Report SGC 102

EVALUATION OF THE EFFICIENCY FACE TO THE NO_X-EMISSIONS FROM EUROPEAN GAS-FIRED HEAT PROCESS EQUIPMENT

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FOREWORD

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SWEDISH GAS CENTRE

Johan Rietz
President

Utvärdering av verkningsgrad kontra NOx-emissioner från europeiska gasinstallationer - ett THERMIE-projekt

SAMMANFATTNING

Inom ramen för EU's THERMIE-program har SGC tillsammans med Gasunie, *Holland*, DGC, *Danmark*, Gaz de France, *Frankrike* och CETIAT, *Frankrike* genomfört ett projekt där man genom mätningar på industriella anläggningar, kartlagt statusen avseende emissioner och verkningsgrader hos modern förbränningsutrustning anpassad för minimala NO_x-emissioner Undersökningen har genomförts under 1997 - 1998 och har omfattat 35 installationer i fem olika länder och inom tre olika kategorier

- pannor
- gasmotorer och turbiner
- industriella applikationer

De 35 olika installationerna som ingått i studien har alla varit relativt moderna låg-NO_x-installationer eller nyligen blivit konverterade till modern låg-NO_x-teknik

Pannor

Totalt har mätningar genomförts på 13 olika gaspannor, sju i Holland och sex i Sverige. De flesta av dessa har varit under 4 MW och några enstaka har varit upp till 12 MW Mätningarna visar inget klart samband mellan NOx-emissioner och verkningsgrad Alla pannor i studien hade en verkningsgrad mellan 80 och 95% och NO_x-emissioner på i genomsnitt 80 - 100 mg/nm^3, 3% O_2 Detta motsvarar 25 - 30 mg/MJ Sju av anläggningarna har brännare med intern rökgasåterföring och dessa visade emissioner som låg något lägre än genomsnittet (50 - 90 mg/nm^3, 3% O_2). I detta intervall låg även vissa installationer med stegad gastillförsel Något sämre värden uppvisade anläggningarna med stegad lufttillförsel eller extern rökgasåterföring

Gasmotorer

DGC har inom projektet genomfört mätningar på 7 olika gasmotorer i Danmark och dessa mätningar har kompletterats med mätningar på motorer i Sverige och Frankrike Elverkningsgraden för motorerna varierar mellan 32 och 40% och NO_x-emissionerna varierar mellan 200 och 800 mg/nm^3, 5% O_2
Detta kan jämföras med emissionsdata för hela den danska gasmotorpopulationen som ligger på i genomsnitt 618 mg/nm^3, 5% O_2 (drygt 200 mg/MJ) Något direkt samband mellan kvävoxidemissioner och verkningsgrad kan ej härledas ur studiens mätningar men generellt sett så har de motorer som arbetar med höga luftöverskott en lägre kväveoxidemissioner och högre verkningsgrad än maskiner som arbetar vid lägre luftöverskott. Höga luftöverskott kan dock ge andra effekter som stigande emissioner av UHC och större risk för misständningar.

Gasturbiner

Tre olika gasturbiner har kontrollmätts inom projektet, två identiska turbiner på 9,4 MW i Frankrike och en svensk turbin på 21 6 MW De franska turbinerna hade en elverkningsgrad på 29 2% och NOx-emissioner på 245 mg/nm^3, 15% O_2(210 mg/MJ) Den svenska turbinen hade en elverkningsgrad på 32 1% och NOx-emissioner på 55 mg/nm^3, 15% O_2 (50 mg/MJ). Mätningarna visar att modern låg-NOx-teknik kan sänka emissionerna väsentligt samtidigt som verkningsgraden påverkas i mycket ringa omfattning.

Industriella processer

Mätningarna inom industrin genomfördes på 11 olika industrier inom 4 olika sektorer

- livsmedelsindustri (torkning)
- keramisk industri
- metallindustri (smältning, värmning)
- papper/textil (torkning)

I flera av de industriella tillämpningarna förekom förvärmning av luften till mellan 300°C och 1000°C Trots förvärmingen så låg i samtliga fall utom ett NO_x-emissionerna på under 400 mg/nm^3, 3% O_2
(motsv. under 120 mg/MJ) Någon enstaka regenerativ brännare låg på ca 1300 mg/nm^3, 3% O_2
Generellt sett så uppvisade samtliga anläggningar stigande emissioner vid stigande processtemperatur medan emissionerna (förutom installationen med regenerativa brännare) föreföll vara relativt oberoende av luftförvärmningstemperaturen
"Konventionell" förbränningsteknik uppvisar här en fördubbling av NO_x-emissionerna när luftförvärmningstemperaturen öka från rumstemperatur till ca 600°C
Mätningarna visade att modern industriell låg-NO_x-teknik har lika hög eller högre verkningsgrad än konventionell teknik trots att emissionerna begränsas till <120 mg/MJ I extremfall med s k flamlös förbränning så nåddes NOx-emissioner på ca 50

mg/MJ vid luftförvärmningstemperaturer på ca 900°C
Dessa nya tekniker (t ex flamlös förbränning) är dock än så länge relativt oprövade och det är därför viktigt att utvecklingsinsatser sätts in för att kartlägga hur de nya teknikerna skall kunna tillämpas inom olika typer av industrier. Detta gäller ett flertal olika områden, från påverkan på produktkvalitet till möjligheter att modellera konvertering av befintliga ugnar.

Slutsatser

35 olika låg-NOx-installationer i fem olika länder har kontrollmätts under normal drift. Mätningarna har visat att

- Pannor med befintlig låg-NOx-teknik når emissioner på 25 - 30 mg/MJ utan några förluster i verkningsgrad
- Gasmotorer har NOx-emissioner på ca 200 mg/MJ med dagens teknik (lean burn motorer)
- Gasturbiner kan utan rökgasrening nå emissionsnivåer på 50 mg/MJ med moderna brännkammare
- Industriella processer utrustade med låg-NO_x-brännare klarar att underskrida 120 mg/MJ och s k flamlös förbränning ger möjligheter till ännu lägre NO_x-emissioner samtidigt som förbränningsprocessen blir mindre känslig för förbränningsluftens förvärmningstemperatur.

De installationer som har studerats inom projektet har i de flesta fall varit så pass nya att man ännu inte kunnat dra några definitiva slutsatser beträffand om drift- och underhållskostnader överstiger motsvarande kostnader för konventionell teknik Vissa installationer (t e x installationer med extern rökgasåterföring förefaller dock ha något högre underhålls kostnader än konventionell teknik

Projektet har genomförts av en projektgrupp med representanter från Gaz de France, Gasunie, DGC, CETIAT och SGC och med finansiellt stöd från EU's THERMIE-program

SUMMARY

In the frame of the THERMIE Contract STR-397-95-FR entitled "Evaluation of the efficiency face to the NOx emissions from European gas-fired heat process equipment", tests have been performed by GAZ DE FRANCE, CETIAT, DGC, GASUNIE and SGC on 35 European industrial sites in order to depict what the European industry using natural gas as an energy source actually looks like in 1997, the levels of efficiency and nitrogen oxides (NOx) emissions currently being achieved These 35 industrial sites were chosen among the three following sectors steam or water boilers, engines or turbines and industrial processes (food processing industry, metallurgy, ceramic, paper and textile industries) The partners focused on relatively new installations or newly retrofitted which were equipped with low NOx technologies

To create an open database between the Partners, a common EXCEL® sheet has been defined and used to report the results for the three sectors concerned including principally the following items

- *General background on the site* it includes the description of the installation, technical characteristics of the furnace, the boiler or the engine, operating scenarios, gas total rating, and depending of the type of installation power density, rated electric power or production rate

- *Description of the equipment* it includes, if available, the control system of the heating equipment and the low NOx techniques identified

- *Description of the measurement techniques* In order to compensate for the lack of international standard, this part has been particularly detailed It includes the description of flue gas analysers (CO, CO_2, O_2, NOx, CH_4, UHC, N_2O, VOC), metering and pressure and temperature probes in terms of measurement principle, supplier, measurement rang and accuracy and gas calibration It precises the position of the sampling points and the type of the sampling line

- *Results* The operating conditions (atmospheric data, type of natural gas burnt during the test and measurement period) are given before the results themselves (complete flue gas analysis and determination of combustion and process efficiencies)

The results show that the situation in terms of NOx emissions and efficiency is quite different from one country to another and for one installation to another

Boilers

For this test campaign, the firetube boilers efficiencies (steam or hot water) range from 78% to 97% which is in accordance with previous and published results The NOx emissions range from below 50 mg/m^3(n) at 3% O_2 to 140 mg/m^3(n) at 3% O_2 which corresponds to low NOx boilers To generalise these results, we could say that efficiencies between 80% to 90% and NOx level between 80 to 100 mg/m^3(n) at 3% O_2 are achievable for a majority of modern or future boilers However the excess air ratio as the power density have a great influence on the performances of the boilers and thus has to be taken into account in the analyse of experimental data Moreover, the study was based mainly on low gas input and hot water boilers for more powerful steam boilers, the conclusions should be adapted

Concerning low NOx technologies, it appears that internal flue gas recirculation and gas staging tend to be the most promising techniques to reduce the NOx emissions from boilers Future R&D work should be carried out to optimise these techniques and to spread them in the industrial field The external flue gas recirculation is also an effective technique which may be applied in the future to be able to reduce the NOx emissions of existing installations

Engines and turbines

The tests have shown that lean-burn gas engines, in the range from 0 5 - 5 MW_e, operate with an electrical efficiency of approx 39-41% and a total efficiency of 85 - 95% (ref to net calorific value) The relative NO_x emissions are 0 8 g $NO_x/kWh_{heat\ and\ power}$

As a side-effect of the engine development toward higher efficiency, the emissions of unburned hydrocarbons (UHC) have generally increased The composition of UHC is similar to that of the natural gas, i e approximately 90% (vol) methane Methane is a strong greenhouse gas, and emissions of UHC thus cause a reduction in the CO_2 reduction benefit obtained by cogeneration

Relatively high emissions of formaldehyde and acetaldehyde have been detected in the engine exhaust, and this is a matter of concern since the species may present a health risk

Turbines are generally larger in rated power than the engines and the electric efficiency is somewhat lower The total efficiency of heat and power is similar to that of the engines The NOx emissions from turbines have been reduced in recent years using low NOx burners The level can be lower than that of the engines The turbines heat supply temperatures are higher than for the engines, and this is important in many industrial applications where steam is needed

Industrial processes

The sector of the thermal industrial processes is very large and the selection of sites is in comparison too small In particular, no very high temperature process has been investigated, such as glass melting or white ceramic furnaces where the temperature could be above 1500°C Moreover, the oldest installation dated from 1992 and we tried to focus on low NOx technologies

However we can clearly observed the expected trends, as the influence of the combustion air temperature and of the process temperature on NOx emissions and combustion efficiency We can indeed remind that the most common way to reduce the CO_2 emissions in natural gas thermal heating equipment consists of increasing the combustion efficiency by recovering the flue gas energy to preheat the combustion air Using low NOx technologies, it is possible to keep the NOx emissions under 400 $mg/m^3(n)$ at $3\%O_2$, even with preheated combustion air The low NOx technologies have yet to be adapted to the industrial processes when the impact between the flame and the load to be treated has a big influence on the final product (in term of quality in particular) Some efforts have to be made to optimise or adapt the low NOx technologies (as examples, extremely high air staging or flameless oxidation techniques) in regards of a large variety of situation and to spread them in all the industrial fields

The process efficiency vary a lot from one installation to another In general, low temperature processes have lower process efficiency (as well as the combustion efficiency and the NOx emissions) For a rational use of energy research should be performed to raise them

As a conclusion, it seems necessary to continue such a survey on Low NOx and high efficiency Best Available Technologies in the different industrial fields and R&D works in terms of comprehension and optimisation of new low NOx techniques and of implementation of these techniques in new or retrofitted installations

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1. INTRODUCTION

The aims of the project STR-0396-95-FR entitled "Evaluation of the efficiency face to the NOx emissions from European gas-fired heat process equipment" are to depict what the European industry using natural gas as an energy source actually looks like in 1997, the levels of efficiency and nitrogen oxides (NOx) emissions currently being achieved, the deviation in practice from the best practices, and indication of the type of actions which could be implemented to improve the situation in particular in order to help industrial consumers in choosing between new investments or retrofitted installations. Moreover, the fact that low NOx burners can be widely used without impairing efficiency or creating additional difficulties in industrial operation or maintenance needed to be checked and proven to manufacturers. There was no general published data available for the industry, only laboratory results from R&D Centers or heating equipment manufacturers. From a technical perspective, the laboratory methods for increasing efficiency and lowering NOx emissions from gas-fired heat-process equipment point indeed to higher achievable standards than is actually achieved in practice.

Due to recent headway in developing new combustion techniques, NOx emissions can be indeed lowered without affecting any of the other basic requirements (quality of combustion, efficiency, equipment reliability, cost, etc.). Nevertheless, any efforts to reduce overall pollutant emissions from process furnaces naturally include installing components that generate little pollution, but also working on energy-saving designs to lower emissions of carbon dioxide (which is a greenhouse gas). Unfortunately, this twofold need can sometimes lead to contradictory effects. First, heat recovery by preheating the combustion air is the main energy-saving technique used. Given the particularly high heat used in industrial processes, this means that the preheated combustion air can reach temperatures as high as 1250°C. Yet these two parameters (the high temperatures of both the combustion air and the process) have a negative impact on nitrogen oxide emissions.

Leaded by GAZ DE FRANCE (France), this project has gathered the following partners : Danish Gas Technology Center (Denmark), Swedish Gas Technology Center (Sweden), GASUNIE (The Netherlands) and Centre Technique des Industries Aérauliques et Techniques (France). The total duration of the THERMIE Contract STR-0397-95-FR is 26 months from 1st April 1996 (according to the amendment to the contract), date of the signature of the contract. The total budget amounts to 330 582 ECU including an EC-support of 200 000 ECU.

The action consisted of the five following tasks :

Task 1 : Definition of the Test and Measurement Methods

The five partners have compared their methodology and measurements techniques to enhance the information and results exchange between them. A common approach has been defined. It includes flue gas analysis (CO, CO_2, O_2, NOx, unburned hydrocarbons, temperature) and combustion efficiency evaluation.

Task 2 : Choice of Industrial Sites

Each partner has chosen a number of sites focusing in each country on the Best Available Technologies. The sample of sites is representative of the industrial distribution. The sites have been selected with the agreement of the European manufacturers concerned. A list of the proposed sites has been sent to the European Commission. According the contract, this list of sites has to stay confidential.

Task 3 : Test Period

The five partners have performed the measurements during a period of one year and half around. A report and synthesis data form has been written for each site.

Task 4 : Synthesis Report

The analysis of all the results has been carried out by all five partners. The synthesis report has been drawn up by Gaz de France with the help and agreement of all partners. This present report will be sent to the Commission for comment before proceeding to the next stage.

Task 5 : Exploitation of the Test Campaign

A first dissimination of the results consists of a oral presentation given at the Internationnal Gas Research Conference in San Diego (US) in November 1998. This conference is the largest conference concerning R&D work on natural gas. The paper of this presentation makes up a good support for other dissemination activities which will be carried out by each partner in a short future :

1. Dissemination of the results to industrial partners and consumers through approved (by the Commission) articles in publications, specialised reviews, papers at congresses, etc.

2. Specific meetings (e.g. workshop(s) in each country) will be organised by the partners for which information dissemination will be the key aim.

3. New research, development and demonstration needs will be identified, in particular to point out the industrial sectors in which further work is required.

The present report has the following outline : after this introduction, the european context is summarised in terms of energy consumption in the countries concerned by the project and in terms of environemental regulations ; this gathered information allow an anlyse of the results from the test in light of existing or new regulations in Europe to examine how the industry manage or will manage to respect them.

Then the choice of the 35 sites on which measurements have been performed is presented. A paragraph is dedicated to NOx formation and to the widest NOx emission reduction techniques.

The following part of the report focused on the results themselves set out in three subparts : boilers, engines and turbines, and industrial processes. Then some comments and recommandations are drawn. Finally a dissemination of the results is proposed before the final conclusion.

2. EUROPEAN CONTEXT

2.1. NATURAL GAS CONTEXT

The energy situation in France, Denmark, Sweden and Netherlands is successively presented. It appears that the natural gas use in these four european countries is rather contrasted : France and Netherlands are quite old natural gas consuming countries, whereas Sweden has been using this fuel only for fifteen years. Denmark and Netherlands are up to now self-sufficient in term of natural gas supply, while Sweden and France import a large majority of their domestic consumption if not all their consumption.

These facts lead directly to some differences in terms of natural gas market share and industrial uses which explain the motivation of the partners to share their knowledge of NOx emissions and Energy performances from a large variety of installations through this european contract.

2.1.1. Energy Consumption in France in 1995

Consumption of natural gas totaled 30.0 Mtoe (million ton oil equivalent) or 1262 10^{15} J (NCV) in 1996, equivalent to 1.7% of worldwide gas consumption. In weather-adjusted figures, this corresponds to 14.4% of primary energy consumption in France, which totaled 208.5 Mtoe (adjusted value). The latter total remained virtually unchanged between 94 and 95, while consumption of oil products (88.4 Mtoe, including 46.54 for transport) dropped slightly (-0.7%) and coal regained the 1993 consumption level (8.3 Mtoe). Table 1 details the share of each energy in France, for the years 1993 to 1996. The share of natural gas, excluding transport, is estimated at 16.60%.

weather-adjusted energy consumption in Mtoe (in 10^{15} J NCV)	1993	1994	1995	1996
coal	8.3	9.1	8.3 (348.6)	8.3
oil	85.1	88.4	87.8 (3712.8)	88.0
natural gas	27.7	29.0	28.7 (1207.6)	30.0
electricity	74.2	76.5	77.3	78.5
other	4.1	4.1	4.0	3.7
total	199.4	221.5	206.1	208.5
relative share of natural gas	13.9%	14.0%	13.9%	14.4%
relative share of natural gas excluding transportation				16.6%

Source : Observatoire de l'Energie

Table 1: breakdown of the energy consumption (in Mtoe) in France in 1995

In 1995, more than 90% of the natural gas consumed in France was imported. Imports were supplied by the Netherlands, Algeria, Russia, Norway and Abu Dhabi, as per the breakdown given below figure 1.

The result has been the presence of two different kinds of natural gas in France, high calorific value gas and low calorific value gas (imported from the Netherlands and distributed solely in northern France).

GAZ DE FRANCE is the largest gas operator in France, insofar as the company sells 86% of the total volume of natural gas consumed by end users. CFM accounts for 8%, followed by GSO for 3%, with the remainder sold by local distribution companies.

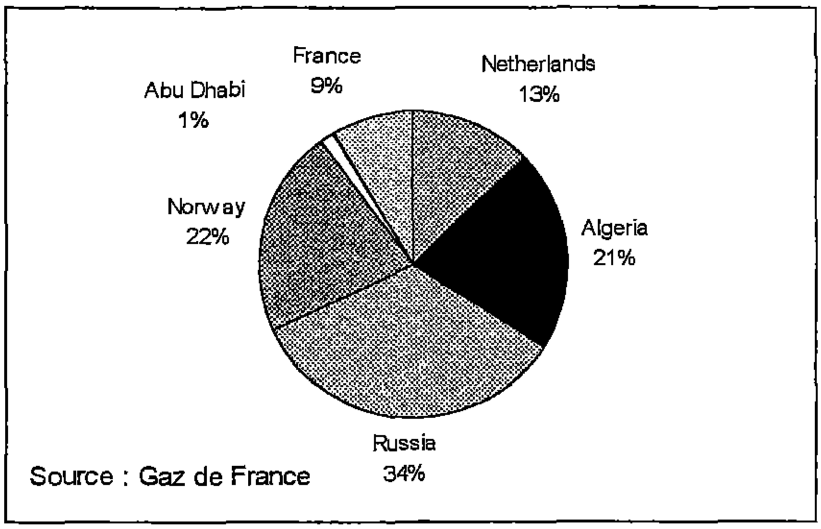


Figure 1 : 1995 Breakdown of natural gas imports in France

The industrial sector's share, in weather-adjusted figures, was 173 TWh, out of a total volume of 397.1 TWh sold in France, which marked a 5.3% increase over 1994. The estimated volume for 1996 is 414 TWh, meaning that sales increased once again, by 4.3% over 1995. Table 2 and figure 2 give the breakdowns of gas sales to the industrial sector in France.

The largest consumer of natural gas is the chemical and chemistry-based sector, where gas is used as either a feedstock or a fuel, mainly in generating steam. However, if we single out the use of natural gas as a fuel, the two largest consumers are on the one hand, the metallurgical and steelmaking industry and, on the other, agribusiness.

sector	consumption in TWh
basic chemistry - synthetic fiber and filament production - chemistry-based and pharmaceutical industries	49.326
agricultural and food-processing industry	23.716
paper and paperboard industry	14.641
electrical and mechanical engineering	11.866
ceramics and building materials industry - construction and civil engineering - various mining industries	10.659
glassmaking industry	7.730
steelmaking industry	7.189
rubber - plastics industry	6.675
metal founding and working	6.278
textile, leather and shoemaking industry	5.436
cement, lime and plaster	4.340
integrated nonferrous metallurgy	4.068
primary processing of steel	2.568
agriculture, forestry, fishing	2.541
electricity	1.205
other industry	12.895
total	171.143 or 554 10^{15} J (NCV)

Source : French Ministry of Industry

Table 2 : 1995 Breakdown of the gas industrial consumption in France

The main trends observed in the curves of natural gas sales since 1980 (see figure 3) are a growth in sales to the agribusiness sector and a diversification in applications (increased sales to other sectors). Such major industrial sectors as the chemical and steelmaking industries remain stable. The emerging markets for natural gas are based above all on new applications. In the industrial sector, this has been largely cogeneration to generate electric power.

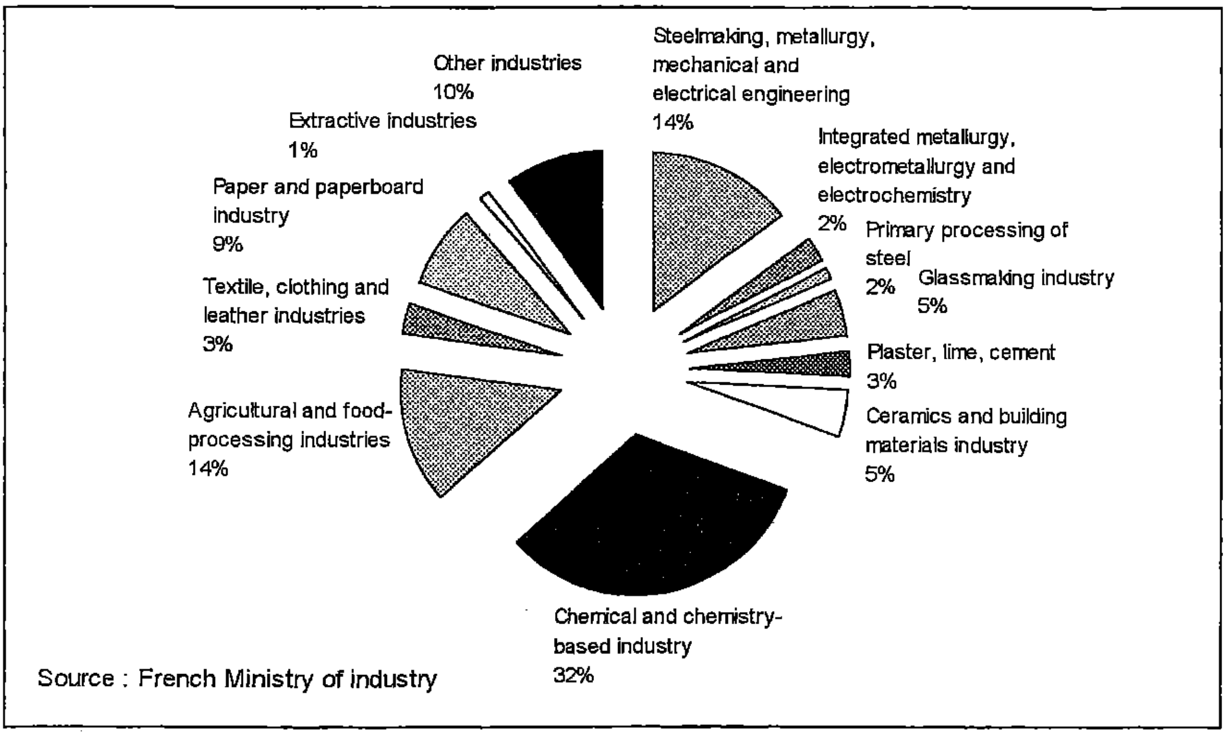


Figure 2 : 1995 Breakdown of the gas industrial consumption in France

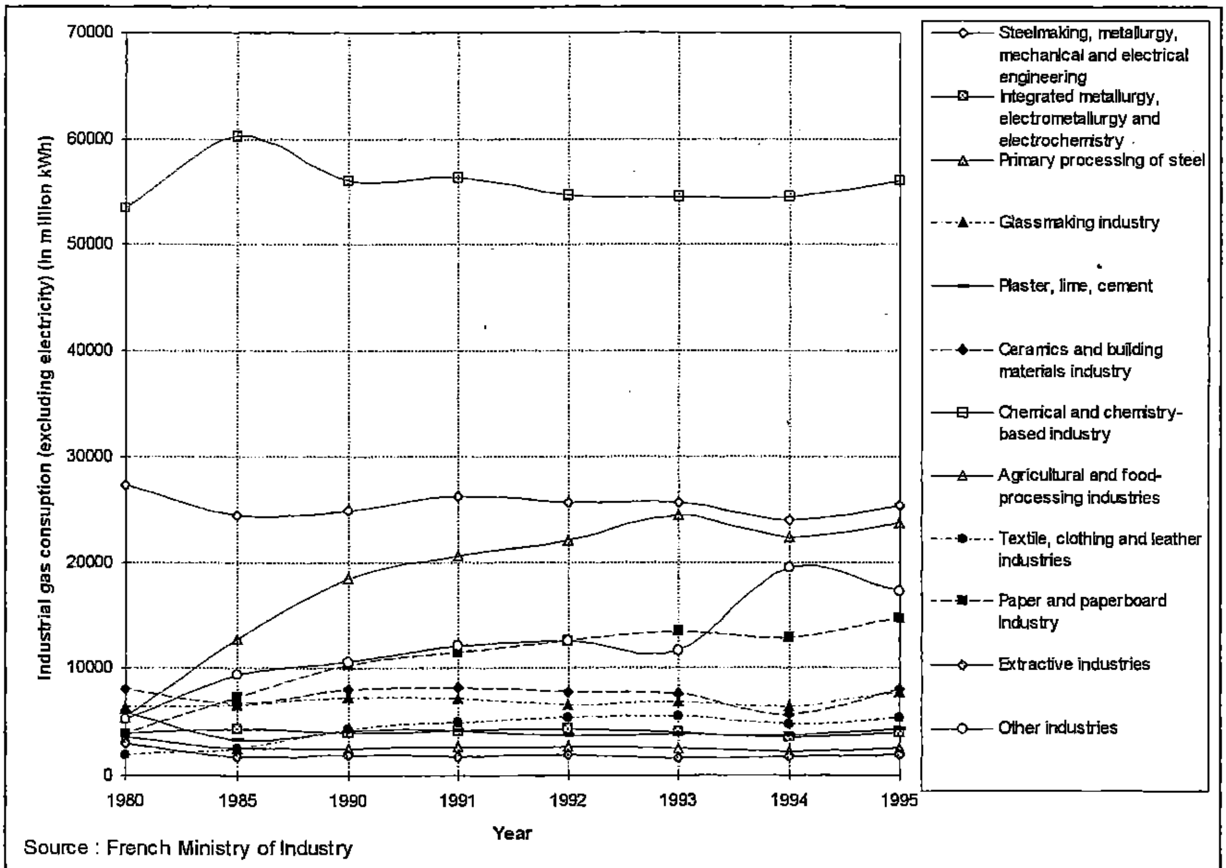


Figure 3 : 1995 Breakdown of natural gas consumption (excluding electricity production)

2.1.2. Energy Consumption in The Netherlands in 1995

Gasunie is the company which purchase natural gas from various production companies in the Netherlands and abroad. It transports the natural gas through an extensive pipeline systems and supplies it in the Netherlands to gas distribution companies, power stations and major industrial users in the Netherlands and to export customers in Belgium, France, Italy and Germany. The principal task of Gasunie is to ensure an uninterrupted supply of gas in the Netherlands. A strong element of the company's policy is also concerned with the efficient utilisation of natural gas.

The Dutch natural gas system arose in the sixties with the exploration of the Slochteren natural gas field, closed to Groningen in the Northern parts of the Netherlands. In 1995 natural gas accounted for 49% of the total domestic energy consumption in The Netherlands, where oil products carried 34% and coal nuclear energies and others sources 17%. The contribution of natural gas to the energy demand of the Netherlands tend to be stable since the mid seventieth ranging around 50%. The 1995 overall energy balance for The Netherlands (General-trade system) is given in the following table 3.

	PJ=petajoule (10^{15} joule)	coal & brown coal	coal products	Crude oil	oil products	natural gas	nuclear energy	electricity	other energy sources	Total
1.	winning	-	-	151	-	2537	43	2	34	2768
2.	import	470	27	4196	1289	116	-	43	-	6140
3.	export	79	33	1680	2416	1220	-	2	-	5430
4.	storage	-	-	-	584	-	-	-	-	584
5.	from reserve	10	-2	10	73	0	-	-	-	91
	domestic consumption	401	-8	2678	-1639	1433	43	43	34	2985
6.	statistic difference	10	5	1	27	-17	-	0	-5	20
7.	consumed saldo	391	-13	2677	-1666	1451	43	43	39	2965
	consumed saldo %	total:	13	total:	34	49	1	1	1	100
8.	producer balance	363	-79	2677	-2499	360	43	-224	-52	589
8.1.	winning companies	-	-	-0	-	28	-	0	-	28
8.2	coke-plants	116	-102	-	1	-	-	0	-	17
8.3	refineries	-	-	2676	-2510	22	-	1	-14	174
8.4	central heat/power	240	22	-	2	229	43	-210	-16	310
8.5	decentral heat/p.	7	-	-	9	59	-	-20	-40	15
8.6	waste incinerators	-	-	-	0	0	-	-4	21	17
8.7	power distributors	-	-	1	-0	22	-	8	-3	28
9.	producer-consumer balance	28	66	-	833	1090	-	267	91	2376
9.1	industry	27	59	-	354	420	-	107	68	1035
9.2	transport	-	-	-	413	-	-	5	-	418
9.3	domestic	0	-	-	6	361	-	71	7	445
9.4	others	1	7	-	60	309	-	84	17	478
11.	energy consumption	19	72	-	902	974	-	294	173	2334
11.1	industry	18	64	-	323	321	-	129	142	996
11.2	transport	-	-	-	413	-	-	5	-	418
11.3	domestic	0	-	-	6	361	-	71	7	445
11.4	others	1	7	-	60	293	-	89	25	475

Table 3 : 1995 overall energy balance for The Netherlands

All data sources mentioned are based on the 1995 overall energy balance publication by the Netherlands central bureau of statistics (CBS). Hence, data without any reference are based on CBS research whereas other sources are mentioned explicitly.

The 1995 total domestic natural gas consumption split into sectors in shown in figure 4. In brief it can be stated that gas consumption in the Netherlands is split into 1/3 energy production, 1/3 industry and 1/3 domestic usage.

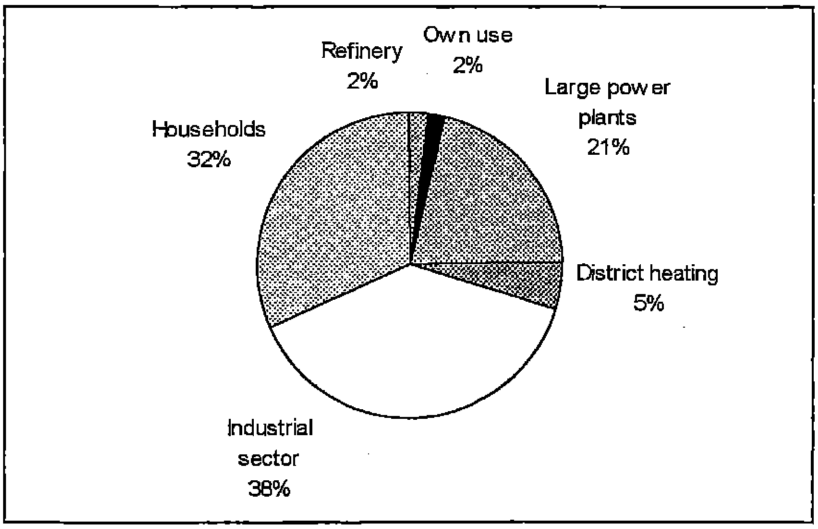


Figure 4 : 1995 Natural gas consumption breakdown in the Netherlands

Figure 5 shows the natural gas consumption for the industry sector only. The chemical industry's consumption is 33%, followed fertiliser industry with 26% and food processing with 17%. The paper and print industry comes fourth with 6% of the total industrial natural gas consumption in the Netherlands. Combined heat and power generation (CHP) for industry is calculated to be 23.6% of the total natural gas consumption by industry.

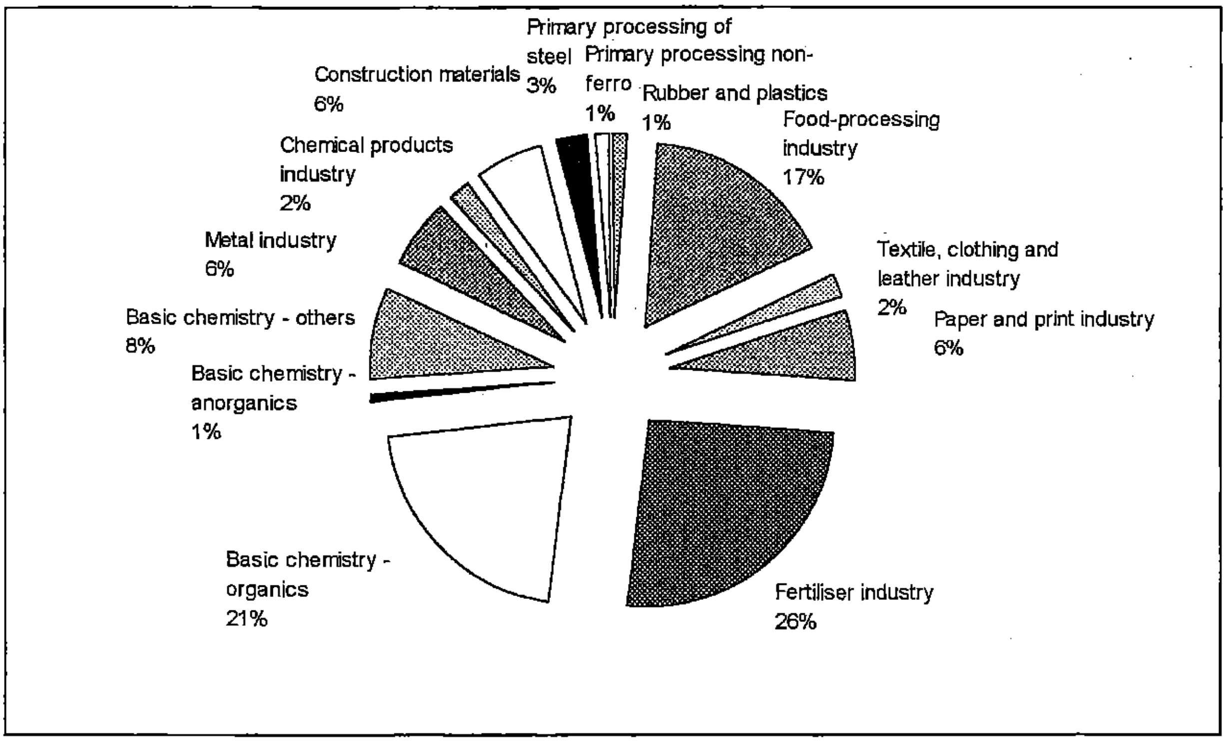


Figure 5 : 1995 Natural gas consumption of the industrial sector in the Netherlands

However, it should be noted that market research at Gasunie showed that the total steam/hot water production by industry accounts for around 37% of the total natural gas consumption by industry. It is believed that this difference is due to the fact that boiler used for heating purposes are not accounted for in the CHP sector but fall under other energetic transformation. Hence, we define the total industrial boiler market as being around 10% of the total domestic market.

Finally, Figure 6 presents the contribution of combined heat and power (CHP) generation to each industry's natural gas consumption. This graph gives a clear indication in which industries boilers are most significant for process operations. The choice of sites is partially based on this analysis. Besides heating purposes, CHP operations account for almost 44% of the natural gas consumption of the chemical industries, followed by the paper and print industry with 24% and food processing with 14%.

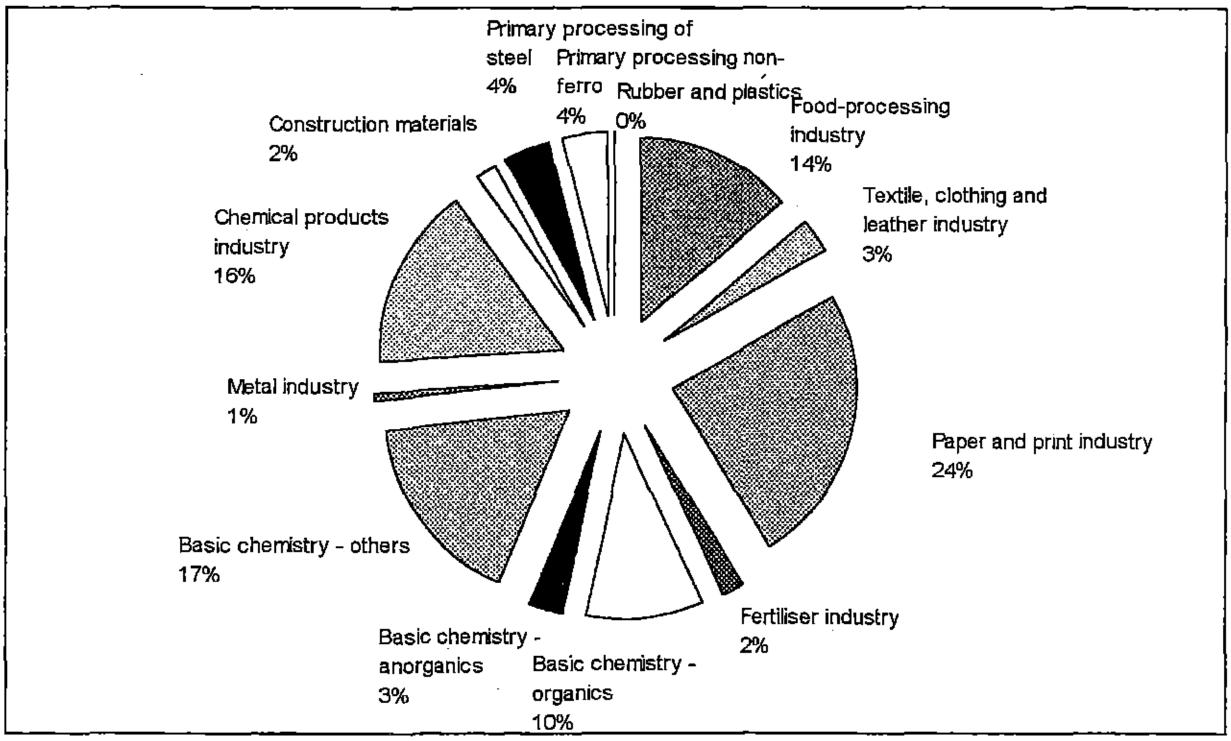


Figure 6 : 1995 CHP contribution to industry's natural gas consumption

2.1.3. Energy Consumption in Denmark in 1995

The Danish natural gas system is only approximately 10 years old. Oil and coal continue to be by far the most important energy sources in Denmark with market shares of 44.2 and 32.2 per cent, respectively, of the Danish primary energy supply. In 1995 the share of natural gas reached just over 15 per cent compare to 8 percent in 1988. By the turn of the century, Dansk Naturgas A/S expects that the share will increase to 25 per cent at the expense of oil and coal. The gas consumption is primarily expected to increase to residential customers and power plants including industrial combined heat and power.

The role of natural gas in Denmark compared to other energy sources, is shown in the Energy Balance 1995 (see table 4).

The consumption of natural gas in the main sectors of use is shown below in table 5 and figure 7.

Direct Energy Content in TJ (TJ = terajoule = 10^{12} joule)	Total	Crude Oil and Refinery Feedstocks	Oil Products	Natural Gas	Coal and Coke	Renew-able Energy etc	Electricity	Distict Heating	Town Gas
Primary Energy Consumption	833 076	417 953	-50 282	131 750	271 391	65 003	-2 858	120	
Primary Production	653 608	391 563		197 042		65 003			
Import	778 933	247 450	195 448		321 472		14 443	120	
Export	-478 727	-213 921	-184 195	-62 649	-660		-17 302		
Marine Bunkers	-67 198		-67 198						
Stock Changes	-53 393	-7 239	6 094	-1 465	-50 783				
Statistical Differences	-146	100	-430	-1 178	1 362				
Refinery	-34 042	-417 953	396 821	-12 910					
Conversion	-910	-417 953	417 043						
Own Use	-33 132		-20 222	-12 910					
Transformation	-138 958		-36 552	-48 973	-254 939	-40 647	124 373	116 470	1 310
Large Power Plants	-126 053		-30 982	-10 484	-251 644	-83	103 908	63 232	
Small-scale CHP Plants	-8 106		-159	-25 110	-1 295	-19 050	16 345	21 163	
District Heating Plants	-5 543		-3 050	-8 860	-1 572	-20 038		27 977	
Autoproducers[1)]	744		-2 254	-3 316	-428	-1 476	4 120	4 098	
Gas Works			-107	-1 203					1 310
Distribution	-31 329			-118			-7 841	-23 318	-52
Final Energy Consumption	628 746		309 985	69 750	16 451	24 356	113 674	93 272	1 258
Non-Energy Use	12 661		12 661						
Transport	185 182		184 322				860		
Industrial Sector	161 960		59 225	31 322	15 897	7 529	42 221	5 665	101
Service Sector	81 306		7 445	12 462	66	1 428	32 861	26 952	92
Households	187 637		46 332	25 966	488	15 399	37 732	60 655	1 065

Nota: Among autoproducers a transformation gain occurs, because delivery of heat to the district heating network mostly takes place as delivery of surplus heat.

Table 4 : Energy Balance in Denmark in1995

Consumption of Natural gas in 1995	TJ
Refinery	12 910
Large Power Plants	10 484
Small-scale CHP Plants	25 110
District Heating Plants	8 860
Industrial Sector	31 322
Service Sector	12 462
Households	25 966
total	131 114

Table 5 : Danish natural gas consumption in 1995 per sector

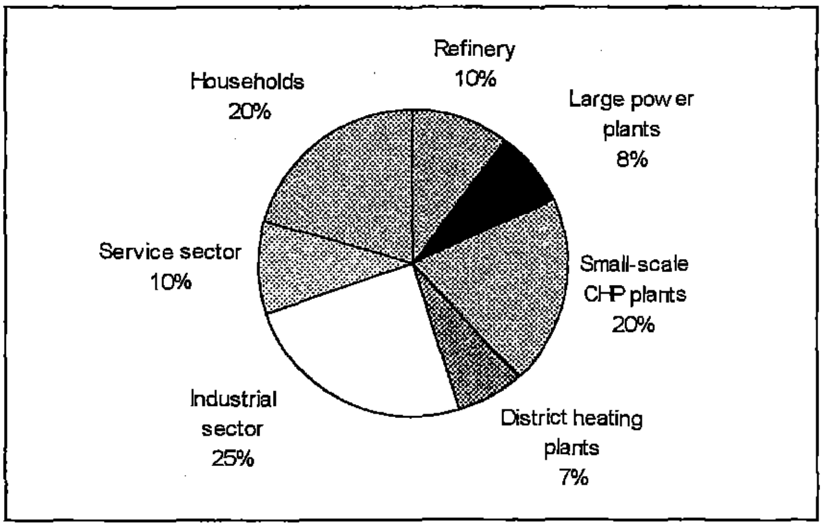


Figure 7 : Danish natural gas consumption in 1995

The importance of small-scale Combined Heat and Power, CHP, is seen from the diagram, it accounts for 18% of the gas used. The technology installed in this sector is mainly lean-burn engines.

2.1.4. Natural Gas in Sweden

Natural gas has been used in Sweden since 1985. The development of the Swedish network for natural gas has taken place gradually. At present the network covers the western part of Scania, parts of central Scania as well as the west coast up to and including Gothenburg, including a high pressure line to Hyltebruk. Thus the introduction of natural gas in Sweden has occured relatively late as compared with other countries in Europe, which means, among other things, that the technical design of the network could to a considerable extent be based on experience from the development of the European networks for natural gas.

Deliveries of natural gas to Sweden take place via a supply pipe under Öresund, from Amager in Denmark to Klagshamn south of Malmoe. Import to the Swedish natural gas network is exclusively made from the Danish natural gas fields in the North Sea. The Swedish natural gas network is connected to the European natural gas network via Denmark and Germany. The possibility of further expansion of the current network northward and eastward as well as the import from other countries is under investigation. To date this has not been implemented.

The import of natural gas has increased from 85 millions m^3 (0,9 TWh) in 1985 to 865 millions m^3 (9,3 TWh) in 1996, corresponding to 20 % of the energy supply within the developed area (see figure 8).

Out of the imported quantity of natural gas approximately 50 % is supplied to the combined power and district heating sectors, whereas supplies to industry constitute approximately 35 %. The remaining 15 % is consumed by the private heating sector.

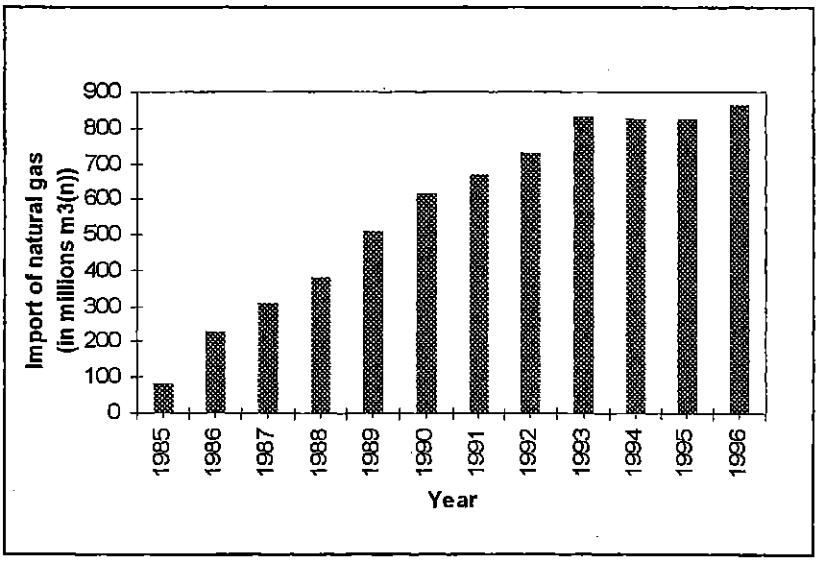


Figure 8 : Import of natural gas. Development during the period 1985-1996

2.2. ENVIRONMENTAL SCOPE

Although the pollutant emissions have already been significantly reduced in the last ten years in Europe (the European initial objectives in terms of NOx and SO_2 reduction have been achieved), the efforts must be carry on. In accordance with the European Environment Agency, it would be difficult to stabilise the CO_2 emissions due to the increase of the road transportation and of the energy consumption. As an example, the french trends in terms of pollutants emissions are presented hereafter. The trends could be however rather contrasted from one country to another, depending on the initial situation, national energy policy, economical situation...

For some twenty years now, the CITEPA ("Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique") has been in charge of evaluating air pollution in France by SO_2, NOx, NMVOC (non methanic volatil organic components), CH_4, CO, CO_2, N_2O, NH_3. The findings of its yearly inventories show that emissions of the main types of pollutants have tended to decline or stagnate over roughly the last fifteen years. This trend is linked primarily to industrial or power generation-related sources.

The graphs below show the trends in NOx and CO_2 emissions in France, by major energy-consuming sector (figures 9 and 10), and the overall trends for the eight pollutants observed (figure 11).

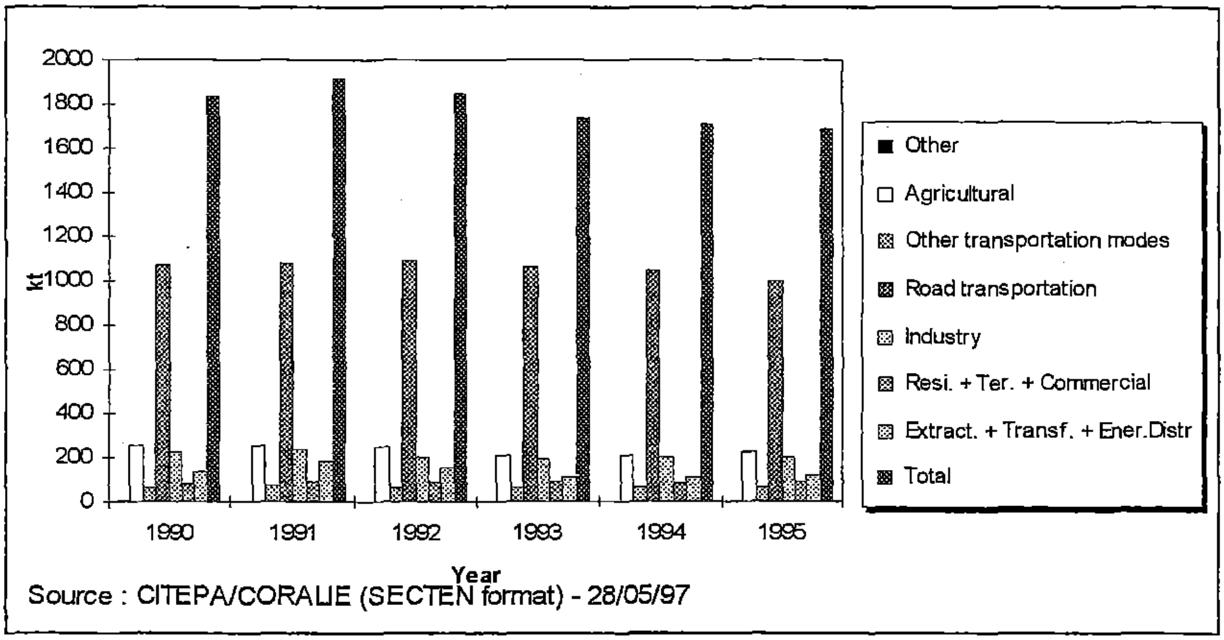


Figure 9 : NOx emissions in France per sector from 1990 to 1995

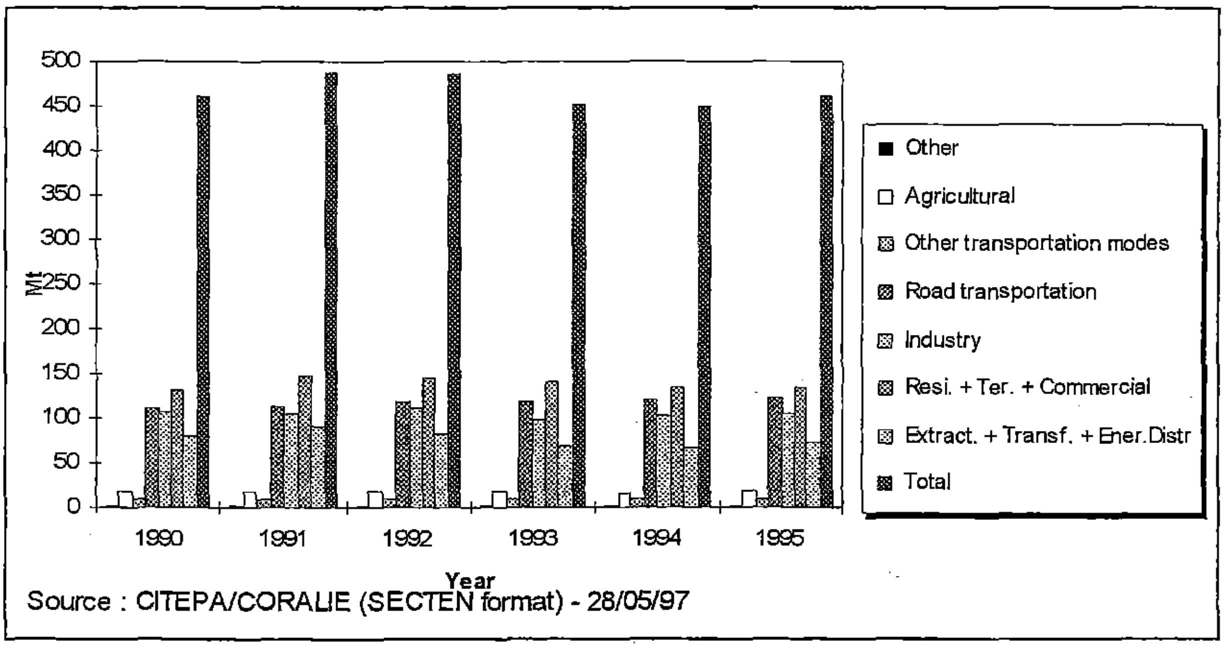


Figure 10 : CO_2 emissions in France per sector

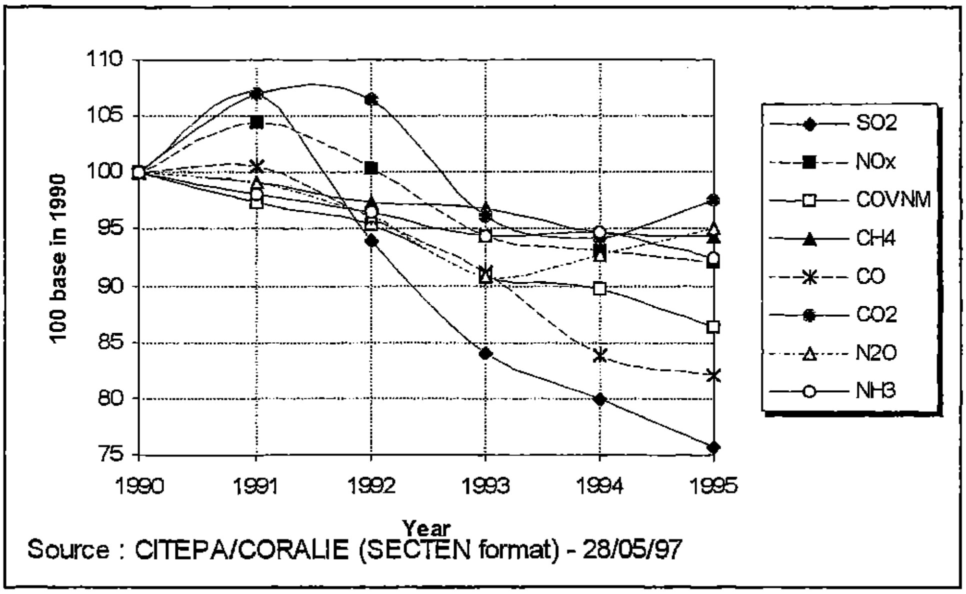


Figure 11 : Evolution of pollutant emissions in France from 1990 to 1995

In France, according to this graph, the NOx emission is slightly globally decreasing since 1990.

2.3. REGULATORY SCOPE

Hereafter are presented the regulatory situation in France, Netherlands, Denmark and Sweden. As for the energy concept, the regulations are very different from one country to another, except those issued from European Directives and a precised comparison is not easy. It should be noticed that emphasis is not put on the same industrial installation in all these four countries.

2.3.1. Regulatory situation in France

The regulatory situation in France regarding fossil fuel combustion is evolving rapidly. A Law on air and rational energy use was passed on December 31, 1996. Yet most of the environmental regulations derive from the Law of July 19, 1976 governing plants classified for environmental protection. For plants to be subject to that law, they must be classifiable and classified, i.e. enter into one of the headings in the nomenclature of classified plants, which was updated recently. Today this listing comprises some 200 headings, one of which, No. 2910, is entitled "combustion plants".

Plants are subject either to registration (the industrial operator submits a registration file to the local administration) or to authorization (the industrial operator requests a permit to operate the plant from the Prefect, the local agent of the Ministry of the Interior), according to the seriousness of the risks or disturbances they may cause. Approximately 500,000 plants are subject to registration and 60,000 to authorization.

Under heading 2910, all plants powered by natural gas, LPG, heavy or light fuel oil, coal or biomass and whose capacity exceeds 20 MW are subject to a authorization, while all plants with an heat input ranging between 2 MW and 20 MW are subject to registration. The latter threshold is lowered to 0.1 MW for all other fuels.

For the record, insofar as such types of plants are not among those studied within the scope of THERMIE project STR-397-95-FR, combustion plants with a capacity above 50 MW, "except for those that use the combustion product in a direct manner in the manufacturing process" -- in actual fact only industrial boilers and thermal generating plants -- are subject to the Decree of June 27, 1990, which implements in French law the European LCP or "Large Combustion Plants" Directive of November 24, 1988. The emission limit values are specified in table 6:

Fuel / limit value	NO_2 mg/m^3(n)	dust mg/m^3(n)	SO_2 mg/m^3(n)
gas	350 at 3% O_2	5 generally 10 blast furnace gas 50 gas from steelmaking	35 generally 5 for LPG
liquid	450 at 3% O_2	50	400 to 1700 depending on heat input
solid	650 at 6% O_2	50 to 100 depending on heat input	400 to 2000 depending on heat input

Nota : Basis for calculation are the followings dry exhaust gases, 0°C, 101,3 kPa

Table 6 : Pollutant emission limits settled by the LCP Directive

The LCP Directive is currently undergoing revision, which would change the limit emission values for boilers yielding 100 or 150 mg/m^3(n) at 3% O_2, exclusively for natural gas. Turbines were affected in this text by a proposed limit value on NOx emissions of 50 mg/m^3(n) at 15% O_2 or 75 mg for turbines used in cogeneration.

The Decree of July 25, 1997 concerns the MCP installation , i.e. all plants covered under heading 2910, mainly boilers, turbines and combustion engines, as well as certain other equipment such as reheating, firing, drying and heat treatment furnaces. Specific sectorial decrees apply to certain industrial sectors, like the glassmaking industry and cement works. The provisions of these decrees are applicable to new plants as of January 1st, 1998, and to existing plants, by stages through to January 1st, 2005. The text stipulates the requirements governing plant design, location and layout, operation and maintenance, as well as the limits on discharges into the water and air.

The limit emission values are set by type of equipment; table 7 lists those values for gas. Theoretically, these are actual values that must not be exceeded. More restrictive values are foreseen for conurbations of more than 250,000 inhabitants, that will concern mainly dust and sulfur oxides, so they will not affect gas-fired plants.

equipment type	nitrogen oxides NO_2 mg/m^3(n)		sulfur oxides SO_2 mg/m^3(n)	dust mg/m^3(n)	CO mg/m^3(n)
	$P < 10$ MW	$P \geq 10$ MW			
boiler	150 at 3% O_2	100 at 3% O_2	35 at 3% O_2	5 at 3% O_2	
turbine	150 at 15% O_2			15 at 15% O_2	100 at 15% O_2
engine	350 at 8% O_2			50 at 5% O_2	800 at 5% O_2
furnace	400 at 3% O_2				

Table 7 : Pollutant emission limits settled by the Decree of July 25, 1997

Some transitional measures are yet precised. For fire-tube boilers, or when more than 50% of the plant's heat input is supplied by fire-tube generators, the limit value for nitrogen oxides emission is set at 150 mg/m^3(n), whatever the heat input. For engines, the nitrogen oxides emission value is set at 500 mg/m^3(n) at 5% O_2 through to January 1st, 2000. For furnaces, the limit threshold for NOx emissions is a target value, provided the combustion agent is preheated to 450°C. The regulatory requirement is to cut NOx emissions by 30%.

There are no regulations currently in application in France governing plants ranging between 20 and 50 MW. The MCP and LCP decrees will be implemented on the basis of the local authority's decision.

For furnaces subject to authorization, a so-called "integrated" Decree was passed in 1993; it has since been rescinded and another, fairly similar draft is under preparation. Nevertheless, it continues to serve as a reference text for authorization orders. It set the threshold for NOx emissions from plants at 500 $mg/m^3(n)$ and that for SOx emissions at 300 $mg/m^3(n)$, whenever the mass flowrate of those pollutants was greater than 25 kg/h; for dust, the threshold limit was set at 100 $mg/m^3(n)$ for a mass flowrate of less than 1kg/h, and at 50 $mg/m^3(n)$ otherwise.

A draft is being prepared for high-capacity turbines and engines.

In addition to the environmental measures, two draft decrees deal with energy consumption, one for 4 to 400 kW hot-water boilers and the other for 400 kW to 50 MW boilers. The latter decree would require new natural gas-fired boilers to achieve at least 90% efficiency at an operating range bounded by its rated heat input and a third of that value. Reductions could be achieved for thermal fluid boilers (7 points at most) and for boilers generating steam or water superheated to more than 110°C (2 points at most). For existing boilers, the threshold would be set by heat input band: in the case of gas, it would be 86% between 0.4 and 2 MW, 87% between 2 and 10 MW and 88% between 10 and 50 MW.

Finally, all plants requiring authorization are subject to indirect taxation according to the rate scale given in table 8 (set by the Decree of 12/08/97). To calculate this tax, NOxemission factors were defined for certain plants in a circular issued by the Ministry of the Environment on December 24, 1990, which was updated to cover low-NOx plants in a circular dated October 3, 1995 (45 g/GJ for gas-fired plants with a heat input of less than 50 MW and, above that capacity, 30 g/GJ).

	F/t emitted
NOx	250
non-methane hydrocarbons, solvents, VOC	250
SOx	180
HCl	180
dust	0

Table 8 : Rate scale of the french pollutant taxation

2.3.2. NOx regulations in The Netherlands

By means of the law "Besluit emissie-eisen stookinstallaties" (BEES), which controls the NO_X emission legislation in the Netherlands, the Dutch government aims to reduce unwanted acid emissions from combustion processes. The first version came into life on 29th of May 1987. After several adaptations to this law, mainly reductions of maximum NO_X emission allowance, the law was renewed in 1993. However, the old law was integrated into this new law, which is called "Wet milieubeheer" - translated "environmental protection law". This new law covers all emission legislation dealing with environmental protection.

It should be noted that the present law cover 26 pages only on NO_X and SO_X legislation. Next to that, for various major industries, there exists either "guidelines" or "agreements", which differ due to location or industrial process. On the other hand, regional authorities are allowed to introduce more stringent emission laws than given in the present law. Hence, this NO_X regulation review will only focus the major Dutch legislation, called BEES version A and B.

Most important point in BEES is the differentiation between existing and new installations. Actually, the lifetime of an installation does not play a role at all but the date of first approval by the emissions authorities.

BEES A : if the date of first approval is before 29th of May 1987 we define the installations as being an existing installation. After this date, the installation is considered to be new.

BEES B : if the date of first approval is before 1st of August 1990 we define the installations as being an existing installation. After this date, the installation is considered to be new.

Finally it should be noted that neither BEES A nor BEES B cover natural gas fired boilers with thermal inputs lower than 2.5 MW_{th}. The present discussion on the new law - to be issued in 1998 - will lower this limit to approximately 0.9 MW_{th}.

2.3.2.1. Present emission legislation for existing installations

In table 9 are the NOx emission rules shown for existing natural gas fired boilers based on BEES A and B. Table 9 uses the following abbreviations and notes :

f.i. = first issued

b.r. = burner retrofit

(1) Factor for different gas quality may be applied for installations up to NOx emissions of 350mg/m^3(n).

(2) Factors for different gas quality and for combustion air preheating may be applied for installations up to NOx emissions of 350mg/m^3(n). If applicable and if present, installations with local fuel generation may apply correction factors up to NOx emissions of 500mg/m^3(n).

(3) Factor for different gas quality and combustion air preheat may be applied for installations up to NOx emissions of 350 mg/m^3(n), for example after burner retrofitting.

BEES A		
Installation	NOx emission legislation	[mg/m^3(n) at 3% O_2]
heating equipment, natural gas-fired < 7.5 MW_{th} for steam and hot water pressure < 1Mpa, without combustion air preheat	500 175 150	(f.i. 01/01/89) (b.r. after 15/09/91) (b.r. after 15/10/92, before 01/01/98) (1)
other boilers in the process industry	500 500 150	(f.i. 01/01/89) (b.r. after 15/09/91) (b.r. after 15/10/92, before 01/01/98) (2)
other boilers NOT in the process industry	500 500 150	(f.i. 01/01/89) (b.r. after 15/09/91) (b.r. after 15/10/92, before 01/01/98) (3)
BEES B		
heating equipment, natural gas-fired < 7.5 MW_{th} for steam and hot water pressure < 1Mpa, without combustion air preheat	175 150	(b.r. after 01/08/90) (b.r. after 15/10/92, before 01/01/98) (1)
other boilers	500 150	(f.i. 15/10/92) (b.r. after 15/10/92, before 01/01/98) (2)

Table 9 : BEES A and B for existing installations

2.3.2.2. Present emission legislation for new installations

In table 10 are the NOx emission rules shown for new natural gas fired boilers subsequently based on BEES A and B with the following abbreviations :

b.r. = burner retrofit

(1) Factor for different gas quality and combustion air preheat may be applied for installations up to NOx emissions of 350mg/m^3(n), for example after burner retrofitting.

NEW INSTALLATIONS	
Installation	NOx emission legislation [mg/m^3(n) at 3% O_2]
heating equipment, natural gas-fired > 10 MW_{th} for steam and hot water pressure < 1Mpa, without combustion air preheat	150 100 (b.r. after 01/01/97) (1)
other boilers in the process industry	150
other boilers NOT in the process industry	150

Table 10 : BEES A and B for new installations

2.3.2.3. Future emission legislation for new installations

The Minister of Environment recently announced that the present legislation is reviewed and will be updated in short course. This update will include lower NOx emission rules. It should be noted that the following paragraphs are based on recent publications by Dutch industry foundations and are NOT yet issued by the Dutch government and thus are NOT yet future laws of the Netherlands and still due to major changes.

However, it is believed that the most important changes with respect to existing gas-fired boilers are :
- The power limit to include installations into BEES will be lowered from 2.5 MW_{th} down to 0.9 MW_{th}.
- From 1st of January 1998 all as-fired boilers have to fulfil the limit of 150 mg/m^3 (n) at 3% O_2.
- NO_x emission standards are decreased for existing installations down to 70mg/m^3(n) when burner retrofit takes place after 1st of January 1998. This decrease is effective for boilers ranging from 2.5 MW_{th} to 10 MW_{th}. Installations above 10 MW_{th} will be addressed in future updates and may still emit 150 mg/m^3(n).

The future NOx emission rules for natural gas fired boilers installations in the Netherlands are shown in table 11 which uses the following abbreviations and notes :

b.r. = burner retrofit

(1) Factor for different gas quality and combustion air preheat may be applied for installations, for example after burner retrofitting.

FUTURE NOx EMISSION LEGISLATION	
Installation	NOx emission legislation [mg/m^3 (n) at 3% O_2]
heating equipment, natural gas-fired > 10 MW_{th}	150
for steam and hot water 2.5 < P < 10 MW_{th}	75 (b.r. after 01/01/98) (1)
new boilers 0.9 < P < 10 MW_{th}	75
other boilers in the process industry	100

Table 11 : Forthcoming NOx regulations for natural gas fired installations

The most important conclusion from this update is that every gas-fired boiler above a thermal input of 2.5 MW_{th} has to fulfil the NOx emission legislation of 150 mg/m^3(n) at 3% O_2. If burner retrofit takes place after 1st of January 1998 the installation has to fulfil NOx emissions at maximum limits of 70 mg/m^3(n) at 3% O_2.

Still BEES will keep the possibilities to apply correction factors to the above mentioned future emission rules. These correction factors are due to either different gas qualities and/or combustion air preheating.

2.3.3. NOx regulations in Denmark

For industries except heat and power plants, the NOx emission limit of 500 mg/m^3(n) is in force when the mass flow of NOx is more than 5 000 mg/h.

Stationary engines and turbines are regulated according to the following limits. More stringent limits have been proposed in April 1998 as indicated in table .

Emission Limits	New plants (proposed)			Existing plants	
	NOx	UHC	CO	NOx	CO
Engines	550	1.500*	500*	650*	650*
Turbines < 50 MW$_{(th)}$	200	-	150	650*	650*
Turbines > 50 MW$_{(th)}$	75$^{1)}$	-	150$^{1)}$	650$^{1)}$	650$^{1)}$
Turbines > 100 MW$_{(th)}$	50$^{1)}$	-	150$^{1)}$	650$^{1)}$	650$^{1)}$

Table 12 : Engines and turbines NOx regulation in Denmark

Notes:

*)Limits apply to 30% power efficiency.
The units are mg/m^3(n), 5% O_2, dry, except 1)
1) mg/m^3(n), 15% O_2, dry
NOx are calculated as NO_2

Correction for efficiency higher than 30% is based on proportionality in the following way:

$$\textit{Actual limit} = 650 \cdot \textit{actual efficiency} / 30 \qquad [mg/m^3\,(n)\text{ at }5\%\ O_2]$$

2.3.4. NOx regulation in Sweden

The total Swedish emissions of sulfurdioxide and nitrogen oxides must according to international agreements be reduced according to the following table 13.

The decrease in total NOx emissions in Sweden since 1980 can be seen in the figure 12 below.

The limits concerning nitrogen oxides emissions are set individually for each separate plant in the operation permit for the plant. Individual limits can be at a lower level than outlined by general rules due to local environmental circumstances. A common limit for new installations (boilers) is 60 mg NOx/MJ and 100 mg NOx/MJ for boilers that are converted to natural gas.

Swedish guidelines for nitrogen oxides limits are presented in table 14. All limits are mean values during the year and presented as the sum of nitrogen monoxide and nitrogen dioxide calculated as NO_2.

	Emission 1980 in kt	Limit year		
		1998 kt	2000 kt	2003 kt
SO_2 all emissions	507		100	
SO_2, plants built before 1987 > 50 MW	112	45		34
NO_2, plants built before1987 > 50 MW	31	19		

Table 13: Swedish limits for SO_2 and NOx emissions

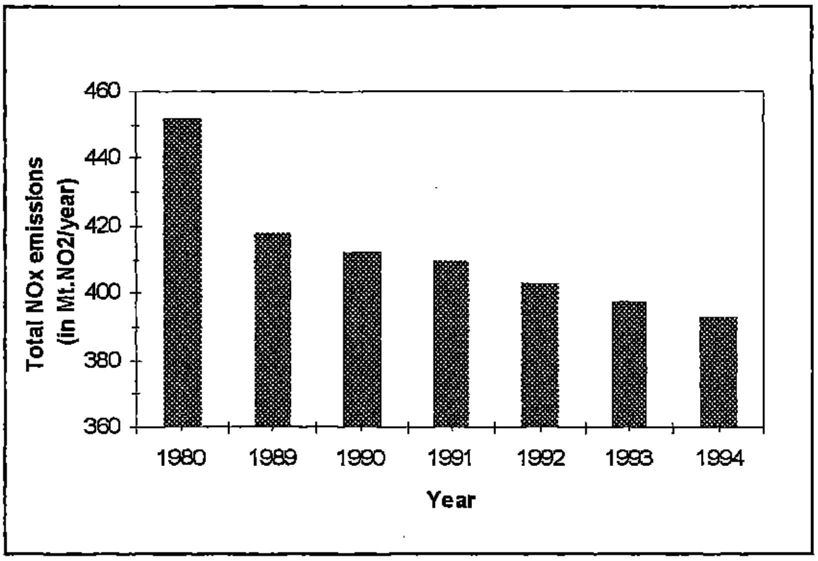


Figure 12 : Decrease in Swedish NOx emissions since 1980

The guidelines for limits within the EC for plants exceeding 50 MW thermal input (see table 6) are used as a complement to the limits in table 14. These limits are valid also in Sweden but are not as strict as the Swedish regulations. It should be noted that the EC-values are calculated on a monthly basis whereas the Swedish values are calculated on a yearly basis.

Plant type	NO_X mg NO_2/MJ fuel yearly mean value
New plants Plants with emissions < 300 t NO_2/year	100 - 200
Plants with emissions > 300 t NO_2/year	50 - 100
Coal fired plants < 500 MW	50
Plants > 500 MW	300
Existing plants Plants with emission < 600 t NO_2/year	100 - 200
Plants with emissions > 600 t NO_2/year	50 - 100

Table 14 : Swedish limit guidelines for NOx

Moreover, the fee for nitrogen oxides emissions is 40 SEK/kg NO_2 (4,8 ECU) and applies to all fuels. The fee is payed by owners of boilers, gas engines and gas turbines producing more than 25 GWh/year.

The amount of nitrogen oxides is normally monitored at larger plants. At smaller plants there is a possibility of paying the nitrogen oxides fee according to a general emission level of 250 mgNO_2/MJ fuel.

The NOx fee system is a "zero system" i e the fees are redistributed to the plants covered by the system in accordance to the amount of energy produced. This results in a system where the plants producing less than the average will get a refund larger than the fee that has been payed by the plant and the plants with nitrogen oxides emissions higher than average will have to pay more than they get out of the system. The development of the specific NOx emissions since 1992, when the system went into operation, is presented in the figure 13 below.

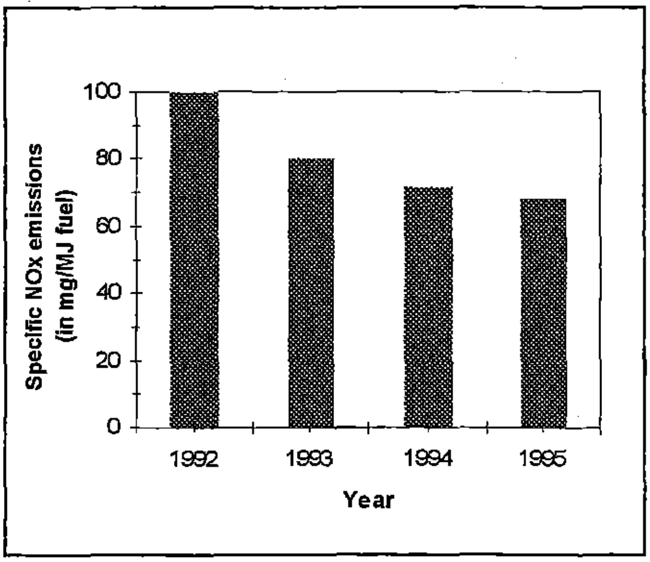


Figure 13 : Decrease in specific NOx emissions from boilers covered by the Swedish NOx -fee system

3. CHOICE OF THE SITES

3.1. CRITERIA OF CHOICE

3.1.1. Efficiency and NOx

Unfortunately, the physical process of combining stable combustion, low excess air levels and low NOx emissions is difficult to realise. Presently there are methods established in which the realisation of one of the measures does not lead to unacceptable problems introducing a combination of all goals : modern burners incorporate high efficiency with moderate NOx emissions.

The widest used technique to increase the efficiency of heating equipment is based on the recuperation of the energy of the combustion products. One solution is to preheat the combustion air through a heat exchanger called « recuperator » ; another one consists of a regenerative system using a pair of regenerators coupled with burners. These two solutions lead to the increase of the combustion efficiency and indirectly the process efficiency which are defined by the following formula :

$$\textit{combustion efficiency} = 1 - \frac{\textit{combustion product losses}}{\textit{energy due to the gas}}$$

$$\textit{process efficiency} = \frac{\textit{energy transfered to the load}}{\textit{energy due to the gas}}$$

Depending on the process itself, the energy of the combustion products could also be used directly in the process in order to preheat the load. For example, economiser are often installed in steam boilers to preheat the water.

The combustion air preheat temperature is however of large influence to the production of NOx. This temperature 'guides' the flame temperature. Combustion air temperatures of 300°C result in flame temperature around 100°C higher than compared to flames based on cold combustion air of 30°C. At 400°C combustion air temperature, the flame temperature rises by 200°C. Thus, the advantage of combustion air preheating lays in the higher efficiency of the heat transfer process but, unfortunately, this is directly coupled to increased NOx emissions. That's why the NOx reduction techniques (see paragraphe 3.4) have to be especially efficient when preheated combustion air is used.

Only recently advanced combustion systems incorporating both high efficiency and low NOx emissions become subject of laboratory research. Pratical demonstration of these promising technologies is foreseen not before the years 2000-2005.

3.1.2. Choice criteria of the tested sites

Two major objectives were chosen to allow a good representation of industrial installations for the present study :

1. Date of first operation and/or burner retrofit (not older than 1st of January 1990) to draw a picture of modern heating equipement, and if possible to point out the best available technologies

2. Installations from almost every industrial sector.

The first and foremost important objective will allow to give a clear indication how modern burner design and NOx reduction techniques are applied in industry. The second objective, which is of minor importance for boiler and engine sites, will allow for an analysis of different industrial sectors and their NOx emission standards.

For the industrial processes, the selection of the sites focused on industrial sectors where no complete data were available even in the gas companies, such as low temperature processes or low firing rate processes. It was clearly decided not to investigate the glass melting processes for which the glass manufacturers have already wide information.

For the engines, the choice was done in order to be representative of the gas engines market in Europe.

The last criterium of selection was, of course the agreement, of the industrialists.

3.2. LIST OF SITES

In totally, tests have been performed at 35 industrial sites. Three kinds of industrial equipment were concerned : boilers (either hot water or steam boilers), engines and turbines (relevant of the European market) and finally industrial processes.

The advantage of conducting such a campaign in different European countries was to find a broader variety of industrial installations and more advanced techniques in use than in a single country due in particular to economical or regulation factors which are very different from a country to another as presented above. Each Partner has chosen sites focusing in each country on the newest equipment or on the Best Available Technologies which are presented below (see « NOx emissions reduction techniques » paragraph 3.4).

For confidentiality reason, the details of each industrial sites concerned by the project are not given in this report as it was agreed by the European Commission in the contract.

3.2.1. Boiler sites

In Europe, a large fraction of the total natural gas consumption is fired in boilers. Industry, as a major client of the gas companies is demanding ca. 50% of the natural gas for use in boilers, whereas the domestic market is almost totally ruled by small scale boilers for heating and hot-water installations. Steam, hot and warm water are final products generated by industrial boiler utilities. In domestic appliances only hot and warm water is produced. Ventilator-driven burners for industrial boilers are in most cases mounted to either two-pass boilers with reversing flame or three-pass boilers. 30% of market shares in the segment boilers up to 2MW thermal input are designed as two-pass boilers with reversing flame. The internal flow of this boiler-principle is known to be critical when NOx emissions should be reduced. However two-pass boilers with reversing flame are known to be very compact, simple and cheap. Therefore present research focuses on the development of retrofit burners for this class of boilers.

The table 15 below gives the list of the 13 boilers sites on which tests have been performed during this project.

boiler site number	purpose	boiler type	thermal input (MW)	NOx reduction technique	control system
1	warm water for cleaning	two-path	1.3	air staging	modulating
2	heating of green houses	three-path	2.3	internal flue gas recirculation	modulating, two speed
3	heating of buildings	two-path	2.4	external flue gas recirculation	modulating
4	steam for sterilisation	two-path	2.5	gas staging	modulating
5	steam production	three-path	3.0	gas staging	modulating
6	heating of green houses	three-path	1.8	gas staging	modulating, two speed
7	heating of building	three-path	1.2	internal flue gas recirculation	modulating
8	steam for food processing	three-path	31.0	internal flue gas recirculation	modulating
9	heating of green houses	three-path	10.9	internal flue gas recirculation	modulating
10	steam production for textiles and wall paper from glass fiber	three-path	10.5	internal flue gas recirculation	modulating
11	steam production for chemical processes	three-path	10.5	internal flue gas recirculation	modulating
12	heating of green houses	two-path	2.2	internal flue gas recirculation	modulating
13	steam for electricity production	water tube	130.0	combination of gas and air staging	modulating

Table 15 : Boiler sites summary

3.2.2. Engine and turbine sites

Most of the engines sites are located in Denmark where, in recent years, a comprehensive installation of gas-engine based cogeneration plants has been accomplished. At present, approximately 720 MW_e natural-gas engine-based cogeneration has been installed. The population is the result of government support, and it illustrates the potential of cogeneration as a mean of reducing the CO_2 emission in Europe. More than 95% of the engine-based power commissioned is based on lean-burn spark ignition engines (see paragraphe 3.4). Only lean-burn gas engines are analysed in this project. 65% of the power of the lean-burn gas engines is based on prechamber engines as presented figure 14. Prechamber engines are most common for large engines - open chamber for smaller units.

The large population of danish engines is in the range from 0.5 - 5 MW_e that is not representative of the engines installed in Europe. That's why, in addition, three other engines with a higher and lower electrical output was tested in France and Sweden. In total, measurements have been performed on 9 engines sites.

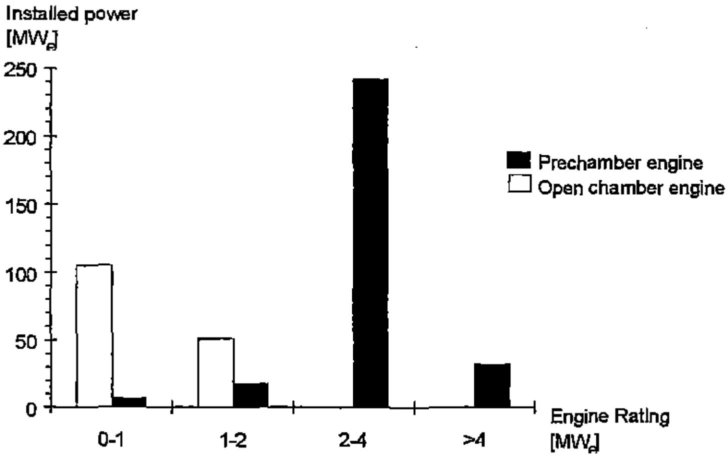


Figure 14 : Installed power of lean-burn gas engines in Denmark

These engines have been installed over few years and most of them are less than five years old, as the evolution of the engines market (see figure 15).

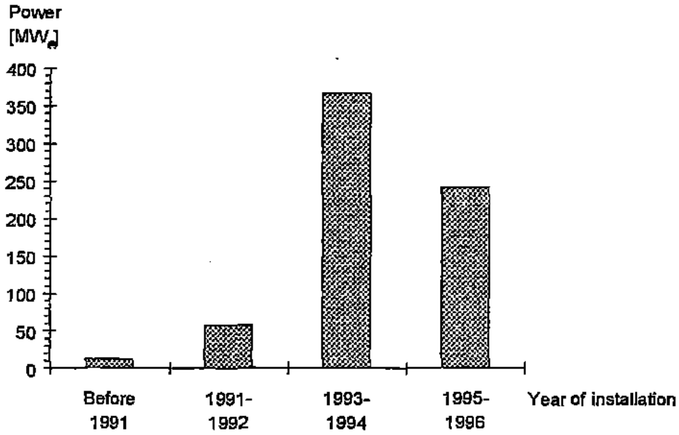


Figure 15 : Year of installation of lean-burn gas engines in Denmark

A significant development has taken place between the "older" and the modern engines in Denmark, although the installation of gas engines in Denmark has been carried out within only a few years.

Nine engine manufacturers dominate the European market as it is presented figure 16 through the Danish figures. Those manufacturers cover more than 90% of the installed power.

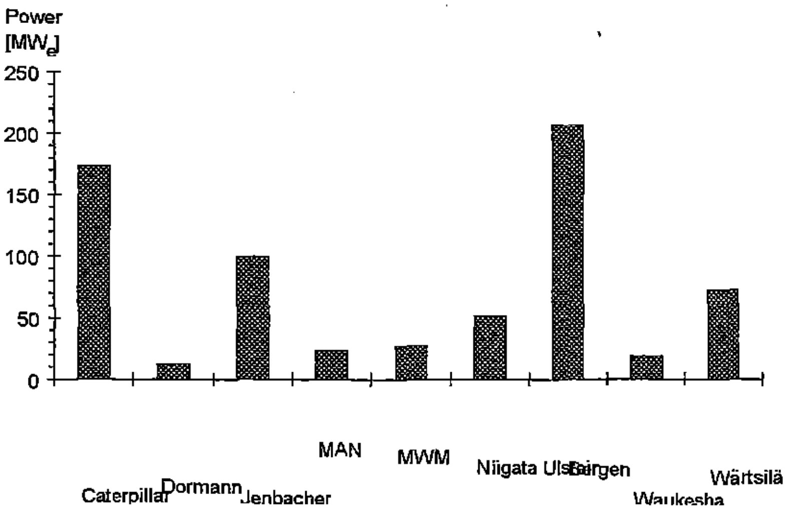


Figure 16 : Installed power of lean-burn gas engines in Denmark

3.2.3. Industrial process sites

Tests have been performed on 11 industrial processes in the following industrial sectors :

- Food processing industry : direct gas fired drier, direct gas spray drier,
- Ceramics : different types of kilns,
- Metallurgy : different types of heat treatment (reheating or melting),
- Paper/Textile : infrared surface treatment, direct gas fired textile drier.

It is clear that the number of selected sites is very small in regard with the large variety of the industrial processes. Attention should be drawn on that fact for the exploitation of the results. When it was the case (and possible during the test period), the different operating conditions of a same installation have been investigated.

Table 16 shortly presents the main features of each industrial process site.

process site number	industrial sector	type of process	production rate	process temperature	combustion air temperature	gas total rating (MW)	number of burners	date of installation
1	metallurgy	heat treatment	4 t	600°C to 1150°C	300°C to 600°C	0.45	9	1996
2	metallurgy	reheating prior to forming	17.6 t/h	1280°C	> 1000°C	2.4	2 pairs	1995
3	metallurgy	aluminium melting	2.5t/h	1100°C	> 1000°C	3.5	1 pair	1995
4	food processing	milk spray tower drier	3.6t/h	200°C	25°C	4.4	1	1993
5	paper	radiant panels	466m/mn	< 80°C	25 °C	0.43	3 x 22	1995
6	ceramic	drying and baking of tiles	46 000 tiles /day	1100°C	25°C	5.40	26 jet and 49 Fleuret burners	1996
7	ceramic	drying and baking of bricks	530 000 bricks / day	980 °C	25°C	14.8	36 jet and 200 fleuret burners	1995
8	textile	heating and drying	12 tà 14 m/mn	180°C	25°C	1.3	4	1992
9	food processing	alfafa drying	4t/h dehydrated product	120°C	25°C	14.0	1	1992
10	textile	heating and drying	32 m/mn	190°C	25°C	2.6	8	1994
11	metallurgy	reheating	180 t/h	1220°C	400°C	96.0	112 (5 types)	1993

Table 16 : Industrial process sites summary

3.3. NOx FORMATION IN NATURAL GAS FLAMES

Natural gas is a particularly advantageous fossil fuel from the viewpoint of environmental protection. Not only does it contain no sulfur, but its combustion generates neither dust nor unburned residues. Furthermore, carbon monoxide (CO) production is well controlled today and, apart from certain specific cases, there is no CO emission from natural gas-fired equipment. The main concern as regards natural gas is thus nitrogen oxide production.

Nitrogen oxides are formed during natural gas combustion, through a complex chemical mechanism involving the molecular nitrogen and oxygen in the air. Such pollutants, grouped together as NOx, consist primarily of:

- Nitric oxide NO,
- Nitrogen peroxide (or nitrogen dioxide) NO_2,

as well as smaller quantities of :

- Nitrogen protoxide N_2O

Three mechanisms for nitric oxide formation are generally accepted today (see figure 17):

- thermal NO (Zeldovich mechanisms),
- instantaneous NO or prompt NO,
- fuel NO.

The mechanisms of prompt NO and fuel NO occur in the oxidation zone, while the thermal NO mechanism occurs downstream of the flame front, in the products of combustion. Although a distinction is made between three mechanisms of nitric oxide formation in flames, the processes are closely related. Figure 14 shows that all three involve O and OH radicals, while the CX radicals appear only in the formation of prompt NO and fuel NO. This is even more significant in the case of process burners, the subject of our study, in which there are major flow and chemistry interactions.

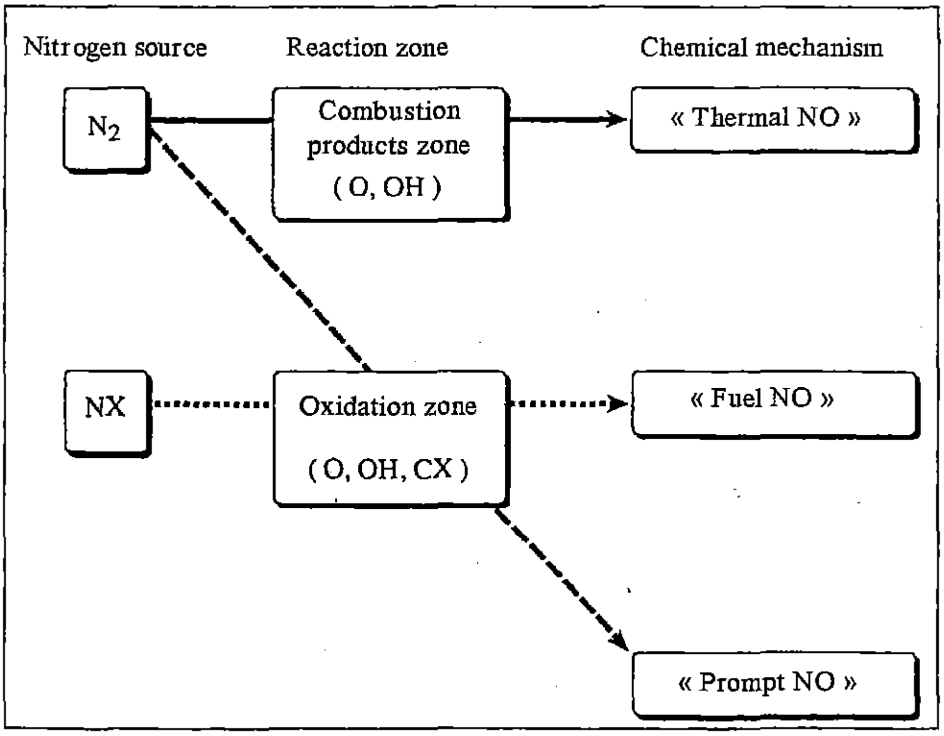


Figure 17 : Sources of nitrogen oxides in fossil fuels combustion

As natural gas contains no bonded nitrogen, the fuel NO mechanism does not occur in natural gas flames. In fact, because of the very high temperatures reached, the thermal NO mechanism is generally prevalent.

Nitrogen dioxide formation only occurs far from the combustion zone, when the NO is oxidized by oxygen during the cooling of the combustion products. As a result, the NO_2 concentration measured in natural gas flames is generally lower than that of NO. However, excessively rapid cooling of the flame may increase the amount of nitrogen dioxide, as is the case in certain processes (e.g. gas turbines).

Flame temperature is also the determining factor in nitrous oxide emission : natural gas-fired furnaces operating at high temperatures emit large amounts of NOx but very little N_2O (in the zones exceeding 1200°C, intensive destruction of N_2O occurs). As a result, the emissions from natural gas flames in process burners are mainly nitric oxide due to the thermal NO mechanism.

From a scientific point of view one can pin point a variety of influences on the production of NOx. However, the most significant correlation has to be seen in the interaction between the flame body and the NOx production rate. Consequently, basic research is focused on flame structures. One of the best studied flames is a simple Bunsen-flame and a lot of results could be transformed to discuss performance and stability criteria of concepts wherein gas, air and combustion products are mixed in heavy turbulence.

One of the results is that there is an exponential correlation between local flame temperatures and the NOx production rates. Therefore, it may be concluded that type and shape of a flame are of significant importance. The amount of flue gas recirculation into the flame front is directly depending on flow characteristics, which finally may be described in the residence time of gas pockets in the high temperature regions of a flame.

However, not only flame properties are relevant for NOx production but also the space in which a flame is fired. Boilers, for example, are characterised by the power which is fired every hour into the defined volume of the boiler. This number is defined as the firing density and given in megawatts per meter cube = $MW/m^3(n)$. Gas-fired installations are rated between 0.3 and 1.4 $MW/m^3(n)$. In practice it is shown that NOx production increases when the firing density exceeds a value of 1 $MW/m^3(n)$. On the other hand, the water temperature is of importance to the NOx production rate. In addition measurements comparing natural gases of different calorific values showed that there is little impact on the variation of NOx when changing to higher or lower calorific gases. Similar, when changing the firing rate, i.e. the installed thermal input, little changes on NOx production are measured.

To shortly conclude, the amount of NOx they emit depends primarily on three chemical influence quantities:

- flame temperature,
- oxygen concentration,
- residence time at a high temperature.

The various operating and design parameters (physical parameters) for thermal equipment could have a direct effect on these three influence quantities. This conclusions are the basis of the development of the low NOx techniques which are detailed below.

3.4. NOx EMISSIONS REDUCTION TECHNIQUES

3.4.1. Introduction

In the following paragraphs a number of burner concepts will be presented and their performances due to efficiency and NOx emissions discussed. Not every burner concept is investigated in the experimental campaign, but will be mentioned due to the objective to give an overall view to present burner development concepts. The test results will highlight the data reduction of all measurements and will briefly discuss NOx versus efficiency numbers. For industrial processes and boilers, the main principe could genrally be used for lowering NOx emissions. The case of the low NOx engines is presented separatly at the end of paragraph 3.4.

To burn natural gas in an efficient and clean flame a variety of low NOx combustion modes are known to combustion engineer. There are :

- burner control
- (internal or external) flue gas recirculation
- gas or air staging
- surface combustion (non-luminous or fully radiant)
- and partially stabilised flames.

The performances of these techniques led to burner designs capable of fulfilling NOx-emission regulations of the past years. However, present days regulations are more stringent and these techniques have to be optimised, mixed together if possible. Recent modern burner designs incorporate also other concepts such as stretched gasinjection, segmented and axial surface burners, swirl burners or burners with large bluff-bodies. In the following, all the major techniques will be briefly discussed.

For example, when carefully adopted to the boiler, most of these newer types come with NOx emissions lower than the most ambitious regulation which is 70 mg/m^3(n) at 3% oxygen in the flue). Lowering local flame temperatures to decrease NOx emissions is the most important feature of the above mentioned techniques.

3.4.2. Burner control

The operating conditions of the burners could have a large impact on NOx emissions as they modify the oxygen concentration, the combustion temperature or the residence time through the modification of the flow pattern. When possible, it is thus important to optimise the operating mode (gas input cycle) and the setting of the heating equipment (air/fuel ratio and gas input). It also works clearly towards a rationalised use of energy.

Stoichiometry is defined as the chemically correct air/fuel ratio where all the fuel and all the oxygen in the mixture will be consumed. Another way in which air/fuel ratio is represented with an excess air ratio referred to as "Lambda" (λ). Excess air ratio is determined with the following formula :

$$\lambda = \frac{\text{Operating air/fuel ratio}}{\text{Stoichiometric air/fuel ratio}}$$

$$\lambda = 1.0 \text{ at the stoichiometric air/fuel ratio}$$

It has been observed that the curve of the NOx emissions versus the air fuel ratio presents a peak just above the stoechiometry (generally between 1.1 and 1.3, depending of the burner). A solution is to avoid to settle the air-gas ratio at the maximum of this curve. For certain burners, reduction up to 50% of the NOx emissions are achievable.

3.4.3. Fluegas recirculation

Flue gas is partially recirculated into the main flame zone to quench the flame which results in lower peak flame temperatures and lower NOx emissions.

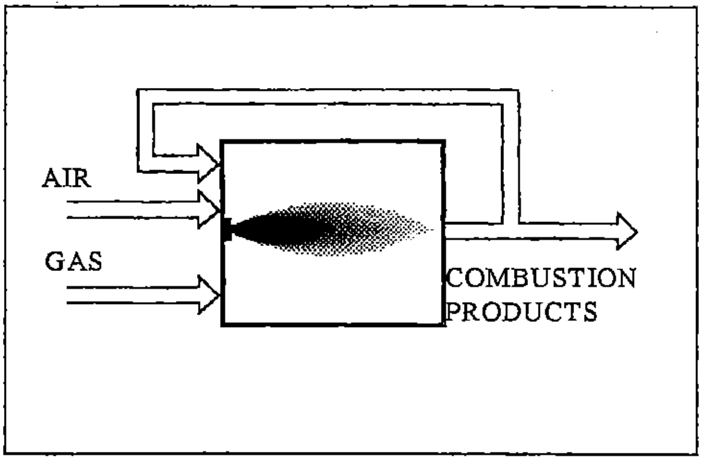


Figure 18 : Schematic of external flue gas recirculation

3.4.3.1. External flue gas recirculation

In average 15% to 20% of flue gases are recirculated into the flame zone. The flue gases are either sucked from the stack or for boilers could be sucked from the reversing chamber between second and third pass and pipelined back to the burner (external). For industrial processes, reduction of more than 30% could be achieved.

This external recirculation allow designs which fulfil the 70 mg $NOx/m^3(n)$ regulation for both the two-pass boiler with reversing flame and the three-pass boiler. Disadvantages of this technique are :

- decreased boiler power
- reduced flame stability
- condensation from flue gases.

Special attention has to be paid to the condensation problem which leads to construction out of corrosion-resistant materials.

External flue gas recirculation was one of the very first techniques to enable low NOx combustion. When looking at natural gas combustion only, there are simpler and cheaper systems available. External flue gas recirculation is still of much importance in combi-boilers where either oil and/or gas may be fired or where gas qualities are differing significantly. In addition external flue gas recirculation is sometimes chosen for installation with thermal inputs above 5 MW because investments into external flue gas ducts are of less significance to the total investments of the boiler and burner.

3.4.3.2. Internal flue gas recirculation

Internal flue gas recirculation is realised by internal flows which bring flue gases back into the flame zones and mix with the fresh gas and air before combustion occurs. Generally special burner tips are mounted to the burners to allow for these flow patterns. The major difficulty of this technique is to guarantee that enough flue gases are recirculated. Therefore internal flue gas recirculation is very often coupled to staged combustion techniques (see below). Those combinations are quite complex and lead to sensitive reactions of the combustion regime due to changes in operation.

Although this technique is able to fulfil the NOx regulations and in contrary to most other techniques very much suited for two-pass boiler with reversing flame, there is still research needed and only recently commercial burners appeared on the market showing already good performance for all the applications (boilers mainly, but also industrial processes).

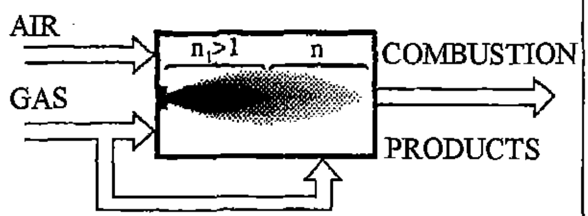
3.4.4. Staged combustion

Staged combustion is defined as the injection of gas and air such that 2 or more distinctive flame regions are created. Very often one can distinguish a primary and a secondary flame zone. Both gas staging and air staging are now available.

3.4.4.1. Staged gasinjection (gas staging)

When a.part of the natural gas is injected earlier into the combustion air, this amount of natural gas creates a primary flames which functions as a pilot burner for the second stage. In addition hot flue gases mix with combustion air, thus lowering the partial oxygen pressure, before combustion occurs in the second stage. Lowering oxygen partial pressure levels leads to lower flame temperature and decreased NOx emissions.Gas staging seems to be a very promising technique to reduce NOx emissions, in particular for boilers and keeping total efficiency at satisfying levels : NOx emissions lower than 70 mg NOx/m^3(n) were already measured for selected burners on boilers. Gas staging is relatively simple to design and thus cheap to realise. However, there are some disadvantages like :

- NO_X emission reduction in two-pass boilers with reversing flame is still not satisfying
- flame stability becomes a critical quality measure
- burner turn-down ratio is very small.



n_1 = Primary air-fuel ratio
n = Total air-fuel ratio ($n \geq 1$)

Figure 19 : Schematic of gas staging

3.4.4.2. Wide-spread gasinjection

The idea behind wide-spread gasinjection is to widen the overall flame volume (body). It is considered that this leads to lower peak-flame temperatures and hence to lower NOx emissions. The natural gas propelling the second combustion stage is injected as far as possible away from the flame stabilisation point (very often a bluff-body design). This injection strategy forms a second flame which is not attached to the first stabilised flame. Hence flue gases can recirculate and penetrate into the air/gas stream before combustion occurs. Consequently, lower NOx production rates are expected.

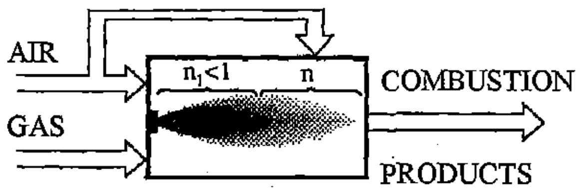
Basically, the combustion air is guided around gas injection nozzles. A perforated bluff-body is shifted to the far end of the burner tip. Primary gas injection takes place before the air penetrates through the perforated bluff-body, which guides this premixed gas/air mixture normal to the plate into the combustion chamber where ignition of this first stage takes place. The second stage is generated by a gas injection nozzles which are mounted on the bluff body. Natural gas penetrates through the combustion air into the external flow field of the combustion chamber. Due to the bluff-body flow field a region of lower pressure is generated just downstream of the first stage. Hence the flow field of the second stage is guided back towards the burner centre line is ignited by the hot flue gases of the first stage. It is believed that stabilisation of this flame is mainly done by the first stage. Some stabilisation may be expected by the mixing characteristic of the flow field just around the gas injection nozzles.

This new combustion mode makes it possible to operate under different boiler conditions with low NOx emissions. Special emphasis should be given to flame detection systems because the second stage is, by no means, stabilised by vanes, plates or bluff-bodies. In fact, the second stage just hovers in the flow field of the first stage. However, careful considerations and design of injection dimensions, directions and speed can guarantee safe combustion.

3.4.4.3. Staged air injection (air staging)

A part of the combustion air is injected far in the combustion chamber in order to creat two or more combustion zones : in the first one the combustion is sub-stoechiometric wich leads to decrease the flame temperature and the oxygen partial level so the NOx production. In the second zone, the flame temperature is kept as low as possible. A heat release between the two combustion zones is yet necessary to achieve a significant NOx emissions reduction. This technique is now widely used for low NOx process burners and the pourcentage of the air staging raise more and more (up to 80% for some advanced burners).

Although there is little theoretical evidence to disqualify air staging to reduce NOx emissions, no practical burner principal for boilers was developed in Europe in the recent years using this technique. The performances of air-staged burners do not compete with other principles. Up to now, the most important objective, NOx emissions lower than 70 mg NOx /m^3(n), is not reached. Moreover, recent tests showed that fouling in the first stage led to burner operation failures. However, further research is supported because of the easy design rules and the very stable primary flame zone.



n_1 = Primary air-fuel ratio
n = Total air-fuel ratio ($n \geq 1$)

Figure 20 : Schematic of air staging

3.4.5. Flameless oxidation technique

The flameless oxidation technique mixes air staging and intensive internal recirculation through the injection of the combustion air at extremly high speed (typically more than 100 m/s) which allow to avoid peak temperatures, even at highest air preheat temperature. The NOx emissions could be drastically reduced. It leads to an unstabilised flame achieved by specific flow and flame velocity : a stable form of combustion takes place without any visible or audible flame. For that reason it was named « flameless oxidation ».

The use of flameless oxidation is dedicated to high temperature processes (i.e. higher than 800°C) and is especially interesting if high air preheat temperatures exists. That's why burners have been developped with integrated recuperative or regenerative systems. Until now flamless oxidation has been applied with successfully mainly in gas-fired furnaces of the steel industry. The achievable NOx emissions request further research to explore other fields of usage.

3.4.6. Premixed combustion on surfaces

High excess air ratios are used to avoid burning the surfaces while fully pre-mixed gas/air mixtures generate flames at or close to the metallic or ceramic surface. In addition a relatively large surface area is needed to stabilise the flame. This large area may be obtained by guiding the gas/air mixture through a large number of small openings in the surface. Perforated metallic fibres or ceramic cylinders are generally chosen as "burners". A blue flame is generated when the flame is slightly lifted from the cylinder surface. Beginning 1990 this technique is applied to domestic appliances to reduce NOx emissions and will be limited in the future to relatively low temperature processes due to materials limitations.

When the surface mixture velocity is reduced the flame will be attached to the surface. By heating up the surface elements the surface starts to radiate. Radiation burners come with good efficiencies and low NOx emissions. However, high investment costs and narrow turn-down ratios are the major bottlenecks to speed up industrial applications. Recent research is focused on methods to increase the turn-down ratios and thus improving safety.

Gasunie Research recently developed a technique to improve the turn-down ratios from 1:3 up to 1:9. The keys to the solution are segmented surface burners which are individually controlled. The developed segmented surface burner has a nominal load of 450 kW and NOx emissions are below 70 mg/m^3(n) for all power settings.

3.4.6.1. premixed surface combustion with axial burners

A special application of pre-mixed, non-luminous, high-loaded surface burners are axial injection burners through metallic fibre structures. Depending on the perforation and the material structure deck-loads of up to 20.000 kW/m^2 may be realised. These high loads allow for small and cheap designs. Similar to standard turbulent diffusion flame burners a perforated plate may be mounted normal to the burner centre line. Hence the flame body will be developed similar to standard burners. Recent research showed that burners with a maximum thermal input of 600 kW could be realised. At 5% oxygen (by volume) in the flue NOx emissions never exceeded levels higher than 70 mg/m^3(n) for all power settings. However, emissions and efficiency of these kind of combustion systems depend highly on the accuracy of the gas/air mixture fraction. A costly sensor and controlling system is needed to bring the boiler/burner system into optimal conditions.

3.4.7. Partially stabilised flames

Partially stabilised flames are generated either by perforated bluff-bodies or by burner near-field aerodynamics which allow to distinguish separated flame structures (i.e. stabilised - non-stabilised). Recent developments showed that highly swirled gas/air flows as well as closed bluff-bodies with gas nozzle injection may guarantee a partially stabilised flame which could allow for NOx emissions below present and forthcoming regulations.

3.4.7.1. Swirl burner

In the last two decades burners using swirled combustion air to stabilise their flames are often applied to boiler operations. Second generation swirl burners apply special swirling devices which decrease the flame length and increasing the heat transfer but allow for short residence times of the combustion educts and products in the peak flame temperature zones. It may be concluded that this kind of modern swirl burners behave similar to fully pre-mixed burners. Locally high excess air number combined with strong internal flue gas recirculation lead to relatively low peak flame temperatures, which result in NOx emissions below 70 mg/m^3(n). A big advantage of swirl burners is their applicability to two-pass boilers with reversing flames. This kind of boilers are cheap and therefore often the choice of the operating companies. However, the high levels of turbulence and swirl result in high pressure drops over the burner. Strong ventilators are required and their energy consumption should be incorporated into the overall burner/boiler efficiency calculations.

3.4.7.2. Swirl burner with enlarged bluff-bodies

Recent results of the intense burner research campaigns high-lighted a new design which is characterised by a closed bluff-body and gas injection nozzles downstream of the bluff-body. A strong low pressure area keeps the flame close to the bluff body. Gas injection is similar to the principle of spreader gas injection. However, a fraction of the gas is now injected into the low pressure area to fuel a very stable primary flame. Therefore this type of burner should be seen as a synthesis of a standard bluff-body and the wide-spread gas-injection type burner. Best operations are expected when applied to three-pass boilers. A number of closed bluff-body systems at thermal inputs ranging from 3 to 4 MW have been investigated. The NOx emissions measured are far below the 70 mg NOx /m^3(n) regulation. However the emissions are very sensitive to the gas nozzle injection angle. Recently, burners based on that principle became commercially available.

The closed bluff-body with separated downstream gas injection nozzles is considered to be a promising design for future low NOx burners. Present and probably forthcoming NOx regulations may be met and most burner/boiler combinations are highly efficient. Unfortunately, applications in two-pass boilers with reversing flames are not (yet) available and more research will be needed.

3.4.8. Comparison of different concept

To allow a quick review and discussion of the burner concepts mentioned above, table 17 shows burner combustion modes for boilers and their features due to NOx emissions, efficiency and investment costs.

	Segmented surface burner	Axial surface burner	Swirl burner	Wide-spread gas injection	Closed bluff-body burner with down-stream gas injection
Boiler efficiency	constant	constant	constant	constant	constant
Turn-down ratio	high	high	limited	limited	limited
Maximum capacity	1 MW	1 MW	15 MW	15 MW	15 MW
Suited for two-pass boilers with revering flame	yes	yes	yes	no	no
Significant reduction possible below 70mg/m^3(n) NOx	yes	yes	yes	no	no
Sensible to gas/air ratio	no	yes	partial	no	no
Sensible to pressure drop	no	no	yes	partial	partial
Retrofit design	quite complex	relatively complex	complex	easy	very easy
Investment costs	high	above average	above average	average	average

Table 17 : Comparison of different burner concepts for boilers

3.4.9. Case of engines and turbines

Development of lean-burn gas engines has focused on improving efficiency and at reducing the emission of NOx. By increased excess air level and compression ratio plus other design improvements, modern lean-burn gas engines have achieved those goals. Modern lean-burn gas engines operate with an electrical efficiency of approx. 39-41% and a total efficiency of 85 - 95% (ref. to net calorific value). Another way to reduce NOx emissions from engines is to treat the combustion products on a catalitic system : That is a « secundary technique ».

3.4.9.1. Lean-burn gas engines

In the past, natural gas engines were commonly operated at an air/fuel ratio which provided the most horsepower for the amount of air being consumed. This air/fuel ratio was fuel rich of "Stoichiometry". In recent years, engines which operate at a much leaner air fuel ratio have been utilized because of their low emissions and low fuel consumption characteristics. With a lean air/fuel ratio ($\lambda > 1.0$) there is more oxygen in the combustion chamber than is required for combustion which leaves a high concentration of oxygen in the exhaust. Fuel consumption in a lean combustion engine is typically 5-12% lower than in a similar stoichiometric combustion engine.

To the rich side of stoichiometry, NOx decreases significantly due to the lack of oxygen in the combustion chamber and lower combustion temperatures. On the lean side of stoichiometry, the NOx reaches a peak because combustion temperature remains high and there is an abundance of oxygen. At increasingly lean air/fuel ratios, the combustion temperature continues to fall and NOx levels fall even though excess oxygen exists in the cylinder. As stated earlier, NOx formation requires the presence of oxygen and nitrogen in a high temperature environment, therefore less NOx is formed at lower temperatures.

Carbon Monoxide levels are also lower in a lean combustion engine than in a stoichiometric engine because there is now plenty of oxygen for the fuel molecules to react with.

Like CO emissions, NMHC emissions also are higher at points rich of stoichiometry because of the lack of oxygen for combustion. NMHC emissions are also minimum at a point slightly lean of stoichiometry and increase at further lean air/fuel ratios. The amount of NMHCS are higher at the lean combustion air/fuel ratio than at stoichiometry.

Ignition of the high air/fuel ratio in a lean combustion engine can be obtained fairly well with a high turbulence open chamber design. Utilizing a pre-chamber with a stoichiometric mixture to ignite a lean main chamber can produce better combustion at leaner air/fuel ratios.

3.4.9.2. Engines with catalytic converter

Emissions from an engine can also be reduced by chemically converting these pollutants into harmless naturally occurring compounds. The most common method for achieving this is through the use of a catalytic converter. In a catalyst converter, the catalyst will either oxidize (oxidation catalyst) a CO or fuel molecule or reduce (reduction catalyst) an NOx molecule. The general (not balanced) reducing reactions are shown below :

$$NO_x + CO \Rightarrow N_2 + CO_2$$
$$NO_x + CH_4 \Rightarrow N_2 + CO_2 + H_2O$$
$$NO_x + H_2 \Rightarrow N_2 + H_2O$$

These reactions are reducing the NOx to nitrogen and oxidizing the fuel and CO molecules. This reactions oxidize some of the CO and NMHC molecules, however further conversion is achieved with an oxidizing catalyst. The oxidizing reactions take place as shown here :

$$CO + \frac{1}{2} O_2 \Rightarrow CO_2$$
$$CH_4 + 2\ O_2 \Rightarrow CO_2 + 2\ H_2O$$
$$CnHm + O_2 \Rightarrow CO_2 + H_2O$$
$$H_2 + \frac{1}{2} O_2 \Rightarrow H_2O$$

A 3-way catalyst contains both reduction catalyst materials and oxidation catalyst materials and is able to convert NOx, CO, and NMHCS to N_2, $C0_2$, and H_20. A catalyst process which causes reactions between several pollutant components is referred to as Non Selective Catalyst Reduction (NSCR). Typically, emission conversion efficiencies for a three-way catalyst operating on a near stoichiometric engine are the followings :

90% decrease in NOx
80% decrease in CO
50% decrease in NMHC

The efficiency of a three way catalyst is highly dependent on the percentages of NOx, CO, O_2, and NMHCS in the reaction. A very narrow air/fuel ratio operating range is necessary to maintain these percentages. Electronic air/fuel ratio controls are offen necessary to maintain this range.

4. RESULTS

4.1. DESCRIPTION OF THE METHODOLOGY AND OF THE PRESENTATION OF THE RESULTS

The five Partners of the project have compared their methodology and measurements techniques to enhance the exchanges of information and results among them. It includes flue gas analysis (CO, CO_2, O_2, NOx, UHC, CH_4, N_2O, NMVOC, temperature, etc.) and combustion efficiency evaluation. The first difficulty of the project was indeed that no international standard are available for this kind of measurement (emmissions + efficiency) on a large variety of installations, in particular for the determination of the combustion efficiency and of the process efficiency. However, the Partners have been inspered by the CEN basic document CR 1404:1994 established by MARCOGAZ under the supervision of the CEN/PC3 « Gas » entitled « Determination of emissions from appliances burning gaseous fuels during type-testing ». It was agreed to keep a large freedom to the experimenter as far as it is clearly reported.

Thus a « standard » report have been defined on a EXCEL® data form to allow a comprehensive reporting for each partner. The biggest work focused on a clear definition of each information required to fill in the standard report.

It contains principally the following items (see annexe 1) :

1 - *General background on the site*

It includes the description of the installation : industrial sector concerned, technical characteristics of the furnace, the boiler or the engine, operating scenarios, gas total rating, and depending of the type of installation power density, rated electric power or production rate.

2 - *Description of the equipment*

Two sheets have been prepared, one for burners (for boilers or industrial processes), the other one for engines. They include, if available the control system of the heating equipment and the low NOx techniques identified.

3 - *Description of the measurement techniques*

In order to compensate for the lack of international standard, this part has been particularly detailed. It includes the description of flue gas analysers (CO, CO_2, O_2, NOx, CH_4, UHC, N_2O, ...), metering and pressure and temperature probes in terms of measurement principle, supplier, measurement rang and accuracy and gas calibration. It precises the position of the sampling points and the type of the sampling line.

The gas analysis are always done on dry gases. The O_2 reference has been chosen according to the regulations, i.e. 3% in the flue gases for boilers and industrial processes, 5% for engines and 15% for turbines.

4 - *Results*

The operating conditions are given before the results themselves : it contains the atmospheric data, the type of natural gas burnt during the test and the measurement period which could vary a lot from one installation to another depending on the stability of heating equipment (generally a boiler is rather stable in comparison with a industrial process which could be operated on a cycling mode). The complete flue gas analysis and the determination of combustion and process efficiency is then reported.

The three following paragraphs present the synthesis of results obtained on all 35 tested sites. The 35 EXCEL® reports are given in a confidential report annexed to this one.

4.2. BOILERS

Thirteen industrial sites, seven in the Netherlands and six in Sweden, were visited and a total number of 40 tests were carried out. Figure 21 shows the thermal input investigated for test sites 1 to 12. Site 13 is a energy producer in Sweden and possesses a total rating of 130 MW. Since all other visited sites are by order of magnitudes smaller than site 13, this report treats this large scale boiler separately.

8 sites are below 4000 kW of nominal load, 4 sites are operating at thermal input between 4000 kW and 12000 kW and site 13 at 130 MW.

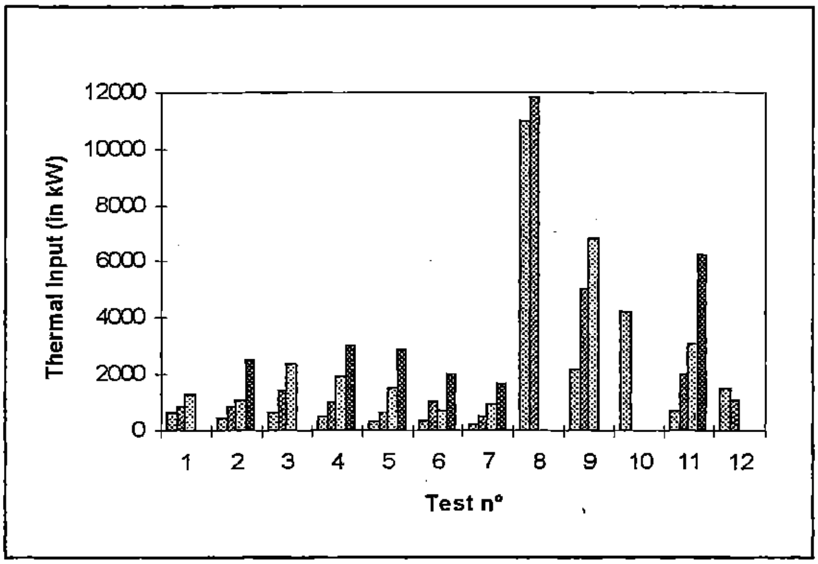


Figure 21 : Thermal inputs of sites 1 to 12

Figure 22 shows all sites and their histories in the years 1970 until 1996. The graph considers not only the date of commissioning (installation) but shows as well the date of last burner retrofit and the introduction of low NOx techniques to the boiler/burner system. More than ¾ of all investigated sites are installed or updated after 1990. Just 3 systems are older. This is in agreement with the objective to choose modern boiler/burner systems to allow some insight into present day's performance of boilers.

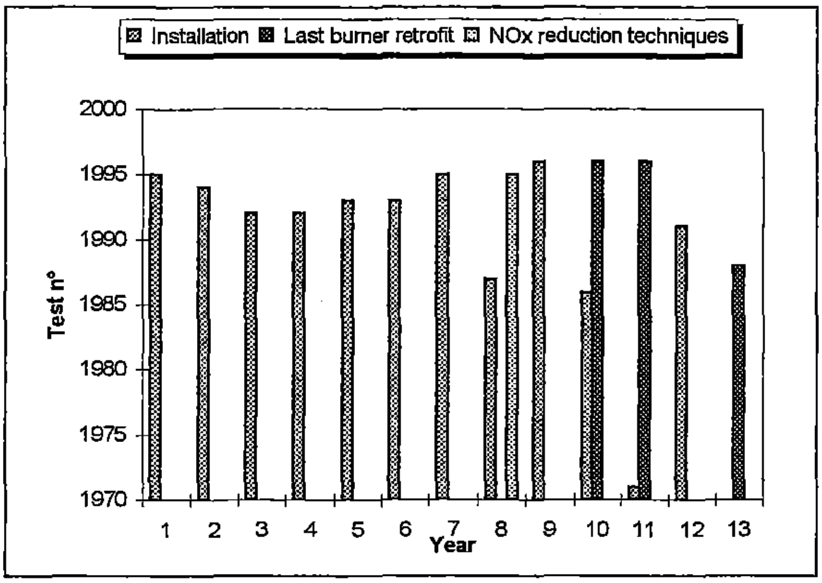


Figure 22 : Date of installation, last burner retrofit and installation of recent NOx reduction techniques versus sites

4.2.1. NOx versus efficiency

Gasunie and SGC results are given in Figure 23. It is shown that between efficiencies of 78% and 97 % there is no clear relation in NOx emission values. NOx emissions range from below 50 mg/m^3(n) up to 140 mg/m^3(n) at 3% O_2. However, a linear regression is performed on the data to highlight the average of NOx emissions versus efficiency. It should be noted that the slope of the regression curve should not be seen as an observation but rather a result by the regression. Instead, it may be concluded that the average boiler tested comes with efficiencies between 80% and 95% and an average NOx emission of 80 to 100 mg/m^3(n) at 3% O_2.

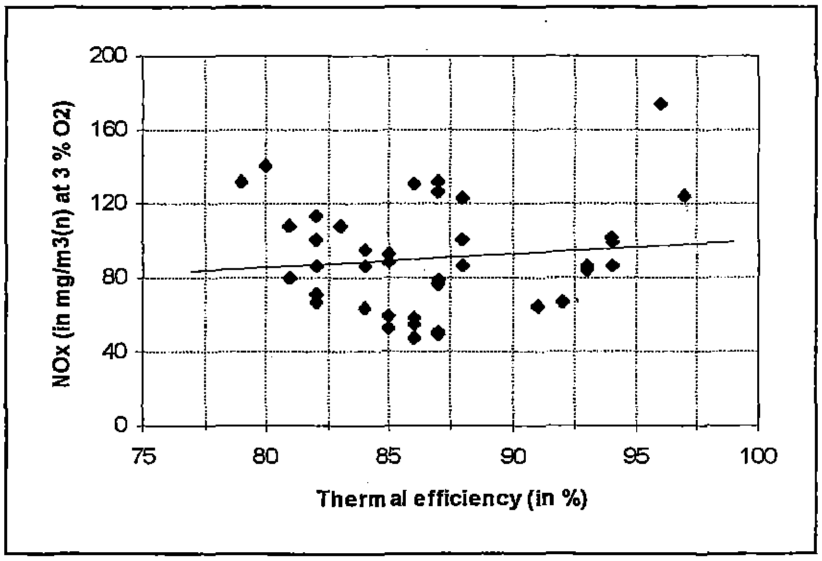


Figure 23 : NOx in mg/m^3(n) at 3% O_2 versus thermal efficiency of all sites

4.2.2. NOx versus thermal input

NOx emissions versus thermal inputs are plotted in Figure 24 for sites 1 to 12. Again, a linear regression model is used to fit the data. As expected from scaling laws, NOx emissions tend to increase with increased thermal input. A simple scaling law may be written as :

$$NOx\left[mg/m^3(n), 3\% \, O_2\right] \approx P^{1/4}$$

where excess air levels should be kept constant.

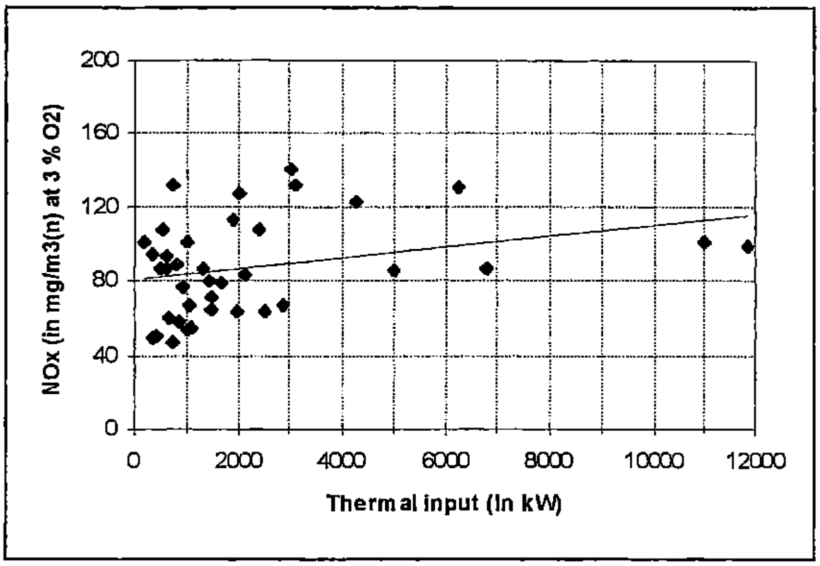


Figure 24 : NOx in mg/m^3(n) at 3% O_2 versus thermal input of sites 1 to 12

The gradient of the regression slope should not be seen as an observation, because the number of tests are too sparse. Site 13 has a thermal input of 130MW and produces NOx emissions in the range between 124 and 174 mg/m^3(n) at 3% O_2. The above scaling law calculates NOx emissions of ca. 225 mg/m^3(n) based on average NOx emissions of 80 mg/m^3(n) at 3% O_2 at thermal inputs of 2 MW. This results differs by ca. 30% from the measured value for site 13. An explanation for this difference is given in the next paragraph.

4.2.3. NOx versus excess air

Figure 25 shows the NO_X emissions in mg/m^3(n) at 3% O_2 over excess air levels during each test. The trendline is based on a linear regression of all data points. Data of site 13 are marked by connected points. It is shown that site 13, the 130MW boiler runs at very low excess air levels. This low excess air levels are the reason that the scaling law mentioned in paragraph 4.2.2 predicts to high NOx emissions when compared to NOx emissions from 2MW$_{th}$ boilers running at excess air levels of around 1.2. Unfortunately it is very difficult to find scaling criteria for the effect of excess air levels on NOx emissions. Therefore the above scaling law should be considered as a good trend, while excess air levels may account for deviations of ca. 30% to the calculated NOx emissions.

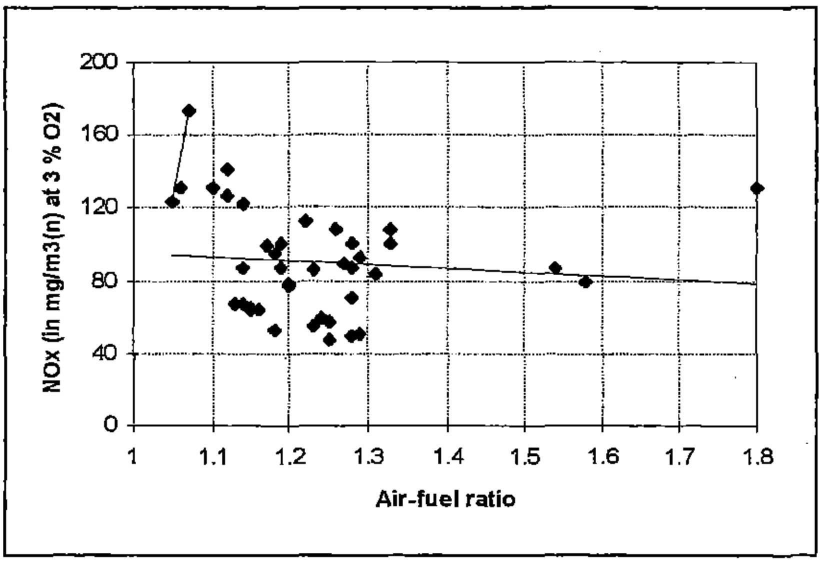


Figure 25 : NOx in mg/m³(n) at 3% O_2 versus excess air of all sites

4.2.4. NOx versus NOx reduction techniques

Two major NOx reduction techniques are applied in the total series of boiler/burner system tested according to the following breakdown :

1. Internal flue gas recirculation: 7
2. Gas staging: 3
3. Air staging: 1
4. External flue gas recirculation: 1
5. Others: 1

In the following the NOx emissions for each investigated NOx reduction techniques are discussed.

4.2.4.1. Internal flue gas recirculation

Figure 26 shows the NOx emissions of burners using internal flue gas recirculation as NOx emissions reduction technique. The NOx measurement do not exceed 100 mg/m³(n) at 3% O_2 and most of the data range in between 60 to 90 mg/m³(n) at 3% O_2. Compared to other NOx reduction techniques, internal flue gas recirculation tends to be the most promising technique to lower NOx emissions from boilers.

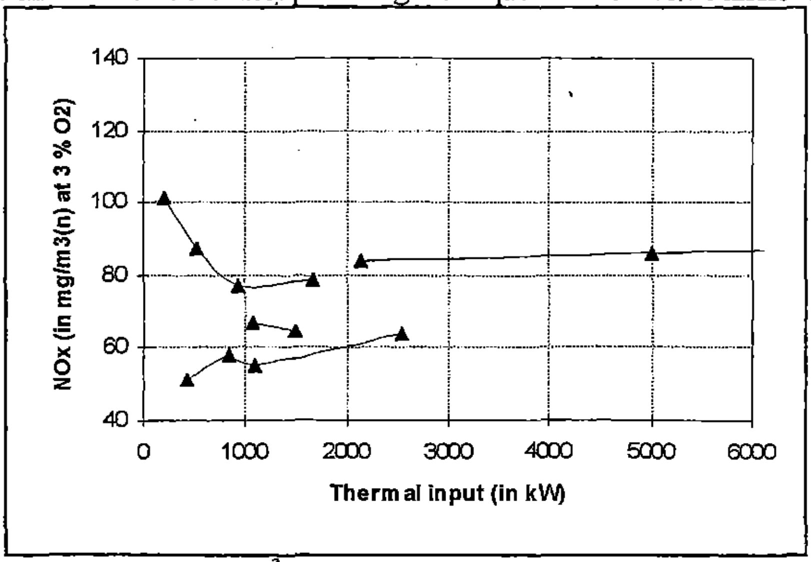


Figure 26 : NOx in mg/m³(n) at 3% O_2 versus thermal input for burners with internal flue gas recirculation

4.2.4.2. Gas staging

The second best NOx reduction techniques is gas staging. Figure 27 shows the NOx emissions of burners using gas staging as NOx reduction technique. There is only one burner/boiler system which exceeds NOx emissions higher than 100 mg/m^3(n) at 3%O_2. In average the performance may be compared to internal flue gas recirculation.

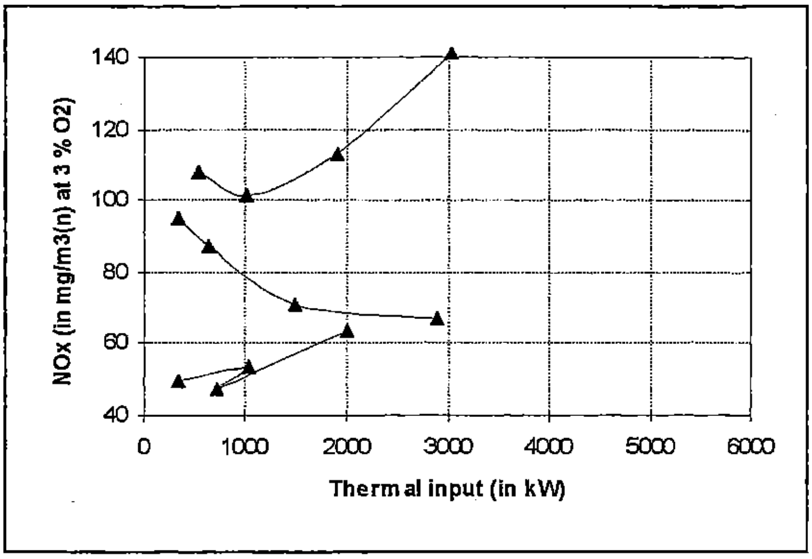


Figure 27 : NOx in mg/m^3(n) at 3% O_2 versus thermal input for burners with gas staging

4.2.4.3. Air staging and external flue gas recirculation

Two tests are done on burners using air staging as NOx reduction techniques, respectively external flue gas recirculation. Figure 28 shows that, when external flue gas recirculation is applied, NOx emissions increase with higher thermal inputs. In this test flue gas temperatures rise from 140°C to 235°C while increasing the thermal input from 650kW to 2400kW. With increasing temperature of the recirculated flue gases, flame temperatures will rise and thus NO_X emissions increase. The second test - air staging - keeps NOx emissions constant, but operates in a lower and smaller range of thermal input variations.

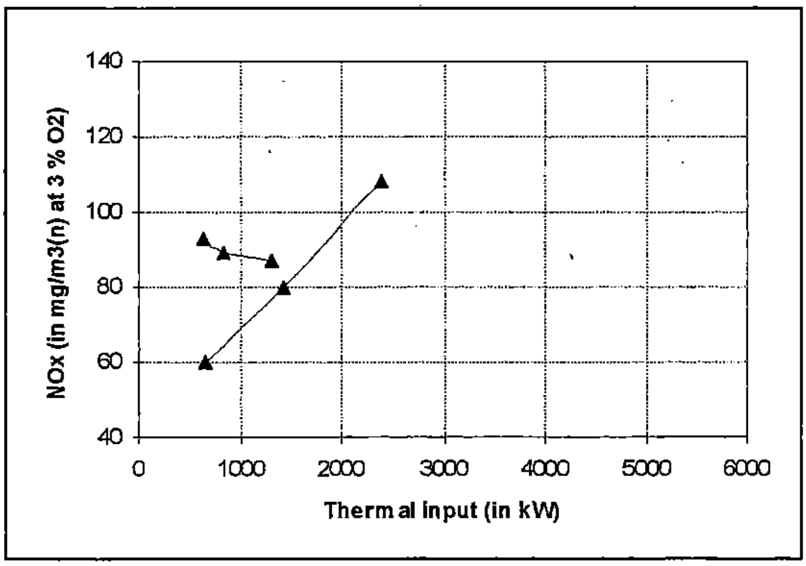


Figure 28 : NOx in mg/m^3(n) at 3% O_2 versus thermal input for burners with air staging

4.2.4.4. Other NOx reduction techniques

Figure 29 is plotted using a logarithmic scale on the axis for thermal input. The reason for this is that, except one using internal flue gas recirculation, all boiler/burner systems at thermal inputs between 4MW to 130MW fall in this category. Obviously, the above mentioned scaling law predicts higher NOx emissions for increased thermal inputs. Therefore NOx emissions always exceed 120 mg/m^3(n) at 3% O_2. From a technical point of view these "large-scale" installations are older when compared to smaller units. Hence, due to high investment costs modern NOx reduction techniques are not always implemented into "large-scale" installations.

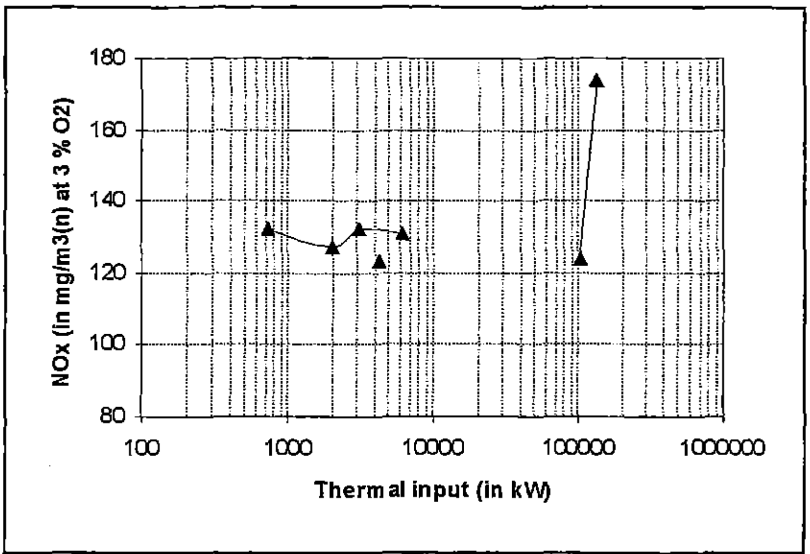


Figure 29 : NOx in mg/m^3(n) at 3% O_2 versus thermal input for burners using other NOx reduction techniques

4.3. ENGINES AND TURBINES

Danish Gas Technology Centre (DGC) has performed measurements of emission and efficiency on more than 60 gas-engine based cogeneration plants over the last 5 years. Under the present project seven engines, operating in cogeneration plants, have been selected for testing in order to complete the picture of the Danish population of engines as two other engines sites and two turbines sites in France and Sweden. The measurements include O_2, CO, NOx, UHC and efficiency. The measurements cover the dominating types of engine in Denmark. The measurements have been carried out at the manufacturer-chosen set-point of the engine.

Furthermore, to extend the analysis of the results of the present THERMIE contract, a list of cogeneration plants in Denmark and the DGC data base containing the previous measurements, forms the basis of the estimation of total emissions of UHC and NOx and of the synthesis of the results presented below.

4.3.1. Engine Efficiency versus NOx and CO Emissions

The results are shown in figure 30te which plots CO and NOx emissions versus efficiency. The electrical efficiency is found to reach 38 - 40% which is in line with the general picture of engines in particular in Denmark. The total efficiency depends on the heat recovery temperature and the heat exchangers. At low return temperature both oil cooler and intake air cooler can contribute. Some deviation from an engine to another could be due to different settings.

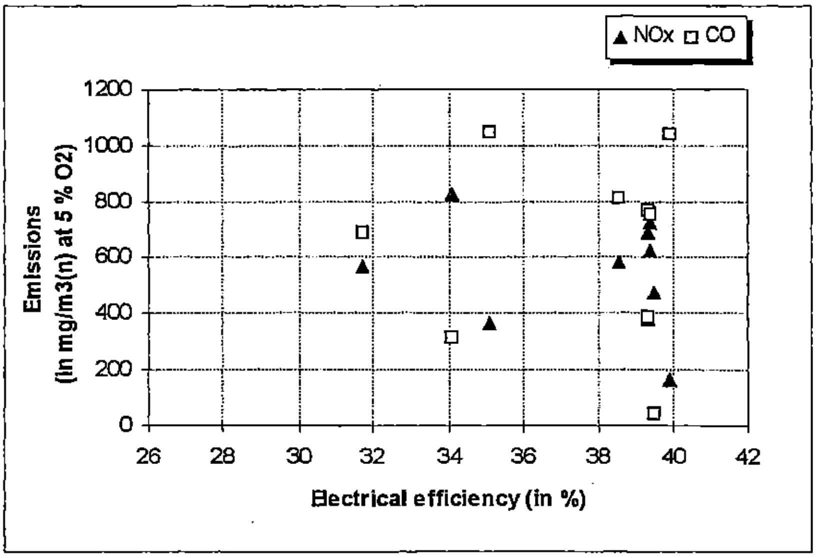


Figure 30 : Emissions versus efficiency

Development of lean-burn gas engines has focused on improving efficiency and on reducing the emissions of NOx. By increased excess air level and compression ratio plus other design improvements, modern lean-burn gas engines have achieved those goals. Modern lean-burn gas engines operate with an electrical efficiency of approx. 39-41%. The total efficiency of produced power and heat is 85 - 95% (ref. to net calorific value).

To compare these results with wider data, Table 18 presents the average electric efficiency and emission levels of the whole population of natural gas engines in Denmark, where each plant is weighted with rated power. The present emission limits and the proposed new limits are also indicated. In 1997 The Danish Environmental Protection Agency has indeed send out a revision of the emission limits for hearing, which includes a limit of UHC. The revision is planned to be in force by 1998. The engines investigated through the THERMIE contract meet current Danish legislation concerning emissions of NOx and CO.

	Unit[1)]	**Average emission from gas engines**	**Emission limits**	**Proposed emission limits (Out for hearing)**
CO	$mg/m^3(n)$	679	650[4)]	500[4)]
NO_x [2)]	$mg/m^3(n)$	618	650[4)]	550
UHC [3)]	$mg/m^3(n)$	2380	None	1500[4)]
Efficiency η_e[4)] **Efficiency, CHP**	% %	38.0 88.0		

1. Corrected to 5% O_2 dry
2. NOx = NO + NO_2, NO calculated as NO_2
3. Total unburned hydrocarbons, expressed as CH_4 equivalents
4. Using Net Calorific Value, (efficiency bonus applies to the limits)

Table 18 : Average Danish emissions (units < $25MW_e$)

The annual power production and emissions of NOx from the Danish natural gas driven engines installed as cogeneration units (< 25 MWe) is estimated as follows:

Power production :	3.15 TWh_e/yr
CHP production :	7.21 TWh/yr
NOx emissions :	6 000 t/yr (calculated as NO_2)
Relative emissions :	0.8 g NOx/kWh (relative to CHP)

In 1994 the total emissions of NOx in Denmark was estimated to 270 000 ton NOx/year.

4.3.2. Efficiency versus UHC emissions

Development of lean-burn gas engines has focused on improving efficiency and at reducing NOx emission. One of the oldest plants, from which measurements are available, was commissioned in 1989. The development has lead to significantly higher efficiency, from 33% in 1989 to above 40% for some of the newest plants.

Higher compression allows better efficiency, but also a risk of knocking. A lean mixture is more resistant to auto-ignition, and at the same time the NOx emission is reduced. This is the reason why large engines have been designed to run on ultra-lean mixtures.

However, the emission of unburned hydrocarbons is generally increasing, and to a large extent this increase in hydrocarbon emission of the newer plants seems to be a side-effect of the development.

Emission of unburned hydrocarbons (UHC) occurs from gas engines as well as from other reciprocation engines. As an example, it has been estimated that the emissions of UHC from the gas engines installed in Denmark corresponds to 3.5% of the gas consumption of these units and the total Danish emissions of UHC from the gas driven engines is estimated as follows :

Power production:	3.15 TWh_e/yr
CHP production:	7.21 TWh/yr
Methane emission:	21 000 t/yr
Relative emission:	2.9 g CH_4/kWh (relative to CHP)

Analyses of the unburned hydrocarbon have shown that the composition of UHC is similar to that of the natural gas, i.e. approximately 90% (vol.) methane. Methane is a strong greenhouse gas, and emission of UHC thus causes a reduction in the CO_2 reduction benefit obtained by cogeneration and the use of natural gas.

The engine design has a very significant influence on the emission of UHC. The excess air ratio and ignition system (open chamber / prechamber) have been found to be the factor of major influence on the emission of unburned hydrocarbons. Moreover, the difference of UHC-emission between engine types exceeds the difference obtainable by usual adjustments of the set-point of the commercial engines.

Open chamber engines have the spark plugs located in the main combustion chamber and have a high-energy ignition. Open chamber engines are running on mixtures with excess air ratio up to 1.8.

Prechambers are used on large engines running on an ultra-lean mixture with excess air ratio above 2.0. A small volume of fuel rich mixture is ignited in the prechamber. It "shoots" into the main combustion chamber as an ignition jet and ignites the lean mixture.

Emissions data from representative Danish gas-fired engines have been analyzed and the data show that engines with ignition chamber have a significantly higher emission of unburned hydrocarbon than open-chamber engines. The two types of engines can be characterized as follows in table 19 :

Type of Engine	Open-chamber	Ignition-chamber
Rated Power (MW)	0.5 - 2	2 - 5
O_2 in flue gas (% Dry)	8 - 10	11 - 13
Efficiency (η_e %)	37 - 39	38 - 41
UHC (% of fuel input)	1 - 2	3 - 6

Table 19 : Comparison between open chamber and ignition chamber engines

4.3.3. Engine with catalysts

The effect of most catalysts, as seen in figure 31nde, is a more or less pronounced reduction in carbon monoxide emission ranging from zero to 100% in efficiency of CO reduction.

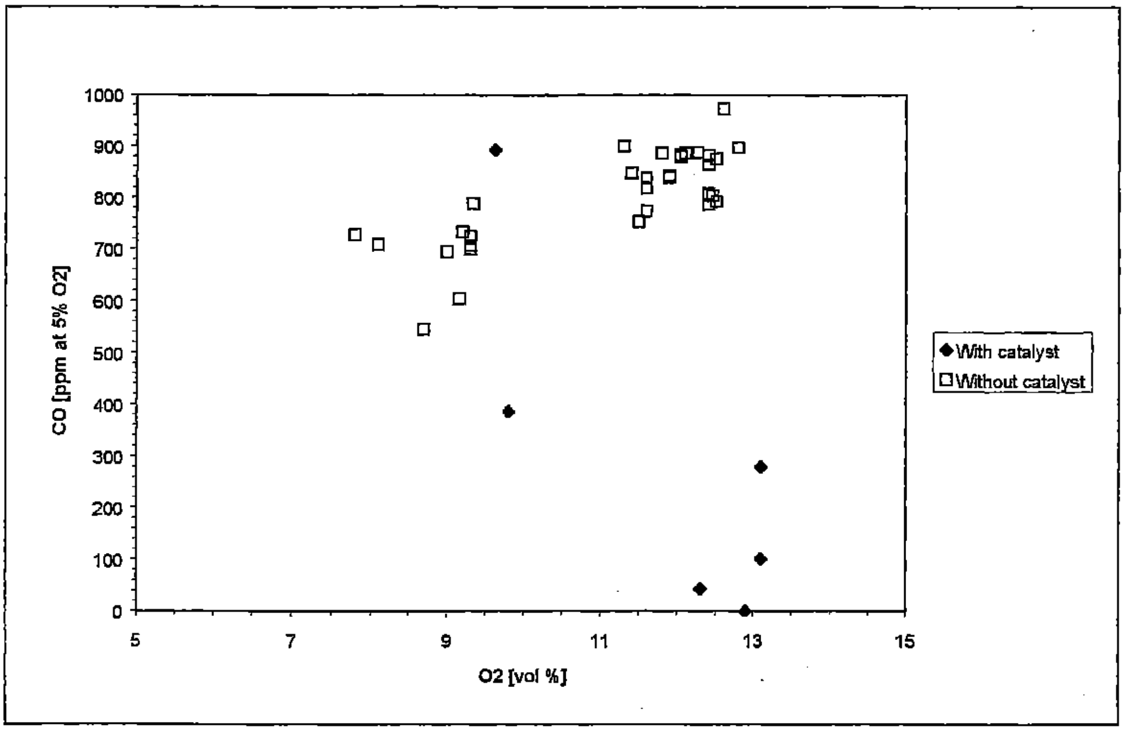


Figure 31 : The effect of catalysts on carbon monoxide emission

With one exception, the black dots are well below the general tendency.

4.3.4. Other emissions

4.3.4.1. Odour emission

Odour emission is a problem for several cogeneration plants. The majorities of cogeneration engines have been installed in district heating plants where they have replaced oil-fired and gas-fired boilers. The plants are typically located in urban areas sensitive to exhaust odour.

The situation in Denmark is, that a number of cogeneration plants have received notice from the authorities to present a plan for odour emission reduction. Different techniques are under consideration, including increased chimney height, treatment by ozone, installation of an oxidation catalyst or a regenerative incinerator.

4.3.4.2. Odour Emission Limits

It can be very difficult to avoid odour emissions from natural or industrial products since the species causing the odour in most cases will be unknown and often present in small amounts. It may in many cases prove impossible to find the species responsible for the odour.

Because it is practically impossible to find the responsible species, the limitation for odour emissions is connected directly to the human sense of odour. The Danish Environmental Protection Agency recommends that the immissions of odour should be less than 5-10 odour units (OU) in urban areas. Based on the test panel measurement of the number of OU in the exhaust sample and the use of a meteorological dispersion model, it is possible to predict the statistical dilution factors in the exposed area.

No standard method for odour sampling and quantification from engine exhaust has been found in the literature. Standardisation work is ongoing, and a proposal is expected in 1997 concerning sampling, sample handling, and the olfactometric method, but not specifically on exhaust gas sampling.

4.3.4.3. Carbonyl Compounds

Significant amounts of particularly formaldehyde and acetaldehyde must be expected to be present in the engine exhaust. Levels of approximately 30 mg/m^3(n) of formaldehyde and 5 mg/m^3(n) of acetaldehyde have been detected with large variations.

The relative high emissions of formaldehyde and acetaldehyde are a matter of concern, since the species may present a health risk.

Two standard methods exist for measurement of carbonyl compounds from combustion systems: The CARB 430 method and the EPA method 530. Both methods consider measurements from stationary combustion sources, and both methods utilise sample extraction by use of an isokinetic probe (quartz/teflon), a heated sample line, collection of samples in impingers, two or three in series, cooled in an ice bath.

With the present knowledge on odour threshold limits, the aldehyde emissions cannot explain the high levels of odour observed from some engines.

4.3.5. Results on turbines

Three turbines, of which two were of the same type and connected to a common stack have been characterised. The results are summarized in table 20.

	Unit[1)]	Two identical turbines	third turbine
CO	mg/nm^3	6	49
NOx [2)]	mg/nm^3	245	55
Heat supply temperature	°C	136-157	103-82
Efficiency η_e[3)]	%	29.2	32.1
Efficiency, CHP	%	78.6	87.7

1. Corrected to 15% O_2 dry
2. NOx = NO + NO_2, NO calculated as NO_2
3. Using Net Calorific Value

Table 20 : Turbines emissions and efficiency

The two identical turbines produce 9.4 MW$_e$ each and the third one produces 21.6 MW$_e$. This last one was deeply investigated in 1993, but the results have been confirmed during a shorter measurement campaign in 1997 performed for this THERMIE Contract

Compared to the engines, the turbines are generally larger in rated power and the electric efficiency is somewhat lower. The total efficieny of heat and power is similar to the engines. Moreover, the heat supply temperature for the turbines is higher, and this is important in many industrial applications where steam is needed.

4.4. INDUSTRIAL PROCESSES

Eleven industrial processes have been investigated for this project. We can classify them in two parts : the low temperature processes (typically, process temperature below 750°C) and the high temperature processes (temperature above 750°C). The results are analysed for these two categories.

As it has been explained in paragraph 3, the NOx emissions are indeed completely different from low and high temperature processes : for the first group, it is expected to have low NOx emission due to low temperature flames even if the installation is not considered intrinsically low NOx ; for the second group, the high flame temperature leads to high levels of NOx.

The low temperature processes concern principally industrial sectors such as food processing, textile and paper industry. The high temperature processes are situated in the metallurgy, ceramic and glass industries. For this project, five sites belong to the low temperature processes and six are high temperature processes. When possible or necessary two or more operating conditions have been studied : so in totally 20 measurements are available.

The graphs given below are based on the experimental measurements : a regression curve has just been drawn as an indicative line and has no reality

4.4.1. NOx versus combustion air temperature

The graph figure 32 presents the emisssions of NOx versus the combustion air temperature : the NOx emissions increase clearly with the combustion air temperature.

We can observe that the combustion air preheating above 1000°C was available for one of the processes : it was a regenerative system, inspired from the regenerators of the large glass melting furnaces. Its NOx emissions are very high, as expected, but we can notice that, although it was a new installation, it uses an old traditional burner (i.e. without any reduction technique). Another point is yet remarkable : with an air preheating at around 825°C, it is achievable to have very low NOx emissions (ca 200mg/m^3(n) at 3% O_2) : this one use one of the best known technologies, i.e. flameless oxidation technique (see paragraph 3.4.5).

With old burners, we were used to observe a doubling or more of the NOx emissions when the combustion air was preheated from 25°C to 600°C. This rule was for example at the basis of the German regulation TA Luft in 1986. The tests performed in this project show that, with advanced low NOx technologies, the influence of the combustion air temperature on NOx emissions could be considerably reduced.

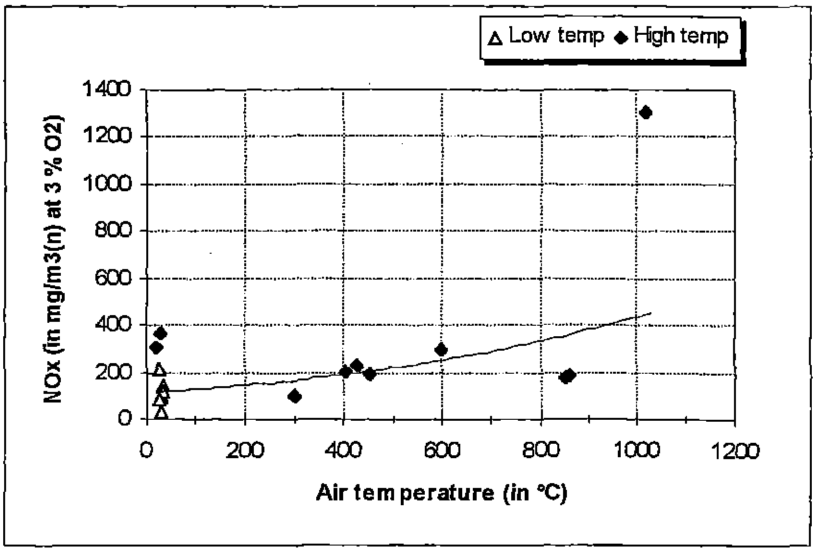


Figure 32 : NOx versus combustion air temperature

4.4.2. NOx versus process temperature

Figure 33 shows the evolution of the NOx levels versus the process temperature : as for the combustion air temperature, the NOx emissions increase with the process temperature. One can moreover notice that the point with the highest NOx emissions, already mentioned (around 1.3g/m^3(n) at 3% O_2) is at the same time the highest temperature process investigated and the highest combustion air temperature. That can explain its extremely high level of NOx (the burner is a regenerative burner). Therefore, it is on this kind of processes that we have to focus on the main efforts in term of NOx reduction.

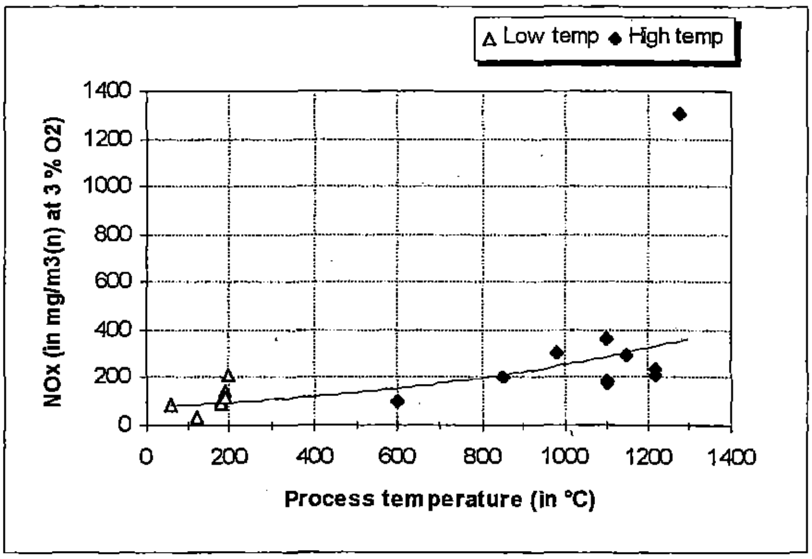


Figure 33 : NOx versus process temperature

As expected, the low temperature processes have lower NOx emissions than high temperature processes. More over we can notice that in comparison with previous results obtained by GDF at the end of the eightees and beginning of the ninetees, the curve has been globally translated towards lower NOx value : the low NOx technologies show a real progress in terms of NOx emissions.

4.4.3. NOx versus combustion efficiency

The NOx emissions evolution with the combustion efficiency is presented figure 34. To make easier the analysis of this graph, the point with the highest level of NOx has been removed. For certain processes it was not possible to evaluate the combustion efficiency as defined in paragraph 3, either because the flue gases was not possible to determine (due to recirculations for example) or because the burners were operating in open air.

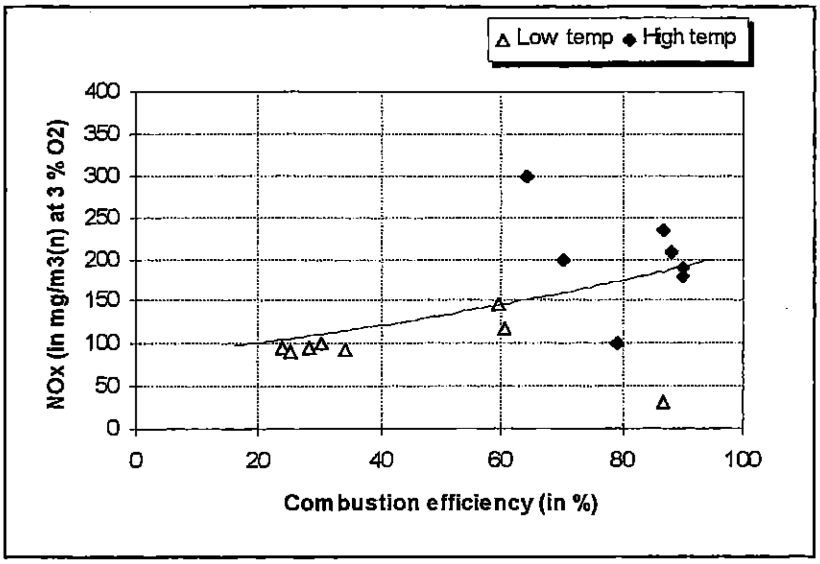


Figure 34 : NOx versus combustion efficiency

The low temperature processes have globally lower NOx emissions and also lower combustion efficiency. There is often no possibility of combustion air preheating which is the more common way to increase the combustion efficiency. Moreover, it could be due to the fact that the energy cost has a lower impact on production costs than for high temperature processes : industry does not indeed focus its investment on energy rational use.

However it can be noticed that the industrial equipment with the lowest combustion efficiency (around 30%) was not working at its right operating conditions : for production reasons (that occurs regularly), the heat treatment performed in the furnace during the test was not the heat treatement for which the furnace was designed. That could explain the relatively bad performance of this industrial process.

4.4.4. NOx versus process efficiency

Figure 35 presents the NOx emissions versus the process efficiency. As for the previous graph figure 34, the point with the highest level of NOx has been removed. The trend is much more difficult to draw : there is no clear relationship between NOx and process efficiency, neither no general rules for high or low temperature processes.

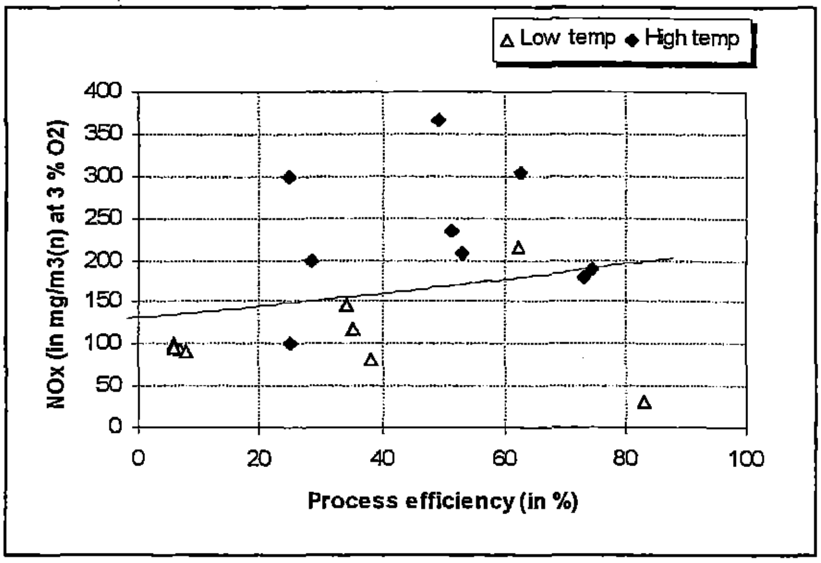


Figure 35 : NOx versus process efficiency

4.4.5. Process and combustion efficiencies

Figure 36 shows the process efficiency versus the thermal input of the process (natural gas only). The thermal input has been plot using a logarithmic scale. We can conclude that the process efficiency increases with the thermal input whatever the type of process. Nevertheless, as for the previous figure 35, the points are to scattered to go into a further analysis.

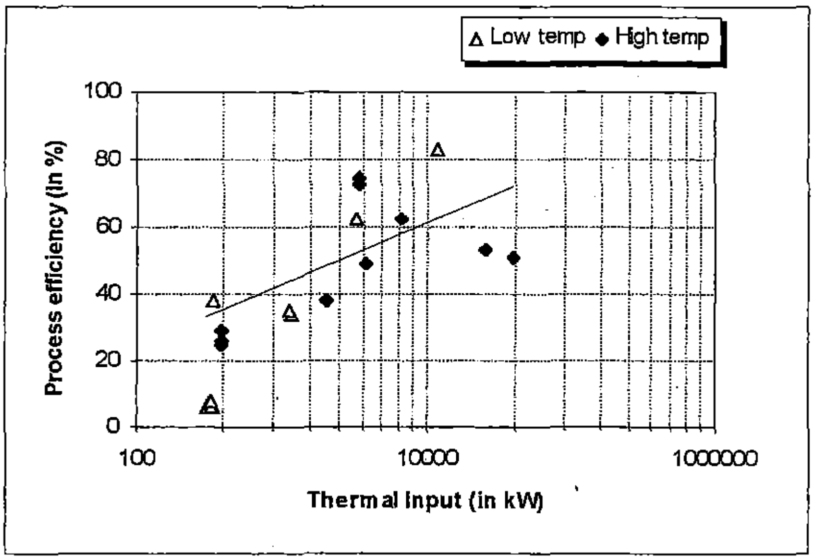


Figure 36 : combustion efficiency versus thermal input

The process efficiency increases clearly with the combustion efficiency whatever the type of process.

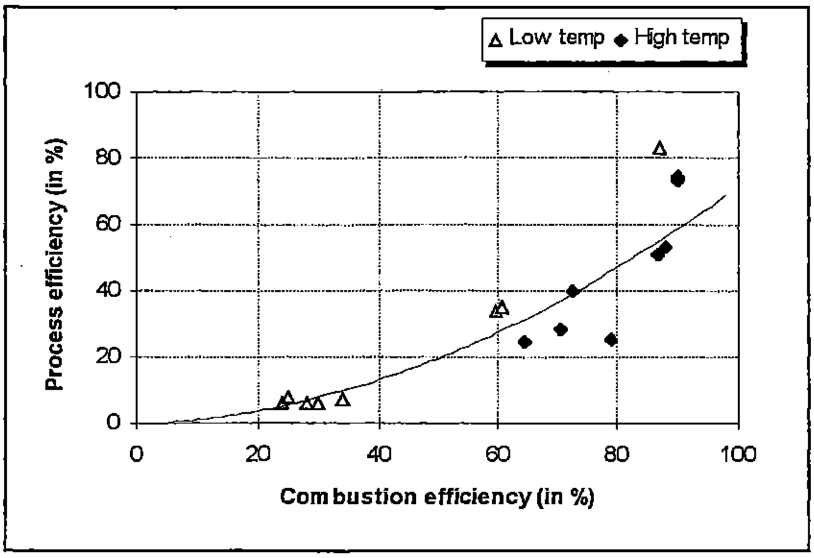


Figure 37 : Process efficiency versus combustion efficiency

Therefore it is of prior interest to work on combustion efficiency improvement, even on low temperature processes to achieve a more rational use of energy.

5. OTHER COMMENTS AND RECOMMENDATIONS

5.1. BOILERS

For this test campaign, the firetube boilers efficiencies (steam or hot water) range from 78% to 97% which is in accordance with previous and published results. The NOx emissions range from below 50 mg/m^3(n) at 3% O_2 to 140 mg/m^3(n) at 3% O_2 which corresponds to low NOx boilers. To generalise these results, we could say that efficiencies between 80% to 90% and NOx level between 80 to 100 mg/m^3(n) at 3% O_2 are achievable for a majority of modern or future boilers. However the excess air ratio as the power density have a great influence on the performances of the boilers and thus has to be taken into account in the analyse of experimental data.

Moreover, the study was based mainly on low gas input and hot water boilers : for more powerful steam boilers, the conclusions should be adapted.

Concerning low NOx technologies, it appears that internal flue gas recirculation and gas staging tend to be the most promising techniques to reduce the NOx emissions from boilers. Future R&D work should be carried out to optimise these techniques and to spread them in the industrial field.

The external flue gas recirculation is also an effective technique which may be applied in the future to be able to reduce the NOx emissions of existing installations.

5.2. ENGINES AND TURBINES

Cogeneration and CHP are the terms used for Combined Heat and Power production. By making use of the waste heat, the total fuel consumption is significantly reduced, and so is the CO_2 emissions. Compared to central power stations without heat utilisation CHP represents a large potential for CO_2 reduction, and if the fuel at the same time is switched from coal to natural gas, the reduction increases.

For example, using Danish figures for coal fired central power plants, the electrical efficiency is 50% and the CO_2 emissions are 780 g/kWh$_{electrical}$; CHP operating on natural gas has a total efficiency on heat and power of 88% and the CO_2 emissions are 230 g/kWh$_{heat\ and\ power}$. This represents a reduction of 70%.

5.2.1. <u>Engines</u>

The tests have shown that lean-burn gas engines, in the range from 0.5 - 5 MW$_e$, operate with an electrical efficiency of approx. 39-41% and a total efficiency of 85 - 95% (ref. to net calorific value). The relative NO_x emissions are 0.8 g NO_x/kWh$_{heat\ and\ power}$..

Some negative environmental effects of gas engines have been observed, and these are being addressed by engine manufacturers, by catalyst manufacturers and by some of the European gas companies. A number of technologies for reduction are being studied, developed and tested.

As a side-effect of the engine development toward higher efficiency, the emissions of unburned hydrocarbons (UHC) have generally increased, and as an example it has been estimated that the emissions of UHC from the gas engines installed in Denmark correspond to 3,5% of the gas consumption.

The composition of UHC is similar to that of the natural gas, i.e. approximately 90% (vol.) methane. Methane is a strong greenhouse gas, and emissions of UHC thus cause a reduction in the CO_2 reduction benefit obtained by cogeneration.

The majority of cogeneration engines have been installed in district heating plants where they have replaced oil-fired and gas-fired boilers. The plants are typically located in urban areas sensitive to exhaust odour, and odour emission is a problem for several cogeneration plants.

Relatively high emissions of formaldehyde and acetaldehyde have been detected in the engine exhaust, and this is a matter of concern since the species may present a health risk.

5.2.2. Turbines

Turbines are generally larger in rated power than the engines and the electric efficiency is somewhat lower. The total efficiency of heat and power is similar to that of the engines.

The NOx emissions from turbines have been reduced in recent years using low NOx burners. The level can be lower than that of the engines. The turbines heat supply temperatures are higher than for the engines, and this is important in many industrial applications where steam is needed.

5.3. INDUSTRIAL PROCESSES

The sector of the thermal industrial processes is very large and the selection of sites is in comparison too small. In particular, no very high temperature process has been investigated, such as glass melting or white ceramic furnaces where the temperature could be above 1500°C. Moreover, the oldest installation dated from 1992 and we tried to focus on low NOx technologies. The picture presented is thus not completely representative for all the installations.

However we can clearly observed the expected trends, as the influence of the combustion air temperature and of the process temperature on NOx emissions and combustion efficiency.We can indeed remind that the most common way to reduce the CO_2 emissions in natural gas thermal heating equipment consists of increasing the combustion efficiency by recovering the flue gas energy to preheat the combustion air. But higher combustion air temperature means higher flame temperature and consequently, in general, higher NOx emissions.

However we can conclude that, using low NOx technologies, it is possible to keep the NOx emissions under 400 $mg/m^3(n)$ at $3\%O_2$, even with preheated combustion air. The low NOx technologies have yet to be adapted to the industrial processes when the impact between the flame and the load to be treated has a big influence on the final product (in term of quality in particular). As an example, further research has to be performed on extremely high air staging or flameless oxidation techniques which seem to be very promising for high temperature processes : identification all the consequences of such techniques, establishement of design rules and pratical limitations for new installations and retrofitted existing installations, by ensuring a safe and reliable operation of these heating principles.

The process efficiency vary a lot from one installation to another. In general, low temperature processes have lower process efficiency (as well as the combustion efficiency and the NOx emissions). For a rational use of energy research should be performed to raise them.

6. DISSEMINATION

The five Partners have prepared a paper which will be presented for the first time at the International Gas Research Conference which will be held in november 1998 in San Diego (US). This conference is world-wild and focused on natural gas techniques from the exploration to the utilisations. This paper will be used by each Partner to prepare local dissemination of the results ; as examples :

- presentation of a poster at a Gaz de France's Symposium in October 1998,
- presentation of the project results at the Swedish Gas Association's yearly convention in November 1998,
- article in the Swedish gas magazine Gasnytt issued by the Swedish Gas Association,
- distribution of the results to the executives at the Swedish Gas Association that are invorlved in a current revision of the environmental legislation concerning the use of different fuels.

Some proposals of papers in industrial magazines (published in the different european countries concerned) have been suggested and will be prepared if accepted by the magazines.

7. CONCLUSION

The tests performed in the frame of the THERMIE Contract STR-397-95-FR confirm that the situation in terms of NOx emission and efficiency is quite different from one country to another and for one installation to another, even for boilers. In particular, the NOx emissions are rather high in comparison with the most advanced techniques where there is still no regulation or no incentive to invest in low NOx technologies. Nevertheless low NOx technologies or installations have been investigated in the three sectors concerned, i.e. boilers, engines and turbines and industrial processes. Some efforts have to be made to optimise or adapt them in regards of a large variety of situation and to spread them in all the industrial fields.

Moreover, if the evaluation of the efficiency of a boiler is rather simple, it is completely different for an industrial process for which the production cycle (in the furnace) has to be taken into account as all the losses (including by walls or by openings) that needs a continuous monitoring during a cycle. An EXCEL® sheet has been defined and used to report the results for the three sectors concerned. It could be the base of the development of an open database.

In addition to enhance understanding of the effectiveness of the various low-NOx techniques for natural gas-fired process equipment, this large-scale test campaign give us a more accurate idea of the real situation and therefore allow us to detect the industrial branches in which further in-depth research should be implemented. As for statutory requirements, both in Europe and in the world generally, regulatory thresholds are rapidly moving toward ever-lower values, which at the same time apply to an ever-broader range of equipment. Even though these regulations initially concern new plants, it was worth determining their feasibility and the modifications in existing plants that would result from these thresholds.

It seems therefore necessary to continue such a survey on Best Available Technologies and R&D works in terms of comprehension and optimisation of new low NOx techniques and of implementation of these techniques in new installations or retrofitted installations.

BIBLIOGRAPHY

[1] « Statistiques de l'industrie gazière en France pour l'année 1995 », Ministère de l'Industrie, de la Poste et des Télécommunications

[2] « Pollution de l'air en Europe », Etude documentaire n°125 de septembre 1997, Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique

[3] « La réduction des émissions d'oxydes d'azote des brûleurs industriels face aux évolutions techniques et réglementaires », Colloque Recherche Gazière-Industrie, Gaz de France, 7 juin 1995

[4] « Oxygen enriched air/natural gas burner system development », Final reprt, Gas Research Institut, novembre 1989

[5] « Flameless oxidation to reduce thermal NO-formation », J.A. Wünning and J.G. Wünning, Energy Combustion Sciences vol 23, 1997

[6] « Determination of emissions from appliances burning gaseous fuels during type-testing », CEN basic document CR 1404:1994 established by MARCOGAZ under the supervision of the CEN/PC3 « Gas »

ANNEX : TEST REPORT EXCEL® SHEET MODEL

Date of the test :		
Report n°		

GENERAL BACKGROUND ON THE SITE

Industrial sector :		KW : food processing space heating, ceramics, metallurgy, paper, textiles, energy production

DESCRIPTION OF THE INSTALLATION

Date of installation :		
Type of the installation : (add a drawing if possible)		KW : hot water boiler, steam boiler, engine, turbine, industrial process
Number of maintenance visits per year (1) :		
Date of the last one (1) :		
Operating conditions		KW : continuous or not
Operational pattern		KW : on/off, variable load
Number of operating hours in operation		

If boiler	Power density (kW/m3)		
	Steam or water pressure (bar)		
	Water or steam temperature (°C)		
	With or without an economiser		
If engine or turbine	Rated electric power (MWe)		
	Rated mecanical power (MW)		
	Heat (MW)		
	Steam (MW)		
If industrial process	Type of process		KW : melting, reheating, drying,
	Production rate		
	Process temperature (°C)		
	Combustion air temperature (°C)		

Total rating (kW)	
If several parallel installations, rating of each (kW)	
Number of burners per installation	
Type of natural gas	

KW : high calorific value, low calorific value

local NOx regulation limit	

(1) if possible
KW = key words
na = not available
nr = no regulation
nc = not concerned

DESCRIPTION OF THE BURNERS

	Burner 1	Burner 2	Burner 3	Burner 4
Burner system				
Date of its installation (1)				
Date of the last verification visit (1)				
Date of the last optimisation (1)				

KW : monobloc, jet, air duct, regenerative, recuperative,

Nominal input per burner (kW)				
NOx reduction technique				

KW : air staging, gas staging, internal recirculation, external recirculation

ENGINE INSTALLATION

	Engine 1	Engine 2
Manufacturer		
Engine type (I.D.)		
No. of cylinders		
No. of revolutions (Rpm)		
Type of load (gen./comp.)		
Rated power (MWe)		
Rated heat (MW)		
Type of fuel(s)		

NOx-reduction technology			KW : stoechiometric, catalyst, lean-burn
Ignition principle			KW : SI open-chamber, SI pre-chamber, pilot injection

MEASUREMENT TECHNIQUES

Emission measurement	Measurement principle	Type of analyser	Measurement range	Measurement uncertainty	Gas of calibration (level and tolerance)
CO_2 content					
CO content					
O_2 content					
CH_4 content					
THC content					
NO content					
NO_2 content					
NO_x content					
N_2O content					

Sampling line

Type		KW : heated or not
Material		KW : stainless, glass, PTFE
Water removal technique		KW : condensation, permeation
If condensation technique, temperature at the exit (°C)		
Number of sampling points		
Position		

	Measurement principle	Measurement range	Measurement uncertainty
Gas flowrate			
Combustion product flowrate			
Air flowrate			
Steam or hot water or pressurized hot water flowrate			
Blowdown flowrate			

	Measurement principle	Measurement range	Measurement uncertainty
Gas pressure (at the meter)			
Air pressure (at the meter)			
Steam pressure			
Process pressure			

	Measurement principle	Measurement range	Measurement uncertainty
Gas temperature (at the meter)			
Air temperature (at the burners)			
Combustion air temperature (ie preheated)			
Combustion products temperature			
Wall temperature (surface outside of the furnace)			
Water temperature			
Load temperature			

Use ti for test instrument in the column measurement principle
Use pi for plant instrument in the column measurement principle

RESULTS

Atmospheric data (mean values)	Pressure (Pa)	Temperature (°C)	Relative humidity (%)

Type of natural gas	CH4 content (%)	C2H6 content (%)	C3H8 content (%)	> C4H10 content (%)
NCV (MJ/m3(n))	N2 content (%)	H2 content (%)	CO2 content (%)	CO content (%)

	Test 1	Test 2	Test 3	Test 4	Test 5
Measurement period (min)					

For each tested operating condition	Test 1	Test 2	Test 3	Test 4	Test 5
Gas flowrate (m3(n)/h)					
Air flow rate (m3(n)/h)					
Thermal input (kW)					
Combustion air temperature (°C)					
Air factor					
Combustion product flowrate (m3(n)/h)					
External recirculation (%)					

Combustion products temperature (°C)					
CO2 mean value (% by vol. of dry gas)					
CO2 SD					
CO mean value (ppmV by vol. of dry gas)					
CO SD					
O2 mean value (% by vol. of dry gas)					
O2 SD					
NO mean value (ppmV by vol. of dry gas)					
NO SD					
NOx mean value (ppmV by vol. of dry gas)					
NOx SD					
NOx mean value (mg NO2/m3(n) at 3% O2					
NOx mean value (mg NO2/MJ NCV)					
CH4 mean value (ppmV by vol. of dry gas)					
CH4 SD					
THC mean value (ppmV by vol. of dry gas)					
THC SD					

SD = Standard Deviation
Use na for not available
Use nd for not determined
Use C for calculated
Use M for measured
Use the factor 2,054 to convert NOx ppm into NOx mg

Energy due to the gas (MJ NCV)						
Energy transfered to the load (MJ NCV)						For engines and turbines heat transfered to the water
Combustion products losses (MJ NCV)						
Electricity production (MJ)						
Combustion efficiency (% NCV)						
Process efficiency (% NCV)						For engines and turbines, power and heat efficiency

Load means either product or water or steam
Combustion efficiency = 1 - combustion products losses/energy due to the gas
Process efficiency = energy transfered to the load/energy due to the gas

m3(n) is the volume at 0°C and 1,013 bar

COMMENTS

Assumed accuracy	
Flowrate	
Species	
Temperature	

REMARKS / OTHER INFORMATION

99-09-01

RAPPORTFÖRTECKNING

SGC Nr	Rapportnamn	Rapport datum	Författare	Pris kr
001	Systemoptimering vad avser ledningstryck	Apr 91	Stefan Grudén TUMAB	100
002	Mikrokraftvärmeverk för växthus. Utvärdering	Apr 91	Roy Ericsson Kjessler & Mannerstråle AB	100
004	Krav på material vid kringfyllnad av PE -gasledningar	Apr 91	Jan Molin VBB VIAK	50
005	Teknikstatus och marknadsläge för gasbaserad minikraftvärme	Apr 91	Per-Arne Persson SGC	150
006	Keramisk fiberbrännare - Utvärdering av en demo-anläggning	Jan 93	R Brodin, P Carlsson Sydkraft Konsult AB	100
007	Gas-IR teknik inom industrin. Användnings- områden, översiktlig marknadsanalys	Aug 91	Thomas Ehrstedt Sydkraft Konsult AB	100
009	Läcksökning av gasledningar. Metoder och instrument	Dec 91	Charlotte Rehn Sydkraft Konsult AB	100
010	Konvertering av aluminiumsmältugnar. Förstudie	Sep 91	Ola Hall, Charlotte Rehn Sydkraft Konsult AB	100
011	Integrerad naturgasanvändning i tvätterier. Konvertering av torktumlare	Sep 91	Ola Hall Sydkraft Konsult AB	100
012	Odöranter och gasolkondensats påverkan på gasrörsystem av polyeten	Okt 91	Stefan Grudén, F. Varmedal TUMAB	100
013	Spektralfördelning och verkningsgrad för gaseldade IR-strålare	Okt 91	Michael Johansson Drifttekniska Inst. vid LTH	150
014	Modern gasteknik i galvaniseringsindustri	Nov 91	John Danelius Vattenfall Energisystem AB	100
015	Naturgasdrivna truckar	Dec 91	Åsa Marbe Sydkraft Konsult AB	100
016	Mätning av energiförbrukning och emissioner före o efter övergång till naturgas	Mar 92	Kjell Wanselius KW Energiprodukter AB	50
017	Analys och förslag till handlingsprogram för området industriell vätskevärmning	Dec 91	Rolf Christensen ÅF-Energikonsult Syd AB	100
018	Skärning med acetylen och naturgas. En jämförelse.	Apr 92	Åsa Marbe Sydkraft Konsult AB	100

99-09-01

RAPPORTFÖRTECKNING

SGC Nr	Rapportnamn	Rapport datum	Författare	Pris kr
019	Läggning av gasledning med plöjteknik vid Glostorp, Malmö. Uppföljningsprojekt	Maj 92	Fallsvik J, Haglund H m fl SGI och Malmö Energi AB	100
020	Emissionsdestruktion. Analys och förslag till handlingsprogram	Jun 92	Thomas Ehrstedt Sydkraft Konsult AB	150
021	Ny läggningsteknik för PE-ledningar. Förstudie	Jun 92	Ove Ribberström Ove Ribberström Projekt. AB	150
022	Katalog över gastekniska FUD-projekt i Sverige. Utgåva 4	Aug 92	Svenskt Gastekniskt Center	150
023	Läggning av gasledning med plöjteknik vid Lillhagen, Göteborg. Uppföljningsproj.	Aug 92	Nils Granstrand m fl Göteborg Energi AB	150
024	Stumsvetsning och elektromuffsvetsning av PE-ledningar. Kostnadsaspekter.	Aug 92	Stefan Grudén TUMAB	150
025	Papperstorkning med gas-IR. Sammanfattning av ett antal FUD-projekt	Sep 92	Per-Arne Persson Svenskt Gastekniskt Center	100
026	Koldioxidgödsling i växthus med hjälp av naturgas. Handbok och tillämpn.exempel	Aug 92	Stig Arne Molén m fl	150
027	Decentraliserad användning av gas för vätskevärmning. Två praktikfall	Okt 92	Rolf Christensen ÅF-Energikonsult	150
028	Stora gasledningar av PE. Teknisk och ekonomisk studie.	Okt 92	Lars-Erik Andersson, Åke Carlsson, Sydkraft Konsult	150
029	Catalogue of Gas Techn Research and Development Projects in Sweden (På engelska)	Sep 92	Swedish Gas Technology Center	150
030	Pulsationspanna. Utvärdering av en demo -anläggning	Nov 92	Per Carlsson, Åsa Marbe Sydkraft Konsult AB	150
031	Detektion av dräneringsrör. Testmätning med magnetisk gradiometri	Nov 92	Carl-Axel Triumf Triumf Geophysics AB	100
032	Systemverkn.grad efter konvertering av vattenburen elvärme t gasvärme i småhus	Jan 93	Jonas Forsman Vattenfall Energisystem AB	150
033	Energiuppföljning av gaseldad panncentral i kvarteret Malörten, Trelleborg	Jan 93	Theodor Blom Sydkraft AB	150
034	Utvärdering av propanexponerade PEM-rör	Maj 93	Hans Leijström Studsvik AB	150

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RAPPORTFÖRTECKNING

SGC Nr	Rapportnamn	Rapport datum	Författare	Pris kr
035	Hemmatankning av naturgasdriven personbil. Demonstrationsprojekt	Jun 93	Tove Ekeborg Vattenfall Energisystem	150
036	Gaseldade genomströmningsberedare för tappvarmvatten i småhus. Litteraturstudie	Jun 93	Jonas Forsman Vattenfall Energisystem	150
037	Verifiering av dimensioneringsmetoder för distributionsledningar. Litt studie.	Jun 93	Thomas Ehrstedt Sydkraft Konsult AB	150
038	NOx-reduktion genom reburning med naturgas. Fullskaleförsök vid SYSAV i Malmö	Aug 93	Jan Bergström Miljökonsulterna	150
039	Pulserande förbränning för torkändamål	Sep 93	Sten Hermodsson Lunds Tekniska Högskola	150
040	Organisationer med koppling till gasteknisk utvecklingsverksamhet	Feb 94	Jörgen Thunell SGC	150
041	Fältsortering av fyllnadsmassor vid läggning av PE-rör med läggningsbox.	Nov 93	Göran Lustig Elektro Sandberg Kraft AB	150
042	Deponigasens påverkan på polyetenrör.	Nov 93	Thomas Ehrstedt Sydkraft Konsult AB	150
043	Gasanvändning inom plastindustrin, handlingsplan	Nov 93	Thomas Ehrstedt Sydkraft Konsult AB	150
044	PA 11 som material ledningar för gasdistribution.	Dec 93	Thomas Ehrstedt Sydkraft Konsult AB	150
045	Metoder att höja verkningsgraden vid avgaskondensering	Dec 93	Kjell Wanselius KW Energiprodukter AB	150
046	Gasanvändning i målerier	Dec 93	Charlotte Rehn et al Sydkraft Konsult AB	150
047	Rekuperativ aluminiumsmältugn. Utvärdering av degelugn på Värnamo Pressgjuteri.	Okt 93	Ola Hall Sydkraft Konsult AB	150
048	Konvertering av dieseldrivna reservkraftverk till gasdrift och kraftvärmeprod	Jan 94	Gunnar Sandström Sydkraft Konsult AB	150
049	Utvecklad teknik för gasinstallationer i småhus	Feb 94	P Kastensson, S Ivarsson Sydgas AB	150
050	Korrosion i flexibla rostfria insatsrör (Finns även i engelsk upplaga)	Dec 93	Ulf Nilsson m fl LTH	150

99-09-01

RAPPORTFÖRTECKNING

SGC Nr	Rapportnamn	Rapport datum	Författare	Pris kr
051	Nordiska Degelugnsprojektet. Pilot- och fältförsök med gasanvändning.	Nov 93	Eva-Maria Svensson Glafo	150
052	Nordic Gas Technology R&D Workshop. April 20, 1994. Proceedings.(På engelska)	Jun 94	Jörgen Thunell, Editor Swedish Gas Center	150
053	Tryckhöjande utrustning för gas vid metallbearbetning -- En förstudie av GT -PAK	Apr 94	Mårten Wärnö MGT Teknik AB	150
054	NOx-reduktion genom injicering av naturgas i kombination med ureainsprutning	Sep 94	Bent Karll, DGC P Å Gustafsson, Miljökons.	100
055	Trevägskatalysatorer för stationära gasmotorer.	Okt 94	Torbjörn Karlelid m fl Sydkraft Konsult AB	150
056	Utvärdering av en industriell gaseldad IR -strålare	Nov 94	Johansson, M m fl Lunds Tekniska Högskola	150
057	Läckagedetekteringssystem i storskaliga gasinstallationer	Dec 94	Fredrik A Silversand Katator AB	150
058	Demonstration av låg-NOx-brännare i växthus	Feb 95	B Karll, B T Nielsen Dansk Gasteknisk Center	150
059	Marknadspotential naturgaseldade industriella IR-strålare	Apr 95	Rolf Christensen Enerkon RC	150
060	Rekommendationer vid val av flexibla insatsrör av rostfritt i villaskorstenar	Maj 95	L Hedeen, G Björklund Sydgas AB	50
061	Polyamidrör för distribution av gasol i gasfas. Kunskapssammanställning	Jul 95	Tomas Tränkner Studsvik Material AB	150
062	PE-rörs tålighet mot yttre påverkan. Sammanställning av utförda praktiska försök	Aug 95	Tomas Tränkner Studsvik Material AB	150
063	Naturgas på hjul. Förutsättningar för en storskalig satsning på NGV i Sverige	Aug 95	Naturgasbolagens NGV- grupp	150
064	Energieffektivisering av större gaseldade pannanläggningar. Handbok	Aug 95	Lars Frederiksen Dansk Gasteknisk Center	200
065	Förbättra miljön med gasdrivna fordon	Aug 95	Göteborg Energi AB	150
066	Konvertering av oljeeldade panncentraler till naturgas. Handbok.	Nov 95	Bo Cederholm Sydkraft Konsult AB	150

99-09-01

RAPPORTFÖRTECKNING

SGC Nr	Rapportnamn	Rapport datum	Författare	Pris kr
067	Naturgasmodellen. Manual för SMHI:s program för beräkn av skorstenshöjder	Dec 95	Tingnert B, SKKB Thunell J, SGC	150
068	Energigas och oxyfuelteknik	Dec 95	Ingemar Gunnarsson Energi-Analys AB	150
069	CO2-gödsling med avgaser från gasmotor med katalysator	Dec 95	Bent Karll Dansk Gasteknisk Center	150
070	Utvärdering av naturgasförbränning i porösa bäddar	Mar 96	Henric Larsson Lunds Tekniska Högskola	150
071	Utvärdering av naturgasdrivna IR-boostrar i ugn för pulverlackering	Nov 95	Ole H Madsen Asger N Myken	150
072	Sammanställning av emissionsdata från naturgas-, biogas- o motorgasdrivna fordon	Jun 96	Hans-Åke Maltesson Svenskt Gastekniskt Center AB	150
073	Livslängdsbestämning för PE-rör för gasdistribution (EVOPE-projektet)	Jul 96	Tomas Tränkner Studsvik Material AB	100
074	Gasblandningar för fordonsdrift. Idéstudie.	Aug 96	Ola Hall Sydkraft Konsult AB	150
075	Gasbranschens miljöhandbok	Sep 96	Jörgen Thunell Svenskt Gastekniskt Center	500
076	Låg-NOx-teknik för gasdrivna processer - dagsläge	Okt 96	Mikael Näslund, LTH Inst.Värme- och Kraftteknik, LTH	150
077	Karakterisering av emissioner från naturgasdrivna lastbilar inom LB 50 -projektet	Dec 96	K-E Egebäck Roger Westerholm	150
078	Uppvärmning med gas i svenska småhus - erfarenheter och framtida teknikval	Nov 96	Mikael Näslund, LTH	150
079	Handledn. för inst av gaseldade IR -värmare. Rådgivning, analys och genomförande	Apr 97	Pär Dalin DITAB	150
080	Mikrokraftvärmeverk med Stirlingmotor	Jan 97	Tomas Nilsson Lunds Tekniska Högskola	150
081	Naturgasbaserad småskalig kraftvärme inom uppvärmningssektorn	Feb 97	Mats Nilsson LTH/MALMÖ	150
082	Kylning och klimatisering av byggnader och lokaler med hjälp av naturgas	Apr 97	Anders Lindkvist Vattenfall Energisystem	150

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083	Naturgassystemet i Sverige - en teknisk beskrivning	Jun 97	Ronny Nilsson, KM	150
084	Livscykelanalyser - Är det något för gasbranschen ?	Sep 97	Jörgen Thunell	150
085	Konvertering av direktelvärmda småhus till naturgasuppvärmning	Dec 97	Mikael Näslund Inst Värme- och Kraftteknik, LTH	150
086	Uppgradering av biogas . Fas 2, Praktiska försök med kondenseringsmetoder.	Jun 97	Ola Lloyd / BioMil AB Johan Nilsson / LTH	150
087	Utveckling av katatalytisk rening av avgaser från befintlig panna	Dec 97	F Silversand, T Hargitai m fl Katator AB	150
088	Technical Description of the Swedish Natural Gas Distr System (På Engelska)	Jun 97	Ronny Nilsson, KM	150
089	Rening av avgaser från en naturgasdriven lean burn motor i en förbr.växlare	Okt 97	Björn Heed Inst för Energiteknik, CTH	150
090	Utsläpp av oreglerade ämnen vid förbränning av olika bränslen	Jun 98	Jörgen Thunell	150
091	Nya metoder för att säkerställa mätnoggrannheten i naturgasnät	Nov 97	Ulf R C Nilsson Luleå TH, Inst Systemteknik	150
092	LB30-projektet - Introduktion av naturgasdrivna tyngre lastbilar	Jan 99	Owe Jönsson Svenskt Gastekniskt Center	150
093	Karaktärisering av emissioner från naturgasdrivna lastbilar inom LB50 -projektet	Sep 98	Karl Erik Egebäck	150
094	Gasdistribution och avgasinstallation i byggnader	Jan 99	Hans Christian Thiis Per Palm	150
095	Karaktärisering av emissioner från naturgasdrivna lastbilar inom LB50 -projektet	Okt 98	Karl Erik Egebäck	150
096	Lifetime of PE-pipes subjected to squeeze off	Nov 98	Tomas Tränkner	150
097	Svensk högskoleförlagd energigasforskning Nutid och framtid	Jan 99	Mikael Näslund, LTH Owe Jönsson, SGC	150
098	Metoder för snabb kvalitetskontroll av PE -rör för gasdistribution	Apr 99	Tomas Tränkner	150

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099	Gas co-firing for NOx-reduction in coal fired boilers	Apr 99	Fredrik Brogaard	200
100	Optimerad samrötning av restprodukter från stad och land	Apr 99	A Dahl, M Linné, L Andersson	150
101	Distribution av biogas i naturgasnät	Jul 99	Kaj Vågdahl	100
102	Evaluation of the efficiency face to the NOx -emissions from European plants	990901	M J Fourniguet, A Quinqueneau, B Karll, P Breithaupt, O Jonsson	150
A01	Fordonstankstation Naturgas. Parallellkoppling av 4 st Fuel Makers	Feb 95	Per Carlsson Göteborg Energi AB	50
A02	Uppföljning av gaseldade luftvärmare vid Arlövs Sockerraffinaderi	Jul 95	Rolf Christensen Enercon RC	50
A03	Gasanvändning för färjedrift. Förstudie (Endast för internt bruk)	Jul 95	Gunnar Sandström Sydkraft Konsult	0
A04	Bussbuller. Förslag till mätprogram	Jun 95	Ingemar Carlsson Ecotrans Teknik AB	50
A05	Värmning av vätskor med naturgas - Bakgrund till faktablad	Okt 95	Rolf Christensen Enerkon RC	50
A06	Isbildning i naturgasbussar och CNG -system (Endast för internt bruk)	Nov 95	Volvo Aero Turbines Sydgas, SGC	0
A07	Större keramisk fiberbrännare. Förstudie	Jan 96	Per Carlsson Sydkraft Konsult AB	50
A08	Reduktion av dioxin, furan- och klorfenoler vid avfallsförbränning	Maj 96	H Palmén, M Lampinen et al Helsingfors Tekniska Högskola	50
A09	Naturgas/mikrovågsteknik för sintring av keramer	Maj 96	Anders Röstin KTH	50
A10	NOx-reduktion genom naturgasinjektion o reburning. Demoprojekt på Knudmoseverket	Apr 96	Jan Flensted Poulsen Völund R & D Center	50
A11	Direkttorkning av socker med naturgas (Endast för internt bruk)	Jul 96	Rolf Christensen Enerkon RC	0
A12	Uppföljning, installation av gaspanna med avgaskondensor, kv Hornblåsaren 6, Råå	Sep 96	Bo Cederholm Sydkraft Konsult AB	50

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A13	Klassningsplaner för gasinstallationer	Jun 97	Carl-Axel Stenberg Greger Arnesson	50
A14	Uppf av drift med natugaseldad kondenserande gaspanna i Rinnebäcksskolan	Okt 97	Bo Cederholm Sydkraft Konsult AB	50
A15	Undersökn o förstärkn av korr.skyddet på gasrör förl i skyddsrör - Delrapport 1	Nov 97	Åsa Marbe, C Johansson Sydkraft Konsult AB	100
A16	Ind - CO2-härdning av betong med naturgas	Feb 98	Åsa Marbe Sydkraft Konsult AB	50
A17	Reservförsörjning med fordonstransporterad LNG	Dec 97	Stig Johansen	50
A18	Emissions- och immissionsmätning vid en naturgaseldad villapanna	Mar 97	David Cooper IVL	50
A19	Katalytisk rening av gaseldade lean -burnmotorer etapp 1 - teoretisk förstudie	Aug98	Fredrik Silversand Katator	100
A20	Europeisk livscykelinventering för naturgas (endast för internt bruk)	Sep 98	Jörgen Thunell	0
A21	Naturgasdrivna järnvägsfordon - Förstudie	Dec 98	Rolf Öberg	100
A22	Catalytic abatement of CO- and UHC -emissions from Gas Fuelled Engines	Feb99	Fredrik Silversand	100
A23	Förläggning av gasrör av polyeten i befintliga massor	Mar 99	Gunnar Bergström Stefan Nilsson	100

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