were selected, with recommendation by SEDUE, mostly from the factories categorized as 1), considering the largeness as stationary air pollution source. However, they also included some service and commercial establishments as pollution sources having small-scale boilers. The detailed questionnaire forms were distributed priorly to the establishments of the category 2), and after receiving the answers, they were visited for confirmation of the answers and for simplified measurements of operational conditions and flue gas characteristics of combustion facilities. Among these establishments, those that are considered particularly important were further selected for the diagnostic survey as categorized in 3). Questionnaire items for the establishments of the category 4) included types of combustion facility, fuel consumption and amount of pollutant emissions in addition to general information on the establishments such as name, address, type of industry and scale. To those establishments emitting pollutants such as HC from non-combustion facilities, the question items concerning this aspect were added.

3.1.2 Representativeness of the Investigated Sources in the Metropolitan Area

In this section, the relation between the sources in this Study investigated and the whole stationary sources in the Metropolitan Area is analyzed.

Table 3.1.2 shows the number of establishments covered by the various investigations described above excluding duplicated ones as far as possible.

Table 3.1.2 Number of Establishments Investigated

Kind of Study	Number of Establishment	Sector
Detailed on-site questionnaire by the JICA Study Team	97 (82)	manufacture, service and commercial
1000 factory questionnaire by SEDUE (in this Study)	969 (935)	manufacture, service and commercial
Existing data of SEDUE	371 (364)	manufacture
DDF's survey *	6,070 (0)	service and commercial
CANAIBAL's survey **	203 (0)	public bath
Total	7,710 (1,381)	

Note: * Survey area limited within DF.
** Survey area limited within DF except 13 bathhouses in MCEM.
( ) Number excluding the service and commercial sector.

As previously shown in Table 2.3.8 and Table 2.3.10, the number of manufacturing industrial establishments is about 19,000 in DF and about 8,000 in MCEM. When these establishments (hereinafter called "factories") are classified by scales in terms of number of employees, and factories of unknown scale are regarded as of micro-scale, the number of each scale of factories in AMCM is as shown in Table 3.1.3.

Table 3.1.3 Number of Factories by Scale in AMCM

Area	Large	Medium	Small	Micro	Total
DF (1987)	207	427	3,911	14,770	19,315
MCEM (1986)	379	247	1,637	5,858	8,121
AMCM Total (percentage)	586 (2.1)	674 (2.5)	5,548 (20.2)	20,628 (75.2)	27,436 (100)

Source: Table 2.3.8 and Table 2.3.10

The number of the factories at 1,381 covered in this Study is about 5% of the total in AMCM. However, since these factories were sampled in order of largeness in scale, it is considered that a large majority of large and medium scale factories in terms of pollutant emission were covered by this Study.

As regards the service and commercial sector, Table 2.3.2 indicates that there are about 191,000 establishments in DF and about 76,000 in the whole State of Mexico. However, the DDF's investigation clarified that there are only some 6,300 establishments or 3.3% of the total in DF that are emitting pollutants. When this ratio is applied to the State of Mexico, the number of the similar establishments is estimated at 2521, i.e., in MCEM less than 2500. These figures indicate that more than 70% of service and commercial establishments emitting pollutants in AMCM were covered by this Study.

In conclusion, information on the total 7710 pollution sources covered by this Study will well represent the characteristics of stationary air pollution sources in AMCM.

3.2 Sources Investigated by Detailed On-site Questionnaire and Diagnostic Survey

3.2.1 Fuel Consumption

Table 3.2.1 summarizes the consumption of fuel by kinds classified by scales of establishments investigated through the detailed on-site survey for a total of 97. As shown in Table 3.2.2, scales of combustion facilities were categorized into four, i.e., large, medium, small, and micro in terms of fuel consumption of combustion facilities that are also categorized into six types. Scale of an establishment was determined using Table 3.2.2 in the manner that if total consumption of a fuel for a same type of facility is categorized as large, this establishment was categorized as large.

Since majority of the establishments fall into the category of large, breakdown of fuel consumption by kinds shown in Table 3.2.1 reflects characteristics of large factories. Heavy oil and natural gas are the major fuels, and diesel, LPG and coke are used as supplement.

Consumption of heavy oil totals to 0.8 million m^3/yr to make up 50% of the total consumption in AMCM. Natural gas consumption amounts to 2.5 billion m^3/yr sharing about 96% of the total in AMCM. Factories categorized as large consumed over 90% of heavy oil and natural gas of their totals consumed by the 97 establishments. Shares of these factories in the totals in AMCM are 46% for heavy oil (by 13 factories) and 93% for natural gas (by 16 factories). Number of large-scale factories by types of industry and by kinds of fuel is shown in Table 3.2.3. Paper, chemical, and non-metallic mineral factories are the dominant constituents of large factories.

Table 3.2.1 Fuel Consumption by the 97 Establishments Investigated by Detailed On-site Questionnaire

Kind of Fuel	Unit	Scale of establishment	Fuel consumption
Heavy oil	$10^3 m^3/yr$	large	747
		medium	45
		small	20
		micro	3
		Sub-total	815
Diesel	$10^3 m^3/yr$	medium	20
		small	8
		micro	1
		Sub-total	29
Natural gas	$10^6 m^3/yr$	large	2,399
		medium	69
		small	9
		micro	1
		Sub-total	2,478
LPG	m^3/yr	large	6,324
		micro	49
		Sub-total	6,373
Coke	ton/yr	large	10,920
		medium	134
		small	24
		Sub-total	11,078

Table 3.2.2 Scale Definition of Combustion Facilities in Terms of Fuel Consumption

FUEL (UNIT)	SCALE	SCALE DEFINITION IN TERMS OF FUEL CONSUMPTION					
		1:BOILER	2:DRYER	3:METAL MELTING FURNACE	4:METAL HEATING FURNACE	5:CERAMIC FURNACE	6:GLASS FURNACE
HEAVY OIL	LARGE	15,001 OR MORE	3,001 OR MORE	3,001 OR MORE	3,001 OR MORE		15,001 OR MORE
	MEDIUM	3,001~15,000	501~3,000	501~3,000	501~3,000	3,001 OR MORE	3,001~15,000
(M3/Y)	SMALL	501~3,000	101~500	101~500	101~500	501~3,000	501~3,000
	MICRO	500 OR LESS	100 OR LESS	100 OR LESS	100 OR LESS	500 OR LESS	500 OR LESS
DIESEL	LARGE	15,001 OR MORE	3,201 OR MORE	3,201 OR MORE	3,201 OR MORE		
	MEDIUM	3,201~15,000	551~3,200	551~3,200	551~3,200		
(M3/Y)	SMALL	551~3,200	101~550	101~550	101~550		
	MICRO	550 OR LESS	100 OR LESS	100 OR LESS	100 OR LESS		
NATURAL	LARGE	15,001 OR MORE	3,501 OR MORE	3,501 OR MORE	3,501 OR MORE		15,001 OR MORE
GAS	MEDIUM	3,501~15,000	601~3,500	601~3,500	601~3,500	3,501 OR MORE	3,501~15,000
(1000M3/Y)	SMALL	601~3,500	101~600	101~600	101~600	601~3,500	601~3,500
	MICRO	600 OR LESS	100 OR LESS	100 OR LESS	100 OR LESS	600 OR LESS	600 OR LESS
LP GAS	LARGE		101 OR MORE				
	MEDIUM						
(M3/Y)	SMALL		51~100				
	MICRO		50 OR LESS				
COKE	LARGE			401 OR MORE			
	MEDIUM			201~400			
(TON/Y)	SMALL			101~200			
	MICRO			100 OR LESS			

Note: The following types of industrial furnaces are categories in the same manner as boiler.
7: cement kiln, 8: asphalt kiln, 9: heating furnace, 10: others

Table 3.2.3 Composition of Large Scale Factories by Industrial Sector and Fuel Kind

Sector	Number of Factories			
	Heavy oil	N. gas	LPG	Coke
Food	1	-	-	-
Drinks	1	1	-	-
Paper and its product	5	2	1	-
Chemicals	2	4	-	1
Petroleum refining	1	1	-	-
Non-metallic minerals	1	5	1	-
Basic metals	-	1	-	-
Power plant	2	2	-	-
Total	13	16	2	1

Among industrial sectors, six sectors of paper, chemical, petroleum refining, non-metallic minerals, basic metals and power generation industries together make up more than 90% of the total consumption of the major fuels, i.e., heavy oil and natural gas. Figure 3.2.1 shows this situation. The consumption by power plants is particularly large with 55% of the total for natural gas and 50% of the total for heavy oil and natural gas in heat equivalent.

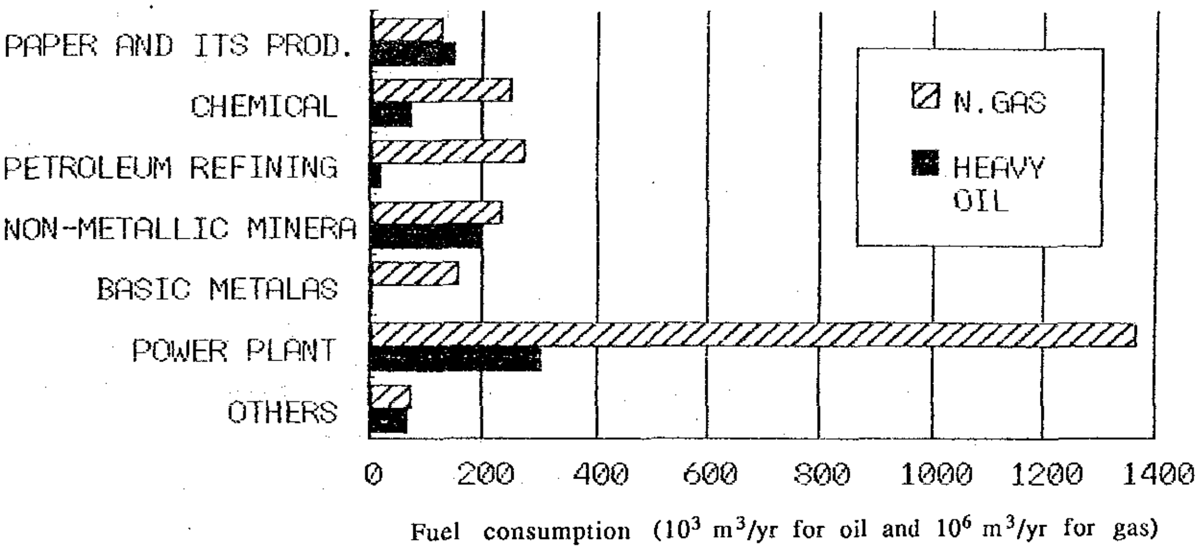


Figure 3.2.1 Consumption of Major Fuels by Types of Industry

3.2.2 Pollutant Emissions

Amounts of emission of NOx, SO_2 and PM (particulate matter) were calculated from fuel consumption and emission factors estimated primarily based on the results of the diagnostic survey. Emission factors for NOx and PM were obtained by taking an average of measured values for each type of combustion facility. They are shown in Table 3.2.4. For the factory subjected to diagnostic survey, an average of values measured for a particular type of facility in that factory was used.

Table 3.2.4 Emission Factors for NOx and PM Obtained by the Diagnostic Survey

Type of Facility	Pollutant	Hevy oil	Diesel	N. gas
		kg/m^3	kg/m^3	kg/1,000m^3
Boiler	NOx	6.4	1.3	1.9
	PM	3.1	0.5	0.0
Dryer	NOx	-	-	4.0
Metal melting furnace	NOx	-	-	0.7
Metal heating furnace	NOx	-	-	1.1
Aggregate dryer	NOx	-	4.7	-
Glass melting furnace	NOx	7.3	-	23.3
Cement kiln	NOx	7.4	-	-
Heating furnace	NOx	-	-	1.6

For boilers of mixed combustion of heavy oil and natural gas, emissions of NOx and PM were estimated using the emission factor obtained for each fuel and by adding amounts of emission obtained separately for heavy oil and natural gas. The ratios of the emission factors of natural gas and heavy oil for NOx and PM are as follows:

NOx natural gas (1000m^3) : heavy oil (1m^3) = 1 : 3.5
PM natural gas (1000m^3) : heavy oil (1m^3) = 1 : 100

Emission of SO_2 was calculated assuming that sulfur in fuel is converted to SO_2 by 100%. For establishments where the sulfur content of fuel was not measured, sulfur content shown in Table 3.2.5 was used.

Table 3.2.6 shows amounts of emissions of NOx, SO_2 and PM calculated under the assumptions stated above and totaled for the 97 establishments subjected to the detailed on-site survey. Breakdown by scales of establishments is also shown in Figure 3.2.2. The annual total emissions are about 16,000 ton for NOx, about 49,000 ton for SO_2, and about 10,000 ton for PM. Large-scale factories emit more than 90% of the total emissions of NOx and SO_2.

Table 3.2.5 Sulfur Content of Fuels

Kind of fuel	Sulfur Content (%)
heavy oil (H) *	3.5
heavy oil (L) **	3.0
diesel	1.0
coke	0.5
natural gas	0
LPG	0

Note: * heavy oil "heavy"
** heavy oil "ecological" and "light"

Table 3.2.6 Pollutant Emission by Scales of Establishment

Pollutant	Emission by Scales of Establishment (ton/yr)				
	large	medium	small	micro	Total
NOx	14,580	978	223	17	15,798
SO_2	50,516	3,115	1,491	170	55,292
PM	6,044	3,746	82	8	9,880

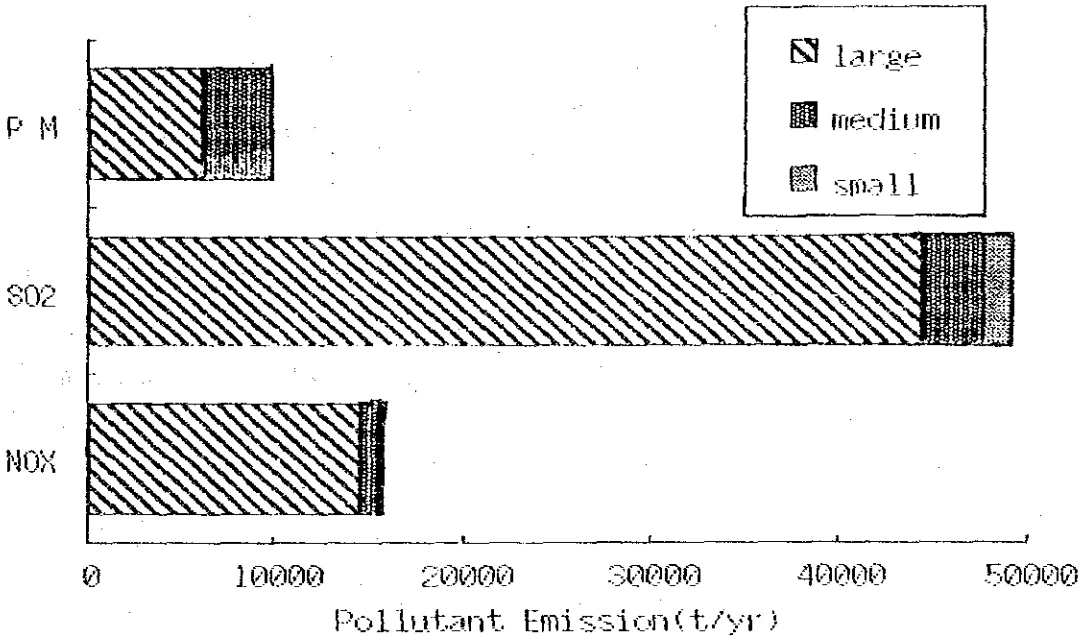


Figure 3.2.2 Pollutant Emission by Scales of Establishment

As for pollutant emissions by types of industry, the previously stated six industrial sectors whose consumption of heavy oil and natural gas is high and the coal and petroleum product sector make up more than 90% of the total for NOx, SO_2 and PM. This feature is also shown in Figure 3.2.3. Among all, the emissions of these three pollutants from the power plants and the non-metallic mineral sector are large. Amount of emission of SO_2 from these two sectors is followed by 11 plants of the paper sector.

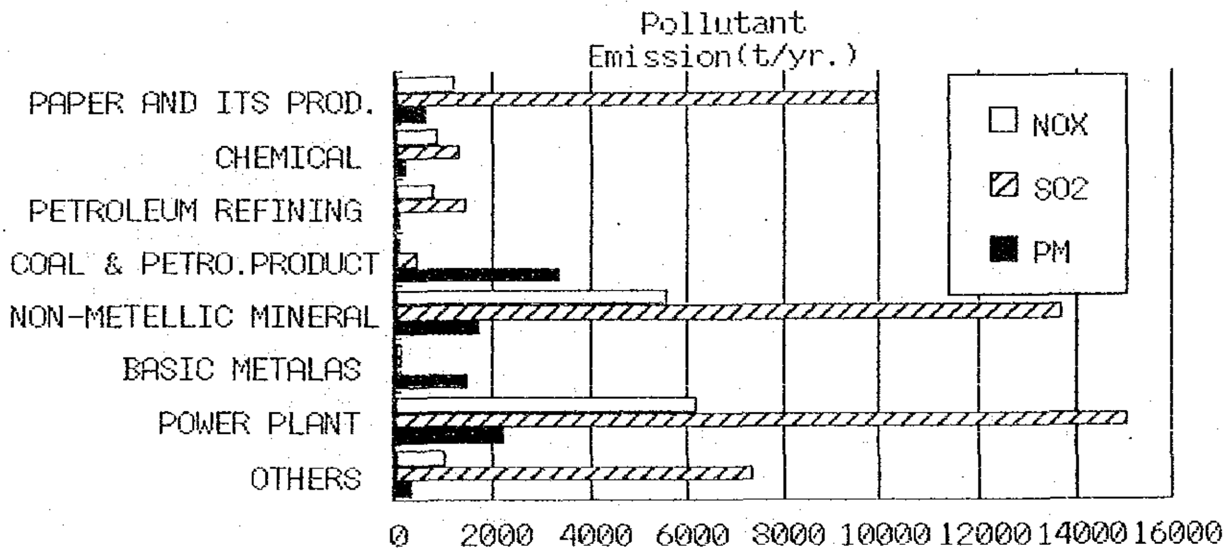


Figure 3.2.3 Pollutant Emission by Types of Industry

Two factories of non-metallic mineral industry make up a large share of the total emission of PM, although their share in fuel consumption is relatively small. This may be partly attributeed to the method of estimation in which a large value of emission factor obtained at one factory through the diagnostic survey was also used for another factory.

Table 3.2.7 shows pollutant emissions by kinds of fuel, and Figure 3.2.4 their ratios in SO_2 and NOx emissions. Almost all of SO_2 emissions is originated from heavy oil, while heavy oil and natural gas make almost equal shares in NOx emission. For PM emissions, since a large portion is originated from raw materials processed in certain types of industrial furnaces, breakdown by fuel types is not meaningful except for boilers.

Table 3.2.7 Pollutant Emission by Kinds of Fuel

Pollutant	Heavy oil (ton/yr)	Diesel (ton/yr)	N. gas (ton/yr)	LPG (ton/yr)	Coke (ton/yr)
NOx	6,277	100	9,395	10	16
SO2	54,581	601	0	0	111
PM	4,018	3,376 *	2,485 *	1	-

Note: * Virtually all of these PM emissions are not originated from fuel but from raw materials processed in industrial furnaces.

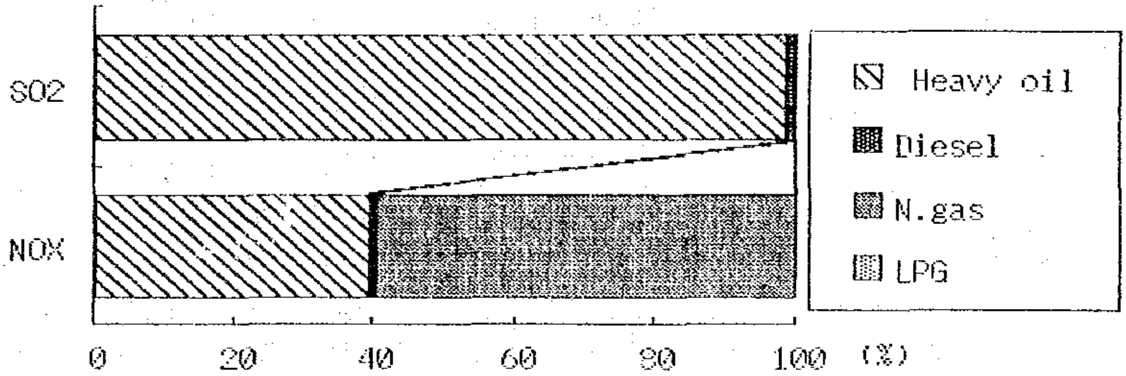


Figure 3.2.4 Ratio of Pollutant Emission by Kinds of Fuel

3.3 Results of Investigation by SEDUE

3.3.1 Questionnaire on 1000 Factories

As a part of the current Study, a questionnaire survey on 1030 factories was conducted by SEDUE. When the factories duplicated with the detailed on-site survey are excluded, the total number of factories reduces to 969. In the following description, this survey will be still referred to as " 1000 factory questionnaire", although the data treated are of those 969 factories. Total consumption of fuels consumed in these 969 factories is shown in Table 3.3.1.

Table 3.3.1 Fuel Consumption Obtained by 1000 Factory Questionnaire

Kind of fuel	Unit	Consumption
Heavy oil	$10^3m^3/yr$	190
Diesel	$10^3m^3/yr$	84
Kerosene	$10^3m^3/yr$	16
Natural gas	$10^6m^3/yr$	735
LPG	$10^3m^3/yr$	(2,928)

The total amount of heavy oil at 190,000 m^3/yr makes up about 12% of the estimated total heavy oil consumption in AMCM, and that of natural gas at 735 million m^3/yr makes up about 30%. The total for diesel is 84,000m^3/yr which makes up about 25% of the assumed total consumption at stationary sources in AMCM.

Since the figure for LPG is excessively large, there may be many errors in answering the questionnaire. Consumption of kerosene is very small.

Table 3.3.2 shows the total emission of NOx, SO_2, and PM.

Table 3.3.2 Pollutant Emission Obtained by the 1000 Factory Questionnaire

Pollutant	Emission (ton/yr)
NOx	3,601
SO_2	14,628
PM	810

Since recording of pollutant emissions in the data base (file name: HORNOS) of the 1000 factory questionnaire has not been completed by SEDUE, pollutant emissions of this portion were estimated by using the emission factors for the major fuels shown in Table 3.3.3

Table 3.3.3 Emission Factors Used for the Factories Included in Data File

Pollutant	Heavy oil (kg/m^3)	Diesel (kg/m^3)	Kerosene (kg/m^3)	N. Gas (kg/m^3)
NOx	7.2	1.8	1.5	2.8
SO_2	68.4	18.7	3.4	0.0096
PM	2.75	1.8	1.2	0.16

3.3.2 Factories Previously Investigated by SEDUE

SEDUE investigated about 600 factories prior to the current Study and the data recorded in the file "DATGEN." By excluding the factories duplicated with the detailed on-site survey or the 1000 factory questionnaire, the total number of factories reduces to 371. Table 3.3.4 shows total consumption of fuels in these 371 factories.

Table 3.3.4 Fuel Consumption Obtained by SEDUE's Existing Data

Kind of fuel	Unit	Consumption
Heavy oil	$10^3m^3/yr$	36
Diesel	$10^3m^3/yr$	8
Kerosene	$10^3m^3/yr$	0
Natural gas	$10^6m^3/yr$	104
LPG	$10^3m^3/yr$	10,122 *

Note : * Since the supply amount of LPG is considered to be roughly equivalent to that of heavy oil in terms of heat value, this figure for LPG seems to be excessively large.

Table 3.3.4 shows total emissions of pollutants obtained from the data file "DATGEN" using the emission factors of Table 3.3.3 as in the case of "HORNOS."

Table 3.3.4 Pollutant Emission Obtained From SEDUE's Existing Data

Pollutant	Emission (ton/yr)
NOx	564
SO_2	2,613
PM	130

3.4 Service and Commercial Establishments

3.4.1 Sources Previously Investigated by DDF

DDF, in 1988, investigated a total of 6,302 service and commercial establishments equipped with combustion facility. Results of the investigation were present in a report entitled "Action Program for Control of Pollution of Mercantile Sector".

Proposes of this investigation were as follows:

1) to prepare an inventory of service and commercial facilities existing in each DELEGACION by means of questionnaire and exhaust gas measurement

2) to know geographical distribution of these facilities in DF

3) to know types of facilities and their operation hours

4) to evaluate emissions of pollutants in relation to consumption of various kinds of fuel

5) to compare and analyze quantities of pollutant emission obtained both from emission factors and sample measurements

6) to prepare a computer data file containing results of the investigation to make available for utilization

7) to present various alternative measures for prevention and reduction of pollutant emissions

(1) Fuel Consumption

Table 3.4.1 shows number of establishments investigated by types of business and kinds of fuel used. Over 50% of all establishments use natural gas, and 80% of them are in the sector of food. Diesel is widely used in other sectors, but a majority of bathhouses use heavy oil.

Table 3.4.2 shows fuel consumption by types of business and kinds of fuel. Diesel and heavy oil are used at an equivalent level about 50,000m^3/yr. Consumption of kerosene is about a half of that of diesel or heavy oil, and consumption of natural gas, when compared in calorific value, is about 1/300 of that of diesel or heavy oil.

Table 3.4.1 Number of Establishments by Types of Business and Kinds of Fuels

Sector	N. gas	Diesel	Heavy oil	Kerosene	Others (1)	Total
Food (2)	3,410	296	5	56	2	3,769
Public bathhouse	0	1	158	73	0	232
Sport center	18	48	11	2	2	81
Hospital	5	13	2	0	0	20
Hotel	11	382	1	10	0	404
Others (3)	810	208	15	718	45	1,796
Total	4,254	948	192	859	49	6,302
Excl. bathhouse	4,254	947	34	786	49	6,070

Note: (1) Firewood and coal

(2) Includes corn flour milling, baker, and tortilla maker

(3) Includes dry cleaner, auto-service shop, coffee milling, laboratories, etc.

Table 3.4.2 Consumption of Fuel by Types of Business

Sector	N. gas (m^3/yr)	Diesel (m^3/yr)	Heavy oil (m^3/yr)	Kerosene (m^3/yr)	Others (ton/yr)
Food	112,516	14,188	24	725	24.7
Public bathhouse	0	48	36,889	12,524	0.0
Sport center	1,057	7,372	7,890	100	0.0
Hospital	1,968	1,324	1,152	0	0.0
Hotel	494	20,331	1,620	204	0.0
Others	35,910	8,260	4,092	12,848	0.0
Total	151,620	51,522	51,668	26,401	24.7
Excl. bathhouse	151,620	51,474	14,779	13,877	24.7

(2) Emission of Pollutants

DDF estimated amounts of emission of SO_2 and PM. As shown in Table 3.4.3, the total emission of SO_2 is 4,135 ton/yr, and PM 306 ton/yr. The emission from food sector, which uses primarily natural gas, is rather small despite the large number of facilities. The emissions from public bathhouses, which use primarily heavy oil, are large although the number of bathhouses are rather small.

Table 3.4.3 Emissions of SO_2 and PM by Types of Business

(Unit: ton/yr)

Sector	SO_2	PM
Food	251	26
Public bathhouse	2,253	136
Sports center	576	35
Hospital	88	6
Hotel	440	42
Others	527	61
Total	4,135	306
Excl. bathhouse	1,882	170

3.4.2 Other Investigation

Following the DDF's investigation described in Section 3.4.1, the National Chamber of Bath Industry (CANAIBAL) surveyed in 1989 a total of 203 bathhouses of which 190 were in DF and 13 in MCEM. This survey is said to have covered about 90% of bathhouses operated in DF in 1989. The purposes of the survey were as follows:

1) to evaluate combustion efficiency and amount of SO_2 emission of each of boilers used in the bathhouses of the CANAIBAL members

2) to collect basic data on operational conditions, status and maintenance of combustion equipment

3) to propose general and specific measures considered to be suitable for improvement of combustion efficiency and reduction of pollutant emissions based on the results of the survey and evaluation

4) to conduct general diagnosis of the actual situation of the sector in relation to contribution to the air pollution

(1) Fuel Consumption

A total of 369 boilers were used in the 203 bathhouses, and 98% of the boilers used heavy oil as fuel, and the rest used diesel or LPG. Total consumption of heavy oil was 130 m^3/day. Assuming 6 days per week of operation, annual consumption of heavy oil is about 40,000m^3. This amount is equivalent to about 5% of the total consumption of heavy oil by the 97 establishments subjected to the detailed on-site questionnaire, sharing a small portion to the total for AMCM. Average consumption per bathhouse is about 200 m^3/yr, and it is a little less than the average of the 9 bathhouses using heavy oil surveyed by the detailed on-site questionnaire at 263 m^3/yr.

(2) Emission of Pollutants

Table 3.4.4 shows amounts of emission of NOx, SO_2 and PM estimated in the survey.

Table 3.4.4 Emissions of Pollutants form Public Bathhouses Surveyed by CANAIBAL

Pollutant	Emission	
	kg/day	ton/yr
NOx	500	156
SO_2	5,560	1,734
PM	1,040	324

When compared with the total emissions of the 97 establishments subjected to the detailed on-site survey, the emissions shown in Table 3.4.4 are 1% for NOx, 2% for SO_2, and 3.3% for PM. Contribution to the air pollution in the Metropolitan Area is considered to be small. The CANAIBAL's study concluded concerning contribution to the air pollution as follows. "The largest cause for air pollution by bathhouses is the quality of fuel. 75% of the amount of pollutants emitted is originated from sulfur, vanadium and sediments contained in the fuel, and these substances present additional difficulty in operation of systems." Also, a program financing improvement of combustion facilities was proposed, since these bathhouses are deemed to present problems to citizens and buildings in neighboring areas.

3.5 Summary

3.5.1 Total Amount of Fuel Consumption and Pollutant Emission

(1) Structure of Fuel Consumption in the Stationary Sources

Fuel consumption figures obtained through the various investigations are summarized in Table 3.5.1.

Table 3.5.1 Fuel Consumption at Stationary Sources in AMCM

Kind of Study		Study Team	SEDUE	SEDUE	DDF	CANAIBAL	Total
Number of Sample		97	969	371	6,070	203	7,710
Fuel	Heavy oil (10^3m^3/yr)	815	190	36	15	40	1,096
	Diesel (10^3m^3/yr)	29	84	8	51	0	172
	Kerosene (10^3m^3/yr)	-	16	0	26	-	42
	N. gas (10^6m^3/yr)	2,478	735	104	0.2	-	3,317
	LPG (10^3m^3/yr)	6	(2,928)	(10,122)	-	0	-
	Coke (10^3ton/yr)	11	-	2	-	-	13

Table 3.5.1 indicates that, in terms of heat value, heavy oil, natural gas and LPG are consumed by large amount. However, since the amount of LPG indicated above is excessively large, there seems to be some errors in the survey data.

The total consumption figures of heavy oil and natural gas in AMCM in 1989 informed by the supply side are 1,607 x 10^3m^3 and 2,584 x 10^6m^3, respectively, as shown in Table 2.4.4. The amounts shown in table 3.5.1 make up 68% of the supply total in 1989 for heavy oil and 128% for natural gas. Since the end of 1989, the use of heavy oil was restrained and partially changed over to natural gas as a measure of air pollution control. As a result, the consumption of heavy oil in 1990, the period of this Study, decrease from the previous year, and the consumption of natural gas increased. The PEMEX's projected amount of supply of natural gas in 1990 was 3.411 million m^3 as shown in Table 2.4.4.

Since the amount of heavy oil consumed in the power plants in 1990 decreased by about 400,000 m^3 from the previous year, the total fuel consumption in the stationary sources investigated in this Study is considered to cover most of the total supply amount in 1990.

Main feature of consumption of each fuel is as follows.

1) Heavy oil

Of the total 1,096 x $10^3 m^3$ shown in Figure 3.5.1, about 75% is used by the 97 establishments surveyed by the Study Team. When the consumption by the 969 establishments (file name: HORNOS) and the 371 establishments (file name: DATGEN) surveyed by SEDUE are added, the percentage becomes 95%.

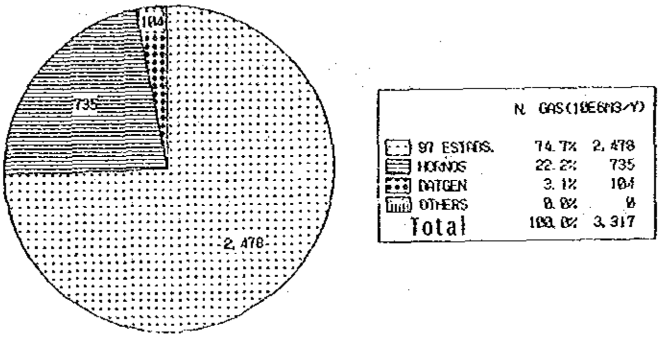


Figure 3.5.1 Heavy Oil Consumption

2) Diesel

Although diesel is used by various sectors, its share in the total energy consumption in stationary sources is rather small.

3) Natural gas

As shown in Figure 3.5.2, the 97 establishments surveyed by the Study Team consumed 75% of the total of 3,317 million m^3. When the 1,340 establishments surveyed by SEDUE (HORNOS and DATGEN) are added, the percentage becomes almost 100%.

Similar to heavy oil, natural gas is mostly used by factories. Consumption by service and commercial sector is negligible.

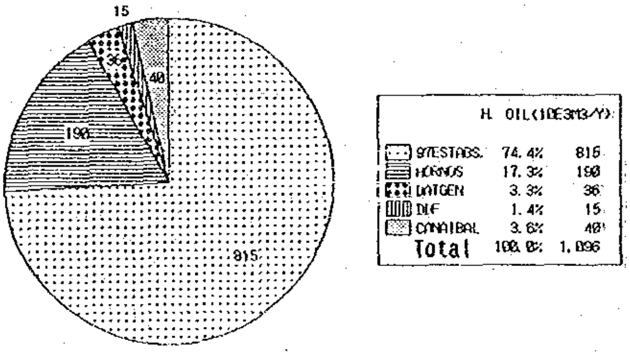


Figure 3.5.2 Natural Gas Consumption

4) LPG

Actual state of consumption of LPG by stationary users are not clear.

5) Kerosene, coke and others

Use of these fuels are limited to small-scale establishments and consumption is small.

(2) Pollutant Emissions From Stationary Sources

Pollutant emissions obtained through the various investigations are summarized in Table 3.5.2.

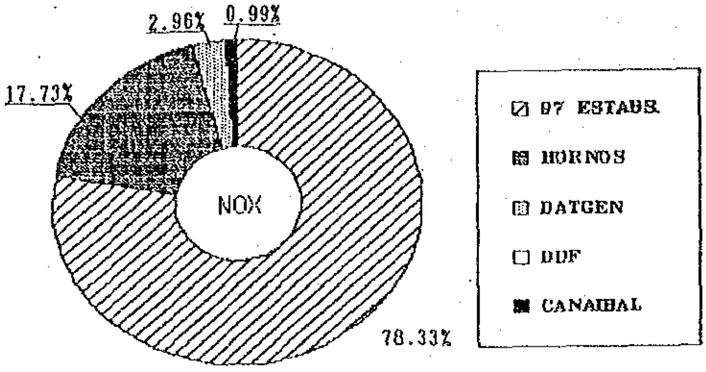
Table 3.5.2 Pollutant Emissions from Stationary Sources in AMCM

Kind of Study		Study Team	SEDUE	SEDUE	DDF	CANAIBAL	Total
Number of Sample		97	969	371	6,070	203	7,710
Pollut-ant	NOx (10^3ton/yr)	15.8	3.6	0.6	0.6	0.2	20.8
	SO2 (10^3ton/yr)	55.3	14.6	2.6	1.9	1.7	76.3
	PM (10^3ton/yr)	9.9	0.8	0.1	0.2	0.3	11.3

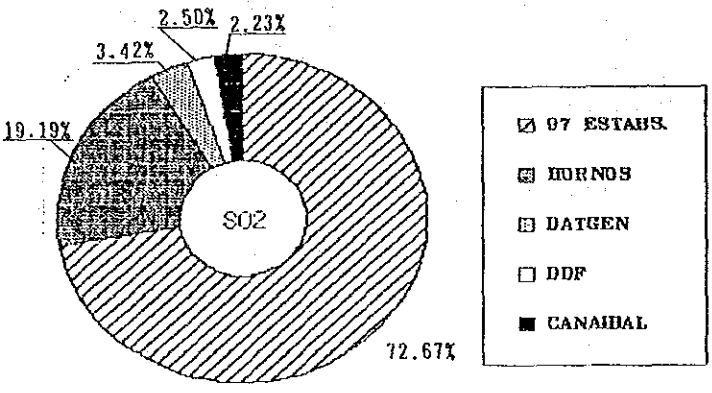
Note: Pollutant emissions by the use of LPG are not included in the samples of the SEDUE's studies.

The emissions from the 97 establishments survey by the Study Team constitute a large portion of the above totals for NOx, SO_2 and PM as shown in Figures 3.5.3. When the 1340 establishments surveyed by SEDUE are added, the percentage becomes 95%.

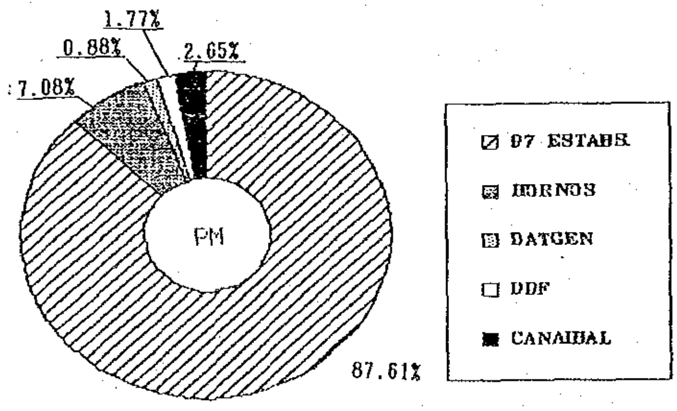
The characteristics of emissions of major pollutants are as follows.



NOX EMISSION



SOX EMISSION



(DDF:SERVICE & COMERCIAL SECTOR IN DF
CANAIBAL:PUBLIC BATH)

PM EMISSION

Figure 3.5.3 Pollutant Emissions from Stationary Sources in AMCM

1) SO_2

Since the cause of SO_2 emissions is largely combustion of heavy oil, the effect of controlling large factories, that are large consumers of heavy oil, is large.

2) NOx

As regards NOx emissions, the contribution of heavy oil and that of natural gas are considered to be at similar levels. Improvements of combustion equipment and combustion method are required for control of NOx emissions in addition to substitution of better quality fuels for the current heavy oil.

3) PM

As regards PM emissions, a considerable amount is originating from processing raw materials in asphalt and cement plants regardless of kind of fuel. Therefore, control of fuel combustion alone is not sufficient to reduce PM emissions.

3.5.2 Distribution of Fuel Consumption and Pollutant Emission by Scale of Sources

(1) Fuel Consumption

The majority of large scale fuel consuming establishments are, as shown in Figure 3.5.4, predominantly those which were selected for the detailed on-site survey. With respect to heavy oil and natural gas, the two fuel types by far the most consumed, the consumption by the top 5 or 6 establishments is higher than any of the establishments included in the other data groups, and their total consumption of these two fuels is approximately 60% of the respective total consumption in the metropolitan area. The ten top ranking factories in consumption of heavy oil and natural gas are shown in Table 3.5.3.

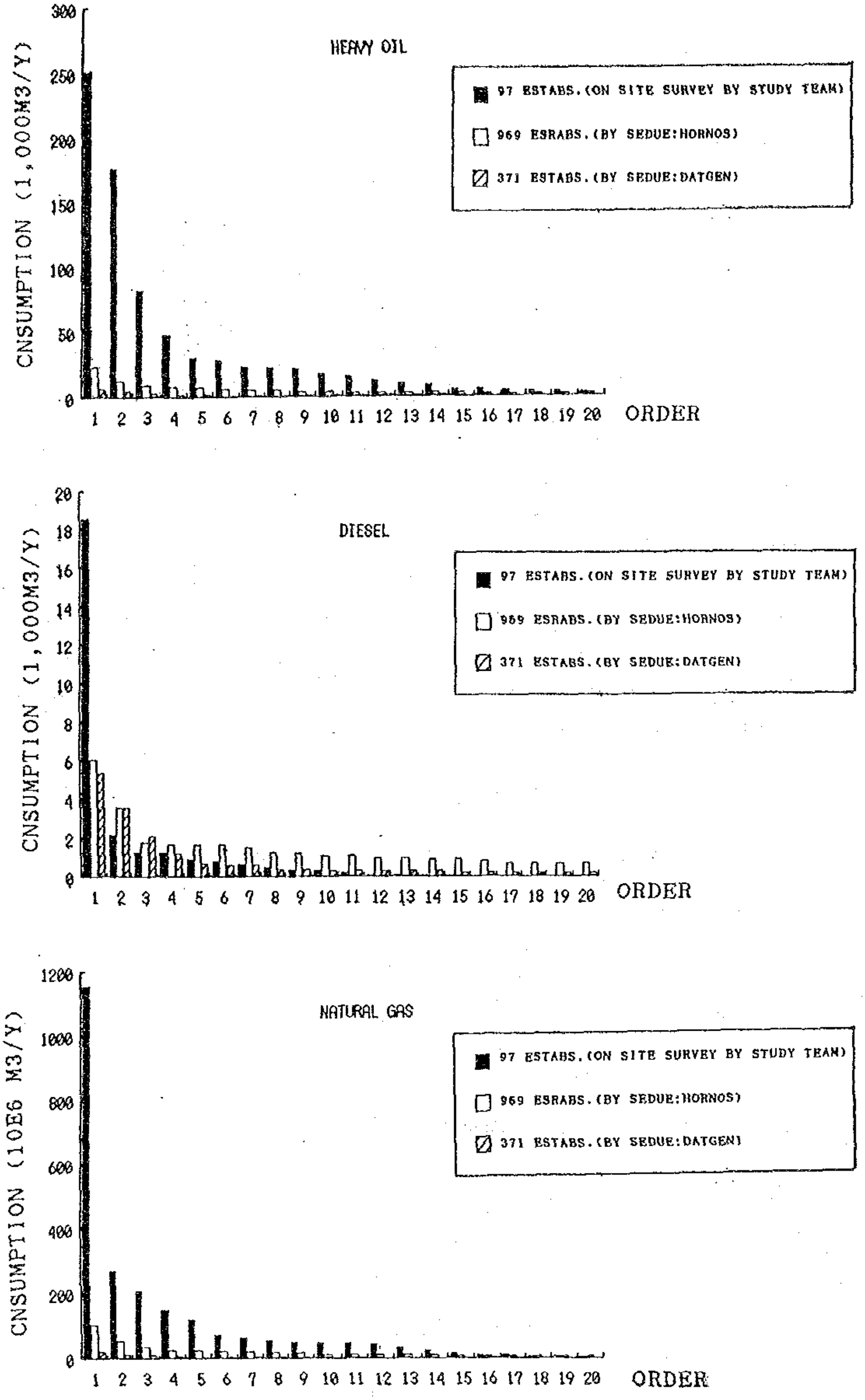


Figure 3.5.4 Fuel Consumption by Top 20 Factories

Table 3.5.3 Top 10 Factories in Fuel Consumption

Rank	Heavy oil	Natural gas
1	Thermoelectric Power (A)	Thermoelectric Power (A)
2	Cement	Petroleum Refinery
3	Paper Products	Thermoelectric Power (B)
4	Thermoelectric Power (B)	Metal Products
5	Petrochemical Products (B)	Chemical Products
6	Alcoholic Drinks	Ceramic Products
7	Chemical Products	Paper Products
8	Glass (A)	Glass (C)
9	Petroleum Refinery	Ceramic Products
10	Paper Products	Alcoholic Drinks

The main types of industry with large fuel consumption are thermal power generation, petroleum refining, cement, glass, and paper products.

(2) Pollutant Emissions

With regard to pollutant emission, as shown in Figure 3.5.5, the major sources are more predominantly among those selected for the detailed on-site survey. Most of the top 10 factories belong to this group, and the total emission magnitudes of these 10 factories are 60% for NOx and SO_2 and 75% for PM of the total emission in the metropolitan area.

The top ten ranking factories in the emissions of NOx, SO_2 and PM are as shown in Table 3.5.4, with thermal power generation, cement, glass and paper products predominating.

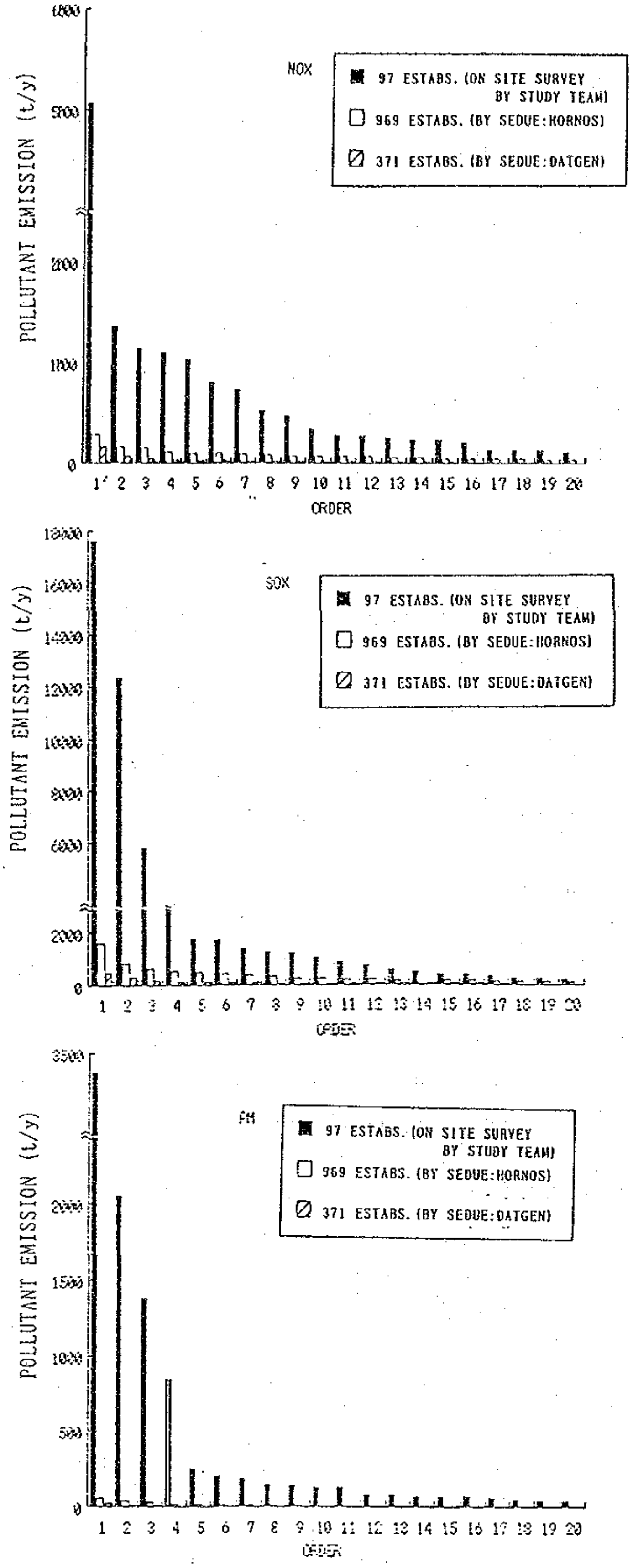


Figure 3.5.5 Pollutant Emission by Top 20 Factories

Table 3.5.4 Top 10 Factories in Pollutant Emission

Order	NOx	SO_2	PM
1	Thermoelectric Power (A)	Cement	Asphalt
2	Cement	Thermoelectric Power (A)	Thermoelectric Power (A)
3	Glass Sheet	Paper	Metal Products
4	Thermoelectric Power (B)	Thermoelectric Power (B)	Cement
5	Glass Bottle	Petrochemical (B)	Paper
6	Glass (C)	Alcoholic Drinks	Glass Sheet
7	Petroleum Refinery	Chemical Products	Glass Bottle
8	Paper	Petroleum Refinery	Thermoelectric Power (B)
9	Glass (B)	Paper Products	Glass (A)
10	Chemical Products	Glass (A)	Alcoholic Drinks

3.5.3 Amount of Pollutant Emission by Types of Combustion Facility

The number of combustion facilities by types found through the various survey by the Study Team and SEDUE are as shown in Table 3.5.5.

As can be seen, the 1,066 establishments surveyed in this Study have approximately 3,600 combustion facilities, of which boilers of various sizes account for approximately 40%. With at least one each combustion facility possessed by the rest of the establishments, there are at least 6,644 additional facilities, making the total number of combustion facilities considered in this Study over 10,000.

The pollutant emission volumes by types of combustion facilities in the 97 establishments surveyed through the detailed on-site questionnaire are shown in Figure 3.5.6. According to the Figure, large boilers are generally large pollution sources. With regard to PM, however, the aggregate dryers of an asphalt plant are by far the largest sources.

Table 3.5.5 Types and Number of Combustion Facilities

Type of Equipment	97 Establishments			969 Establishments (HORNOS)		Subtotal		371 Estabs. (DATGEN)
	scale	number of equipment	share (%)	number of equipment	share (%)	number of equipment	share (%)	number of estabs.
Boiler	LA	38	13	1.170	35	1.363	37	21
	ME	39	13					
	SM	64	21					
	MI	52	17					
	Subtotal	193	63					
Dryer	LA	6	2	507	15	536	15	11
	ME	3	1					
	SM	9	3					
	MI	6	2					
	Subtotal	24	8					
Aggregate Dryer	ME	3	1					
	MI	2	1					
	Subtotal	5	2					
Metal Heating Furnace	ME	7	2	894	27	928	25	8
	SM	9	3					
	Subtotal	16	5					
Heating Furnace	LA	5	2					21
	ME	5	2					
	SM	6	2					
	MI	2	1					
	Subtotal	18	6					
Glass Furnace	LA	9	3	765	23	813	22	
	ME	11	4					
	Subtotal	20	7					
Ceramic Furnace	LA	2	1					
	ME	3	1					
	SM	10	3					
	Subtotal	15	5					
Metal Melting Furnace	LA	1	0					10
	ME	1	0					
	SM	1	0					
	MI	5	2					
	Subtotal	8	3					
Cement Kiln	LA	3	1					2
Ohters	ME	2	1					47
Total	–	304	100	3.336	100	3,640	100	120
Unknown	–	1	–	–	–	–	–	251

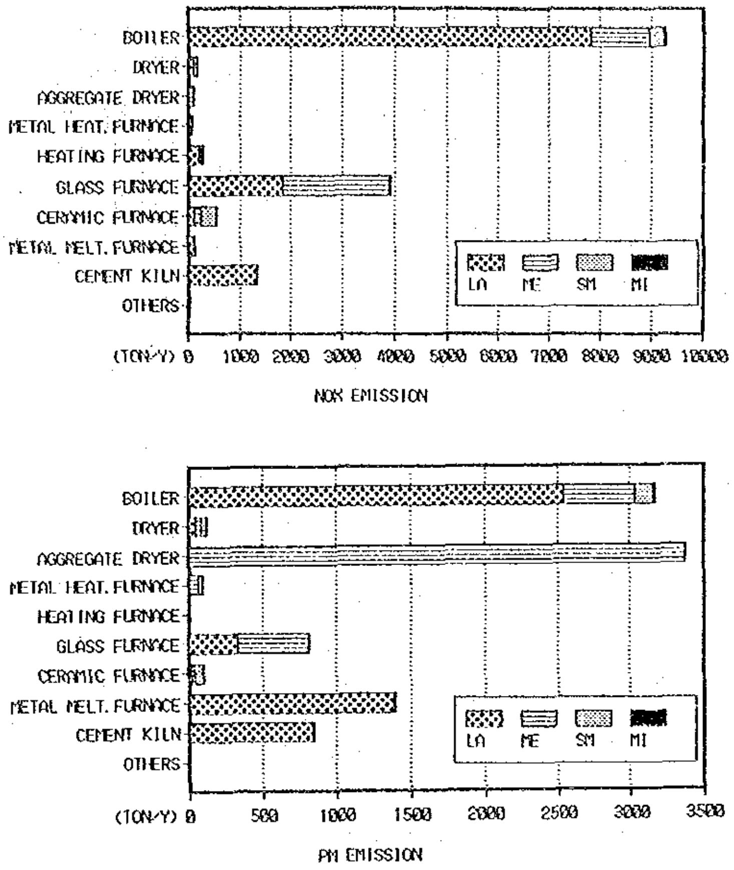


Figure 3.5.6 Pollutant Emission by Types and Scales of Combustion Facility in the 97 Establishments for the Detailed On-site Questionnaire

3.5.4 Geographical Distribution of fuel Consumption and Pollutant Emission

Figure 3.5.7 shows the distribution of the on-site-surveyed 97 establishments and the SEDUE-covered 1,340 establishments in the Study area expressed with the density of establishments in the 2 km square areas. These establishments, which are considered to include most of major factories in AMCM, are concentrated in the northern part of DF and its extension in the State of Mexico.

This distribution is nearly in correspondence with the urbanization distribution shown in Figure 3.5.8.

Figures 3.5.9 through 3.5.12 show the areal distribution of fuel consumption and pollutant emission.

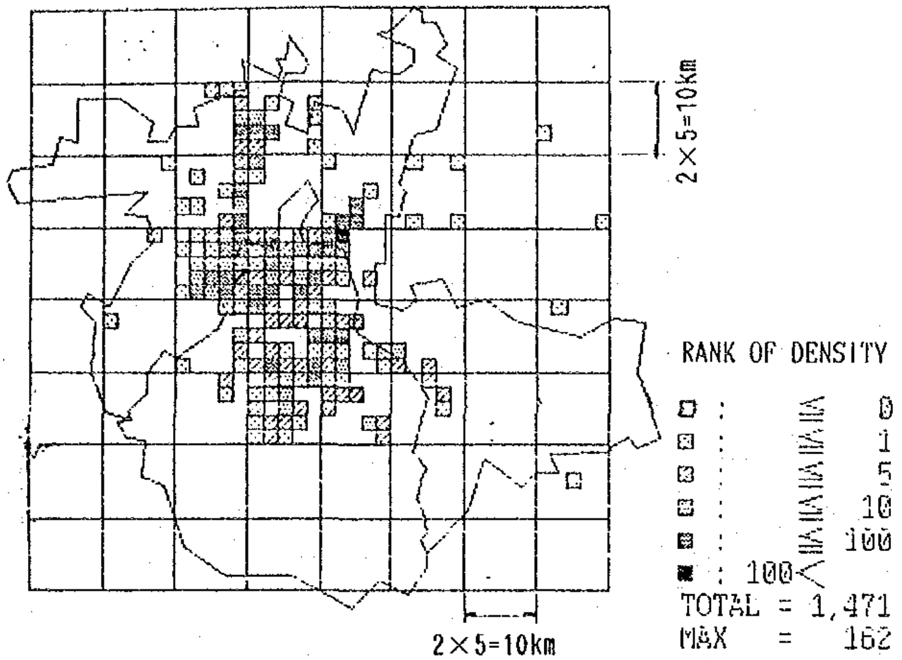
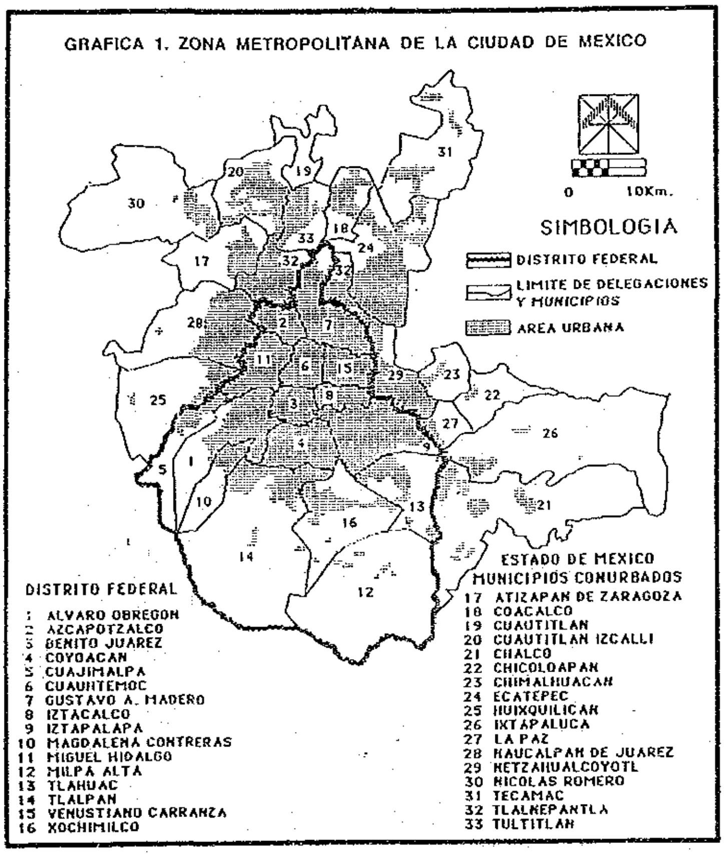


Figure 3.5.7 Factory Density Distribution in AMCM



Source: Integrated Program Against Atmospheric Pollution in the Mexico City Metropolitan Zone - A Common Agreement, Oct. 1990

Figure 3.5.8 Distribution of Urbanized Zones in AMCM

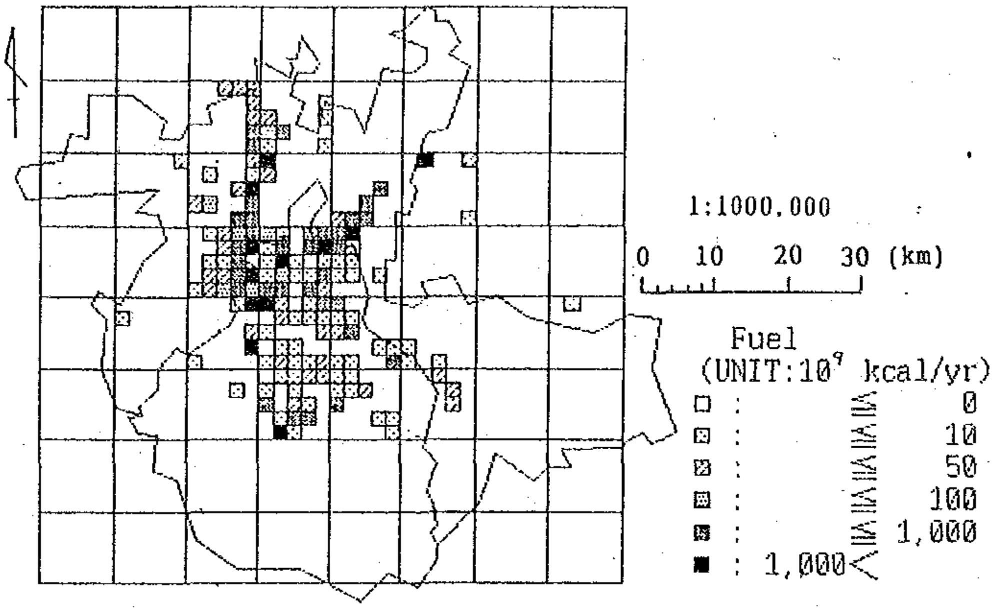


Figure 3.5.9 Areal Diustribution of Fuel Consumtpion

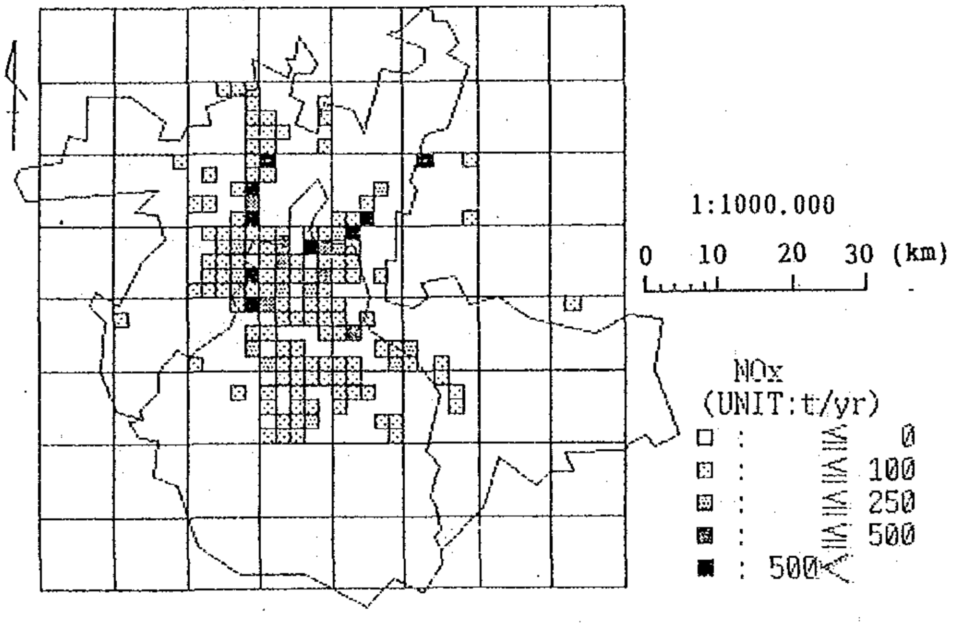


Figure 3.5.10 Areal Distribution of NOx Emissions

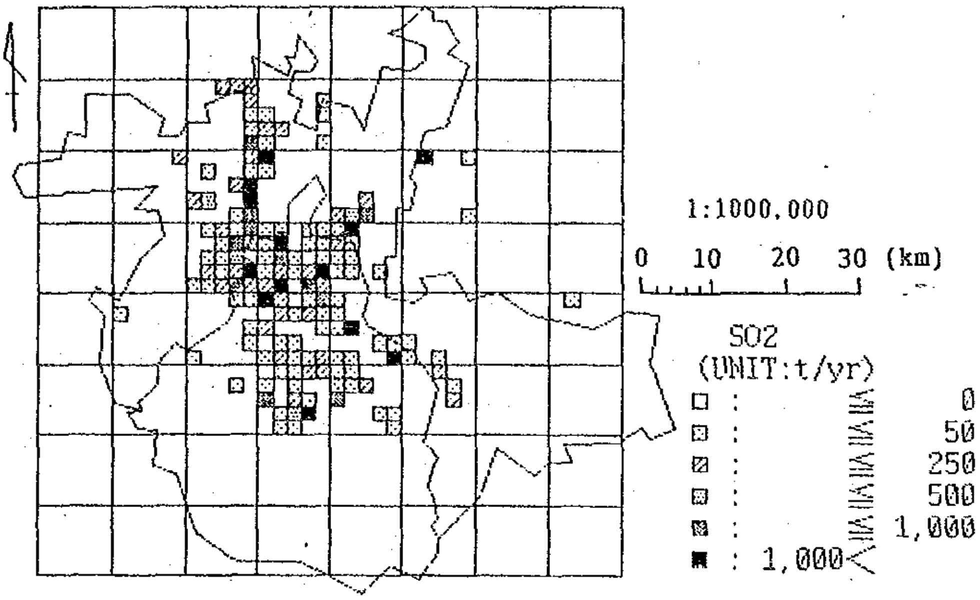


Figure 3.5.11 Areal Diustribution of SO_2 Emissions

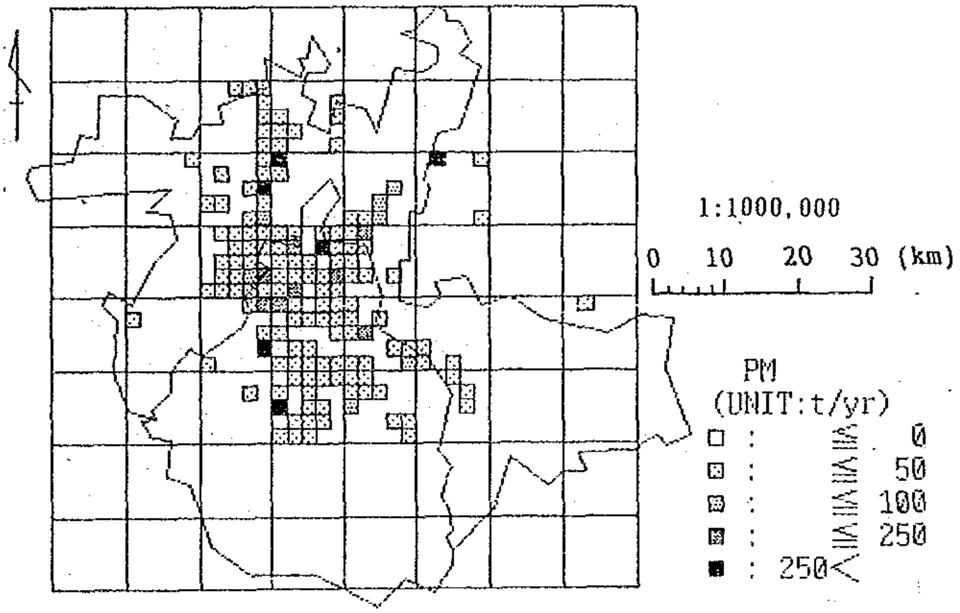


Figure 3.5.12 Areal Distribution of PM Emissions

CHAPTER 4 BASIC DISSCUSSIONS ON AIR POLLUTION CONTROL OF STATIONARY SOURCES

CHAPTER 4 BASIC DISCUSSIONS ON AIR POLLUTION CONTROL OF STATIONARY SOURCES

In this Chapter, various emission control technologies for nitrogen oxides (NOx) and smoke and soot (or particulate matter: PM) which are the major target air pollutants in this Study, will be explained. Explanation and discussion will be made particularly in detail on those technologies that are considered to be effectively applicable to the stationary air pollution sources in the Metropolitan Area, referring to field data that represent actual situation of stationary sources in the area.

Then, consideration will be made on the basic approach for planning control measures for stationary sources in the Metropolitan Area.

4.1 Outline of Source Control Measures

Table 4.1.1 summarizes currently available emission control technologies for sulfur oxides (SOx), nitrogen oxides (NOx), and smoke and soot.

More detailed explanations are given on the technologies for control of NOx and smoke and soot in the following Sections.

Table 4.1.1 Emission Control Technologies for SOx, NOx, and Particulate Matter (PM)

Category	Technology	Reduction Effect			Applicable Facility Scale
		SOx	NOx	PM	
Improvement of fuel	Reduction of S content of fuel (reduction of N content is difficult)	Large	Some	Some	All
Change of fuel	From heavy oil to natural gas or diesel	Large	Effective	Effective	All
Improvement of combustion control (energy saving)	1. Improvement of heat recovery 2. Optimization of air flow 3. Low air-ratio combustion	Reduction of emissions resulting from reduction of fuel use (indiredt effect)			All
Improvement of combustion method	1. Improvement of operational condition				
	• Low air-ratio combustion	-	Effective	Increase	All
	• Reduction of combustion chamber loading	-	Effective	Decrease	All
	• Reduction of air preheating temperature	-	Effective	Tends to increase	Large
	2. Improvement of equipment				
	• Low-NOx burner	-	20-45%	Increase with some burners	Small to medium
	• Two-stage combustion	-	20-45%	Slight tendency to increase	Lage
	• Off-stoichiometric combustion	-	20-45%	Slight tendency to increase	Facilities with 2 or more burners
	• Exhaust gas recirculation	-	20-45%	Slight tendency to decrease	Large
	• Steam/water injection	-	20-45%	Slight tendency to decrease	All
	• In-furnace denitration combustion (OFA method)	-	30-40%	Slight increase	Large
	• In-furnace denitration combustion (MACT method)	-	50%	Slight increase	Large
	3. Emulsion Combustion	Effective by addition of alkali metals	30-50%	20 - 40%	All
Exhaust gas treatment	1. Dust removal				
	• Electric precipitator	-	-	90% or more	Lage
	• Bag filter	-	-	90% or more	All
	• Scrubber	90% by use of absorbent	-	90% or more	All
	• Centrifuge	-	-	90% or more	Small to medium
	• Inertial force				
	Louver type	-	-	70-80% for <15μm	All
	Multi-baffle type	-	-	70-80% for <5μm	All
	• Gravity	-	-	50% for <50μm	All
	2. Desulfurization	90% or more	-	50% or more	All
	3. Denitration	-	90% or more	-	Large
	4. Total treatment of exhaust gas	90% or more	90% or more	90% or more	Large
Others	1. Plant relocation	Effects at original site are large. But high cost and availability of a suitable new location are required.			All
	2. District heat supply	Energy-saving effect due to concentrating scattered sources. But control measures are required at the heat supply source.			Small to medium
	3. Higher smokestacks	Ground-level concentration is reduced. But the total emission is unchanged.			All

4.2 NOx Control Technologies

4.2.1 Principles of NOx Generation

When a material is burnt, nitrogen (N_2) in the air and organic nitrogen in the material (fuel N) bind with oxygen (O_2) to produce nitrogen oxides (NOx). NOx produced by binding between nitrogen in the air and oxygen is called thermal NOx and the other is called fuel NOx.

(1) Thermal NOx

The factors in the generation of thermal NOx include: (1) O_2 concentration in the combustion zone, (2) combustion temperature (flame temperature), and (3) combustion gas detension time at high temperature. The reaction is endothermic; generation of NOx increases as the temperature rises.

Moreover, NOx generation increases as the detension time at high temperature becomes longer and the O_2 concentration becomes higher. (See Figures 4.2.1, 4.2.2, and 4.2.3.)

(2) Fuel NOx

Fuel N in heavy oil or coal is incorporated into the complex aromatic nucleus in the forms of pyridine, quinoline, pyrol, indol, and carbazol. It is also contained in sludge or dust in the form of ammonium or protein.

Fuel N is considered to be more easily oxidized than N_2 in the air. But the oxidation process and natures of decomposed intermediate products are not well known.

Assuming that N contained in a fuel by 0.1% is totally converted into NO, its concentration under the condition of 0% O_2 becomes as follows:

heavy oil	approx. 155 ppm
coal	approx. 200 ppm
sludge (3,300 kcal/kg.DS)	approx. 440 ppm
municipal wastes (1,700 kcal/kg)	approx. 755 ppm

The concentration becomes larger as the calorific value per unit weight of the fuel is smaller.

The fuel NOx actually generated occupies a certain percentage of the above values. This ratio is called the fuel NOx conversion ratio.

The generation of fuel NOx exhibits the following tendencies:

1) Under combustion conditions with air deficiency or low excess air ratio, the generation of fuel NOx is suppressed (Figure 4.2.4).

2) The fuel NOx conversion ratio decreases with increasing N content in fuel (Figure 4.2.5). But the amount of NO generated increases with the increasing N content.

3) The generation of fuel NOx is faster than that of thermal NOx. Moreover, the effect of temperature on the rate of fuel NOx generation is small i.e., fuel NOx is generated even at relatively low temperature.

4) The amount of NOx generation varies with the state of air-fuel mixing (Figure 4.2.6). NOx generation increases with higher degree of mixing.

4.2.2 Methods for Reduction of NOx Emission

There are three basic methods for reducing NOx emission from a combustion facility:

- Control of NOx generation itself
- Reduction of exhaust gas volume by fuel saving (reduction of NOx amount)
- Removal of generated NOx (denitration)

(1) Control of NOx Generation

Considering the principles of NOx generation, the generation can be suppressed by taking the following measures:

1) Keep the O_2 concentration low in the combustion reaction zone
(Low air-ratio combustion, two-staged combustion, off-stoichiometric combustion, emulsion conbustion, etc.)

Source: "Technical Manual for Reduction of Nitrogen Oxides Emissions," Tokyo Metropolitan Government, Environmental Protection Bureau, 1985

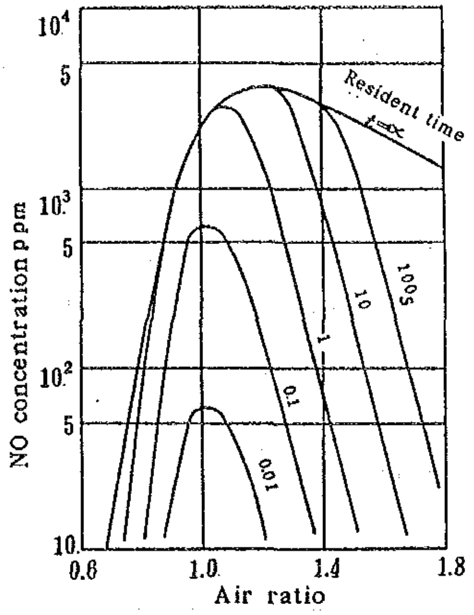


Figure 4.2.1 Detension Time and NOx Generation at Theoretical Combustion Temperature

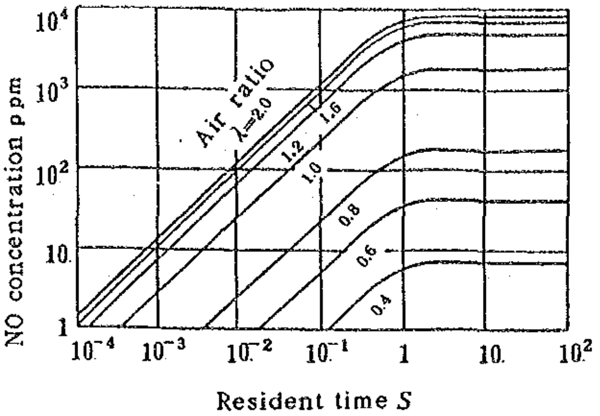


Figure 4.2.2 NOx Generation and Detension Time at T=2,200°K (Influence of Air Ratio)

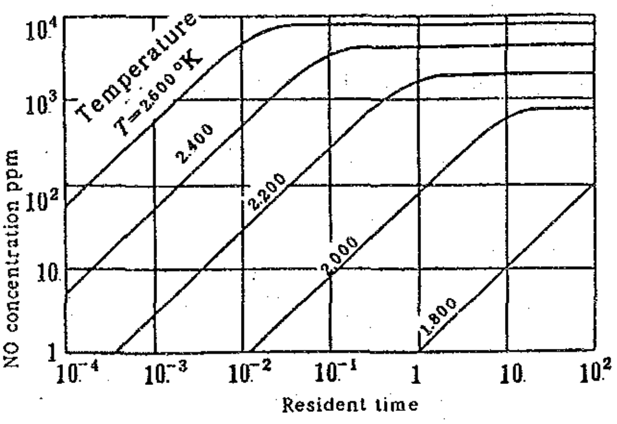


Figure 4.2.3 NOx Generation and Detension Time (Influence of Temperature)

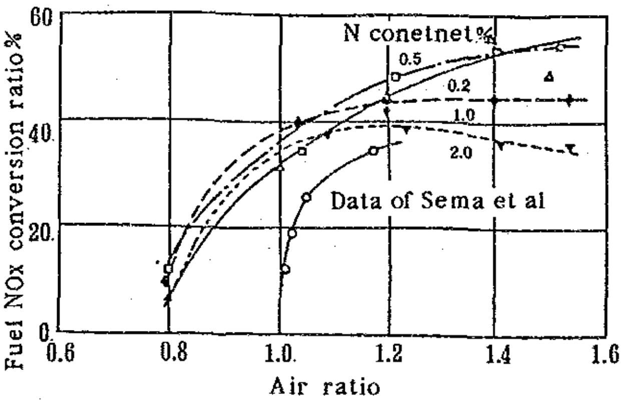


Figure 4.2.4 Fuel NOx Conversion Ratio and Air

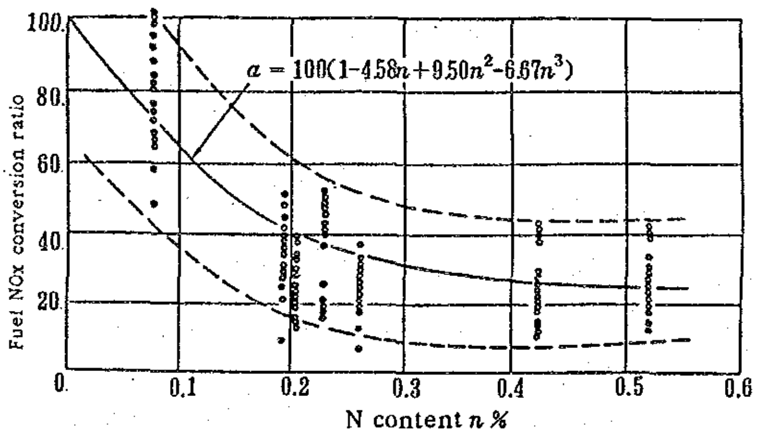


Figure 4.2.5 N Content and Fuel NOx Conversion Ratio

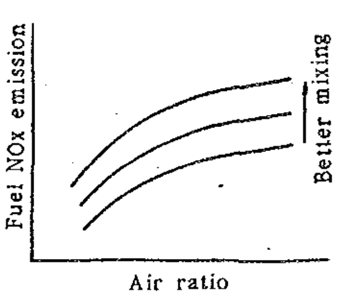


Figure 4.2.6 Air Ratio and Fuel NOx Emission (at Constant N Content))

2) Keep the flame temperature as low as possible
(Flue gas recirculation, steam/water injection, emulsion combustion, etc.)

3) Reduce the detension time at high temperature
(Rapid mixed combustion, combustion with extremely fine atomization of O/W type emulsion, high-speed heat transmission type low-NOx burner)

The speed of fuel oil combustion is closely related to the particle diameter of the atomized fuel oil and can be expressed as follows:

$$Do^2 = Rt$$

Do: Initial diameter of atomized particle
R : Constant (Verocity gradient of combustion)
t : Required combustion time (second)

4) Reduce the N content in fuel
(Change to quality fuel)

However, an excessive decrease of 1) air ratio or 2) flame temperature causes incomplete combustion, with a possible increase in the generation of pollutants (HC, CO, and PM) and a decrease in the thermal efficiency.

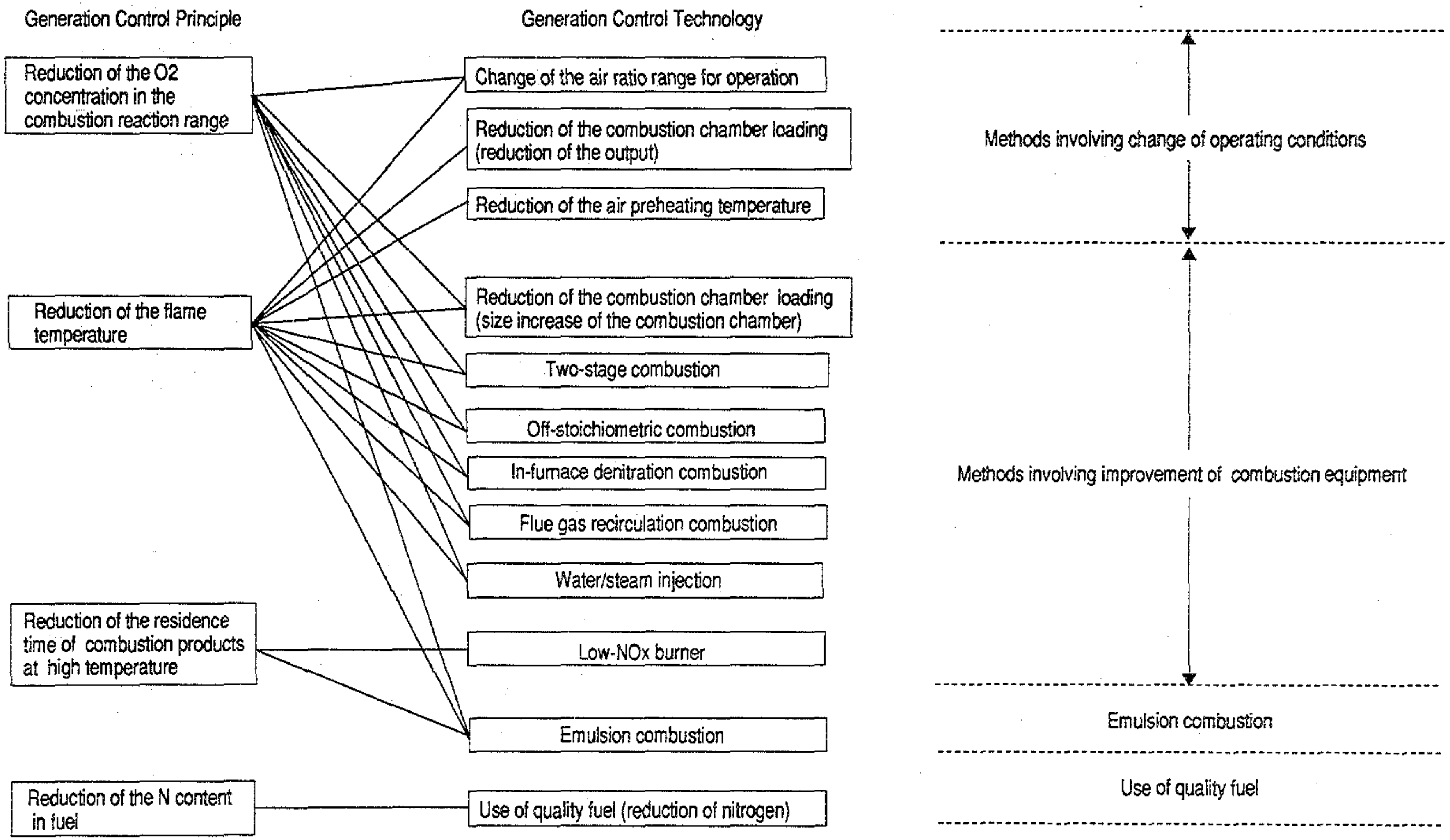
NOx control technology is thus required for effective suppression of NOx while preventing an increase in the generation of other pollutants and a large decrease in thermal efficiency.

Various control technologies may be classified according to the control principles as shown in Table 4.2.1. In addition, other combustion methods with high efficiency have also been put into application, such as a bell-type divided flame combustion method (shortening of the detension time at high temperature through high speed heat release), internal NOx reducing combustion (reduction reaction) method, etc.

(2) Reduction of NOx Emission by Energy Saving

The gross NOx emission amount is reduced by reducing fuel consumption thereby decreasing the amount of exhaust gas without increasing the NOx concentration through stabilization of furnace or boiler operation.

Table 4.2.1 NOx Generation Control Principles and Technologies



1) Energy Saving by Control of Furnace Operation

Energy consumption can be reduced by controlling the temperature of the material being heated (prevention of overheating, etc.) and by preventing air intrusion into the furnace.

2) Installation of Energy Saving Equipment

The waste heat can be recovered by installing an economizer (in case of a boiler) and an air preheater. In the case of ordinary burners, the NOx concentration will increase when air is preheated. Therefore, a low-NOx burner which does not cause an increase of NOx concentration by air preheating needs to be used.

3) Low Air-Ratio Combustion

The low air-ratio combustion enables a reduction in fuel consumption and a resultant reduction of exhaust gas amount, leading to a reduction of the NOx concentration itself.

(3) Denitration

Denitration is employed when to control NOx generation by changing combustion method is difficult or there are certain constraints to control NOx generation during combustion. For example, strengthening of NOx generation control may decrease NOx, but it may also hinder heat transmission to the material inside the furnace, thereby adversely affecting the quality of products or causing secondary pollution through generation of particulate matter (PM) or CO. In the case of solid waste incinerator, NOx generation control may cause incomplete combustion and unburnt materials may remain in the ash. This method should be considered in such cases, or when a high degree of reduction of NOx emission is required.

1) Non-catalytic Denitration

In this method, NH_3 or urea is blown into flue gas of around 900°C containing NOx in order to reduce NOx to N_2. The NOx reduction rate by this method is normally around 40 - 70%.

2) Simplified Denitration Method

The non-catalytic denitration method requires that a considerable amount of NH_3 be blown in order to increase the denitration rate. This is often associated with an increase in non-reacted NH_3. The simplified denitration method employs a simple catalytic layer in the flue so as to utilize such non-reacted NH_3 to enhance the denitration rate while preventing release of NH_3.

3) Flue Gas Denitration Method

Wet and dry methods are available, and the dry method is currently used in most cases. In the wet method, NO is oxidized to more reactive NO_2 by ozone or other oxidizing agents, and then washed and absorbed by water or alkalis. In the dry method, reduction of NOx by NH_3 is enhanced by the use of a catalyst. The flue gas temperature is 200 - 300°C and the denitration rate is 90% or more.

In some cases, however, problems such as damaging of the catalyst by SOx or clogging of the catalystic layer with smoke and soot may occur.

4.2.3 Technologies to Control NOx Generation

NOx generation control technologies may be classified in relation to the generation principles as shown in Table 4.2.1.

(1) Use of Quality Fuel

Use of a quality fuel with less N content such as natural gas, diesel or kerosene will decrease generation of the fuel NOx. In the case of Mexico, which is an oil-producing country, use of heavy oil is naturally given a high priority. It has been planned, as described in Section 2.5.3, that low-sulfure heavy oil will be produced by hydrogenation, and will be supplied mainly to two power plants from 1995. Though the sulfur content may be decreased to 0.8%, no substantial decrease in the viscosity and N content can be considered. If the power plants in AMCM, where natural gas is currently used by 80%, use the desulfurized heavy oil by 100%, the NOx emission amount is expected to increase substantially, and its control is very important. As will be described later, lowering of viscosity of a fuel leads to finer atomization of the fuel enabling low-NOx combusition.

Therefore, study on emulsification of heavy oil is recommended as a method to decrease the viscosity substantially.

(2) Methods Involving Change of Operating Conditions

1) Change of Air Ratio Range

The relationship between air ratio and NOx emission can be generally classified into three patterns as shown in Figure 4.2.7. Which pattern prevails depends on the range of air ratio and the mixing state of fuel and air in the combustion chamber (see Figure 4.2.8).

Of the above three patterns, the basic pattern corresponds to the curve "a" which has a peak of NOx emission at a certain air ratio. The curve "b" prevails when the air ratio range is above the peak point of curve "a" and the curve "c" prevails when the range is below the peak point. Most of large boilers in power plants show the curve "c". It is therefore necessary to carry out thorough review of individual facilities when determining how to change the air ratio.

i) Oxygen Concentration in Exhaust Gas

The oxygen concentration in exhaust gas varies depending on the fuel consumption, primary and secondary air volumes, or tertiary air (cold air directly entering into the furnace for some reason) volume. Fuel consumption may be known by recording the instantaneous consumption with a flow meter. The primary air volume is measured with a pressure gauge. But since the secondary air volume is too large in most cases in AMCM, it is not measured at all or, if measured, the reading is not exact enough. Furthermore, causes and amount of the tertiary air are not known in many cases. Hence the volume of air entering the furnace is hard to grasp correctly. Use of an oxygen meter enables monitoring of changes in the air volume in certain cases.

ii) Primary Air in the Burner

Primary air in the burner is used to atomize liquid fuel. If stable combustion is achieved with a minimum amount of the primary air, it leads to energy saving. Figure 4.2.10 shows a practical example of the relationship between primary air consumption and fuel consumption.

iii) Decrease of Tertiary Air

Since tertiary air is cold, prevention of its entry is expected to contribute to energy saving. Tertiary air is mostly drawn through the burner tile when the internal pressure is negative. There is an example that control of the opening area of the burner tile has contributed to a 3 - 4% energy saving. In another example based on the same concept, an unused burner was pulled out and the burner opening covered with a lid, thereby contributing to energy-saving. Since many of recuperators for combustion facilities in AMCM are outdated, allowing the entry of tertiary air, care must be taken so as to monitor the O_2 concentration of exhaust gas from time to time at the inlet and the outlet of the flue.

iv) Seminar on Combustion With Appropriate Air Ratio

SEDUE, DDF, GEM, and the Study Team held a seminar on combustion with appropriate air ratio and fuel saving, with the participation of 112 plants in AMCM in March, 1990. In this seminar, many questions and answers were exchanged. Later on, with the understanding that combustion with an appropriate air ratio would lead to saving of fuel consumption and reduction of NOx, a few plants improved their combustion operation by reducing excessively high air ratio to appropriate one. Table 4.2.2 shows some of these examples.

Figure 4.2.11 shows the data related to flue gas loss, fuel saving ratio, and air ratio used in the seminar.

Table 4.2.2 Examples for Reduction of Pollutant Emissions by Combustion with Appropriate O_2 Content

Name of Plant	Year of Investigation	Fuel	O_2 (%)	NOx (ppm)	Dust (g/Nm^3)	Flue Gas (Nm^3/hr)	Remarks
VIDRIERA ORIENTAL	1987	Heavy oil (H)	8.4	1858	1.32	10,700	Previous JICA Study
	1990	Heavy oil (H)	2.9	645	0.76	11,300	Diagnostic survey in this Study
ANDERSON CLAYTON	1987	Heavy oil (H)	6.8	255	1.33	24,300	Previous JICA Study
	1990	Heavy oil (H)	4.8	205	0.21	24,200	Diagnostic survey in this Study

Source: ibid.

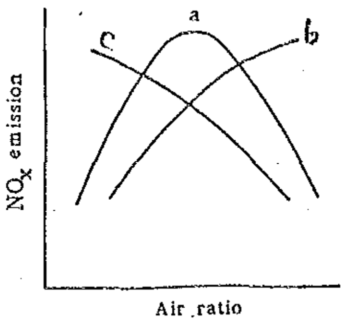


Figure 4.2.7 Geeral Relation Between Air Ratio and NOx Emission

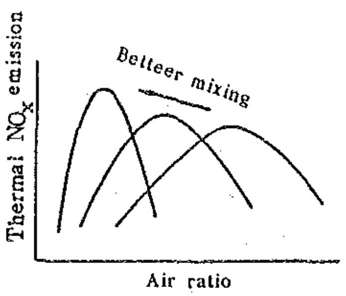


Figure 4.2.8 Air Ratio vs Thermal NOx Emission

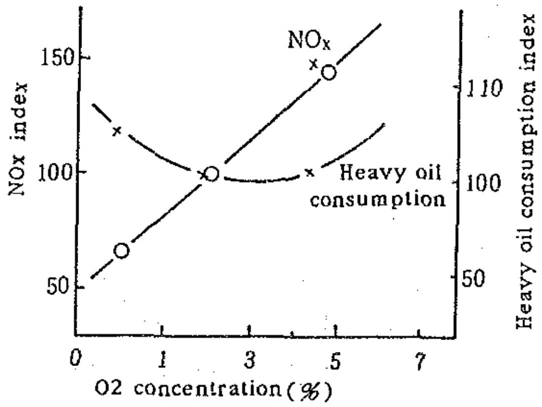


Figure 4.2.9 Relationship between NOx at Oxygen Concentration of Flue Gas and Heavy Oil Consumption

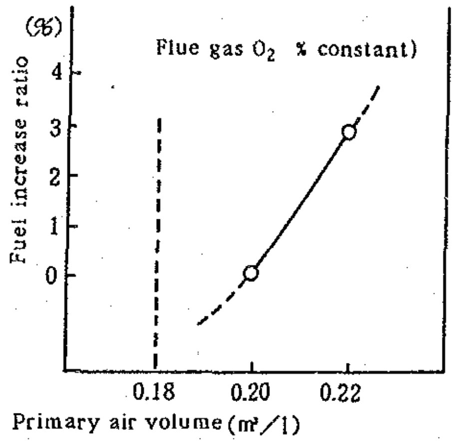
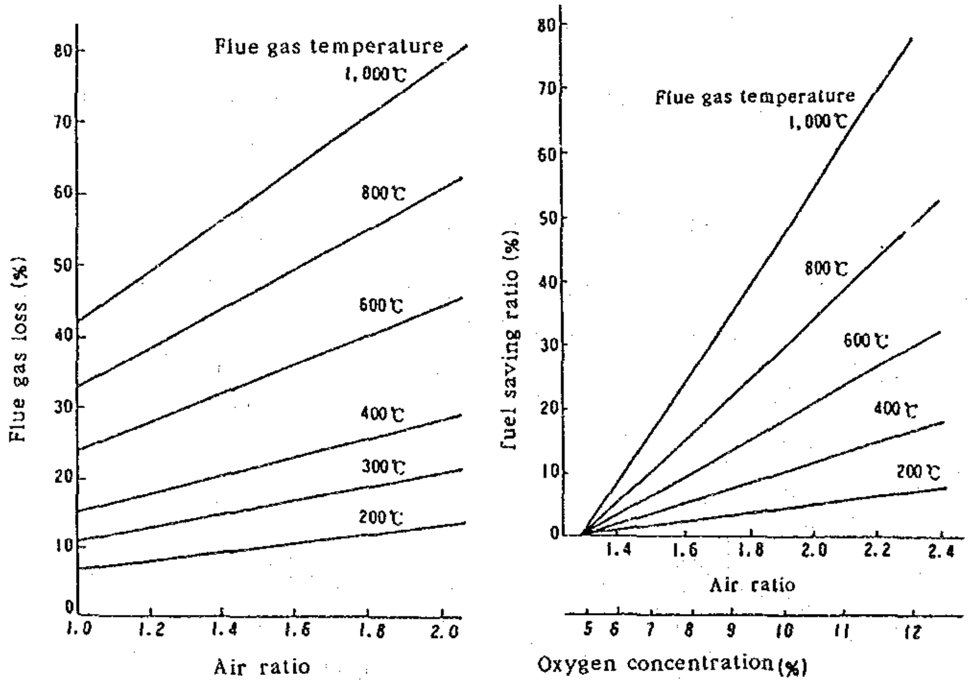


Figure 4.2.10 Primary Air Volume vs Fuel Consumption



Air ratio versus flue gas loss

Fuel saving ratio when the air ratio is adjusted to 1.30

Figure 4.2.11 Flue Gas Loss, Fuel Saving Ratio, and Air Ratio

v) Test on Low Air-ratio Operation and NOx Reduction

The Study Team tested operation of the nine boilers and one glass melting furnace at the times of the detailed on-site questionnaire and the diagnostic survey by measuring the NOx concentration while changing the O_2 concentration in flue gas. The results are shown in Table 4.2.3, which indicate that NOx can be reduced by 10 - 50% if the air ratio is kept at an appropriately low level.

Appropriate air ratio is said to be normally 1.1 - 1.3, and most burners within this range have the characteristics of curve "b" in Figure 4.2.7. Accordingly, combustion with low air ratio is generally considered as a measure to reduce NOx generation.

Table 4.2.3 Reduction of NOx by Low-O_2 Combustion

Name of Plant	O_2 (%)	NOx (ppm)	NOx Converted to 0% O_2 (ppm)	Kind of Fuel
FIBRAS SINTETICAS	5.5 3.4	320 287	434 346	Heavy oil
UNIROYAL	10.0 8.5	158 145	302 244	Heavy oil
PAPELERA IRUNA	11.8 10.3 9.3	130 128 115	297 251 206	Heavy oil
CERVECERIA MODELO	6.4 5.5 4.3	238 240 242	342 325 304	Heavy oil
BANOS SANTIAGO	10.3 8.8	148 125	290 215	Heavy oil
REFINERIA 18 DE MARZO (G-1 boiler)	5.1 3.5	135 75	178 90	Natural Gas
QUIMICA LUCAVA	4.8 2.5	280 255	363 289	Heavy oil
VIDRIERA ORIENTAL	6.0 2.8 1.9	664 660 660	930 762 726	Heavy oil
EMPAQUES DE CARTON UNITED	6.8 5.4 5.0	190 195 187	281 263 245	Heavy oil
REFINERIA 18 DE MARZO (G-3 boiler)	7.1 6.9 6.8 5.5 5.3	112 100 84 77 60	169 149 124 104 80	Natural Gas

vi) Actual Status of Excess Air Ratio Operation in AMCM

The O_2 concentration of flue gas was measured during the on-site questionnaire and the diagnostic survey. The 23 boilers were operated with excessive air, i.e., the O_2 concentration of 5.9% or more as shown in Table 4.2.4.

It is considered that guidances by combustion expert are necessary so that factories understand the effects of combustion with an appropriate air ratio on reducion of NOx emission.

Table 4.2.4 Examples for Combustion With Excessive Air in AMCM

No.	Boiler Evaporation Capacity (ton/hr)	Kind of Fuel	O2 Concentration (%)
1	1.5	Diesel	13.6
2	1.75	Heavy oil	13.8
3	10.8	Heavy oil	9.5
4	7.6	Heavy oil	11.8
5	45.0	Natural gas	5.9
6	2.6	Heavy oil	8.4 - 11.2
7	12.0	Heavy oil	6.5
8	45.4	Heavy oil	6
9	1.6	Heavy oil	9
10	9.5	Heavy oil	7.9
11	13.6	Heavy oil	8
12	0.6	Heavy oil	10.4
13	0.8	Heavy oil	10.9
14	1.9	Heavy oil	11.1
15	1.3	Diesel	9.4
16	1.0	Heavy oil	14
17	1.9	Heavy oil	16 - 18
18	6.8	Heavy oil	9.5
19	2.6	Heavy oil	14
20	unknown	Heavy oil	11.9
21	9.0	Heavy oil	7.7
22	1.7	Heavy oil	13.4
23	4.7	Heavy oil	9.1

2) Reduction of Combustion Chamber Loding
(Reduction of Output)

Generally, increased loading to the combustion chamber causes increased NOx generation. This may be attributed to increase in the furnace temperature. In this context, reduction of loading to the combustion chamber is effective for reduction of NOx generation. Figure 4.2.12 shows typical examples of this effect for oil heating furnaces equipped with low-NOx burners.

However, reduction of the combustion chamber input load means something different in the case of furnace enlargement with the combustion rate kept constant (size increase of the combustion chamber, described later) and in the case of reduction of the combustion rate with the furnace size kept unchanged (reduction of the output). Generally, reduction of the output is associated with poor mixing of fuel and air, resulting in a reduction of NOx (see Figure 4.2.13). But there are some types of burners so constructed that a reduction of output causes an improvement of mixing. In this case, reduction of the output leads to an increase in NOx generation (see Figure 4.2.14).

Burners which are designed to reduce NOx through circulation of the combustion gas in the furnace by utilizing the momentum of fuel or air flow tend to increase NOx generation when the output is reduced.

3) Reduction of Air Preheating Temperature

Reduction of the air preheating temperature leads to a decrease in the combustion temperature and to reduction of NOx generation. On the other hand, this measure is not favorable in terms of particulate matter (PM) because recombustion of soot is suppressed. In general, however, the effect of this measure on NOx reduction is more immediate than the unfavorable effect on PM. Note that reduction of the air preheating temperature is not effective for reduction of fuel NOx, and therefore, is not very effective for heavy quality oils. In terms of energy saving, this measure reduces thermal efficiency and has little effect when applied along with two-staged combustion or flue gas recirculation.

As shown in Figure 4.2.15, certain low-NOx burners recently developed have a less tendency toward NOx increase with the increased air

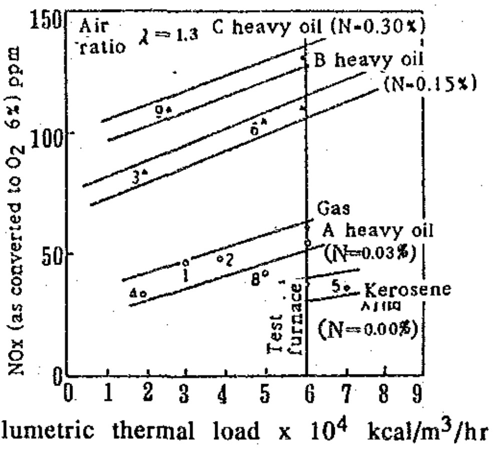


Figure 4.2.12 Effect of Volumetic Thermal Load of Furnace on NOx Generation

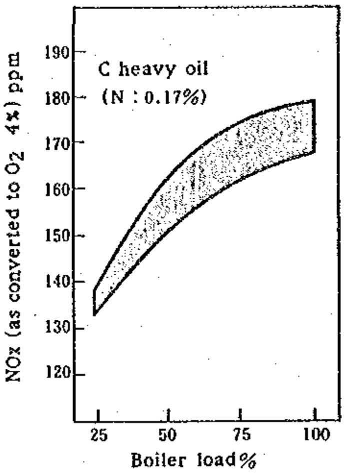


Figure 4.2.13 Reduction of NOx by Lowering Boiler Load

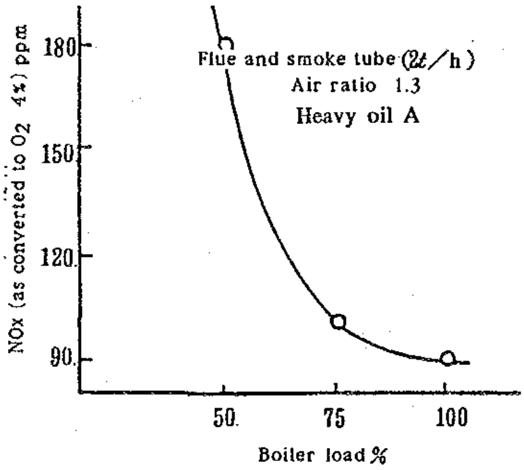


Figure 4.2.14 NOx Concentration vs Loading for a Certain Rotary Burner

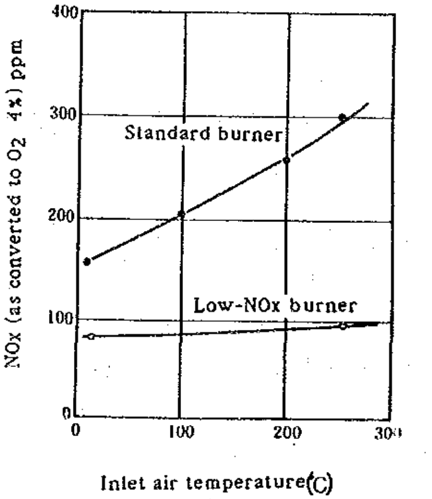


Figure 4.2.15 Air Temperature vs NOx for Heavy Oil Combustion

Source: ibid.

preheating temperature. In particular, the burners having a function of two-staged combustion are reported to show this tendency.

(3) Methods Involving Improvement of Combustion Equipment

1) Low-NOx Burners (LNB)

Low-NOx burners currently available for practical operation may be classified according to construction and NOx control mechanism as follows:

i) Well-mixed type (WMT)
ii) Divided flame type (DFT)
iii) Self-recirculation type (SRT)
iv) Two-stage combustion type (TCT)
v) Off-stoichiometric combustion type (OCT)
vi) Water/steam injection type (WIT)
vii) Combined type (CT)

Low-NOx burners may be considered the most readily available NOx control means for medium and small combustion systems. However, in the case of heavy quality oils such as Mexican heavy oil, the reduction ratio is as low as 10 - 30%. The use of low-NOx burner will thus prove more effective when mixed combustion with natural gas is employed or the viscosity of heavy oil is reduced beforehand by appropriate means such as oil emulsification. In Mexico, ordinary types of burners for mixed combustion of natural gas and heavy oil are currently is used, but their low-NOx version is not yet available. Development of such low-NOx burners are necessary.

Each type of burner is described below according to the above classification.

i) Well-mixed type (WMT)

The construction of this type of low-NOx burner is shown in Figure 4.2.16. In this burner, the gaseous fuel or liquid fuel atomized with air or steam is jetted normally to the center axis through many ports provided on the circumference of the end portion of the burner gun set to the center axis of the throat (air Venturi). Fuel collides with the

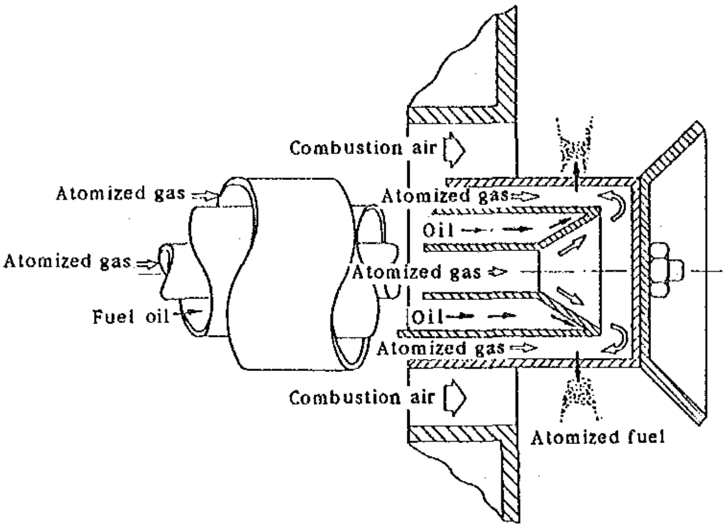


Figure 4.2.16 Well-mixed Type Low-NOx Burner (Film Radiation)

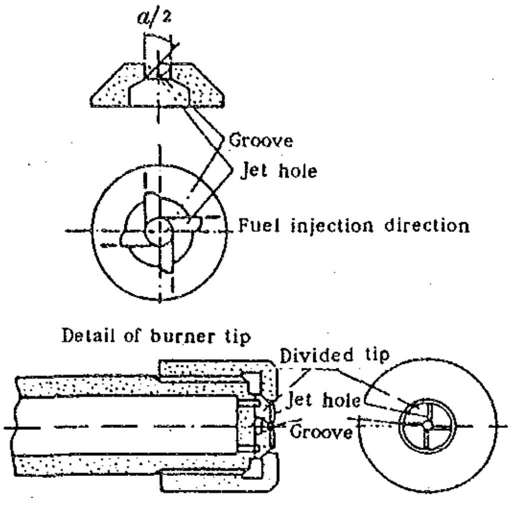


Figure 4.2.17 Divided Flame Type Low-NOx Burner (Vortex Type Oil Pressure Injection Burner)

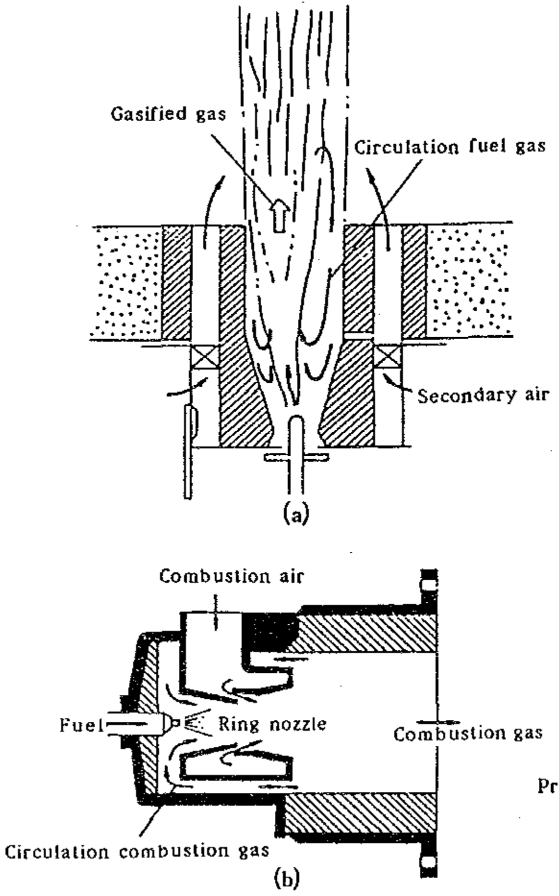


Figure 4.2.18 Self-recirculation Type Low-NOx Burner

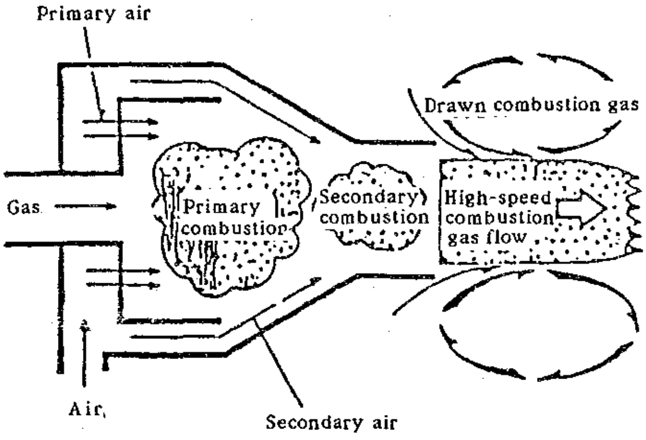


Figure 4.2.19 Two-stage Combustion Type Low-NOx Burner

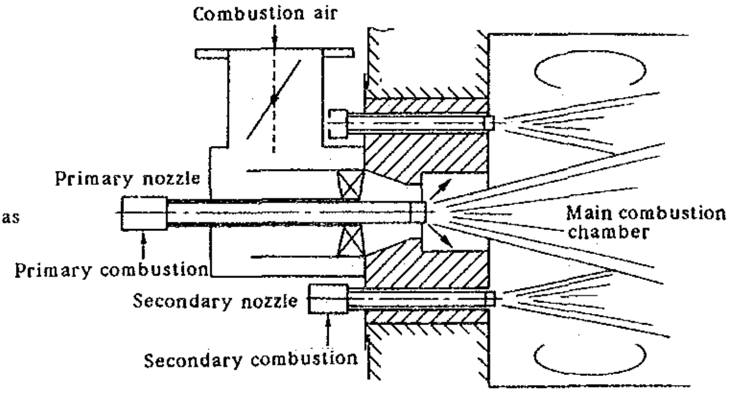


Figure 4.2.20 Reverse Two-stage Combustion Type Low-NOx Burner

Source: ibid.

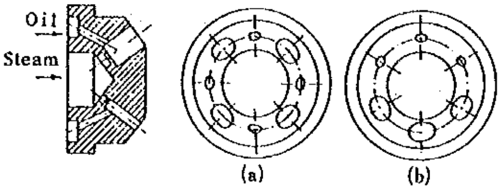


Figure 4.2.21. Typical Jet Hole Layout of the Self-Biased Atomizer Type Low-NOPx Burner

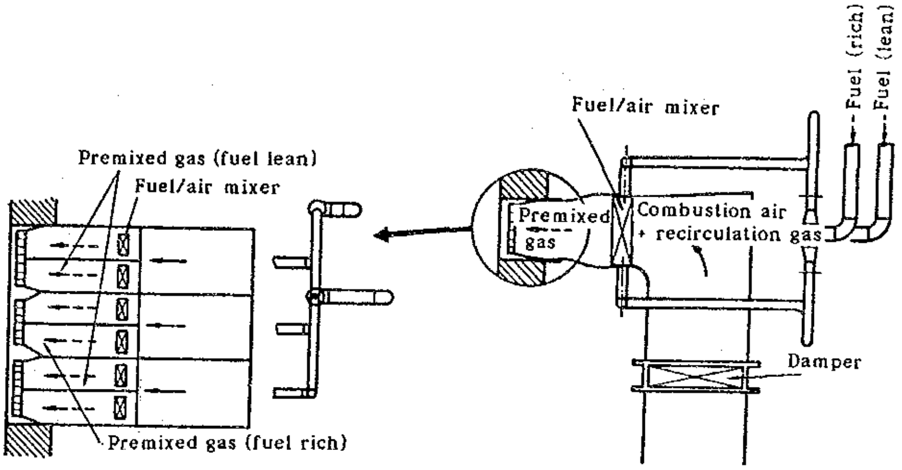


Figure 4.2.22 Off-stoichiometric Combustion Type Low-NOx Burner for Gas

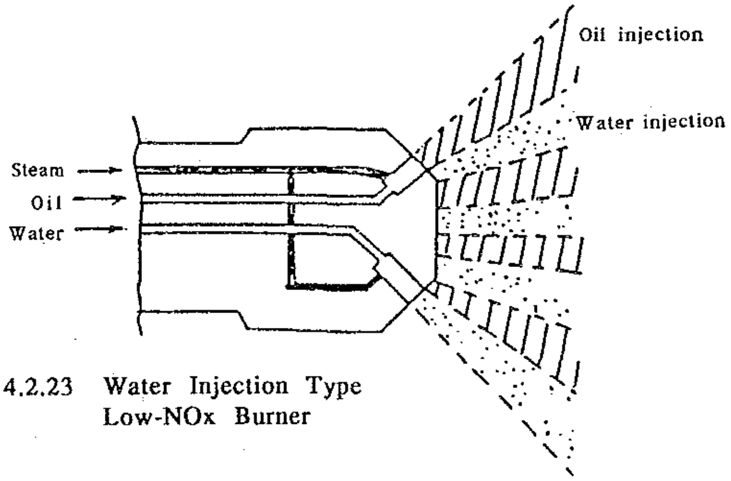


Figure 4.2.23 Water Injection Type Low-NOx Burner

Source: ibid.

air and is rapidly mixed with it. This pre-mixture is released in a wide angle circumferentially by the help of a deflector provided at the end of the burner gun. Active re-circulation zones are formed behind the deflector and near the front wall of the burner, and a film-like, uniform, annular flame of short length and low brightness is formed.

Because of heat radiation from the flame itself, the flame temperature is not so high and the detension time in the high temperature zone is short, resulting in the reduction of thermal NOx.

ii) Divided flame type (DFT)

As shown in Figure 4.2.17, the divided flame type burner has grooves at the burner tip to divide the flame into multiple, independent, small flames. Reduction of the flame temperature and shortening of the detension time thus achieved suppress generation of thermal NOx.

iii) Self-recirculation type (SRT)

The self-recirculation type low-NOx burner utilizes the momentum of combustion air flow or fuel flow to recirculate a portion of the combustion gas to the combustion zone. As shown in Figure 4.2.18, this type of burners can be classified into two kinds depending on the difference in circulation method. In (a) of this Figure, high-speed fuel jet flow causes a portion of the combustion gas to be drawn into the burner tile through the Coanda effect. In this way, a partial combustion reaction occurs in a direction opposite to the main fuel jet flow. At the same time, the combustion gas produced is dragged in the fuel jet flow enabling thermal decomposition and gasification of the fuel. The temperature of combustion gas itself decreases, allowing gasification combustion mainly of CO and H_2 at the burner tile outlet. This combustion is highly effective in reducing NOx. In (b), on the other hand, the total amount of combustion air is blown through a gap called a ring nozzle, producing a pressure difference before and after the nozzle. Part of the combustion gas is circulated to the front of the ring nozzle where the fuel is jetted. As the fuel is thermally decomposed by the high temperature gas, then contacts the air, combustion is rapidly completed.

iv) Two-stage combustion type (TCT)

Though there are burners with three stages or more, they are included here in the two-stage combustion type burners, which consist of the first and the second stages for combustion.

General structure of this type of burner is shown in Figure 4.2.19. In the first-stage of combustion, the air ratio is set far below (around 0.5 - 0.7, though varying depending on the fuel) the conventional staged combustion method and the fuel is decomposed to generate a combustion gas consisting mainly of CO and H_2. This gas is completely burnt with secondary air in the second stage.

For gas combustion, there is a reversed two-stage combustion method in which primary combustion is effected with a high air ratio and the combustion is completed with a low air ratio by blowing fuel again in the secondary combustion zone (see Figure 4.2.20).

In this case, generation of NOx can be suppressed by the low flame temperature during primary combustion and the low concentration of oxygen during the secondary combustion.

v) Off-stoichiometric combustion type (OCT) (Self-biased atomizer type)

The off-stoichiometric combustion type low-NOx burner forms both the fuel lean and fuel rich zones in one flame enabling staged combustion and control of the maximum flame temperature. The construction of the burner tip called the self-biased atomizer (SBA) is shown in Figure 4.2.21. Fuel from large nozzles is burnt in the fuel rich state while that from small nozzles is burnt in the air excess state. Figure 4.2.22 shows the construction of the off-stoichiometric combustion type (OCT) burner for gas combustion. Nozzles for rich fuel and lean fuel are provided alternately.

This type of the low-NOx burners were installed in a power generation boiler in the 18 de Marzo refinery of PEMEX for the field test of performance as a part of this Study. The result of the test proved effective in reducing NOx emission. A detailed description on the test is given in the Appendix.

vi) Water/steam injection type (WIT)

The water injection type low-NOx burner, as shown in Figure 4.2.23, has small holes for water injection apart from fuel nozzles in the burner nozzle tip. NOx generation is controlled mainly by decreasing the flame temperature while particulate matter is reduced by the steam.

vii) Combined type (CT)

Low-NOx burners that combine the functions possessed by the above types of burner have been developed. A combination will prove effective if an NOx control principle does not overlap. In particular, a combination of functions that can reduce both thermal NOx and fuel NOx will prove effective for fuels with a high N content. Table 4.2.5 shows various low-NOx burners developed to date in Japan.

Table 4.2.5 Names and Control Technologies of Low-NOx Burners

Name of Burner	Control Technology	Name of Burner	Control Technology
CAP	Two-stage combustion	RB	Two-stage combustion
FH	Two-stage combustion	NPL	Self-recirculation
R	Self-recirculation	YLAP	Self-recirculation
HLF	Self-recirculation	Voltmetric	Self-recirculation
RSNT	Self-recirculation	Self-Bias	Off-stoichiometric combustion
SPP	Self-recirculation	Low-PM	Off-stoichiometric combustion
PM	Off-stoichiometric combustion	UN	Water injection
SE	Off-stoichiometric combustion	MR	Two-stage combustion + self-recirculation
MNL	Reversed two-stage combustion	CDC	Two-stage combustion + Off-stoichiometric combustion
TZ	Reversed two-stage comcustion	JSR	Water injection + divided flame
GNC	Self-recirculation + two-stage combustion	MS	Reversed two-stage combustion + two-stage combustion
SRG	Two-stage combustion + self-recirculation	DF-CN	Two-stage combustion
HLN	Self-recirculation + two-stage combustion	PG Dual Register	Two-stage combustion
XB	Self-recirculation + divided flame	SCR	Two-stage combustion
TCG	Self-recirculation + Off-stoichiometric combustion	Pulverized coal PM	Two-stage combustion + Off-stoichiometric combustion
YRW	Well-mixed + self-recirculation	VD	Two-stage combustion
VGSA	Self-recirculation + Off-stoichiometric combustion + two-stage combustion	Controlled Flow/Split-Flame	Two-stage combustion + divided flame
KTC	Two-stage combustion	SM	Two-stage combustion

Source: ibid.

2) Reduction of Combustion Chamber Loading
(Size Increase of the Combustion Chamber)

Reduction of the input load by increasing the furnace size is a reliable way of controlling NOx. This method brings about a relatively uniform temperature distribution of the combustion gas with lowered maximum temperature, resulting in reduction of the NOx concentration. Reduction of smoke and soot results from the prolonged detension time that promotes recomubstion of unburnt fuel.

3) Two-stage Combustion

In this method, the amount of air necessary for combustion is supplied in the two separate stages. Around 80% of the required air is supplied in the first stage, causing incomplete combustion in the O_2 deficient state in order to lower the combustion temperature. Remaining air is then supplied through the secondary air inlet to enable the secondary combustion of unburnt contents. Since the flame becomes longer than usual, applicability of this method depends on the shape of the combustion chamber. Substantial reconstruction works are required to adapt this method to a conventional system as described below:

i) Installation of the secondary air inlet to the boiler main body (see Figure 4.2.24)

ii) Repair of the tubes on the boiler wall

iii) Installation of air duct, damper and control system

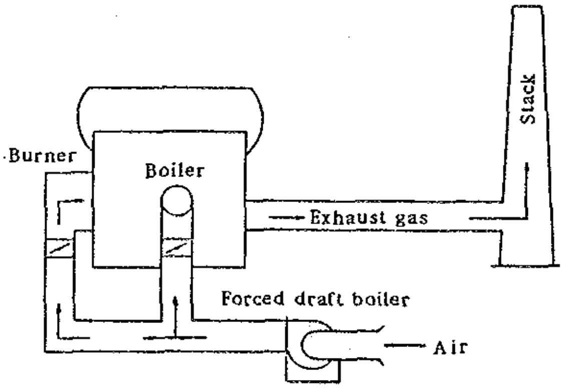


Figure 4.2.24 Two-stage Combustion in Boiler

The factors affecting the NOx control effect in this case include the ratio of the primary air volume to the secondary air volume and the position of the secondary air inlet. The inlet position is generally on the side, but may be on the front.

There is another method achieving a similar effect in that some of the burners are turned off while supplying air only, and supply of combustion air is reduced for the burners which are on. This method is called the quasi two-stage combustion or the burner-cut method.

The two-stage combustion is generally suited to large facilities and will prove more effective when used in combination with the flue gas recirculation method described later. This combination is expected to achieve a substantial reduction of NOx for the corner firing system such as the No. 2 and No. 3 boilers in the Valle de Mexico thermal power plant.

The two-stage combustion is also one of a few methods that offer suppression of fuel NOx generation.

4) Off-stoichiometric Combustion

This method can be applied to a boiler having multiple burners. The burner ports are divided into two groups. A fuel-rich state is set for one group while a fuel-lean state is set for another group.

NOx generation is controlled by the reduced O_2 concentration in the fuel-rich portion and by the reduced temperature with an excess air in the fuel-lean portion.

The following critical requirements must be satisfied to apply this method:

i) Use of burners with satisfactory mixing performance

ii) Understanding on the tendency of NOx generation for the wide range of air ratio

iii) Selection of the appropriate fuel-rich/lean air ratios according to such tendency

5) In-furnace Denitration Combustion

As a variation of off-stoichiometric combustion, there is a method called in-furnace denitration combustion in which additional amount of hydrocarbon fuel is blown into the combustion gas of the fuel thereby reducing (denitrating) NOx in the gas. Into the gas produced by combustion of the fuel by the main burner, the same kind of fuel (about 0 - 15%) is blown by another burner so as to decompose NOx in the gas. Then, the deficiency in the air is supplemented to complete the combustion. Generally, this method is employed for relatively large furnaces mostly in combination with flue gas recirculation and low-NOx burners. This method has been applied to tangential combustion (corner firing) of large power generation boilers, with noticeable success in NOx reduction.

6) Exhaust Gas Recirculation

This method involves recirculation of a portion of the combustion gas through a duct, and mixing into combustion air, thereby reducing the oxygen content in the combustion air (see Figure 4.2.25). The resulting increase of heat capacity of the gas causes a decrease in the combustion temperature, thus suppressing the NOx generation. The maximum recirculation ratio is limited by the combustion stability limit, and normally determined in terms of the NOx reduction effect at around 15 - 20%.

As the volume of combustion gas passing through the boiler increases by the volume of recirculation, and the temperature of combustion air increases, it is necessary to increase the size of the boiler and to augment the capacity of the forced draft fan (FDF). The existing boiler capacity is reduced to 70 - 80%. By the principle, this method is effective in reducing thermal NOx, but ineffective in reducing the fuel NOx.

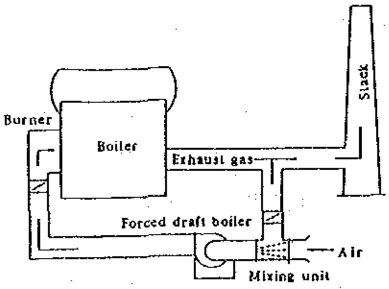


Figure 4.2.25 Exhaust Gas Recirculation
(Example of Mixed Suction of Air and Flue Gas by FDF)

7) Water/Steam Injection

In this method, water or steam is injected into the combustion flame to lower the flame temperature, thereby suppressing NOx generation. By injecting water or steam into flame, latent heat is utilized to increase the heat capacity and lower the flame temperature.

Injection is directed either into the combustion air or into the flame from the burner throat. The NOx reduction effect is nearly proportional to the injection amount, and the decrease in thermal efficiency is rather small unless the amount of injection is excessive. This may be attributed to a fact that the heat transmission rate increases, in spite of reduced heat absorption in the furnace by the decrease in the flame temperature, because the flow rate in the convection zone increases following an increase in combustion gas and the injection heat transmission increases due to an increase in partial pressure of H_2O.

Practically speaking, however, a portion of the steam generated by the boiler is lost by the amount of injection, e.g., the overall efficiency decreases by 2 - 3% by the steam injection of 0.3 - 0.4 kg/10^4 kcal. This method proves most effective when gas is burnt, but large effect cannot be expected when oil is burnt.

(4) Emulsion Combustion

1) Emulsion Fuel

Emulsification refers to dispersion of one of two liquids which are not usually mixed together such as oil and water into another in small drops; their diameters are normally a few microns.

Figure 4.2.26 shows a microscopic photo of emulsion.

Emulsion is roughly classified into two types as shown in Figure 4.2.27 : 1) water-in-oil (W/O) type (water drops dispersed in oil), and 2) oil-in-water (O/W) type (oil drops dispersed in water).

The emulsion state differs depending on the kind of stirrer used, the stirring method, and the kind of surfactant. The oil-water ratio can be freely chosen for both emulsion types. Figure 4.2.28 shows a general relation between the oil-water ratio and the viscosity. In the case of the water-in-oil type, the viscosity of emulsion increases gradually with an increasing number of water drops, and then to become a gel state of low fluidity. The viscosity of the oil-in-water type, on the other hand, decreases greatly with increasing water content.

Figure 4.2.29 shows the relation between temperature and viscosity of emulsion fuels from the result of the experiment on the O/W type emulsification conducted in this Study in Mexico using Mexican heavy oils. A 28% addition of water reduced the viscosity from original 1,100 cSt (50°C) to 40 cSt (50°C), a decrease to 1/26. In this state, atomized combustion is possible even at room temperature. In the experiment, satisfactory results were obtained in atomized combustion without need of oil preheating.

In the selection of a surfactant and additives for the emulsified combustion system, the following consideration shall be made:

i) They must not contain sulfur, nitrogen, and harmful heavy metals which are causes of secondary pollution.

ii) Emulsion must be stable, particularly free from separation due to temperature change.

iii) They are inexpensive.

iv) Emulsions must not be broken by acid or alkaline.

v) Due attention must be paid to prevent rusting of combustion equipment.

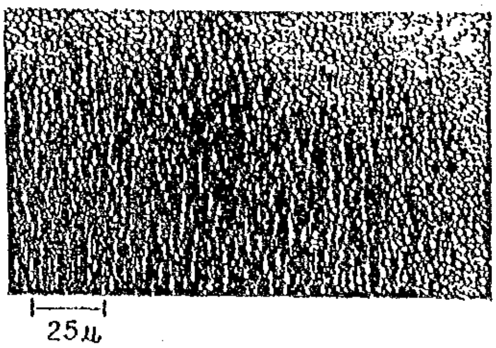


Figure 4.2.26 Microscopic Photo of Emulsion

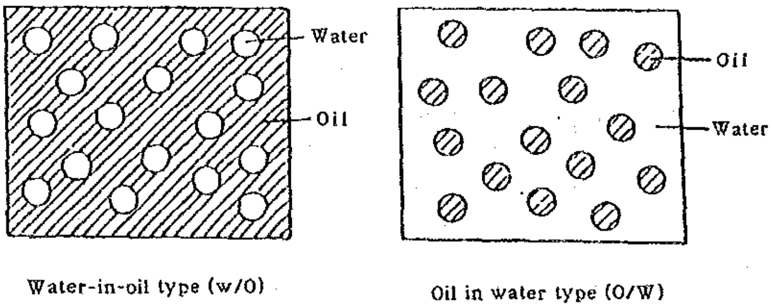


Figure 4.2.27 Types of Emulsion

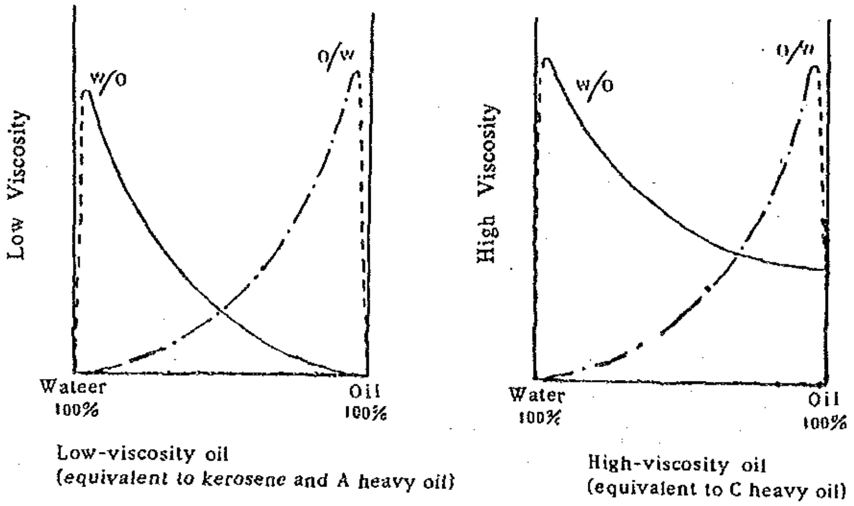


Figure 4.2.28 Change of Viscosity of Emulsion

Source: "Combustion System Utilizing Emulsion," Japan Oil Chemistry Association, Kansei Division, Text for the 39th Meeting of the Interfacial Chemistry, 1976.

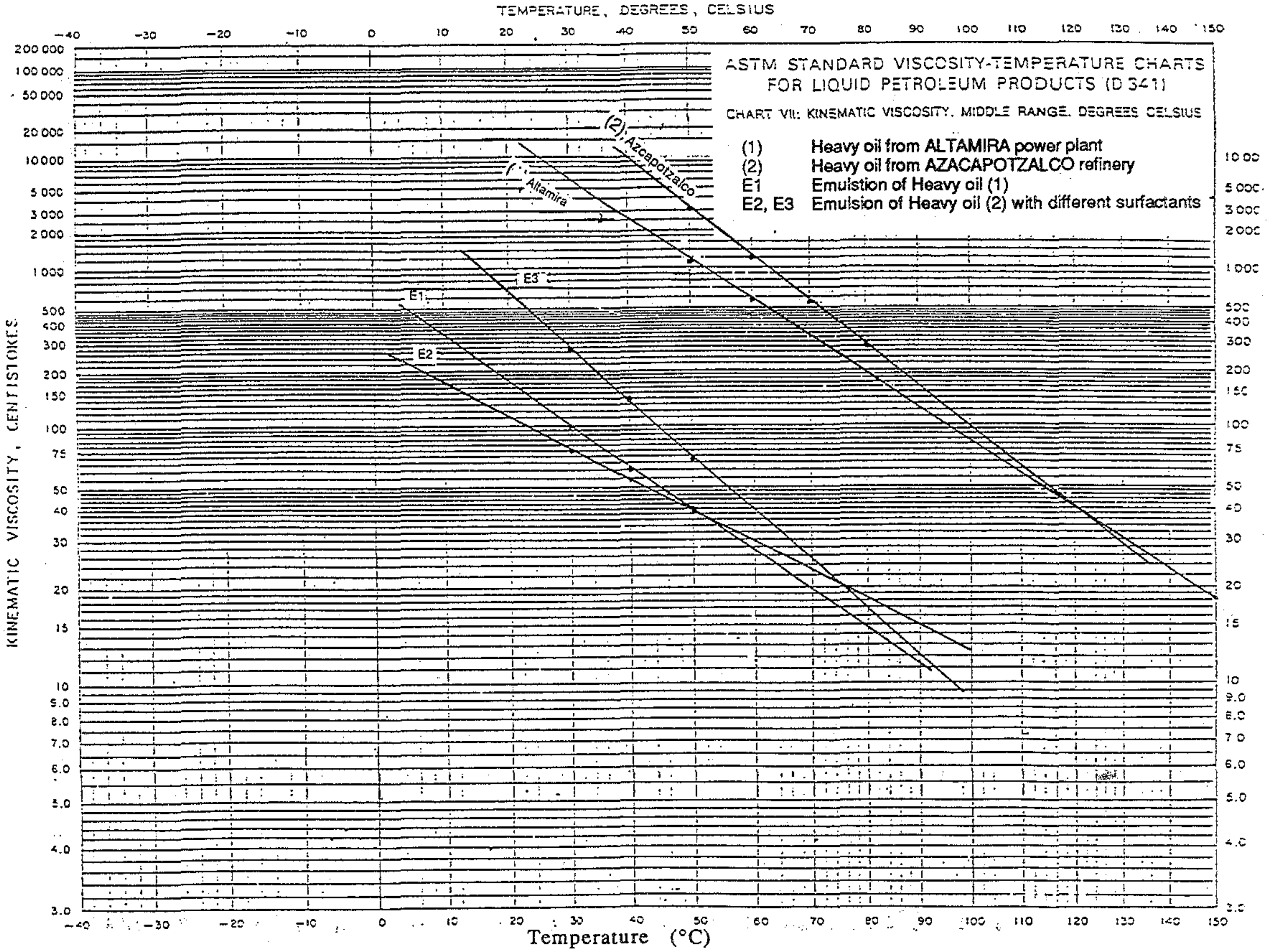


Figure 4.2.29 Relationship Between Temperature and Viscosity for Heavy Oil and Its Emulsion

2) Mechanizm of NOx and Smoke and Soot Control in Emulsion Combustion

Figure 4.2.30 shows an outline of mechanizm of emulsion combustion.

Mechanizm of reduction in generation of NOx and smoke and soot is described below. More detailed descriptions are given in the Appendix.

i) Combustion with low excess air through promotion of atomization into fine particles

Fuel particles atomized to 30 - 150μm are broken into still finer particles through evaporation of water contained in the emulsified fuel. As emulsion particles of 0.5 - 5μm are dispersed in atomized fuel drops, the oil drop - air contact area increases rapidly, thereby enabling reduction of smoke and soot and NOx through the low excess air combustion.

ii) Removal of local high-temperature zones by water droplets in emulsion fuel

Water is uniformly dispersed in fuel, which leads to a uniform flame as a whole, thereby suppressing appearance of local high-temperature zones.

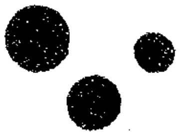
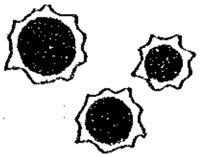
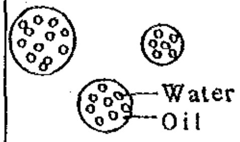
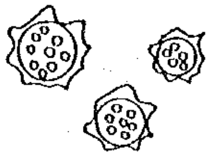
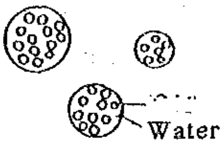
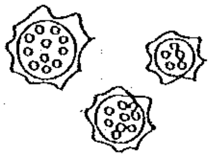
iii) Heat absorption through evaporation of water

Thermal NOx can be reduced by lowering the combustion temperature. The latent heat of evaporation of water in the emulsion fuel lowers the combustion temperature, thereby reducing generation of thermal NOx.

iv) Heat absorption by water gas reaction

At a high temperature of over 1,000°C, the water gas reaction occurs between water in emulsion and carbon in fuel. This reaction is endothermic and favorable for removal of local high-temperature zones.

$$H_2O + C\,(\text{fuel}) \xrightarrow[\text{1000°C or more}]{} H_2 + CO - 28.1\ \text{kcal}$$

	Atomization ⇨	Ignition/ combustion start ⇨	Conbustion under way ⇨	Combustion gas
Normal atomization combustion				
	Particle size 30 - 150 μm	Ignition and combustion begin on the oil drop surface. Internal evaporation and gasification accelerate.	Combustion proceeds through acceleration of gasification inside particles	Larger particles delay in combustion completion, resulting in soot
Water-in-oil type (W/O)				
Emulsion combustion	0.5 - 5μm emulsion particles dispersed in atomized particles	Start of ignition and combustion. Particles are broken down into much finer particles by sudden expansion due to evaporation of water in emulsion	Sudden expansion of oil drop surface area (area of contract with air), combustion with lean air, and removal of local high-temperature portion, thereby suppressing NOx generation	Particle size is extremely small, enabling uniform completion of combustion, and thereby suppressing soot generation
Oil-in-water type (O/W)				

Source: ibid., 1976

Figure 4.2.30 Mechanism of Emulsion Combustion

4.2.4 Energy Saving Technologies for Reduction of NOx Emission

(1) Outline of Energy Saving Technology

As one method of reducing NOx emission, saving of fuel and energy can be considered. Energy saving measures for combustion facilities such as boilers and heating furnaces include :

1) combustion rationalization

2) heat conduction rationalization

3) heat discharge loss prevention, and

4) utilization of recovered heat of flue gas

The most important consideration in the measure 1) is the perfect combustion with low excess air, i.e., appropriate operational control of *appropriate combustion facilities maintaining a optimum air ratio* achieving low concentration of NO, particulate matter and CO.

In Japan, the standard air ratios for boilers and industrial furnaces are specified based on the Factory Energy-use Rationalization Law (Energy-saving Law). With respect to boilers, excluding those of natural draft and balanced draft, the standard air ratios for power stations are between 1.05 and 1.1 for both liquid fuel and gaseous fuel, and those for other boilers range between 1.1 and 1.3. The standard air ratios for industrial furnaces are as shown in Table 4.2.6.

Table 4.2.6 Standard Air Ratio for Industrial Furnaces in Japan

Division	Standard Air Ratio
Foundry metal melting furnace	1.3
Continuous billet heating furnace	1.25
Metal heating furnace other than continuous billet heating	1.3
Continuous heat treatment furnace	1.3
Gas generation furnace and gas heating furnace	1.3
Petroleum heating furnace	1.4
Thermal decomposition furnace and reforming furnace	1.3
Cement kiln	1.3
Alumina kiln and lime kiln	1.4
Continuous glass melting furnace	1.4

(Note) The standard air ratios in this Table apply to the values measured at the outlet of the furnace under operation at around the rated loading after checking and repair.

The measure 2) deals with the prevention of discharge of high-temperature flue gas without effective heat utilization in the heat conduction portion of furnaces due to insufficient and/or contaminated heat conduction surface. For batch heating systems, the reduction of a large amount of heat stored at starting and ending of operation caused by unreasonably thick furnace walls is also a major theme in this category.

The measure 3) mainly deals with the prevention of heat discharge through furnace walls. An appropriate thermal insulation should be applied.

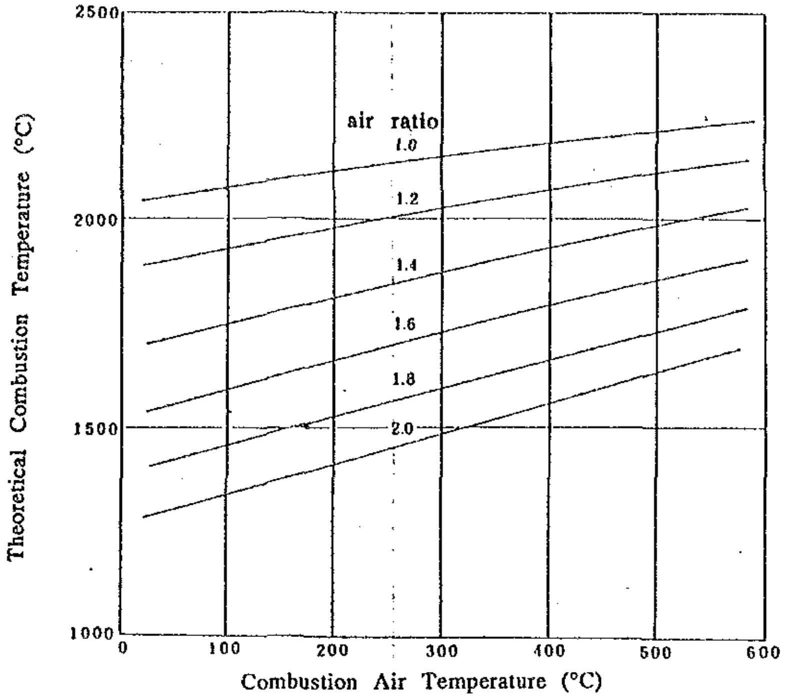
The measure 4) is for the recovery and utilization of the heat of the flue gas before discharged through the stack. In the case of boilers, possible energy-saving practices include combustion air preheating by flue gas, boiler feedwater preheating, and its use as thermal media in other facilities. The first two methods are for recycling of recovered heat to the boiler, so that the boiler input heat can be reduced by the amount of recovered heat. Since feedwater preheaters (economizer) only heat feedwater, they have no adverse effect on NOx generation. But air preheaters raise combustion air temperature and flame temperature, and consequently may increase NOx generation. For this reason, economizers are more recommendable than air preheaters for boilers. Economizers used to pose a problem of limited heat recovery efficiency related to the sulfuric acid dew point. However, utilization of hard glass tubes resistant to sulfuric acid has greatly improved the heat recovery efficiency of economizers.

With respect to combustion air preheaters, the kineticaly analyzed relationship between the combustion air temperature and the theoretical combustion temperature is shown in Figure 4.2.31, and the resulting relationship between the air temperature and the NOx concentration is shown in Figure 4.2.32, which shows that the NOx concentration increases from 130 ppm for air of normal temperature to 250 ppm for air preheated to 250°C, under otherwise equal conditions.

According to other examples, where the NOx concentration with air of normal temperature was assumed to be 100 ppm for propane, 80 ppm for natural gas, and 150 ppm for heavy oil, it increased by the ratios shown in Figure 4.2.33 when air was preheated. As can be seen, when the C-class heavy oil is burnt with air heated to 250°C, 260 ppm of NOx is generated. The air temperature vs. NOx curve for heavy oil burning given in Figure 4.2.15 also shows nearly the same NOx increase ratio resulting from higher air temperature in the case of ordinary burners.

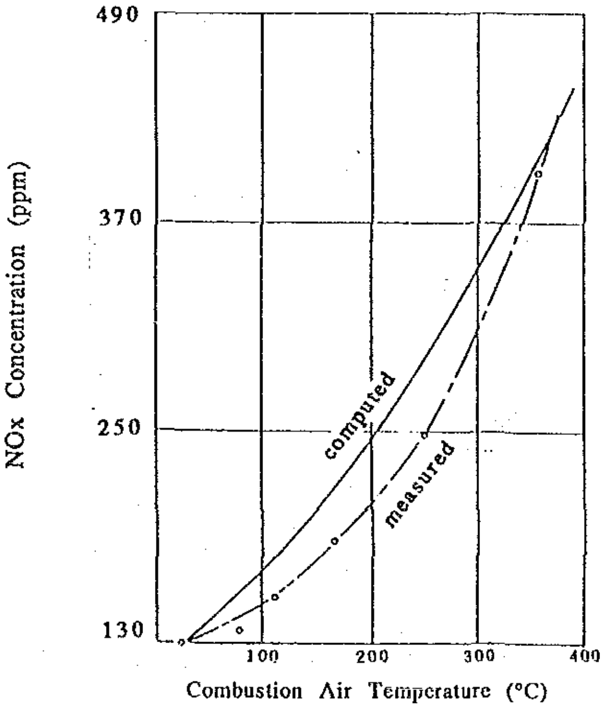
For combustion facilities adopting some low NOx combustion measures, the NOx increasing effect of higher air temperature varies with the kind of low NOx combustion measures, combustion chamber shape and kind of fuel used. But in an average, increase of NOx concentration over that prevailing under the normal air temperature is : 10 to 20 ppm at an air temperature of 100°C, 25 to 60 ppm at 200°C, and 40 to 100 ppm at 300°C.

The two-stage combustion and the off-stoichiometric combustion are less influenced by high air temperature. That is to say, in the two-stage combustion, the adverse effect of high temperature on NOx generation can be suppressed in the first stage combustion zone where air ratio below the theoretical level is used, through reducing influence of high temperature by promotion of air-liquid mixing (or air-gas mixing). The bottom curve in Figure 4.2.15 is considered as an example of this feature. However, with existing boilers, it must be understood that unless the shape and the size of the combustion chambers are thoroughly studied, the NOx suppression



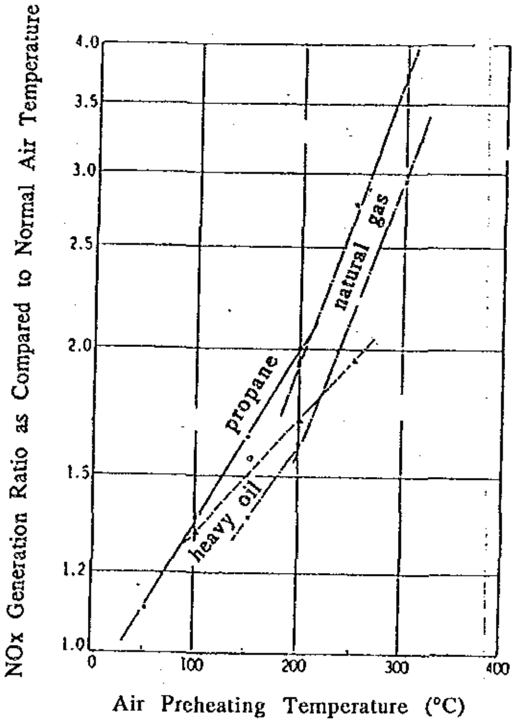
Source: Nagata, K., Technical Data Book for NOx Reduction Measures, Fuji Technosystem, March 1974.

Figure 4.2.31 Relation Between Combustion Air Temperature and Theoretical Combustion Temperature



Source: Sames as Figure 4.2.31.

Figure 4.2.32 NOx Concentration vs Combustion Air Temperature



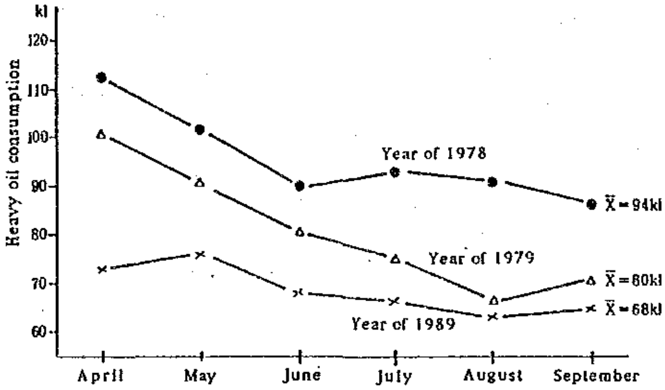
Source: Japan Industrial Furnace Assoc., Industrial Furnace Energy Saving Mannual, Nov. 1981.

Figure 4.2.33 NOx Generation vs Air Preheating Temperature effect of the two-stage combustion and the off-stochiometric combustion cannot be fully realized.

(2) Examples of NOx Reduction Through Energy Saving

1) Fuel Saving Through Improvement of Existing Facilities and Installation of Water Heater

Figure. 4.2.34 shows an example of a Japanese plant. Consumption of heavy oil in the existing boiler was reduced through: 1) effective utilization of hot effluent water, 2) improvement of drain trap, 3) improvement of heat insulation of steam piping, and 4) installation of a water heater. As a result, the consumption of heavy oil was reduced in 1980 by 15% from the 1979 level, and in 1981 by 15% from the 1980 level.



Source: "Energy Saving Guidance Manual," Small and Medium-sized Enterprises Agency, 1983.

Figure 4.2.34 Energy Saving with Boiler

2) NOx Reduction by Increased Radiation Area and Improved Heat Insulation of Furnace Ceiling at Glass Factory

A Japanese major glass factory implemented the following measures against the previous NOx concentration of 1,000 to 1,100 ppm at 5% O_2 combustion in order to meet the more stringent regulation.

a) The former air atomizing oil burner was replaced by a pressure injection spray burner.

b) The furnace ceiling height was increased to increase combustion chamber volume and heat radiation area.

c) Combustion at low excess air; previous 2 to 3% O_2 was reduced to below 1%.

d) Improvement of heat insulation mainly in the furnace ceiling.

The above measures resulted in 30 to 40% reduction of NOx level, bringing it below 500 ppm (at 5% O_2).

The heavy oil burners are of the flat flame type, one each installed at each air passage. The furnace temperature conditions are : 1600°C at ceiling, 1500°C at side wall, 1450°C for flue gas at the regenerator inlet, and 1250 to 1300°C for combustion air. C-class heavy oil with viscosity of 500 to 700 cSt, S content of 3%, and N content of 0.4% was used previously, and atomized at a pressure of 30 kg/cm^2g. But now higher quality oil with a lower N content is used.

(3) NOx Reduction of Boilers in Public Bathhouses in AMCM by Energy Saving

There are numerous small boilers in more than 200 bathhouses in AMCM. These boilers have an evaporation rate between 0.5 ton/hr - 2 ton/hr. A majority of bathhouse boilers use heavy oil, and others use lighter oils such as diesel and kerosene.

The boilers are mostly of the flue and smoke tube type; only one of the 11 bathhouses investigated used the water-tube type. Most of these boilers were purchased from small makers, or elsewhere as used ones. They have been used for 10 to 30 years, beyond their service limits, and are mostly outdated.

Only a few measurement data are available on the nature of flue gas from bathhouse boilers. Particularly for NOx and smoke and soot, there is only one example of measurement conducted in the diagnostic survey in the present Study for a 1.5 ton/hr boiler.

This boiler uses heavy oil. The measurement was made with a loading rate of around 80%, showing the NOx concentration of 125 ppm at 10.5% O_2 or 190 ppm as converted to 5% O_2, and that of particulate matter at $0.15 g/m^3$.

According to the "Integrated Program Against Air Pollution in the Metropolitan Area," the amount of pollutant emissions from public bathhouses is to be reduced by at least 10% under the supervision of UNAM.

At least 40 bathhouses are to be modernized within 6 months from October 1990. Others are to install devices to improve combustion process and to control pollutant emissions.

The following points on combustion control must be taken into account to ensure satisfactory combustion and to control emissions of NOx and smoke and soot from the bathhouse boilers within AMCM.

i) Appropriate preheating temperature

The preheating temperature of heavy oil for the previously stated boiler was low at 50°C, resulting in poor atomization and drip burning of the fuel.

ii) Virtually all of these boilers have no oil flow meters, pressure gauges, and other measuring instruments. These should be installed.

iii) Faulty heat insulation

The surface temperature of some boilers was high. These boilers need heat insulation.

iv) Wide openings, with large volumes of air leak-in

Since excessively large air ratio causes increased NOx concentration, these openings must be plugged.

v) Natural drafting should be replaced by forced drafting so long as it is possible.

vi) Inadequate knowledge of energy saving

Since heat loss of flue gas is large and fuel is wasted due to excess air combustion, education of boiler operators are necessary.

vii) Guidance on installation of recuperator

A vertical stack lining type recuperator should be provided upon replacement with a new boiler.

4.3 Soot Control Technologies

4.3.1 Characteristics of Soot and Mechanism of Soot Generation

(1) Characteristics of Soot

The combustion is a complicated series of reaction. Carbon particles resulting from combustion of various fuels are called soot. Since no soot is generated without carbon particles produced in the flame during combustion, the cause of soot generation lies in the combustion process. Carbon particles and soot generated in the flame have almost an identical nature.

Within the flame of burning gaseous hydrocarbon, carbon particles are dispersed independently and flocculated into large soot particles at the end of the flame. Though carbon particles in the flame are nearly spherical, they may often clump together and become strings near the flame end or after sampling.

The size of carbon particles ranges between 10 and 1000Å, and the carbon structure differs depending on the kind of fuel and its combustion conditions. The carbon particles also contain hydrogen by 1 - 6% by weight.

The soot thus produced from burning fuel acts as nuclei which absorbs sulfuric acid generated from burning sulfur in fuel, producing a snow-like material growing at around the dew point of combustion gas. This material is called snow smut, acid smut or snow fume.

The chemical composition of snow smut differs depending on the kind of fuel and processes of combustion but it normally ranges between 20 - 50% in carbon content, 10 - 40% in sulfur content, and 10 - 30% in ash content. The particle size is relatively large and may be identified with the naked eye. Certain types of snow smut generated in the flue may often grow into large lumps which, due to weight, drop around the stack causing damages.

(2) Mechanism of Soot Generation

The mechanism of soot generation has not yet been fully understood, but it is believed that substances with high carbon content are gradually produced through dehydrogenation and decomposition, as well as through generation of aromatic rings and polimerization, during combustion of hydrocarbon fuel, finally producing carbon particles. In other words, dehydrogenation and condensation are the principal factors in the generation of carbon. However, specialists differ in opinion concerning which of these reactions occur first or whether they proceed simultaneously.

(3) Kind of Fuel and Generation of Carbon

The nature of fuel greatly affects the generation of carbon or soot, as generally described below:

1) Generation of soot tends to increase with the increasing C/H ratio of fuel.

2) Fuels whose dehydrogenation is easier than breakdown of carbon bonds
(-C-C-) tend to produce more soot.

3) Hydrocarbons which readily undergo dehydrogenation, polymerization, and cyclization (generation of aromatics) reactions tend to produce more soot.

4) Hydrocarbons which are readily decomposed or oxidized produce less soot.

(4) Soot From Gas Combustion

Hydrocarbons in the gas phase produce less soot than in the liquid or the solid phase.

1) Pre-mixed Combustion

The flame surface temperature is considerably high and the fuel-air contact is sufficient. Hence the oxidation speed is much higher than the speed of carbon generation through dehydrogenation or condensation, and almost no carbon is generated. The flame of pre-mixed combustion becomes non-luminous because almost no carbon is produced and gases that are irrelevant to carbon generation such as CO and H_2 are produced as in the case of emulsion combustion.

2) Diffusion Combustion

The flame temperature during diffusion combustion does not rise much because the speed of oxidation is limited by the air diffusion. This feature promotes dehydrogenation and condensation. Moreover, since the detension time of intermediate products in the flame becomes longer, carbon particles are readily produced in the flame and thus soot is produced. Therefore, the diffusion combustion produces normally luminous flame.

3) Combustion Within the Combustion Chamber

If there is 10% excess air, both pre-mixed combustion and diffusion combustion can achieve nearly complete combustion without soot generation within the combustion chamber. If the air ratio is less than the theoretial value, even gas fuel produces soot. Excessively large air ratio, on the other hand, causes a drop in the temperature of the combustion chamber, resulting in incomplete combustion.

(5) Soot From Oil Combustion

The process of combustion of atomized liquid oil is similar to that in diffusion combustion of gas fuel. Though carbon is produced in the flame, the oxidation speed is higher than the speed of dehydrogenation or condensation when the air diffusion speed is high, resulting in relatively small amount of soot residue after combustion.

Burning of atomized heavy oil, however, leaves coke deposits after evaporation of oil droplets. These deposists, called cenosphere, are much larger in size than carbon produced from the gas reaction, and the sizes are related to that of the atomized oil droplets. Sparking in the flame occurs when cenosphere is heated to brightness in high-temperature, and this may be attributed to large drops of atomized oil due to the use of heavy quality oil or faulty atomization. Consequently, the carbon produced from burning of heavy oil consists of that originated from the gas phase reaction and cenosphere.

(6) Soot Generation by Combustion of Mexican Heavy Oil

Heavy oil usually contains around 10% residual carbon (Conradson carbon) that tends to produce soot by combustion. Under favorable combustion conditions, however, a large portion of residual carbon burns; 97 to 98% in small to medium boilers of around a 10 ton/hr evaporation rate, and 98 to 99.5% in large boilers in which the initial stage soot is re-burned during the long detension time in the furnace. Accordingly, 2 to 3% of the residual carbon is released into the atmosphere from small boilers as soot, and 1% of that from large boilers.

However, heavy oil in Mexico, especially Maya heavy oil, contains much Conradson carbon as shwon in Table 4.2.9, and even the small amount of soot resulting from combustion of such oil is one of the major air pollutants in Mexico. When 1 ton of heavy oil burns per hour in a boiler of say, 12 ton/hr evaporation, the theoretical gas volume is approximately 13,250 Nm^3 per hour for a flue O_2 content of 4%. When 16.8% Conradson carbon burns up to 97.5% and 2.5% become soot, the amount of soot is $0.317 g/Nm^3$, which is visible as black smoke. Even when the soot is only 1% of the Conradson carbon, as in large boilers, the soot content is $0.127 g/Nm^3$, which is below the permissible soot level of $0.18 g/Nm^3$ in Mexico. But since this permissible level is scheduled to be changed to more stringent one, further measures for soot reduction are required.

4.3.2 Technologies to Control Soot Generation

In order to reduce the smoke and soot emission, its generation must first be controlled, and for this end, the main methods considered are: 1) use of high quality fuel, 2) emulsion combustion, and 3) combustion improvement.

(1) Use of High Quality Fuel

The main fuels in use in AMCM are, in the falling sequence of smoke and soot generation, heavy oil, diesel, kerosene, LPG, and natural gas. Since heavy oil is the highest in smoke and soot generation, either its quality improvement or replacement by other kinds of fuel is advisable.

When the heavy oil hydro-desulfurization project of PEMEX is implemented, the Conradson carbon in heavy oil will also be removed by around 50% by the desulfurization process. Therefore, the use of such desulfurized heavy oil can be one good method of reducing smoke and soot generation.

One possible process of stepwise replacement of heavy oil to better fuels is as follows:

1) Mixed combustion of heavy oil and diesel. At 50% mixing, the Conradson carbon is reduced to half.

2) Complete replacement by diesel oil, or mixed combustion of heavy oil and natural gas.

3) Replacement by natural gas.

There are also the following heavy oil reforming possibilities:

1) Cracking of heavy oil into light oil

2) Asphalt removal from heavy oil by solvent

(2) Emulsion Combustion

While the emulsion combustion has been described as a NOx generation control technology under 4.2.3, it is also very effective in reducing smoke and soot generation.

Usually, commonly used NOx reduction methods such as low air ratio combustion, two-stage combustion, and in-furnace denitration tend to increase smoke and soot generation between 20 and 40%. The emulsion combustion is capable of reducing smoke and soot considerably. When it is combined with the fuel change as listed under (1), not only smoke and soot can be reduced, but also the processing cost can be substantially reduced.

(3) Improvement of Combustion Method

There are various types of boilers. But almost all of them have a combustion chamber enclosed with a water-cooled wall. At a time of starting, the temperature in the combustion chamber is low, and soot tends to be easily produced. Therefore, smoke and soot generation can be prevented considerably if the diesel oil is used at the time of starting, and then, it is changed to a heavy oil after the rise of temperature in the combustion chamber.

Recent medium-to-small boilers have a relatively high capacity in combustion chamber load. Sudden cooling of the flame by contact with the water-cooled wall in the combustion chamber or adhesion of sprayed oil droplets to the wall surface may cause smoke and soot generation It is therefore necessary to pay due attention to following items in the design stage:

i) Satisfactory atomization of burners

ii) Combustion air supply method

iii) Appropriate relationship between the flame shape and combustion chamber

For flue and smoke tube boilers having a small cross sectional area and a large length, design should aim at slow combustion with long flames, and for boilers with a large cross sectional area and a short length, at quick combustion with broad and short flames.

4.3.3 Dust Collectors

(1) Classification of Dust Collectors

A gas containing solid or liquid particles in a state of fine particles is generally called aerosol. A dust collector separates and collects these fine particles from aerosol.

One or more dust collecting forces, such as gravity, inertia, centrifugal force, thermal force, diffusion force, electric force, and sonic force are employed to separate fine particles. Dust collectors are classified according to the principal collecting force as shown in Table 4.3.1.

Among these dust collectors, an ultrasonic dust collector is not yet industrialized at present because of problems in performance, economy and noise.

Table 4.3.1 Classification of Dust Collector

Dust Collecting Force Name of Dust Collector	Gravity	Inertia	Centrifugal Force	Thermal Force	Diffusion Force	Electric Force	Sonic Force
Gravitational Dust Collector	◎						
Inertial Dust Collector	○	◎	○				
Centrifugal Dust Collector	○	○	◎	△			
Scrubbing Dust Colletor	○	◎		△	◎	△	
Filter Dust Separator	○	◎			◎	△	
Electrostatic Precipitator	○	○			○	◎	
Sonic Precipitator	○		○				◎

Note: Forces indicated with ◎and ○ are principal dust collecting forces while those with △ are used when flocculation is intended.

(2) Performance of Dust Collector

The characteristics of combustion exhaust gas and particulate matter contained in the gas vary widely depending on the type and construction of combustion equipment, kind and mixing ratio of fuel and raw material, and combustion and other operating conditions. They greatly affect the performance of a dust removal system.

The characteristics of prtticulate matter affecting the performance are the particle size distribution, concentration, specific gravity, composition, electric resistance, characteristics hygroscopic characteristic, and adhesiveness. On the other hand, the characteristics of gas affecting the performance are the gas volume, water content, dew point, temperature, composition, viscosity, density, and pressure.

Problems in terms of safety are explosiveness and toxicity of particulates and gas while those concerned with durability of the collecting system include corrosiveness and abrasiveness. It is therefore necessary for planning of a dust collector to carry out an in-dept preparatory study to understand the generation process, amount, and nature and its variation of smoke and soot.

In order to have them fully demonstrate their functions, dust collectors must be operated to collect dust at a gas flow speed (called a basic flow rate) appropriate to respective collectors.

Table 4.3.2 shows the typical basic flow rate and applicable particle size (diameter of the particle that is collected with 50% efficiency = d_{50}) of various dust collectors.

Table 4.3.2 Basic Flow Rate and Applicable Particle Size of Various Dust Collectors

Classification	Type	Basic Flow Rate (m/s)	Minimum Applicable Particle Size (μm)
Gravity Dust Collection	Settling chamber	1 - 3	50
Inertial Dust Collection	Louver type	15 >	15
	Multi baffle type	1 - 5	5
Centrifugal Dust Collection	Tangential inflow type	7 - 15	5
	Axial reversion type	8 - 13	5
Scrubbing Dust Collection	Cyclon scrubber type	1 - 2	1
	Spray tower	1 - 2	3
	Filling tower	0.5 - 1	1
	Theisen washer	300 - 750 rpm	0.2
	Jet scrubber	10 - 20	0.2
	Venturi scrubber	60 - 90	0.1
Filtration Dust Collection	Bag filter	0.3 - 10 cm/s	0.1
	Air cleaner	2 - 4	0.1
Electrostatic Precipitator	Dry type	0.5 - 2	0.05
	Wet type	1 - 3	0.01

Principles and structyures of major types of dust collector are described below.

(3) Centrifugal Dust Collector (CDC)

1) Principle

The centrifugal dust collector gives the exhaust gas revolving motion so that particles separate from gas under centrifugal force. Particles settle under gravity to be collected in the dust hopper. There are cyclon and rotary types. The cyclon type is employed in most cases.

The cyclon type is simple in construction, low in equipment cost and able to collect dusts of 5 - 10 μm or more. This type of dust collector is employed in a wide range of fields, not only as an independent dust collector, but also as a pre-treatment system for a scrubber, a filtration dust collector, or an electrostatic precipitator. The pressure loss is normally 80 - 100 mmH_2O though it varies depending on the type of cyclon and flow rate.

2) Structure

The cyclon type dust collector is marketed under various brand names, but may be roughly classified into the tangential inflow type and the axial flow type depending on how the raw exhaust gas is introduced.

i) Multi cyclon

The basic flow rate of cyclons is generally set around 12 m/s in consideration to the operation cost while depends on the pressure loss. A cyclon needs to use a cylinder of smaller inner diameter if finer particles are to be collected. Therefore, when the amount of exhaust gas is large and a high dust collection rate is required, multiple small-size cyclons are used in parallel. This is called the multi cyclon system. The minimum inner diameter of cylinder of a small-sized cyclon is generally around 100 mm in view of ash clogging. In the case of oil combustion, its limit is around 150 mm.

ii) Tangential inflow cyclon

The gas flow rate at inlet of the tangential inflow cyclon is generally 7 - 15 m/s. Within this range, the effect of gas speed on the dust collection ratio is relatively small though varies with the nature of dust.

The tangential inflow cyclon is further divided into straight upward flow and eddy flow types. The pressure loss is around 100 mmH_2O in the straight upward flow type when the basic flow rate is 12 m/s. The pressure loss is lower by about 30% in the eddy flow type.

The tangential inflow type is suitable for an independent cyclon when the dust particle size is large or when the amount of gas to be treated is small. When this type is to be used as multi cyclon system, uniform distribution of inflow gas to each unit cyclon is difficult. Therefore, the blow-down method needs to be employed to enhance the dust collection ratio through absorption of about 5% of gas from the dust hopper.

iii) Axial flow type

The axial flow cyclon is divided into reversible and straight forward types, but the reversible type is mostly used.

The axial flow cyclon can treat about three times as much as the tangential inflow cyclon when the pressure loss is same. Moreover, this type enables uniform distribution of inflow gas to each unit cyclon without difficulty and is used mainly as a multi cyclon system of large capacity and high dust collection ratio.

The pressure loss in the reversible type is around 80 mmH_2O at a basic flow rate of about 12 m/s. The straight forward type has a pressure loss of only 40 - 50 mmH_2O and requires only a small installation space, but is not widely employed today because a loss of pressure balance occurs frequently in cyclon, resulting in a sharp drop of the dust collection rate.

(4) Scrubbing Dust Collector (SDC)

1) Principle

The scrubbing dust collector separates and collects fine particles of dust in gas by means of water droplets, water film, or air bubbles formed by dispersing water or inflow gas.

The scrubbing dust collector uses the forces of inertia, diffusion, flocculation, or gravity. Inertia and gravity ensure higher dust collection effect when the particle size is larger. The diffusion force proves more effective with decreasing particle size, and the flocculation force exerts higher dust collection action when the range of particle size distribution is wide.

Among these dust collecting forces, inertia becomes the most influential when the dust particle size exceeds 1 μm.

2) Structure

In the scrubbing dust collector, various contrivances are incorporated for forming of water droplets and water films as well as for washing method in order to achieve improvement in dust adhesion to water droplets and flocculation of dusts. This type of dust collector is marketed in diverse configurations. It may be roughly classified as water saving type, pressure water type, packed tower type or rotary type according to the performance indicated. Table 4.3.3 shows the major characteristics of the scrubbing dust collector.

Table 4.3.3 Characteristics of Principal Scrubbing Dust Collectors

Name of Dust Collector	Basic Flow Rate (m/s)	Liquid/gas Ratio (l/m3)	Pump Pressure	Pressure loss (mmH2O)	d50 (μm)
Spray Tower	1 - 2	2 - 3	Medium	10 - 50	3.0
Packed tower	0.5 - 1	2 - 3	Small	100 - 250	1.0
Cyclon Scrubber	1 - 2	0.5 - 1.5	Medium	120 - 150	1.0
Theisen Washer	(300-750 rpm)	0.7 - 2	Small	-50 - -150	0.2
Jet Scrubber	10 - 20	10 - 50	Large	0 - -150	0.2
Venturi Scrubber	60 - 90	0.3 - 1.5	Small	300 - 800	0.1

i) Water saving type

In this type, a certain amount of water or other liquid is stored in the dust collection chamber and the gas containing dust is passed at high speed through the chamber. Water droplets or a water film is formed to wash the dust-containing gas. The water level adjustment and water film state greatly affected he performance. This type is advantageous in that only a small amount of make-up water is enough to complete scrubbing and collection because the retained water is recirculated.

Normally, the 50% critical cut size is around 1 μm at superior performance and the pressure loss is roughly within a range of 100 to 200 mmH_2O, though it varies with the type and performance.

ii) Pressure water type

The pressure water type supplies water under pressure to wash the dust-containing gas. This type includes the venturi scrubber, jet scrubber, spray tower, and cyclon scrubber. The one ensuring the highest dust collection ratio among them is the venturi scrubber, which offers d_{50} at around 0.1 μm. As shown in Table 4.3.3, the pressure loss is extremely high.

3) Performance

The performance of a scrubbing dust collector is judged on the basis of the factors listed below.

i) Water saving type

Water droplets become smaller and can collect more fine particles when the gas speed (basic flow rate), with which the dust-containing gas blows up water to form water droplets or a water film, is increased.

ii) Pressure water type

a) Venturi and jet scrubbers can produce smaller water droplets and collect finer particles when the gas speed (basic flow rate) at the throat increases.

b) For the spray tower and cyclon, on the other hand, the dust collection ratio can be increased when the apparent gas speed (basic flow rate) in the tower slows down, the liquid-gas ratio increases, and the period of contact between water droplets and dust-containing gas becomes longer.

c) For spray nozzles with a given bore size, water droplets become smaller and finer particles can be collected when the water pressure is higher.

iii) Packed tower type

The dust collection ratio rises when the apparent speed (basic flow rate) in the tower is low, the dust-containing gas stays longer in the packed layer, the packing surface area is large, packing density are high, and the gas flow in the packed layer is uniform.

iv) Rotary type

Generally, the dust collection ratio rises as the rotating speed or the liquid-gas ratio becomes higher, though the utility cost increases.

v) To enhance the dust collection efficiency in the scrubbing dust collector, it is essential to collect fine water droplets with fine particles adhering, i.e., to enhance the water droplet collection efficiency of a gas-liquid separator. This applies not only to the scrubbing dust collector, but also to the wet-type gas treatment system.

(5) Filter Dust Separator (FDS)

1) Principle

Filter dust separators are roughly divided into two types: 1) surface filtration type bag filter which separates and collects dust on the surface of a relatively thin filter cloth, and 2) internal filtration type packed layer filter in which dust is separated and collected in a layer packed with filtration medium such as glass fibers.

The dust collection mechanism of filter dust separators is totally the same as that of scrubbing dust collector. Inertia, diffusion, gravity and shielding are used as dust collection forces.

2) Structure

i) Packed layer filter

Packed layer filters are classified into: 1) air ventilation filter, and 2) mobile bed type filter for treating smoke amd soot.

In the mobile bed filter, particulate media are packed in a wire-net filtration layer and dust in the gas is collected in this layer. The volume of the gas moving through the filtration media governs the dust collection efficiency. The apparent filtration rate of the gas to be treated is within a range of 0.1 - 2 m/s and set to the lower level when finer particles are contained in the gas.

ii) Bag filter

When the particulate-laden gas stream is passed through a fabric filter, particles are initially retained on the fabric by the following processes: 1) gravity settling for coarse particles, 2) inertial impaction for relatively coarse particles exceeding 1 μm, and 3) direct interception or diffusion for finer particles. In this way, the dust layer with many bending perforations is formed over the fabric surface. This dust layer is called "primary dust layer" or "initial layer".

The void ratio of a new woven fabric is 60 - 70%. It decreases to 10 - 15% when the primary dust layer is formed. Such small perforations enables collection of finer particles.

Since the bag filter collects fine particles with bending perforations in the dust layer, clogging of the filter tends to occur. The operation temperature above the dew point of SO_3 is also necessary when the inflow gas contains SO_2.

(6) Electrostatic Precipitator

In principle, the electrostatic precipitator is able to collect submicron particles with ease and is less sensitive to the nature of smoke and soot. This type of dust collector has been used widely even before 1970 in the fields of pollution control, recovery of valuable materials, quality improvement of products, and air conditioning.

1) Principle

The electrostatic precipitator employs electrical force, diffusion, inertia, and gravity as dust collecting forces. The principal force used is electrical force.

The electrostatic precipitator develops unequal electrical field having a wire discharge electrode for a negative pole and a plate dust-collecter for a positive pole. The 60 kv ultra-high voltage DC power supply is used for charging.

Adequate strengthening of this electric field causes local breakdown of gas around the discharge electrode, causing so-called corona discharge to generate negative corona (brush corona). In this state, ionization of gas molecules proceeds, generating a number of negative and positive ions. Positive ions are immediately neutralized by the discharge electrode, but negative ions and free electrons run toward the dust collecting electrode, forming a netative ion curtain.

When the particulate-laden gas is passed through this electric field, particles are electrically charged almost instantaneously due to collision of ions and electrons to particles under action of the electric field and collision due to thermal motion of ions. Particles thus charged are separated and collected with the Coulomb's force by the dust collection electrode.

2) Structure

The industrial electrostatic precipitator for treatment of smoke and soot has a discharge electrode as its negative pole to utilize the negative corona which has a large difference between initial corona and flashover voltages and ensures stable operation at high application voltage. This is to enable supply of sufficient charge voltage and discharge current at all times regardless of a substantial change of the nature of smoke and soot produced by operating conditions.

On the other hand, the electrostatic precipitator for air cleaning normally employs the positive corona, with less generation of ozone, because change in the nature of polluted air is rather small.

4.4 Assumptions and Approach to Stationary Source Control Planning

4.4.1 Prospect of Demand and Supply of Fuels

(1) Prospect of Energy Demand by Stationary Pollution Sources

As has been described in Chapter 2, Section 2.5, AMCM is restricting expansion of industrial activity. Especially for activity types requiring much energy and water consumption and discharging much pollutants, strict restrictive measures including relocation and shutdown of plants are adopted.

As an notable example of such measures, the shutdown of the refinery process in the 18 de Marzo Refinery which was the only oil refinery plant in AMCM can be named.

On the other hand, the population of the metropolitan area, approximately 15 million at present, has been increasing, but with the decreasing rate of growth since 1980, and is expected to reach around 18 million in 2010.

With this population growth, the service and commercial industry will continue expanding, and will provide in turn increasing employment. However, since the stationary pollution sources in the service and commercial industry consume far less fuel than those in the manufacturing industry, the overall fuel demand in the metropolitan areas is not considered to be influenced by the increasing number of these facilities.

Considering the above mentioned factors together, the fuel consumption in the future by the stationary pollution sources in AMCM is assumed to be unchanged from the present level.

(2) Characteristics and Prices of Major Fuels

1) Currently Supplied Fuels

The most desirable fuel from the air pollution control viewpoint is one that emits least quantity of pollutants per unit heat output. Table 4.4.1

shows the pollutant emissions per unit heat output of the major fuels currently in supply.

Table 4.4.1 Emission Factors for Fuels per Unit Heat Output

		Heavy oil	Diesel	Natural gas
Emission factor ($kg/10^6$ kcal)	NOx	0.74	0.20	0.33
	SO_2	7.00	2.12	0.001
	PM	0.28	0.20	0.02
Calorific value	(10^6 kcal)	$9.77/m^3$	$8.80/m^3$	$8.52/10^3m^3$

As shown in the Table, natural gas is the lowest in both SO_2 and PM emissions followed by diesel. Heavy oil is the highest.

Table 4.4.2 shows a comparison of prices of the major three fuels in terms of calorific value.

Table 4.4.2 Price of Major Fuels per Unit Heat Value

		H. oil	Diesel	N. gas
Calorific value	(10^3 kcal)	9.77/l	8.80/l	$8.52/m^3$
Price	(Pesos)	228/l	605/l	$245/m^3$
	(Pesos/10^3 kcal)	23.3	68.8	28.8

In price per unit heat, heavy oil is the lowest followed by natural gas. The price of diesel is about 3 times that of heavy oil, and 2.4 times that of natural gas.

2) Desulfurized Hevy Oil (DHO) and Desulfurized and Emulsified Heavy Oil (DEHO)

It is expected that desulfurized heavy oil (DHO) with the S content at 0.8% will be supplied from the year 1995 as a measure to reduce SO_2 emissions. As a measure to reduce NOx and PM emissions, emulsification of this DHO can be considered. Effects of DHO and the emulsified DHO (DEHO) in pollutant reduction as compared with the current heavy oil are estimated as shown in Table 4.2.3. Note that the actual effects of DEHO need to be confirmed by thorough demonstration tests.

Table 4.4.3 Price of Major Fuels per Unit Heat Value

	NOx (%)	SO_2 (%)	PM (%)
Current heavy oil	0	0	0
DHO	10	73	20
DEHO	30	73	40

Note: DHO = desulfurized heavy oil
DEHO = desulfurized and emulsified heavy oil

Since the price of DHO has not been decided yet, it is set to 320 pesos per liter in this Study by adding the estimated desullfurization cost of US$ 5.00/barrel to the price of the current heavy oil. And the price of further improved DEHO is expected to be 390 pesos per liter. When changes in the calorific value by these processes are taken into consideration, their prices per unit heat are 33 pesos/1,000 kcal and 40 pesos/1,000 kcal, respectively. These prices are substantially higher than that of the current heavy oil, but still lower than that of diesel. The above prices will be used in this Study in order to clarify the costs of air pollution control measures. However, since the prices of individual fuels are determined through the nationl energy policy, the prices shown above may be changed, and therefore, fuel expenses in individual sources estimated in this Study may be changed.

(3) Fuel Supply by Kinds

Supply of the desulfurized heavy oil of the S content at 0.8% is expected in AMCM from 1995 to meet the demand sufficiently.

PEMEX is planning to increase natural gas supply to the metropolitan area up to 1994 (see Table 2.4.4). When the production of hydro-desulfurized heavy oil will have started, the natural gas supply will be reduced temporarily.

The annual consumption of diesel by the stationary pollution sources in the metropolitan area at present is estimated to be around 500,000 m^3, which is only one 5000th of the total consumption of diesel by the stationary users in the nation (approx. 25×10^{12} kcal = $2.5 \times 10^9 m^3$, from Table 2.4.1), and one 2000th of the national total for the final consumption industry sector,

$1.0 \times 10^9 m^3$. This means that if the factories in the metropolitan area will need it, the supply can be increased without much difficulty, on middle and long term basis.

4.4.2 Approach to Air Pollution Control Planning of Stationary Sources

(1) Assumptions and Premises

The study of stationary source control measures for the metropolitan area will be made under the following assumptions or premises:

1) Supply of desulfurized heavy oil (S : 0.8%) will be made by sufficient amount for demand in the metropolitan area from around 1995.

2) The energy consumption by the stationary air pollution sources in the future of 2000 - 2010 will not increase from the present level.

3) The amounts of emission of SO_2, NOx and smoke and soot from large scale emission sources are to be reduced by certain degrees from the level of 1990.

(2) NOx Control Measures

To control NOx, the most effective method is, as with other pollutants, to suppress its generation. To be practical for the sources in AMCM, the study priority will be given to the improvement of combustion method such as flue gas recirculation, two-stage combustion, low-NOx burners, emulsion combustion, and in-furnace denitration combustion (OFA method, MACT method, etc.). With respect to the emulsion combustion, its principles have been technologically confirmed, but there are not many cases of practical application in Japan. And since its NOx reduction effect varies considerably depending on the types of fuels and burners, a commercial scale test with Mexican heavy oil should be conducted to confirm its NOx reduction effect and cost effectiveness as a prerequisite to practial application.

(3) SOx Control Measures

When the supply of the desulfurized heavy oil as mentioned above will have started, the SO_2 emissions from the stationary sources in the metropolitan area will be reduced to around 30% of the present level. But for some sources such as the power plants, additional SO_2 control measures will be needed. The following are available at present: 1) change to better quality fuel, and 2) flue gas desulfurization.

In the present Study, flue-gas desulfurization will be excluded because of huge costs, and fuel improvement through mixing the desulfurized heavy oil with other quality fuels will be mainly taken into consideration.

(4) Particulate Matter Control Measures

Since particulate matter can be reduced basically through generation control technologies such as fuel improvement and combustion method improvement, priority will be placed on generation control.

For controlling dust generated during the process of drying raw materials and products, introduction of bag filters or electrostatic precipitators of high efficiency will be basically taken into consideration.

(5) Process of Changing to Better Quality Fuel

The use of better quality fuels in place of the current fuel is effective in reducing all three types of pollutants; SO_2, NOx and particulate matter. For the facilities currently using only heavy oil, the following fuel improvement processes are considered to be practical:

1) Mixed burning of heavy oil and diesel or natural gas until the start of supply of the desulfurized heavy oil.
2) The above heavy oil is replaced by the desulfurized heavy oil as its supply starts.
3) When further improvement is required, either diesel only is used or the desulfurized heavy oil and natural gas are used for mixed combustion.

The concrete procedure should be determined case by case in consideration of the peculiar conditions of the individual facilities.

CHAPTER 5 DIAGNOSIS OF THE SELECTED STATIONARY SOURCES AND STUDY OF POLLUTION CONTROL MEASURES

CHAPTER 5 DIAGNOSIS OF THE SELECTED STATIONARY SOURCES AND STUDY OF POLLUTION CONTROL MEASURES

5.1 Selected Stationary Sources and Facilities

A total of 25 establishments were selected as representative stationary sources of air pollution in AMCM.

The selection was made under the following considerations.

1) While establishments considered as large scale pollution source should be preferentially selected, those representative of small to medium scale sources should be also included.

2) There should be a variety in the kind of pollutant emitting facilities. Industrial furnaces of the kinds representative of AMCM should be included as well as various types and scales of boilers.

3) Types of industry should be representative of AMCM.

Under such considerations, about 100 establishments were selected through consultation with SEDUE. They were invited to an explanation seminar and visited by the Study Team and the Mexican counterpart for the detailed on-site questionnaire. Basic information as stationary pollution source was thus collected from 97 establishments actually visited.

Through the careful review of the above information on the 97 establishments, the 25 establishments were selected for the diagnostic survey. They are shown in Table 5.1 with their facilities subjected to diagnosis. A total of 54 facilities were diagnosed.

Table 5.1 Facilities Investigated by Diagnostic Survey

No.	Identity of Establishment	Visit No.	Type of Industry	Industrial boiler				Industrial furnace						
				Large capacity	Medium capacity	Small capacity	HTM* boiler	Oil heating	Dryer	Aggregate dryer	Cement kiln	Glass melting	Metal heating	Metal melting
1	Thermoelectric Power Plant (A)	69	Electric power	4										
2	Thermoelectric Power Plant (B)	70		2										
3	Petroleum Refinery	57	Petroleum refinery	1	4			9						
4	Chemical Products Factory (A)	1	Chemical products		1	1	2		2					
5	Chemical Products Factory (B)	62				1		1						
6	Chemical Products Factory (C)	72				2								
7	Chemical Products Factory (D)	24				1								
8	Chemical Products Factory (E)	67				1								
9	Petrochemical Products Factory (A)	16	Petrochemical products		2									
10	Petrochemical Products Factory (B)	8			2									
11	Petrochemical Products Factory (C)	87				1								
12	Asphalt Plant	11	Petroleum products							3				
13	Cement Factory	41	Non-metal mineral products							1	1			
14	Glass Factory (A)	68										1		
15	Glass Factory (B)	31										1		
16	Glass Factory (C)	23										2		
17	Rubber Products Factory	14	Rubber and plastic		1									
18	Paper Factory	30	Paper and its products		2									
19	Paper Products Factory (A)	34				1								
20	Paper Products Factory (B)	76				1								
21	Metal Products Factory (A)	55	Metal products										1	
22	Metal Products Factory (B)	19												1
23	Food Products Factory	65	Food		1									
24	Alcoholic Drinks Factory	47	Drinks	1										
25	Public Bathhouse	52	Bathhouse			1								
	Total Number			8	13	10	2	10	2	4	1	4	1	1

Note : HTM boiler = Heat transfer medium boiler

5.2 Results of Diagnosis and Study of Pollution Control Measures

Major items investigated in the diagnosis of each selected facility are as follows:

1) Outlines of the facility

2) Kind of fuel, its sulfur content, and consumption amount

3) Operational conditions in combustion: fuel pressure, combustion temperature, fuel-air ratio, etc.

4) Exhaust gas flowrate and concentration of pollutants including NOx, PM, CO, CO_2 and O_2.

An outline of these basic data obtained from each facility at each establishment is given in Table 5.2.

The result of the diagnostic survey and necessary control measures, their costs and effects in pollutant emission reduction are presented hereafter by each of the selected establishments.

There are some cases in which estimation of the rate of pollutant emission reduction is difficult particularly for PM. Amount of the PM generation varies widely depending on the shape of boiler or furnace, the volumetric loading rate, and the excess air ratio. The reduction ratios for PM indicated for each combustion facility in the following sections were estimated under the assumption that the combustion is made with an appropriate air ratio in each facility.

The present annual total emissions of pollutants indicated for each source were estimated based on the fuel consumption per hour and the weight of pollutant emission per hour at the time of the diagnostic survey for each facility and the annual total consumption of fuels in each facility.

Table 5.2 Outline of Results of Flue Gas Measurement in the Diagnostic Survey

No.	Name of Establishment	Visit No.	Name of Facility	Date		Time	Recuperator		Stack Gas												Fuel Consumption			Sulfur	NOx		Emission		
							02 (%)	Ts (℃)	02 (%)	Ts (℃)	NOx (ppm)	CO2 (%)	CO (%)	PM (mg/m3)	v (m/s)	Diam. (m)	Area (m2)	Air ratio	H2O (%)	Qdry (m3N/hr)	Gas (m3/hr)	Oil (l/hr)	Diesel (l/hr)	in Oil w/w(%)	(02 0%) (ppm)	(02 5%) (ppm)	NOx (kg/hr)	SO2 (kg/hr)	PM (kg/hr)
1	THERMOELECTRIC POWER PLANT (A)	69-1	No.1 Boiler	Sep. 4		15:00-16:00	1.3	-	3.6	159	170	8.3	<0.05	45	23.8	3.800	11.341	1.21	13	414,000	30,200	1,600	-	3.52	205	156	140	110	19
		69-2	No.2 Boiler	Sep. 4	1	12:30-13:30	3.8	412	4.5	177	86	8.4	<0.05	4.7	24.0	3.900	11.946	1.27	12	427,000	32,200	870	-	3.52	109	83	75	60	2.0
				Sep. 13	2	13:30-14:30	-	369	5.3	152	101	9.8	<0.05	470	26.0	3.900	11.946	1.34	10	501,000	18,400	20,500	-	3.52	135	103	100	1,400	240
		69-3	No.3 Boiler	Nov. 14		13:30-14:30	6.3	380	8.4	132	113	7.3	<0.05	-	31.5	3.900	11.946	1.67	9	642,000	24,900	15,000	-	3.57	188	143	150	1,100	-
		69-4	No.4 Boiler	Sep. 13		14:30-15:30	1.6	-	7.0	182	149	6.6	0.10	120	14.8	Rectan.	37.975	1.50	11	837,000	55,500	6,000	-	3.52	224	170	260	420	100
2	THERMOELECTRIC POWER PLANT (B)	70-1	No.1 Boiler	Sep. 6	1	13:00-14:00	2.3	-	7.1	170	233	7.0	<0.05	45	19.9	2.320	4.227	1.51	11	128,000	8,300	2,600	-	3.43	352	268	61	180	5.8
					2	15:30-16:30	3.4	-	7.7	169	214	7.4	-	270	20.6	2.320	4.227	1.58	11	134,000	4,600	6,500	-	3.43	338	257	59	440	36
		70-2	No.2 Boiler	Sep. 6		13:30-14:30	1.3	367	5.1	185	168	8.6	<0.05	25	28.8	2.260	4.011	1.32	12	169,000	10,600	2,400	-	3.43	222	169	58	160	4.2
3	PETROLEUM REFINERY	57-5	AA-F1 & F2 Heating furnace	Sep. 25		12:30-13:30	-	-	5.5	555	89	8.3	<0.05	< 0.3	8.0	3.430	9.240	1.35	11	60,500	‡ 6,100	-	-	-	121	92	11	-	< 0.018
		57-6	AA-F3 Heating furnace	Sep. 10		15:00-16:00	-	-	6.8	400	54	7.8	<0.05	0.7	1.9	2.134	3.577	1.48	10	6,900	‡ 540	-	-	-	80	61	0.77	-	0.0048
		57-4	RV-H1 Heating furnace	Sep. 10		13:00-14:00	-	-	6.9	384	52	6.3	<0.05	1.3	5.9	1.980	3.079	1.49	12	18,500	‡ 1,500	-	-	-	77	59	2.0	-	0.024
		57-10	AW-H1 Heating furnace	Sep. 11		13:00-14:00	-	-	2.2	610	71	10.2	<0.05	0.9	4.2	2.134	3.577	1.12	13	11,200	‡ 540	-	-	-	79	60	1.6	-	0.010
		57-12	RE-H10 Heating furnace	Sep. 21		15:00-16:00	-	-	13.0	420	27	3.7	<0.05	< 0.2	3.9	3.048	7.297	2.63	7	29,000	‡ 1,300	-	-	-	71	54	1.6	-	< 0.0058
		57-13	AR-H1 & AU-H1 Heating furnace	Sep. 18		13:00-14:00	-	-	9.6	375	30	6.8	<0.05	1.4	4.5	2.841	6.339	1.84	7	31,200	‡ 2,300	-	-	-	55	42	1.9	-	0.044
		57-16	AQ-H1 Heating furnace	Sep. 14		12:30-13:30	-	-	10.9	418	50	5.1	<0.05	< 0.5	7.7	1.450	1.651	2.08	8	12,900	‡ 700	-	-	-	104	79	1.3	-	< 0.0065
		57-1-1	G1 Boiler	Sep. 27	1	12:30-13:30	4.1	298	5.1	232	142	8.4	<0.05	90	13.5	2.134	3.577	1.32	12	63,800	ˆ 4,900	ˆ 570	-	3.17	188	143	19	36	5.7
							4.1	298	5.1	232	142	8.4	<0.05	90	13.5	2.134	3.577	1.32	12	63,800	‡ 2,800	‡ 400	-	3.17	188	143	19	25	-
					2	14:15-14:45	4.0	306	5.1	237	135	8.6	<0.05	16	13.0	2.134	3.577	1.32	11	61,500	‡ 3,200	-	-	-	178	136	17	-	0.98
		57-1-2	G2 Boiler	Sep. 11		14:00-15:00	4.1	380	4.6	217	112	8.5	<0.05	6.0	6.1	2.134	3.577	1.28	13	29,500	‡ 2,600	‡ 1,500	-	3.17	143	109	6.8	94	0.18
		57-1-3	G3 Boiler	Sep. 17		12:00-13:00	9.3	326	10.5	242	49	5.7	<0.05	7.1	8.2	2.134	3.577	2.00	8	39,800	‡ 1,800	ˆ 380	-	3.17	98	75	4.0	24	0.28
		57-2	G5 Boiler	Sep. 26		12:30-13:30	3.0	420	5.5	220	120	8.6	<0.05	51	7.8	3.275	8.424	1.35	11	89,900	‡ 8,800	ˆ 1,100	-	3.17	163	124	22	69	4.6
		57-3	CP Boiler	Sep. 19		13:30-14:30	-	-	1.3	282	105	11.5	<0.05	< 0.2	7.8	2.134	3.577	1.07	13	33,100	‡ 2,200	ˆ 470	-	3.17	112	85	7.1	29	< 0.0066
4	CHEMICAL PRODUCTS FACTORY (A)	1-5	No.D Boiler	Oct. 8		16:30-17:00	-	-	0.9	267	30	10.9	0.70	1.5	8.3	0.763	0.457	1.04	14	4,600	450	-	-	-	31	24	0.28	-	0.0069
		1-1	No.E Boiler	Oct. 8		13:00-14:00	-	-	4.1	253	66	9.3	<0.05	0.9	7.6	1.266	1.259	1.24	11	12,300	1,000	-	-	-	82	62	1.7	-	0.011
		1-6	Heat medium boiler 100	Oct. 9		14:00-15:00	-	-	4.9	198	68	7.3	<0.05	< 0.4	10.2	0.350	0.096	1.30	13	1,400	180	-	-	-	89	68	0.20	-	< 0.0006
		1-8	Heat medium boiler 300	Oct. 9		11:30-12:30	-	-	7.8	170	92	7.1	<0.05	< 0.4	9.0	0.580	0.264	1.59	9	3,700	300	-	-	-	146	112	0.70	-	< 0.0015
		1-11	No.1 Dryer for detergent	Oct. 9		13:00-14:00	-	-	18.6	116	15	1.3	<0.05	27	24.5	1.240	1.208	8.75	12	50,800	300	-	-	-	131	100	1.6	-	1.4
		1-12	No.2 Dryer for detergent	Oct. 8		13:00-14:00	-	-	18.8	82	12	0.8	<0.05	43	15.8	1.680	2.217	9.55	15	63,800	360	-	-	-	115	87	1.6	-	2.7
5	CHEMICAL PRODUCTS FACTORY (B)	62-1	No.1 Boiler	Oct. 29	1	12:00-13:00	-	-	9.8	185	185	7.5	<0.05	-	6.0	0.400	0.126	1.88	6	1,200	-	25	-	2.81	347	264	0.46	1.4	-
					2	15:00-15:30	-	-	4.2	215	265	11.5	<0.05	420	12.0	0.400	0.126	1.25	8	2,100	-	120	-	2.81	331	252	1.1	6.6	0.88
		62-2	Oil heating furnace	Oct. 30		12:30-13:30	-	-	10.3	370	23	7.6	<0.05	33	5.5	0.150	0.018	1.96	5	110	-	-	8	1.02	45	34	0.01	0.13	0.0036
6	CHEMICAL PRODUCTS FACTORY (C)	72-1	No.1 Boiler	Nov. 12		14:20-15:10	-	-	10.8	164	42	5.3	<0.05	7.5	3.0	0.360	0.102	2.06	8	490	110	-	-	-	86	66	0.04	-	0.0037
		72-2	NO.2 Boiler	Nov. 12		15:30-16:00	-	-	7.1	154	44	7.2	<0.05	< 0.9	1.7	0.350	0.096	1.51	10	260	100	-	-	-	66	51	0.02	-	< 0.0002
7	CHEMICAL PRODUCTS FACTORY (D)	24-1	No.4 Boiler	Oct. 1	1	13:00-14:00	-	-	1.8	280	50	9.8	0.15	< 0.2	13.0	0.635	0.317	1.09	14	4,900	530	-	-	-	55	42	0.50	-	< 0.0010
					2	15:20-15:30	-	-	2.8	302	59	9.9	<0.05	-	18.0	0.635	0.317	1.15	12	6,700	700	-	-	-	68	52	0.81	-	-
8	CHEMICAL PRODUCTS FACTORY (E)	67-1	No.1 Boiler	Nov. 6	1	12:30-13:30	-	-	7.0	295	147	9.2	<0.05	51	6.9	0.930	0.679	1.50	10	5,700	-	170	-	3.02	221	168	1.7	10	0.29
					2	13:30-14:30	-	-	11.4	285	100	6.3	<0.05	-	7.4	0.930	0.679	2.19	7	6,300	-	540	-	3.02	219	167	1.3	32	-
9	PETROCHEMICAL PRODUCTS FACTORY (A)	16-3	No.3 Boiler	Sep. 20	1	11:20-12:20	3.9	345	6.9	190	283	10.0	<0.05	5.8	8.7	1.520	1.815	1.49	8	23,800	-	1,800	-	2.97	421	321	14	110	1.4
					2	12:50-13:50	3.3	341	8.8	210	295	9.6	<0.05	78	9.3	1.520	1.815	1.72	5	25,300	-	2,100	-	2.97	508	387	15	120	2.0
		16-4	No.4 Boiler	Sep. 21	1	14:00-15:00	5.5	473	7.4	270	165	6.7	<0.05	< 0.1	12.5	1.670	2.190	1.54	10	34,500	3,200	-	-	-	255	194	12	-	< 0.0035
					2	15:30-16:10	2.6	-	4.6	252	192	8.0	<0.05	-	10.2	1.670	2.190	1.28	13	28,200	3,200	-	-	-	246	187	11	-	-
10	PETROCHEMICAL PRODUCTS FACTORY (B)	8-2	NO.2 Boiler	Oct. 10		13:00-14:00	2.9	342	5.2	217	247	11.0	<0.05	37	8.6	1.970	3.048	1.33	10	36,600	-	2,200	-	2.91	328	250	19	130	1.4
		8-3	NO.3 Boiler	Oct. 10		12:30-13:30	-	-	5.8	253	319	12.0	<0.05	230	2.6	1.500	1.767	1.38	7	6,100	-	600	-	2.89	441	336	4.0	34	1.4
11	PETROCHEMICAL PRODUCTS FACTORY (C)	87-1	No.1 Boiler	Nov. 16	1	12:30-13:30	-	-	12.8	193	177	5.5	<0.05	190	6.2	0.400	0.126	2.56	4	1,200	-	45	-	2.88	453	345	0.44	2.6	0.23
					2	14:24	-	-	8.3	250	275	8.0	<0.05	-	11.8	0.400	0.126	1.65	7	2,000	-	130	-	2.88	455	346	1.1	7.4	-
12	ASPHALT PLANT	11-1	No.1 Kiln for aggregate	Oct. 5		13:30-14:30	13.8	143	16.7	104	45	2.6	<0.05	1,900	15.0	Rectan.	1.515	4.88	13	39,900	-	-	850	1.05	220	167	3.7	15	76
		11-2	No.2 Kiln for aggregate	Oct. 5		11:30-12:40	12.4	156	16.2	96	65	3.7	0.05	3,000	14.0	1.210	1.150	4.37	17	27,600	-	-	850	1.05	284	217	3.7	15	83
		11-3	No.3 Kiln for aggregate	Oct. 16		13:00-14:00	-	-	16.5	88	45	2.9	<0.05	6,200	33.4	Rectan.	0.901	4.67	14	54,400	-	-	950	1.05	210	160	5.0	17	340
13	CEMENT FACTORY	41-8	No.4 SP Kiln	Sep. 18	1	12:30-13:30	6.5	-	7.5	143	320	22.1	<0.05	430	16.1	2.200	3.801	1.56	11	99,700	-	9,000	-	3.66	498	379	66	-	43
					2	14:20-15:20	8.1	-	8.9	140	315	19.5	<0.05	-	15.2	2.200	3.801	1.74	11	94,300	-	8,000	-	3.66	547	417	61	-	-
		41-10	No.8 Dryer	Sep. 17		14:20-15:20	16.6	-	17.3	95	26	1.5	<0.05	< 0.1	7.6	1.755	2.419	5.68	25	28,500	640	-	-	-	148	112	1.5	-	< 0.0029
14	GLASS FACTORY (A)	68-2	No.B Glass melting furnace	Sep. 28		13:00-14:00	-	-	2.9	810	645	17.4	<0.05	760	3.9	1.720	2.324	1.16	12	11,300	-	1,400	-	2.70	748	570	15	74	8.6
15	GLASS FACTORY (B)	31-2	No.2 Glass melting furnace	Sep. 24		14:00-15:00	0.9	1,400	5.4	843	1195	11.4	<0.05	480	4.3	1.220	1.169	1.35	15	3,900	310	-	-	-	1,609	1,226	9.6	-	1.9
16	GLASS FACTORY (C)	23-1	No.84 Glass melting furnace	Nov. 13		15:30-16:30	5.8	-	6.6	418	580	10.7	<0.05	390	3.8	3.217	8.128	1.46	14	29,200	2,300	-	-	-	846	644	35	-	11
		23-2	No.82 Glass melting furnace	Nov. 13		15:30-16:30	2.8	-	6.0	465	690	10.5	<0.05	120	4.2	3.217	8.128	1.40	14	30,300	1,800	-	-	-	966	736	43	-	3.6
17	RUBBER PRODUCTS FACTORY	14-1	Boiler	Sep. 25	1	12:30-13:30	-	-	8.5	280	145	6.8	<0.05	260	14.1	0.690	0.374	1.68	11	6,400	-	430	-	2.99	244	186	1.9	25	1.7
					2	14:30-14:40	-	-	6.2	330	250	10.5	<0.05	190	18.9	0.690	0.374	1.42	9	8,100	-	710	-	2.99	355	270	4.2	42	1.5
18	PAPER FACTORY	30-1	No.1 Boiler	Oct. 4		12:30-13:30	11.0	286	12.5	198	178	8.3	<0.05	-	-	1.960	3.017	2.47	9	-	-	710	-	-	440	335	-	-	-
		30-2	No.1 + No.2 Boiler	Oct. 4		14:00-15:00	10.0	462	11.5	218	148	6.2	<0.05	440	7.8	1.960	3.017	2.21	6	34,400	-	1,700	-	3.01	327	249	10	100	15
19	PAPER PRODUCTS FACTORY (A)	34-1	No.1 Boiler	Sep. 27		12:40-13:40	5.6	385	10.3	255	124	7.4	<0.05	280	5.0	1.650	2.138	1.96	7	14,300	-	820	-	2.95	243	185	3.6	48	4.0
20	PAPER PRODUCTS FACTORY (B)	76-1	No.1 Boiler	Nov. 7	1	11:00-12:00	-	-	6.6	345	184	9.6	<0.05	34	14.3	0.730	0.419	1.46	10	6,700	-	780	-	2.93	268	204	2.5	45	0.23
					2	12:30-13:30	-	-	5.2	345	191	10.8	<0.05	-	13.7	0.730	0.419	1.33	10	6,400	-	780	-	2.93	254	193	2.5	45	-
21	METAL PRODUCTS FACTORY (A)	55-1	Heating furnace for billet	Nov. 5		11:30-12:30	-	-	3.4	925	143	9.3	<0.05	-	17.6	0.610	0.292	1.19	12	2,900	780	-	-	-	171	130	0.85	-	-
22	METAL PRODUCTS FACTORY (B)	19-1	Melting furnace for aluminum	Nov. 8	1	13:30-14:15	-	-	15.7	280	9	2.7	<0.05	570	3.6	0.747	0.438	3.96	4	2,100	72	-	-	-	36	27	0.04	-	1.2
				Nov. 9	2	15:00-16:00	-	-	6.8	890	28	7.3	<0.05	130	17.0	0.470	0.173	1.48	10	1,700	120	-	-	-	41	32	0.10	-	0.22
23	FOOD PRODUCTS FACTORY	65-2	NO.2 Boiler	Oct. 31	1	11:30-12:00	4.6	285	5.4	182	182	10.5	<0.05		4.1	1.677	2.209	1.35	10	13,600	-	2,800	-	2.94	245	187	5.1	160	-
					2	14:00-15:00	4.1	350	4.8	235	205	11.5	<0.05	210	7.9	1.677	2.209	1.30	10	23,500	-	4,500	-	2.94	266	202	10	260	4.9
24	ALCOHOLIC DRINKS FACTORY	47-2	No.2 Boiler	Sep. 26	1	15:00-16:00	2.5	320	4.3	178	242	12.0	<0.05	410	16.9	1.748	2.400	1.26	10	61,600	-	5,400	-	2.96	304	232	31	310	25
					2	16:20-17:20	3.1	320	6.1	175	239	11.3	<0.05	-	16.1	1.748	2.400	1.41	7	61,000	-	4,700	-	2.96	337	257	30	270	-
25	PUBLIC BATHHOUSE	52-1	No.1 Boiler	Nov. 19		12:30-13:30	-	-	10.5	170	125	6.0	0.25	150	4.2	0.550	0.238	2.00	7	1,600	-	100	-	2.94	250	190	0.41	5.8	0.24

Note: Visit No. :Number in order of visiting for on-site questionnaire survey of 97 establishments.
Recuperator:02 and Ts for recuperator were measured at the inlet.
Qdry :Flue gas quantity at dry base.
‡ :Estimated by the refinery.
ˆ :Estimated by the Study Team.