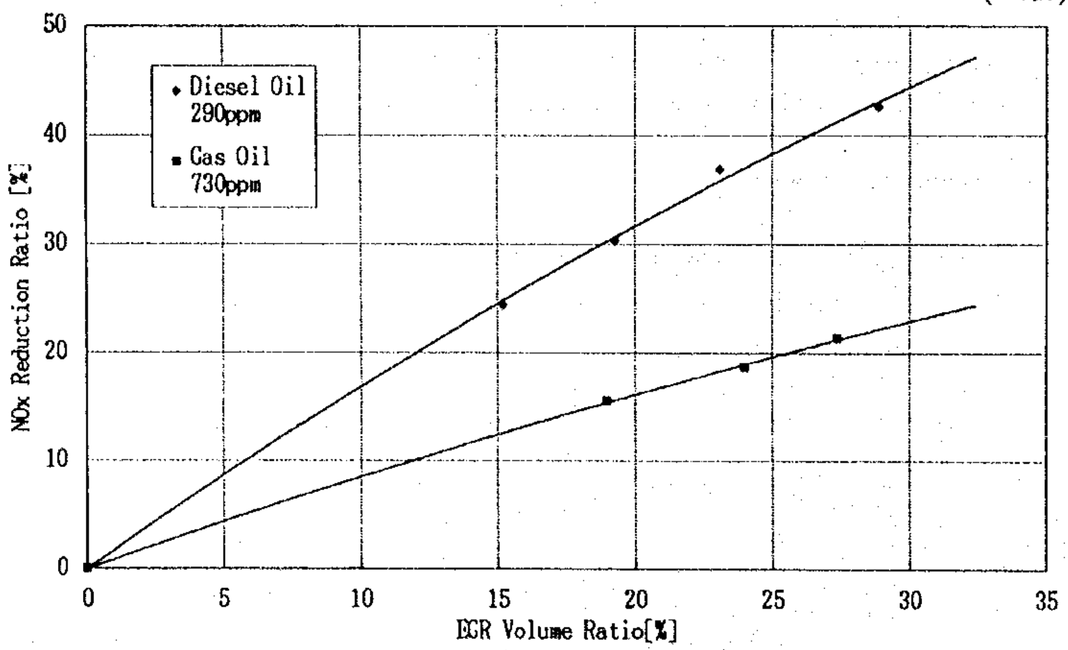


Figure 4.5.14 Effect of EGR on NOx Reduction by N Content of Fuel (Fuel load : 160 ℓ/h)

At the nozzle angle of 50° with the oxygen concentration of 3% and 5%, the NOx concentration increased by 27% and 12%, respectively. Similarly, at the nozzle angle of 70°, the NOx concentration increased by 20% and 23% when the oxygen concentration was 3% and 5%, respectively.

2) Burner position

Variation of the NOx concentration when the burner nozzle was moved backward by 100mm from the optimal nozzle position was tested. The NOx concentration increased 22% with both diesel and gas oil compared with the NOx concentration in the standard position.

3) Atomizing medium

Table 4.5.5 shows the comparison of NOx concentrations in the cases of air atomization and steam atomization.

Table 4.5.5 Comparison of NOx Concentrations by Steam Atomization and Air Atomization

	NOx Concentration by Steam Atomization (ppm)		NOx Concentration by Air Atomization (ppm)		Increase of NOx Conc. by Air Atomization (%)	
	3 % O_2	5 % O_2	3 % O_2	5 % O_2	3 % O_2	5 % O_2
Diesel oil	63	74	95	95	51	28
Gas oil	85	95	120	134	41	41

Note : Normal Burner : 160 ℓ/h load

The NOx concentration increased by 28% - 51% by the air atomization compared with the steam atomization.

4) Mixing method and atomizing steam pressure

Table 4.5.6 shows the comparison of NOx concentrations in the cases of the inner-mixing method and the outer-mixing method with the atomizing steam pressures of 1 kgf/cm^2 and 2 kgf/cm^2.

Table 4.5.6 Comparison of NOx Concentrations by Outer-mixing Method and Inner-mixing Method

		Inner-mixing				Outer-mixing				NOx Increase by Outer-mixing			
		3 % O2		5% O2		3 % O2		5% O2		3 % O2		5% O2	
Atomizing Steam Pressure (kgf/cm2)		1	2	1	2	1	2	1	2	1	2	1	2
NOx Conc. (ppm)	Diesel Oil	55	55	63	61	50	77	55	53	-9%	40%	-13%	-14%
	Gas Oil	81	83	93	93	78	117	88	83	-4%	41%	-5%	-5%

Note : Standard Burner : 160 ℓ/h load

The NOx concentration is generally lower with the outer-mixing method than that with the inner-mixing method. However, depending on the steam pressure, the NOx concentration may drastically increase with the outer-mixing. Atomization at an appropriate steam pressure is particularly important for the outer-mixing method.

4.5.2 Energy Saving Measures and Their Effects

(1) Energy Saving Measures for Boilers

Generally, not all of the heat generated by combustion is utilized, and some portion is released. Minimizing this loss of heat is most desirable. As boilers are made to have a structure for using heat effectively, their thermal efficiency (effective heat/supplied heat) is higher than that of other combustion equipment; the thermal efficiency (boiler efficiency) of flue and smoke tube boilers with the capacity under 5 t/h is 82 - 88%, and that of the boilers with the capacity between 5 t/h and 20 t/h is 87 - 90%. Because of such high thermal efficiency, energy-saving techniques for boilers are limited.

Examples of common measures being employed are as follows:

1) Measures by equipment

a) Recovery of exhaust gas heat
   Economizer
   Air preheater

b) Recovery of heat of blow water
   Heat-recovery type blowing device

2) Measures by combustion technique

a) Complete combustion of fuel

b) Combustion with appropriately low air ratio

c) Combustion with appropriate boiler load

3) Measures by boiler maintenance

a) Removal of scale on the heat transmitting surface of the water side

b) Removal of soot on the heating transmitting surface of the gas side

In the test plant, an economizer, an air preheater, and a heat-recovery type blowing device are installed as energy saving equipment.

(2) Heat Balance

It is necessary to identify the streams of heat accurately, calculate heat input and output, and clarify the effects of energy saving measures. The evaluation of heat input and output is called heat balance calculation or heat budget calculation.

In this Study, the heat balance of the test boiler was evaluated on the following items:

i) Concentration of residual O_2 in exhaust gas

ii) Recovery of exhaust heat by an economizer

iii) Boiler load (fuel consumption)

1) Method of heat balance calculation

The heat balance calculation was carried out under the following conditions according to JIS (B8222).

i) Range of heat balance

The range of heat balance calculation is shown in Figure 4.5.15.
Heat input and heat output and circulating heat are as follows:

a) Heat input

Heat value of fuel
Sensible heat of fuel
Sensible heat of combustion air
Sensible heat of feedwater

b) Heat output

Retaining heat of generated steam
Loss of heat due to exhaust gas
Loss of heat due to incomplete combustion
Loss of heat due to radiation, etc.

c) Circulating heat

Retaining heat of atomizing steam
Recovery of heat by economizer

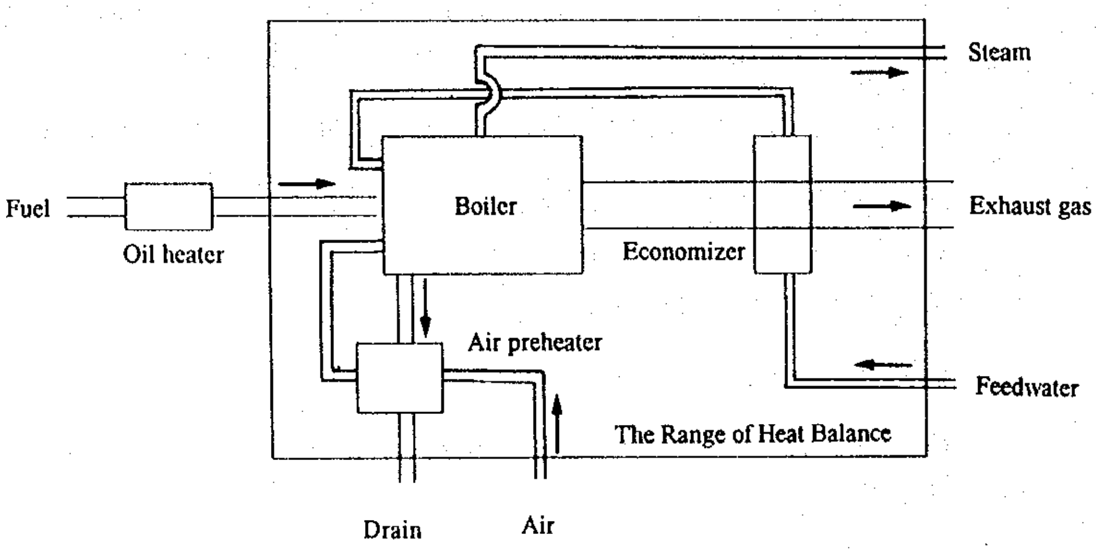


Figure 4.5.15 The Range of Heat Balance

ii) Unit of heat balance calculation

Recently, the system of international (SI) units has been increasingly adopted in metrology, and [Pa] and [J] have been employed respectively for pressure and heat values; these physical quantities are frequently used for heat balance.

However, considering that this change in use of the unit system is not complete and the actual situation varies by country, the non-international unit system (1 kcal = 4,187 kJ, 1 kgf/cm^2 = 9.81x10^4 Pa) has been employed as a basis. Heat balance calculations are usually made per unit quantity of fuel (kg - fuel) or unit quantity of raw material. In the following, heat balance per 1 kg of fuel is calculated.

iii) Method of calculating heat balance

a) Basic conditions

Reference temperature: Temperature of outside air
Atmospheric pressure: Local pressure at the ground
Evaluation period: At least one hour

b) Calculation of heat input

a. Fuel heat value

- Calorific value of fuel
  Lower calorific value measured by IMP was used.

- Sensible heat of fuel
  (Sensible heat of fuel) = (Mean specific heat of fuel) x {(Temperature of fuel) - (Reference temperature)}
  Mean specific heat of fuel : 0.48 kcal/kg·°C

b. Sensible heat of air

(Sensible heat of air) = (Volume of air) x (Mean specific heat of air) x {(Air temperature) - (Reference temperature)}

The test boiler has an air preheater. But the heat of the combustion air is treated as circulating heat as the air preheater uses the generated steam as a heat source. Usually, if preheating is not carried out, the air temperature for combustion is the reference temperature and the sensible heat is zero. For this boiler, as a rise of the air temperature due to the forced draft fan was found, the sensible heat of the air was accounted for. Mean specific heat of dry air was assumed to be 0.31 kcal/(m^3 N·°C), and the moisture in the air was neglected.

The amount of air discussed here is that required to burn 1 kg of fuel, and obtained by multiplying the theoretical amount of air by the excess air ratio.
(Actual air volume) = (Theoretical air volume) x (Excess air ratio)

c. Sensible heat of feedwater

(Sensible heat of feedwater)
= (Volume of feedwater) x (Mean specific heat of feedwater) x
{(Temperature of feedwater) - (Reference temperature)}
= (Volume of feedwater) x {(Enthalpy of feedwater) - (Enthalpy of water with reference temperature)}

d. Heat value of atomizing steam

Steam is used to atomize liquid fuel. As this steam is a part of that generated by the boiler, the heat retained in the atomizing steam is the circulating heat. Therefore, it is not counted in the heat balance as heat input. However, since it is released out of the domain as exhaust gas, sensible heat and latent heat are counted as heat output.

c) Calculation of heat output

a. Retaining heat of generated steam
(Retaining heat of saturated steam)
= (Amount of generated steam) x {(Enthalpy of saturated steam generated) - (Enthalpy of water with reference temperature)}

The amount of generated steam is the same as that of feedwater. The degree of dryness of steam is assumed to be 98% and the consumption of atomizing steam is assumed to be 0.15 kg/kg-fuel.

b. Lost heat due to exhaust gas

Lost heat due to combustion exhaust gas is calculated by separating retaining heat of the dry exhaust gas and retaining heat of water vapor in the exhaust gas.

- Retaining heat of dry exhaust gas
(Retaining heat of dry exhaust gas)
= (Volume of dry exhaust gas) x (Mean specific heat of dry exhaust gas) x
{(Temperature of exhaust gas) - (Reference temperature)}

Volume of dry exhaust gas used here was calculated based on the analysis of fuel composition conducted by IMP.

$$A_0 = \frac{22.4}{0.210}\left\{\frac{c}{12} + \frac{1}{4}\left(h - \frac{0}{8}\right) + \frac{s}{32}\right\}$$

$$G' = (m - 0.21)A_0 + 22.4\left(\frac{c}{12} + \frac{s}{32} + \frac{n}{28}\right) \text{ (m}^3\text{N/kg-fuel)}$$

$$m = \frac{(N_2)}{(N_2) - \frac{0.79}{0.21}(O_2)}$$

where, A_0: Theoretical air volume (m^3N/kg-fuel)

G' : Volume of dry exhaust gas (m^3N/kg-fuel)

m : Excess air ratio (Actual air volume/theoretical air volume)

c, h, o, s, n and w : Mass ratio of elements in fuel

Mean specific heat of dry exhaust gas : 0.33 kcal/($m^3N \cdot$ °C)

c. Retaining heat of water vapor in exhaust gas

Sensible heat of hydrogen and water in fuel and sensible heat and latent heat of steam for atomizing fuel are accounted.

(Retaining heat of water vapor in exhaust gas)
= (Amount of atomizing steam) x(Mean specific heat of steam) x
{(Temperature of exhaust gas) - (Reference temperature)} +
(Amount of atomizing steam) x (Latent heat of evaporation) +
(Water of fuel origin) x (Mean specific heat of steam) x
{(Temperature of exhaust gas) - (Base temperature)}

Water of fuel origin:	9 h + w (kg/kg-fuel)
Amount of atomizing steam :	0.15 (kg/kg-fuel)
Mean specific heat of steam:	0.45 (kcal/kg · °C)
Latent heat of evaporation :	600 (kcal/kg)

d. Lost heat due to radiation, etc.

As it is difficult to directly measure the heat losses such as that due to radiation from the surface of a boiler, valves, etc., the JIS prescribes that these losses can be calculated by multiplying the calorific value of fuel by the ratio of the loss due to heat release. When the boiler load is 5 t/h, this heat loss is assumed to be 2.0%.

Other heat losses are assumed to be measurement errors.

e. Others

As boiler water was not blown during the measurement of heat balance, losses due to blow water were not taken into account.

2) Results of heat balance calculation

An example of heat balance calculation is shown below.
The economizer was used as a energy saving equipment.

Fuel used:	Gas oil
Components of fuel (% in mass) :	

C : 85.59 S : 1.57 SG : 0.886 H : 12.56
N : 0.25 O : 0.1 H_2O : 0.2

Calorific value of fuel :	10,087 kcal/kg
Fuel consumption:	159.2 ℓ/h = 141.1 kg/h
Temperature of fuel :	24°C
Reference temperature (Temperature of outside air):	27°C
Atmospheric pressure:	574 mmHg
Temperature of combustion air:	36°C
Volume of feedwater:	2,146 ℓ/h
Temperature of feedwater :	34°C at inlet of economizer 48°C at outlet of economizer
Gauge pressure of generated steam :	7.0 kgf/cm^2
Degree of dryness of steam :	0.98
Amount of steam for fuel atomization:	0.15 kg/kg-fuel
Temperature of combustion exhaust gas:	102°C at outlet of economizer 236°C at inlet of economizer
Composition of dry exhaust gas:	CO_2 : 13.2% CO : 0.0% O_2 : 3.0% N_2 : 83.8%

The heat balance table is shown in Table 4.5.7 and an illustrative heat balance is shown in Figure 4.5.16.

Table 4.5.7 Heat Balance Table

Heat input	kcal/kg-fuel	%
Heat value of fuel	10087.0	98.7
Sensible heat of fuel	-1.4	0.0
Sensible heat of combustion air	35.7	0.3
Sensible heat of feedwater	106.4	1.0
Total	10227.7	100.0
Heat output (effective	**kcal/kg-fuel**	**%**
Retaining heat of generated steam		
Heat absorbed by boiler body	9192.9	89.8
heat absorbed by economizer	211.4	2.1
Total	9404.3	91.9
Circulating heat	**kcal/kg-fuel**	
Heat absorbed in feedwater	212.8	
Sensible heat of atomizing steam	93.4	
Heat output (heat loss)	**kcal/kg-fuel**	**%**
Retaining heat of dry exhaust gas	299.5	2.9
Heat of steam originating from fuel	38.9	0.4
Retaining heat of atomizing steam	95.1	0.9
Others	390.7	3.9
Total	824.2	8.1

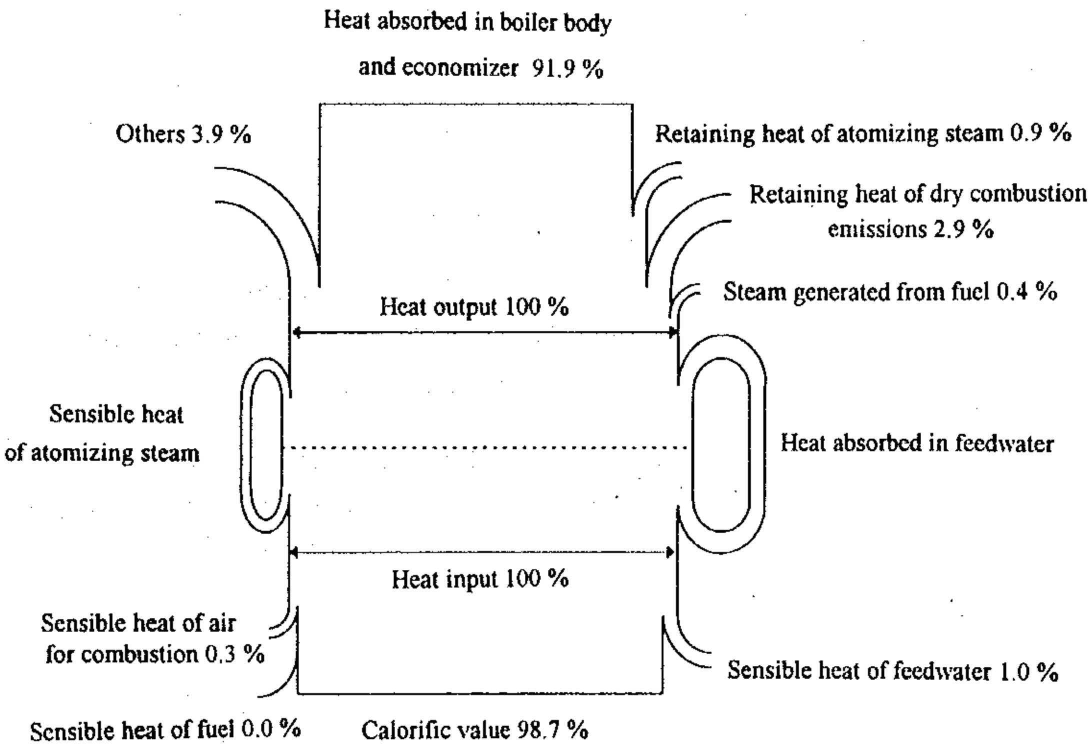


Figure 4.5.16 Boiler Heat Balance

From the above result, the boiler efficiency according to the heat-input-and-output method is:

$$\frac{\text{Effective heat out put}}{\text{Total input heat}} \times 100 = \frac{9{,}404}{10{,}228} \times 100 = 91.9\%$$

The boiler efficiency according to the heat-loss method is:

$$\left(1 - \frac{\text{Total heat loss}}{\text{Total heat input}}\right) \times 100$$

where, total heat loss

= (Retaining heat of exhaust gas including water vapor) + (Retaining heat of atomizing steam) + (radiated heat) + (Other heat loss)

Assuming that the heat loss due to radiation and other causes is 2% of the total heat input (according to JIS), the boiler efficiency is:

$$\left\{1 - \frac{(338.4 + 95.1 + 204.6)}{10{,}228}\right\} \times 100 = 93.8\%$$

Namely, the boiler efficiency according to the heat-input-and-output method is 91.9%, and that according to the heat-loss method is 93.8%. The difference between them is considered to be caused by errors in measurements.

(3) Effects of Energy Saving Measures

1) Influence of boiler load and oxygen concentration on boiler efficiency

The influences of the boiler load and the oxygen concentration of exhaust gas were investigated. The result is shown in Table 4.5.8, and the relation between the boiler load and the boiler efficiency is shown in Figure 4.5.17.

There is a tendency that the higher the boiler load, the lower the efficiency. This is because the exhaust gas temperature becomes higher as the boiler load is increased.

Table 4.5.8 Boiler Efficiency Classified by Parameters

Boiler Load		50%		67%		83%	
Fuel consumption	(l/h)	121.2	121.2	162.1	160.5	200.2	201.7
O_2 concentration	(%)	2.0	7.0	1.5	7.0	1.2	7.0
Exhaust gas Temp.	(℃)	220	235	243	258	262	281
Boiler efficiency	(%)	88.6	84.6	85.0	82.4	83.8	82.0

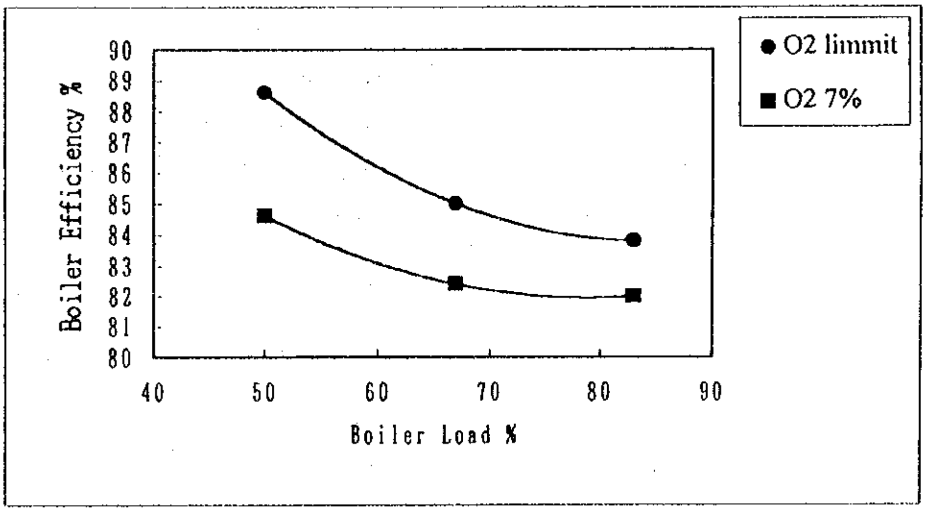


Figure 4.5.17 Boiler Load vs. Boiler Efficiency

There is a 2 - 4 % difference in the boiler efficiency depending on the oxygen concentration in exhaust gas. Minimizing the oxygen concentration of the exhaust gas is an effective energy saving measure.

As the turn down ratio for the tested boiler is 5:1, the minimum load is approximately 20%. At this load the low air ratio combustion is difficult, and the boiler efficiency tends to be lower.

2) Improvement of air ratio

When the fuel load is 160 ℓ/h, the annual operating hours of the boiler is 4,500 hrs, and the boiler efficiency is improved by 2.6% by changing the air ratio, the fuel consumption can be reduced by 18,720 ℓ in a year. The effects this improvement of the air ratio on the reductions of fuel cost and NOx emission were calculated for the cases of gas oil and diesel oil.

i) Economic effects of improving air ratio

Boiler load :	67%
Fuel consumption :	160 ℓ/h
Annual operating hours of boiler :	4,500 hours (about 50%)
Improvement of the air ratio :	Reduction from 1.49 to 1.07
Increase of boiler efficiency :	2.6%
Price of gas oil :	US$ 133/kℓ
	(As of May in 1995, US$ 1 = N$ 5.6)
Price of diesel oil :	US$ 236/kℓ

Annual reduction of fuel consumption is as follows:

160 ℓ/h x 4,500 h/y x 0.026 = 18,720 ℓ

The reduction of fuel cost in the case of gas oil is:

18,720 ℓ/y x US$ 0.133/ℓ = US$ 2,490 /y

The reduction of fuel cost in the case of diesel oil is:

18,720 ℓ/y x US$ 0.236/ℓ = US$ 4,418 /y

ii) Effect on reduction of NOx

Fuel used :	Gas Oil (CG: 0.886)
Annual fuel consumption :	637,920 kg/y
NOx concentration with the air ratio of 1.49 :	92 ppm
NOx concentration with the air ratio of 1.07 :	94 ppm

Volume of dry exhaust gas with the air ratio of 1.49:	15.7 m^3/kg-fuel
Volume of dry exhaust gas with the air ratio of 1.07:	11.1 m^3/kg-fuel

Annual amount of NOx emission with respective air ratio is as follows:

$$92\text{ppm} \times \frac{46\text{kg}}{22.4\text{m}^3} \times \frac{1}{1{,}000{,}000} \times 15.7\text{m}^3/\text{kg} \cdot \text{fuel} \times 637{,}920\text{kg/y} = 1{,}892\text{kg/y}$$

$$94\text{ppm} \times \frac{46\text{kg}}{22.4\text{m}^3} \times \frac{1}{1{,}000{,}000} \times 11.1\text{m}^3/\text{kg} \cdot \text{fuel} \times 637.920\text{kg/y} = 1{,}367\text{kg/y}$$

In addition, taking into account of the NOx reduction due to the improved boiler efficiency, the reduction of NOx emission resulting from the low air ratio combustion is :

1,892 kg-NOx/y - 1,367 kg-NOx/y x (1 - 0.026) = 561 kg-NOx/y.

Therefore, the reduction ratio of NOx emission is 29.6%.

Similarly, the effect in the case of diesel oil is calculated as follows :

NOx concentration with an air ratio of 1.49 :	64 ppm
NOx concentration with the air ratio of 1.07 :	65 ppm
Annual amount of NOx emission with the air ratio of 1.49 :	1,316 kg/y
Annual amount of NOx emission with the air ratio of 1.07 :	945 kg/y
Annual amount of NOx reduction when improvement of boiler efficiency is taken into account :	396 kg/y
NOx reduction ratio under the same condition :	30.1%

According to the questionnaire survey, the arithmetic mean of the exhaust gas oxygen concentration for boilers in ZMCM using liquid fuel was 6.83%. If current facilities are amenable to low air ratio combustion, it is expected to bring about considerable effects. However, the low air ratio combustion requires measuring equipment and engineers for combustion control.

3) Effects of economizer in energy saving

i) Reduction of fuel consumption by economizer

When retaining heat of exhaust gas is recovered by an economizer, the rate of recovery is calculated under the following conditions:

Temperature at inlet of economizer :	236°C
Temperature at outlet of economizer :	102°C

Volume of dry exhaust gas : 12.1 m^3N/kg-fuel
Specific heat of dry exhaust gas : 0.33 kcal/($m^3N \cdot$ °C)

The rate of recovery of the retaining heat of the dry exhaust gas is as follows :

(236°C - 102°C) x 0.33 kcal($m^3N \cdot$ °C) x12.1 (m^3N/kg-fuel) = 535 kcal/kg-fuel

For reference, the retaining heat of water vapor in the exhaust gas is calculated as shown below.

Amount of atomizing steam and steam originating from the fuel is as follows :

0.15 kg/kg-fuel + (9 x 0.1256 + 0.002) kg/kg-fuel = 1.28 kg/kg-fuel

Since mean specific heat of steam is 0.45 kcal/(kg°C), and the latent heat is 600 kcal/kg, the retaining heat is as follows:

[0.45 (kcal/kg · °C) x(236°C - 102°C)+ 600 (kcal/kg)] x 1.28 (kg/kg-fuel)
= 845 kcal/kg-fuel.

As latent heat recovered from this heat retained in the steam in exhaust gas is unknown, it is assumed that only sensible heat has been recovered as calculated below.

0.45 (kcal/kg · °C) x(236°C - 102°C) x 1.28 (kg/kg-fuel) = 77.2 kcal/kg-fuel.

Therefore, the total amount of heat recovered is :

531 + 77 = 608 kcal/kg-fuel

As heat input is 10,228 kcal/kg-fuel, the heat recovery rate is :

608 (kcal/kg-fuel)/10,228 (kcal/kg) x 100 = 5.9%.

5.9 % of heat input can be recovered. However, it is necessary to consider acid corrosion of the flue duct caused by sulfur in fuel. As the sulfur content of gas oil is 1.57 %, the SO_2 concentration in the exhaust gas when the air ratio is 1.07 is as follows :

$$0.0157\text{kg} \times \frac{22.4\text{m}^3}{32\text{kg}} \times \frac{1}{11.10} \times 1{,}000{,}000 = 990\text{ppm}$$

Assuming that SO_2 is converted to SO_3 by 3%, the concentration of SO_3 in the exhaust gas is about 30 ppm, and its mass concentration is :

30 ppm x 80 kg/22.4 m^3 = 107 mg/m^3N

From the relationship between SO_3 concentration in exhaust gas and the acid dew point shown in Figure 4.5.18, the temperature of exhaust gas must be kept above 140°C in the case of combustion of gas oil. Therefore, when acid-resisting materials are not used for the flue duct on the downstream side of the economizer, it is necessary to keep the outlet temperature above 140°C, or to keep the inside of the flue duct over 140°C with exhaust gas passed through a bypass duct.
In this case, heat recovered is 439 kcal/kg-fuel, and the recovery ratio is 4.3%.

Similarly, as the sulfur content of diesel oil is 0.45%, the dew point temperature is 110°C, and the heat recovered is calculated to be 576 kcal/kg-fuel. Assuming the heat input in this case is 10,300 kcal/kg-fuel, the heat recovery ratio is :

$$\frac{576\text{kcal/kg} \cdot \text{fuel}}{10{,}300\text{kcal/kg} \cdot \text{fuel}} \times 100 = 5.6\%$$

The annual reduction of fuel comsumption is calculated from the above results as follows:

In the case of gas oil :
160 ℓ/h x 4,500 h/y x 0.043 = 30,960 ℓ/y
In the case of diesel oil :
160 ℓ/h x 4,500 h/y x 0.056 = 40,320 ℓ/y.

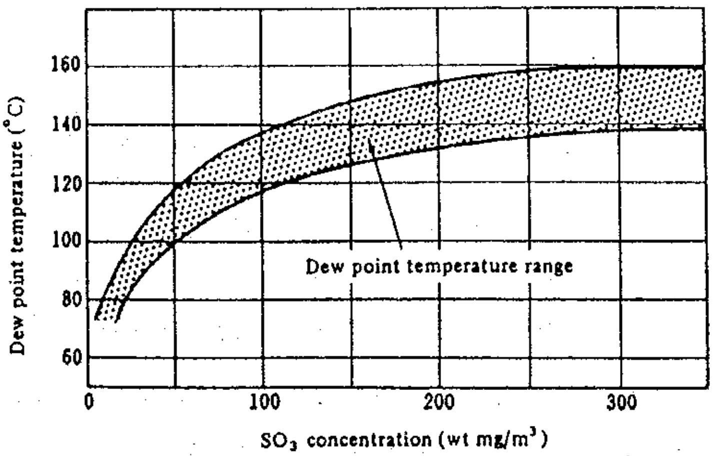


Figure 4.5.18 SO_3 Concentration in Exhaust Gas vs. Dew Point Temperature

ii) Economic evaluation of economizer

Use of an economizer allows reduction of the fuel cost as shown below.

In the case of gas oil:

30,960 ℓ/y x US$ 0.133 /ℓ = US$ 4,118 /y

In the case of diesel oil:

40,320 ℓ/y x US$ 0.236 /ℓ= US$ 9,516 /y

Although the economizer used in the test plant is made of acid-and-heat-resisting glass, economizers made of stainless steel can be used depending on the conditions of the exhaust gas temperature and the feedwater temperature.
Reference prices of economizers in Japan made of acid-and-heat-resisting glass and stainless steel are US$ 40,000 and US$ 15,000, respectively. The number of years required to recover the equipment cost is shown in the following table.

Material of economizer	Gas oil	Diesel oil
Glass	9.8 years	4.2 years
Stainless steel	3.7 years	1.6 years

(The equipment costs are examples in Japan, and do not include the costs for transportation, customs, installation, piping and ducts, and interest.)

When diesel oil is used with employment of a stainless steel made economizer, the equipment cost can be recovered in 1.6 years by the reduction of fuel cost.

4) Effect of air heater in energy saving

i) Effect of air heater in reducing fuel comsumption

The heat source of the air heater installed in the test plant is the generated steam, which is an internal heat source. When the fuel load is 160 ℓ/h (gas oil), and the steam pressure is 7 kgf/cm^{2}G, the air temperature at the inlet of the air heater is 38°C, and that at the outlet of the air heater is 143 °C, respectively.
Assuming that the air ratio is 1.07, the heat recovered in this cse is as follows:

Volume of the combustion air :	11.07 m^{3}N/kg-fuel x 1.07 = 11.84 m^{3}N/kg-fuel
Specific heat of dry air :	0.31 kcal/(m3N·°C)
Heat received by the air :	11.84 x 0.31 x(143°C -38°C) = 385 kcal/kg-fuel

Since the heat input when gas oil is used is 10,228 kcal/kg, the heat recovery ratio is :

385.4 / 10,227.7 x 100 = 3.8%

Similarly, the recovery ratio in the case of diesel oil is calculated to be 3.4%.

When the heat recovered from the exhaust gas of liquid fuel is used as a heat source of the air heater, the heat recovery ratio is inevitably reduced, as it is necessary to take account of acid corrosion due to sulfur in fuel. Assuming that the exhaust gas temperature is 236°C and the combustion air temperature is 38°C, it is estimated that the limit of the exhaust gas temperature at the outlet of the air heater is 140°C, and that of the preheated air temperature is 100°C. Under these conditions, the ratio of recovery of the exhaust gas heat is 2.2%.

ii) Influence of the air heater on NOx concentration

An air heater has an influence on the NOx concentration through the increased temperature of the combustion air, though retaining heat of the exhaust gas can be recovered. The relation between the temperature of preheated air and NOx concentration shown previously in Figure 4.4.5 is also shown in Table 4.5.9.
When the air is preheated to 100°C from the normal air temperature of 36 - 37 °C, the NOx concentration increases by 10.4 % in the case of gas oil and 14.9 % in the case of diesel oil.

Table 4.5.9 The Relation Between Preheated Air Temperature and NOx Concentration

Diesel oil		Gas oil	
Temperature(°C)	NOx(ppm)(5% O_2)	Temperature(°C)	NOx(ppm)(5% O_2)
37	67	36	96
51	69	68	99
93	75	101	107
136	80	136	110

Annual amount of NOx emission is calculated under the following conditions:

Fuel consumption	:	160 ℓ/h		
Oxygen concentration in exhaust gas	:	1.5 %		
Combustion air temperature	:	gas oil	:	36°C
		diesel	:	37°C
NOx concentration (at 5% oxygen)	:	gas oil	:	96 ppm
		diesel	:	67 ppm

Annual amount of NOx emission is as follows:

In the case of gas oil :

$$96\text{ppm} \times \frac{46\text{kg}}{22.4\text{m}^3} \times \frac{1}{1{,}000{,}000} \times 11.1\text{Nm}^3/\text{kg} \cdot \text{fuel} \times 637{,}920\text{kg/y} = 1{,}396\text{kg/y}$$

In the case of diesel oil :

$$67\text{ppm} \times \frac{46\text{kg}}{22.4\text{m}^3} \times \frac{1}{1{,}000{,}000} \times 11.3\text{Nm}^3/\text{kg} \cdot \text{fuel} \times 608{,}760\text{kg/y} = 947\text{kg/y}$$

Taking the energy-saving effect into account, the amount of NOx emission when the air is preheated to about 100°C by the air heater is as follows:

In the case of gas oil :
1,396 kg-NOx/y x 1.104 x(1 - 0.038) = 1,483 kg/y
In the case of diesel oil :
947 kg-NOx/y x 1.149 x(1 - 0.034) = 1,051 kg/y

Therefore, the annual amount of the NOx emission increases by 6.2 % and 11.0 %, respectively.

iii) Economic evaluation of air heater

The reduction in the fuel cost when retaining heat of the exhaust gas is recovered by the air heater is US$ 2,107/yr for gas oil and US$ 3,738/yr for diesel oil.
Since a reference price of a Japanese made air heater is about US$ 24,000, the time required for recovering the investment is 11.4 years in the case of gas oil and 6.4 years in the case of diesel oil. Therefore, economic feasibility of this investment is low.

5) Heat recovery from blow water

The boiler in the test plant is equipped with a device to recover heat from blow water. Although the main purpose of boiler water blowing is to discharge a certain volume of the boiler water to lower the concentration of impurities when the water-feeding pump is operating, this device recovers heat of the drained water to preheat the feedwater. Energy-saving and economic effects of this device are calculated under the following conditions :

Fuel consumption :	142 kg/h
Volume of feedwater:	2,146 ℓ/h

Temperature of feedwater:	20°C
Volume of blow water:	322 ℓ/h (15%)
Steam pressure :	7 kg/cm^{2}G
Temperature of steam :	168.4°C
Enthalpy of steam :	166 kcal/kg
Temperature at outlet of the blowing device :	73°C

Under these conditions, the heat released from blow water per hour, that is, the heat recovered into feedwater per hour, is calculated as follows:

322 ℓ/h x(166 kcal/kg - 73 kcal/kg) x 1 = 29,981 kcal/h.

As the consumption of gas oil is 142kg/h, the heat recovered is :

$$\frac{29{,}981\text{kcal/h}}{142\text{kg/h}} = 211\text{kcal/kg - fuel}$$

As the calorific value of gas oil is 10,087 kcal/kg, the recovery ratio is :

$$\frac{221\text{kcal/kg} \cdot \text{fuel}}{10{,}087\text{kcal/kg}} \times 100 = 2.20\%$$

For diesel oil, the same calculation results in 2.18 %.

Annual reductions in fuel consumption and fuel cost are as follows :

For gas oil :	15,840 ℓ/y and US$ 2,107/y
For diesel :	15,696 ℓ/y and US$ 3,704/y

As a reference price of a heat-recovery type blower is US$ 7,000, the recovery period is :

$$\frac{\text{US\$7,000}}{\text{US\$3,704/y}} = 1.89\text{year for diesel oil.}$$

The cost of the equipment will be recovered in 1.9 years in the case of diesel oil.

4.6 Remodeling of Normal Oil Burner

(1) Purpose of Burner Remodeling

As a result of the tests, it became clear that a sufficient effect in reducing NOx can not be obtained by the exhaust-gas recirculation when the nitrogen content of fuel is high, and the necessity to use low-NOx burners is high for combustion of fuel with a high content of nitrogen. However, as low-NOx burners are expensive, it is considered to be difficult financially for small-to-medium enterprises to employ low-NOx burners for their boilers.

Therefore, methods of remodeling existing burners to low-NOx type were studied, and a test was conducted to confirm the effect of the remodeling. Among low-NOx burners, the self-recirculation type burners recirculate the exhaust gas to realize reducing combustion within the combustion zone. This type is effective against the nitrogen in fuel, and remodeling of standard burners to this type is easy. Therefore, the normal burner was remodeled into this type.

(2) Concept of Remodeling

The normal burner was remodeled into the following structure for the purpose of adding self-recirculation functions that allow combustion in the reducing atmosphere while maintaining the basic structure of the normal burner.

1) Combustion air is divided into the primary air and the secondary air while enabling control of each air volume.
2) The primary air inlet is throttled to bring about the Venturi effect which recirculates part of the exhaust gas.
3) The secondary air is introduced into the flame to compensate for incomplete combustion due to the recirculation of exhaust gas (principle of two-stage combustion).

The structures of the normal burner and the remodeled burner are shown in Figures 4.6.1 and 4.6.2.

(3) Remodeling Method

Actual works for the remodeling are as follows :

1) Removal of a part of the burner tile
2) Installation of a secondary air duct and an air inlet
3) Installation of a partition to separate the primary air and the secondary air

4) Installation of a nozzle for the primary air
5) Installation of a nozzle for the secondary air
6) Change of shape of the flame stabilizer
7) Installation of a self-recirculation device

(4) Change of Structure as a Result of Remodeling

As shown in Figure 4.6.1 for the normal burner, all the combustion air enters the burner from the inlet, passes through the wind box and the air sleeve, and is given swirling motion by the flame stabilizer. Then, it is mixed with atomized fuel sprayed from the burner nozzle and dispersed for combustion in the flue.

The structure of the remodeled self-recirculation burner, as shown in Figure 4.6.2, allows the combustion air to be divided into primary and secondary air, each of which is controlled independently. The primary air passes the window box and the air sleeve, and is blown off to the self-recirculator from the primary air nozzle installed by removing a part of the burner tile. As the holes of this nozzle head are narrowed, the exhaust gas is drawn in by the Venturi effect. The primary air is given swirling motion by the flame stabilizer surrounding the burner nozzle and provided for combustion. This combustion exhibits a flame of incomplete combustion under the reduced atmosphere, because part of the exhaust gas is circulated.

The secondary air is led in front of the self-recirculator from the wind box through the secondary air nozzle, which is divided into eight to sixteen passes. As this nozzle is divided within the wind box, deviation in air volume may occur according to the positions of the nozzle holes due to the air current in the wind box, resulting in incomplete combustion in some zones. Therefore, the sectional areas of some nozzle holes were adjusted so that the combustion air is distributed uniformly into the flame. Figure 4.6.3 is the cross section of the secondary air nozzle.

(5) Test Operation

Test burner remodeling was encountered by various problems. The problems and their solutions to complete the remodeling were as follows:

1) Leak from the partition wall for the primary and secondary air

To make burner restoration to the original status easy after the combustion test, the partition wall was made simple. But this caused a leak from the primary air side to the secondary air side. As a countermeasure, the leak was filled with silicon seal and fireproof mortar.

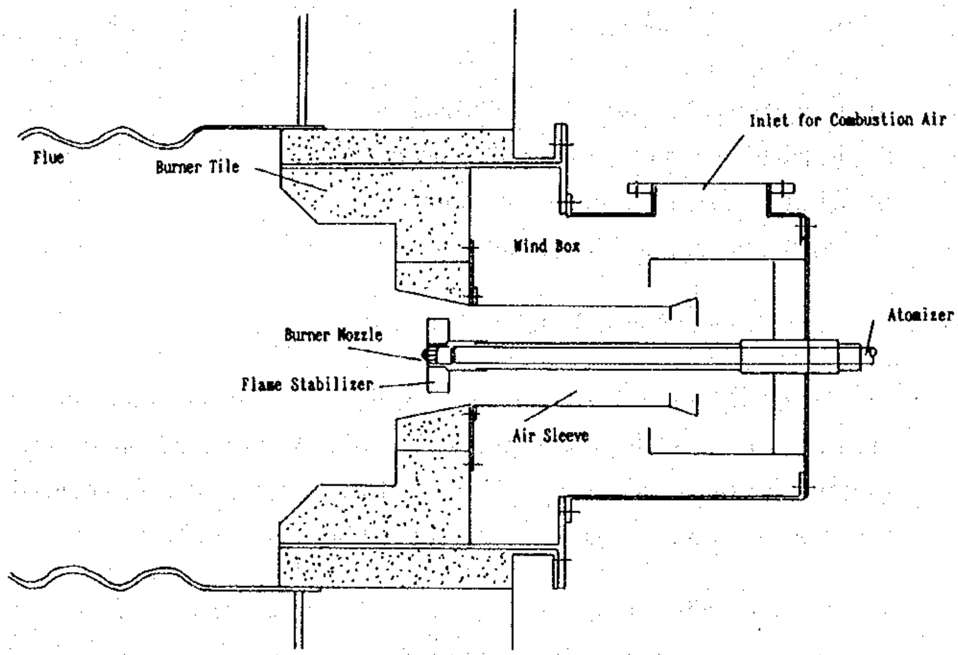


Figure 4.6.1 Structure of Normal Burner

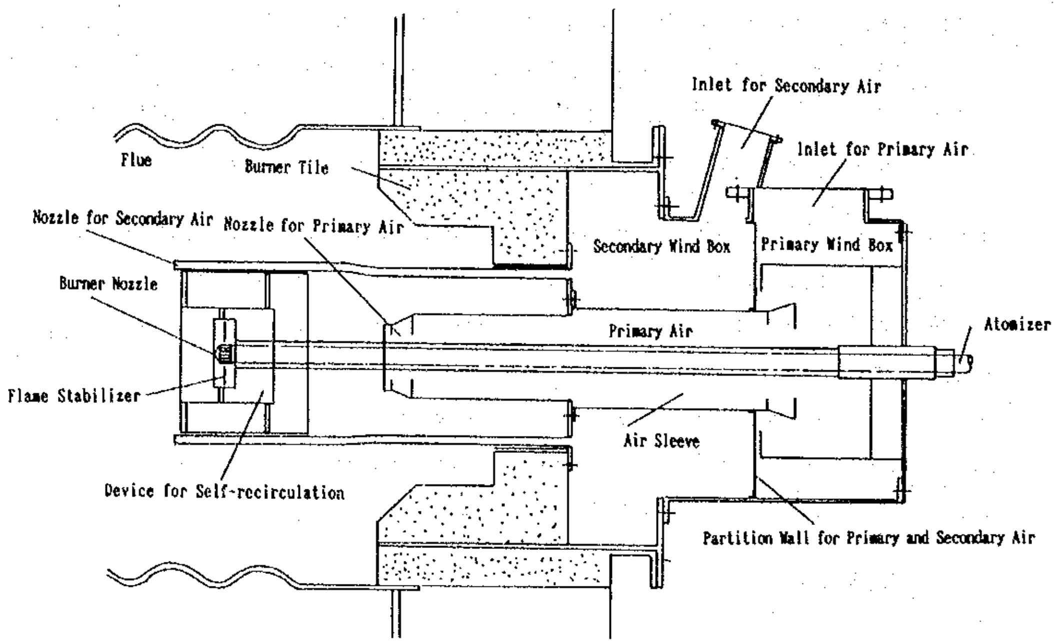


Figure 4.6.2 Structure of Remodeled Burner

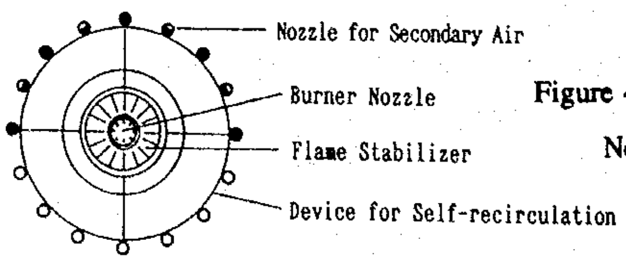


Figure 4.6.3 Cross Section of Nozzle for Secondary Air

2) Leak from the part of the primary air nozzle

As some of the primary air entered the flue without passing through the nozzle, the recirculation current was destroyed. As a countermeasure, the entry of air was prevented by welding the primary air nozzle onto the air sleeve.

3) Incomplete combustion due to insufficient secondary air

Initially, as there were eight nozzle holes for secondary air, the insufficient air volume resulted in incomplete combustion. As countermeasures, the number of nozzle holes was increased to sixteen, and sectional areas of the holes were adjusted to balance the air volume.

(6) Result of the Test

When gas oil (160 ℓ/h) with a nitrogen content of around 3500 ppm was burnt with the normal burner, the NOx concentration in exhaust gas was 260 to 280 ppm at an oxygen concentration of 3%. The remodeled self-recirculation burner reduced the concentration by about 20% under the same conditions; it ranged from 200 to 220 ppm.

(7) Restoration

After the test, all parts installed for remodeling were removed and the burner was restored to its original structure.

(8) Evaluation of Remodeled Burner

From this remodeling, positive results comparable to low-NOx burners on the market were obtained. As the remodeling cost was approximately US$6,000, which is about 15 % of the price (around US$40,000) of a Japanese made low-NOx burner, it is possible to cover the cost by reducing the fuel cost by means of improving combustion management.

However, since shapes and specifications of burners used in ZMCM are different, a sufficient attention should be paid upon remodeling of burners to ensure the recirculation of exhaust gas for enabling the reducing combustion.

CHAPTER 5 PROPOSALS ON IMPROVEMENT OF COMBUSTION TECHNIQUES FOR ZMCM

Chapter 5 Proposals on Improvement of Combustion Techniques for ZMCM

Based on the results of the investigation of stationary sources and the combustion tests as described so far, proposals will be made for the stationary sources in ZMCM, regarding the improvement of combustion techniques for NOx emission reduction and energy saving.

Section 5.1 presents proposals based on the results of the combustion tests for boilers burning liquid fuels. In Section 5.2, existing knowledge concerning energy saving in boilers is summarized as a guidance. Section 5.3 gives suggestions concerning natural gas combustion in boilers mainly based on the existing knowledge. Section 5.4 deals with particular industrial furnaces that are also major sources of the NOx emission in ZMCM other than boilers, and proposes NOx reduction measures considered to be effective among existing methods.

5.1 Conclusions Obtained from the Results of the Combustion Test

Based on the results of the combustion tests using diesel oil and gas oil, the following are proposed for improvement of combustion techniques for ZMCM.

5.1.1 Low-NOx Combustion Techniques

(1) Boilers Burning Diesel Oil

The results of the tests on diesel oil having a nitrogen content of 270 ppm showed that the NOx concentration in exhaust gas did not exceed the emission standard of 110 ppm with both steam atomization and air atomization. Accordingly, it is considered that no particular measures for NOx reduction are necessary for boilers burning diesel oil. However, improvement of combustion techniques is still desirable in view of reduction of the total emission of NOx and energy saving.

(2) Boilers Burning Gas Oil

The results of the tests on gas oil having a nitrogen content of 720 ppm revealed that the NOx concentration in exhaust gas would exceed the emission standard of 110 ppm under certain conditions of combustion with normal burners. The boiler and the burners used in the combustion tests were designed so that both are well balanced with each other. Moreover, the tests were conducted by skilled engineers with a boiler which was equipped with all the necessary control devices. Such conditions are considered to be not common for boilers in ZMCM. Taking into account of unfavorable conditions that may be imposed on these boilers, it is natural to think that there should be the cases where introduction of certain low-NOx combustion techniques is necessary for boilers burning gas oil. Major techniques for low-NOx combustion that are judged to be effective for boilers burning gas oil based on the results of the combustion tests are as follows.

1) Introduction of steam atomization

Although it is necessary to modify existing air atomization type burners to steam atomization type, its NOx reduction effect is estimated to be large, or a maximum 30 - 40 % according to the test result.

2) Remodeling of normal burners

NOx reduction of a maximum of 20% was achieved by remodeling the normal burner so as to provide it with the function of self-recirculation of exhaust gas.

3) Low air ratio combustion

NOx concentration can be reduced by 30% by decreasing the air ratio from 1.49 to 1.07. Low-air ratio combustion is an effective measure for NOx control, but it requires equipment for combustion control.

4) Introduction of low-NOx burners

NOx reduction by 7 - 30 % was achieved in the tests of 3 types of low-NOx burners. Since the NOx reduction effect tends to increase as the air ratio decreases, careful operation with air supply control is required to maximize the effect of low-NOx burners.

5) Introduction of EGR

In the combustion tests, a maximum of 22% NOx reduction was achieved by the use of the exhaust gas recirculation device.

Among above techniques, 1) introduction of steam atomization, 2) remodeling of normal burners, and 3) low air ratio combustion are considered to be suitable for small-to-medium size boilers since these techniques require relatively small investments. However, there are certain difficulties in adapting additional parts to existing boilers.

On the other hand, 4) introduction of low-NOx burners and 5) introduction of EGR have higher possibilities for medium-to-large size boilers since required investments would be larger than that for the former 3 techniques. Since there would be few technical difficulties, surer effects can be expected.

5.1.2 Operation Techniques for Energy Saving

Energy saving operation is primarily aimed at saving of fuel. However, since the fuel saving directly leads to the reduction of the exhaust gas volume, the NOx emission can be also reduced. Energy saving operation techniques such as low air ratio combustion, use of an economizer, and combustion air preheating, were studied with the test boiler. As a result, the possiblities of tangible effects in economy and NOx reduction were demonstrated. Since the reduction of production costs to be brought about as a result of employing these techniques is a good incentive, they should be positioned at the core of improvement of combustion techniques for ZMCM.

(1) Combustion with Appropriate Air Ratio

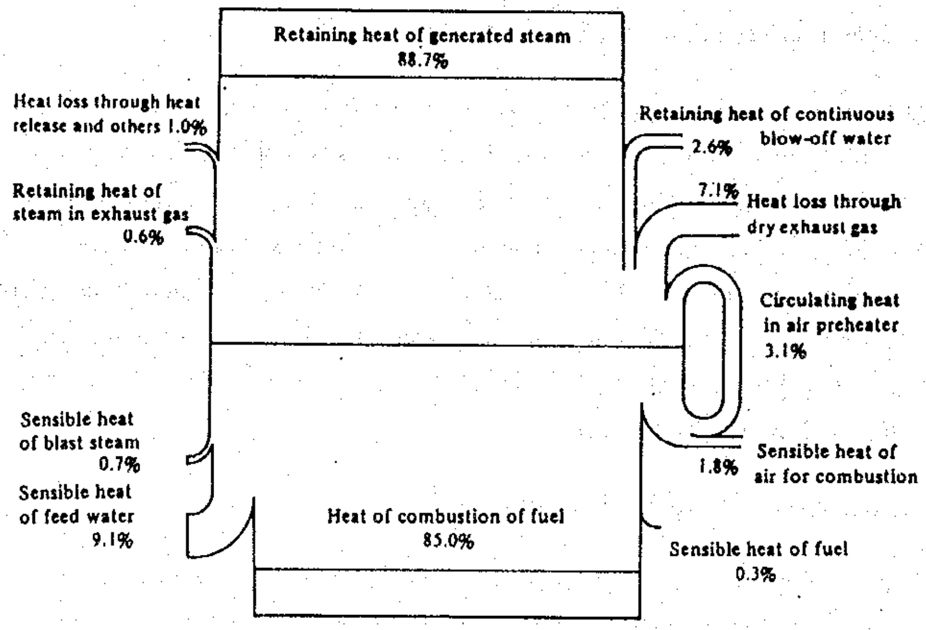
High air ratio combustion is a cause for emissions of NOx in high concentrations which is common in many stationary combustion facilities in ZMCM. Only a small number of combustion facilities were operated with the exhaust gas oxygen concentration at 4% or less : 14 facilities or 10% of 140 facilities surveyed by questionnaire, and 11 facilities or 15% of 69 facilities surveyed on site. These figures indicate not much improvement since the time of the previous JICA study conducted in 1990 - 1991. It is recommended to make much effort in energy saving and NOx emission reduction based on the understanding of the influence of the air ratio on the NOx concentration and the exhaust gas heat loss.

1) Fuel saving by operation with appropriate air ratio

The largest heat loss in a boiler is the heat loss due to exhaust gas (see Figure 5.1.1). Since this heat loss is determined from the volume and the temperature of the exhaust gas, it is necessary to minimize the volume of the exhaust gas. When the temperature of the exhaust gas is constant, the volume of the exhaust gas, i.e. the heat taken away by the exhaust gas increases in proportion to the air ratio. Therefore, it is important to maintain the air ratio at an appropriate level.

Figure 5.1.2 gives rates of the heat loss by the exhaust gas in relation to the air ratio classified by exhaust gas temperature (200 - 1,000°C).

If the air ratio is adjusted to 1.30 for a combustion device which has been operated at an air ratio of more 1.30, the effect on fuel saving resulting from this adjustmet is obtained from Figure 5.1.3.



Evaporation multiple $= \frac{13.67 \text{ kg}}{1 \text{ kg} \times 0.93 \text{ kg/lit.}} \times 1000 = 14.7$ ton/kl.

Figure 5.1.1 Example of Heat Balance for 20 ton/h Boiler (Source : Ref. D7)

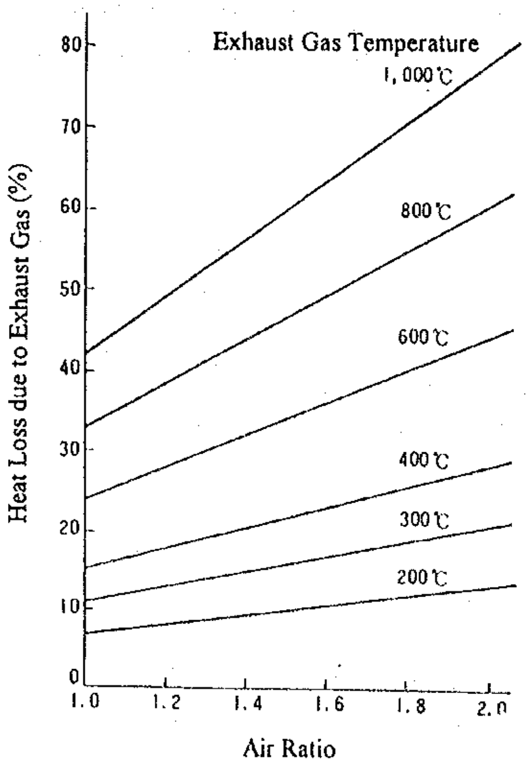


Figure 5.1.2 Air Ratio vs. Heat Loss by Exhaust Gas (Source : Ref. D9)

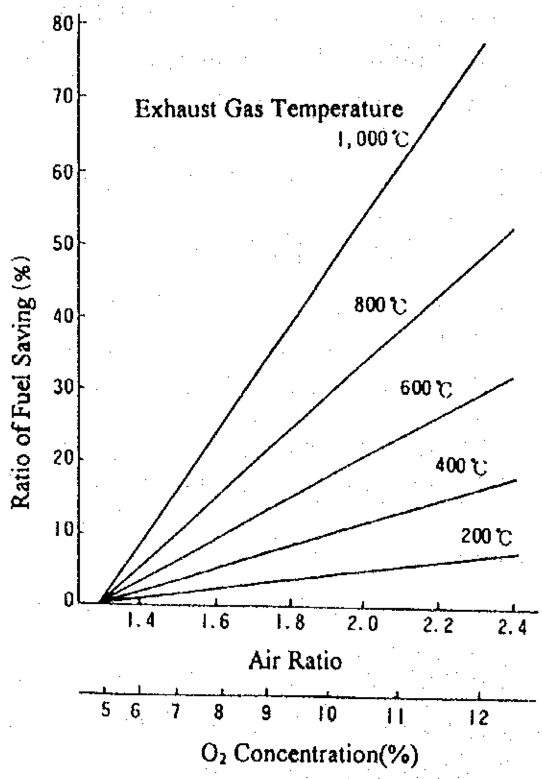


Figure 5.1.3 Fuel Saving by Adjusting Air Ratio to 1.30 (Source : ibid.)

Equations for calculating air ratio (m) are as follows:

General Expression

$$m = \frac{(N_2)}{(N_2) - \frac{79}{21}\left[(O_2) - \frac{1}{2}(CO)\right]}$$

Simple Expression

$$m = \frac{21}{21 - (O_2)}$$

Note: (O_2), (N_2) and (CO) represent the volume percent of the indicated gas.

2) Relation between oxygen concentration and NOx concentration in exhaust gas

From the results of combustion tests, examples of the influence of the oxygen concentration on the NOx concentration will be shown for gas oil combustion.

As shown in Figures 5.1.4 and 5.1.5, the NOx concentration with oxygen concentration of 7% is higher by about 30% than that with oxygen concentration of 3% in combustion of both of two kinds of gas oil. The same is true for diesel oil.

It must be recognized that low air ratio (low oxygen) combustion is the basis for controlling NOx emissions, and it is most important to keep the oxygen concentration in exhaust gas at 3% or less.

3) Methods for low air ratio combustion

Generally, appropriate air ratio increases in the order of gas, oil, and coal. The important points for adjusting the air ratio at an appropriate level are described below.

i) Adjusting air volume

Whether or not an air ratio is appropriate can be confirmed by analyzing the oxygen concentration in the exhaust gas. For daily management, adjustments have to be made by observing the state of the flame and the smoke. Air volume should be adjusted by observing smoke from the smokestack. The amount of air should be adjusted to a slight excess of that which generates a small amount of black smoke.

When gas oil or diesel oil is burned, the amount of air is close to being appropriate if the flame is bright with its center somewhat black. This can be observed through the front window of the boiler.

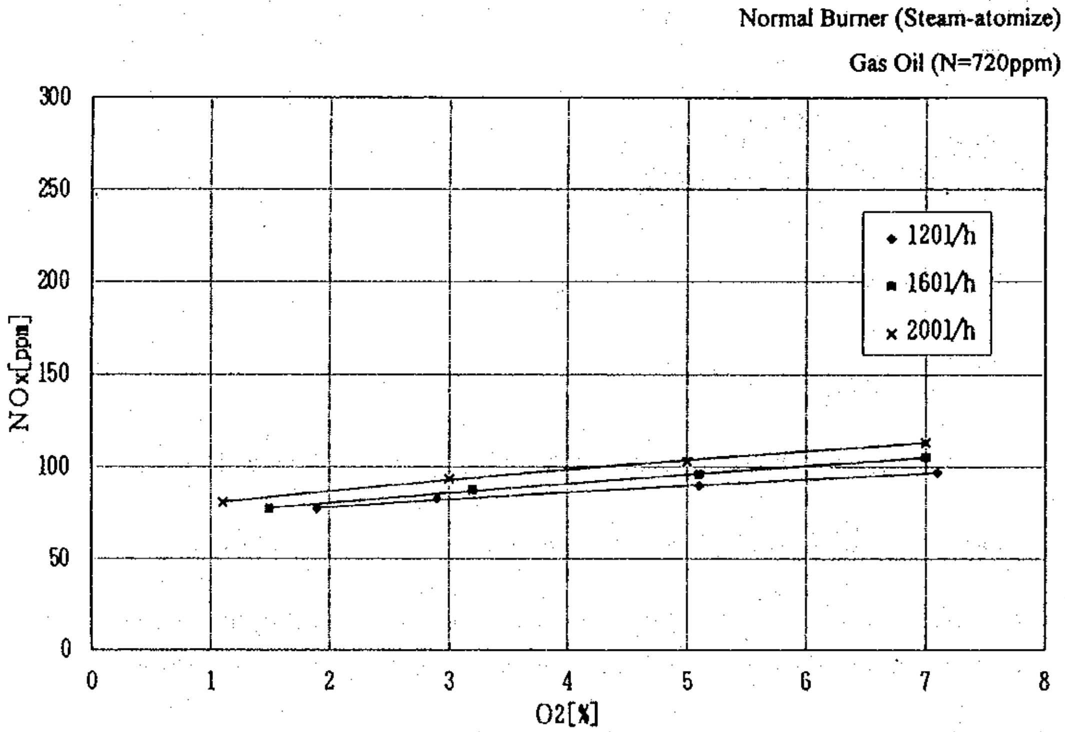


Figure 5.1.4 O_2 Concentration vs. NOx Concentration in Combustion of Gas Oil (N=720 ppm) by Steam-atomized Normal Burner

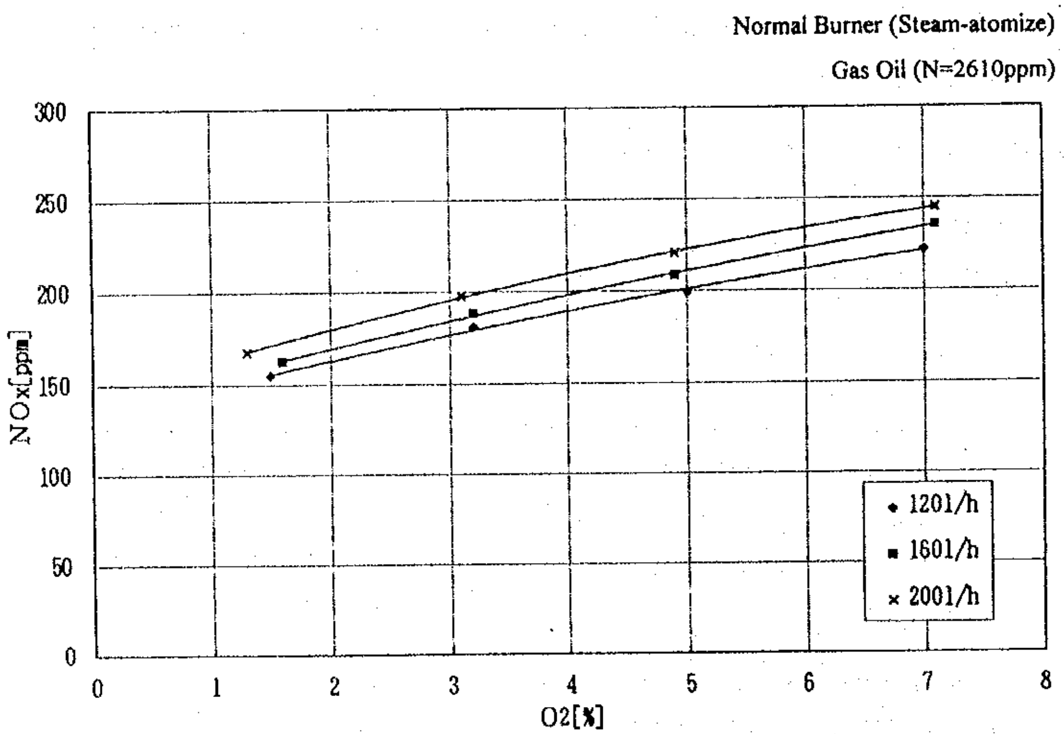


Figure 5.1.5 O_2 Concentration vs. Nox Concentration in Combustion of Gas Oil (N=2,610 ppm) by Steam-atomized Normal Burner

If the air amount is less than appropriate, the flame becomes black, and soot is generated. On the other hand, when there is excessive air, the length of the flame is extremely short and branched, and vacillaties violently. The color of the flame becomes light yellow.

ii) Criteria for air ratio

In adjusting the air ratio, the type of fuel, loading rate, composition of control equipment must be taken into consideration. For reference, the air ratio criteria in Japan are shown in Table 5.1.1. These values are applicable for steady-state operation at indicaded loading rates.

Table 5.1.1 Standard Air Ratio for Boilers (in Japan)

Boiler Category		Loading rate (%)	Standard air ratio			
			Solid fuel	Liquid fuel	Gas fuel	Blast furnace gas and other by-produced gases
Electric power plant boilers		75 ~ 100	1.2 ~ 1.3	1.05 ~ 1.1	1.05 ~ 1.1	1.2
Other boilers	Evaporation rate more than 30 t/h	75 ~ 100	1.2 ~ 1.3	1.1 ~ 1.2	1.1 ~ 1.2	1.3
	Evaporation rate 10 to 30 t/h	75 ~ 100	-	1.2 ~ 1.3	1.2 ~ 1.3	-
	Evaporation rate less than 10 t/h	75 ~ 100	-	1.3	1.3	-

Source : Ref. D8

5.2 Energy Saving Measures for Boilers

5.2.1 Energy Saving Items for Boilers

Items for energy saving with boilers exist in many areas as shown in Figure 5.2.1. Some important subjects are described in the following sections.

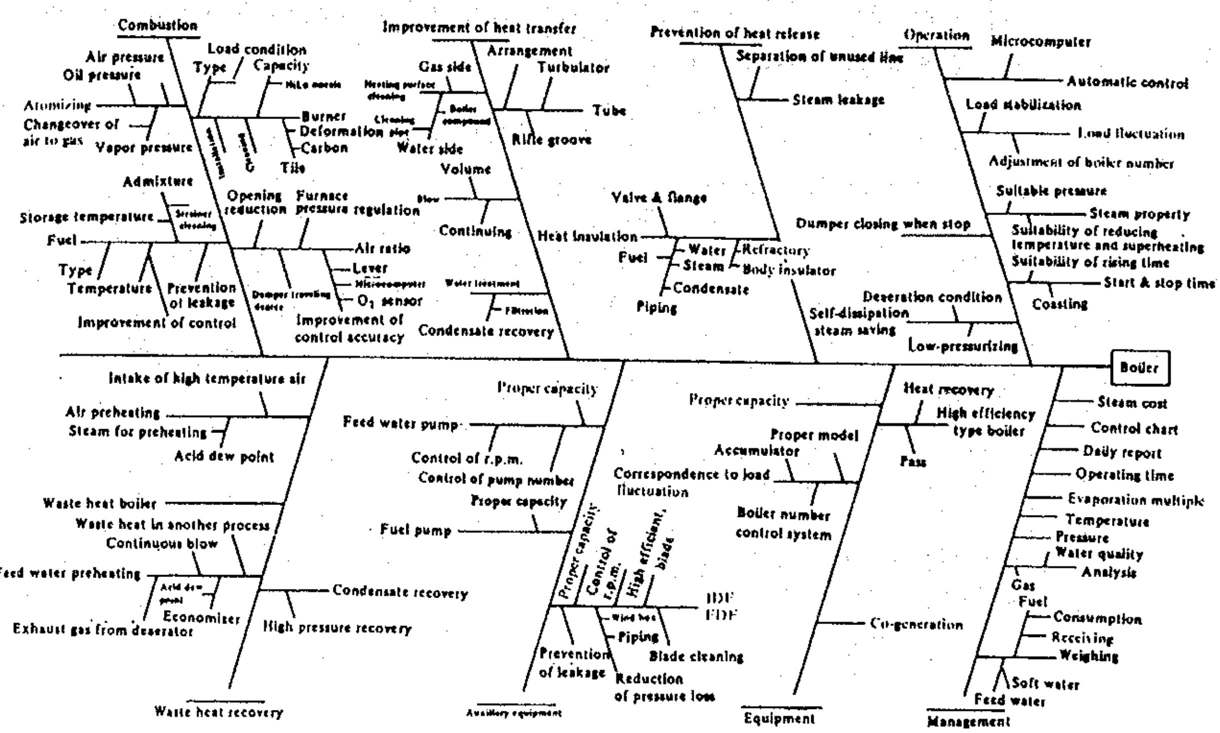


Figure 5.2.1 Energy Saving Items for Boilers (Source : Ref. D7)

5.2.2 Improvement of Heat Transfer

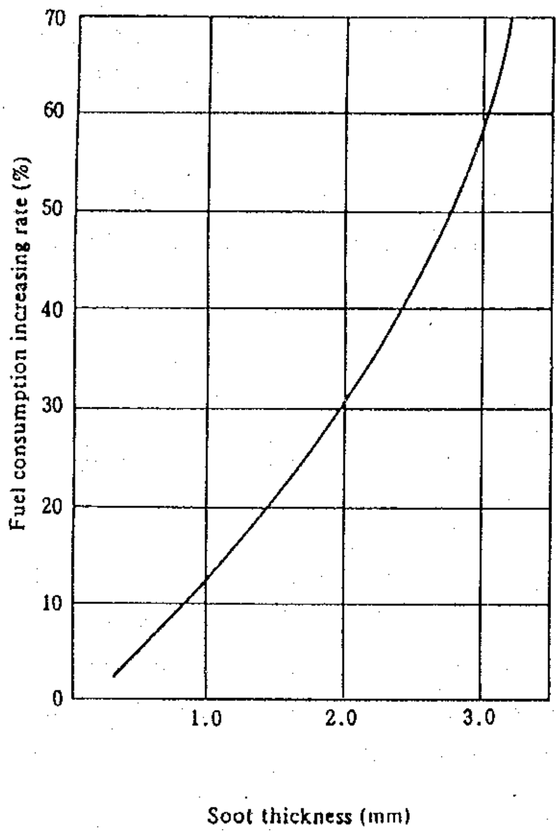
As shown in Table 5.2.1, the thermal conductivity of soot and scale is only 1/100 to 1/1,000 of that of mild steel although the value further depends on the composition and the status of adherence. Therefore, their existence on heat transfer surfaces is similar to application of heat insulation, and they reduce the thermal efficiency of boilers remarkably (see Figures 5.2.2 and 5.2.3).

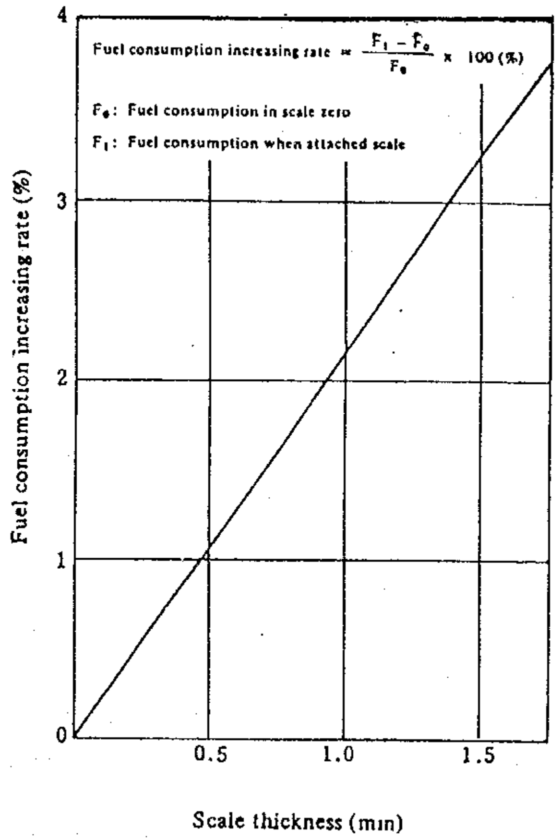
To avoid scaling, softening of boiler water, proper blowing, and regular cleaning are necessary.

Table 5.2.1 Thermal Conductivity of Scale and Other Substances

Scale and other substance	Thermal conductivity (kcal/mh°C)
Soot	0.06 ~ 0.1
Oil matter	0.1
Scale as main component of silicate	0.2 ~ 0.4
Scale as main component of carbonate	0.4 ~ 0.6
Scale as main component of sulfate	0.6 ~ 2
Mild steel	40 ~ 60

Source : Ref. B10





(Source : Ref. D9)

Figure 5.2.2 Example of Fuel Loss Due to Soot on Heating Surface

Figure 5.2.3 Example of Relation Between Scale Thickness and Fuel Loss

Cleaning the heat transfer surface of the water side is usually done once a year, although the frequency depends on the degree of water treatment. It should be done manually with a brush or chemically using an acid with an inhibitor added.

The heat transfer surface of the gas side should be cleaned with a brush once every 1 - 3 months. Even within this period, if the temperature of the exhaust gas has increased by 30°C from that after cleaning, it is necessary to clean the surface.

For flue and smoke tube boilers having surplus capacity, a common practices is to insert tabulators made of special steel into smoke tubes to improve the heat transfer of boundary films through generation of turbulent flow of the gas.

5.2.3 Heat Recovery From Exhaust Gas

In boilers, the basic points are to maintain an appropriate air ratio and to minimize dirt on the heat transfer surface so that the temperature of the exhaust gas does not increase. If the temperature of the exhaust gas is still high, heat from the exhaust gas should be recovered to be utilized for preheating feedwater and combustion air for increasing the overall thermal efficiency. In many cases, large boilers have both an air preheater and a feedwater preheater, and smaller boilers have either one of them.

In addition to the energy saving effect of the increase of incoming heat, air preheating improves ignitability and flame stability, and enables the lower air ratio resulting from the increase of combustion speed. The flame temperature also increases, and energy saving can be expected.

On the other hand, when the combustion air is preheated, attention must be paid to : 1) increase of NOx generation due to the increased flame temperature, and 2) heat-resistivity of the part of the burner where the combustion air is introduced.

When an economizer is planned to be installed, a comprehensive comparative study should be made of various options such as condensate recovery and preheating feedwater by the heat recovered from continuous blowing, solar heat, and the heat recovered from other processes. When the temperature of the feedwater has been already increased to a certain degree by other heat sources, the economic efficiency of the economizer might fall.

Heat efficiency of boilers is generally higher than that of industrial furnaces, and the temperature of exhaust gas is also relatively low. Among them, large boilers have economically favorable conditions for installation of waste heat recovering facilities. Therefore, the exhaust gas temperature is generally low. Gaseous fuels have a low sulfur content, in general, and it is possible to recover heat to the point of a low exhaust gas temperature.

The Japanese standard for the exhaust gas temperature is shown in Table 5.2.2, which specifies the standard temperatures classified by boiler capacity and fuel type. These standard values are for the conditions where the outside air temperature is 20°C and the loading rate is 100% after regular maintenance.

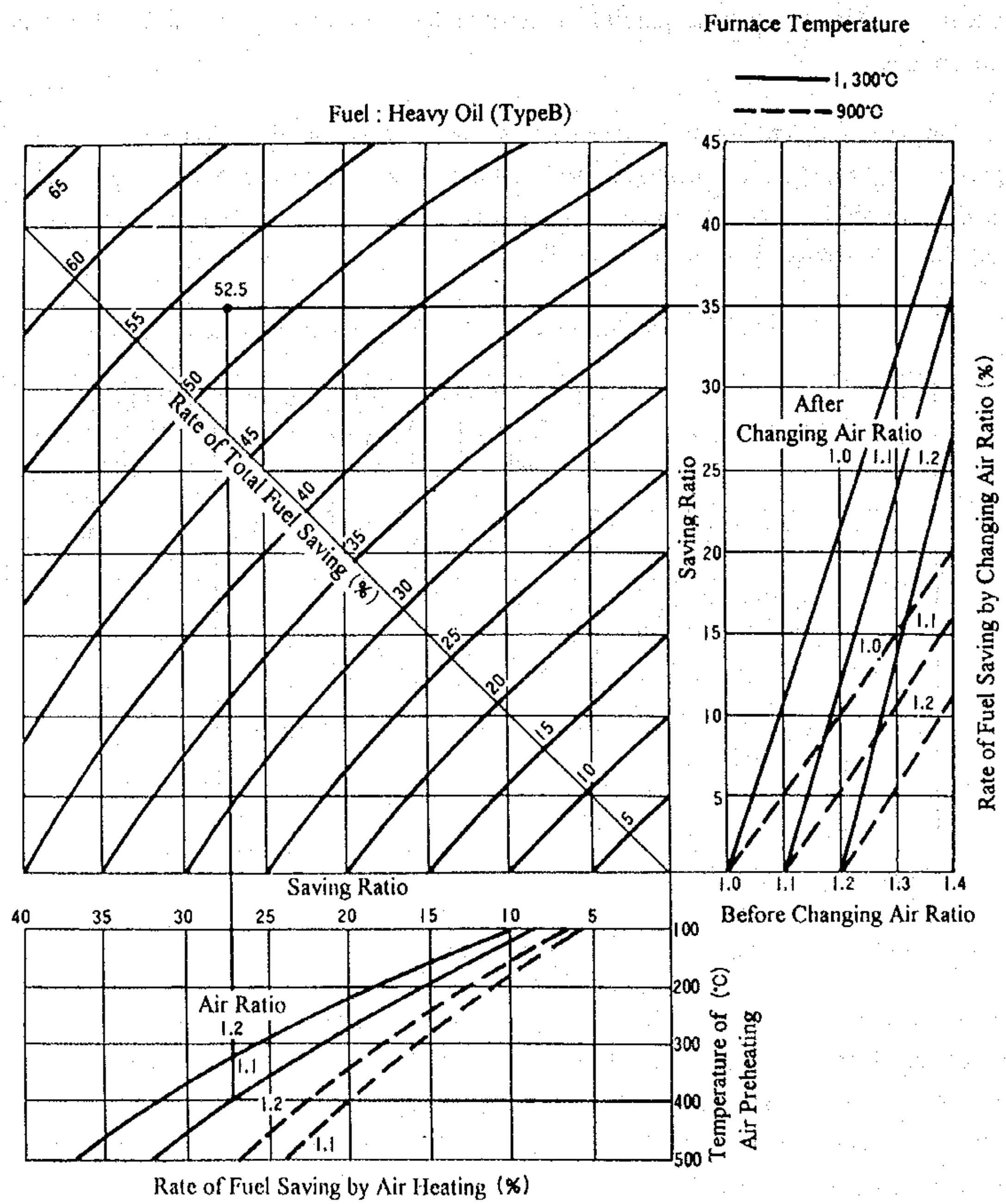
Table 5.2.2 Standard Exhaust Gas Temperature of Boiler (in Japan)

Boiler Category		Standard exhaust gas temperature (°C)			
		Solid fuel	Liquid fuel	Gas fuel	Blast furnace gas and other by-produced gases
Electric power plant		-	145	110	200
Others	Evaporation rate more than 30 t/h	200	200	170	200
	Evaporation rate 10 to 30 t/h	250	200	170	-
	Evaporation rate 5 to10 t/h	-	220	200	-
	Evaporation rate less than 5 t/h	-	250	220	

Source : Ref. D8

5.2.4 Fuel Saving by Air Ratio Adjustment and Air Preheating

Figure 5.2.4 shows the rates of fuel saving by air ratio adjustment, air preheating, and both of them combined. For example, if the air ratio is changed from 1.4 to 1.1 in a furnace where the temperature is 1,300°C, the rate of fuel saving is 35%. If the combustion air is preheated to 400°C in the same furnace, the rate of fuel saving is 27 %. When both are done at the same time, the total fuel saving is 52.5 %.



(Source : Ref. D9)

Figure 5.2.4 Rate of Total Fuel Saving by Air Ratio Adjustment and Air Preheating

As a measure to improve combustion efficiency in boilers, heating furnaces, and various industrial furnaces, preheating of the combustion air is employed. In this case, the rate of fuel saving achieved by the air preheating can be found in the following manner. Fuel consumption when air is not preheated is given by Equation (1). Fuel consumption when air is preheated is given by Equation (2). Therefore, the rate of fuel saving when air is preheated is expressed by Equation (3).

$$\frac{Q_0}{H_A} \text{ [kg(fuel)/h]} \quad \cdots\cdots (1)$$

$$\frac{Q_0}{H_B} = \frac{Q_0}{H_A + P} \text{ [kg(fuel)/h]} \quad \cdots\cdots (2)$$

$$\frac{\dfrac{Q_0}{H_A} - \dfrac{Q_0}{H_A + P}}{\dfrac{Q_0}{H_A}} = \frac{P}{H_A + P} \quad \cdots\cdots (3)$$

Q_0 : Heat spent in boiler, furnace etc. (kcal/h)

P : Heat brought in by preheated air (kcal/kg-fuel)

H_A : Effective heat when air is not preheated (kcal/kg-fuel)
H_A = (Real heat value of fuel) - (Heat taken away by exhaust gas)

H_B : Effective heat when air is preheated (kcal/kg-fuel)
$H_B = H_A + P$

5.2.5 Prevention of Heat Release

Boilers are designed so that most parts of heat radiating surfaces are in contact with water or steam thereby preventing heat radiation as much as possible, and thermal insulation is generally well provided.

However, in many cases for boilers in ZMCM, thermal insulation is not applied for feedwater pipes around boiler, valves, flanges, etc.

In the case that warm water such as condensate is recycled into the feedwater tank, there are many instances in which the method of adjusting the water surface is unsatisfactory and the recovered warm water is permitted to overflow. When overflow is necessary, piping should be provided such that it allows cooler water at the bottom to overflow.

The Japanese criteria for energy saving do not give concrete figures for heat insulation. They are provided in the Japan Industrial Standards (JIS A 9501). JIS prescribes that the thickness of the thermal insulation should be determined so that the total cost of the following is minimized: 1) annual fuel cost equivalent to heat loss from the surface after thermal insulation, and 2) annual depreciation of the cost required for the thermal insulation work. Namely, the thickness of thermal insulation may be determined according to prevailing prices of fuel and thermal insulation work to obtain the maximum economy.

5.2.6 Others

(1) Energy Saving for Ancillary Equipment

In large boilers, the capacity of the blower and the feedwater pump should be rationalized. If there are many cases of low-load operation, losses due to area contraction at valves and dampers should be reduced by controlling the number of revolutions.

Dust that has adhered to the air preheater and the fan should be removed regularly to prevent reduction of efficiency due to pressure losses.

(2) Operation

If steam is required only during the daytime, the use of once-through boilers is advisable because of their quick start-up. Some considerations are required in the case of flue and smoke tube boilers. For example, the time for start-up should not be too short, and the operation should be stopped before the end of the work by estimating the time during which the remaining pressure can be used. When the boiler operation is stopped, the damper should be closed to prevent cooling down of the boiler.

(3) Daily Management

To improve energy saving for boilers, it is primarily important to install necessary measuring equipment to assess the status of daily operation. In particular, monitoring of the evaporation ratio, i.e., the amount of the steam generated per unit amount of the fuel consumed, is important. When the performance is found to have declined, causes should be examined and suitable measures should be taken immediately.

Table 5.2.3 is an example of a daily report. For management of boiler operation, data should be recorded for the indicated items. In addition, it is recommended to prepare a graph to show long-term trends for evaporation ratio, temperature of feedwater, temperature of exhaust gas, oxygen concentration in exhaust gas etc., in order to find abnormalities at an early stage. Showing the recorded data in this way also helps to enhance the awareness of the boiler operators of energy saving.

Table 5.2.3 Daily Report of Boiler Operation (Source : Ref. D7)

Manager	Chief operator	Early attendance	Day service	Night service

Date Weather Ambient temperature inside °C Outside °C

	Hours	Pressure kg/cm²	Feed water temperature °C	Feed water quantity: Meter reading	Feed water quantity: Consumption lit.	Fuel oil quantity: Consumption lit.	Fuel oil quantity: Meter reading	Fuel oil temp.: Service tank °C	Fuel oil temp.: Heater outlet °C	Oil pressure: Primary kg/cm²	Oil pressure: Secondary kg/cm²	Exhaust gas temperature °C	Exhaust gas % CO₂	Furnace pressure mmAq	WB static pressure mmAq	Outlet static pressure mmAq	
Every hour measured matters (Hours should be entered from the bottom to the upper.)																	
					(A)	(B)											
					(Take care to the ratio. Example: 13:1)												
	Reading in previous day				Reading in previous day												

	Item	Result: Good	Result: No	Checker
Daily inspection	Relief valve			
	Water gage blowing			
	Automatic feedwater regulator			
	Low water level governor 1st step			
	Low water level governor 2nd step			
	Low water level governor 3rd step			
	Flame detector			
	Combustion state			
	Firing equipment			
	Feed water device			
	Automatic controller			
	Control interlocking device			
Total	Feed water quantity (A)			lit./d
	Fuel oil quantity (B)			lit./d
	Evaporation multiple (A)/(B)			///
	Boiler efficiency			%
	Operating time			h
Fuel	Carry-over			/
	Today receiving quantity			/
	Stock			/

Reference

Boiler efficiency $\frac{Gs(i''-i')}{Lf.r.Hl} \times 100$

Gs = Evaporation kg/h ≒ Feed water quantity lit./h lit./d Blow quantity is reduced.

i'' = Specific enthalpy of generated steam Kcal/kg
Dryness 98%

i' = Specific enthalpy of feedwater Kcal/kg

Lf = Fuel oil quantity lit./h. lit./d

r = Meter passing specific gravity
Specific gravity converted with the meter passing temperature.

Hl = Hh − 6 × 9 × h Kcal/kg
According to the Hh analysis table.
h: Kerosine. Light oil. A grade fuel oil 13%. B grade fuel oil 12%. C grade fuel oil 11%

- Factor $\alpha = \frac{i''-i'}{r.\ Hl} \times 100$
  The factor can be calculated from the average pressure, feedwater temperature, fuel oil temperature, fuel oil specific gravity and low calorific value.
- Evaporation multiple = $\frac{Gs}{Lf} = \frac{\text{Feedwater quantity lit./h. lit./d}}{\text{Fuel oil quantity lit./h. lit./d}}$
- Boiler efficiency = $\frac{Gs}{Lf} \times \alpha\%$
- Steam unit price = $\frac{\text{Fuel unit price Bt/kl}}{\text{Evaporation ratio Ton/kl}}$ Bt/Ton

	Blowing time	Pressure kg/cm²	Blowing quantity l
Boiler water blowdown			
	Continuing blow		
	Total blowing quantity		

	Chemical name	Input g.	Input hour
Chemical injection agent			

	Previous day	Today	Pour
Chemicals pouring device			

	Item	Unit
Water softener	Previous meter reading	/
	Today's meter reading	/
	Treating water quantity	ton
	Basic cycle	ton
	NaCl quantity	kg
	Hardness analysis	Good or no

	Sampling	Pressure kg/cm²	State of boiler. Before and after blowing.
Boiler water	Yes		
	No		

Water quality test				
Feed water	PH		—
	Conductivity		μΩ/cm
	Chloride ion		ppm
	Hardness		ppm
Boiler water	PH		—
	Conductivity		μΩ/cm
	Chloride ion		ppm
	Hardness Phosphate ion		ppm

Description)

5.3 Low-NOx Combustion Methods for Natural Gas

Since construction works needed to supply natural gas to the test plant fell far behind the schedule for various reasons, it was not possible to conduct a comprehensive combustion test for natural gas within the scheduled period ending in mid-December 1994. Therefore, technical data and examples of Japanese experience concerning natural gas combustion are introduced below as a guide for conducting combustion tests of natural gas by the Mexican side.

5.3.1 Methods of Low-NOx Combustion

Methods of low-NOx combustion that can be considered for natural gas boilers are as follows:

a) Improvement of the functioning of low-NOx burners
b) Employment of various low-NOx combustion techniques using existing burners
c) Low-NOx burner plus low-NOx combustion techniques

In the case of a) above, there have been practical examples of achieving NOx concentrations below 50 ppm when a self-recirculation type burner is improved by adding a function of off-stoichiometric combustion (OFS) or two-stage combustion (TS), divided flame combustion (DF), or thin flame combustion (TF).

In the case of b), NOx concentrations below 50 ppm have been also achieved by the combinations of exhaust gas recirculation (EGR) and OFS or steam injection (SI). But these are mostly applied for large-scale boilers having many burners, and are not generally applicable to small-scale boilers.

In the case of c), the representative combinations are the self-recirculation type low-NOx burner plus EGR or SI. In the case of the combination with EGR, there is a practical example in Japan in which a NOx concentration below 30 ppm was achieved with an EGR volume ratio of 10%.

EGR is a method of reducing NOx generation by lowering the flame temperature through recirculating a part of combustion exhaust gas into combustion air. Its effect is large and there are many examples of its adoption. It is considered to be most effective to employ EGR as a low-NOx combustion method for fuels of a low nitrogen content such as natural gas.

The SI method lowers the flame temperature by injecting steam into the combustion chamber, and is said to bring about NOx reduction of around 10%. However, it is not considered to be the best method of NOx reduction in view of energy saving, since it self-consumes generated steam.

5.3.2 Effects of EGR

(1) NOx Reduction Effect

Figure 5.3.1 shows the NOx reduction ratio by the use of EGR by EGR volume ratio and nitrogen content of fuel. The NOx reduction ratio increases as the nitrogen content of fuel decreases, showing the effectiveness for natural gas.

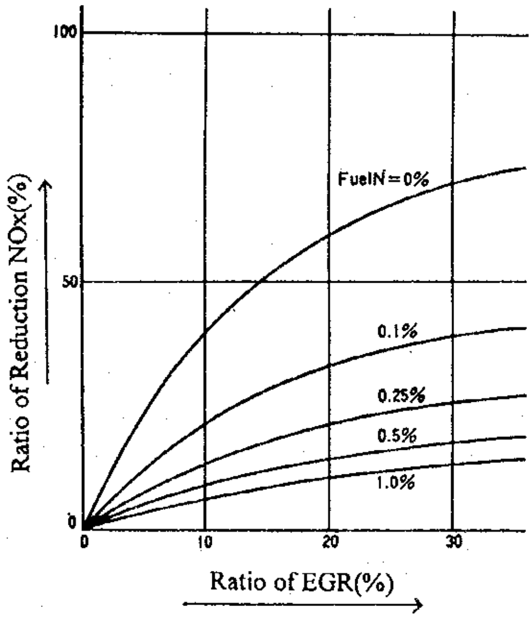
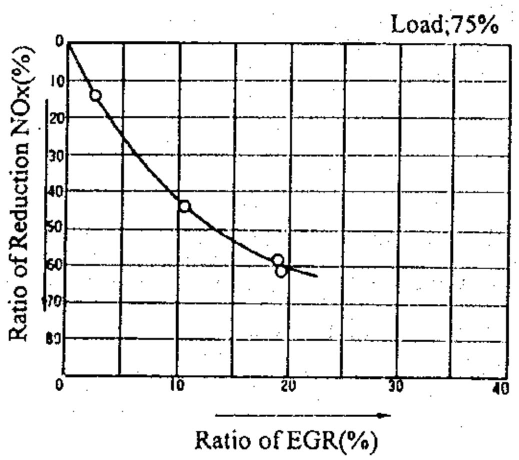
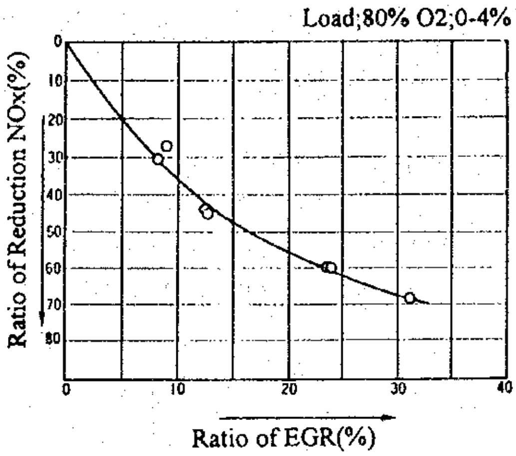


Figure 5.3.1 Effect of EGR on NOx Reduction by EGR Ratio and Nitrogen Content of Fuel (Source : Ref. B11)

Figure 5.3.2 and 5.3.3 shows two examples (A and B) of EGR test using low-NOx burners in Japan in which smoke tube boilers of similar type and capacity to the test boiler (3.6 ton/h flue and smoke-tube boiler) in Pachuca were used.

The average NOx reduction by EGR is around 40% when the EGR rate is 10% and around 60% when the EGR rate is 20%.





(Source : Ref. B12)

Figure 5.3.2 Ratio of EGR vs. Ratio of NOx Reduction (example A)

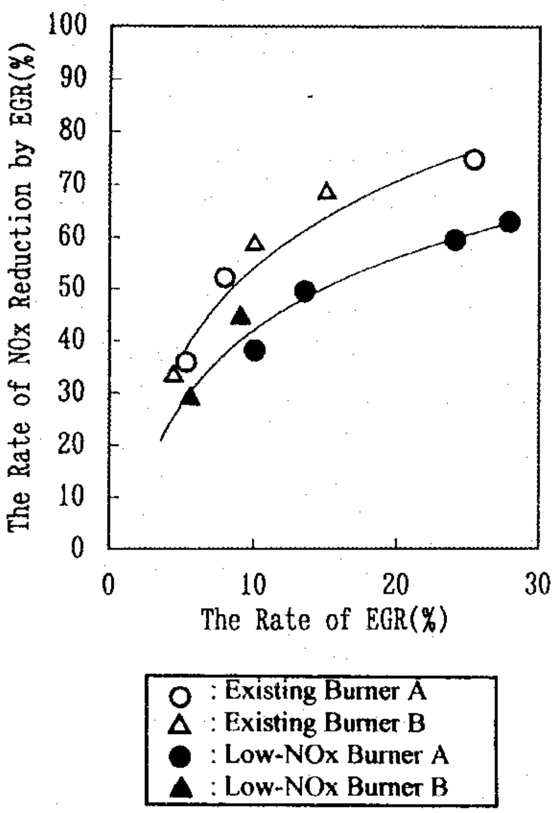
Figure 5.3.3 Ratio of EGR vs. Ratio of NOx Reduction (example B)

Figure 5.3.4 shows the NOx reduction ratio of using EGR when the initial NOx concentrations (without EGR) are 120 - 130 ppm and 60 - 70 ppm. Although there seem to be cases in which above-mentioned rates of reduction are not applicable because of different conditions such as types and structures of boilers and burners, the NOx reduction of EGR effect tends to be smaller as the initial NOx concentration is lower such as the case of using low-NOx burners. The effect of EGR in reducing NOx increases sharply with the increase of EGR ratio when the EGR ratio is lower than 15 - 20%. However, its effect tends to level off as the EGR ratio is increased beyond that range.

(2) Energy Saving Effect and Safety Measures

Although EGR unites two themes, i.e., energy saving and low-NOx combustion, it is also necessary to consider the negative effects. Employment of EGR inevitably increases the length of the flame and brings about a tendency to raise the temperature at the outlet of the combustion chamber. However, there are other factors that govern the outlet temperature of the combustion chamber such as air ratio and combustion load, etc.. Compared with the influence of these factors, that of EGR is very small. The influence of EGR on exhaust gas temperature is even smaller.

As a safety measure, it is necessary to monitor the oxygen concentration of the combustion air continually so that the concentration can be kept at 16% or more after being mixed with exhaust gas.



	Burner	Initial NOx Value (at O2 5%)	Boiler Capacity
○	Exist	125	Watertube 25t/h
△	Exist	128	Watertube 31t/h
●	Low NOx	60	Smoketube 3.6t/h
▲	Low NOx	70	Smoketube 3t/h

Figure 5.3.4 Some Examples of Test Result Employing EGR in Combustion of Natural Gas in Actual Plants
(Source : Edited from technical data of Osaka Gas, Co. and others)

5.4 NOx Reduction Measures for Particular Industrial Furnaces

5.4.1 Glass Melting Furnace

Factories in ZMCM that emit NOx with the highest concentration are glass factories, of which the number is also larger in comparison to other cities.

In glass melting furnaces, glass must be kept at a constant temperature of 1,500°C or more. As most low-NOx combustion methods for boilers ultimately result in lowering the flame temperature, they cannot be used for glass melting furnaces.

Almost all glass melting furnaces have a regenerator (sometimes, a heat-exchange system) for heating the secondary combustion air by using the heat of the exhaust gas in order to increase the temperature inside the furnace and to save fuel. NOx control measures generally employed in glass melting furnaces are shown below.

- NOx control measures for glass melting furnace
  - Melting methods to supress NOx generation
    - Use of electricity in combination with fuels
    - Use of oxygen burners
    - Treatment in a regenerator
    - Use of high grade fuels
  - Installation of denitration facility

(1) Reduction of NOx by Combined Use of Fuel and Electricity

In conventional tank furnaces using heavy oil for manufacturing glass bottles, there are many examples of using electricity in combination with the heavy oil. However, the percentage of use of electricity in these furnaces is still small and the main purpose of the combination is to increase yield rather than to control NOx emission.

There is a type of furnace which uses electricity at a higher ratio than that of those electric boosters. This type uses electricity by a half of required energy. It was reported that, with this furnace, the ceiling temperature was lowered by about 100°C from that of all-fuel furnaces. Generally, as the percentage of electricity use is increased, the size of the furnace can be made smaller. Therefore, the detention time of the combustion gas in the combustion chamber becomes shorter and a considerable reduction of NOx can be expected. Glass Factory (A) in ZMCM operates a facility in such a way with good results.

(2) Reduction of NOx with Oxygen Burners

For combustion of natural gas, which does not contain nitrogen, Glass Factory (A) developed a NOx reduction method in which oxygen is used instead of air for combustion. They have been operating production facilities employing this method since 1993.

The NOx concentration in their glass melting furnace (TF-UMT) at the time of the previous JICA study (in 1990) was 1,226 ppm (at 5% O_2). During the visit for the present Study, it showed a drastic decrease to only 60 - 70 ppm. The reason for this success is that low-priced oxygen has become available through the development of a method that allows N_2 and O_2 in the air to be easily separated by use of synthetic zeolite. With this method, oxygen can be easily manufactured also on-site.

For the absorption and the separation of N_2, molecular sieves 5A are usually used. When natural mordenite is used, it adsorbs a considerable amount of N_2 even under normal temperature, and its adsorbing capacity is larger than that of synthetic zeolite. A process for separating N_2 from air was developed using this characteristic, and it is used for welding and for oxygen inhalation devices. This natural mordenite is said to be found in Mexico and Argentina, and its use is expected in the future.

(3) Reduction of NOx Generation in Regenerators

1) Uniform Gaseous Phase Reaction by the Use of Ammonia

EXXON developed a non-catalytic process using NH_3 as a reducing agent (the license has expired). The agent is applied to the area where the temperature is 750 - 1,000°C near the outlet of a regenerator. With O_2 at 1 - 10%, the mol ratio of NH_3/NO at 1, the mol ratio of H_2/NH_3 at 3 or less, and by adding C_2H_4 or C_3H_8 by 0.01% (100 ppm), it is possible to reduce NOx emission by 60 - 90%.

2) Urea Solution Spraying Method

This method calls for spraying a 20% urea solution near the outlet of the regenerator where the temperature is around 1,000°C. With O_2 of 1 - 10% and the urea/NO mol ratio of 1.1, NOx emission can be reduced by about 40%.

5.4.2 Rotary Cement Kilns

For rotary kilns for cement, fuel consumption per unit production has been improved and NSP kilns (neo-suspension preheater type kiln), which reduce NOx generation by improved combustion, have been developed. Also, technique combining the NSP and the non-selective contact reduction method has been developed and practically applied. For NSP kilns, a combustion chamber called a gas generator is installed in front of the suspension preheater, and NOx is removed by reducing gases such as CO and H2 generated in the generator, and the catalytic actions of the raw materials of cement. With this combination technique, a denitration rate of around 60% is obtained. As it does not require installation of large equipment, the economic burden is small.

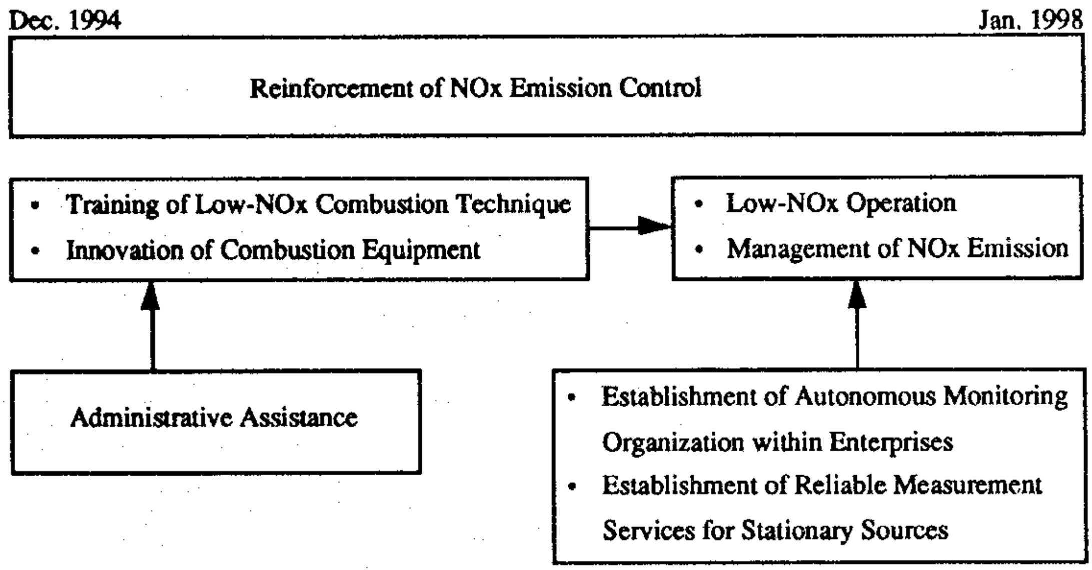
CHAPTER 6 RECOMMENDATIONS FOR DISSEMINATION OF LOW-NOx COMBUSTION TECHNIQUES AND INSTITUTIONAL DEVELOPMENT

Chapter 6 Recommendations for Dissemination of Low-NOx Combustion Techniques and Institutional Development

The characteristics of stationary sources in ZMCM have been understood as described in the previous chapters with respect to fuel used, number and specifications of equipment, and operational condition. Suitable low-NOx combustion techniques for these stationary sources were verified for different types of fuel in the combustion test conducted in Pachuca. In this chapter, necessary measures for dissemination of combustion techniques suitable for ZMCM are recommended in order to achieve compliance with the regulation for NOx emission.

In Mexico, introduction of low-NOx combustion technique is at an early stage, and the system of emission monitoring has not been completely established yet. Therefore, dissemination of low-NOx combustion techniques should be promoted in parallel with the establishment of emission monitoring system. Since it is expected to take a considerable time to promote these two subjects in parallel, the target time of implementing recommended measures is set as January 1998 when the emission standards of NOx and other pollutants are tightened.

The aim of the recommended measures is that most stationary sources comply with the coming emission standards from the target time. Measures recommended in the following sections have mutual relations as shown in the following Figure.



Recommended Measure for Dissemination of Low-NOx combustion Techniques and Institutional Development

6.1 Development of Capability of Boiler Operators for NOx Emission Reduction

6.1.1 Necessity of Technical Improvement

In order to introduce various combustion techniques for reducing emissions of NOx and smoke from stationary sources, development of the capability of personnel engaged in operation of combustion facilities is necessary.

In Mexico, combustion technology to secure the safety operation of boilers was explicitly stipulated in the Regulation for the Inspection of Boilers and Pressure Vessels in 1936, which is still in force now with some modifications. This regulation prescribes requirements of the personnel engaged in boiler operation such as plant masters, operators and firemen, and contains the compulsory examination for qualification of the relevant personnel.

In addition, another scheme for development of capability of the personnel engaged in operation of combustion facilities is provided by CONAE on the voluntary basis for the dissemination of energy-saving operation.

Combustion techniques related to safety and energy saving have successfully taken root through the above-mentioned legal requirements and capacity development scheme. Low-NOx and low-smoke combustion technologies must be disseminated in a similar manner to comply with the emission standards. The present situation regarding compliance with the standards is not satisfactory.

Meanwhile, the NOx emission standards were revised in December 1994 as "NOM-085-ECOL-1994" as described in Chapter 2. The revision of NOx emission standards is shown in Table 6.1.1. Under the new standards, it has become easier for boiler owners to comply with them until December 31, 1997, but the standards will become more stringent from 1998 than the previous ones for most boilers of a capacity above 43,000 MJ/hr, while for the others the standards will be less stringent than the previous ones.

Therefore, many enterprises, particularly those having large boilers, are considering the adoption of NOx control measures to meet the new emission standards. However, operation of combustion equipment for NOx reduction requires promotion of the skill of operators. For this purpose, conduct of technical training is recommended particularly for those who are engaged in the operation of boilers of a capacity above 43,000 MJ/hr.

Combustion facilities other than boilers are excluded in the subsequent discussions because they are also excluded in the emission standards of NOM-085.

Table 6.1.1 Revision of NOx Emission Standard for Boiler

Capacity of boiler (MJ/hr)	Fuel type	NOx emission standard (ppm)					
		Until Dec. 1994		Until Dec. 1997		From Jan. 1998	
		ZMCM	RP	ZMCM	RP	ZMCM	RP
up to 5,250	heavy oil or gasoil	NA	NA	NA	NA	NA	NA
	other liquid	NA	NA	NA	NA	NA	NA
	gas	NA	NA	NA	NA	NA	NA
5,250 to 43,000	liquid	150	270	220	400	190	375
	gas	130	180	220	400	190	375
43,000 to 110,000	liquid	140	250	180	400	110	375
	gas	120	160	180	400	110	375
above 110,000	solid	NA	NA	160	400	110	375
	liquid	130	240	160	400	110	375
	gas	100	150	160	400	110	375

Source: Refs. B3, B6
Note: 1) RP: Areas other than the metropolitan areas of México, Monterrey, Guadalajara and the critical zones
2) NA: Not applicable

6.1.2 Techniques to be Introduced

(1) Basic Consideration on the Subjects

The combustion techniques for technical training should be those that are helpful for boilers of the capacity larger than 43,000 MJ / hr using gas or diesel oil or gas oil to meet 110 ppm of the NOx standard.

The adoption of appropriate combustion facilities and advanced technology is effective only when operators are familiar with suitable combustion techniques. This is why a training course to develop the capacity of boiler operators is proposed in the context of wider adoption of low-NOx combustion techniques. The main subjects to be learned in the training course are suggested to be the following four items:

a. Mechanism of NOx and smoke generation through combustion
b. Principles of pollutants reduction and their application
c. Operation methods that reduce pollutants (including practical exercise)
d. Energy saving operation

Subjects a. and b. above were presented as the basic knowledge in a separate volume, Text Book for Combustion Test, prepared in the early stage of the present Study. An operation method for pollutants reduction common to boilers regardless of the kind of fuel is the low air ratio combustion: it is the essence of low-NOx combustion. The effect of the low air ratio combustion in the NOx reduction should be demonstrated during the course. Visible differences of flames caused by air ratio should also be presented.

The course is to use an advanced boiler of small capacity, so that the trainees would have an opportunity to directly confirm the theory of NOx reduction learned in the lecture. Another expected advantage of the practice is that the trainees would discover the way to apply low-NOx technology suitable to their plants based on the recognition of similarity and difference between their plants and the test plant when the practice is held.

(2) Object Techniques for Training by Kind of Fuel

1) For Boilers Burning Diesel Oil or Gas Oil

The exhaust gas recirculation (EGR) method and low-NOx burners of the self-recirculating type are considered to be appropriate technologies to be introduced in Mexico. As a result of the test, it was found that the fuels with an ordinary content of nitrogen, 270 ppm for diesel and 720 ppm for gasoil, can be burnt with the exhaust gas NOx concentration lower than 110 ppm by using normal burners with afore-mentioned techniques, EGR.

As for diesel oil combustion, the NOx concentration was controlled within 110 ppm by atomizing either with air or steam as shown in Table 6.1.2. As for gas oil, it was found that the NOx concentration was possible to be controlled below 110 ppm by using steam atomizing and maintaining the oxygen content in exhaust gas below 6%. It is desirable that the oxygen content, however, be controlled at 3% or less in view of the energy saving.

Table 6.1.2 Exhaust Gas NOx Concentration in the Combustion Test for Oils of Ordinary Nitrogen Content Using Normal Burner

Condition	NOx concentration (ppm)	
	Diesel oil	Gas oil
Air atomizing	90 - 100	80 - 160
Steam atomizing	60 - 90	80 - 120
Oxygen content in exhaust gas	1 - 7 %	
Boiler loading rate	50 - 90 %	

2) For Boilers Burning Natural Gas

The EGR method is considered to be an appropriate method to be introduced in Mexico. Test results are not available because the tests of gas combustion were not conducted since the fuel was not available during the scheduled test period. But since specifications of natural gas do not vary so much by countries, the low-NOx techniques for gas-fired boiler used in Japan are thought to be also applicable to the boilers in México. Natural gas, in general, contains little nitrogen. Since the EGR method is most effective in reducing NOx emission in combustion of low-nitrogen fuel, it is most suitable to be used in the natural gas combustion.

6.1.3 Initial Stage of Capacity Development

The technology transfer seminar conducted in the present Study can be considered as the technical training in the initial stage of the capacity development of boiler operators in Mexico.

(1) Program of Technical Training

The course of technical training in Mexico should focus on improvement of knowledge of NOx reduction and the operational techniques related to boiler operation. These subjects can be learned effectively in a combination of lecture and practice. The lecture and group exercise were conducted in the technology transfer seminar in the current Study in the following manner.

1) Lecture
   a. Explanation of the outline of the course
   b. Introduction of theoretical matters on low-NOx combustion and energy saving
   c. Explanation of outline of the test plant and test operation

2) Group Exercise at the Test Plant
   a. Explanation for the function of the plant in relation to the control parameter
   b. Practice of combustion control
   c. Evaluation of test results

(2) Participants of the Program

The selection of participant enterprises for the technology transfer seminar in the present Study was undertaken by INE, and persons to attend the course were selected among the plant master (Jefe de planta), engineers, operators and management staff by the participant enterprises. The enterprises having large boilers were given a priority for the participation. But those having smaller ones who had serious problems in reducing NOx emission were also accepted for participation. In addition, the government organizations concerned also dispatched their personnel. As a result, 21 private enterprises and 9 government organizations dispatched 76 participants.

All participants were classified into three groups as shown below, and given different practice program respectively: