Combustion of Chemical Substances and the Impact on the Environment of the Fire Products: 1/3 Scale Room Furnace Experiments

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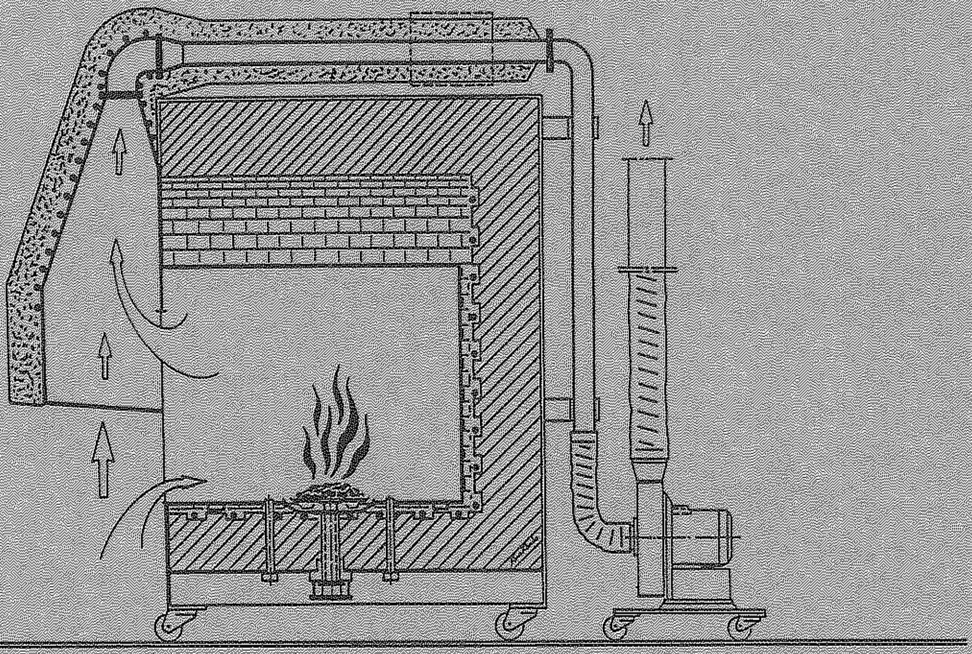


B. Andersson, F. Davie, G. Holmstedt, A. Kenéz and S. Särdqvist

Combustion of Chemical Substances and the Impact on the Environment of the Fire Products

1/3 Scale Room Furnace Experiments

Lund, 1994

Abstract

This report describes the results obtained from fire tests in a 1/3-scale room. The aim of the study was to investigate how changes in external radiation and oxygen supply affect the production of smoke and toxic gases.

The ventilation was varied to simulate under- and well-ventilated fires. The thermal exposure to the materials was varied to simulate fires of different sizes. Fifty-nine tests were performed, with polystyrene, FR polystyrene, polypropylene, nylon and PVC. Measurements were made of the contents of O_2, CO_2, CO, NO_X and HC in the exhaust gases.

The impact of external radiation was mainly to increase the pyrolysis rate, and thus the rate of heat release, and to drive the fire into under-ventilation.

The degree of ventilation proved to have the greatest impact on the combustion efficiency. The smoke production was almost constant for polypropylene and nylon. The CO production appeared to be the most complex of the parameters to describe, and the expected increase in CO yield at low yields of CO_2 could not be seen. The generation of NO_X was low for the two substances without chemically bound nitrogen, but for nylon, the generation was significant. The production of low molecular weight HC was essentially constant for all three materials. Almost all the carbon was recovered in well-ventilated fires, but at under-ventilated conditions, only 30% of the carbon from the fuel was detected.

The toxic potency of the exhaust gases was estimated using the N-gas model, and proved to be relatively low. Lack of oxygen and the production of carbon oxide had the greatest impact on the toxicity for polystyrene and polypropylene, while NO_X represented the main part for nylon. The survival fraction and the decomposition products from the original materials are not considered in the model. It can therefore not be assumed that the model reflects all aspects of the toxicity problem.

Svensk sammanfattning

Rapporten beskriver resultat från brandförsök i 1/3 rumsskala. Målet var att undersöka hur brandgasernas sammansättning påverkas av yttre värmestrålning och ventilationsgraden.

Ventilationsgraden varierades för att simulera välventilerad och underventilerad brand. Den yttre strålningen varierades för att simulera bränder av olika storlek. Totalt utfördes 59 försök, med polystyren, brandskyddad polystyren, polypropylen, nylon och PVC. Halten O_2, CO_2, CO, NO_X och HC mättes i brandgaserna.

Den yttre strålningen inverkade huvudsakligen genom att öka pyrolyshastigheten, och effektutvecklingen, för att därigenom driva branden in i underventilation.

Ventilationsgraden hade störst effekt på förbränningseffektiviteten. Rökproduktionen var nära konstant för polypropylen och nylon. CO-produktionen är komplex, men den förväntade ökningen i produktionen av CO vid låga halter CO_2 kunde inte ses. Produktionen av NO_X var låg för ämnen utan kemiskt bundet kväve, medan mängden var signifikant för nylon. Den uppmätta mängden lätta kolväteföreningar var konstant för de tre ämnena. Vid välventilerade bränder återfanns nästan allt kol i rökgaserna. Endast 30 % av kolet återfanns vid underventilerade förhållanden.

Brandgasernas giftighet var låg, enligt en uppskattning med N-gasmodellen. Syreunderskott och produktionen av CO och CO_2 förklarar giftverkan för polystyren och polypropylen. Produktionen av NO_X slår igenom i giftverkan för nylon. I modellen är inte hänsyn tagen till pyrolysprodukter m.m. Detta gör att modellen inte ger en heltäckande bild av brandgasernas giftighet.

Acknowledgements

This work was financed by The Swedish Environmental Protection Agency (Statens Naturvårdsverk), The National Board for Industrial and Technical Development (NUTEK), The Swedish Rescue Services Board (Räddningsverket), and The Swedish Fire Research Board (BRANDFORSK). The administration of the project was dealt with by the CEC STEP programme.

We would like to thank Neste Chemicals, Finland, Cheminova A/S, Denmark and ICI Ltd, UK, for supplying the chemicals.

Contents

Nomenclature

A	[m^2]	Exhaust duct area
b		Toxicity calculation constant, 122 000
D	[ob]	Optical density per meter length
D_m	[obm^3/g]	Mass optical density
FED	[-]	Fractional effective Exposure Dose
$\Delta H_{C,ox}$	[kJ/gO$_2$]	Net heat release per unit mass of oxygen consumed
ΔH_{CO}	[kJ/g]	Heat of formation for CO, 3.946 kJ/g
ΔH_T	[kJ/g]	Theoretical heat of combustion for the substance
I_0/I	[-]	Relation between light intensity in the exhaust duct without smoke and during the test
L	[m]	Beam length of light in the smoke
LC_{50}	[g/m^3]	Burned mass of material per unit air volume which when inhaled causes 50% mortality in exposed rats
$LC_{50}(i)$	[ppm]	Concentration of the gas i which when inhaled causes 50% mortality in exposed rats
$M(i)$	[g/mole]	Molecular weight of the substance i
m		Toxicity calculation constant, -18
m_i	[g]	Amount of the gas i produced
m_{FUEL}	[g]	Total mass loss of the fuel
$\dot{m}_{FUEL}$	[g/s]	Mass loss rate of the fuel
Δp	[Pa]	Pressure difference in the exhaust duct
Q	[kJ]	Total heat released
q	[kW]	Rate of heat release
T_e	[K]	Temperature in the exhaust duct
$\dot{V}$	[m^3/s]	Volume flow in the exhaust duct at 20°C
X_i	[-]	Mole fraction of the gas i in the exhaust duct
X°_i	[-]	Mole fraction of the gas i in the incoming air, $X^\circ_{O_2} = 0.209$
Y_i	[g/g]	Measured amount of the gas i per unit mass of fuel burned
α		Expansion factor due to chemical reaction of air which is depleted of its oxygen, 1.1
χ	[-]	Combustion efficiency
ϕ	[-]	Oxygen depletion factor
Ψ_i	[g/g]	Theoretical amount of the gas i per unit mass of fuel burned
Ψ_C	[g/g]	Mass fraction of carbon in the fuel

Introduction

This report describes the equipment, the experiments, the analytical methods used and the combustion products identified in work package 4 of the STEP project *Combustion of Chemical Substances and the Impact on the Environment of the Fire Products*. The project is part of the CEC STEP programme (STEP CT91-0109) and was initiated in July 1991.

The main project

The objective of the STEP project was to obtain data concerning the identification of combustion products from fires in warehouses containing commercial chemicals. The project comprised experiments on various scales in order to identify the source term characteristics and the relation between bench-scale testing and real fires. The project was originally planned to contain the following work packages:

- Identification of fire types
- Micro-scale combustion experiments
- Cone calorimeter experiments
- Model-scale sensitivity tests
- Particle characterisation
- Large-scale indoor combustion experiments
- Large-scale outdoor combustion experiments
- Elaboration of guidelines

The participants in the project were Risø National Laboratory (Denmark) - also the co-ordinator of the project; South Bank University (UK), VTT Technical Research Centre of Finland (Finland); SP, Swedish National Testing and Research Institute (Sweden) and Lund University (Sweden).

Work package 4, model-scale sensitivity tests

This report describes the results obtained from experiments carried out in work package 4, "Model-scale sensitivity tests", which was carried out at Lund University. Results from the study of correlations between the cone calorimeter, the model-scale tests and real fires are described in a separate report, entitled *Combustion of Chemical Substances and the Impact on the Environment of the Fire Products, Scaling effects.*

It is known that the generation of combustion products is sensitive to turbulence fluctuations in gas concentrations and temperatures which occur in the flames of large-scale fires. This makes micro-scale experiment results questionable. However, it is not economically feasible to carry out extensive full-scale experiments to provide toxicity data. Model scale room tests provide a middle path for the acquisition of relevant data.

The combustion chamber constructed for the tests was electrically heated, and the thermal exposure to the materials was varied. Room ventilation was changed to simulate fires in nearly closed buildings as well as fires with almost unrestricted access to air.

Thus, the question is: How do the level of thermal radiation and the degree of ventilation affect the generation of combustion products?

Experimental methods

Basically, the combustion chamber used is a 1/3-scale test room. The test samples were placed in a load cell in the middle of the chamber. The combustion chamber is equipped with a hood connected to an exhaust duct from which gas samples were collected and analysed. The opening height of the chamber is adjustable, and there it is also possible to expose the combustible materials to external radiation.

The combustion chamber

In Figure 1, the equipment used in the tests is shown. It consists of a stainless steel combustion chamber fitted inside a furnace. The combustion chamber was designed at the Department especially for the project. It has the dimensions of a 1/3-scale test room. The internal dimensions are 78 cm (width) x 75 cm (depth) x 79 cm (height) giving a volume of 0.46 m^3.

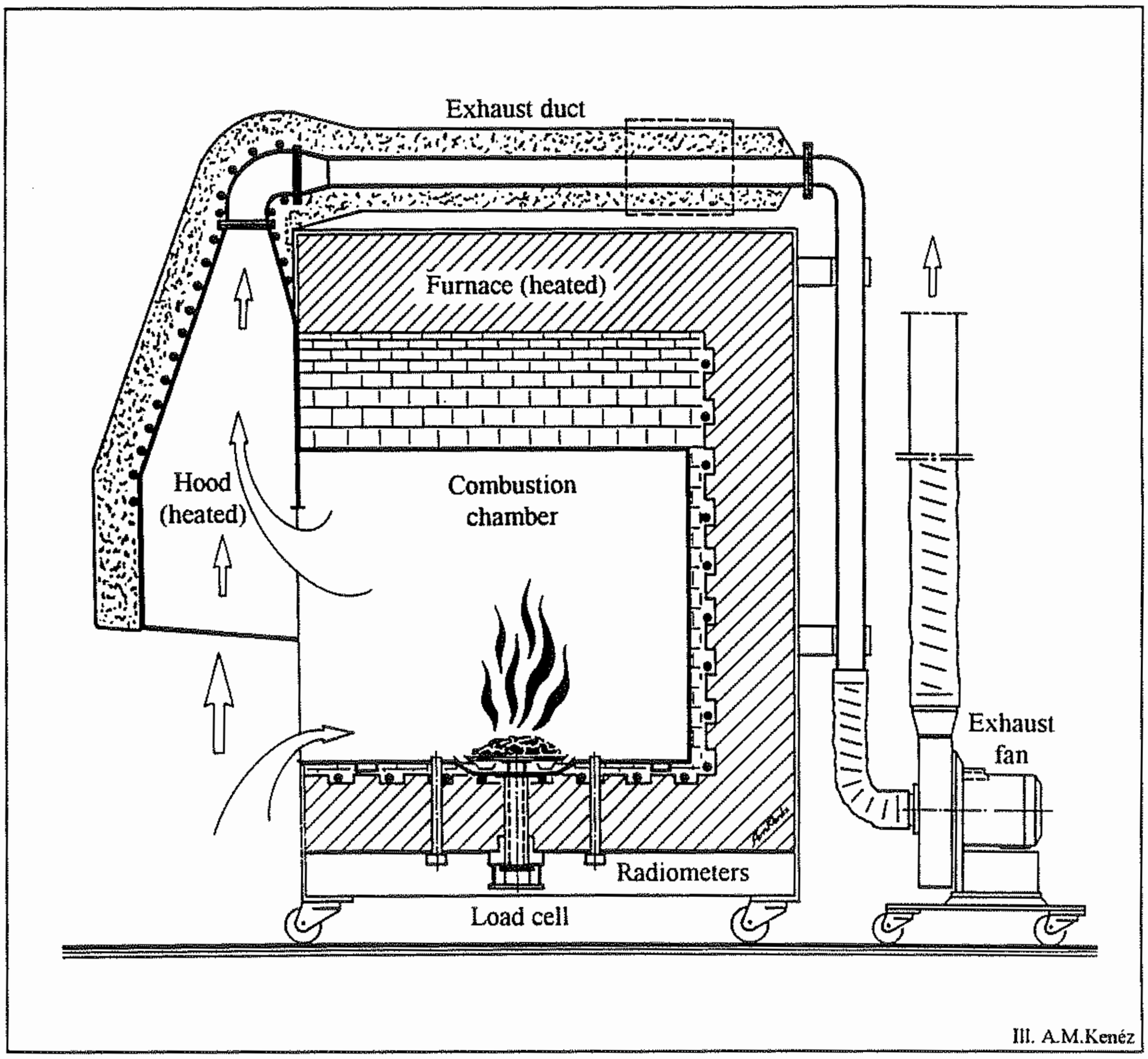


Figure 1. Schematic view of the combustion chamber constructed for the tests.

The opening to the hood is 45 cm wide, and by using stainless steel covers, different opening heights can be obtained. The walls of the chamber can be electrically heated to a temperature corresponding to radiation of up to about 50 kW/m².

In this study, openings of 32 cm and a 15 cm height were used. With these relatively small openings, the flame reaches up into the smoke layer when the layer has descended. This means that after ignition, the fire is well ventilated and at the end of the test the fire is under-ventilated. It was also planned to carry out some tests with a larger opening height, which would leave the flame unaffected by the smoke layer - the largest flames were about 0.5 m in height.

The thermal exposure to the materials was varied to simulate fires of different sizes. In this study, tests were performed with two radiation levels: 0 kW/m² (no external radiation) and 10 kW/m².

Measuring equipment

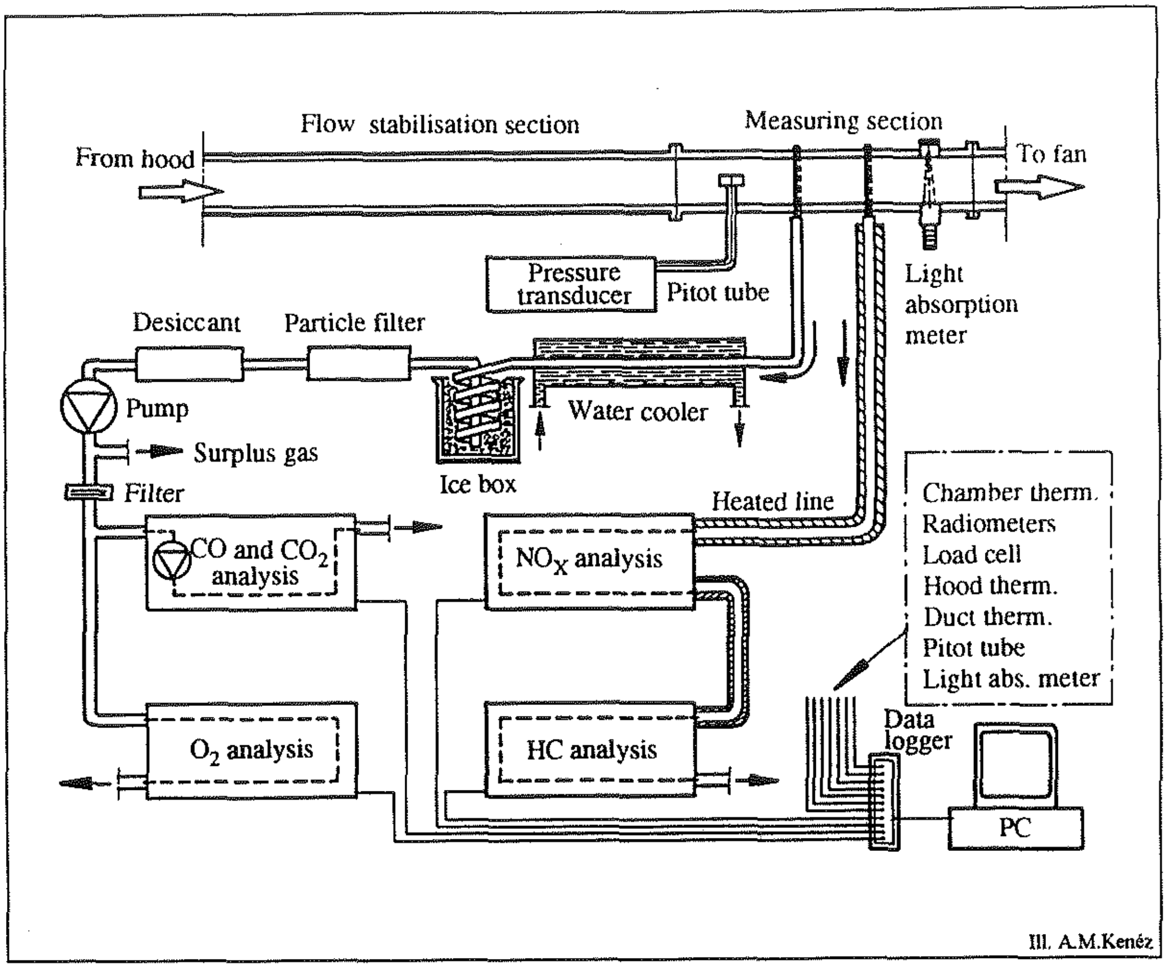
The measuring equipment used is listed in Table 1. A load cell is placed at the bottom of the chamber. Gunners' radiometers are placed in front of and behind the load cell to measure the radiation to the floor of the chamber. The two radiometers were calibrated according to a proposed NT FIRE method [1] in a spherical furnace.

Table 1. Measurement equipment used in the tests.

Measurement	Equipment	Range
Radiation	Gunners' radiometers	0 - 100 kW/m²
Mass	Load cell	0 - 10 kg ± 1 g
Smoke	Lamp with colour temperature 2900°C and photo-cell	0 - 100%
Pressure drop	Pressure transducer connected to a bi-directional Pitot tube	0 - 400 Pa
Temperature	Thermocouple Chromel Alumel, ϕ 0.51 mm	0 - 1300°C

An electrically heated hood which collects the smoke and combustion gases is located outside the opening. The hood is connected to an exhaust duct, which includes a flow stabilisation and a measuring section where the sampling probes are located. The system is thermally insulated. The smoke is exhausted by a 2.2 kW radial fan.

The measuring section in the exhaust duct contains a bi-directional Pitot tube, a thermocouple and a light absorption meter. Probes were also mounted in the measuring section, to determine the contents of O_2, CO_2, CO, NO_X and HC (unburned hydrocarbons) in the exhaust gases.



Ill. A.M.Kenéz

Figure 2. The gas analysis equipment used in the tests.

Table 2. The gas analysis equipment used in the tests.

Measurement	Equipment	Range	Calibration gas
O_2	Siemens Oxymat 5E Paramagnetic	10 - 21 vol%	21% 9.94%
CO	Siemens Ultramat 22P Non-dispersive IR-absorption	0 - 1 vol%	2020 ppm 196 ppm
CO_2	Siemens Ultramat 22P	0 - 20 vol%	4.96% 0.491%
NO_X	Analysis Automation Limited Chemiluminescent analysis, model 443	0 - 100 ppm	93.6 ppm
HC	Siemens Fidamat K FID (flame ionisation detector)	0 - 100 ppm	50.9 ppm propane

The mass flow in the exhaust duct was calculated according to NT FIRE 025 [2], using measurements from a bi-directional Pitot tube [3] with a thermocouple mounted in the measuring section of the exhaust duct. The smoke extinction was also measured according to NT FIRE 025. During the tests, measurements of the contents of O_2, CO_2, CO, NO_X and HC (unburned hydrocarbons) in the exhaust gases were made.

The gas analysis equipment is shown in Figure 2 and listed in Table 2. The samples for O_2, CO_2 and CO measurements were cooled and dried. The samples for NO_X and HC measurements were collected in a sampling line heated to 200 °C with a heated smoke filter. The gas analysis equipment was calibrated with zero gas and span gases of known concentrations. The concentrations of the span gases were chosen to be of the same order of magnitude as the test samples. In addition, the accuracy of the complete rate of heat release apparatus was checked with a propane burner of known RHR before the tests.

All measurements were performed on-line and a Slumberg data-logger was used to collect the data and transfer them to a PC. The scan interval was 5 s. In calculating the gas concentrations, a time correction of 10 s was employed, due to the delay in the gas sampling system. The test data file contains the temperature and volume flow in the duct, the gas yields, the light obscuration, the mass loss rate and the rate of heat release, calculated from the oxygen consumption. The accumulated values were also stored.

Ignition

After calibrating the equipment, the data-logger was started. The sample was placed on an aluminium tray (15 cm x 20 cm) in the load cell. The position was in the middle of the combustion chamber, about 50 mm above the chamber floor. The sample was then immediately ignited and was left to burn until self-extinction. Normally, very little remained on the tray after the test.

All the substances were ignited with a match. Nylon was difficult to ignite and was therefore soaked in 1 dl methanol before ignition. Igniting the nylon with a gas burner for a period of 3 minutes was also tested. The two methods gave the same ignition, but the ignition period was not used in the calculations.

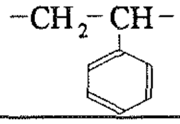
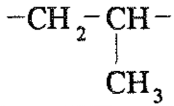
Test substances

In this study, polystyrene, polystyrene with a fire-retardant agent, polypropylene, nylon and PVC were tested, giving a total of 59 tests. In Table 3, a list is given of the number of tests performed and the number reported in this paper. The mass of each sample and the form of the substance are also given. The amounts of material were chosen to give an even rate of heat release of the order 10 kW. The results showed that the peak of the heat release rates varied between 5 and 15 kW. The chemical contents of the materials are given in Table 4.

Table 3. Number of tests performed and analysed in this study, mass of each sample, and the form of the material.

Substance	Performed tests	Analysed tests	Sample mass	Form
Polystyrene	18	10	50 - 60 g	Expanded, cut in blocks of 25 - 30 g
FR Polystyrene	3	-	50 - 60 g	Fire-retardant agent added. Expanded, cut in blocks of 25 - 30 g
Polypropylene	19	7	70 - 75 g	Non-woven sheets folded to 4 layers.
Nylon 6.6	16	11	150 g	Pellets
PVC	3	-		Powder
Total	59	28		

Table 4. Chemical contents of the substances in this report.

Substance	Chemical structure	Chemical formula
Polystyrene		C_8H_8
Polypropylene	 $-CH_2-\underset{\underset{CH_3}{\vert}}{CH}-$	C_3H_6
Nylon 6.6	$NH\,(CH_2)_6\,NHCO\,(CH_2)_4\,CO$	$C_{12}H_{22}O_2N_2$

Calculation methods

As there is an accumulating effect in the combustion chamber, and as the burning times are short (only up to 5 - 10 min.), the integrated values over the whole burning period were used in the calculations and in the presentation of the results. For nylon, the effect of the igniting methanol is taken into consideration by starting the calculations when the methanol fire has declined.

The heat of combustion for the materials was measured in a bomb calorimeter at the Swedish National Testing Institute [4], see Table 5. The values were found to agree with those given in the literature [5]. Heat of formation and other constants used in the calculations, were taken from the literature [6].

The uncertainty in most measurements is of the order of 10%. This includes fluctuations in the flow, temperature and gas analysis equipment. For smoke measurements, the uncertainty is about 30%, and in the result tables the background bias due to smoke logging on the equipment is given for each test.

Heat release

The heat released was calculated using the standard oxygen consumption calorimetry method [7, 2], through measurements of O_2 together with CO_2 and CO.

The volume flow $\dot{V}$ [m^3/s] in the duct was calculated using the exhaust duct area A [m^2], the measured pressure difference, Δp [Pa], and the gas temperature, T_e [K]. 0.9 is the ratio of the average mass flow per unit area to the mass flow per unit area in the centre of the exhaust duct. 1.08 is a calibration constant for the bi-directional Pitot tube.

$$\dot{V} = 22.4 \cdot A \cdot {}^{0.9}\!/_{1.08} \sqrt{\frac{\Delta p}{T_e}}$$

The rate of heat release, q [kW], was calculated using:

$$q = \Delta H_{C,ox} \cdot 1.31 \cdot 1000 \cdot \frac{\phi}{1 + \phi(\alpha - 1)} \dot{V} \cdot X^{\circ}_{O_2}$$

$\Delta H_{C,ox}$ [kJ/gO_2] is the heat released per unit mass oxygen consumed. The values can be found in Table 5. The density of oxygen is 1.31 kg/m^3. A value of 1.1 was used for the expansion factor α. ϕ is the oxygen depletion factor, i.e. the fraction of the incoming air that is fully depleted of its oxygen. This can be calculated from:

$$\phi = \frac{X^{\circ}_{O_2}(1 - X_{CO_2}) - X_{O_2}(1 - X^{\circ}_{CO_2})}{X^{\circ}_{O_2}(1 - X_{O_2} - X_{CO_2})}$$

X° is the mole fraction of gases in the incoming air and X the mole fraction in the exhaust duct. The value of $X^{\circ}_{O_2}$ used was 0.209. In the following calculations, the integrated value of q, i.e. the total heat release, Q [kJ], is used.

Combustion efficiency

The combustion efficiency χ was calculated in two different ways: one based on oxygen consumption calorimetry, and one based on carbon oxide production calorimetry.

Using oxygen consumption calorimetry, the combustion efficiency was calculated using the total heat release, Q [kW], divided by the mass of fuel and the theoretical heat of combustion, employing the constants listed in Table 5. m_{FUEL} [g] is the total mass of consumed fuel, and ΔH_T [kJ/g] is the heat of combustion for the substance.

$$\chi_{OX} = \frac{Q}{m_{FUEL} \cdot \Delta H_T}$$

The combustion efficiency was calculated in a similar way based on carbon dioxide and carbon monoxide production calorimetry [8]. Ψ_i is the maximum yield according to Table 5, and Y_i is the actually measured yield of the products. ΔH_{CO} is the heat of formation for CO, 3.946 kJ/g.

$$\chi_{CO_2+CO} = \frac{\dfrac{\Delta H_T}{\Psi_{CO_2}} \cdot Y_{CO_2} + \dfrac{(\Delta H_T - \Delta H_{CO} \cdot \Psi_{CO})}{\Psi_{CO}} \cdot Y_{CO}}{\Delta H_T}$$

Table 5. Substance-related constants used in the calculations.

Substance	$\Delta H_{C,ox}$ [kJ/gO_2]	ΔH_T [kJ/g]	Ψ_C [g/g]	Ψ_{CO_2} [g/g]	Ψ_{CO} [g/g]	Ψ_{NO_2} [g/g]
Polystyrene	12.93*	39.85**	0.923	3.38	2.15	-
Polypropylene	12.62*	43.31**	0.856	3.14	2.00	-
Nylon	12.30*	29.58**	0.637	2.34	1.49	0.407

* Reference [7]
** Reference [5]

Smoke production

The optical density per meter length, D [ob] is defined as:

$$D = (10/L)\log(I_0/I)$$

L [m] is the beam length of light in the smoke. I_0 is the light intensity without smoke and I the intensity during the test, i.e. with smoke. In this report the integrated value of D multiplied with the volume flow at exhaust temperature, and divided by the total mass loss is used, giving the mass optical density, D_m [obm³/g].

$$D_m = \int \frac{D \cdot \dot{V} \cdot T_e}{m_{FUEL} \cdot T_0} dt$$

Note that the mass optical density is expressed in obm³/g. To obtain the value expressed in m²/g (log scale), D_m is divided by 10. $D_m(\ln 10)/10 = 0.23D_m$ gives the smoke extinction expressed in m²/g (ln scale).

Combustion gas yields

The measured concentrations of CO_2, CO, NO_X and HC (unburned hydrocarbons) are presented as the gas yields, Y_i [g/g]. The combustion gas yields were calculated using measurements of the total production of gas, m_i [g], and the total mass of the sample burned, m_{FUEL} [g].

$$Y_i = \frac{m_i}{m_{FUEL}}$$

In the result diagrams, the CO_2 yield is normalised by the maximum theoretical yield for each substance. Knowing the carbon content of the fuel, Ψ_C [g/g], the maximum yields, Ψ_i, [g/g] of CO_2 and CO, can be calculated. These are given in Table 5. The maximum yields were calculated using the molecular weights, $M(CO_2) = 44.01$ g/mole, $M(CO) = 28.01$ g/mole and $M(C) = 12.01$ g/mole and assuming that all of the carbon is converted to CO_2 and CO, respectively.

$$\Psi_{CO_2} = \Psi_C \cdot \frac{M(CO_2)}{M(C)} \qquad \Psi_{CO} = \Psi_C \cdot \frac{M(CO)}{M(C)}$$

The theoretical yield of NO_2 for nylon is calculated in the same way assuming that the nitrogen content of the fuel is converted to NO_2. $M(NO_2) = 46.01$ g/mole, and $M(\text{Nylon}) = 226.32$ g/mole.

$$\Psi_{NO_2} = 2 \cdot \frac{M(NO_2)}{M(\text{Nylon})}$$

The gas analysis equipment measures unburned hydrocarbons with a boiling point below 200°C. The hydrocarbons are calculated as propane equivalents. Hydrocarbons with a boiling point over 200°C, soot particles etc., are here defined as the survival fraction and are not included in the unburned hydrocarbons.

Toxic potency

The toxic potency of the exhaust gas can be estimated using the N-gas toxicity model developed by NIST [9]. The model takes narcotic gases (CO, CO_2, HCN) as well as irritant gases (HCl, HBr) into account. The model also takes into account the toxic effects which are seen when the oxygen concentration is decreased. The Fractional effective Exposure Dose, FED, is expressed as:

$$FED = \frac{m[CO]}{[CO_2]-b} + \frac{[HCN]}{LC_{50}(HCN)} + \frac{21-[O_2]}{21-LC_{50}(O_2)} + \frac{[HCl]}{LC_{50}(HCl)} + \frac{[HBr]}{LC_{50}(HBr)}$$

All values are in ppm except the O_2 concentration, which is in %. m and b are empirical constants. If the CO_2 concentration is below 5%, m = -18 and b = 122 000. If the CO_2 concentration is above 5%, m = 23 and b = 38 600.

The model is based on 30 minutes' exposure of rats plus a subsequent 14 days post-exposure observation period. By definition, FED = 1 means a 50% mortality rate, but due to non-linearities in the model, 50% mortality is expected when the FED value is 1.1 ± 0.2. A lower FED value means a lower rate of mortality.

Additional contributions must be included in the model for the STEP project since other gases are generated in significant amounts. In this report, the FED expression is modified to:

$$\mathrm{FED} = \frac{m[\mathrm{CO}]}{[\mathrm{CO_2}]-b} + \frac{2}{3}\cdot\frac{[\mathrm{NO_X}]}{\mathrm{LC_{50}(NO)}} + \frac{1}{3}\cdot\frac{[\mathrm{NO_X}]}{\mathrm{LC_{50}(NO_2)}} + \frac{21-[\mathrm{O_2}]}{21-\mathrm{LC_{50}(O_2)}}$$

In the calculations in this study, values integrated over the whole burning period were used. The toxicity calculations are the exception, due to the used N-gas model. For toxicity calculations, the peak values were used instead, together with the actual air flow rate and mass loss rate. In the expression above, the NO/NO_2 ratio is assumed to be 2/1. This is because measurements were made on NO_X rather than NO or NO_2.

The following LC_{50}(i) values were used:

$LC_{50}(O_2)$	5.4 %	[9]
$LC_{50}(NO)$	7000 ppm	[10]
$LC_{50}(NO_2)$	170 ppm	[11]

The FED value depends on the produced volume of smoke gases, and the mass burned. Therefore an LC_{50} value was calculated. The LC_{50} value is defined as the burned mass of material per unit air volume in which the smoke gases are diluted, that causes 50% mortality in exposed rats. The LC_{50} value [g/m³] was calculated using the mass loss rate, $\dot{m}_{FUEL}$ [g/s] and the air flow $\dot{V}$ [m³/s].

$$LC_{50} = \frac{\dot{m}_{FUEL}}{FED \cdot \dot{V}}$$

The mass loss measurement proved to be sensitive to pressure differences in the combustion chamber when the smaller opening was used. Therefore, the mass loss rate was expressed as:

$$\dot{m}_{FUEL} = m_{FUEL} \cdot \frac{q}{Q}$$

It should be noted that the results of the estimates of FED and LC_{50} values described above might be misleading for some substances. First of all, the effects of the individual toxicants are assumed to be additive, but this is not necessarily the case. For example, it is known that NO_2 and CO_2 show synergistic effects. Other substances show antagonistic effects. The effects of the organic decomposition products are not included and furthermore, long-term effects can not be evaluated by the model. Therefore, LC_{50} should primarily be used to compare different experimental test results.

Test results

The results of the measurements are presented here in the form of diagrams. The numbers referring to the tests can be found in the end of this chapter:

Table 6:	Opening heights and external heat flux.
Table 7:	Mean combustion efficiency calculated in two ways.
Table 8:	Total and peak heat release and mass loss.
Table 9:	Mean gas yields.
Table 10:	Peak gas concentrations and toxic potential.

In Appendices 1 to 5, diagrams are presented, showing RHR, mass loss, and the production rate of smoke, CO_2, CO, NO_X and HC as a function of time for each test, including the tests not analysed in this study.

Although up to four tests were carried out with the same test set-up, no mean test values were calculated, thus the results presented are the actual test results.

As previously mentioned, the uncertainty is 10% for gas yields and for the combustion efficiency. For smoke production, the uncertainty is 30%. Fluctuations in both the gas flow and the gas analysis measurements are included.

Combustion efficiency

In Figures 3 (for polystyrene), 4 (polypropylene) and 5 (nylon), the combustion efficiency (calculated from oxygen consumption) is compared with the normalised CO_2 yield. All data show good linearity, independent of the opening height and the external heat.

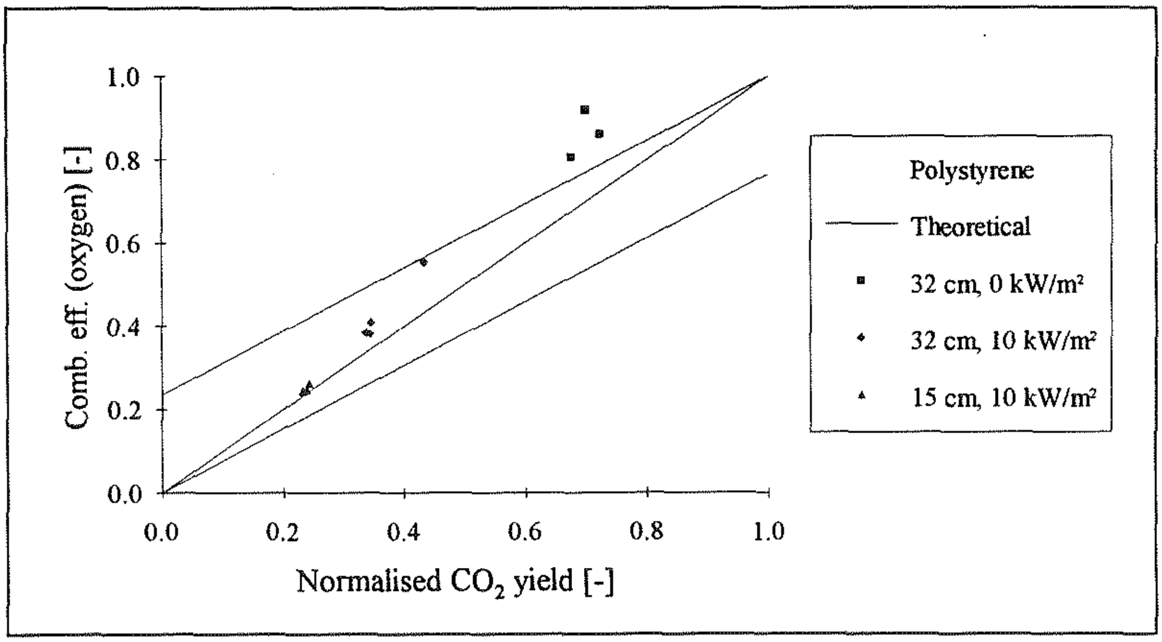


Figure 3. Combustion efficiency calculated from oxygen consumption calorimetry compared with the normalised CO_2 yield for polystyrene.

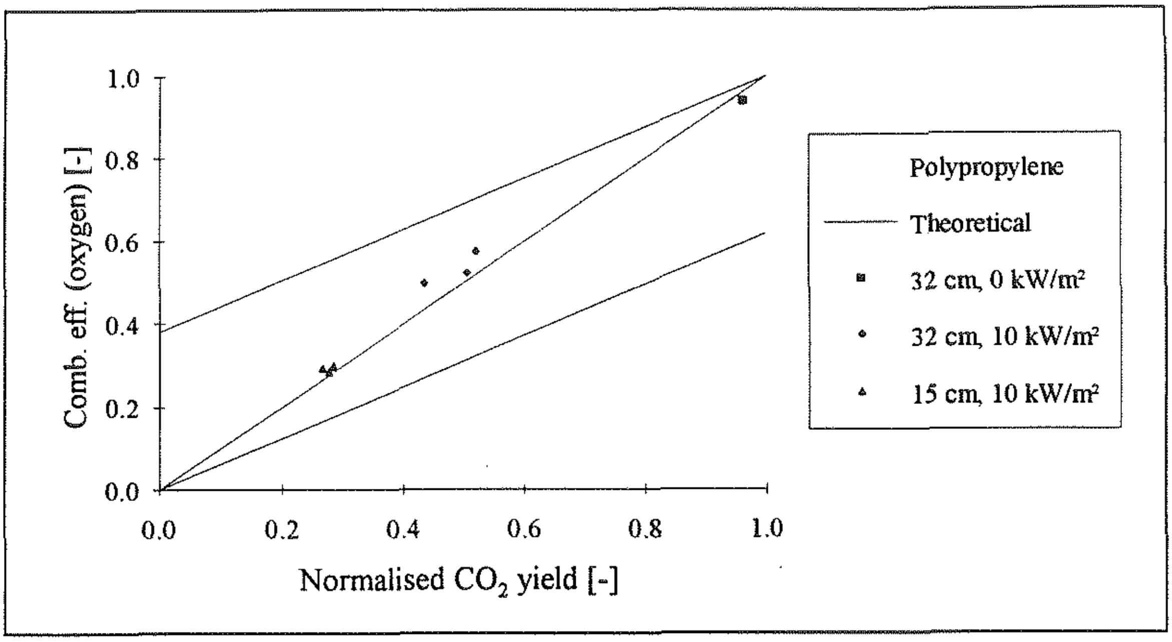


Figure 4. Combustion efficiency calculated from oxygen consumption calorimetry compared with the normalised CO_2 yield for polypropylene.

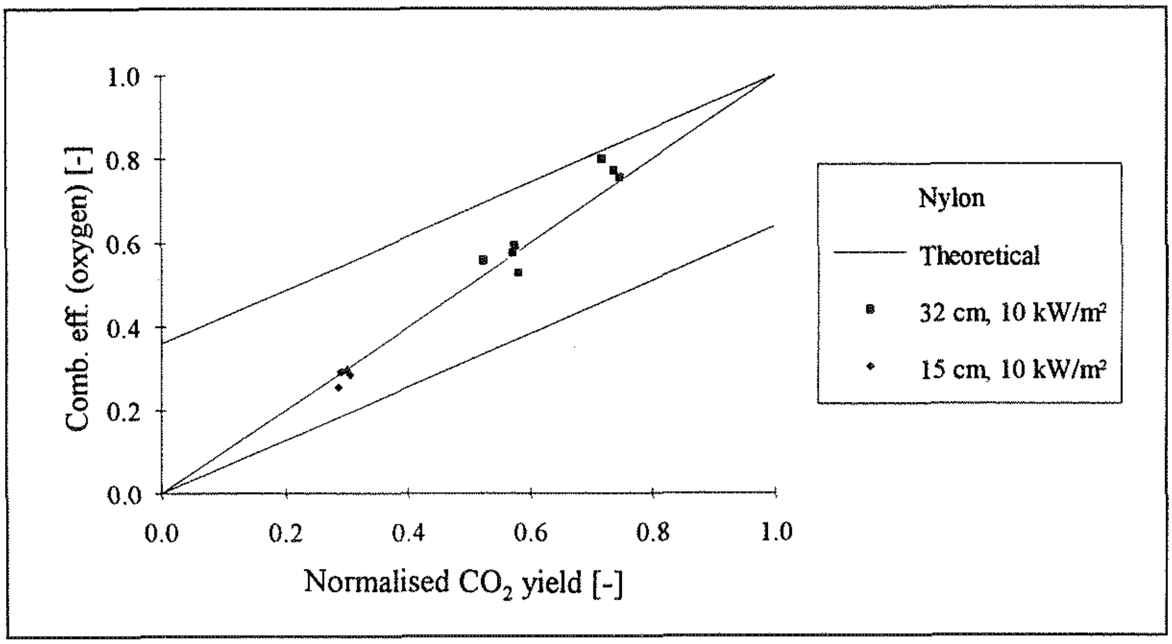


Figure 5. Combustion efficiency calculated from oxygen consumption calorimetry compared with the normalised CO_2 yield for nylon.

Three theoretical lines are included in each figure. The lowest line represents the energy content of the CO_2 produced. The line in the middle represents the energy content if hydrogen is consumed in the same proportion as the H/C ratio in the fuel, i.e. if the relation between the combustion efficiency and the CO_2 yield is linear. Finally, the top line represents the total energy content if all the hydrogen in the fuel is consumed and the energy produced by the CO_2 is added.

Comparing the chemical combustion efficiencies calculated from oxygen consumption calorimetry and from carbon oxides generation calorimetry gives the results, shown in Figure 6. The combustion efficiency is defined as the energy released divided by the maximum possible energy release. The results should be the same for the two methods, if hydrogen is converted to H_2O in the same proportion that carbon is converted to CO_2.

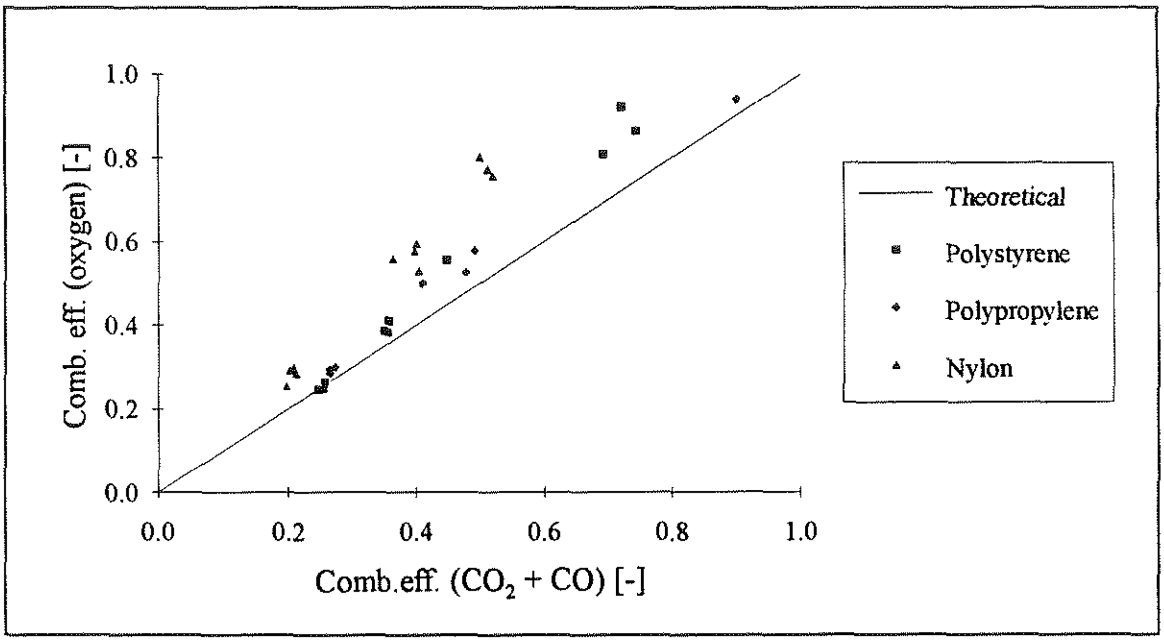


Figure 6. Comparison between the combustion efficiencies calculated from oxygen consumption and carbon oxides production calorimetry, respectively.

For all the substances, the CO_2 yield is lower than the theoretical value, or alternatively, the combustion efficiency is higher.

The combustion efficiency based on oxygen consumption is higher than that based on CO_2 and CO for the three substances. The difference is quite constant, and is larger than the uncertainty of 10%. This is probably due to the same reason that the combustion efficiency based on oxygen was higher than predicted compared with the CO_2 yield.

The differences could be attributed to systematic measuring errors. It may also be that the hydrogen in the fuel is converted to H_2O in a larger extent than carbon to CO_2. This explanation is, however, not plausible, as the error is small for low CO_2 yields and larger at high yields.

It is possible that the error could be attributed to the consumption of oxygen to form oxygen containing products other than CO_2 and H_2O, i.e. CO, NO_X etc. Generally, however, these values are low, and with this explanation, the error would be large at a low combustion efficiency and small at complete combustion.

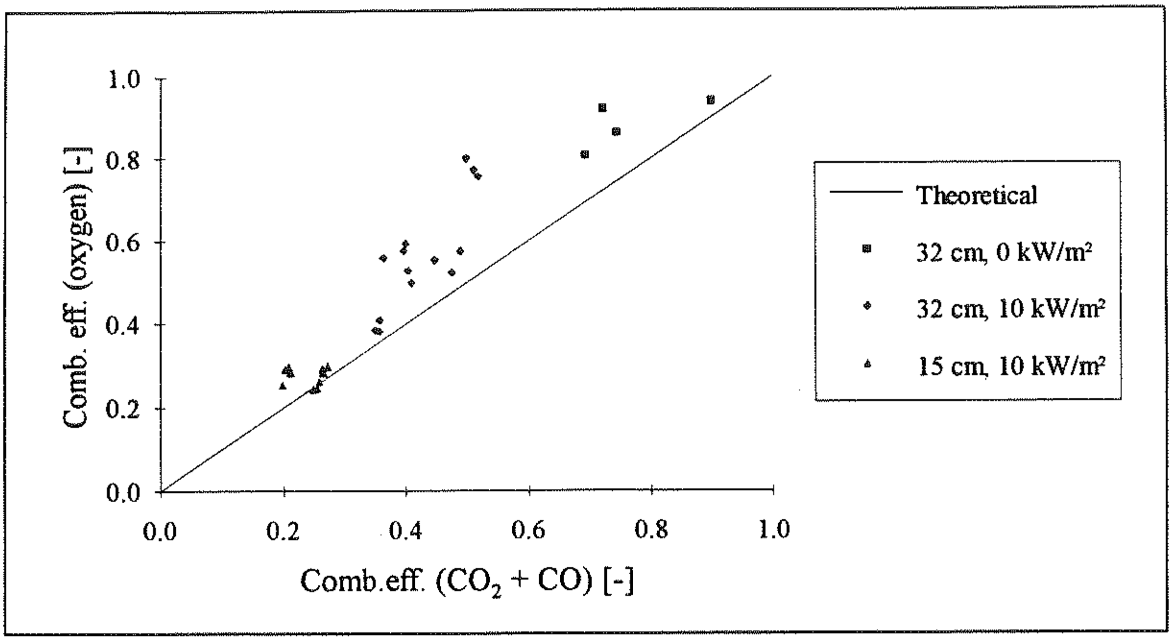


Figure 7. As in Figure 6, but showing the test set-up (chamber opening height and external heat) instead of the tested substances.

Figure 7 is similar to Figure 6, but shows that the test set-up; the chamber opening height and the heat flux, have a larger impact on the result than the material. The data in Figure 7 are gathered fairly well, while those in Figure 6 are well mixed along the whole line.

Smoke production

The smoke production is shown in Figure 8 in terms of the mass optical density. Polystyrene shows a large increase in the smoke production with an increasing CO_2 yield. During tests with a low degree of ventilation (low CO_2 yield), large smoke "flakes" could be seen. This means that the buoyancy of the smoke was not high enough for all smoke particles to be collected in the exhaust hood.

For nylon, the generation of smoke was quite constant, compared with the CO_2 yield. Polypropylene shows a more complex pattern, but the tendency is for the smoke generation to be constant.

The smoke yield [g/g] can only be calculated if the particle optical density, POD, and the H/C ratio of the smoke are known. The POD varies with the wavelength of the light used in the light absorption measurements, the burning material and the degree of ventilation. This means that POD values for well-ventilated fires from the literature can not be used with reasonable accuracy [12].

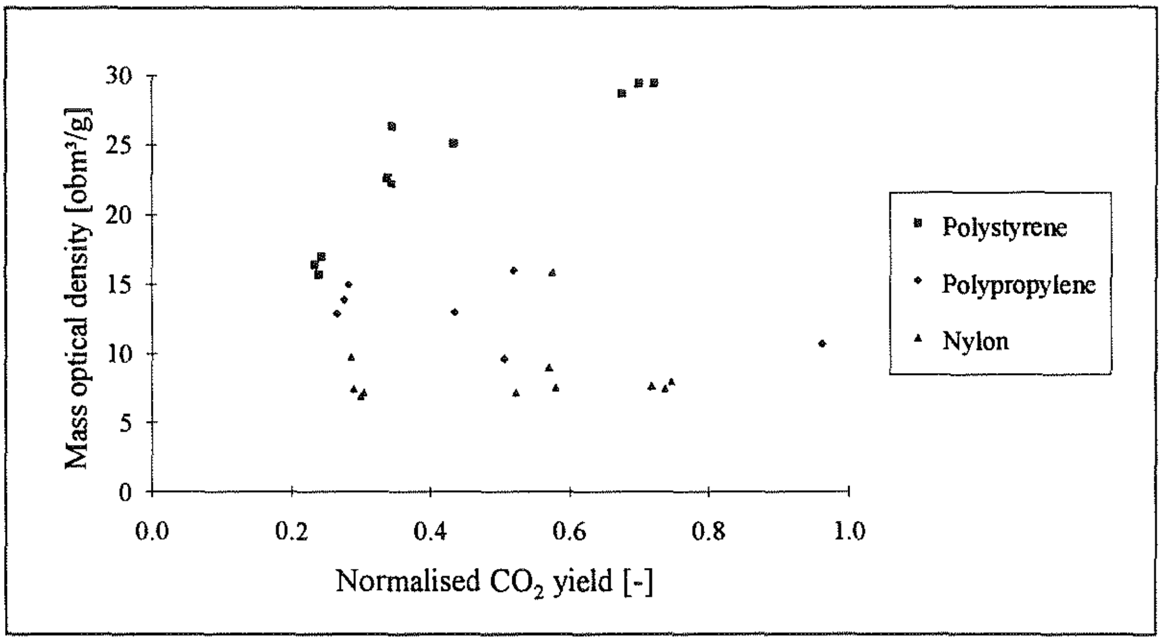


Figure 8. Smoke production in terms of the mass optical density compared with the normalised CO_2 yield for the three substances tested.

CO yield

The CO yield appeared to be the most complex of the parameters to describe. It also exhibits different patterns for the different substances. Polystyrene shows the highest yields. For nylon, the CO yield is low, and decreases with decreasing CO_2. Polypropylene shows a pattern somewhere in between those of polystyrene and nylon.

The ratio between CO_2 and CO was found to be almost independent of the external heat in the range investigated. The expected increase in CO yield at low yields of CO_2 which is reported by others can not be seen for any of the materials tested here.

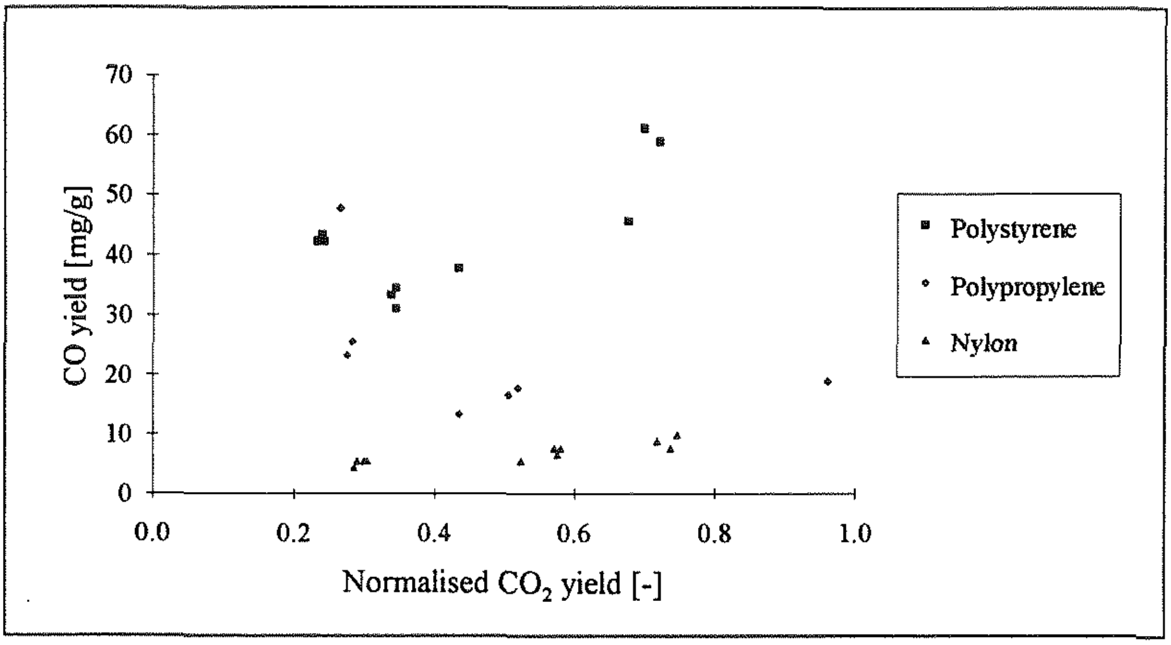


Figure 9. CO yield as a function of the normalised CO_2 yield for the three materials tested.

NO_X yield

The yields of NO_X are shown in Figure 10. They are quite constant, and are independent of both radiation level and degree of ventilation. The yields are low for the two materials without chemically bound nitrogen. For nylon, which contains nitrogen, the yields of NO_X are significant, and about 20 times higher: 13 to 18 mg/g. The theoretical yield of NO_2 is, however, much higher: 407 mg/g.

The smoke temperatures were not high enough for any significant amounts of NO_X to be produced due to the oxidation of nitrogen in the air.

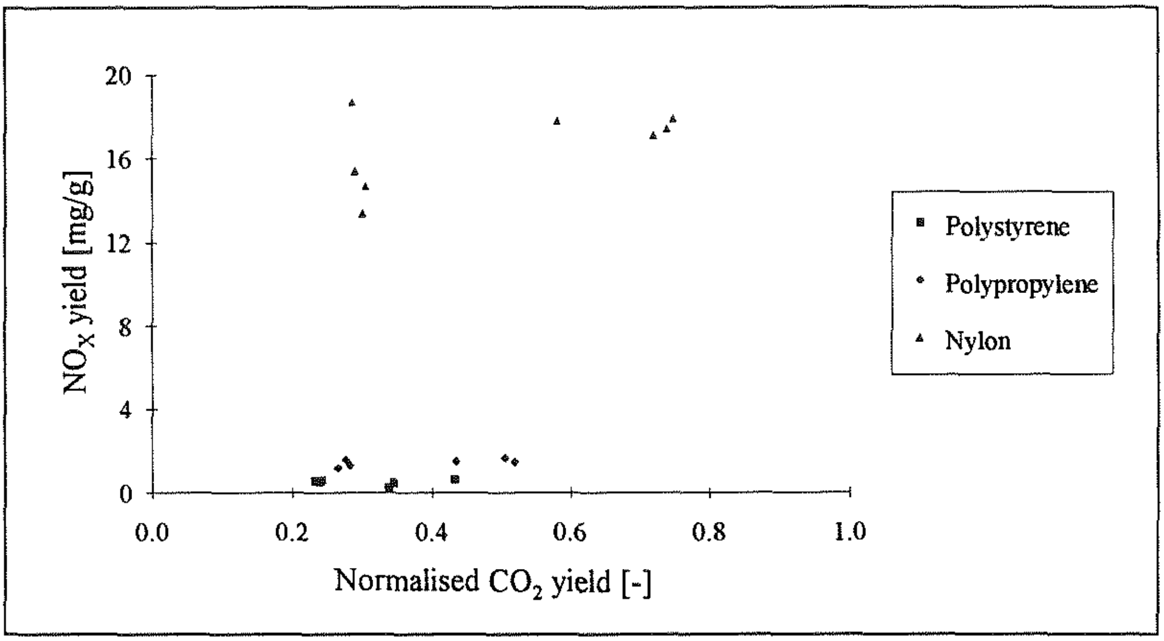


Figure 10. The yield of NO_X compared with the normalised yield of CO_2 for the three materials. For polystyrene and polypropylene, the yields are low, while for nylon a significant amount of NO_X is produced.

HC yield

The production of unburned hydrocarbons (with a boiling point above 200°C), calculated as propane equivalent, is shown in Figure 11.

The HC yields are quite constant, and independent of both radiation level and degree of ventilation for all three substances. Polystyrene has a yield of 30 to 35 mg/g, polypropylene of 5 to 10, and nylon about 1 mg/g. The pattern is similar to that of the smoke production shown in Figure 8; polystyrene has the highest yields, and nylon the lowest.

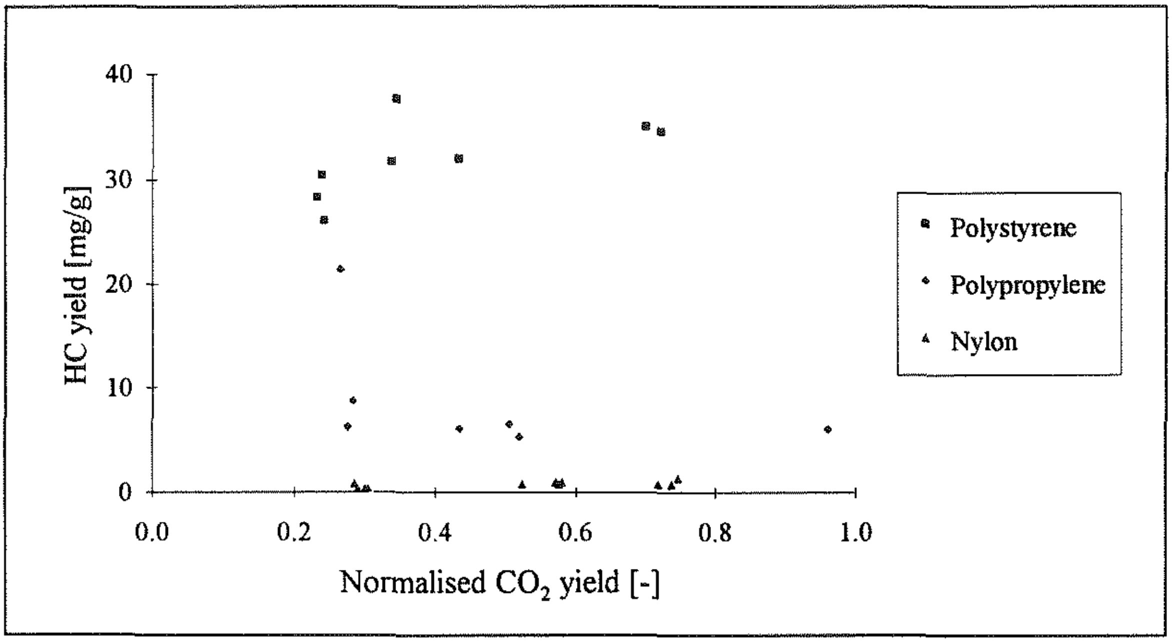


Figure 11. Yield of unburned hydrocarbons as a function of the normalised yield of CO_2 *for the three materials tested.*

Toxic potency

In Figure 12 the toxic potencies of the materials are shown, expressed as the Fractional effective Exposure Dose, FED. An interesting factor is how large a part of the FED is due to the generation of NO_2, for the nitrogen-containing nylon.

No major difference in toxicity was found between polystyrene and polypropylene. As a significant part of the nitrogen in the material is converted to NO_2, the toxic potency is higher for nylon than for substances without nitrogen.

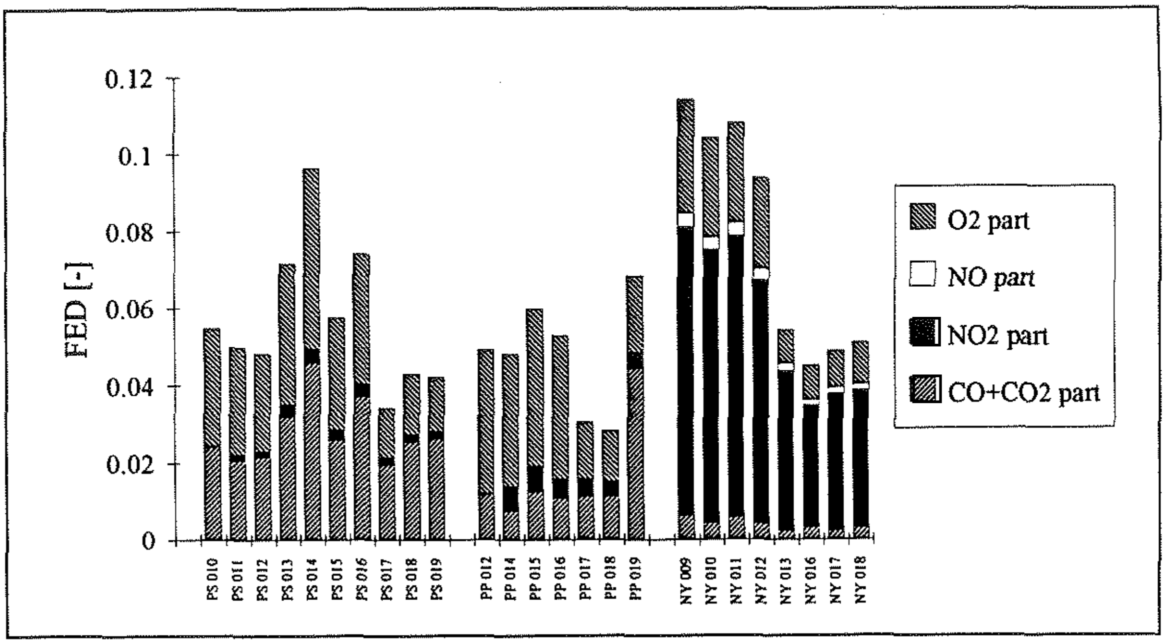


Figure 12. The FED values obtained from the tests expressed as the sum of toxic potency from lack of O_2, and generation of NO, NO_2, CO and CO_2.

An LC_{50} value can be calculated from the FED, and the results are shown in Figure 13. The LC_{50} values vary by a factor of 2 for all three materials. The reduction in toxic potential of the smoke is probably due to the low combustion efficiency, giving a low O_2 consumption and low CO_2 production.

It is important to note that all toxicants are not included in the toxicity model. The survival fraction and decomposition products from the original substance, the heavier hydrocarbons and the smoke are examples of products that are not included in the model. It can therefore not be assumed that the model reflects all aspects of the toxicity problem.

Nylon is more toxic than the other two polymers at the same CO_2 yield. This is because of the large impact on the toxicity of the NO_X. The toxicity associated with nylon is reduced by a factor of less than 2 at a lower CO_2 yield.

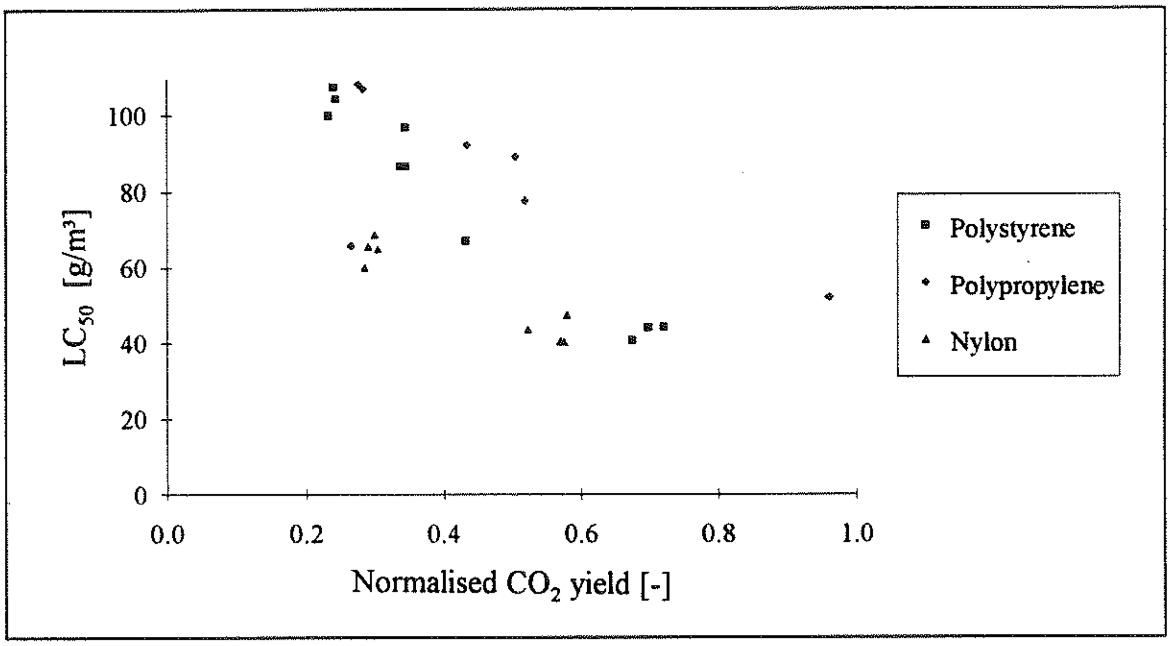


Figure 13. LC_{50} as a function of the normalised CO_2 yield for the materials tested.

Carbon balance

Figure 14 shows the fraction of carbon measured in the tests as a function of the combustion efficiency. The fraction of carbon from CO_2, CO and HC is included in the measured part of carbon. The unburned hydrocarbons are calculated as the propane equivalent. The fraction of carbon that is not quantified consists mainly of the survival fraction of heavier hydrocarbons, decomposition products, and soot. The carbon content of the smoke can only be calculated if the particle optical density, POD, and the H/C ratio of the smoke are known.

In well ventilated fires, almost all the carbon is recovered, but at low combustion efficiency, only 30% of the carbon from the fuel is detected.

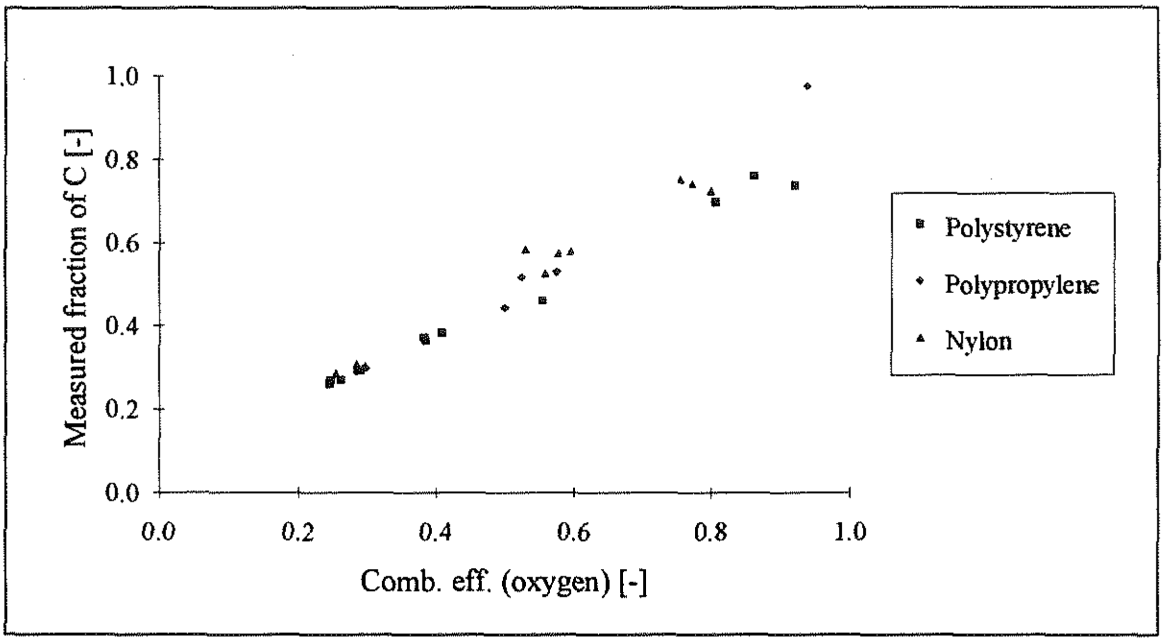


Figure 14. The measured part of carbon compared with the combustion efficiency. The yields of CO_2, CO and HC are included in the measured part of C. The carbon in the soot and the survival fractions is not included.

Data tables

Table 6. Opening heights and external radiation for each test.

Test no.	Open. h. [cm]	Ext. rad. [kW/m²]
PS 010	32	0.0*
PS 011	32	0.0*
PS 012	32	0.0*
PS 013	32	9.2*
PS 014	32	9.0*
PS 015	32	9.0*
PS 016	32	9.2*
PS 017	15	10.8**
PS 018	15	6.6**
PS 019	15	9.1**
PP 012	32	0.0*
PP 014	32	8.6*
PP 015	32	9.2*
PP 016	32	9.0*
PP 017	15	5.7**
PP 018	15	5.5**
PP 019	15	4.8**
NY 006	32	10.1*
NY 007	32	10.7*
NY 008	32	9.8*
NY 009	32	8.8*
NY 010	32	9.0*
NY 011	32	8.4*
NY 012	32	9.0*
NY 013	15	11.6*
NY 016	15	9.1**
NY 017	15	10.1**
NY 018	15	8.6**

PS: Polystyrene, PP: Polypropylene, NY: Nylon.
* Mean value from two radiometers ** One radiometer

Table 7. Mean combustion efficiency calculated in two different ways.

Test no.	χ_{ox} [-]	c_{co_2+co} [-]
PS 010	0.81	0.69
PS 011	0.92	0.72
PS 012	0.86	0.74
PS 013	0.55	0.45
PS 014	0.41	0.36
PS 015	0.38	0.36
PS 016	0.38	0.35
PS 017	0.26	0.26
PS 018	0.25	0.26
PS 019	0.25	0.25
PP 012	0.94	0.90
PP 014	0.52	0.48
PP 015	0.58	0.49
PP 016	0.50	0.41
PP 017	0.30	0.27
PP 018	0.29	0.26
PP 019	0.29	0.26
NY 006	0.76	0.52
NY 007	0.77	0.51
NY 008	0.80	0.50
NY 009	0.53	0.40
NY 010	0.59	0.40
NY 011	0.58	0.40
NY 012	0.56	0.36
NY 013	0.26	0.20
NY 016	0.29	0.20
NY 017	0.29	0.21
NY 018	0.30	0.21

Table 8. Total and peak heat release and mass loss in the tests.

Test no.	Total heat release [kJ]	Total mass loss [g]	Rate of heat release [kW]	Mass loss rate [g/s]	Air flow [m³/s]
PS 010	1710	43	14.3	0.36	0.160
PS 011	2200	60	13.0	0.36	0.160
PS 012	2060	60	11.8	0.34	0.160
PS 013	1100	50	13.9	0.63	0.130
PS 014	980	60	17.8	1.09	0.130
PS 015	910	60	11.8	0.78	0.140
PS 016	920	60	13.3	0.87	0.135
PS 017	520	50	5.4	0.52	0.145
PS 018	490	50	6.6	0.67	0.145
PS 019	510	53	5.9	0.61	0.145
PP 012	4560	110	12.0	0.29	0.110
PP 014	1590	70	13.0	0.57	0.130
PP 015	1740	70	15.4	0.62	0.130
PP 016	1510	70	13.5	0.62	0.125
PP 017	970	75	6.3	0.48	0.145
PP 018	920	75	5.8	0.47	0.150
PP 019	950	75	8.7	0.68	0.150
NY 006	3350	150			
NY 007	3430	150			
NY 008	3450	150			
NY 009	2350	150	10.8	0.69	0.125
NY 010	2640	150	9.4	0.53	0.125
NY 011	2560	150	9.9	0.58	0.130
NY 012	2480	150	8.9	0.54	0.130
NY 013	850	112	4.2	0.56	0.170
NY 016	1300	150	3.8	0.43	0.145
NY 017	1270	150	3.9	0.47	0.145
NY 018	1320	150	4.7	0.53	0.150

PS: Polystyrene, PP: Polypropylene, NY: Nylon

Table 9. Mean gas yields in the tests.

Test no.	CO_2 yield [g/g]	Mass opt. density [obm^3/g]	CO yield [mg/g]	NO_X yield [mg/g]	HC yield [mg/g]
PS 010	2.29	28.7	46		
PS 011	2.37	29.4 ± 0.6	61		35
PS 012	2.44	29.4 ± 1.2	59		35
PS 013	1.47	25.1 ± 3.6	38	0.63	32
PS 014	1.17	26.3 ± 0.4	34	0.45	75
PS 015	1.17	22.2 ± 1.4	31		38
PS 016	1.14	22.6 ± 1.5	33	0.24	32
PS 017	0.82	17 ± 1.5	42	0.59	26
PS 018	0.81	15.7 ± 1.9	43	0.52	30
PS 019	0.79	16.4 ± 1.6	42	0.56	28
PP 012	3.02	10.71	19		6.1
PP 014	1.59	9.62 ± 1.7	17	1.67	6.6
PP 015	1.63	16 ± 0.9	18	1.47	5.4
PP 016	1.37	13 ± 1.0	13	1.5	6.1
PP 017	0.89	15 ± 4.5	26	1.32	8.9
PP 018	0.87	13.9 ± 1.2	23	1.59	6.3
PP 019	0.83	12.9 ± 1.8	48	1.19	21.4
NY 006	1.74	8 ± 2.7	10	17.9	1.4
NY 007	1.72	7.5 ± 2.4	8	17.4	0.78
NY 008	1.68	7.7 ± 1.6	9	17.1	0.88
NY 009	1.36	7.55 ± 1.2	8	17.8	1.04
NY 010	1.34	15.9 ± 0.3	7		0.88
NY 011	1.33	9.04 ± 0.7	8		1.05
NY 012	1.22	7.2 ± 1.8	6		0.88
NY 013	0.67	9.8 ± 2.7	4	18.7	0.9
NY 016	0.68	7.5 ± 0.1	6	15.4	0.36
NY 017	0.71	7.18 ± 0.2	6	14.7	0.45
NY 018	0.70	6.93 ± 0.0	6	13.4	0.43

PS: Polystyrene, PP: Polypropylene, NY: Nylon

Table 10. Peak gas concentrations and toxic potential in the tests.

Test no.	O_2 conc. [%]	CO_2 conc. [ppm]	CO conc. [ppm]	NO_X conc. [ppm]	FED [-]	LC_{50} [g/m³]
PS 010	20.52	3630	160	0.01	0.055	42.9
PS 011	20.56	3300	138	0.60	0.050	39.7
PS 012	20.60	3410	143	0.60	0.049	36.0
PS 013	20.53	4730	209	1.40	0.065	60.0
PS 014	20.40	5720	297	1.70	0.088	47.9
PS 015	20.60	3960	171	1.20	0.054	71.6
PS 016	20.55	5060	242	1.45	0.069	72.3
PS 017	20.82	1430	132	0.80	0.033	424.5
PS 018	20.78	1595	171	0.85	0.042	240.5
PS 019	20.80	1650	176	0.85	0.041	305.5
PP 012	20.39	4950	77	0.02	0.051	48.3
PP 014	20.45	3520	50	3.10	0.049	49.0
PP 015	20.34	3850	83	3.20	0.061	69.0
PP 016	20.40	3850	72	2.40	0.054	82.7
PP 017	20.76	1375	77	2.10	0.031	161.6
PP 018	20.79	1430	77	1.80	0.029	276.8
PP 019	20.68	1870	297	1.90	0.069	145.0
NY 006						
NY 007						
NY 008						
NY 009	20.51	3300	42	38.00	0.116	33.1
NY 010	20.57	2750	29	36.00	0.106	33.3
NY 011	20.57	3080	39	37.00	0.110	33.7
NY 012	20.61	2640	28	32.00	0.095	30.8
NY 013	20.86	880	17	21.00	0.055	49.5
NY 016	20.85	1045	22	16.00	0.046	69.5
NY 017	20.85	990	17	18.00	0.049	23.7
NY 018	20.82	1100	22	18.00	0.052	64.5

PS: Polystyrene, PP: Polypropylene, NY: Nylon

Discussion

The goals of this study were to investigate how changes in external radiation and oxygen supply affect the production of smoke and toxic gases in a 1/3-scale room fire.

The results of the measurements are presented as mean values from each period. As the tests were performed in a 1/3-scale room, the fires were well ventilated at ignition, and at the end of the test more or less under-ventilated. The measured rate of heat release from the solid materials burned in these tests increased with time until most of the fuel was consumed, and did not reach a stationary state. Due to the nature of the toxicity model, the peak values were used instead of the mean values in the toxicity calculations.

The impact of external radiation is mainly to increase the pyrolysis rate and thus the rate of heat release and, in these experiments, to drive the fire into the under-ventilated regime. Thus the level of external heat flux seems to affect only the pyrolysis rate and the temperature level in the upper layer of the room (external radiation comes from heated walls). However, some materials, such as nylon and PVC need additional heat to ignite.

In fires in enclosed spaces changes in the availability of oxygen are reflected by changes in the combustion efficiency and the generation of smoke and toxic products.

With a decreasing level of ventilation, the combustion efficiency and the production of CO_2 become lower as expected and in agreement with the literature [8, 13, 14]. The combustion efficiency is similar whether calculated using oxygen consumption or carbon oxide calorimetry.

The production of smoke is constant or increases slightly with reduced ventilation for nylon and polypropylene, as expected from literature values [8]. The decrease in smoke production for polystyrene with decreased ventilation was unexpected and could be attributed to a low convected heat and large smoke particles which resulted in smoke fall-out on the floor and beside the collecting hood at under-ventilated conditions.

The production of CO is a complex process. An interesting result from these tests is that the CO yield does not increase with decreasing CO_2 yield, as in experiments with the same materials under a hood [8]. One explanation might be that in hood experiments, with a great deal of entrained air in the fire plume, the conversion of CO to CO_2 is frozen out, resulting in higher levels of products of incomplete combustion [13, 14]. In these tests, the upper layer temperature was probably higher and the gas residence times longer to allow nearly complete oxidation of CO to CO_2 at over-ventilated and slightly under-ventilated conditions. It seems clear [14] that the upper layer in room fires is far from homogeneous and that reactions with CO must take place within the upper layer in certain scenarios. More detailed studies, both experimental and theoretical (CFD) are being initiated.

The yields of NO_X were low for the two substances without chemically bound nitrogen, since the conditions in ordinary room fires do not promote the formation of NO_X from the nitrogen in the air. For nylon, which has fuel nitrogen, the yields are significant: about 20 times higher. There are no major variations in the yield depending on the degree of ventilation. However, the yields are only 3 to 5% of the theoretical maximum yield.

The yields of unburned low-molecular weight hydrocarbons, measured as propane equivalents, are generally low, 1 to 40 mg/g, and there are no major variations with the degree of ventilation. However, by studying at the combustion efficiency and the carbon balance one can conclude that soot, monomers, unburned fuel etc., increase drastically with reduced ventilation to nearly 70%. This part, called the survival fraction, is a topic which needs more comprehensive study.

For all substances, the calculated LC_{50} values for the measured gases are relatively high. Lack of oxygen and the CO/CO_2 ratio have the largest impact for polystyrene and polypropylene. For nylon, the production of NO_X represents the main part of the toxicity. It is important to note that all toxicants are not included in the toxicity model. The survival fraction and the decomposition products from the original materials are not included in the model. These products represent almost 0% of the carbon content under well-ventilated conditions and up to 70% at under-ventilated conditions. It may thus not be assumed that the toxicity model reflects all aspects of the toxicity problem, especially at under-ventilated conditions.

References

[1] Nordtest Inquiry No 1131-93, *Heat Flux Meters: Calibration*, Finland, 1993.

[2] NT FIRE 025, *Surface Products: Room fire tests in full scale*, Approved 1991-05 Nordtest, ISSN 0283-7188, Finland, 1991.

[3] McCaffrey, B. J., Heskestad, G., *A Robust Bidirectional Low-Velocity Probe for Flame and Fire Application*, Combustion and Flame 26, pp 125 - 127, 1976

[4] Månsson, M., Blomqvist, P., Isaksson, I., Rosell, L., *Sampling and Analysis of Smoke Gas Components from the SP Industry Calorimeter,* SP- Swedish National Testing and Research Institute. SP Report 1994:35, 1994

[5] Drysdale, D. D., *Thermochemistry*, SFPE handbook of Fire Protection Engineering, ed. P. J. DiNenno, SFPE, 1988.

[6] Drysdale, D. D. *An Introduction to Fire Dynamics*, John Wiley & Sons Ltd, 1985.

[7] Babrauskas, V., Grayson, S. J., *Heat Release in Fires*, Elsevier Applied Science, England 1992.

[8] Tewardsson, A., Jiang, F. H. and Morikawa, T., *Ventilation-Controlled combustion of Polymers*, Combustion and Flame 95, pp 151-169, 1993.

[9] Babrauskas, V. et al., *Toxic Potency Measurement for Fire Hazard Analysis*, NIST special publication 827, U.S. Government Printing Office, 1991.

[10] *Registry of Toxic Effects of Chemical Substances,* RTECS database.

[11] Purser, D. A., *Interactions Between Behaviour Patterns and Physiological Impairment in Escape from Room Fire.* Interflam '93, Oxford, UK, ed. Franks, C.A., Interscience Communications Ltd., pp 579-593, 1993.

[12] Newman, J. S., Steciak, J., *Characterization of Particulates from Diffusion Flames*, Combustion and Flame 67, pp 55-64, 1987.

[13] Gottuk, D. T., Roby, R. J., Peatross, M. J., and Beyler, C. L., *Carbon Monoxide Production in Compartment Fires*, Journal of Fire Protection Engineering, vol. 4, pp 133-150, 1992.

[14] Pitts, W. M., *The Global Equivalence Ratio Concept and the Prediction of Carbon Monoxide Formation in Enclosure Fires*, NIST Monograph 179, U.S. Government Printing Office, 1994.

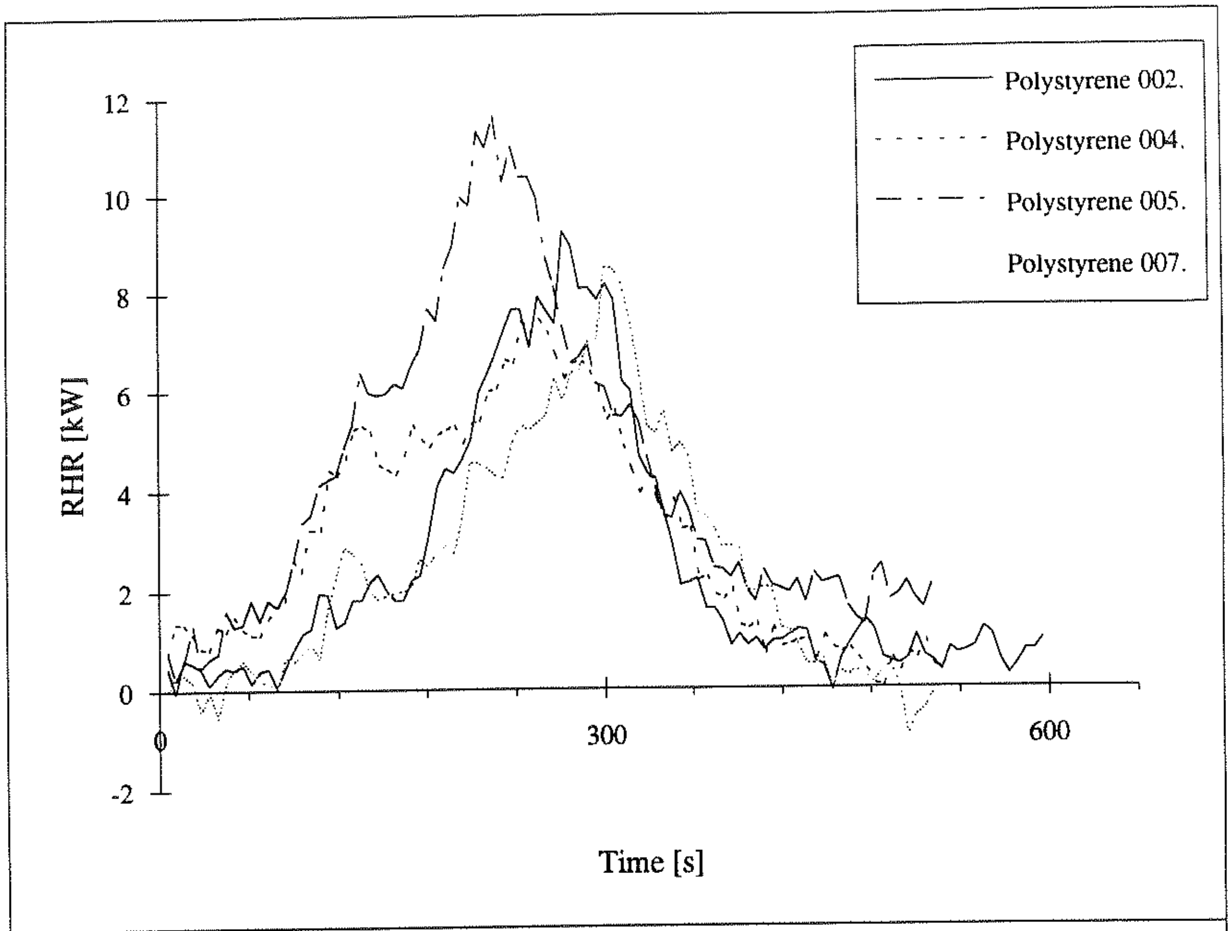
Appendix 1: Test results for POLYSTYRENE

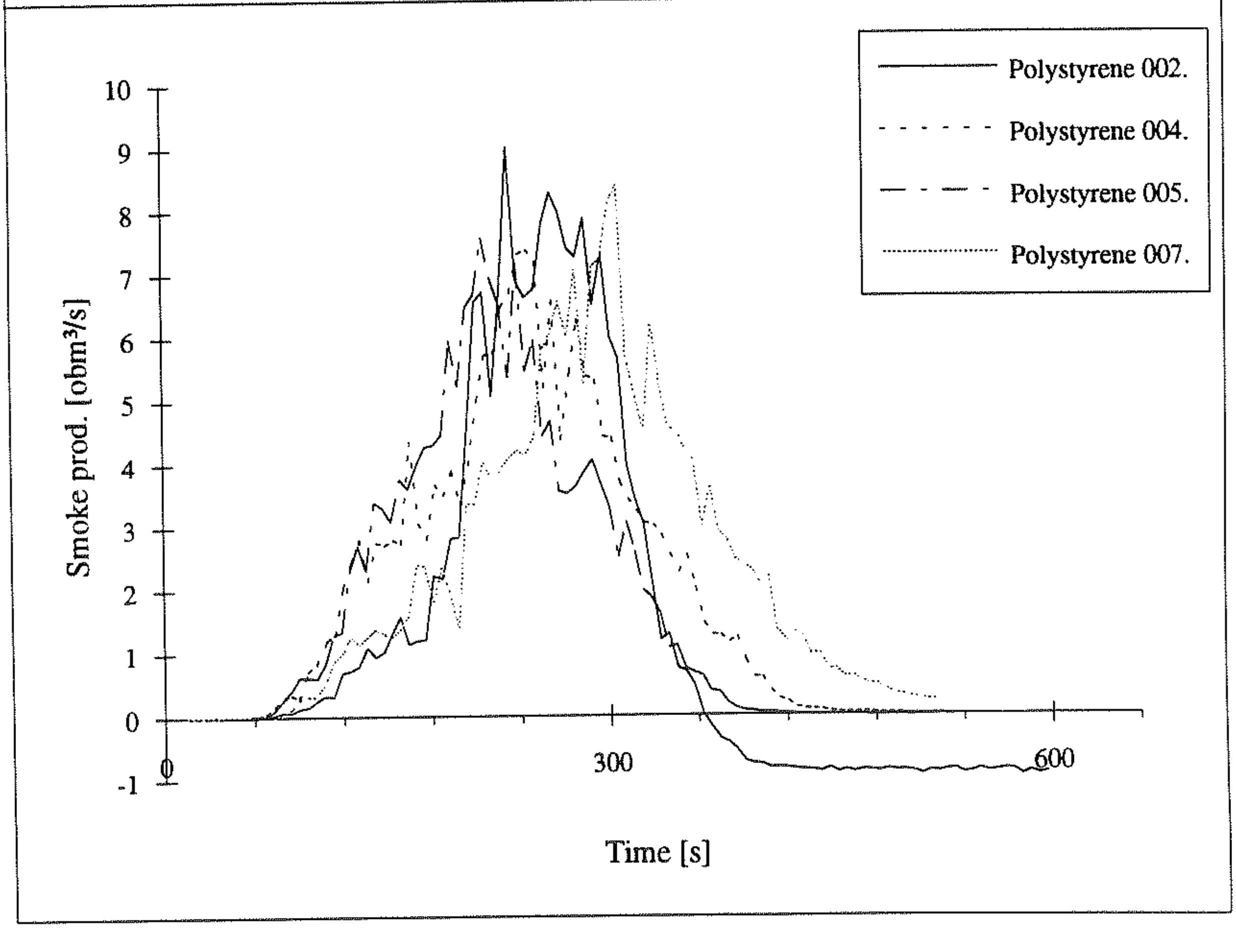
Contents:

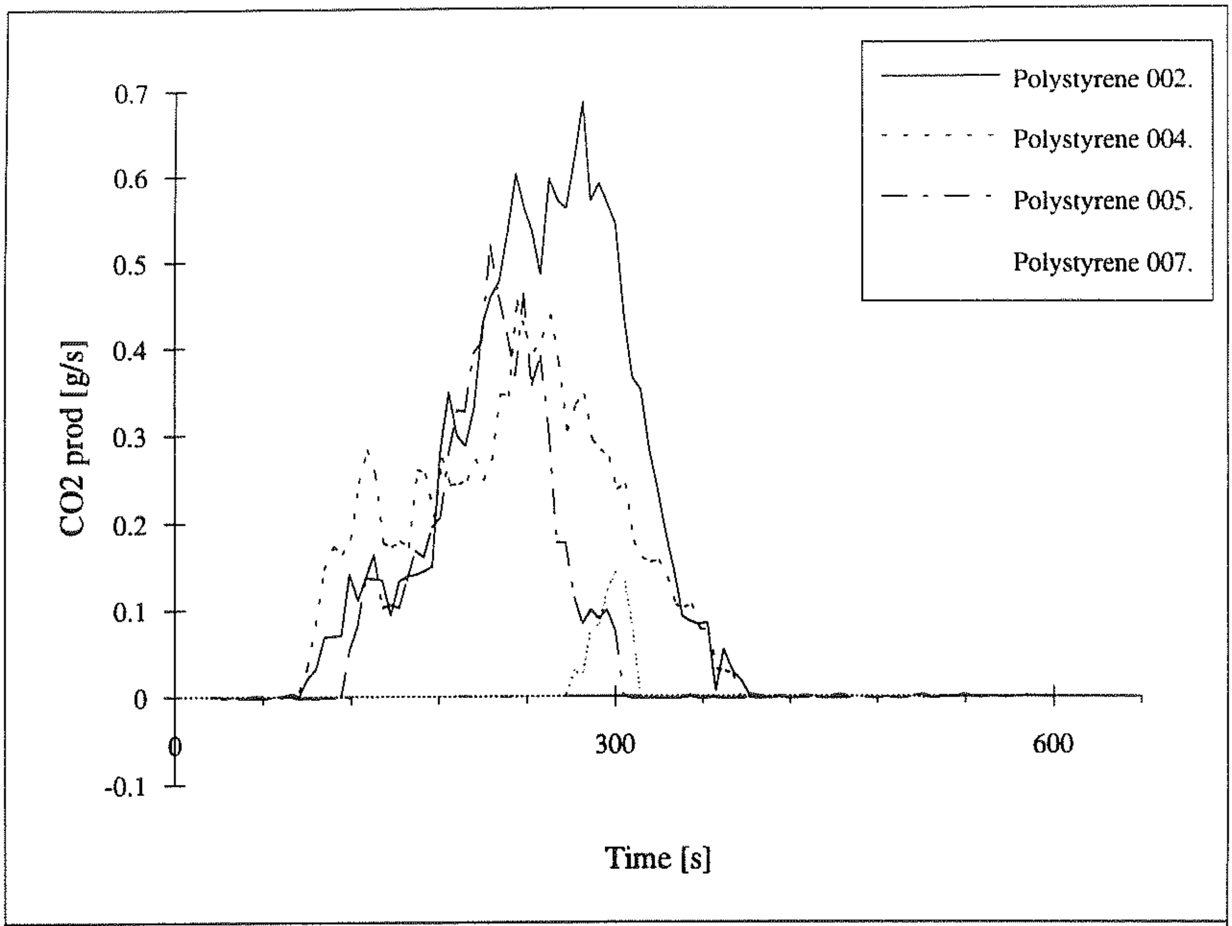
Test	RHR page	Smoke prod. page	CO_2 prod. page	CO prod. page	NO_X prod. page	C_nH_{2n} prod. page	Mass loss page
002	1	1	2	2	3	3	4
004	1	1	2	2	3	3	4
005	1	1	2	2	3	3	4
007	1	1	2	2	3	3	4
008	5	5	6	6	-	-	8
010	5	5	6	6	-	-	8
011	5	5	6	6	7	7	8
012	5	5	6	6	7	7	8
013	9	9	10	10	11	11	12
014	9	9	10	10	11	11	12
015	9	9	10	10	11	11	12
016	9	9	10	10	11	11	12
017	13	13	14	14	15	15	16
018	13	13	14	14	15	15	16
019	13	13	14	14	15	15	16

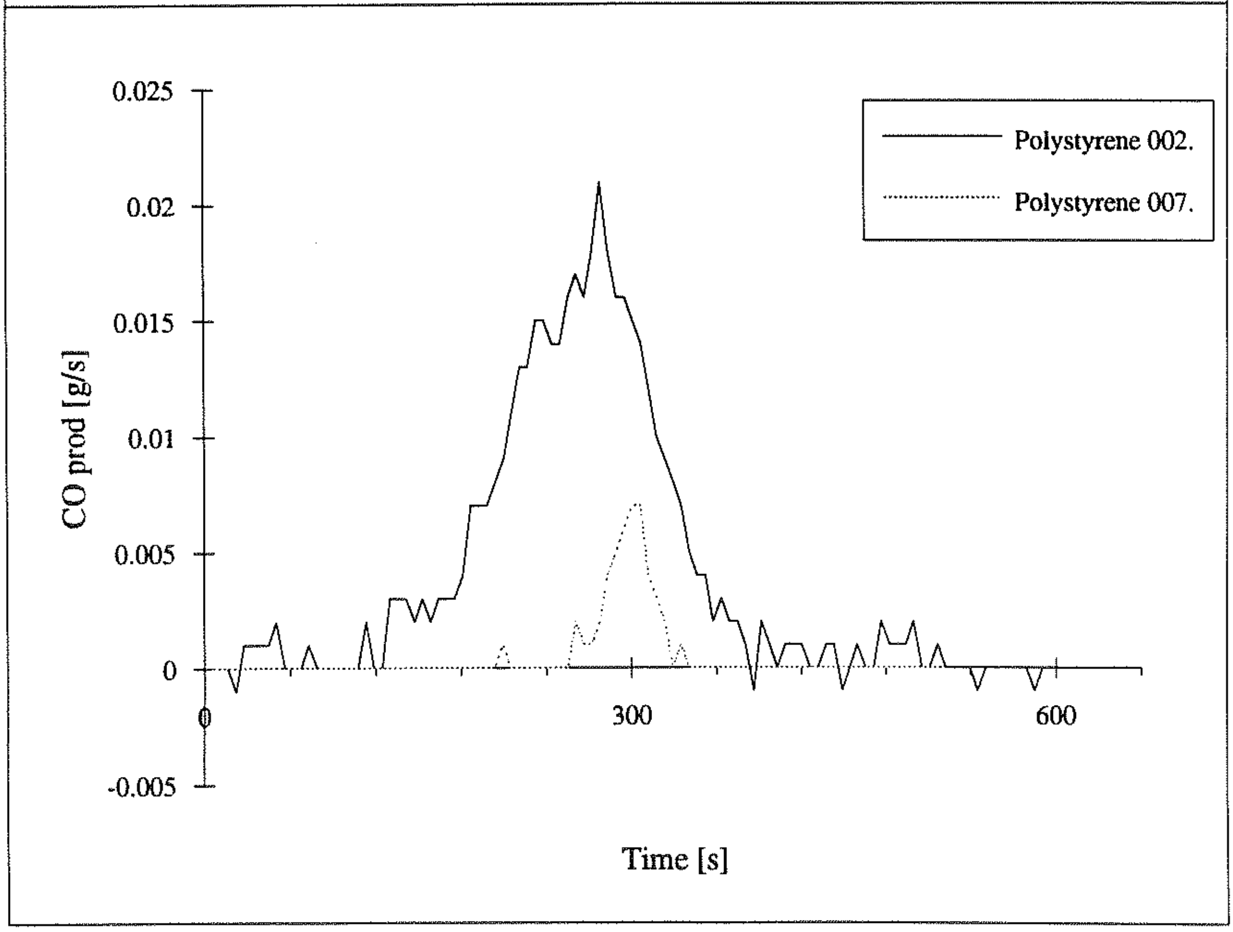
Corrections of the data were made in the study (not carried out in the appendix):

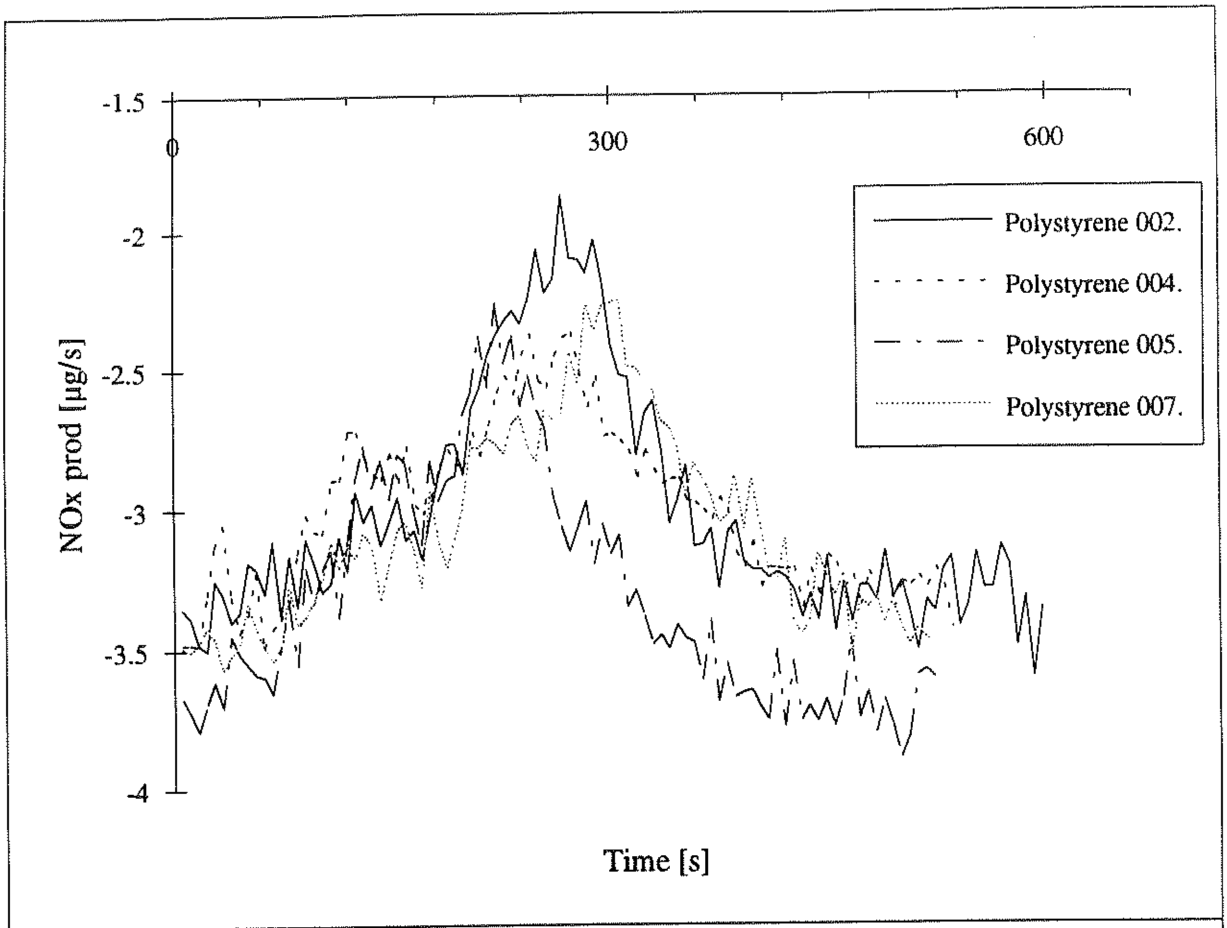
- The RHR values were multiplied with 12.9/13.1 as the measuring program does not consider the actual heat released per unit mass oxygen consumed.
- The CO_2 and CO values were multiplied by 0.91 due to a calibration error in the gas analysis equipment.

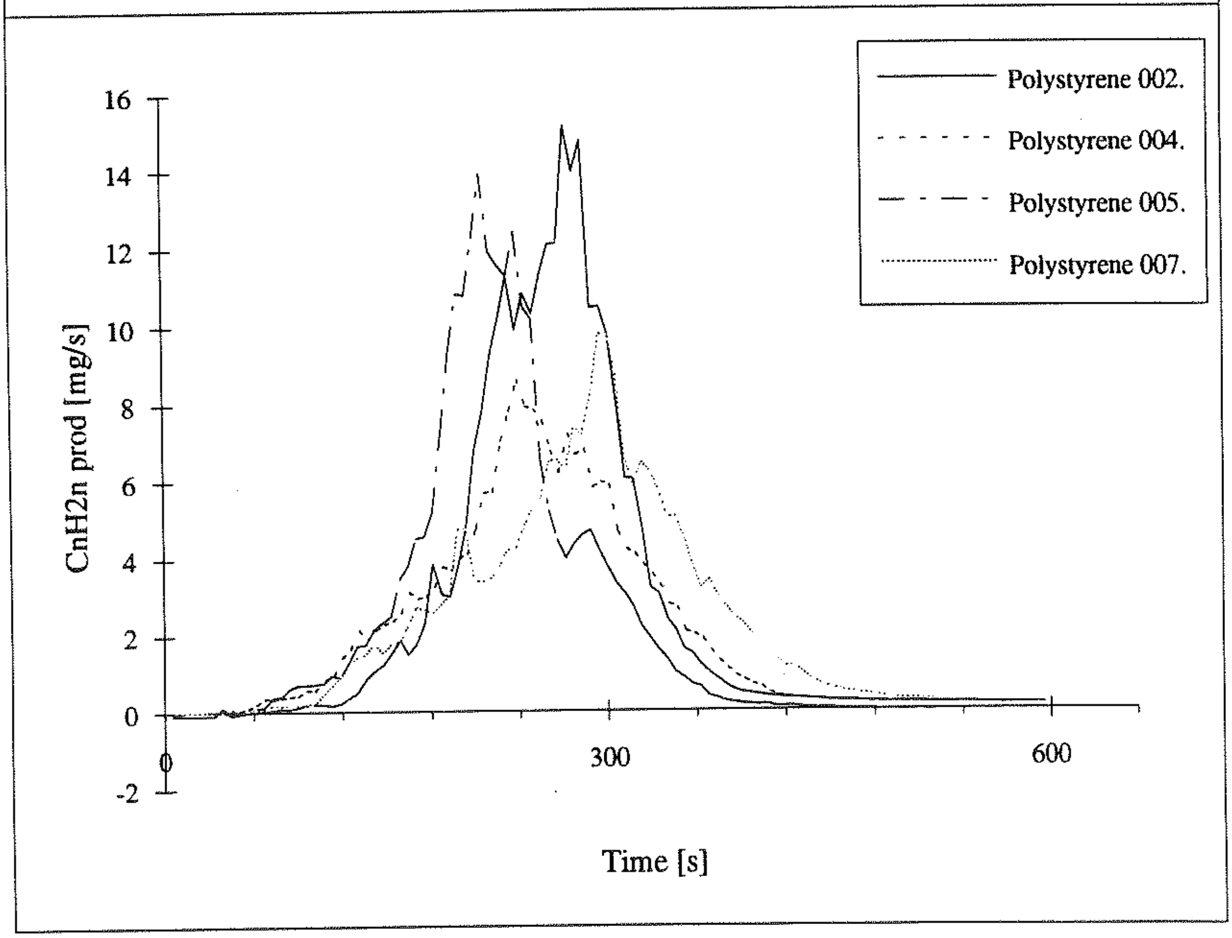

Polystyrene 002.
Polystyrene 004.
Polystyrene 005.
Polystyrene 007.
RHR [kW]
12
10
8
6
4
2
0
-2
0
300
600
Time [s]


Polystyrene 002.
Polystyrene 004.
Polystyrene 005.
Polystyrene 007.
Smoke prod. [obm³/s]
10
9
8
7
6
5
4
3
2
1
0
-1
0
300
600
Time [s]

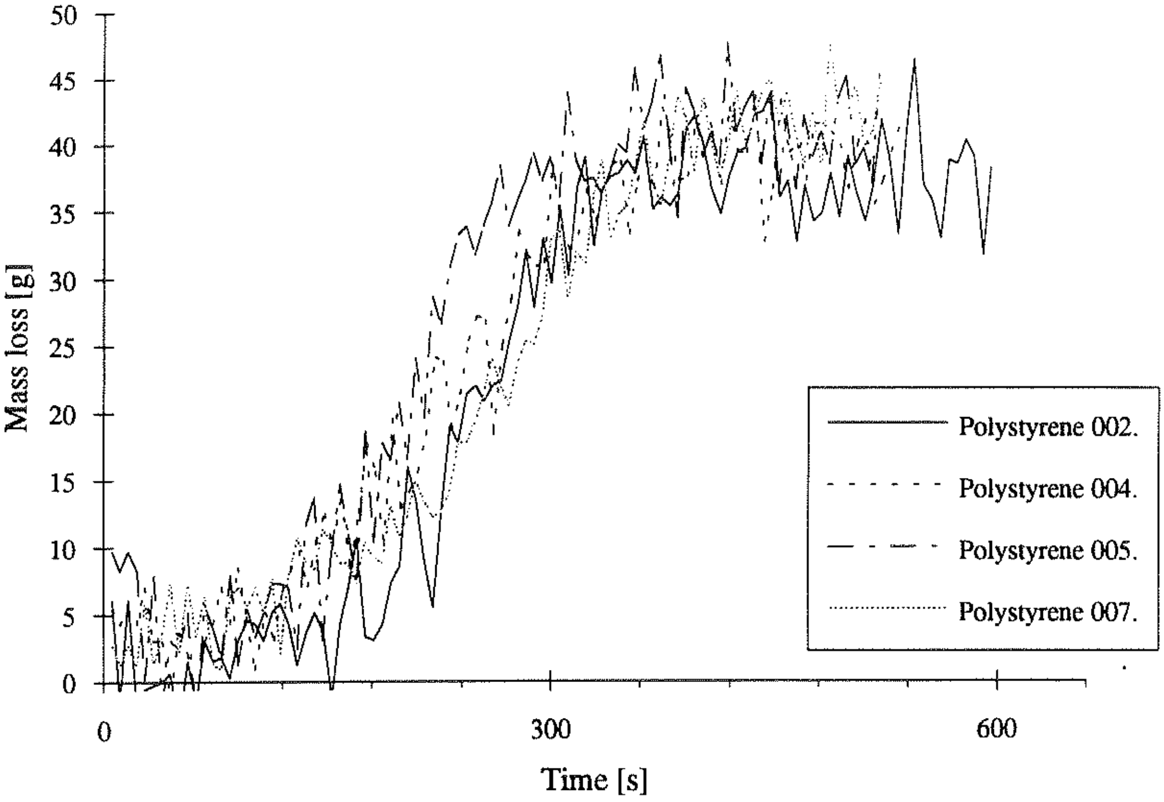

Polystyrene 002.
Polystyrene 004.
Polystyrene 005.
Polystyrene 007.
CO2 prod [g/s]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
300
600
Time [s]

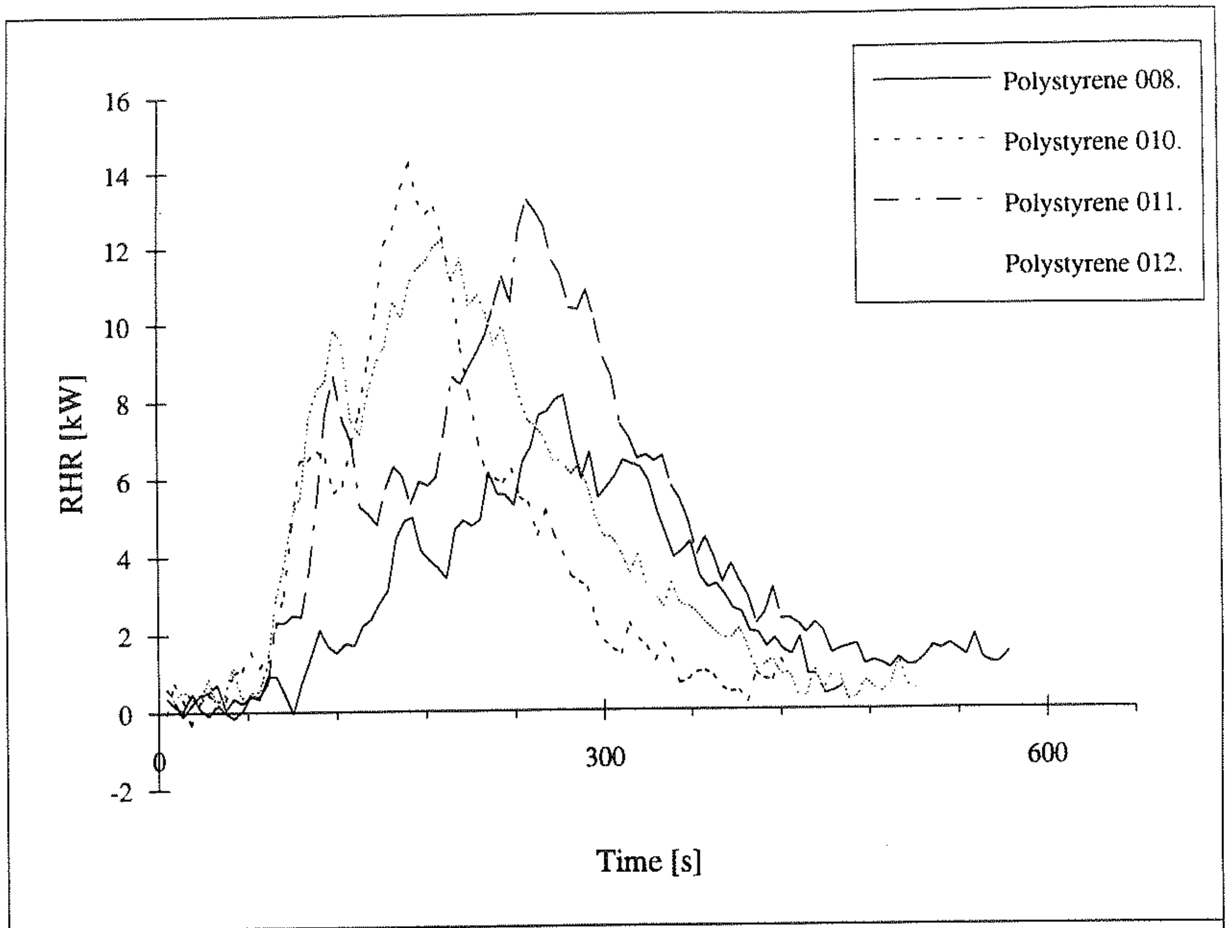

Polystyrene 002.
Polystyrene 007.
CO prod [g/s]
0.025
0.02
0.015
0.01
0.005
0
-0.005
0
300
600
Time [s]

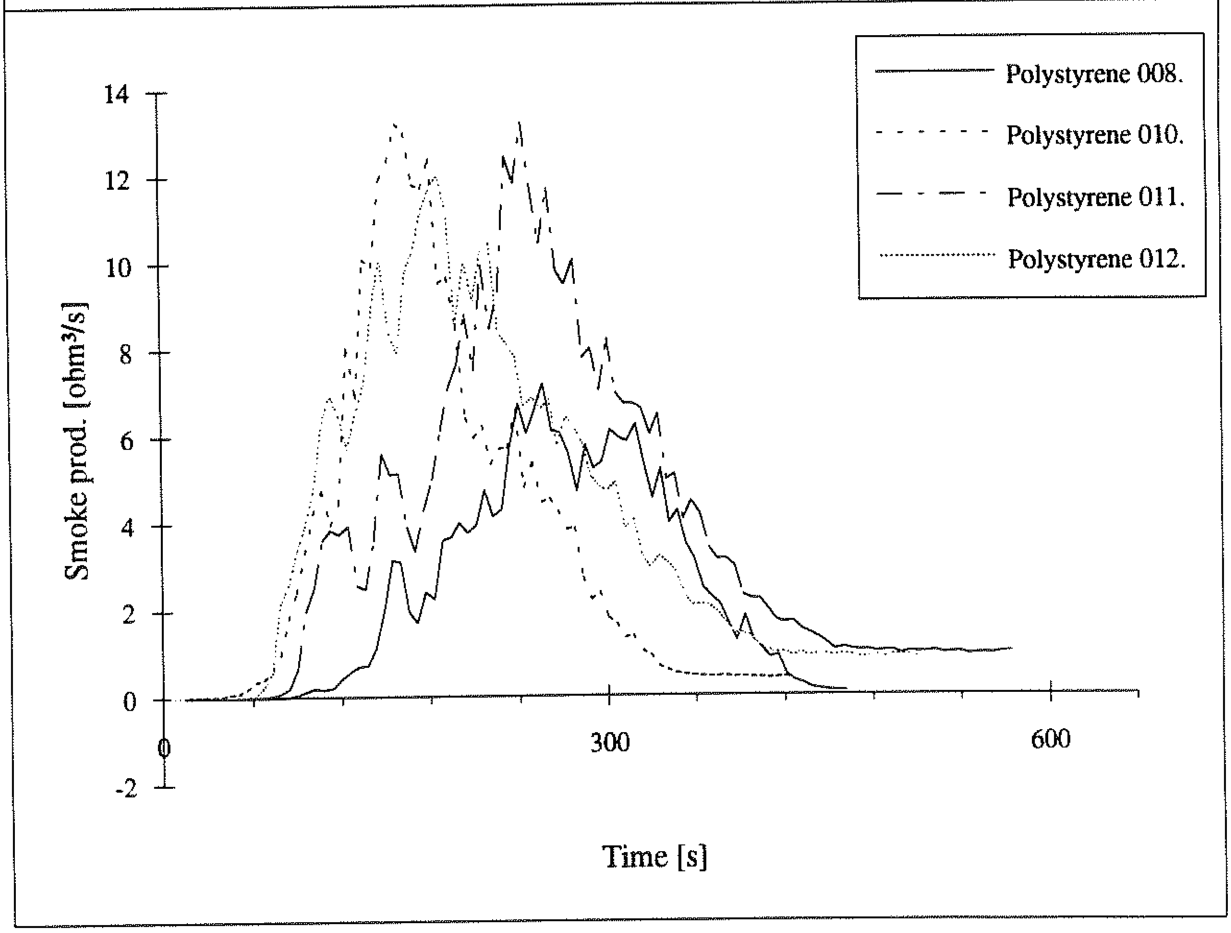


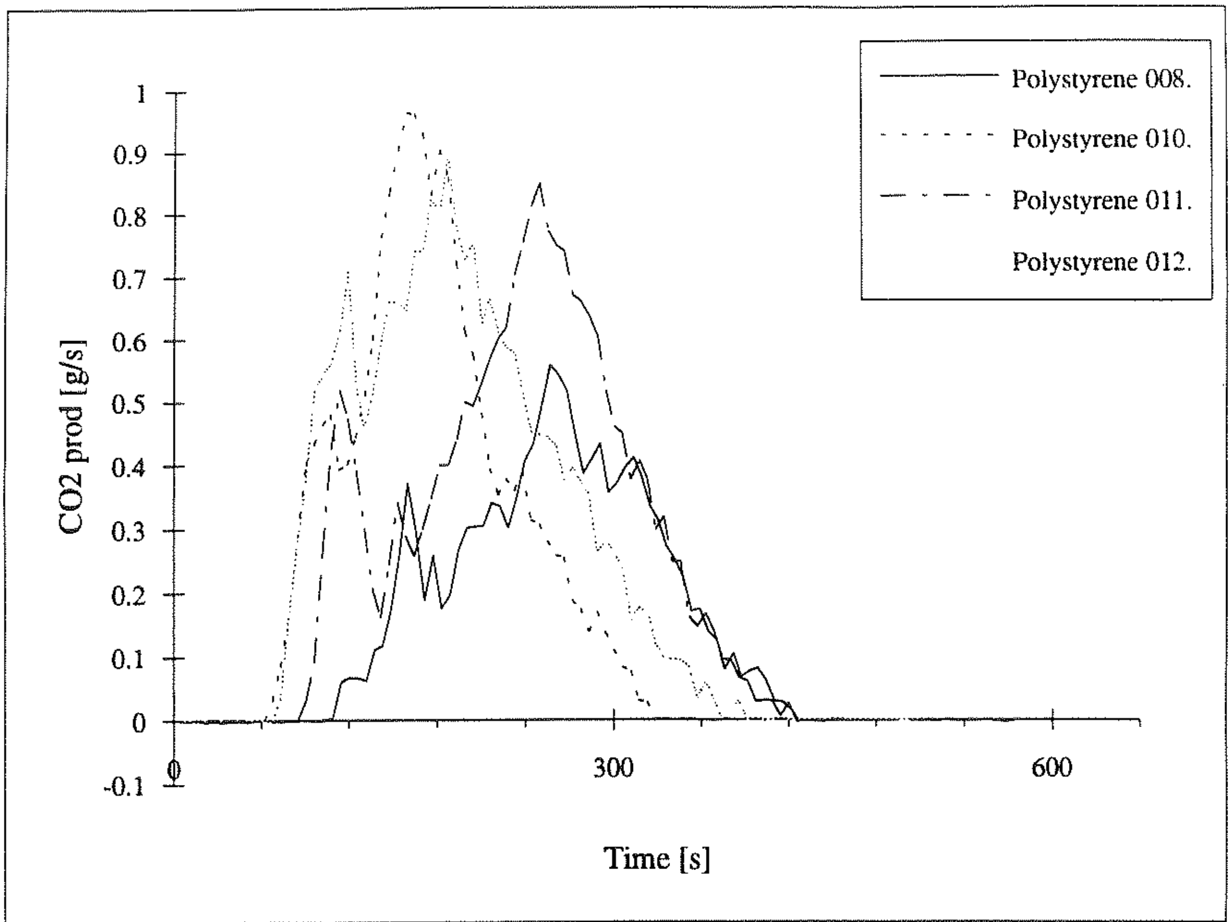


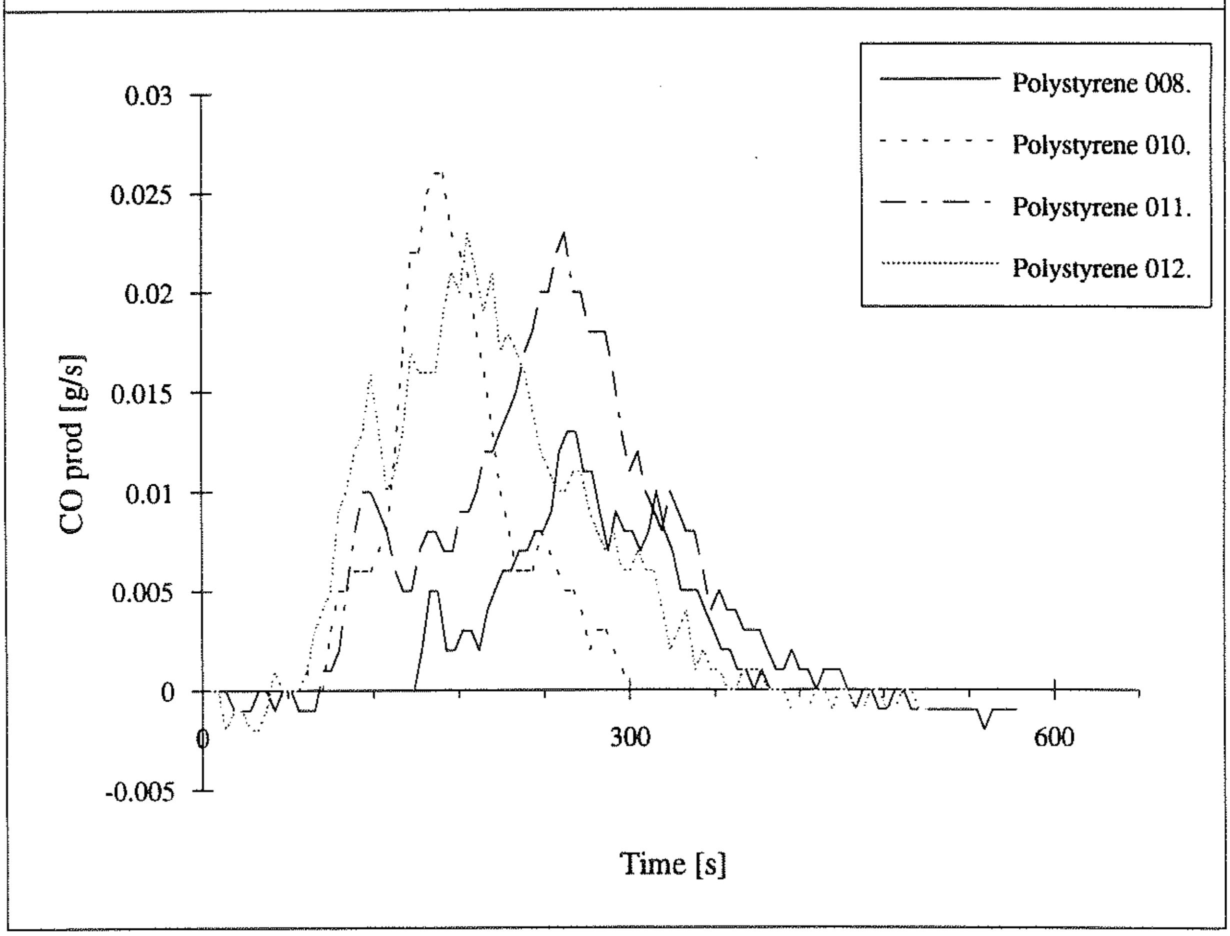
Appendix 1: Polystyrene

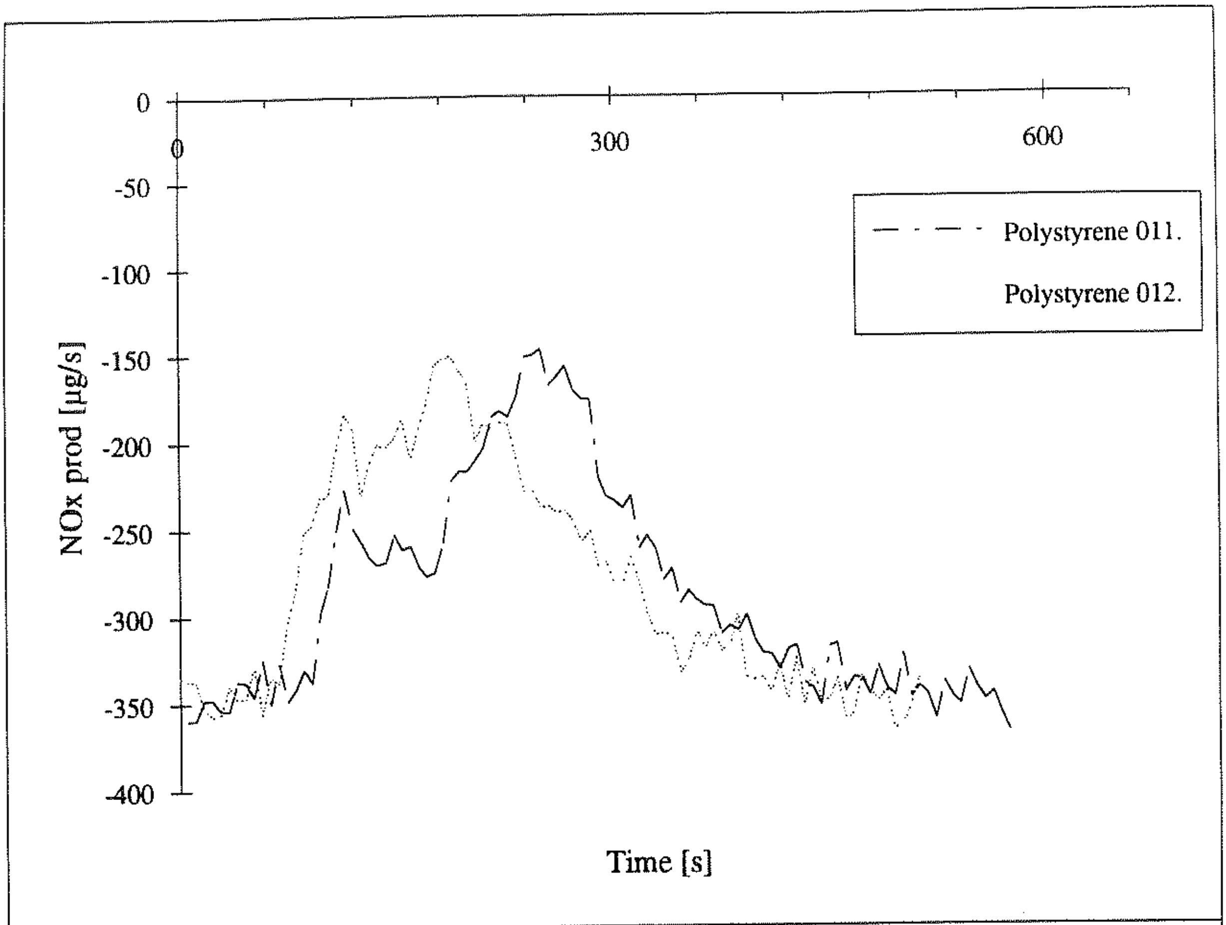

Mass loss [g]
50
45
40
35
30
25
20
15
10
5
0
0
300
600
Time [s]
Polystyrene 002.
Polystyrene 004.
Polystyrene 005.
Polystyrene 007.

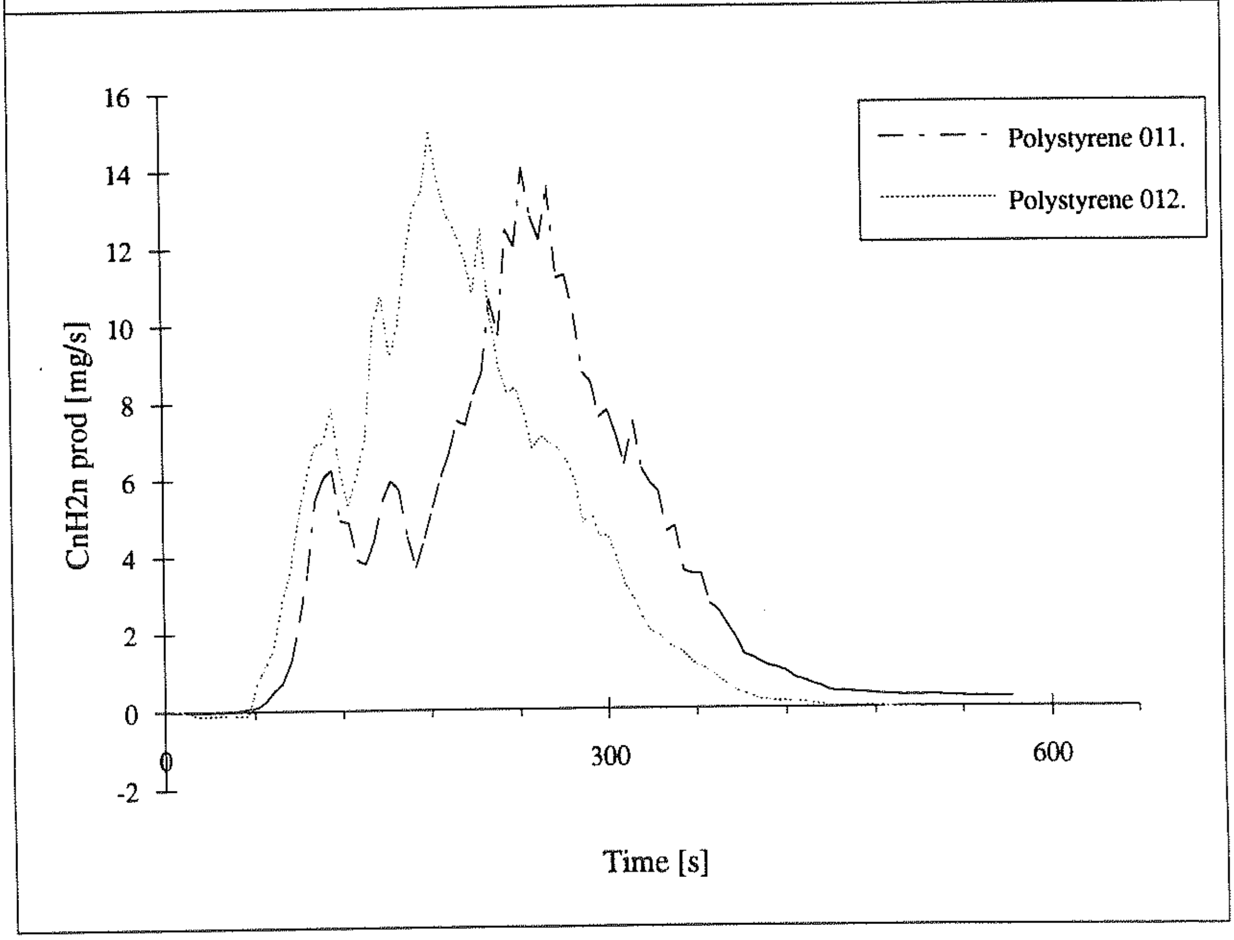

RHR [kW]
16
14
12
10
8
6
4
2
0
-2
0
300
600
Time [s]
Polystyrene 008.
Polystyrene 010.
Polystyrene 011.
Polystyrene 012.

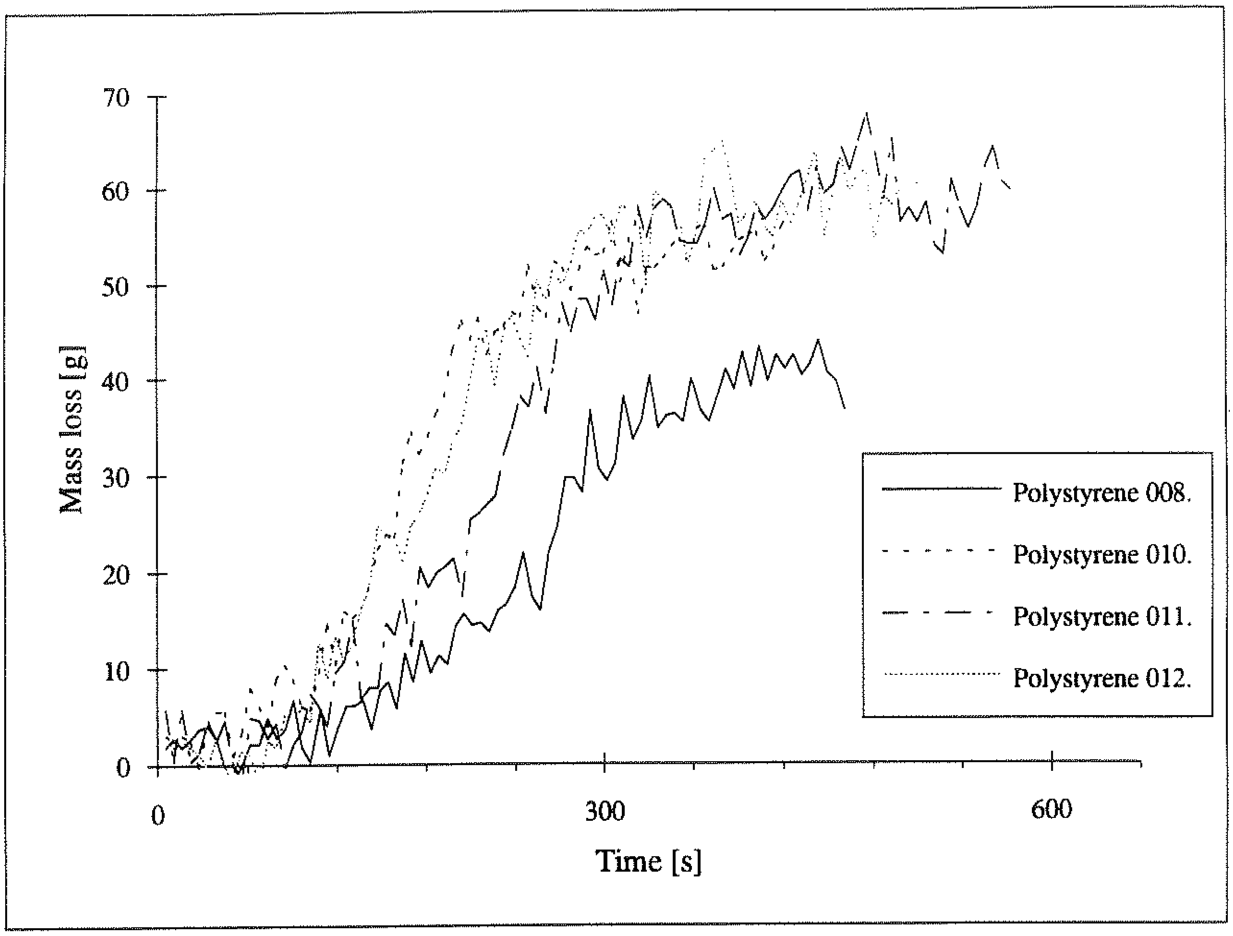

Smoke prod. [ohm³/s]
14
12
10
8
6
4
2
0
-2
0
300
600
Time [s]
Polystyrene 008.
Polystyrene 010.
Polystyrene 011.
Polystyrene 012.

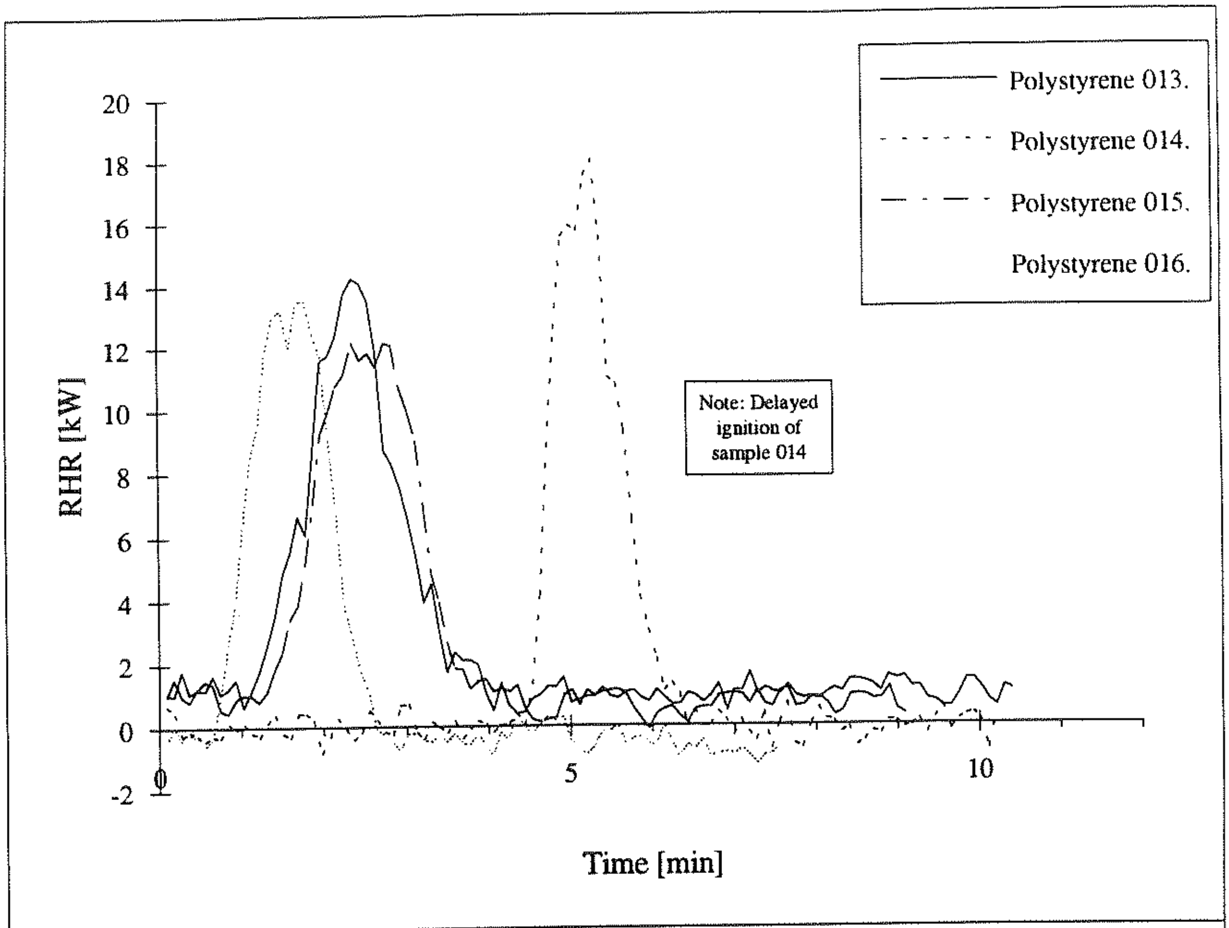

Polystyrene 008.
Polystyrene 010.
Polystyrene 011.
Polystyrene 012.
CO2 prod [g/s]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
300
600
Time [s]

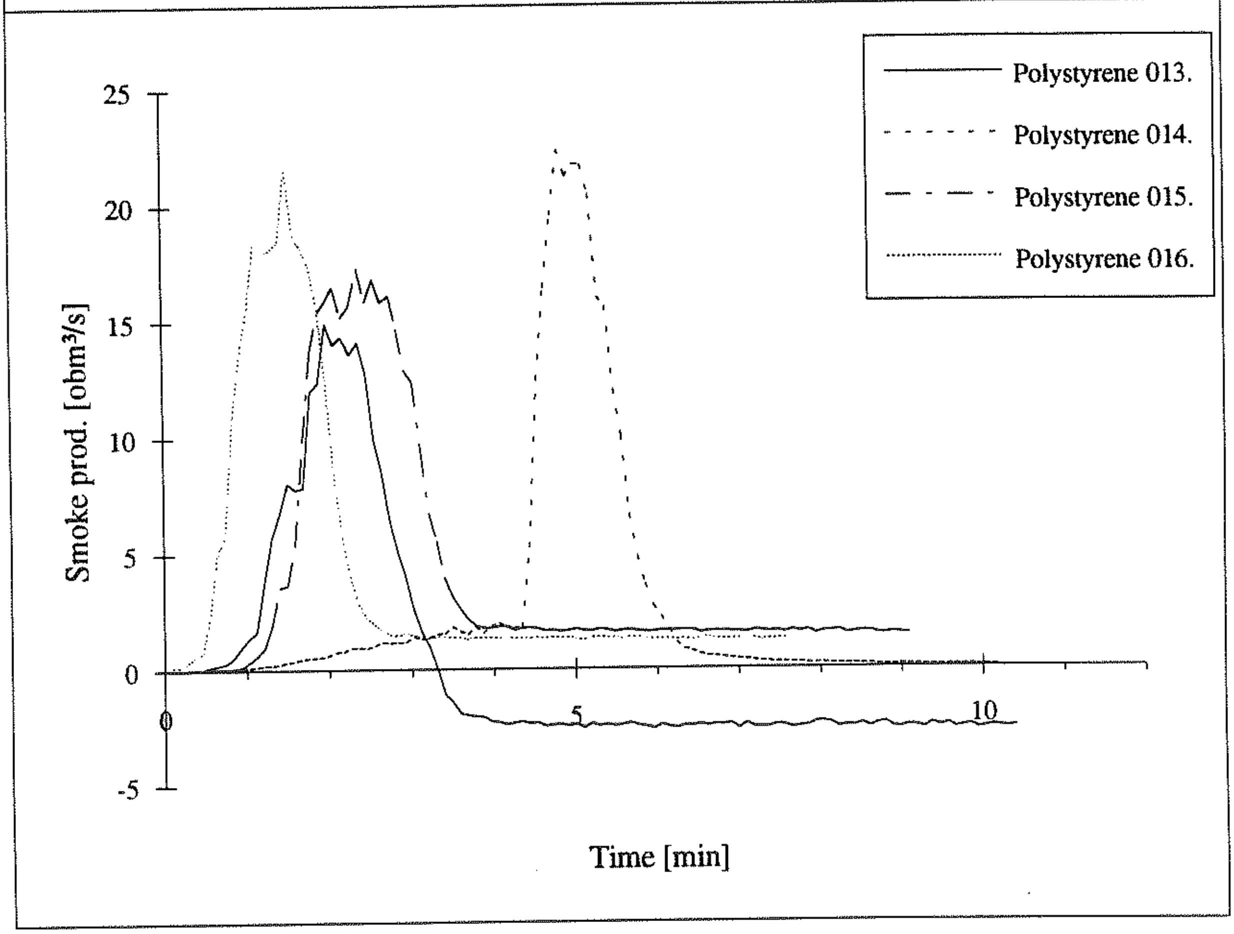

Polystyrene 008.
Polystyrene 010.
Polystyrene 011.
Polystyrene 012.
CO prod [g/s]
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0
300
600
Time [s]


NOx prod [µg/s]
0
-50
-100
-150
-200
-250
-300
-350
-400
0
300
600
Time [s]
Polystyrene 011.
Polystyrene 012.

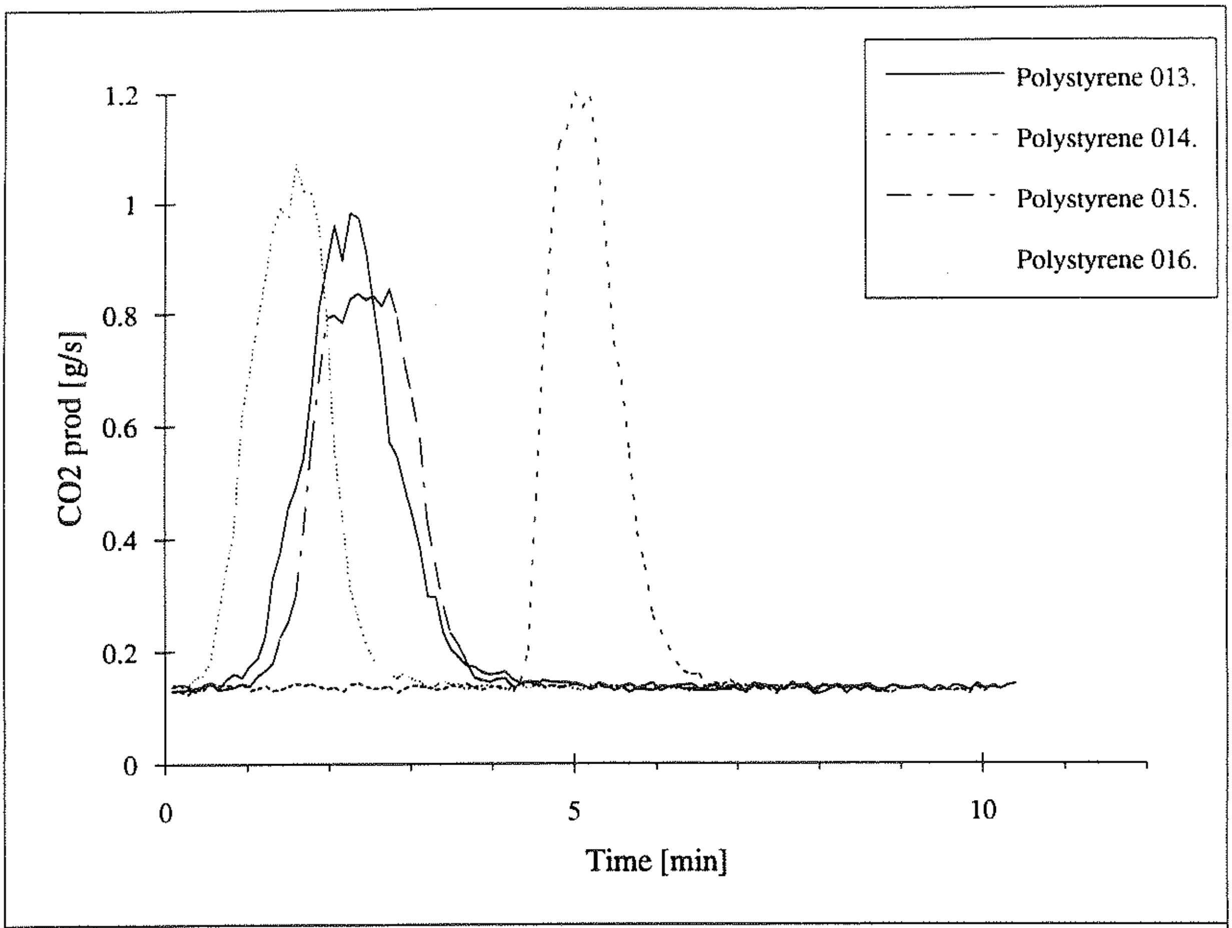

CnH2n prod [mg/s]
16
14
12
10
8
6
4
2
0
-2
0
300
600
Time [s]
Polystyrene 011.
Polystyrene 012.

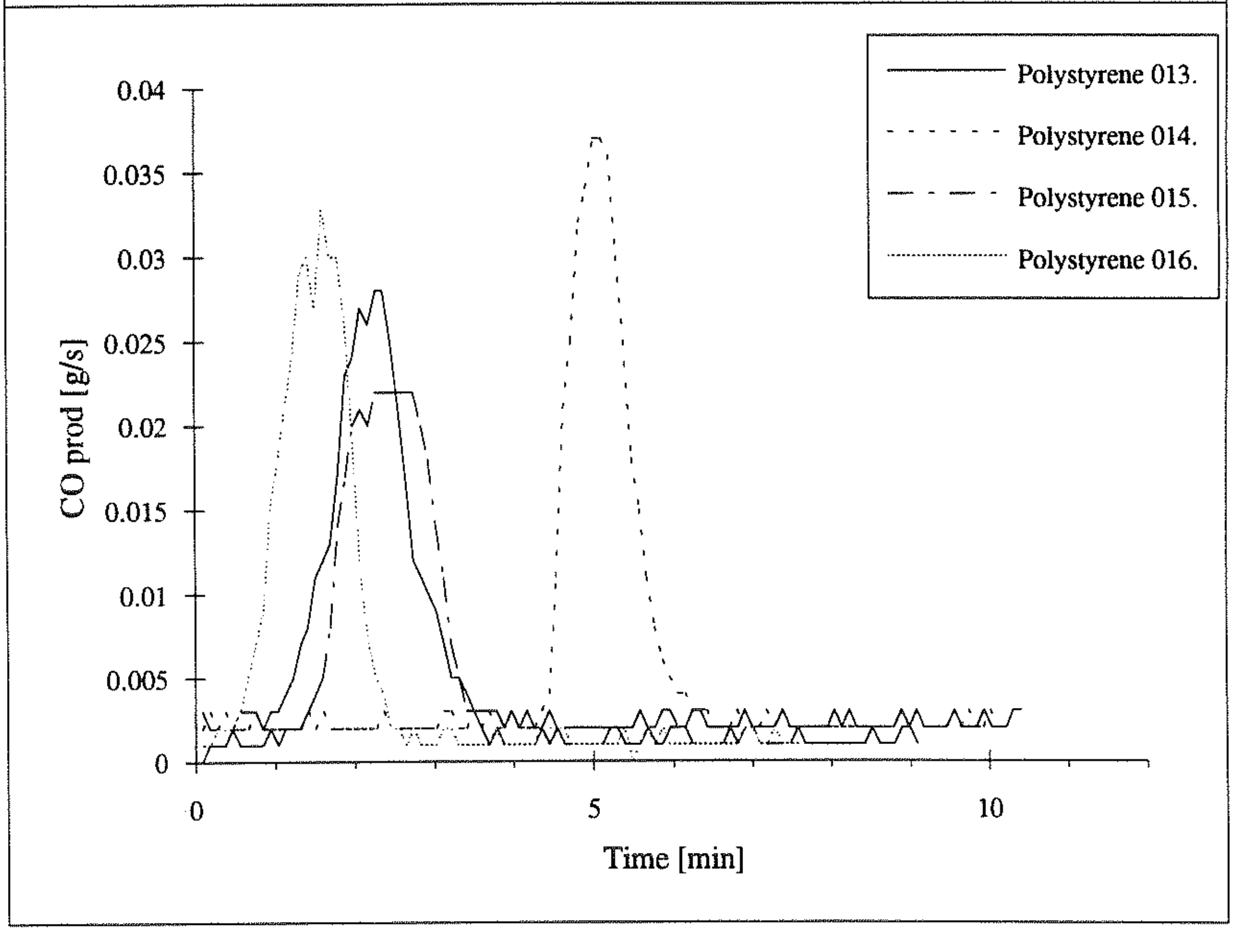

70
60
50
40
30
20
10
0
Mass loss [g]
0
300
600
Time [s]
Polystyrene 008.
Polystyrene 010.
Polystyrene 011.
Polystyrene 012.

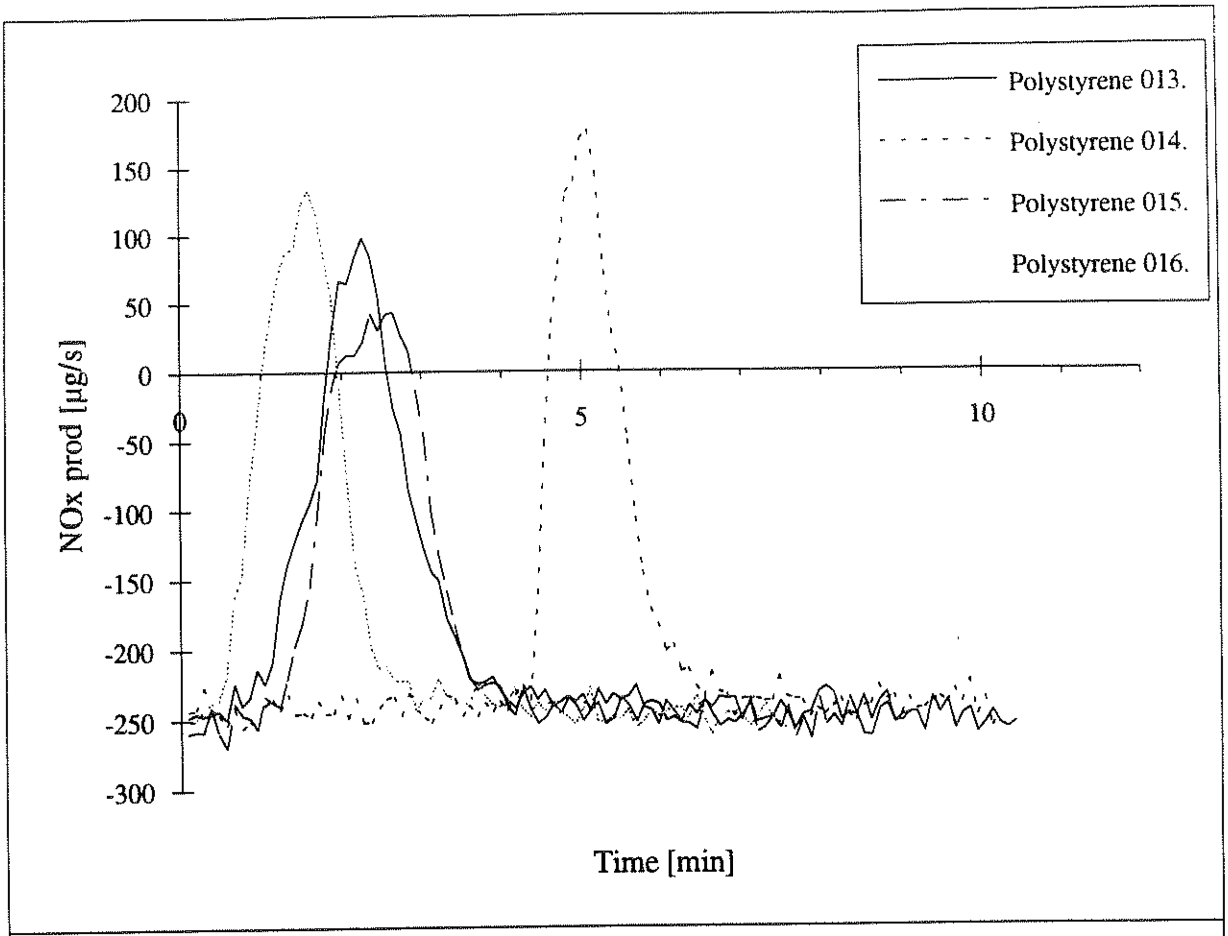


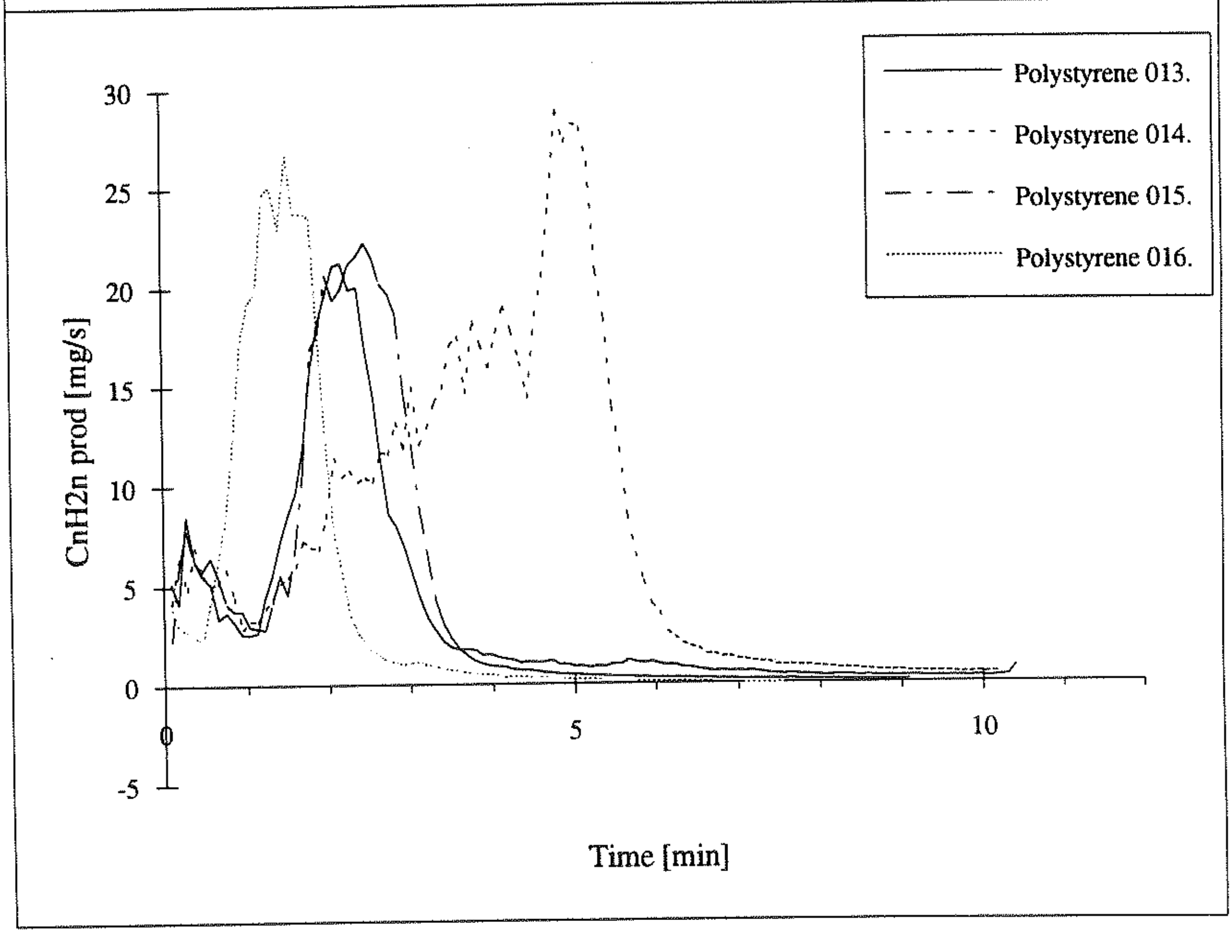


Appendix 1: Polystyrene

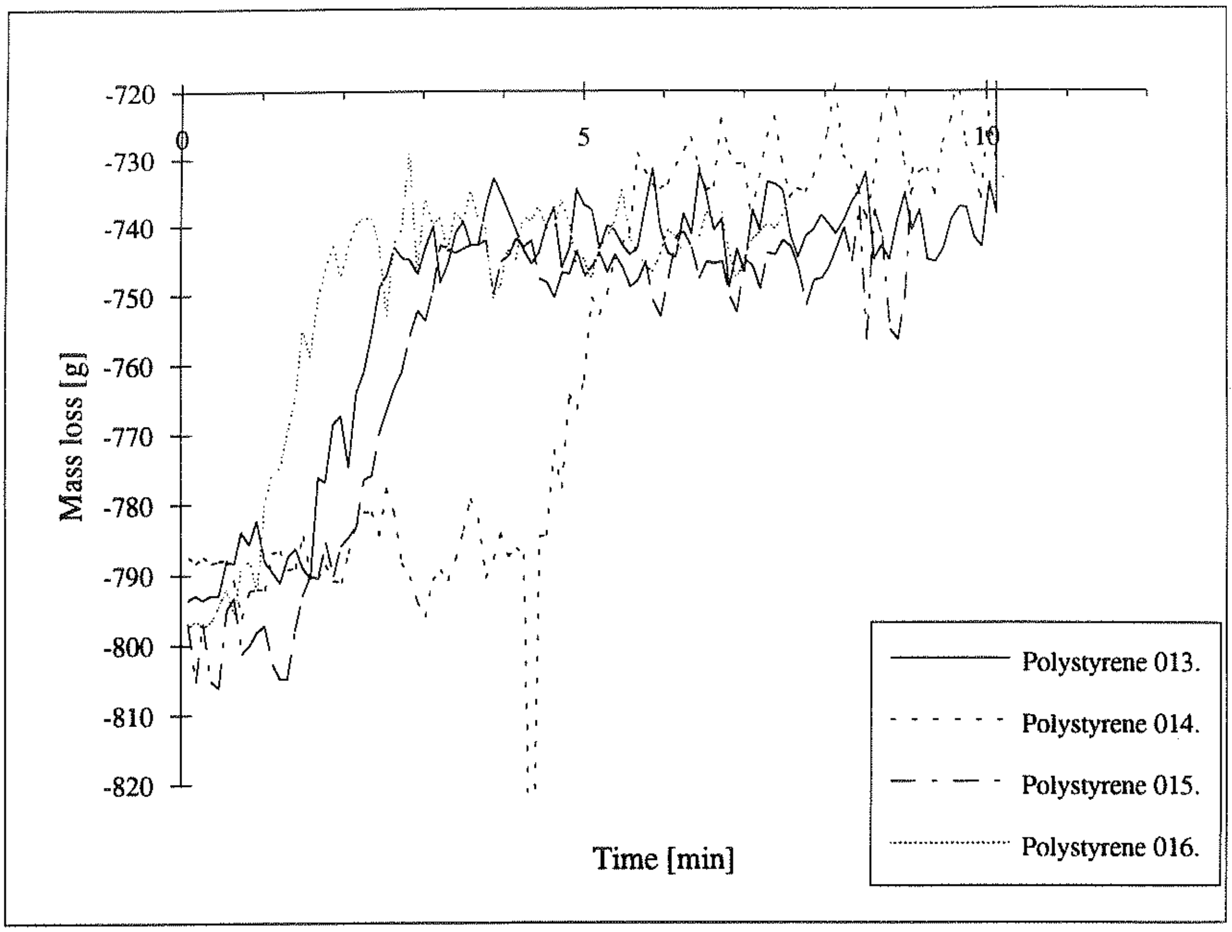

Polystyrene 013.
Polystyrene 014.
Polystyrene 015.
Polystyrene 016.
CO2 prod [g/s]
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
Time [min]

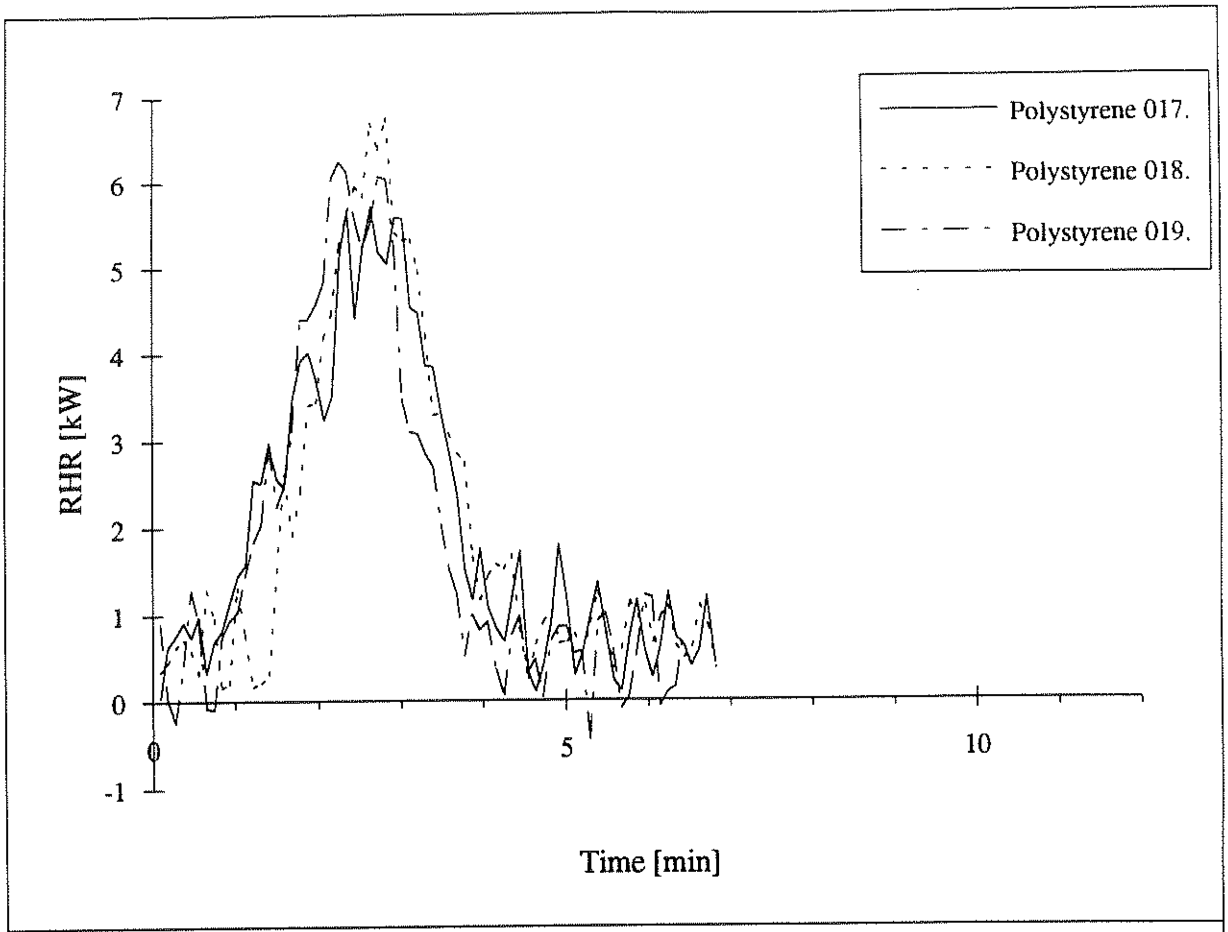

Polystyrene 013.
Polystyrene 014.
Polystyrene 015.
Polystyrene 016.
CO prod [g/s]
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
Time [min]

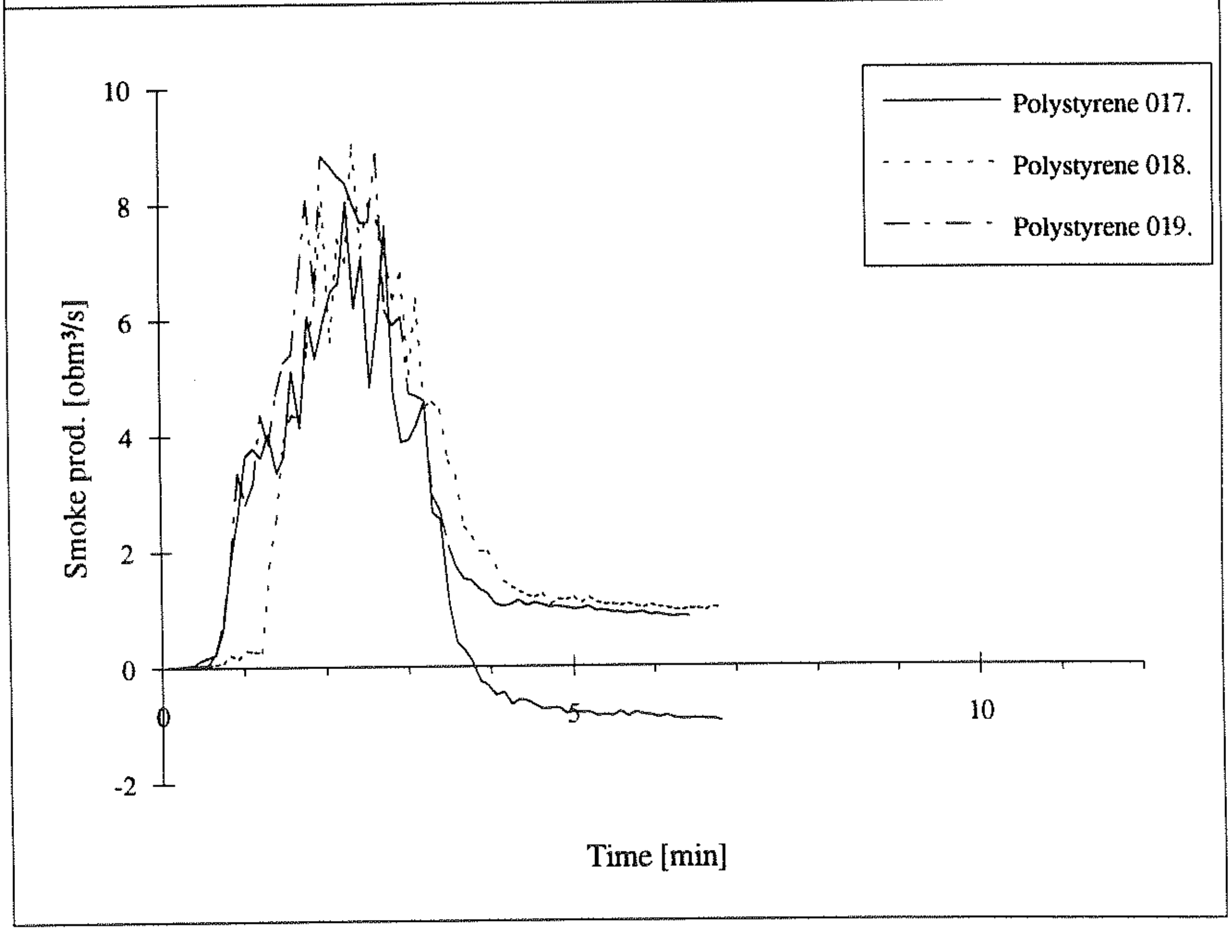


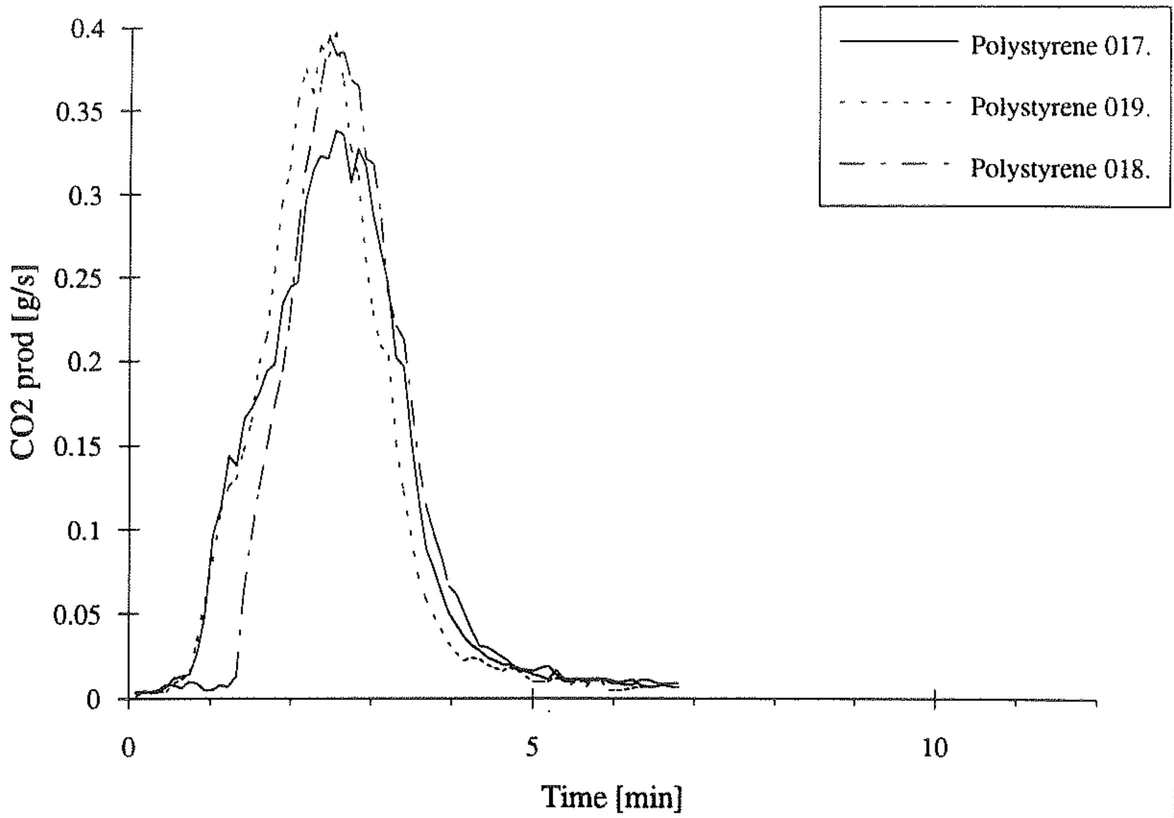


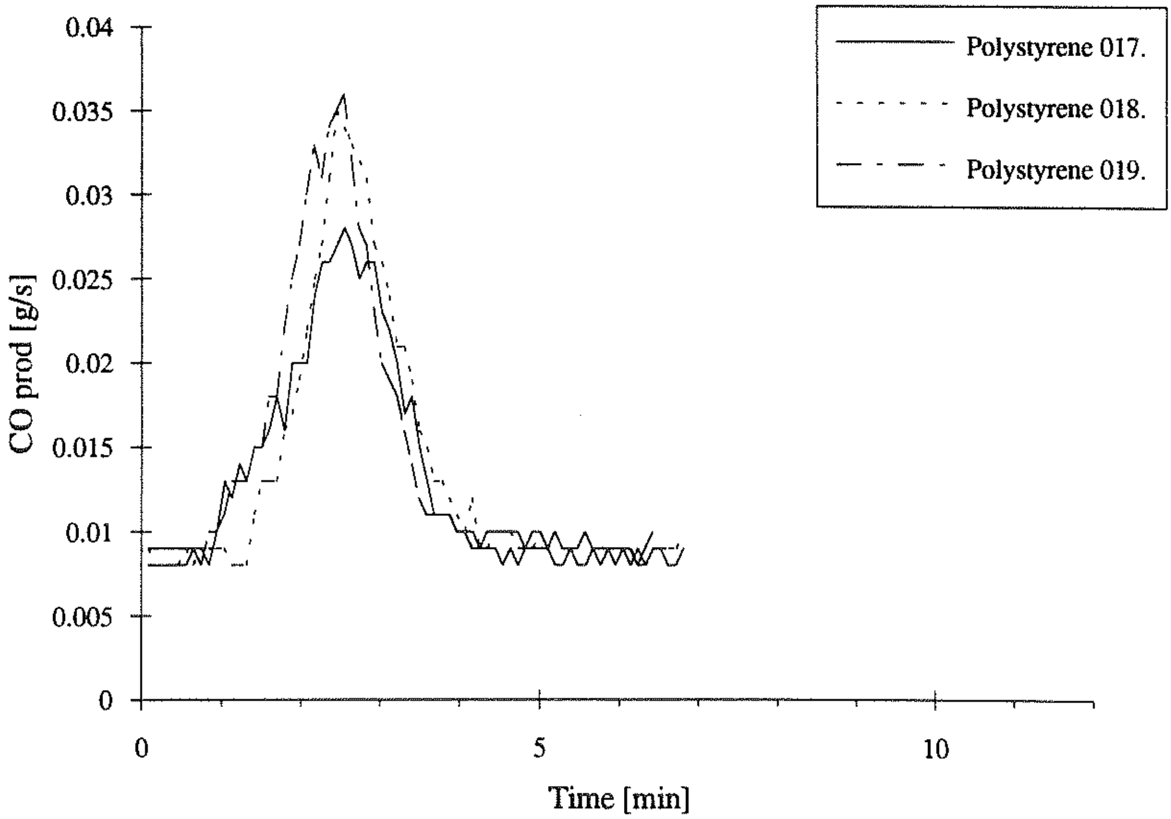
Appendix 1: Polystyrene

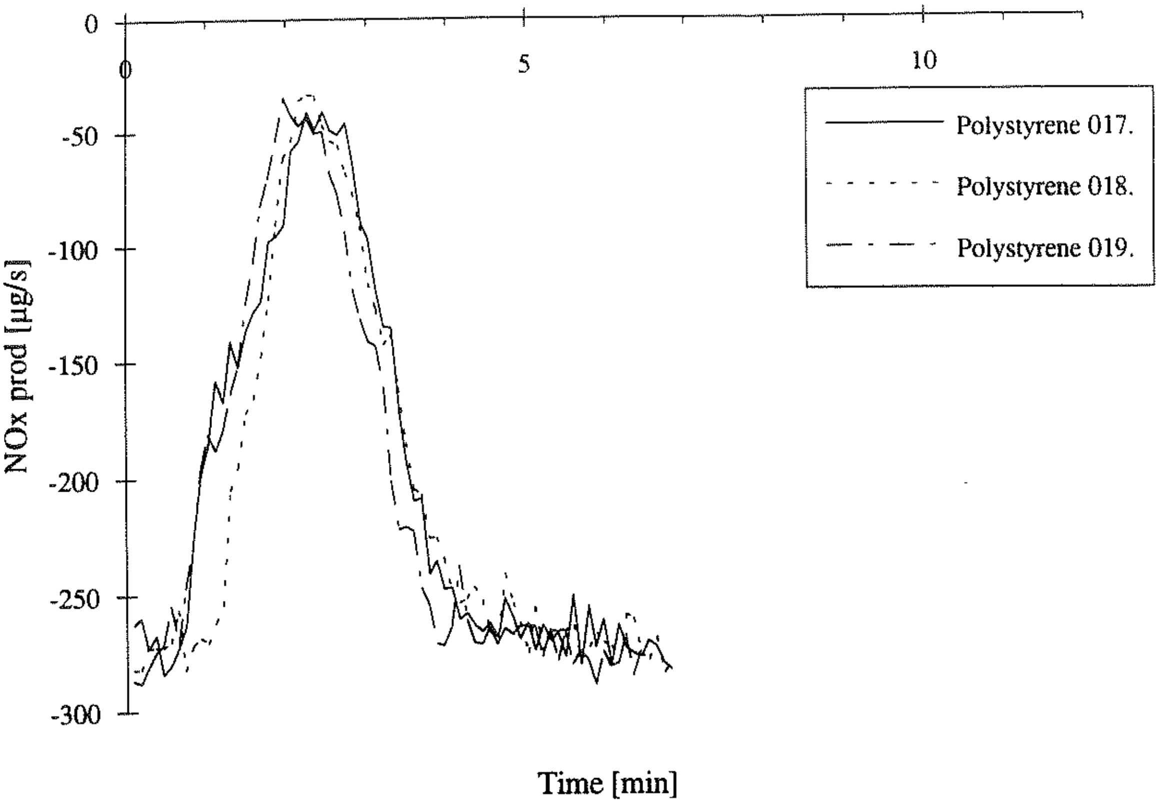

Mass loss [g]
-720
-730
-740
-750
-760
-770
-780
-790
-800
-810
-820
0
5
10
Time [min]
Polystyrene 013.
Polystyrene 014.
Polystyrene 015.
Polystyrene 016.

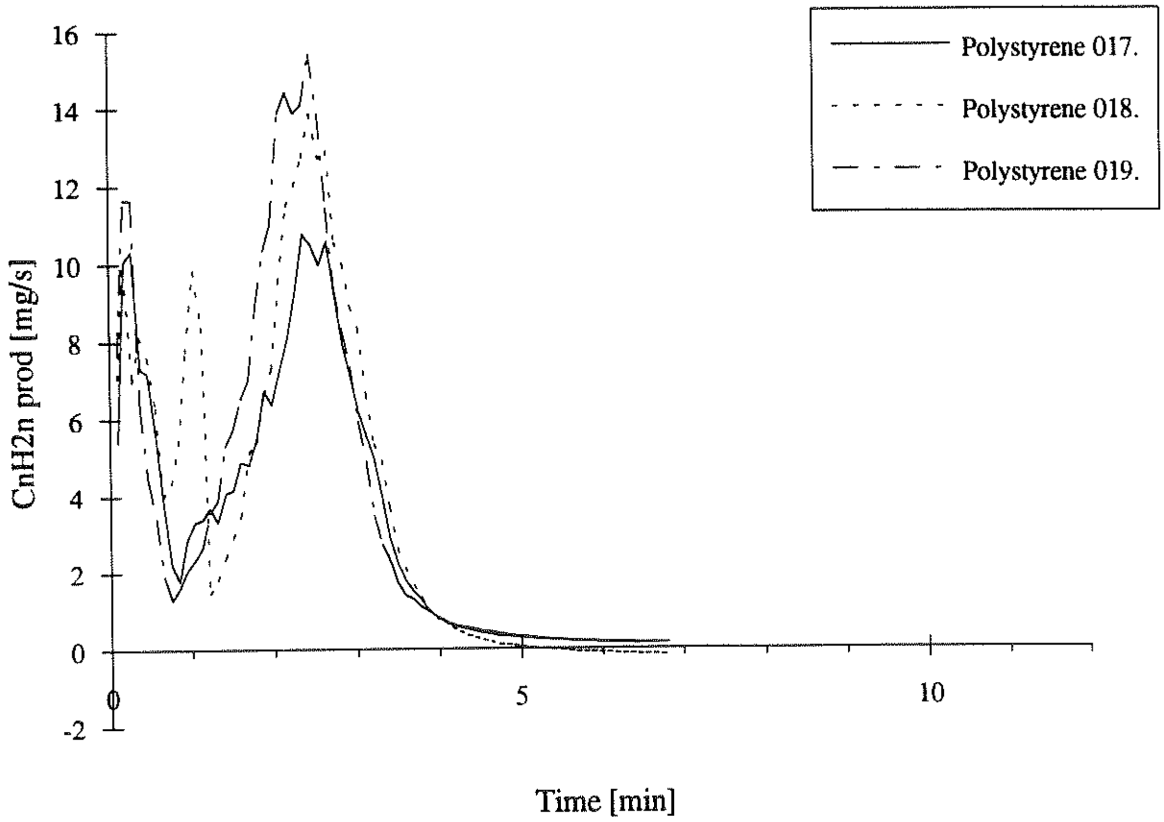

7
6
5
4
3
2
1
0
-1
RHR [kW]
0
5
10
Time [min]
Polystyrene 017.
Polystyrene 018.
Polystyrene 019.


10
8
6
4
2
0
-2
Smoke prod. [obm³/s]
0
5
10
Time [min]
Polystyrene 017.
Polystyrene 018.
Polystyrene 019.

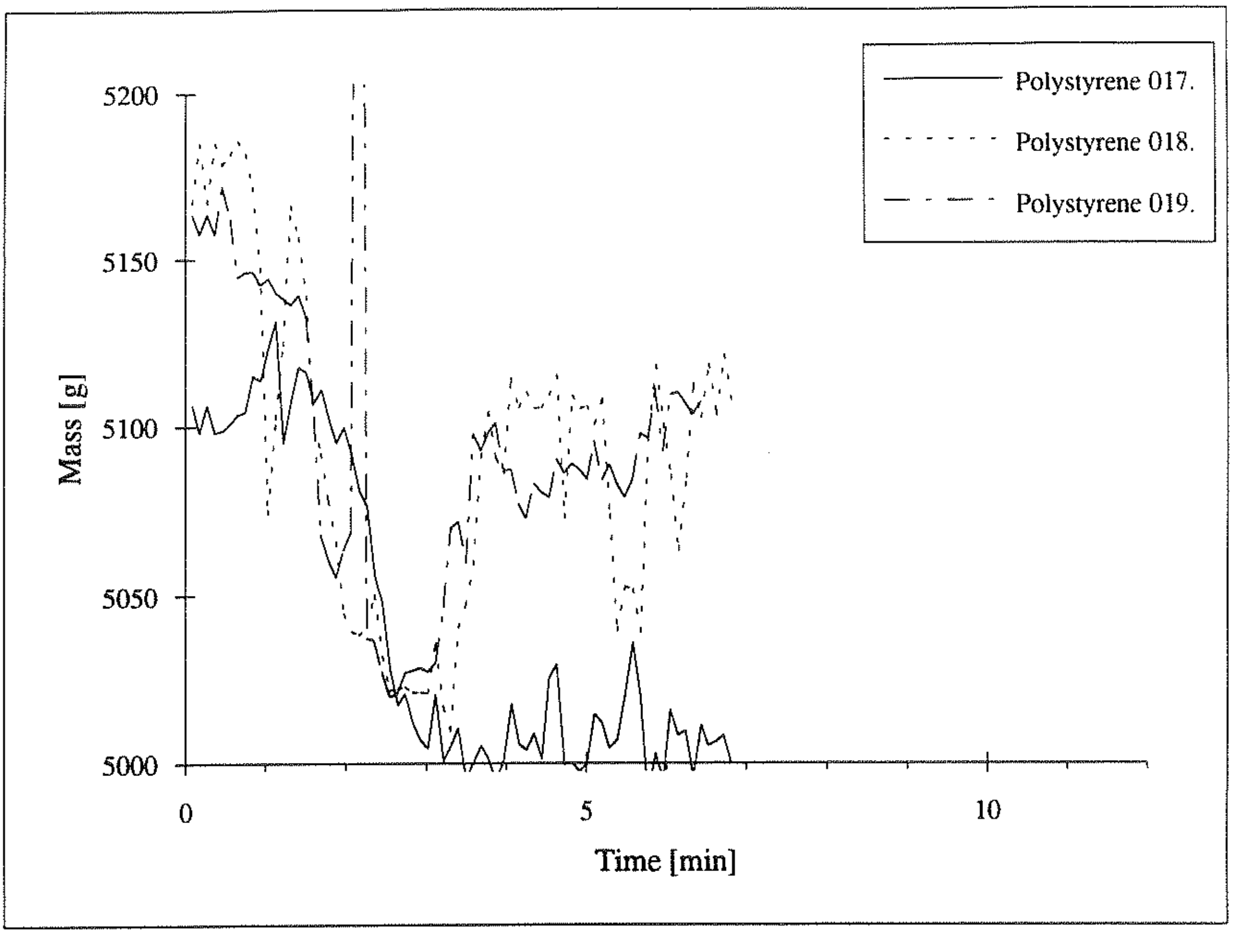

0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
CO2 prod [g/s]
0
5
10
Time [min]
Polystyrene 017.
Polystyrene 019.
Polystyrene 018.


0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
CO prod [g/s]
0
5
10
Time [min]
Polystyrene 017.
Polystyrene 018.
Polystyrene 019.





Appendix 1: Polystyrene


Polystyrene 017.
Polystyrene 018.
Polystyrene 019.
Mass [g]
5200
5150
5100
5050
5000
0
5
10
Time [min]

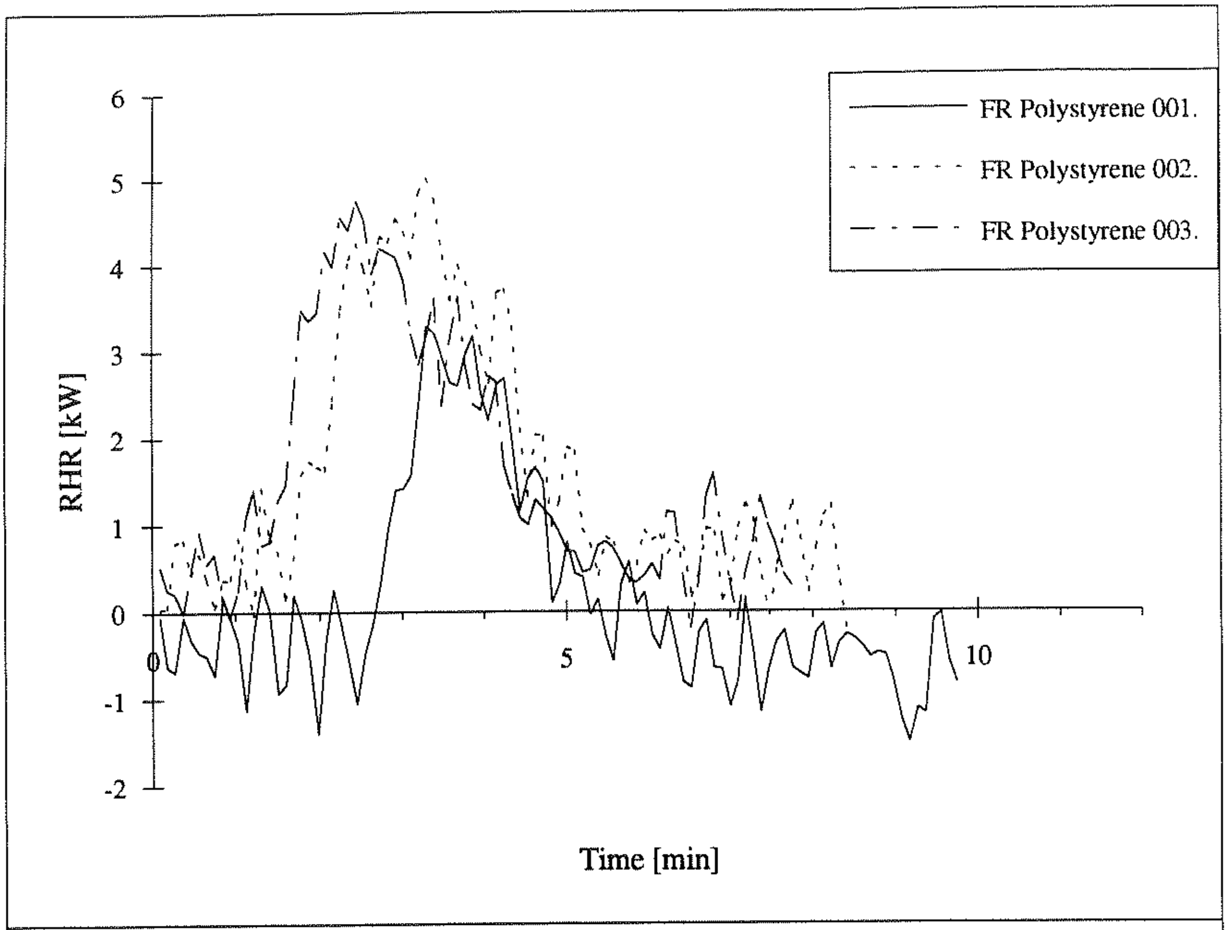
Appendix 2: Test results for
FIRE-RETARDED POLYSTYRENE

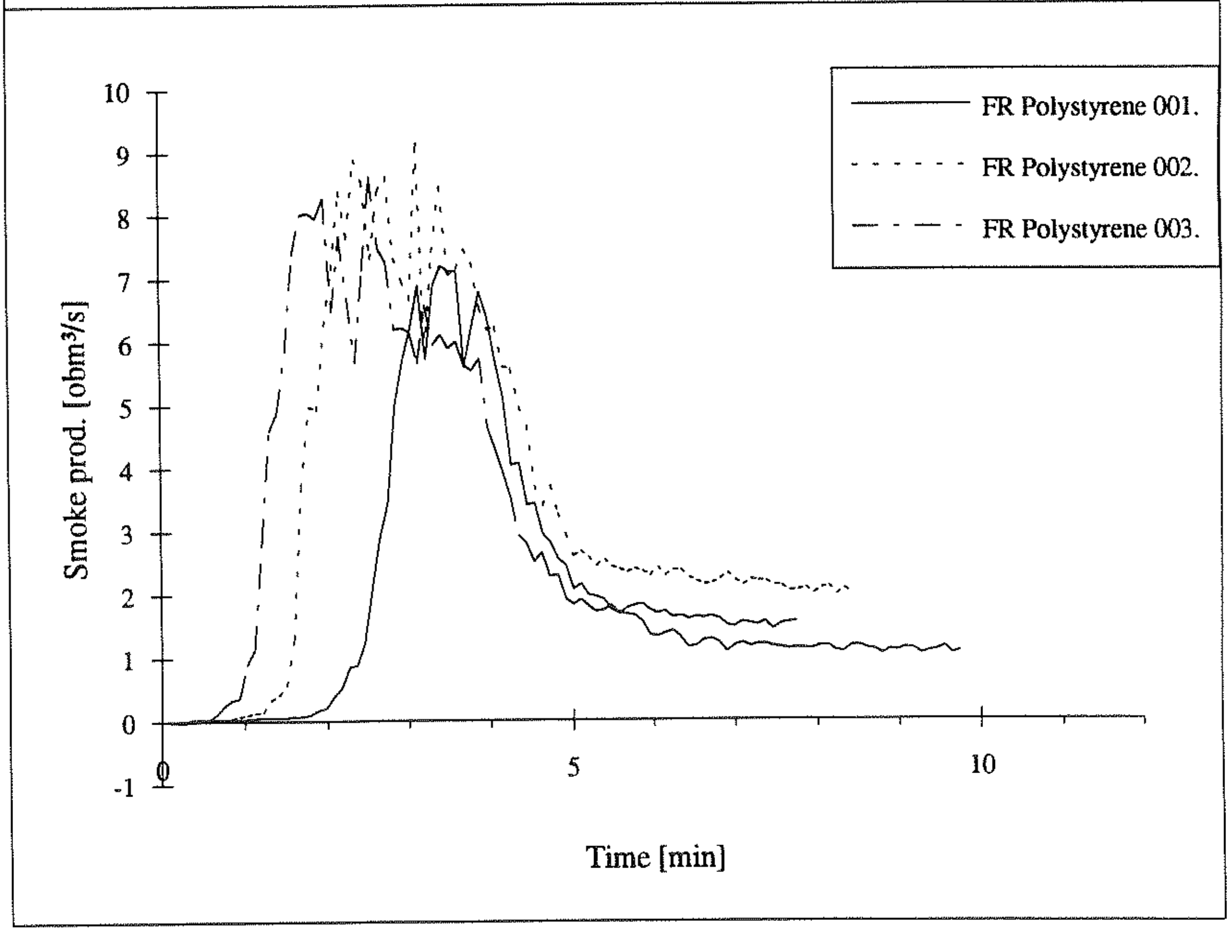
Contents:

Test	RHR page	Smoke prod. page	CO_2 prod. page	CO prod. page	NO_X prod. page	C_nH_{2n} prod. page	Mass loss page
001	1	1	2	2	3	3	4
002	1	1	2	2	3	3	4
003	1	1	2	2	3	3	4

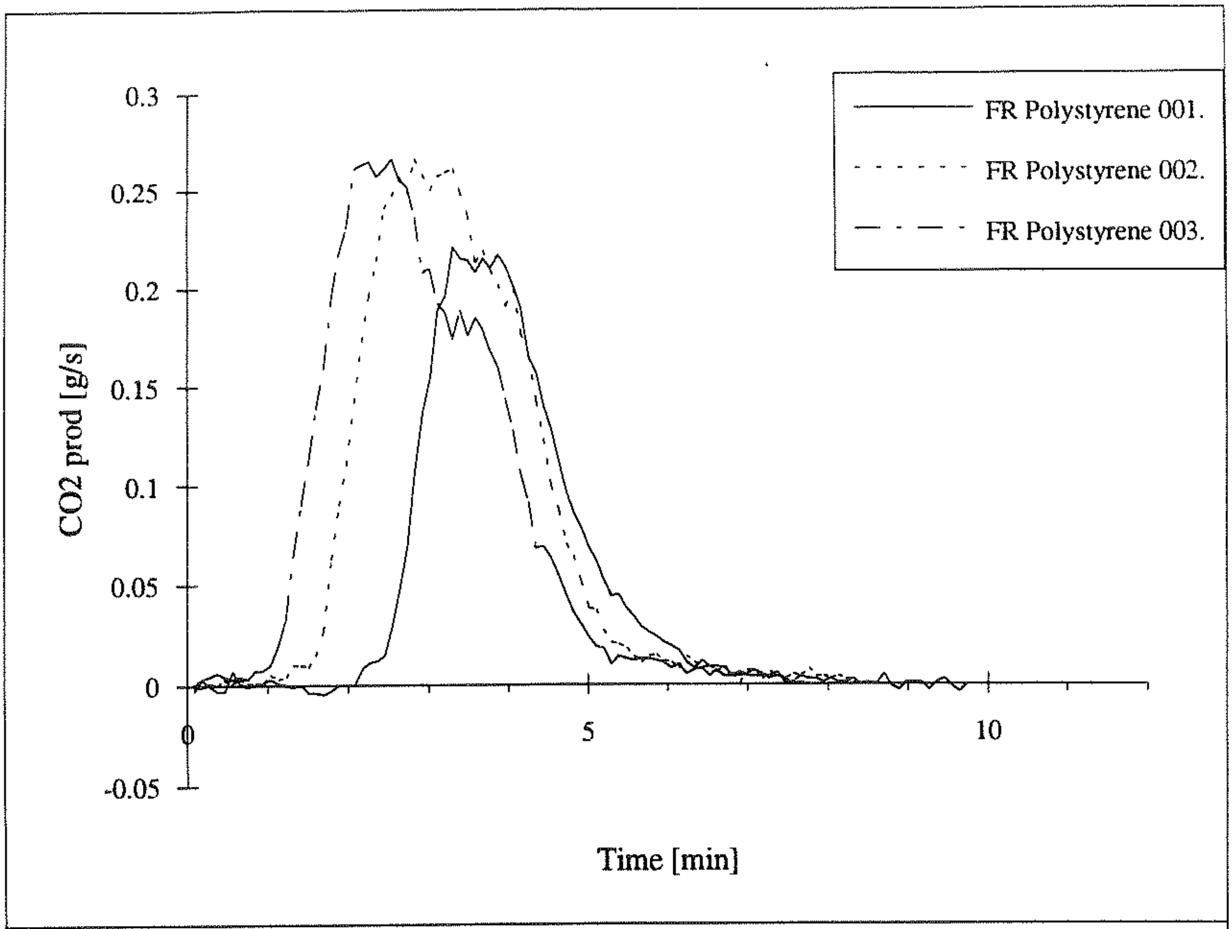
Corrections of the data were made in the study (not carried out in the appendix):

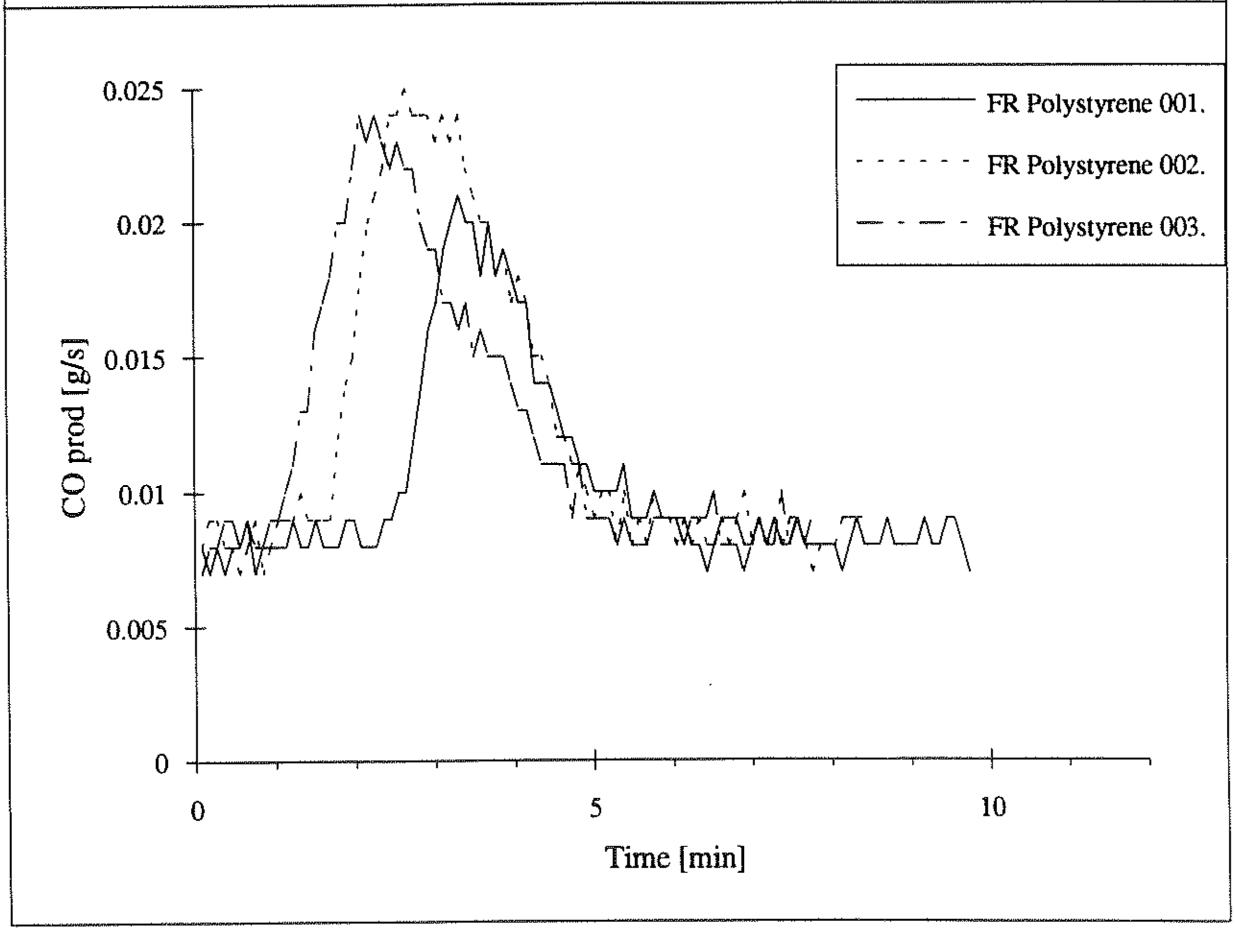
- The RHR values were multiplied with 12.9/13.1 as the measuring program does not consider the actual heat released per unit mass oxygen consumed.
- The CO_2 and CO values were multiplied by 0.91 due to a calibration error in the gas analysis equipment.



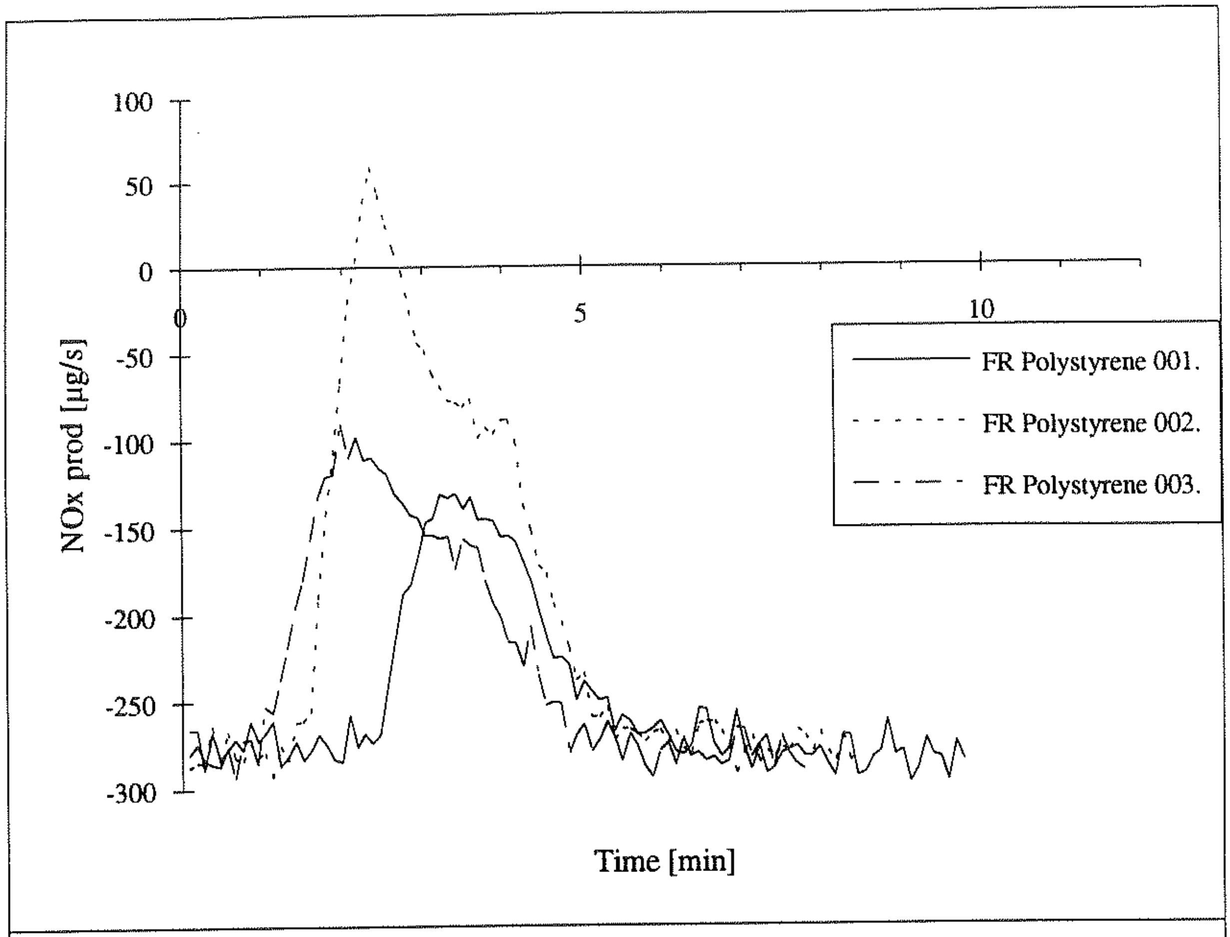


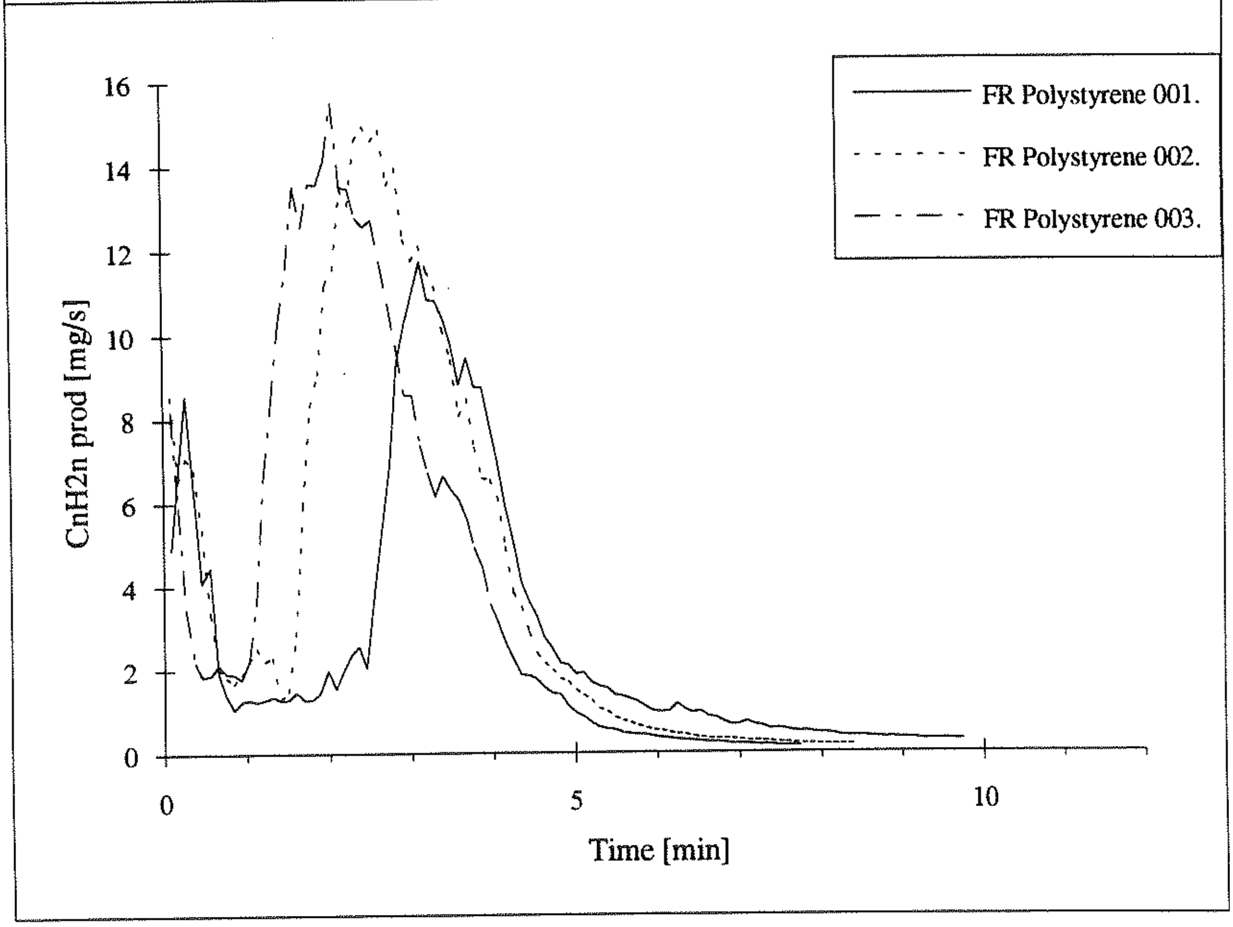
Appendix 2: FR Polystyrene



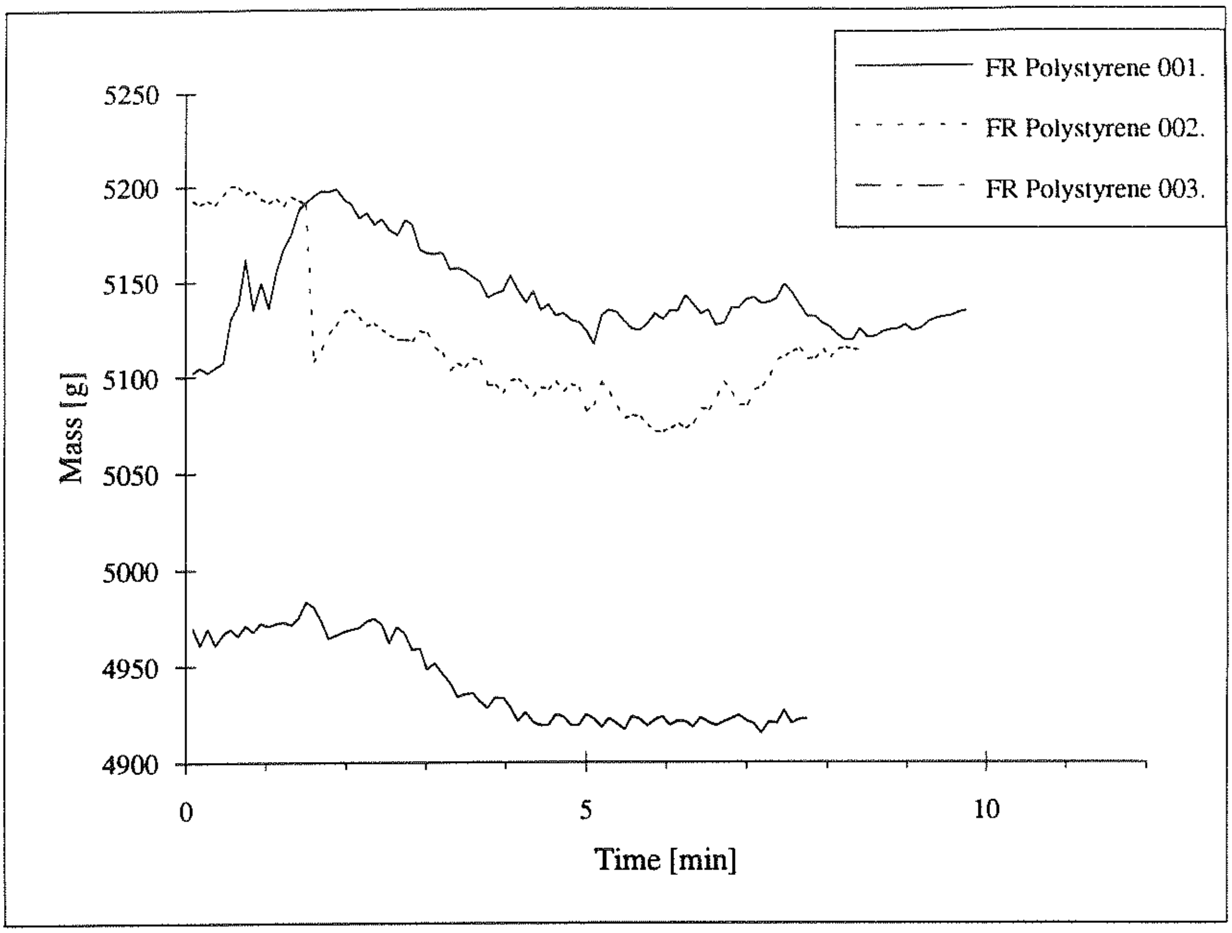


Appendix 2: FR Polystyrene





Appendix 2: FR Polystyrene


FR Polystyrene 001.
FR Polystyrene 002.
FR Polystyrene 003.
Mass [g]
5250
5200
5150
5100
5050
5000
4950
4900
0
5
10
Time [min]

Appendix 3: Test results for POLYPROPYLENE

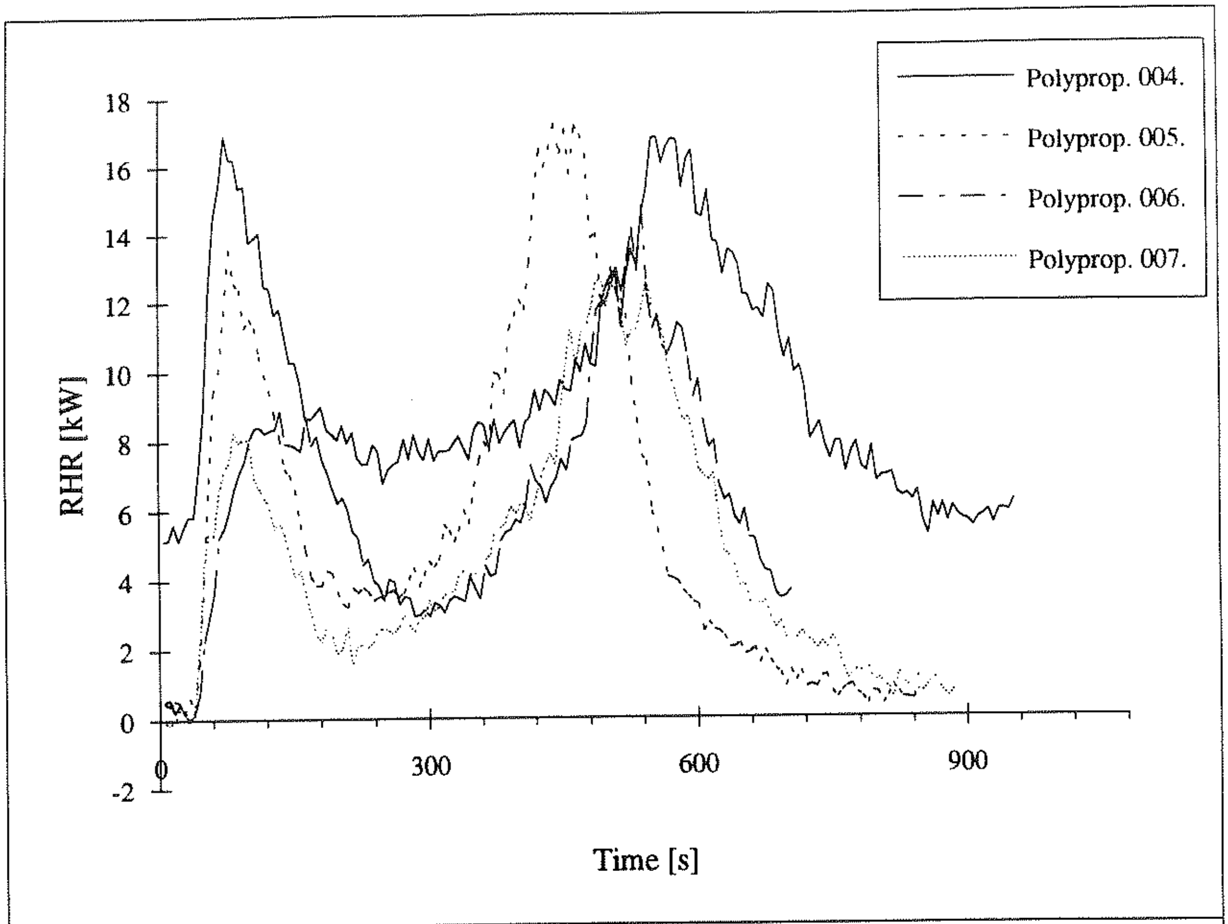
Contents:

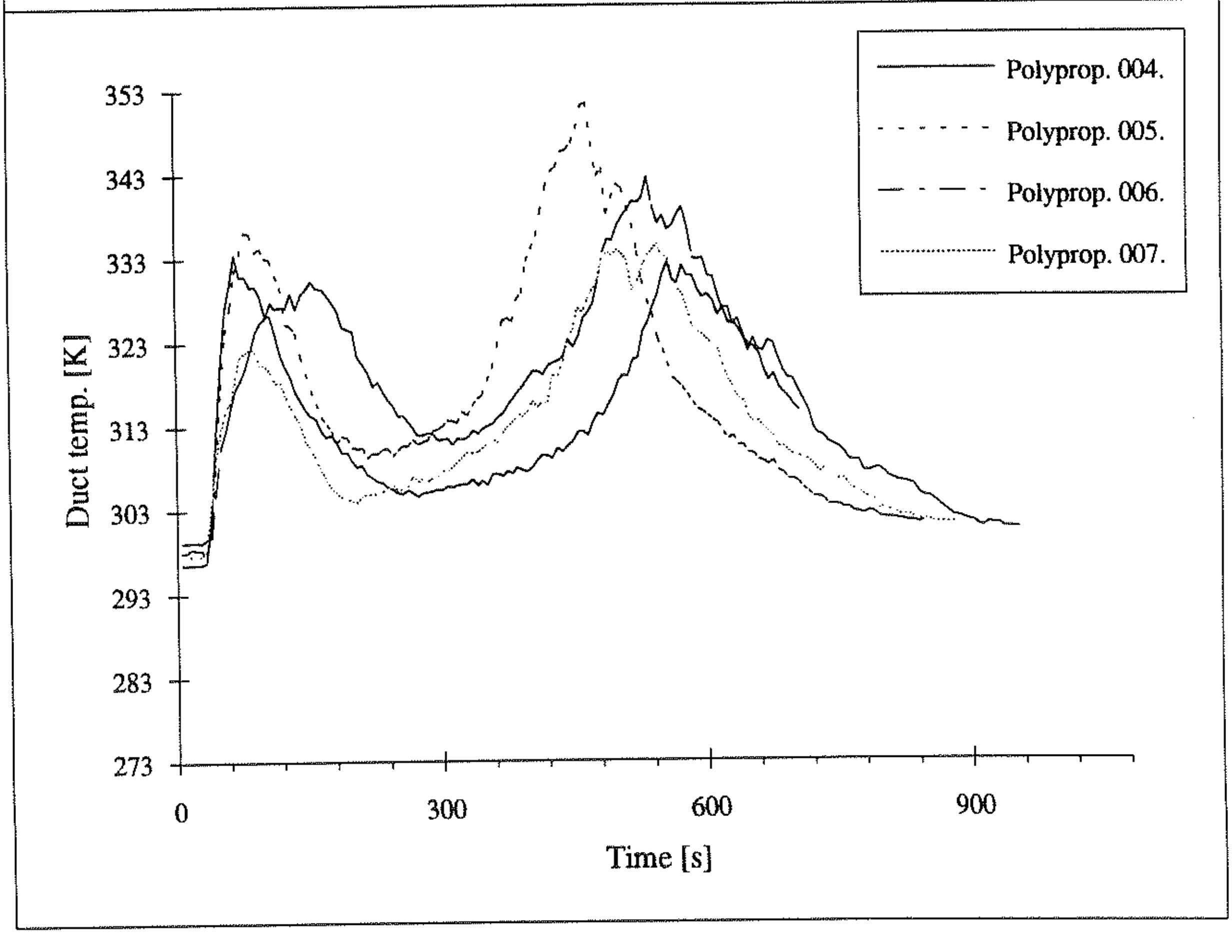
Test	RHR page	Smoke prod. page	Duct temp. page	CO_2 prod. page	CO prod. page	NO_X prod. page	C_nH_{2n} prod. page	Mass loss page	Duct flow page
004	1	-	1	2	2	3	3	4	4
005	1	-	1	2	2	3	3	4	4
006	1	-	1	2	2	3	3	4	4
007	1	-	1	2	2	3	3	4	4
008	5	-	5	6	6	7	7	8	8
009	5	-	5	6	6	7	7	8	8
010	5	-	5	6	6	7	7	8	8
011	5	-	5	6	6	7	7	8	8
012	9	9	-	10	10	11	11	12	-
013	13	13	-	14	14	15	15	16	-
014	13	13	-	14	14	15	15	16	-
015	13	13	-	14	14	15	15	16	-
016	13	13	-	14	14	15	15	16	-
017	17	17	-	18	18	19	19	20	-
018	17	17	-	18	18	19	19	20	-
019	17	17	-	18	18	19	19	20	-

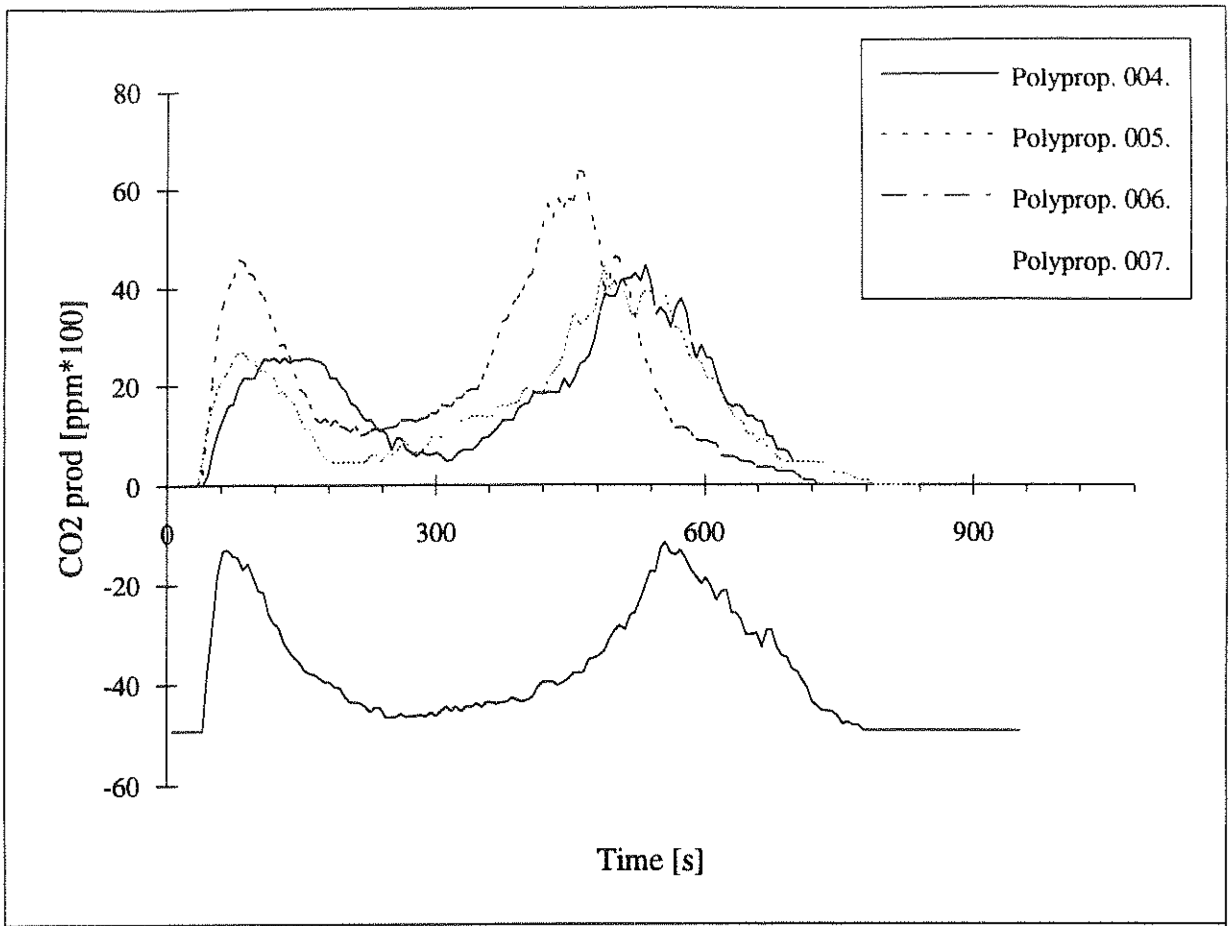
The gas production rate is given in g/s in all diagrams. Polypropylene tests 004 to 011 are exceptions, where the production rate is given in ppm. Therefore, the duct flow and temperature is given as well.

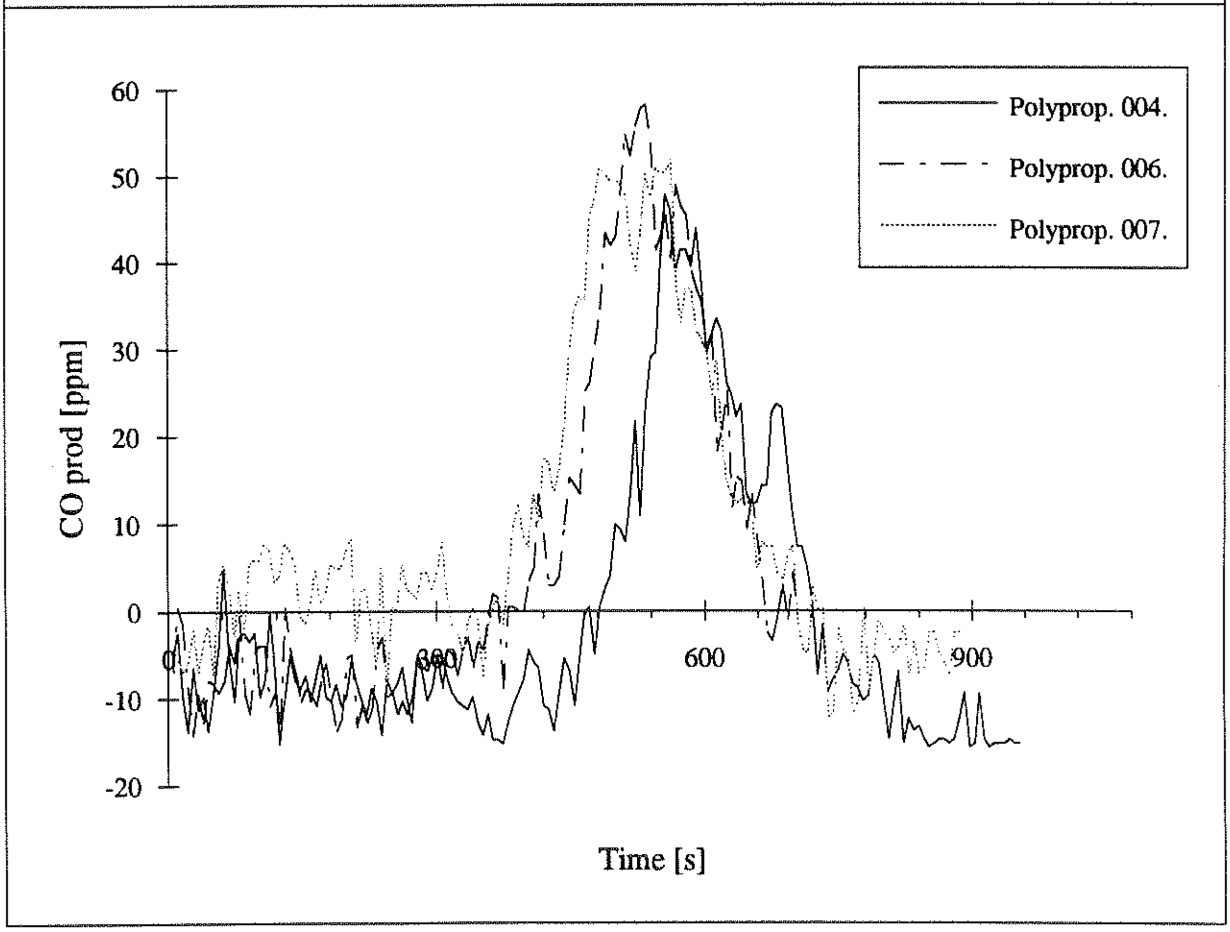
Corrections of the data were made in the study (not carried out in the appendix):

- The RHR values were multiplied with 12.6/13.1 as the measuring program does not consider the actual heat released per unit mass oxygen consumed.
- The CO_2 and CO values were multiplied by 0.91 due to a calibration error in the gas analysis equipment.

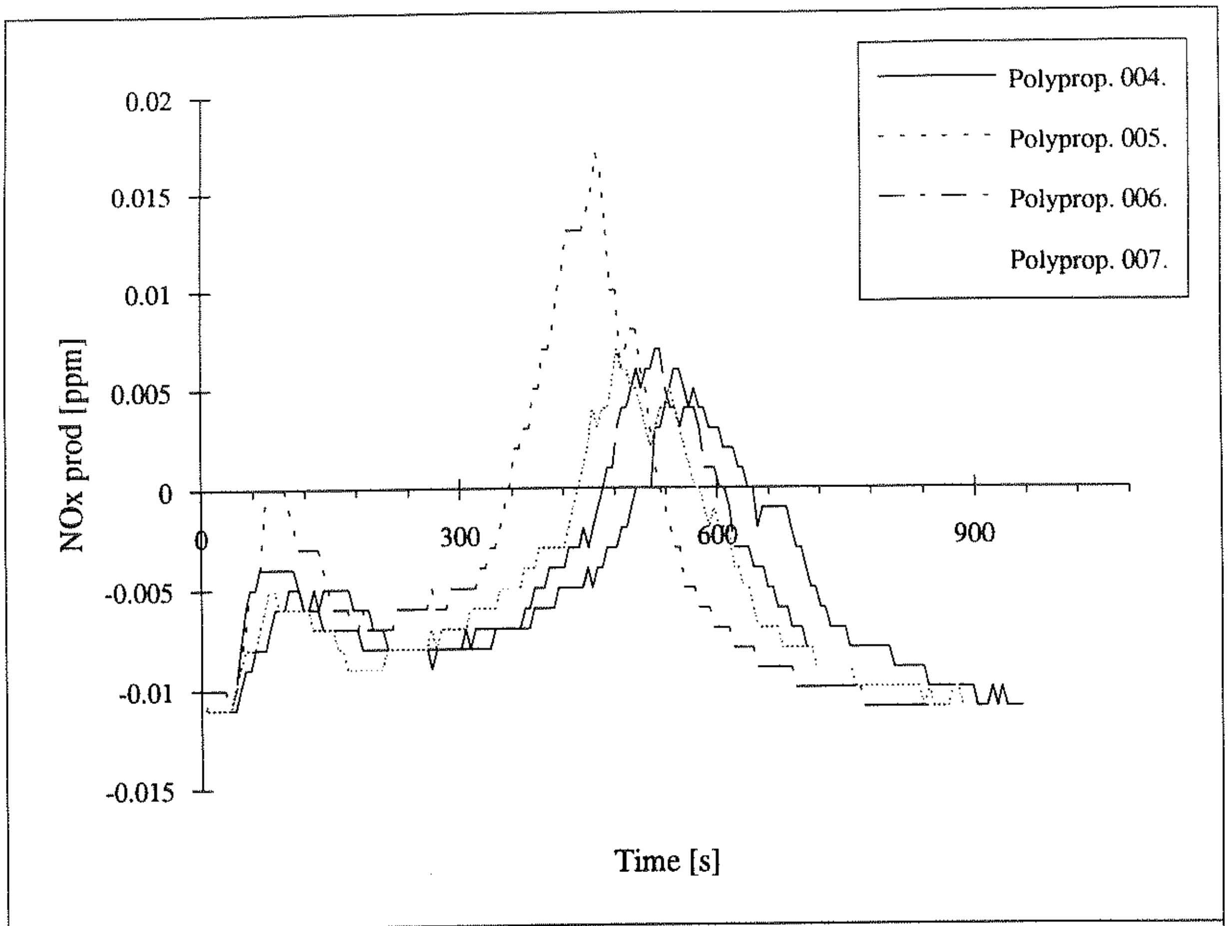

Polyprop. 004.
Polyprop. 005.
Polyprop. 006.
Polyprop. 007.
RHR [kW]
18
16
14
12
10
8
6
4
2
0
-2
0
300
600
900
Time [s]

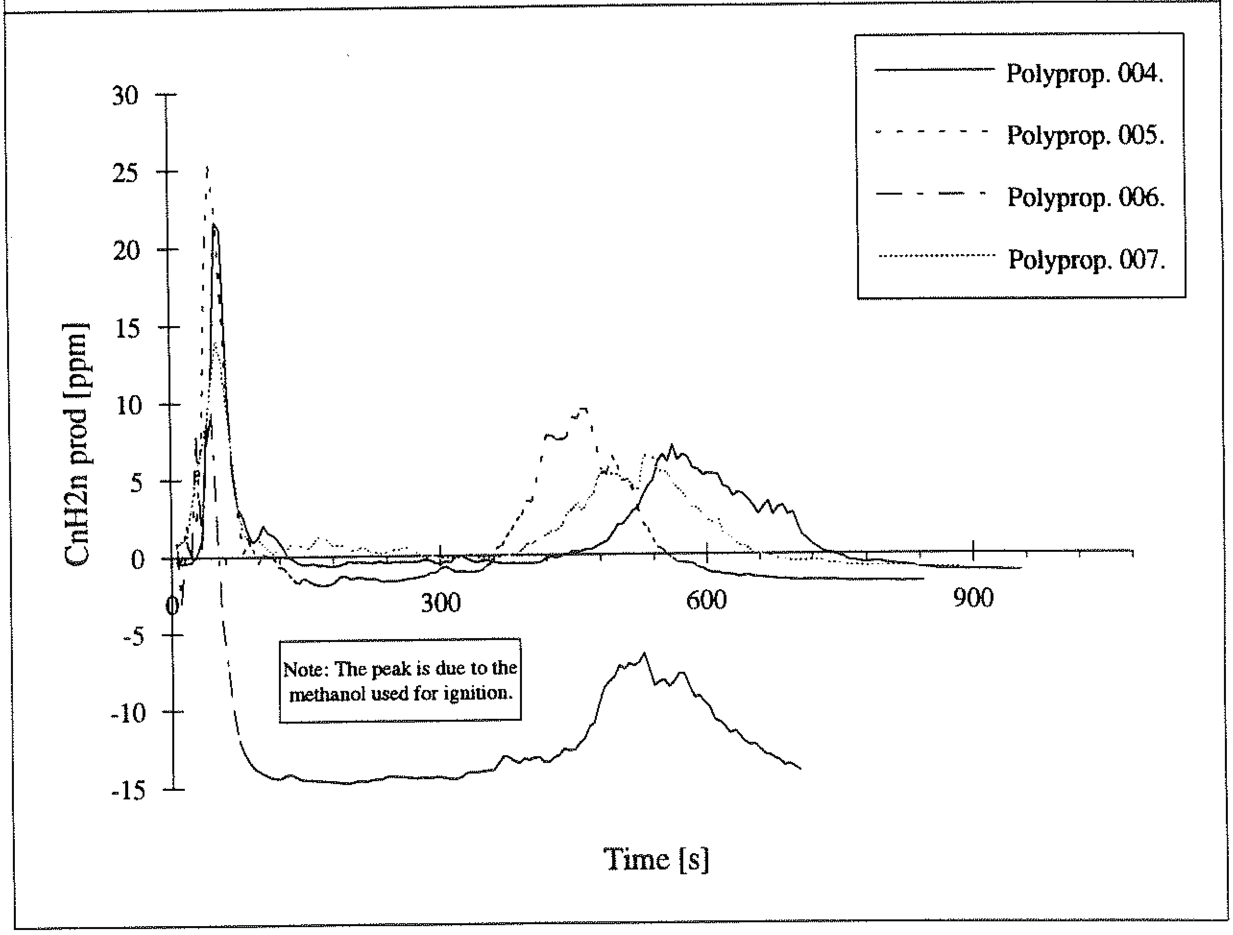

Polyprop. 004.
Polyprop. 005.
Polyprop. 006.
Polyprop. 007.
Duct temp. [K]
353
343
333
323
313
303
293
283
273
0
300
600
900
Time [s]



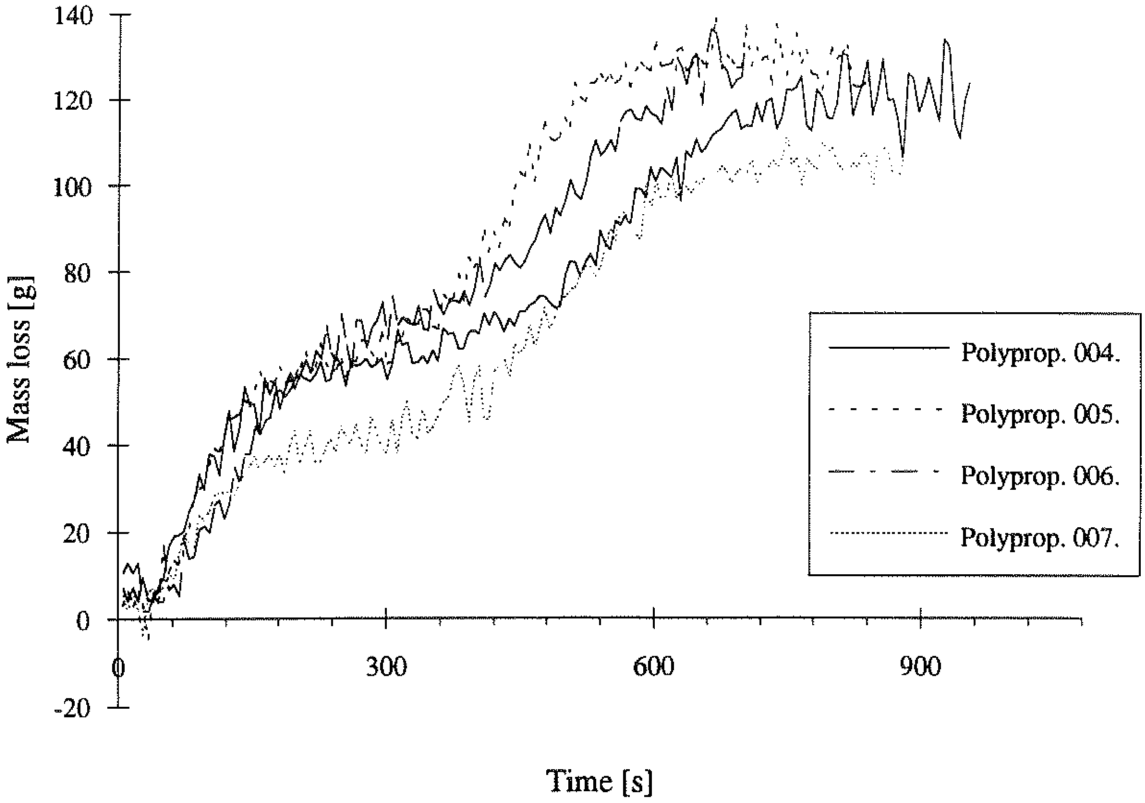


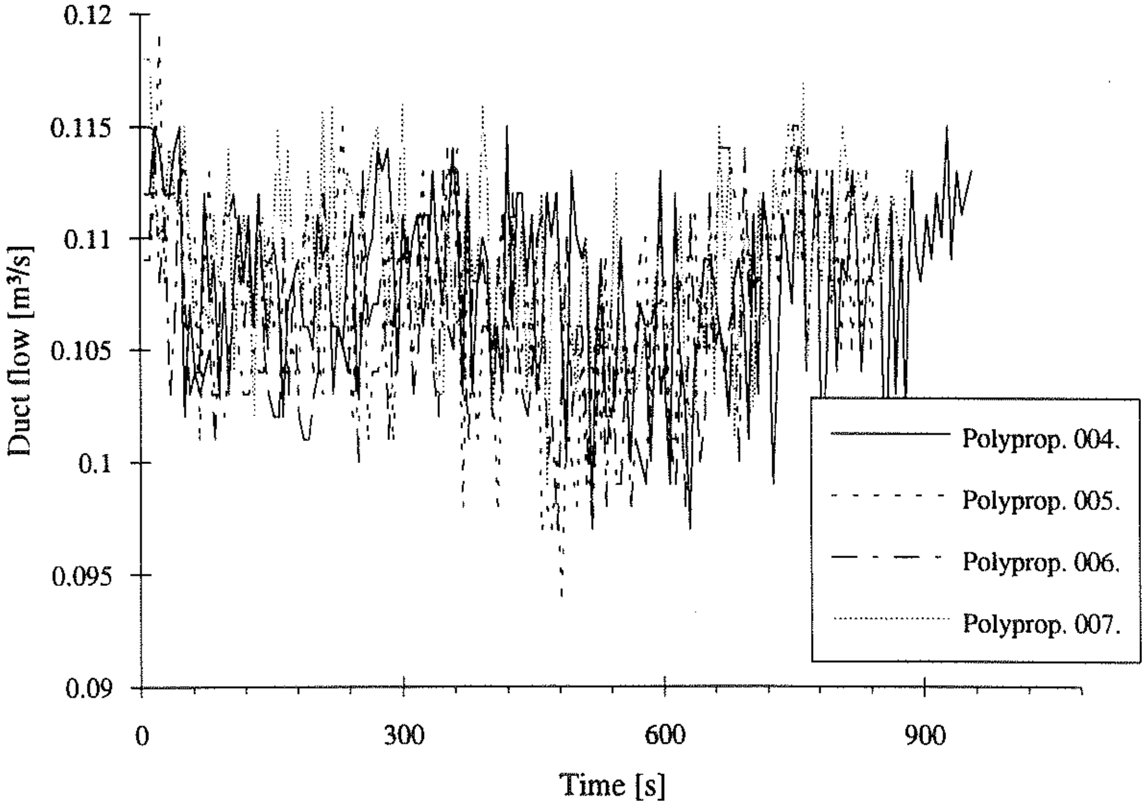
Appendix 3: Polypropylene

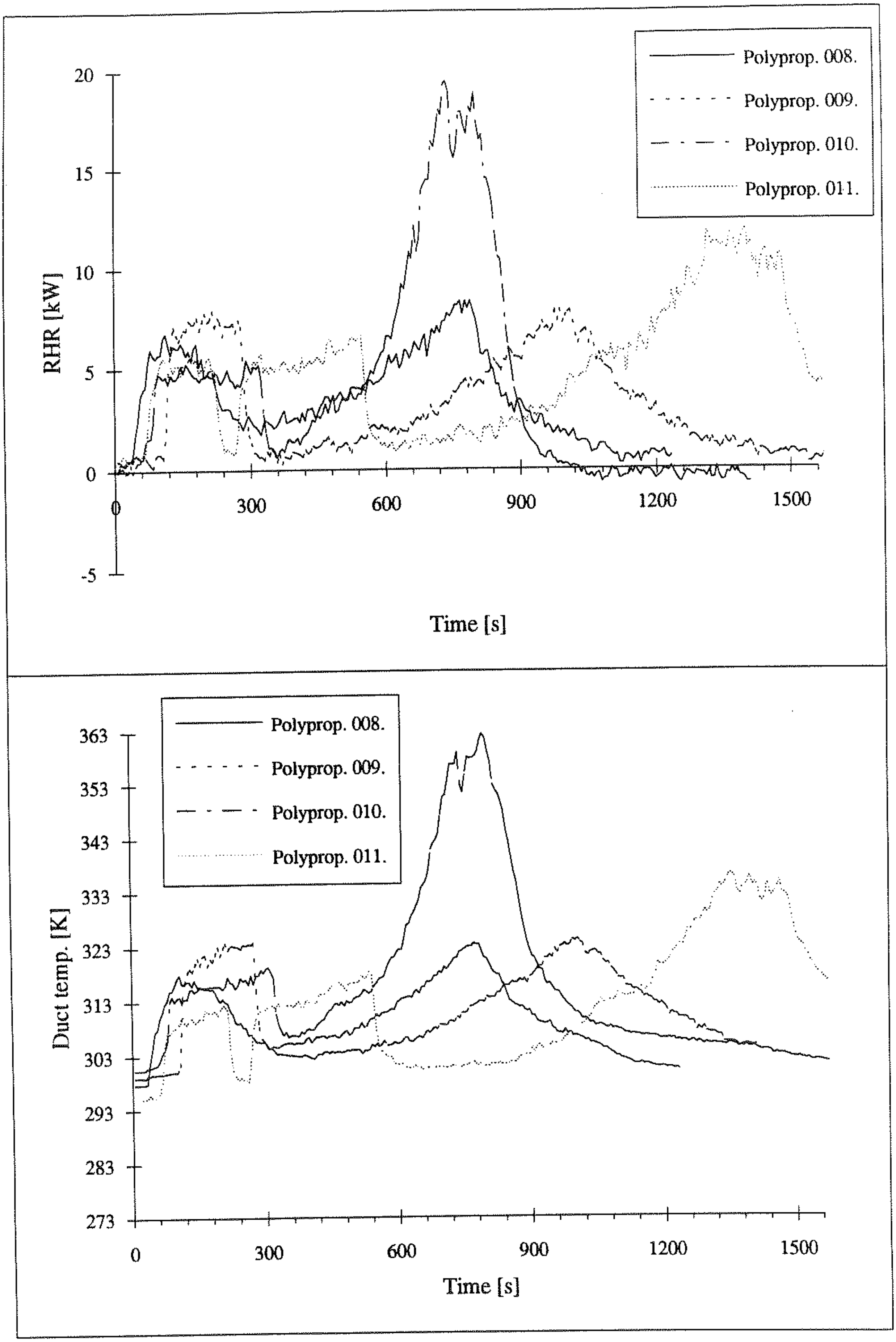


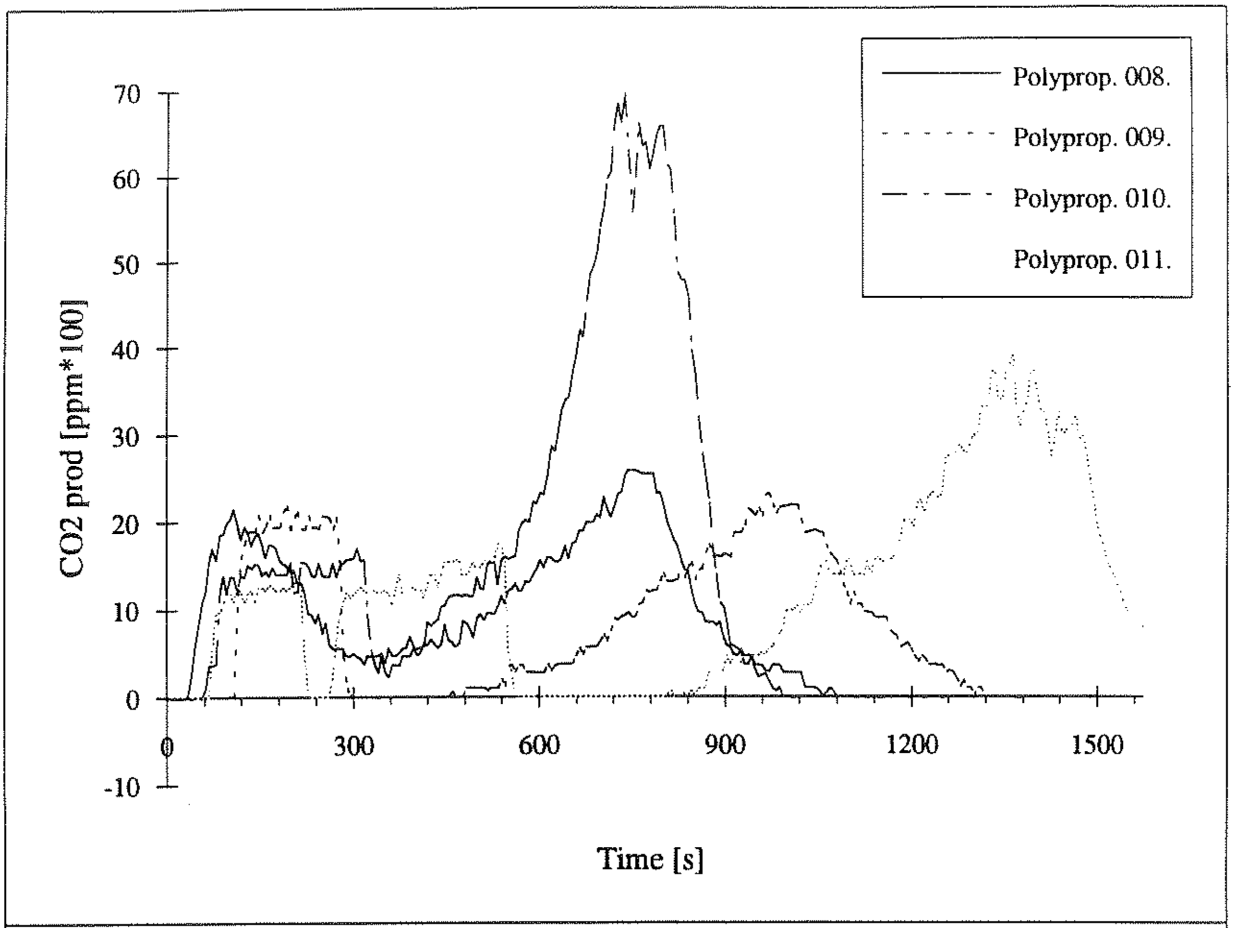


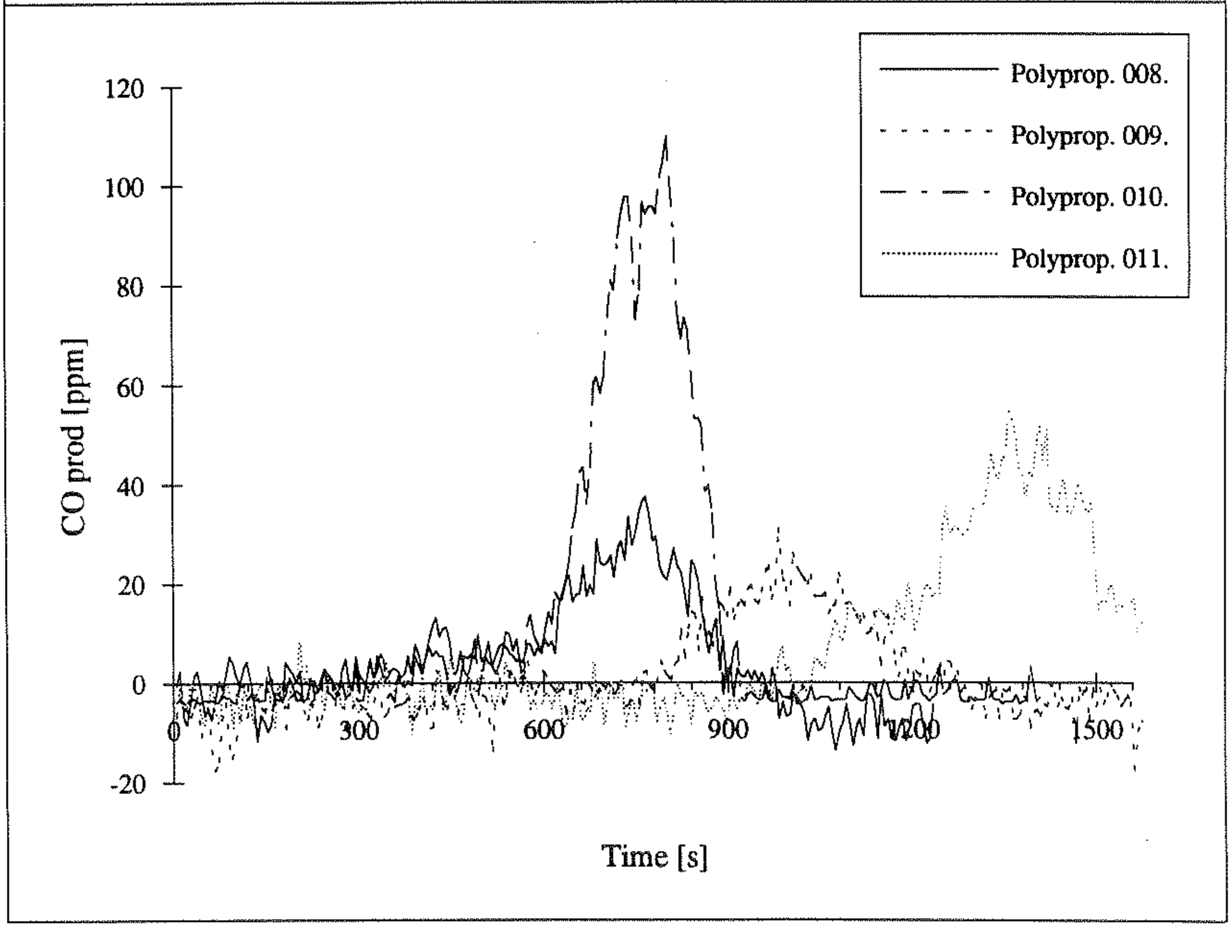
Appendix 3: Polypropylene

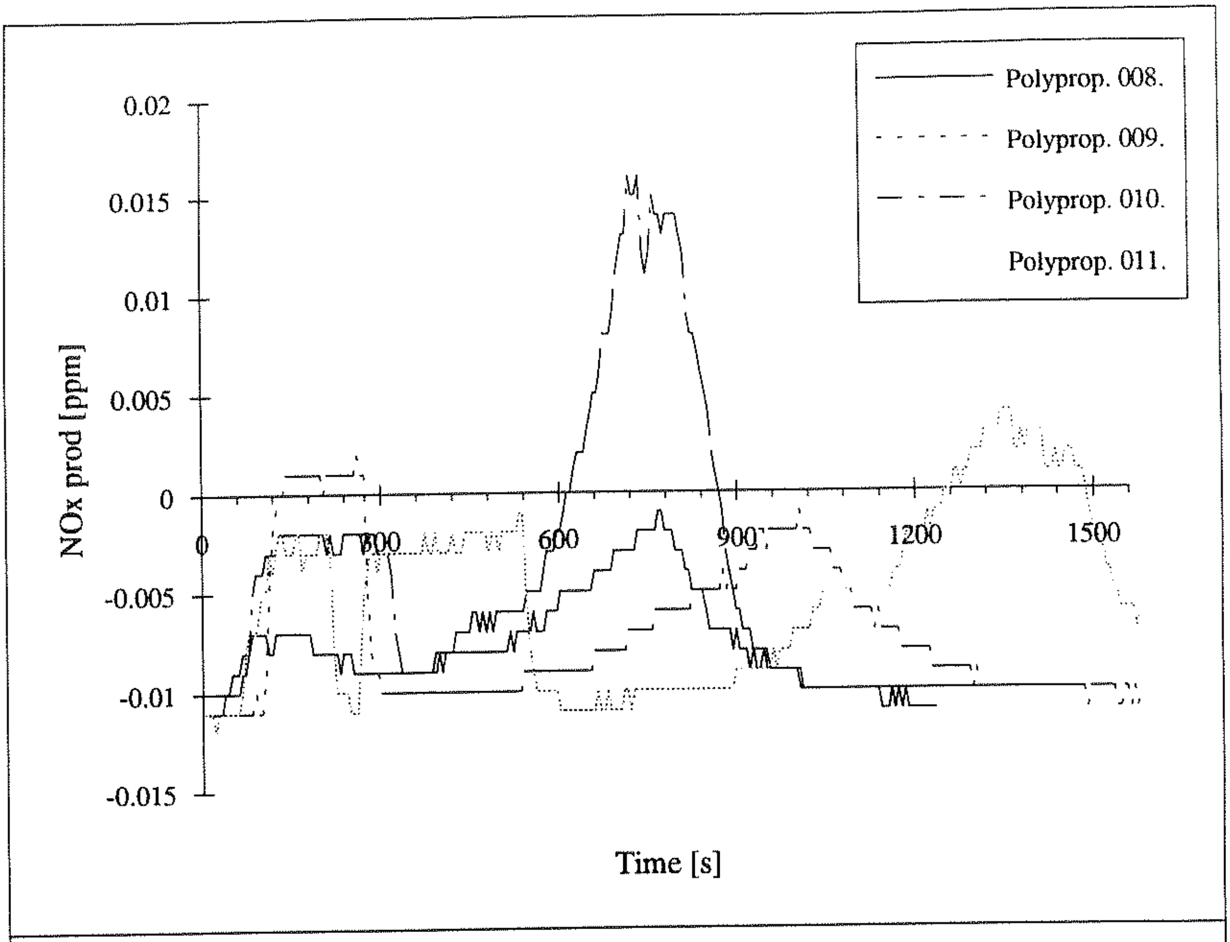

140
120
100
80
60
40
20
0
-20
Mass loss [g]
0
300
600
900
Time [s]
Polyprop. 004.
Polyprop. 005.
Polyprop. 006.
Polyprop. 007.

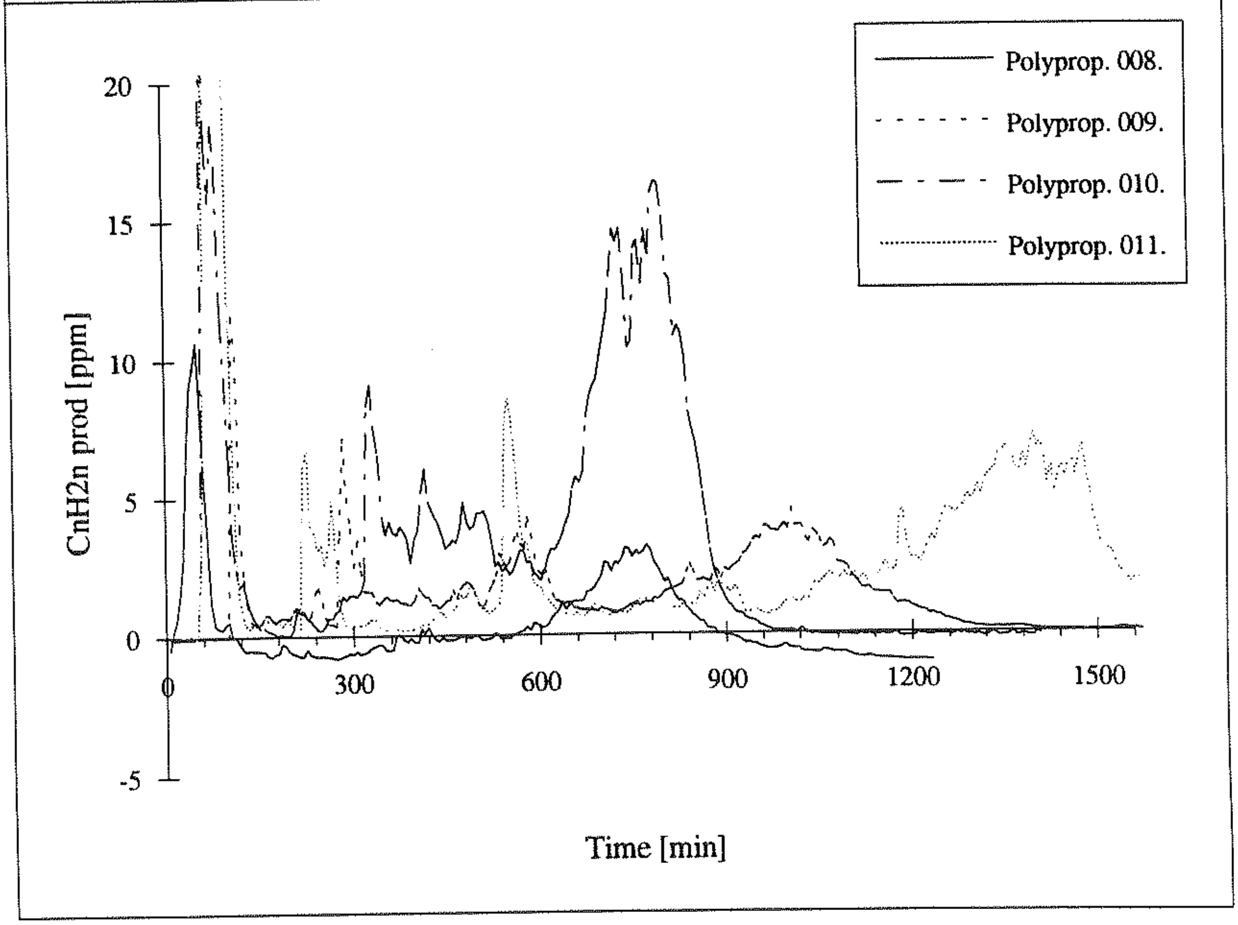

0.12
0.115
0.11
0.105
0.1
0.095
0.09
Duct flow [m³/s]
0
300
600
900
Time [s]
Polyprop. 004.
Polyprop. 005.
Polyprop. 006.
Polyprop. 007.


Polyprop. 008.
Polyprop. 009.
Polyprop. 010.
Polyprop. 011.
RHR [kW]
20
15
10
5
0
-5
0
300
600
900
1200
1500
Time [s]
Polyprop. 008.
Polyprop. 009.
Polyprop. 010.
Polyprop. 011.
Duct temp. [K]
363
353
343
333
323
313
303
293
283
273
0
300
600
900
1200
1500
Time [s]

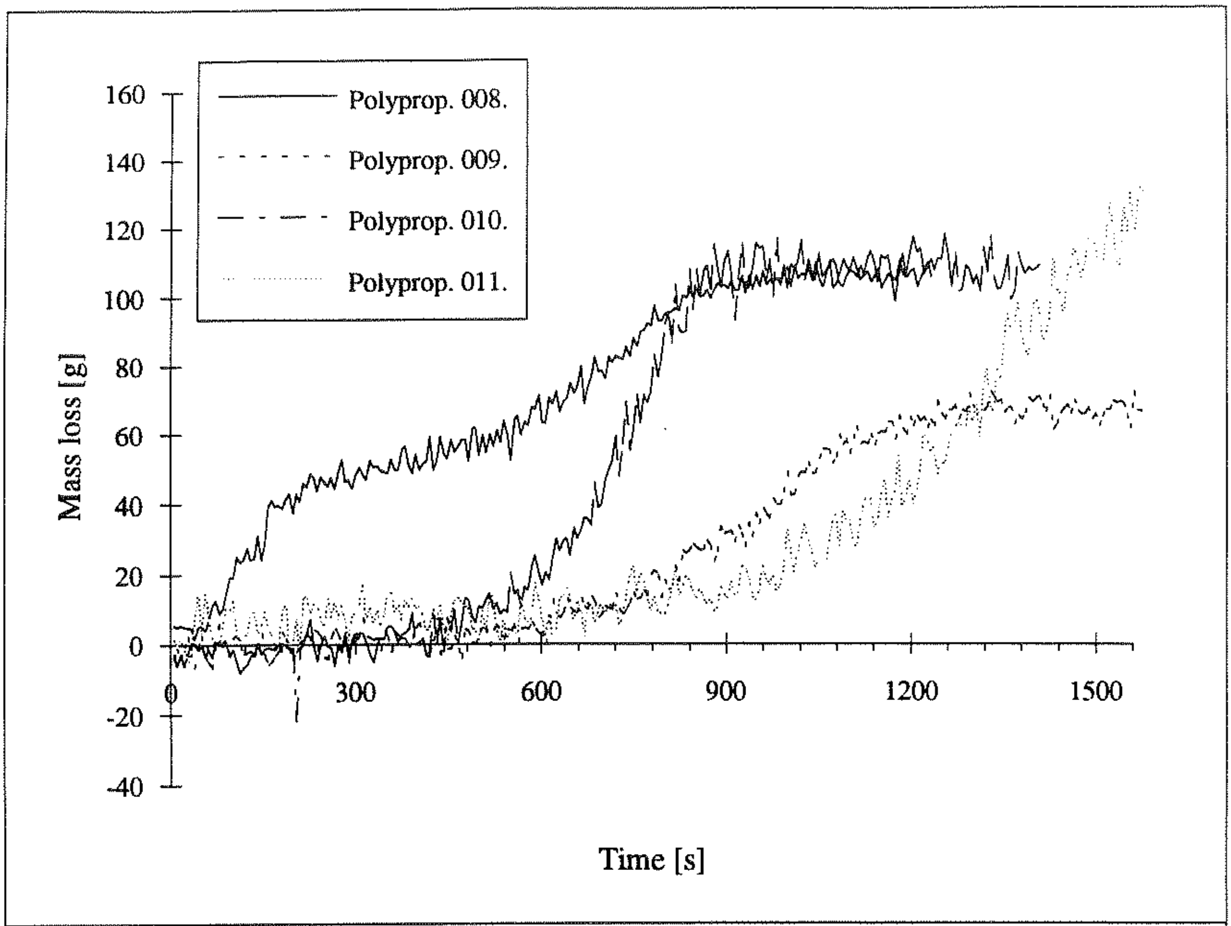

70
60
50
40
30
20
10
0
-10
CO2 prod [ppm*100]
0
300
600
900
1200
1500
Time [s]
Polyprop. 008.
Polyprop. 009.
Polyprop. 010.
Polyprop. 011.

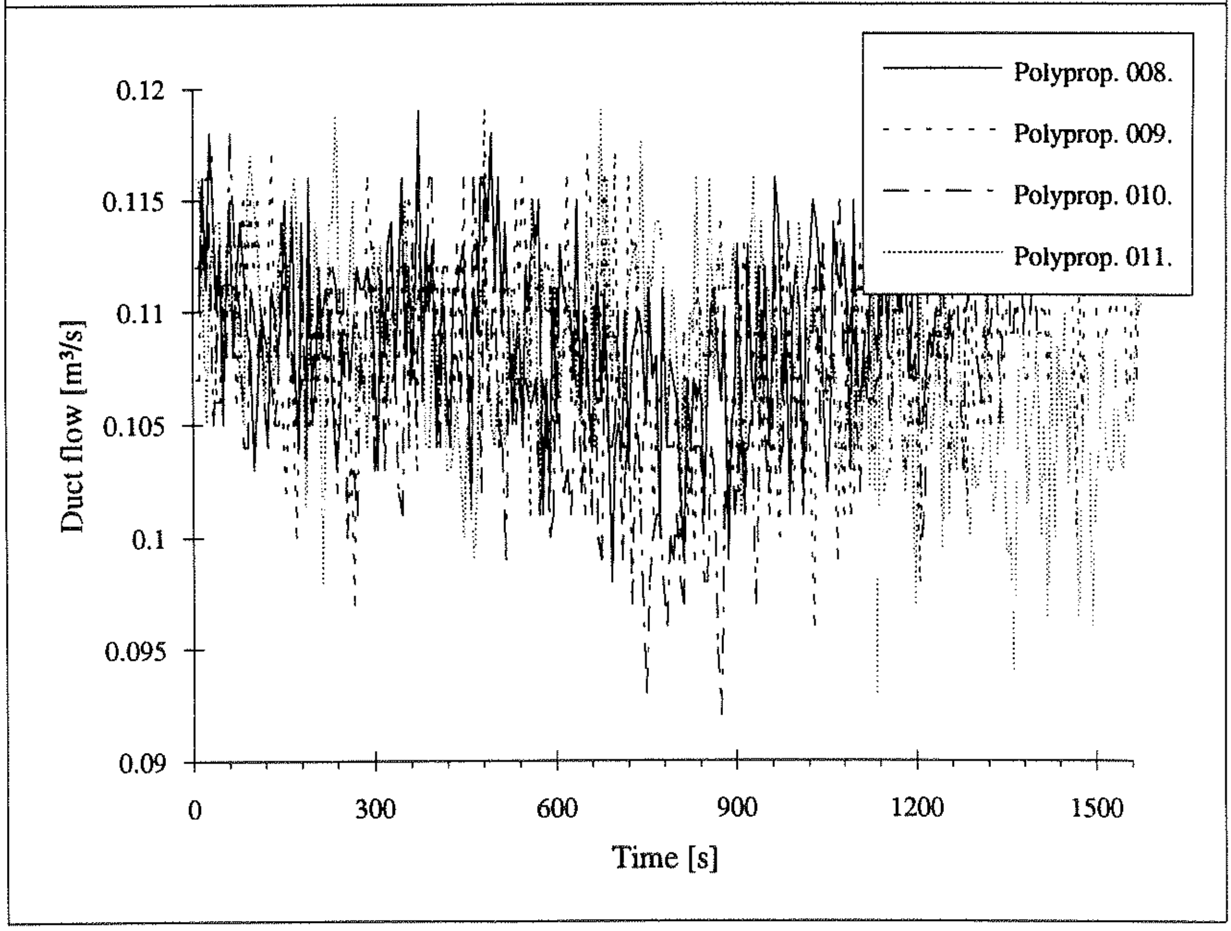

120
100
80
60
40
20
0
-20
CO prod [ppm]
0
300
600
900
1200
1500
Time [s]
Polyprop. 008.
Polyprop. 009.
Polyprop. 010.
Polyprop. 011.

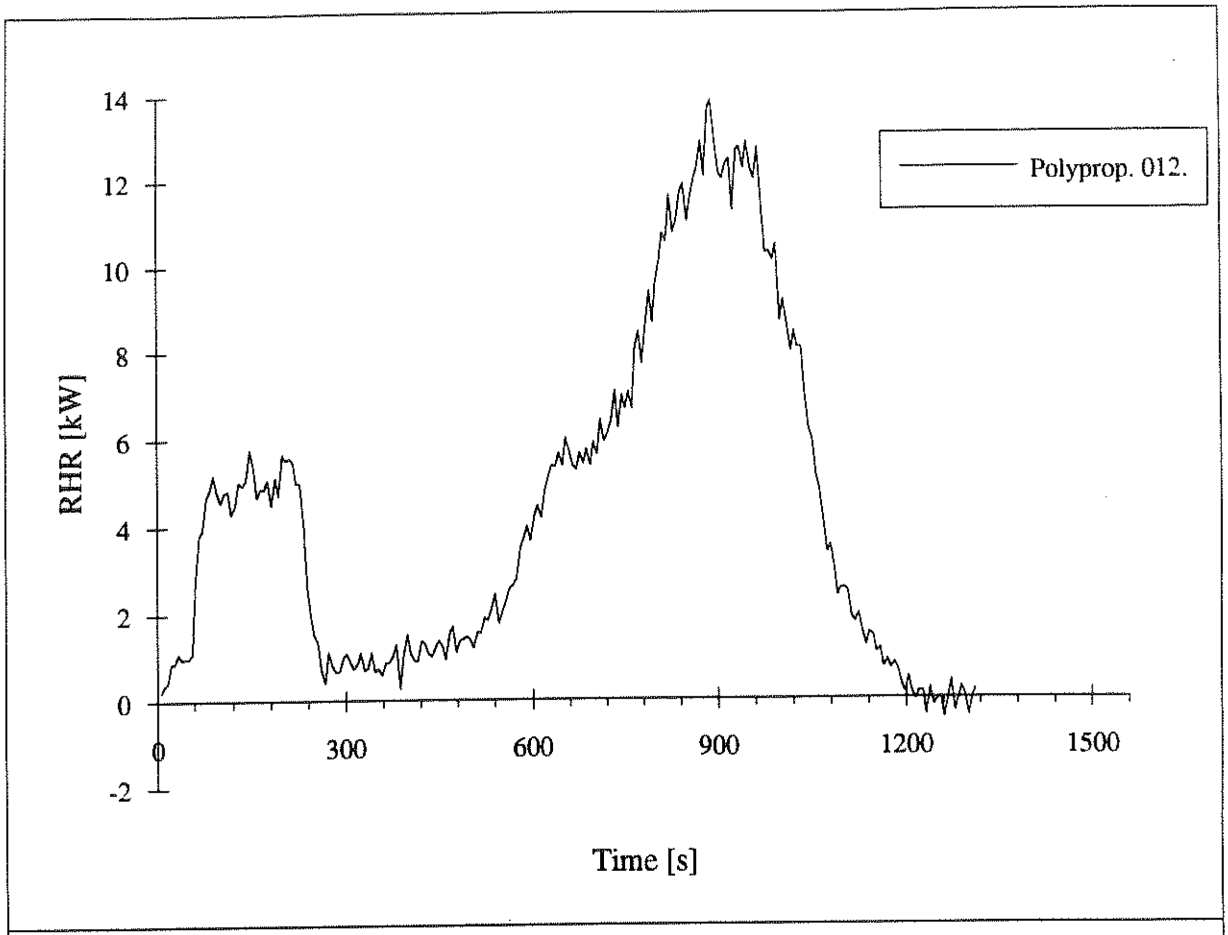


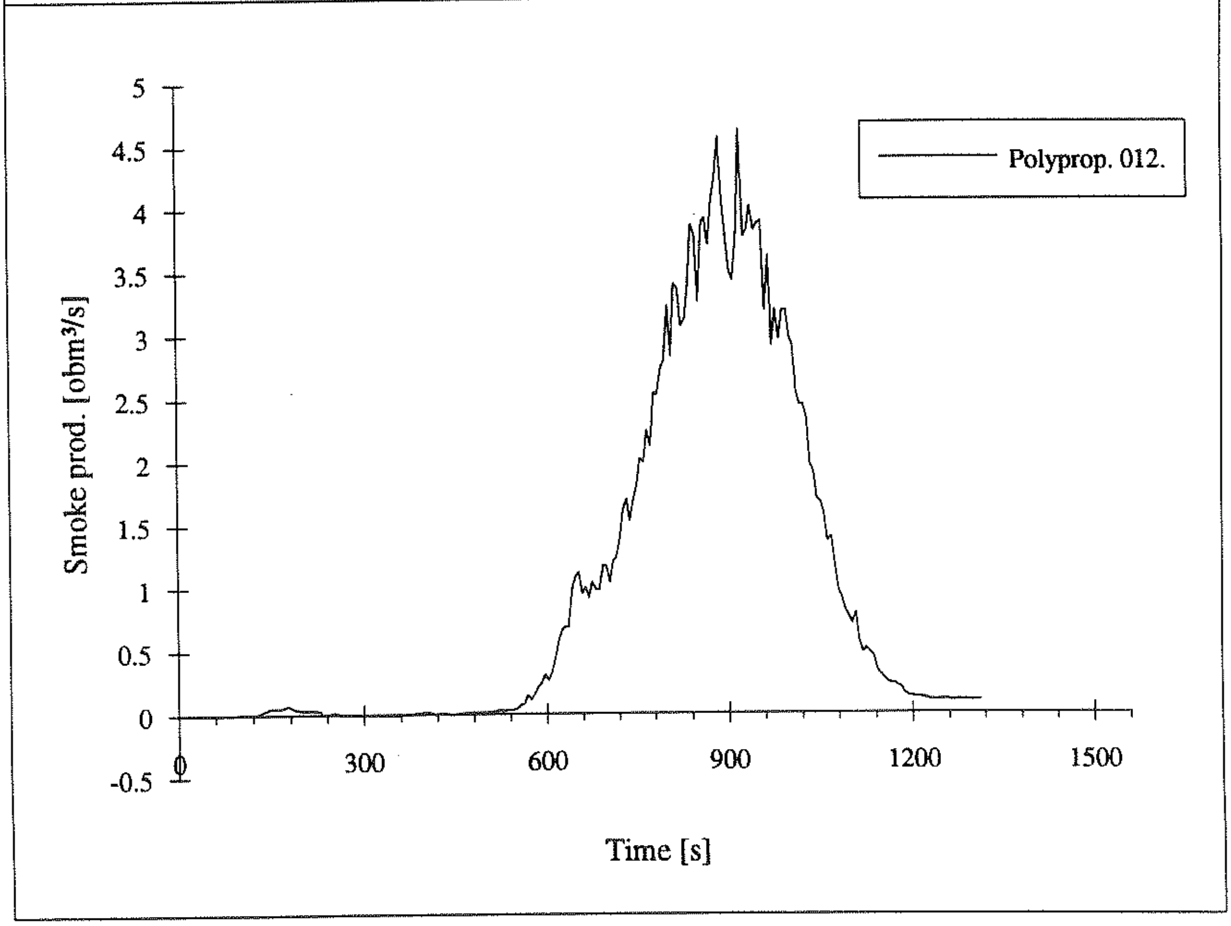


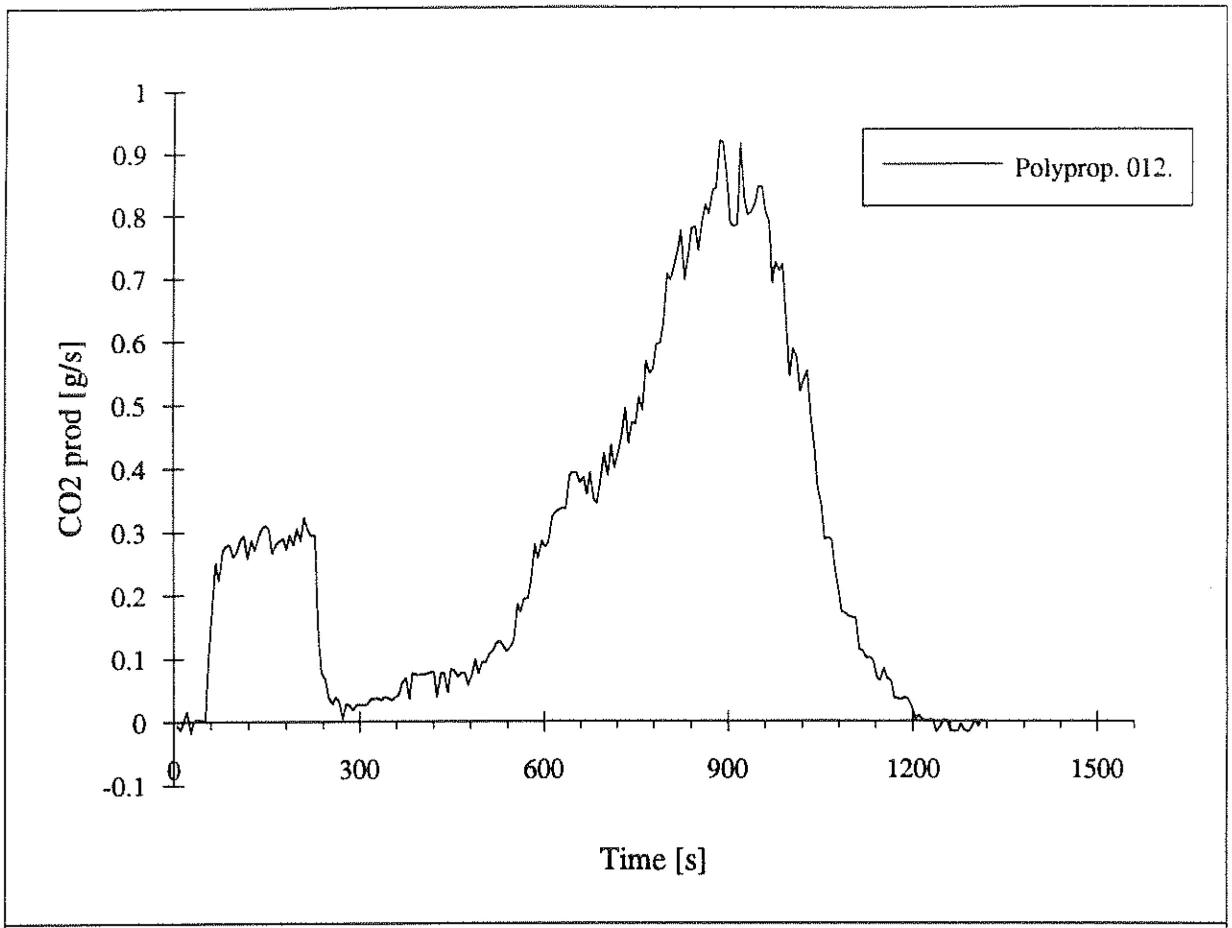
Appendix 3: Polypropylene

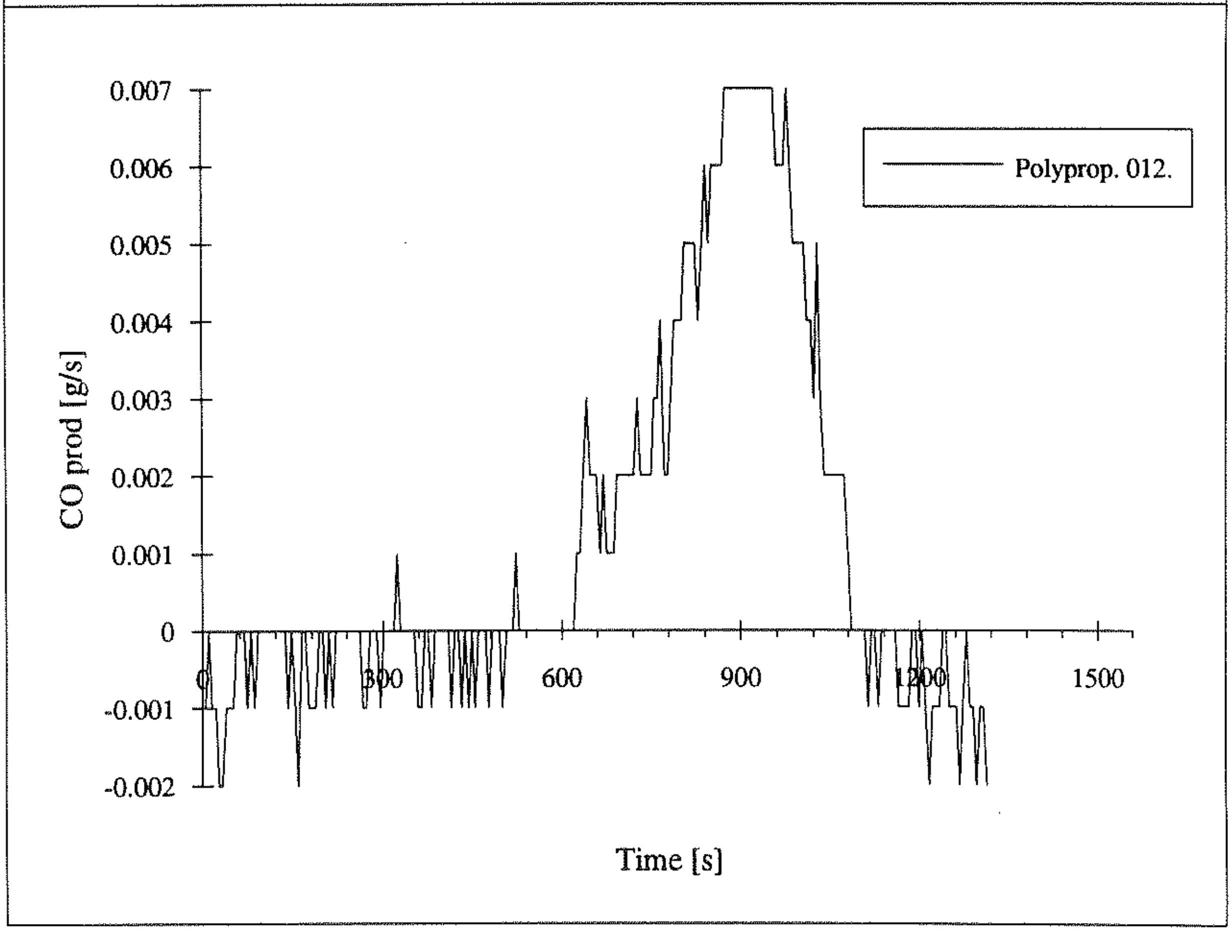

Polyprop. 008.
Polyprop. 009.
Polyprop. 010.
Polyprop. 011.
Mass loss [g]
160
140
120
100
80
60
40
20
0
-20
-40
0
300
600
900
1200
1500
Time [s]

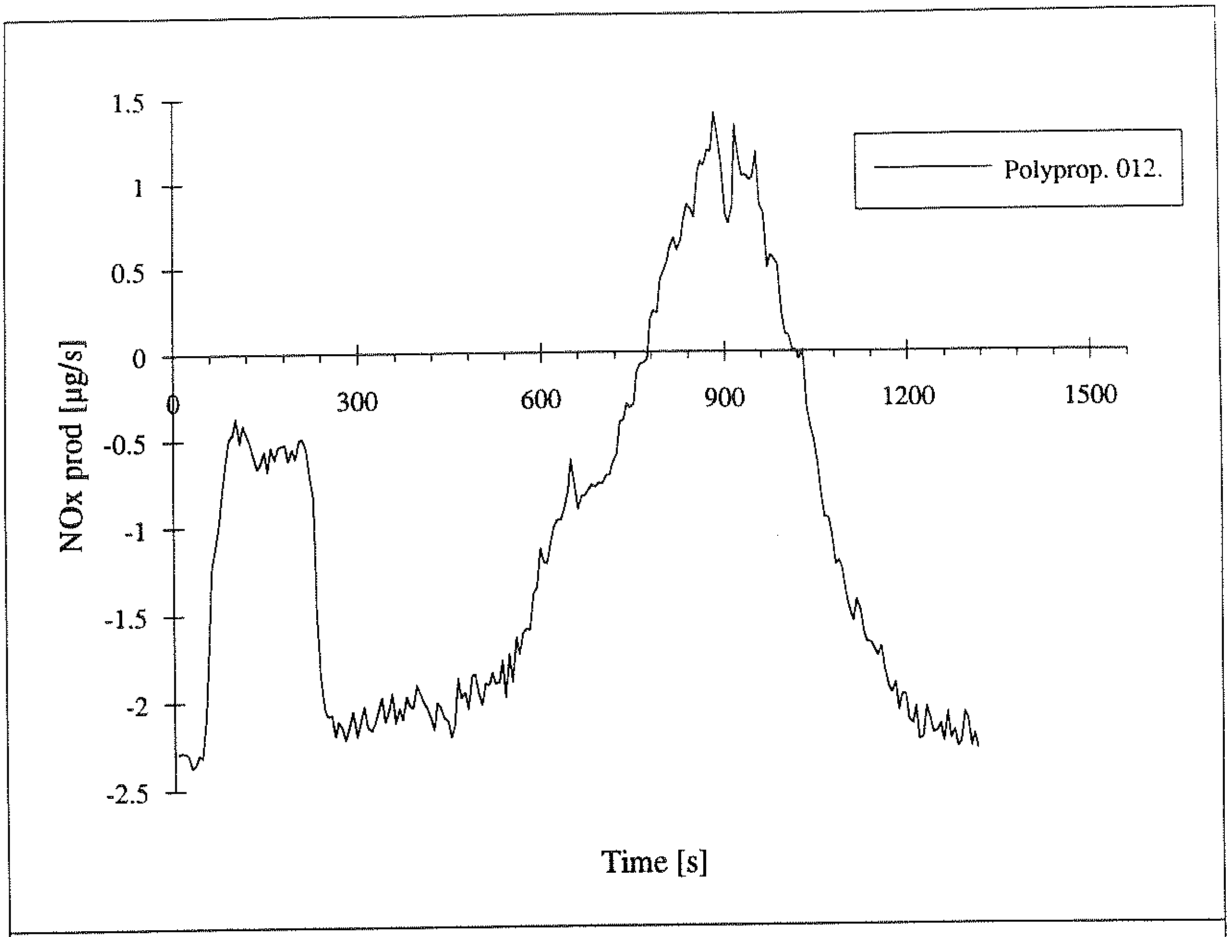

Polyprop. 008.
Polyprop. 009.
Polyprop. 010.
Polyprop. 011.
Duct flow [m³/s]
0.12
0.115
0.11
0.105
0.1
0.095
0.09
0
300
600
900
1200
1500
Time [s]

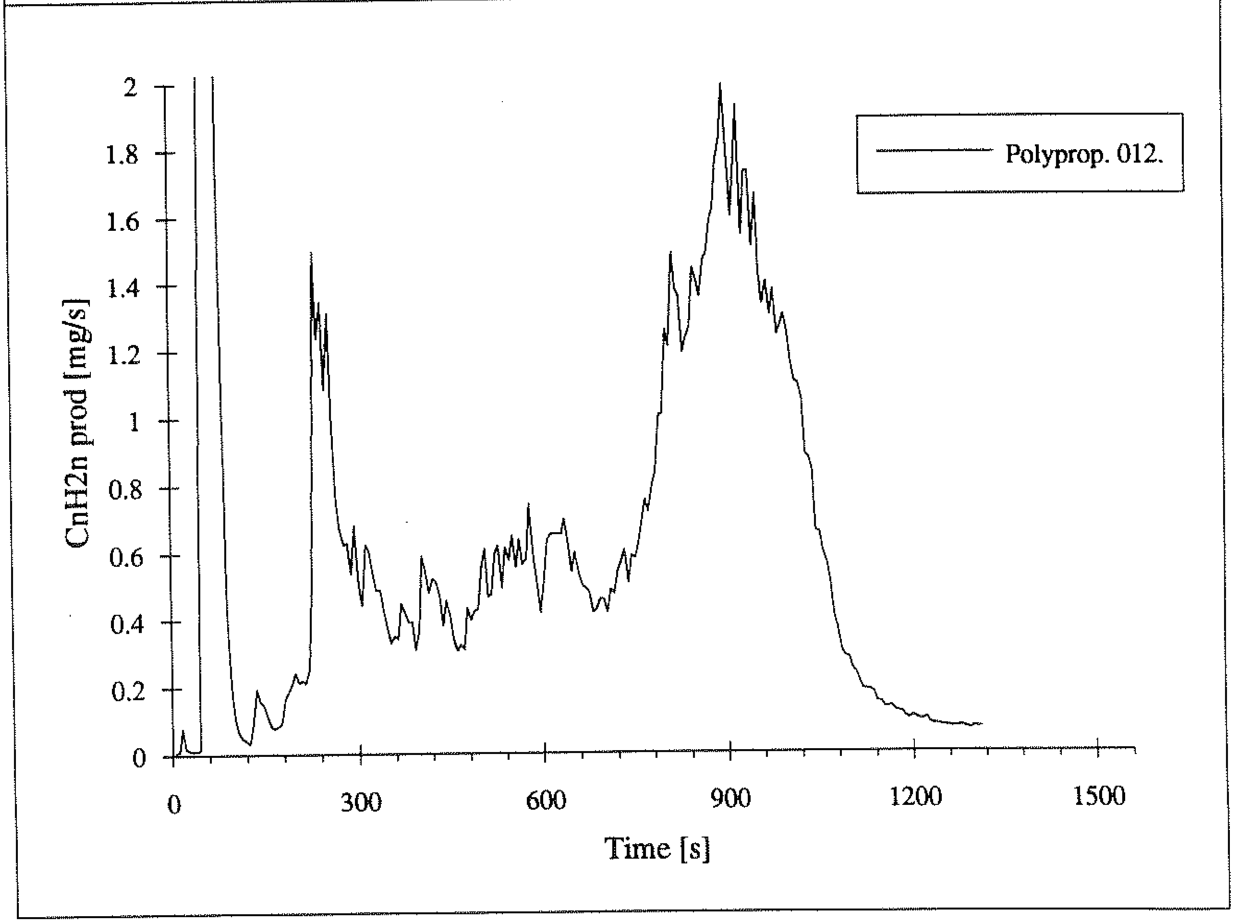

RHR [kW]
14
12
10
8
6
4
2
0
-2
0
300
600
900
1200
1500
Time [s]
Polyprop. 012.

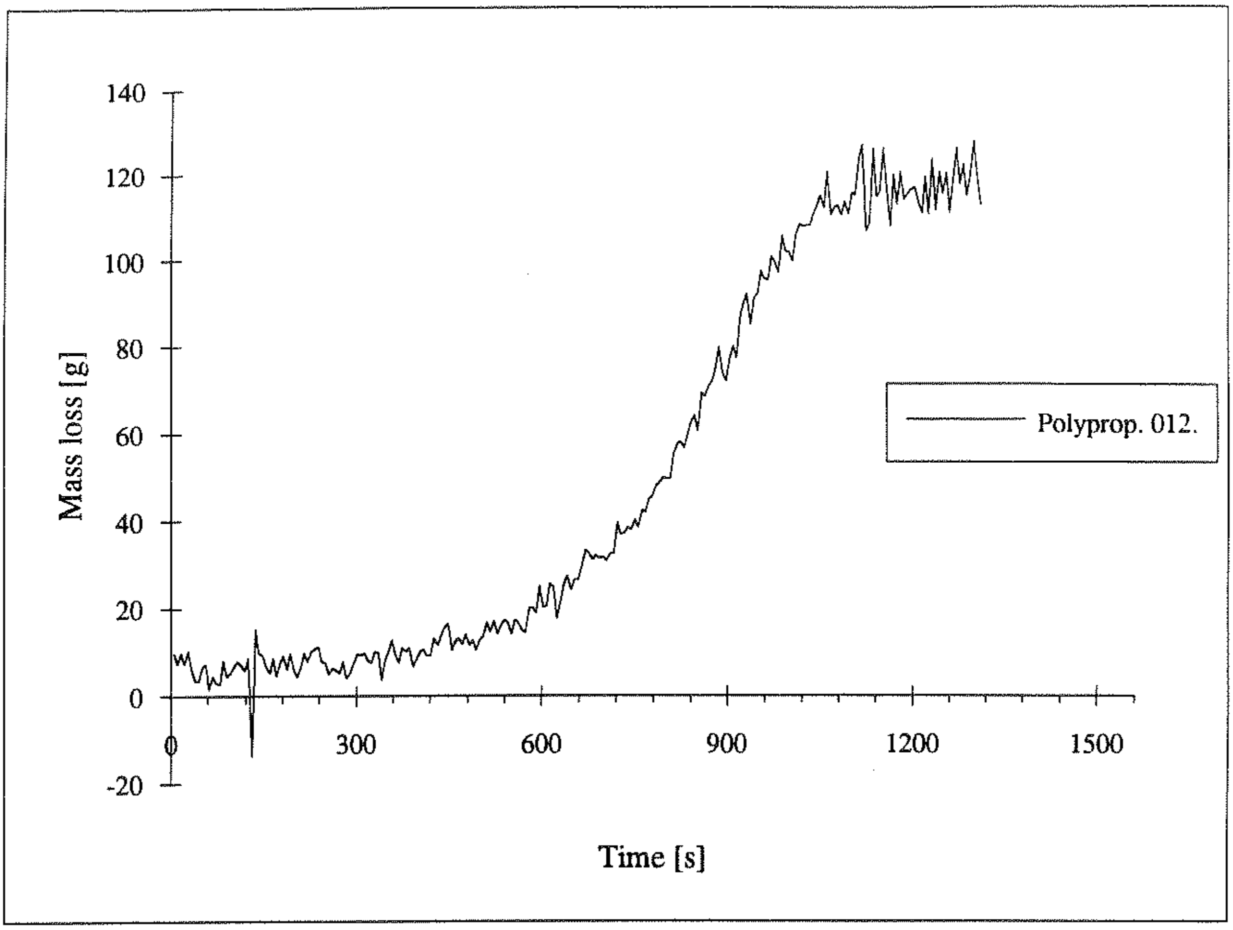

Smoke prod. [obm³/s]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
300
600
900
1200
1500
Time [s]
Polyprop. 012.

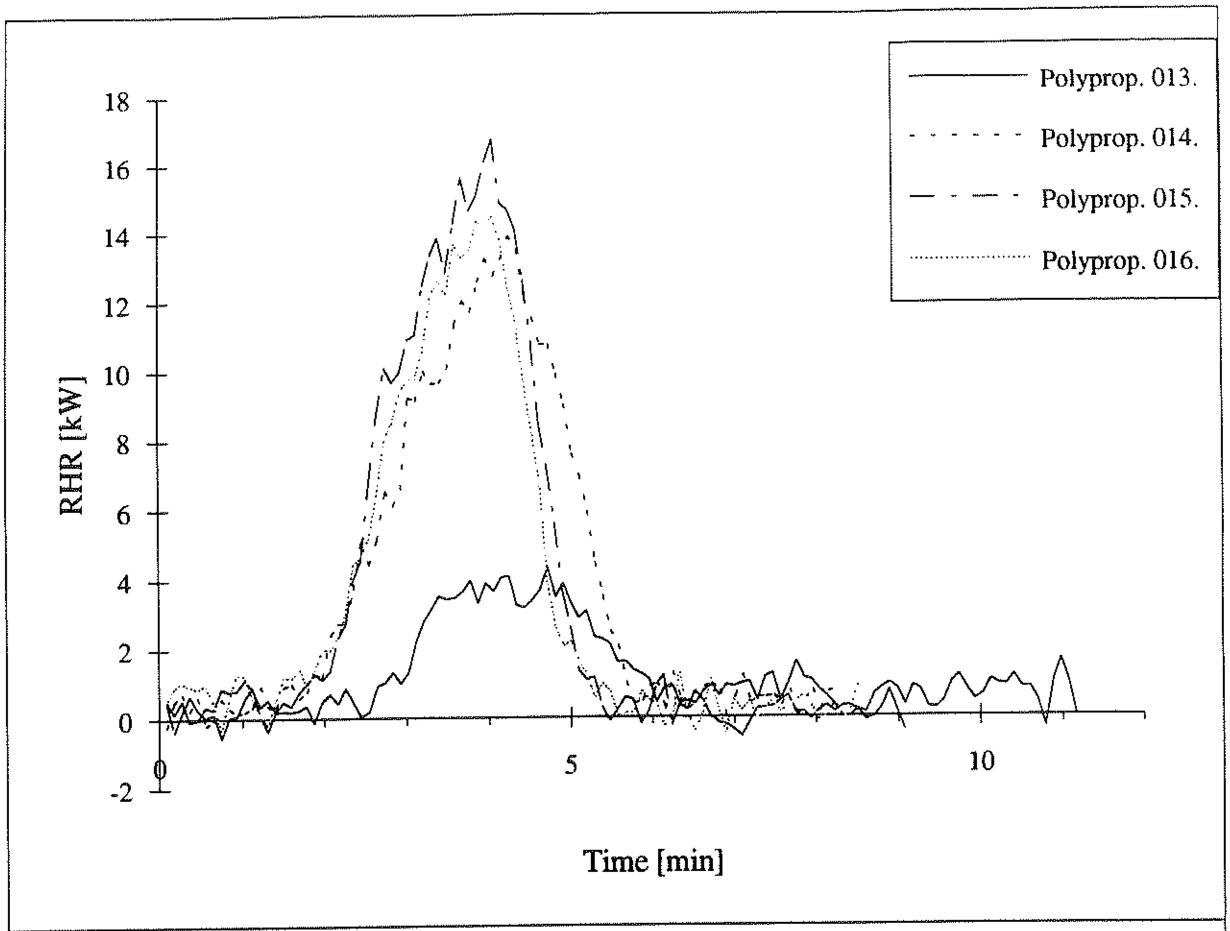

CO2 prod [g/s]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
300
600
900
1200
1500
Time [s]
Polyprop. 012.

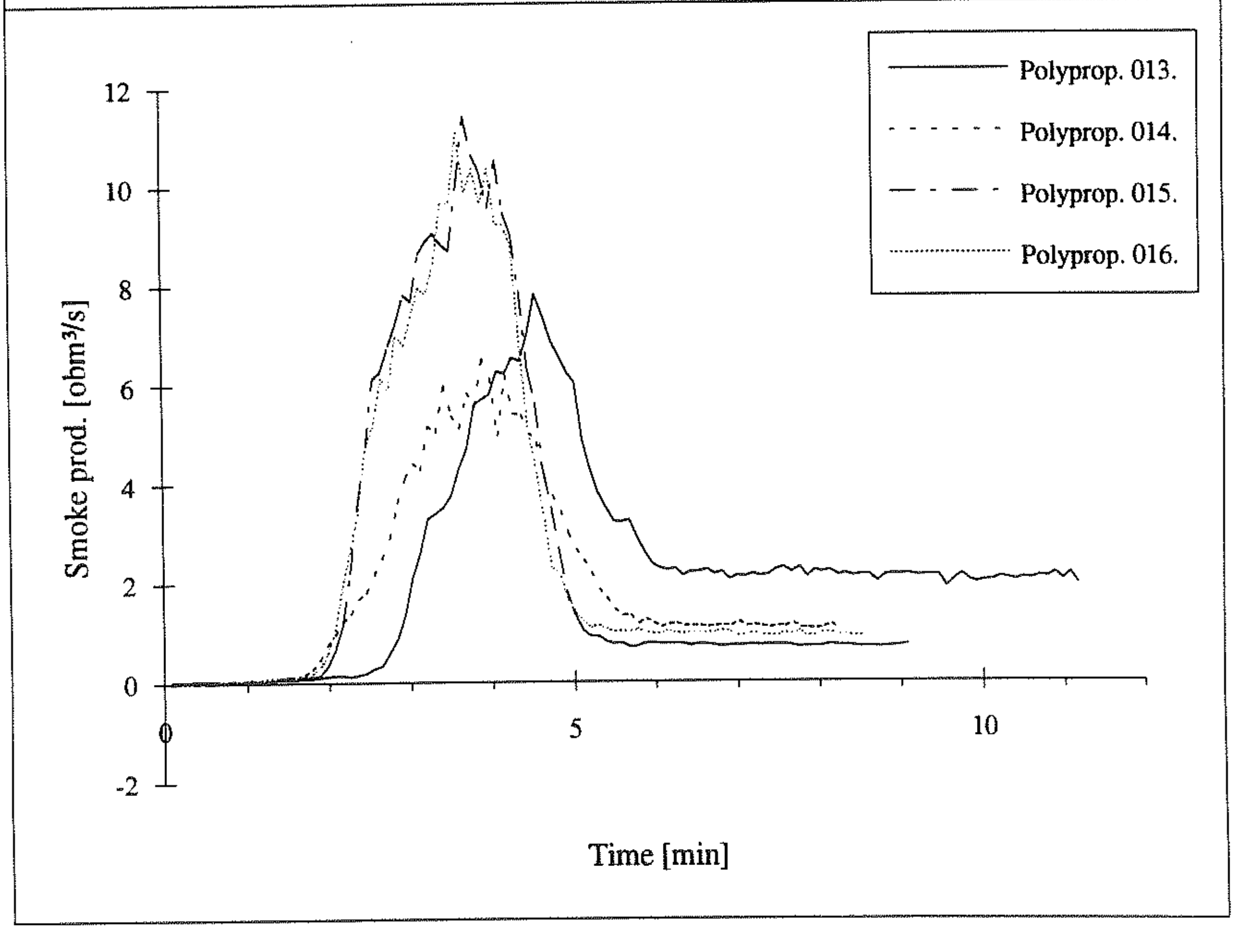

CO prod [g/s]
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
0
300
600
900
1200
1500
Time [s]
Polyprop. 012.


1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
NOx prod [µg/s]
0
300
600
900
1200
1500
Time [s]
Polyprop. 012.

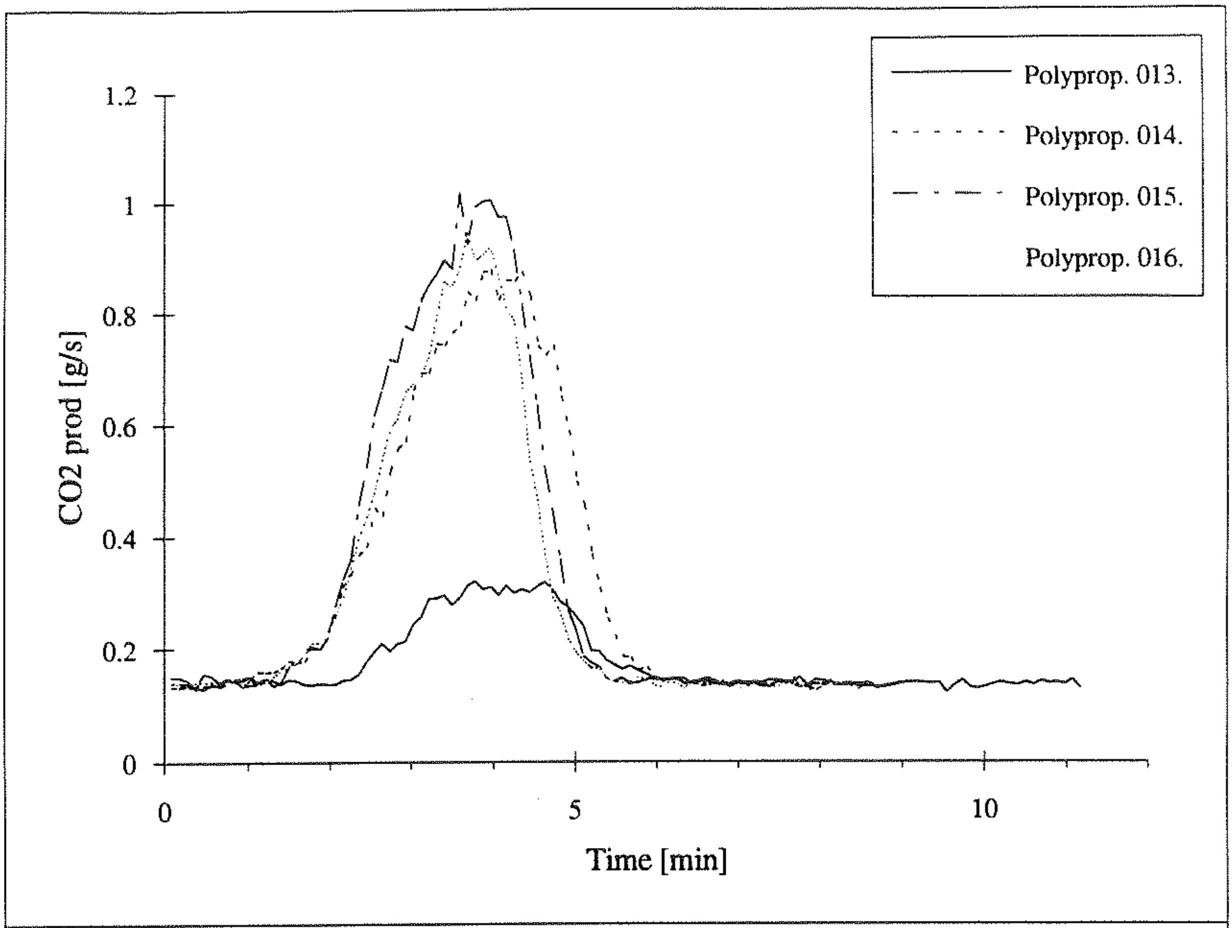

2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CnH2n prod [mg/s]
0
300
600
900
1200
1500
Time [s]
Polyprop. 012.

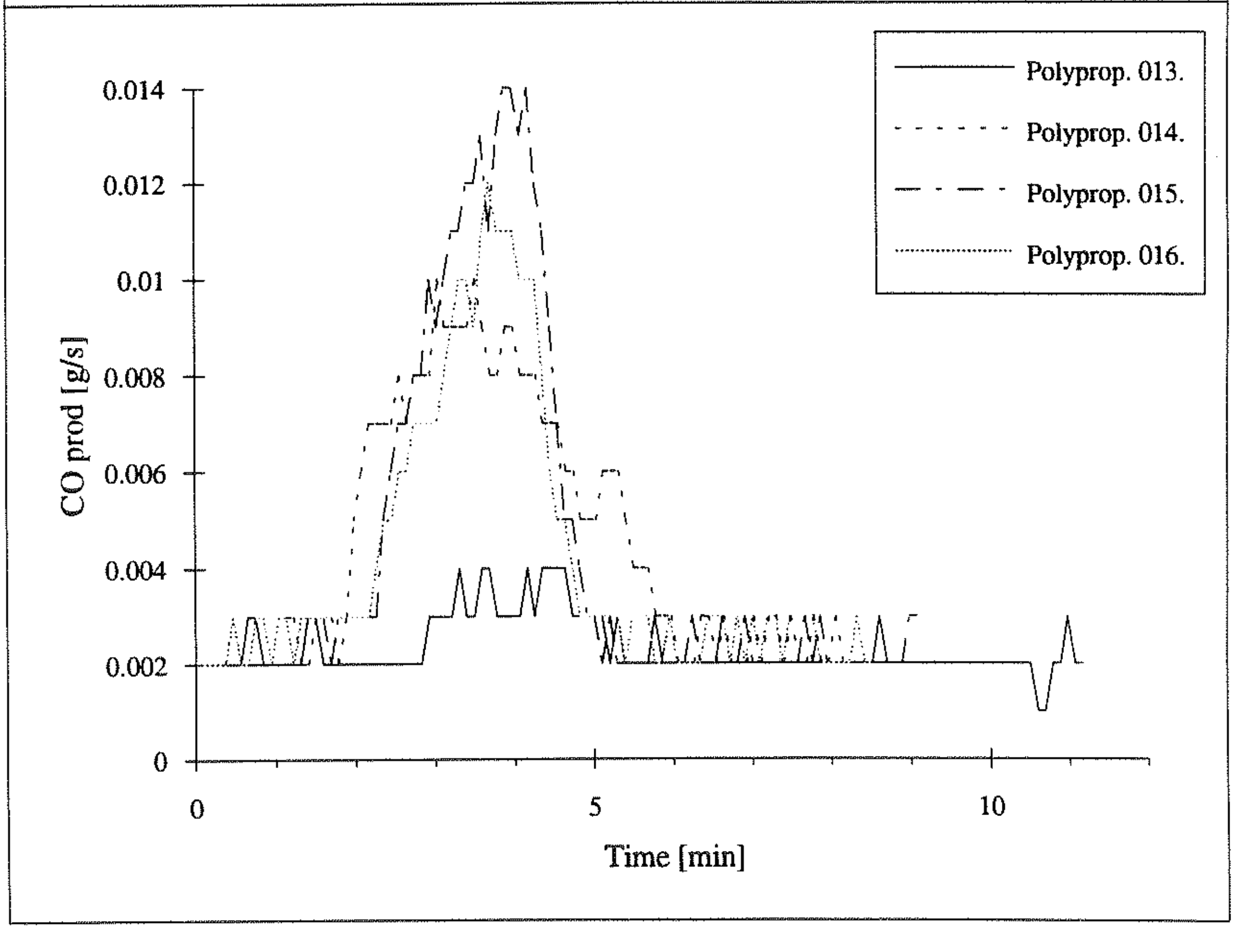

Mass loss [g]
140
120
100
80
60
40
20
0
-20
0
300
600
900
1200
1500
Time [s]
Polyprop. 012.

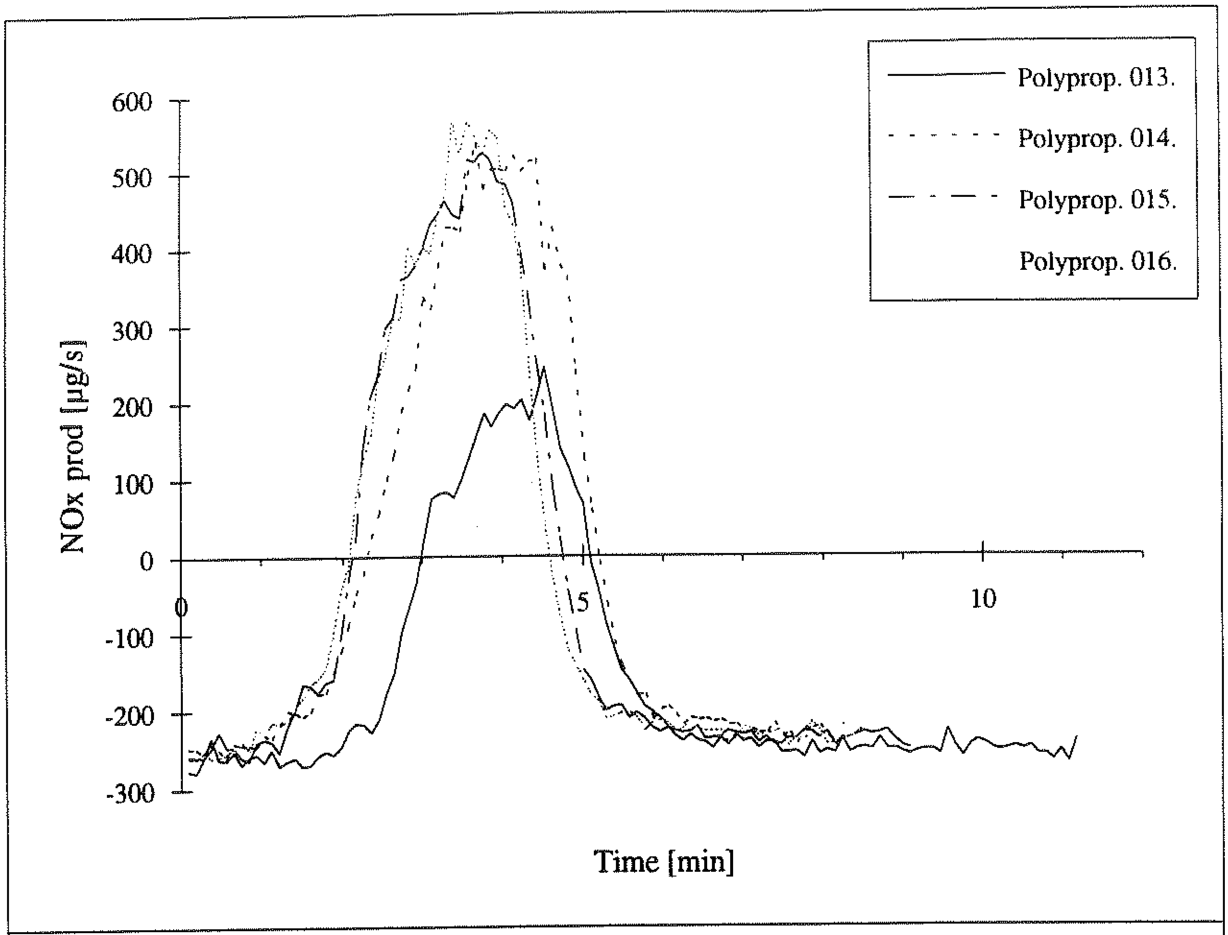


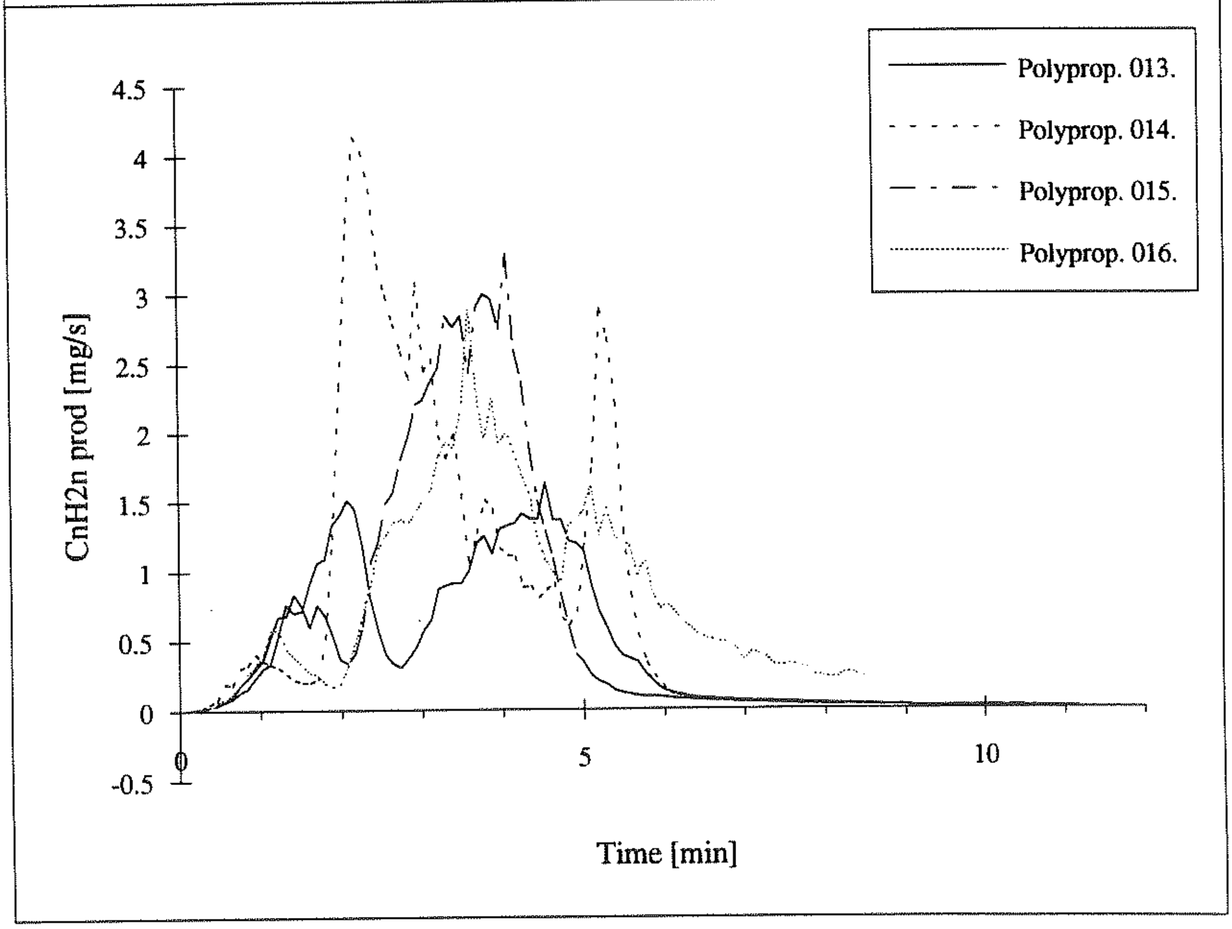


Appendix 3: Polypropylene

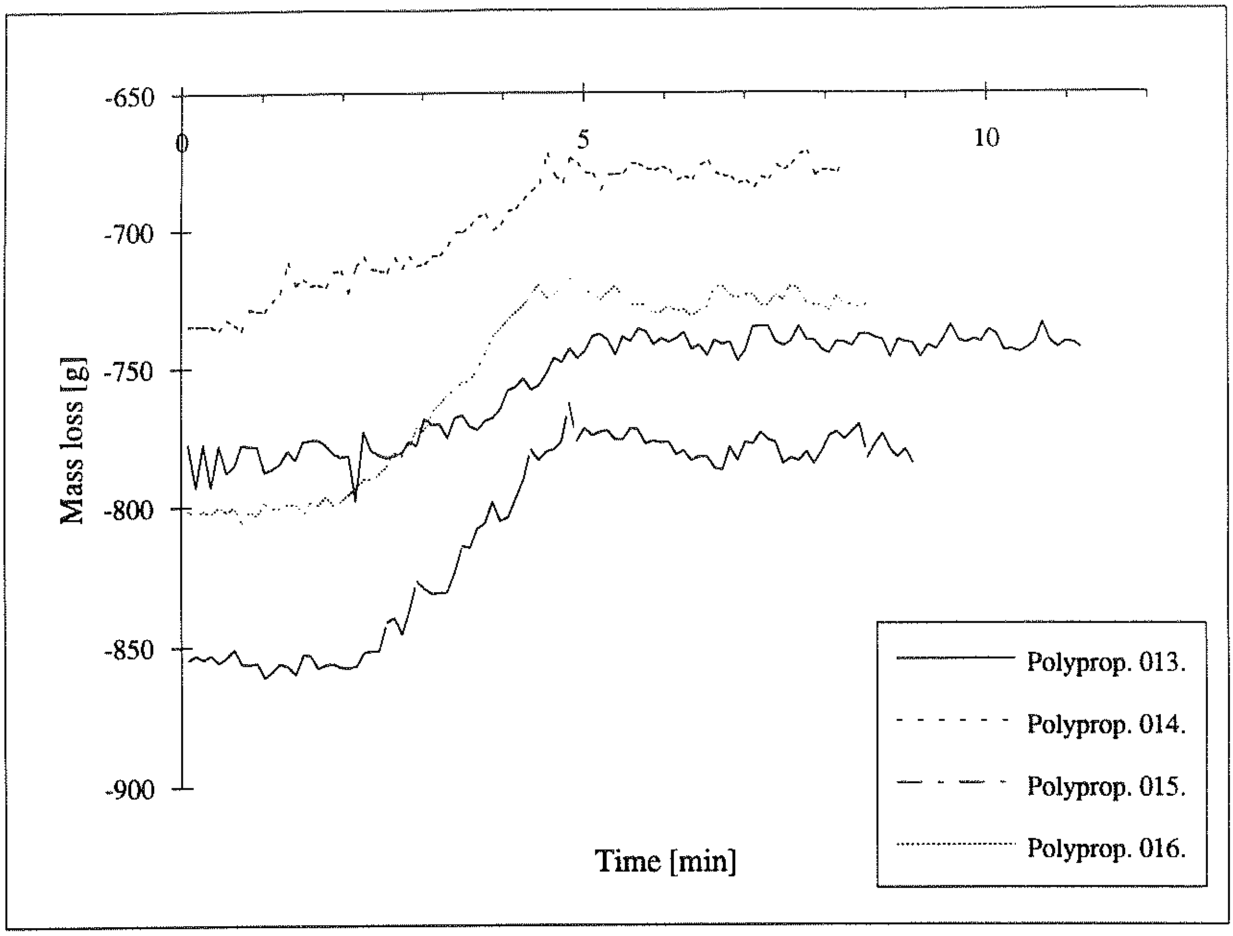

Polyprop. 013.
Polyprop. 014.
Polyprop. 015.
Polyprop. 016.
1.2
1
0.8
0.6
0.4
0.2
0
CO2 prod [g/s]
0
5
10
Time [min]

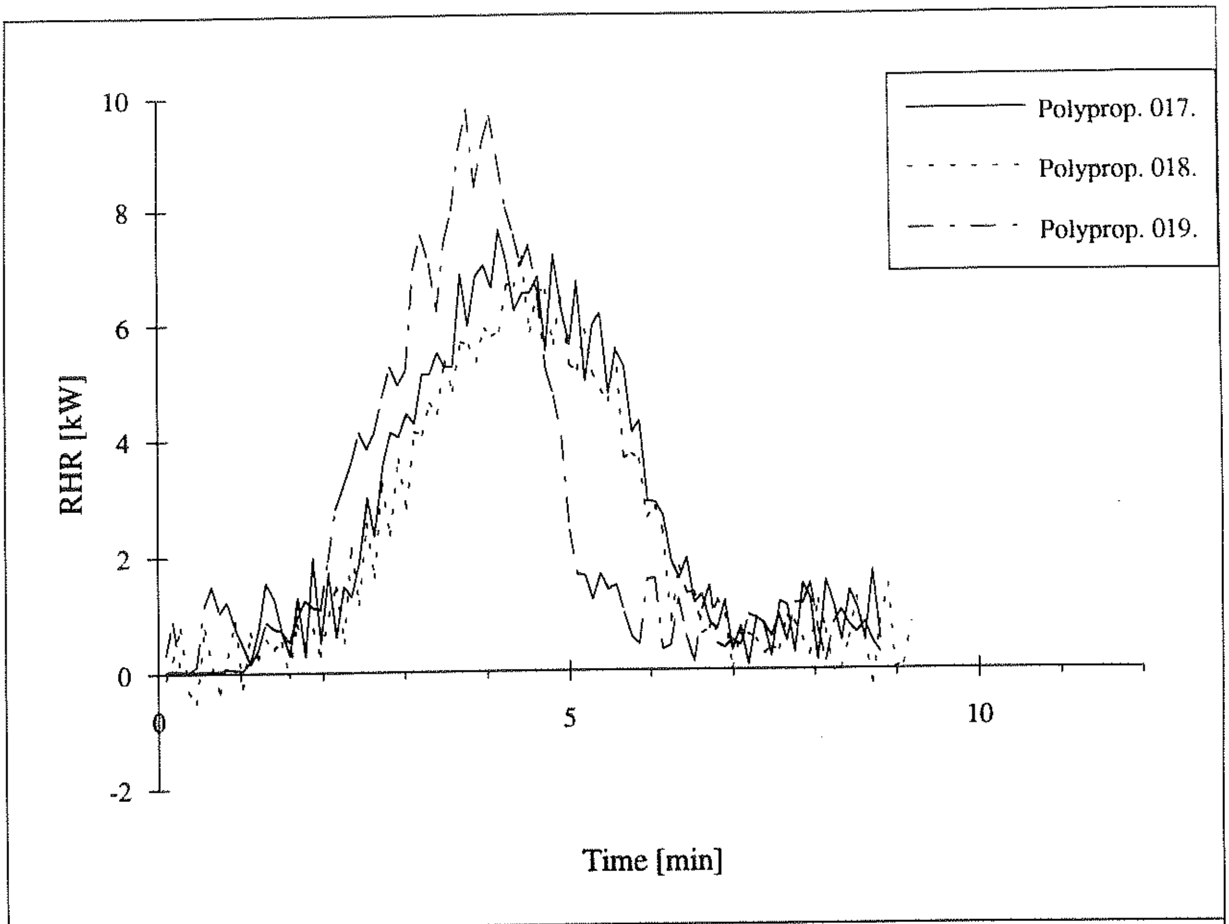

Polyprop. 013.
Polyprop. 014.
Polyprop. 015.
Polyprop. 016.
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
CO prod [g/s]
0
5
10
Time [min]

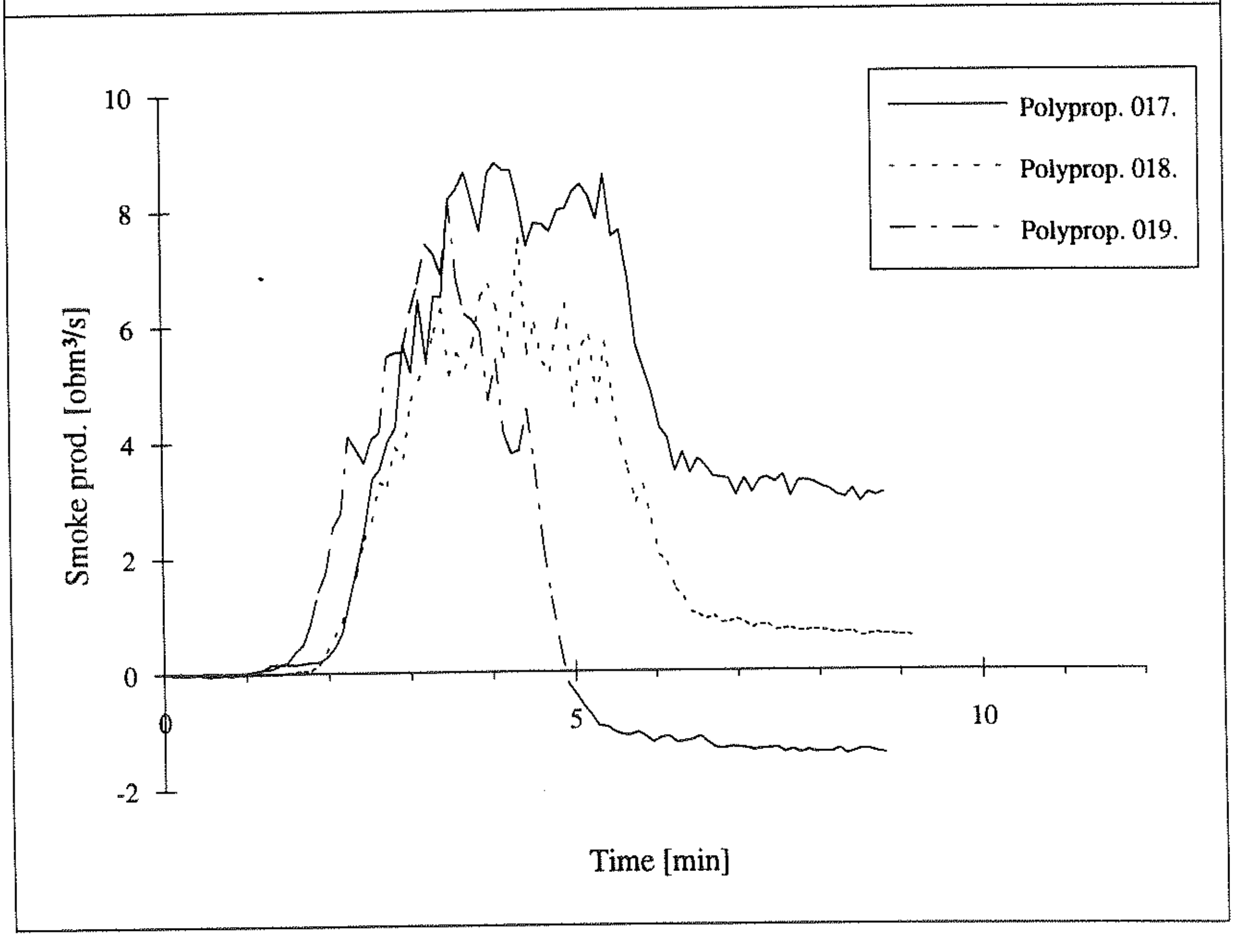


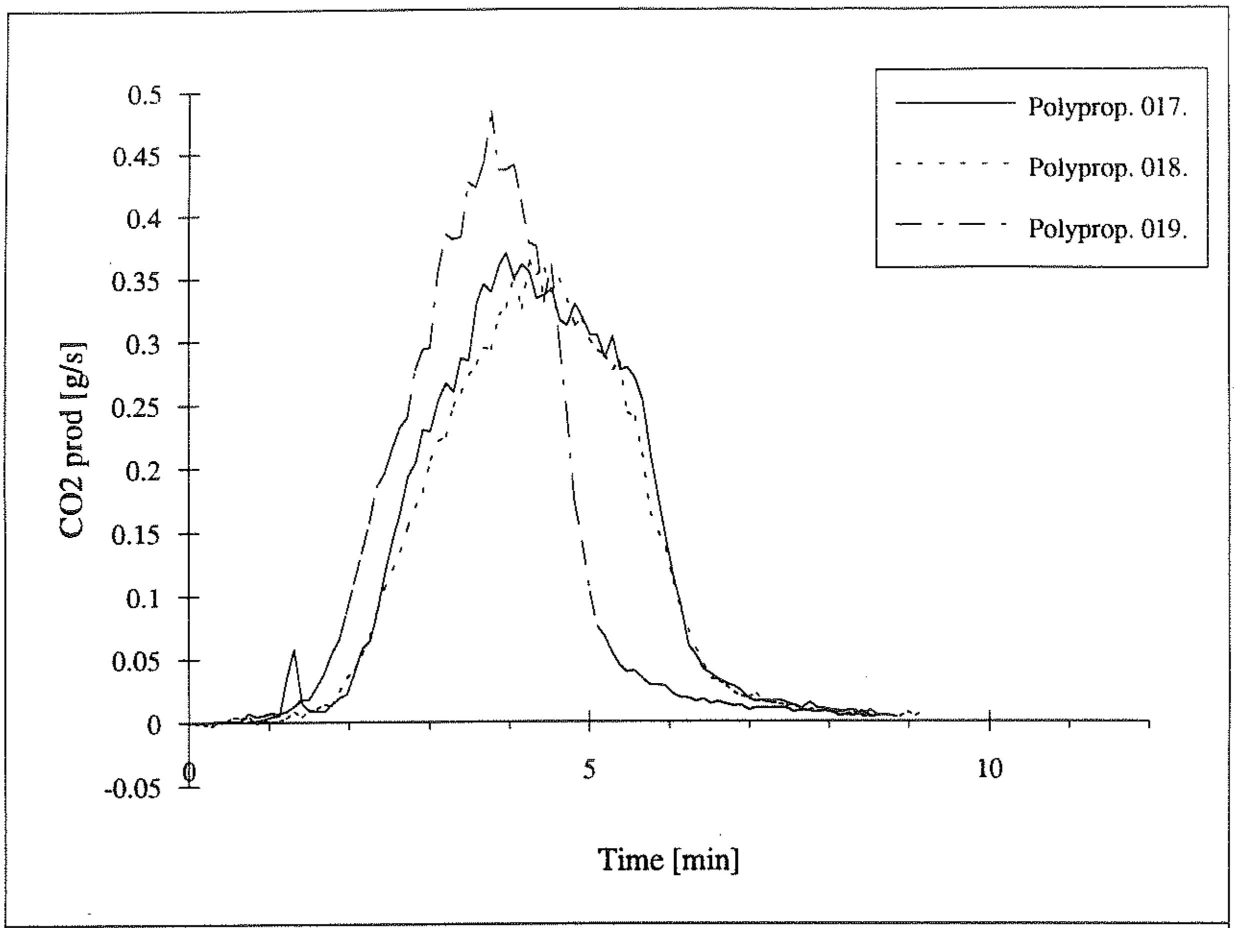


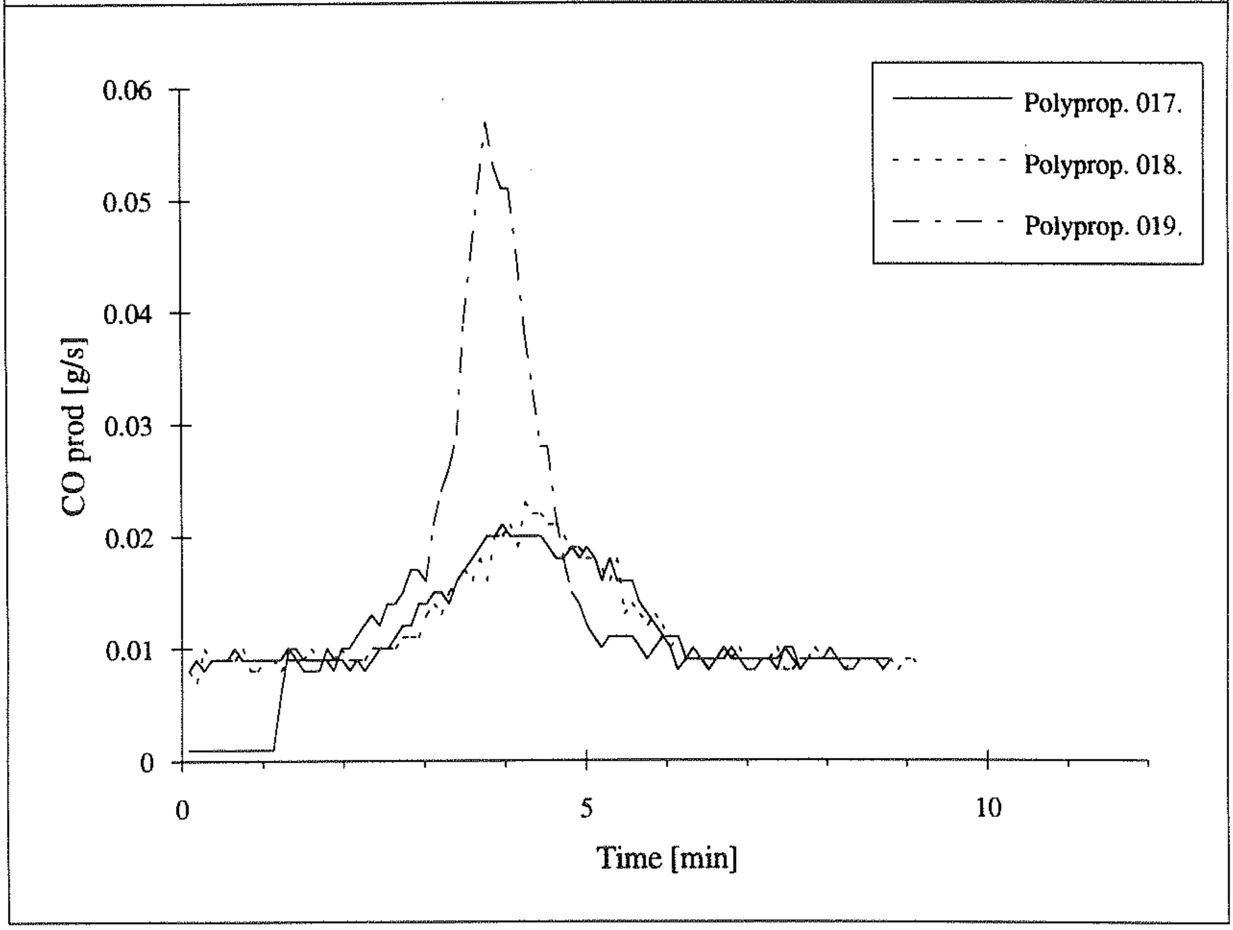
Appendix 3: Polypropylene

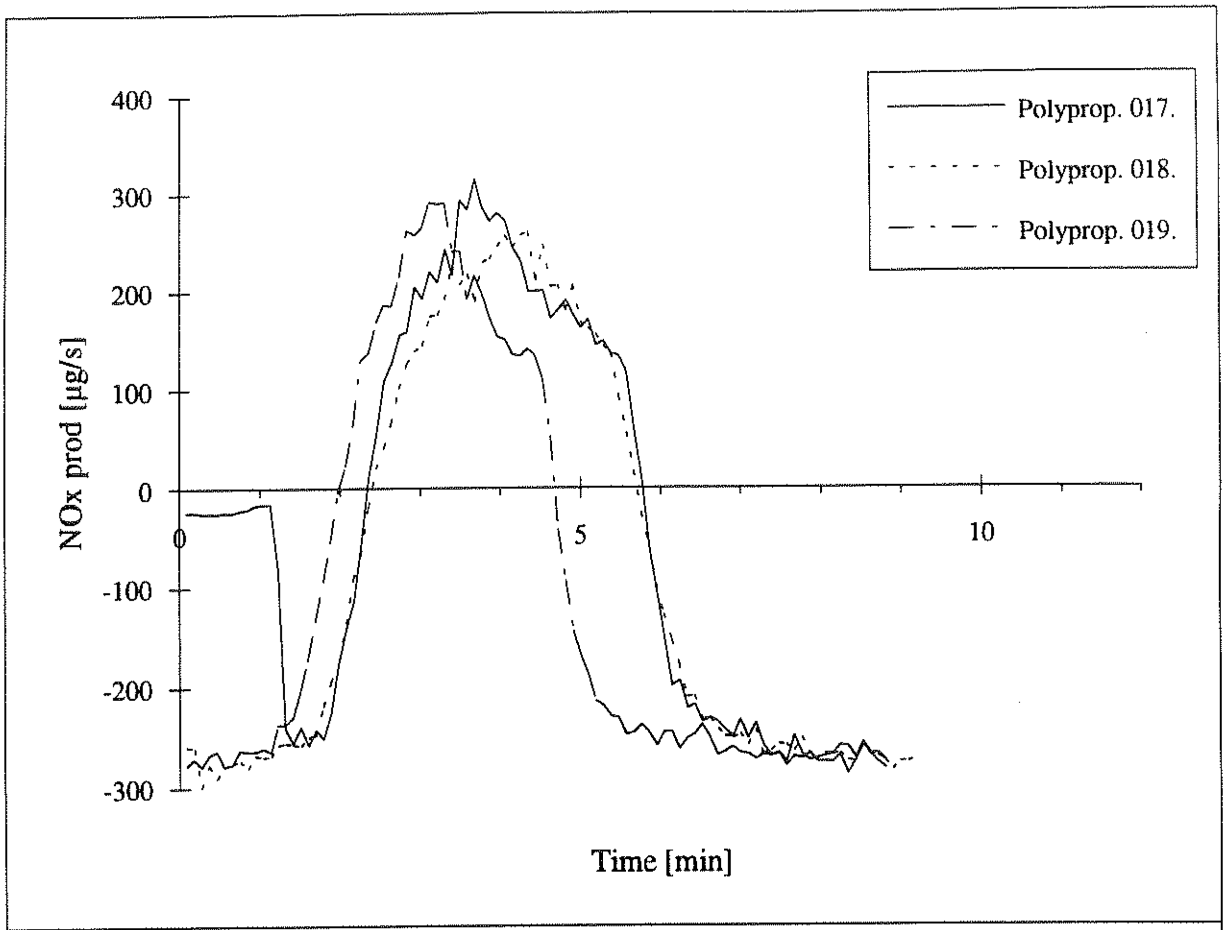

-650
-700
-750
-800
-850
-900
Mass loss [g]
0
5
10
Time [min]
Polyprop. 013.
Polyprop. 014.
Polyprop. 015.
Polyprop. 016.

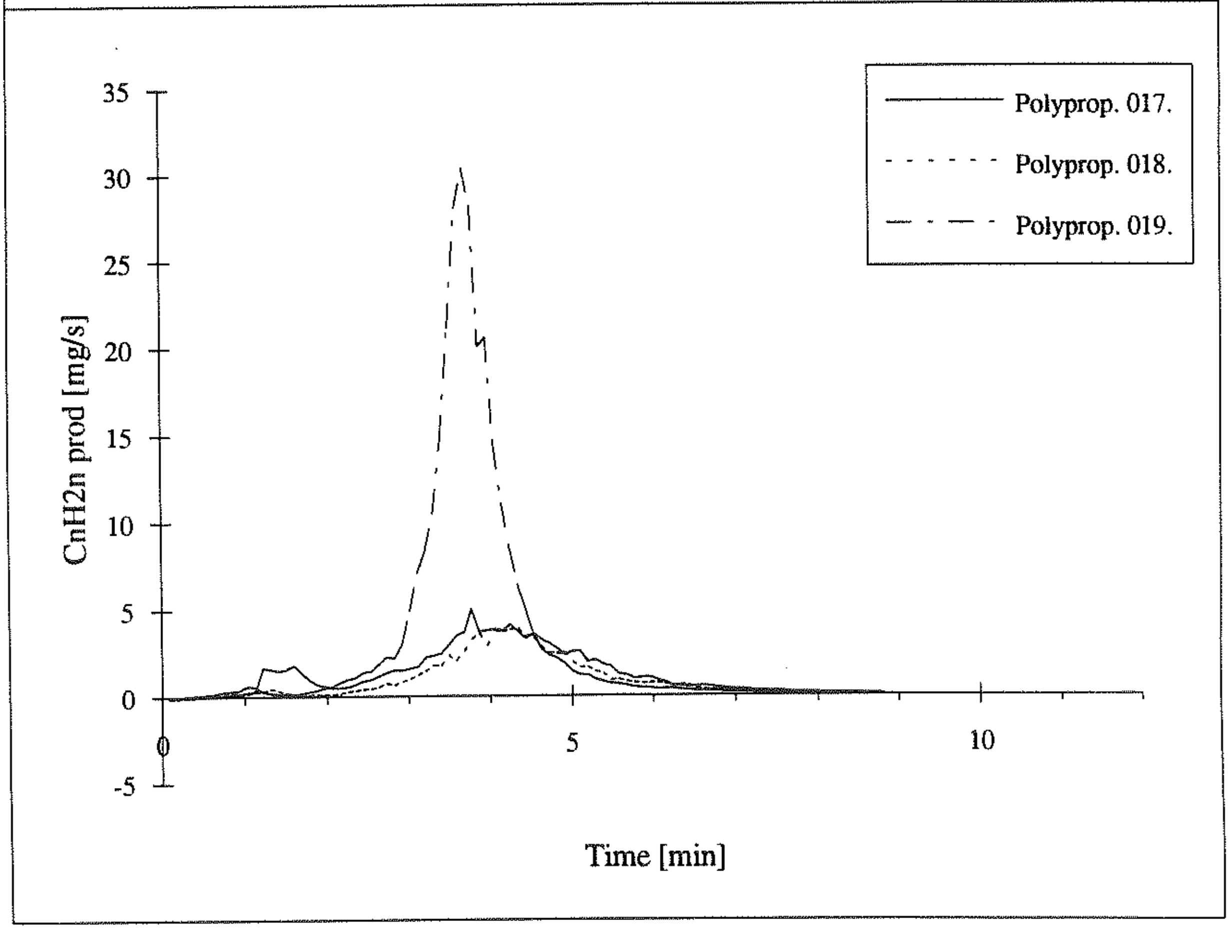

10
8
6
4
2
0
-2
RHR [kW]
0
5
10
Time [min]
Polyprop. 017.
Polyprop. 018.
Polyprop. 019.


10
8
6
4
2
0
-2
Smoke prod. [obm³/s]
0
5
10
Time [min]
Polyprop. 017.
Polyprop. 018.
Polyprop. 019.

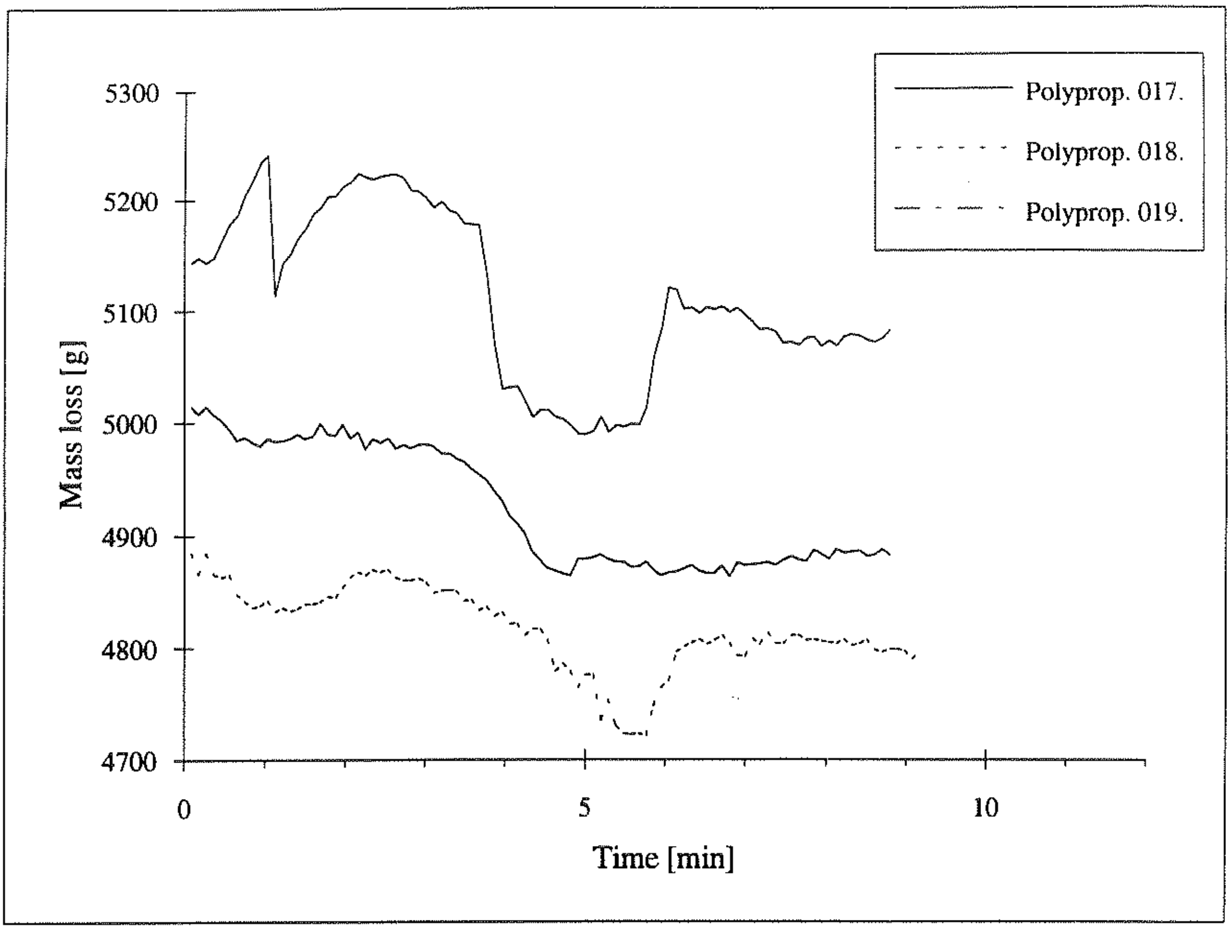

Polyprop. 017.
Polyprop. 018.
Polyprop. 019.
CO2 prod [g/s]
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
5
10
Time [min]


Polyprop. 017.
Polyprop. 018.
Polyprop. 019.
CO prod [g/s]
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
Time [min]





Appendix 3: Polypropylene


Polyprop. 017.
Polyprop. 018.
Polyprop. 019.
Mass loss [g]
5300
5200
5100
5000
4900
4800
4700
0
5
10
Time [min]

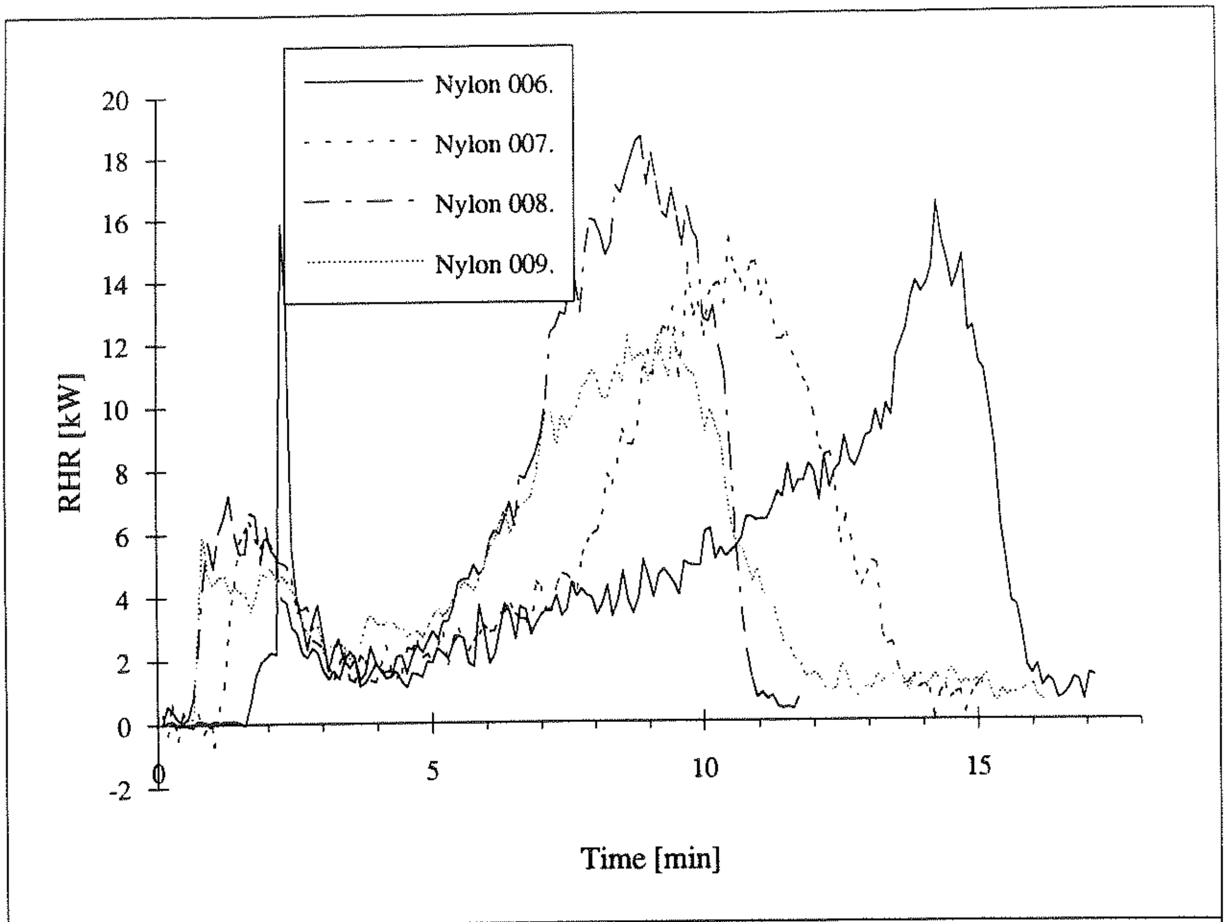
Appendix 4: Test results for NYLON

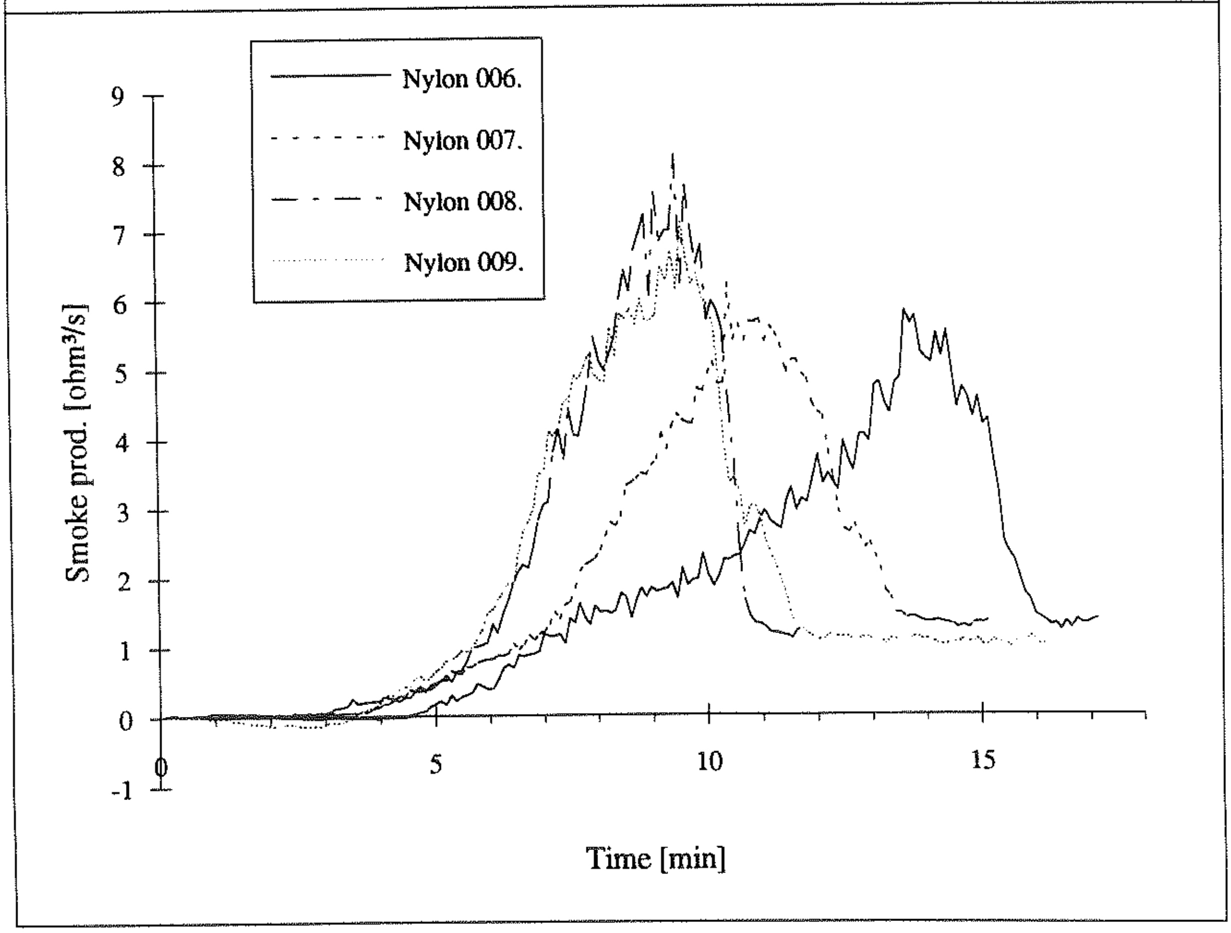
Contents:

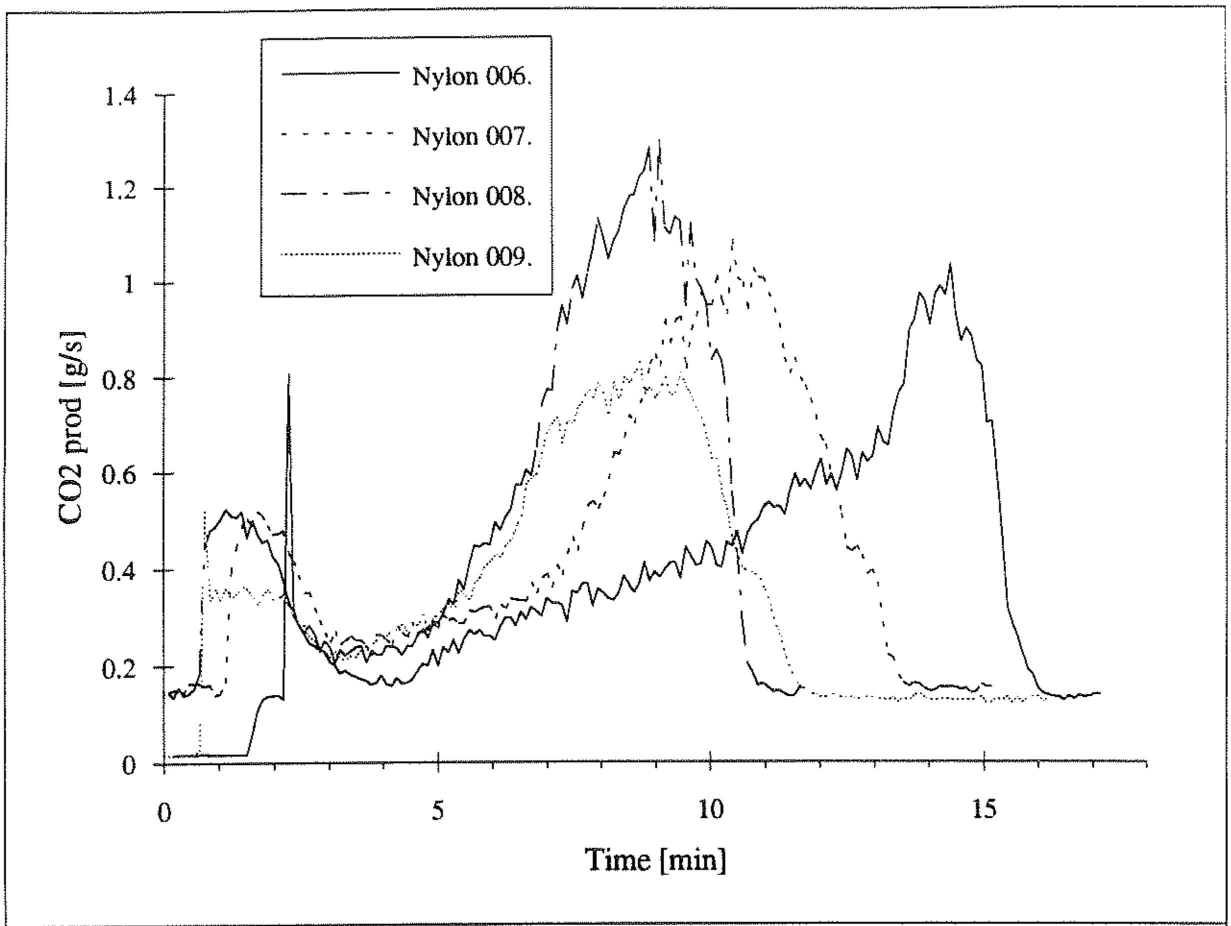
Test	RHR page	Smoke prod. page	CO_2 prod. page	CO prod. page	NO_X prod. page	C_nH_{2n} prod. page	Mass loss page
006	1	1	2	2	3	3	4
007	1	1	2	2	3	3	4
008	1	1	2	2	3	3	4
009	1	1	2	2	3	3	4
010	5	5	6	6	7	7	8
011	5	5	6	6	7	7	8
012	5	5	6	6	7	7	8
013	5	5	6	6	7	7	8
014	9	9	10	10	11	11	12
016	9	9	10	10	11	11	12
017	9	9	10	10	11	11	12

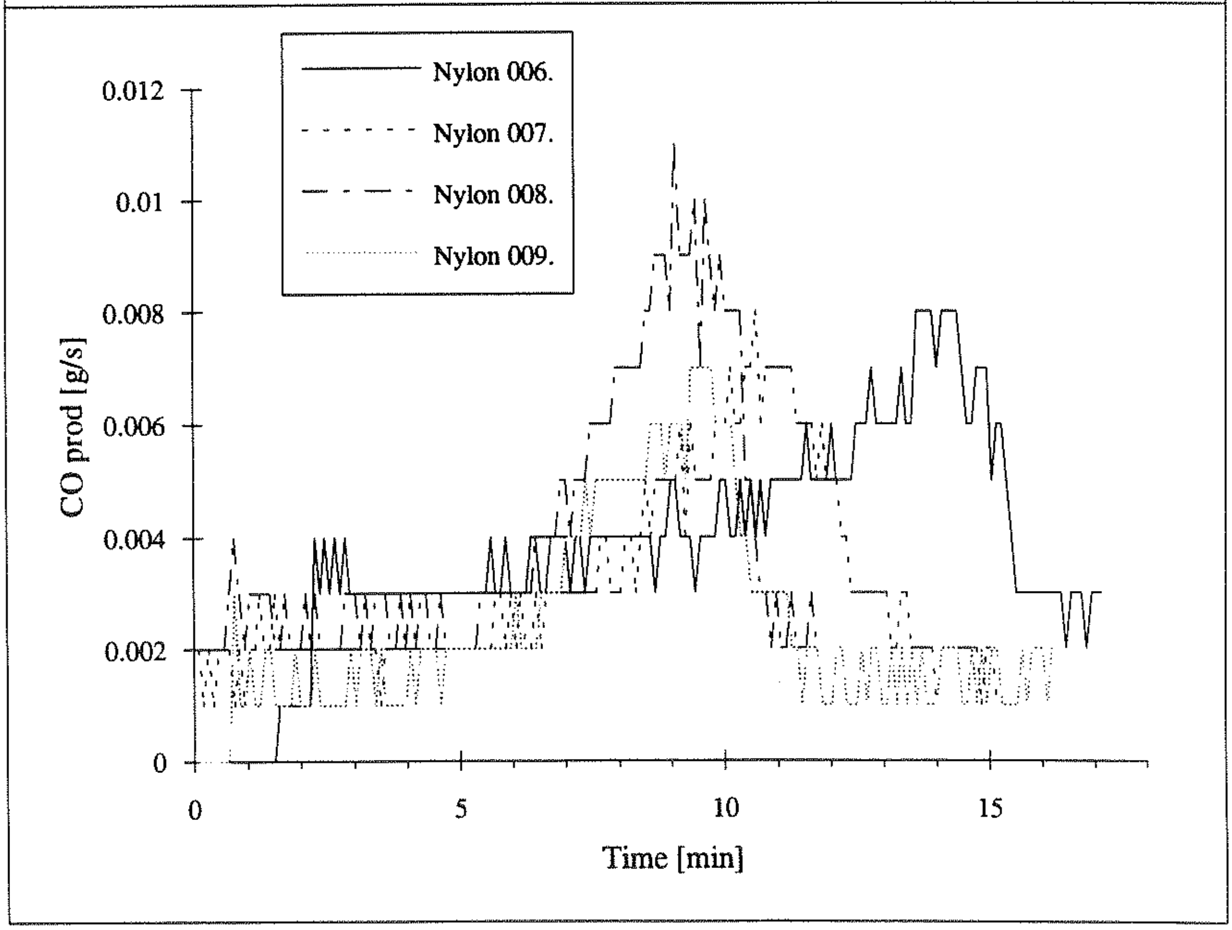
Corrections of the data were made in the study (not carried out in the appendix):

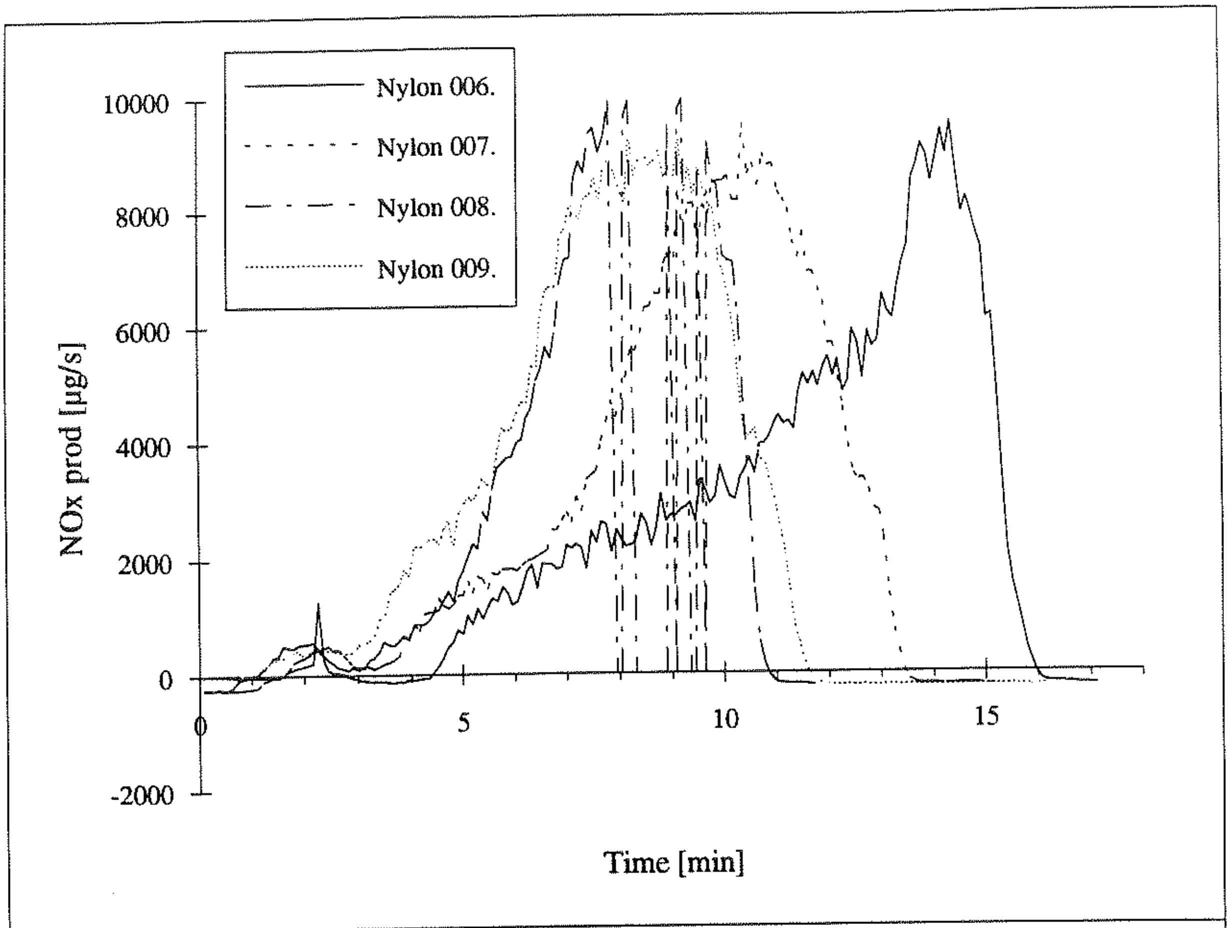
- The RHR values were multiplied with 12.3/13.1 as the measuring program does not consider the actual heat released per unit mass oxygen consumed.
- The CO_2 and CO values were multiplied by 0.91 due to a calibration error in the gas analysis equipment.

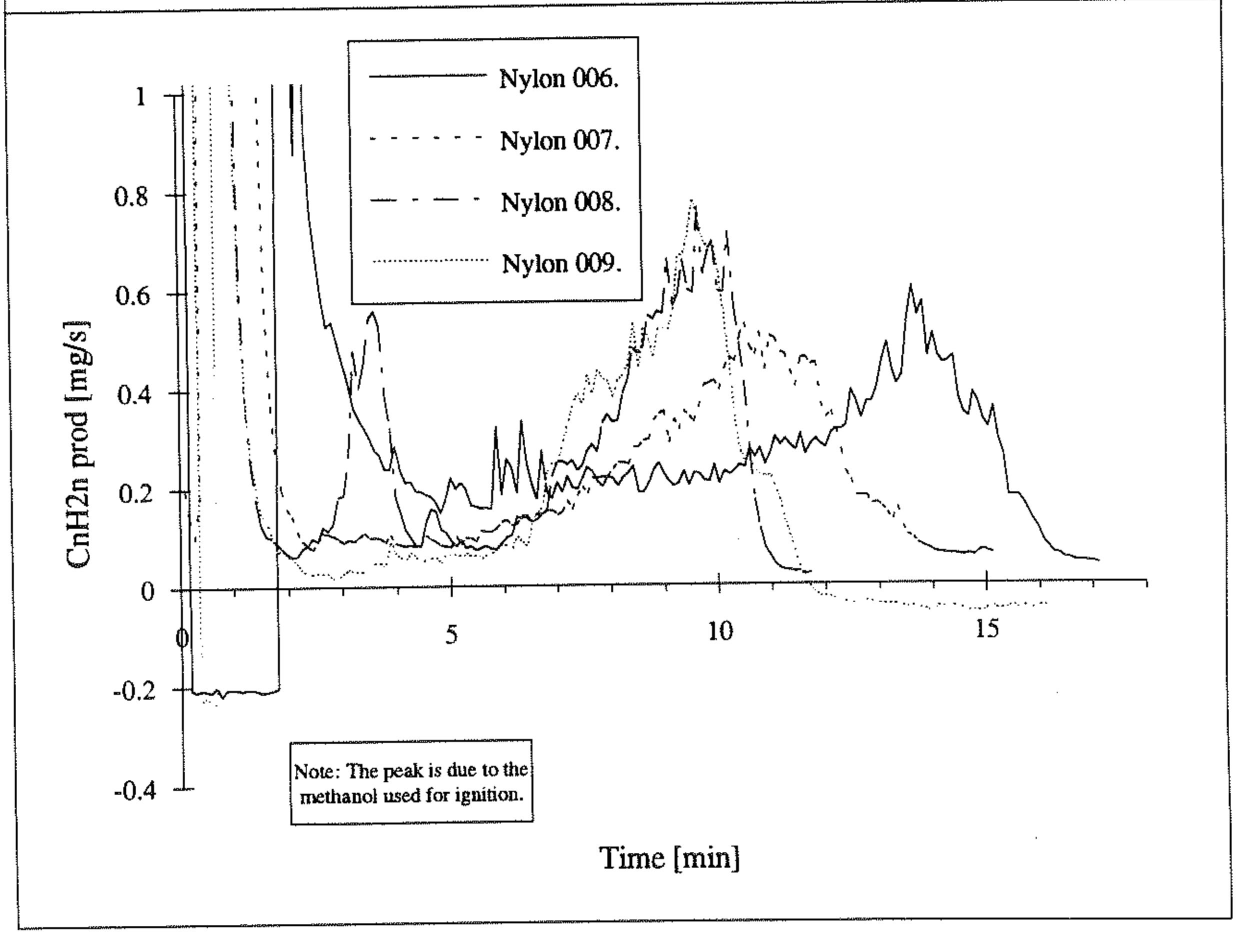

Nylon 006.
Nylon 007.
Nylon 008.
Nylon 009.
RHR [kW]
20
18
16
14
12
10
8
6
4
2
0
-2
0
5
10
15
Time [min]

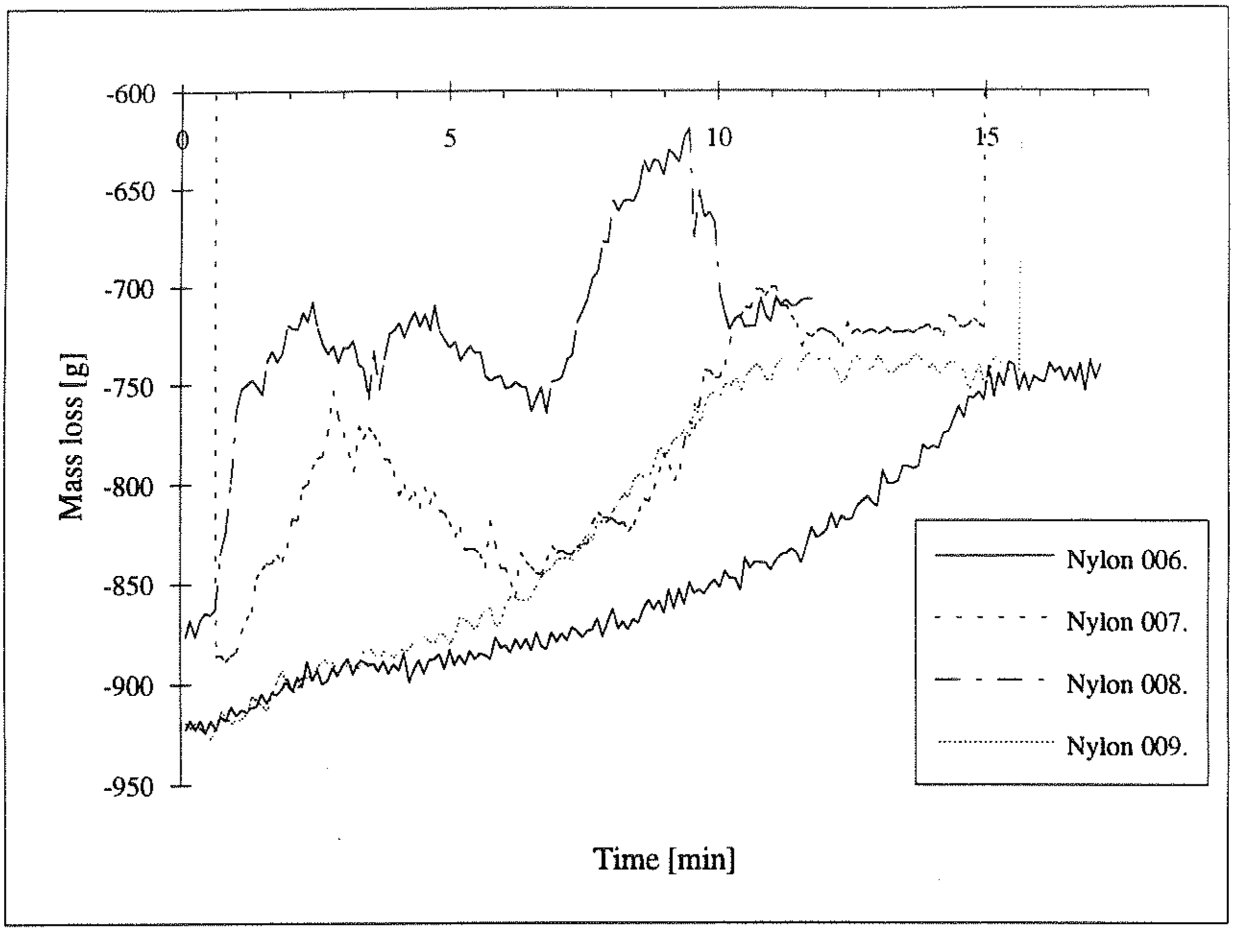

Nylon 006.
Nylon 007.
Nylon 008.
Nylon 009.
Smoke prod. [obm³/s]
9
8
7
6
5
4
3
2
1
0
-1
0
5
10
15
Time [min]

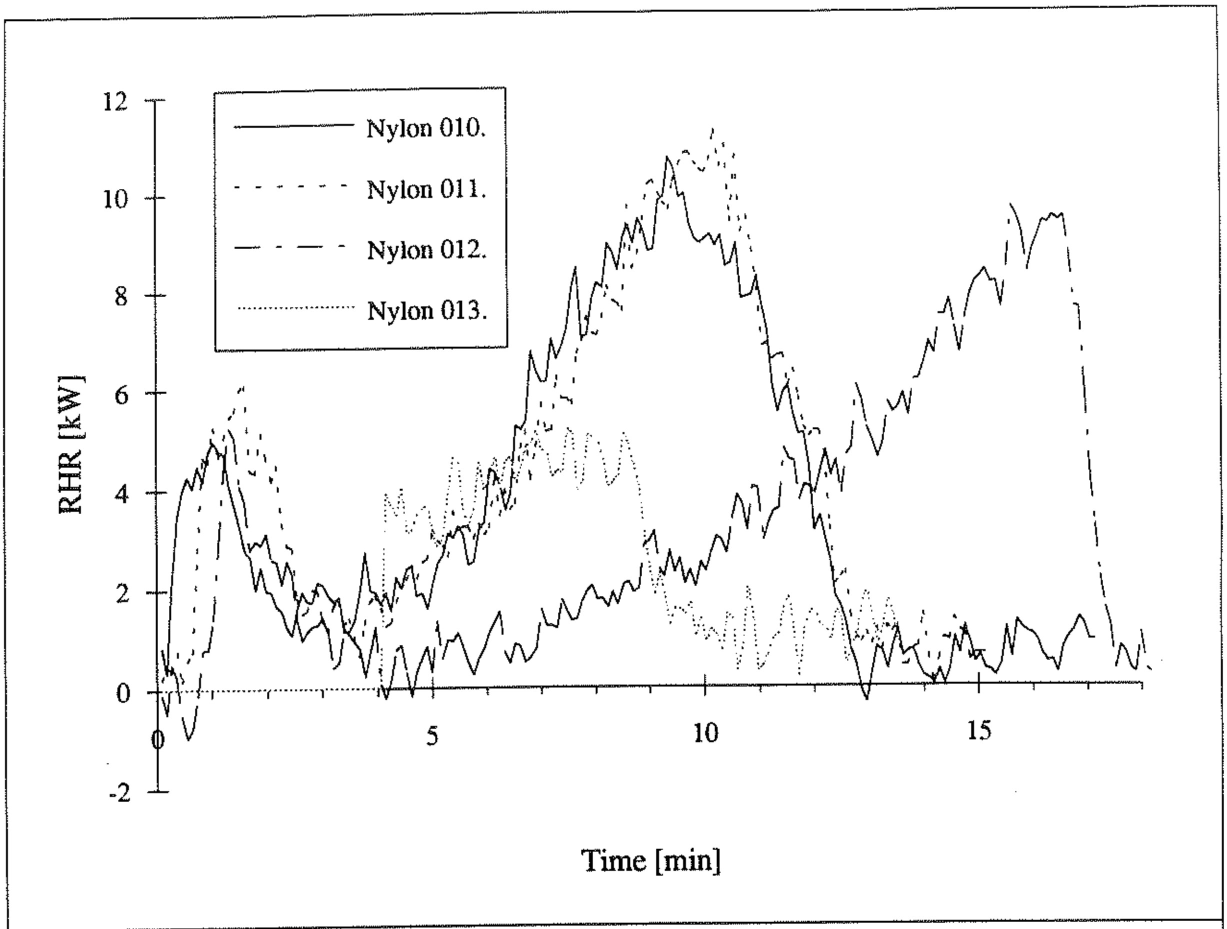

Nylon 006.
Nylon 007.
Nylon 008.
Nylon 009.
CO2 prod [g/s]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
Time [min]

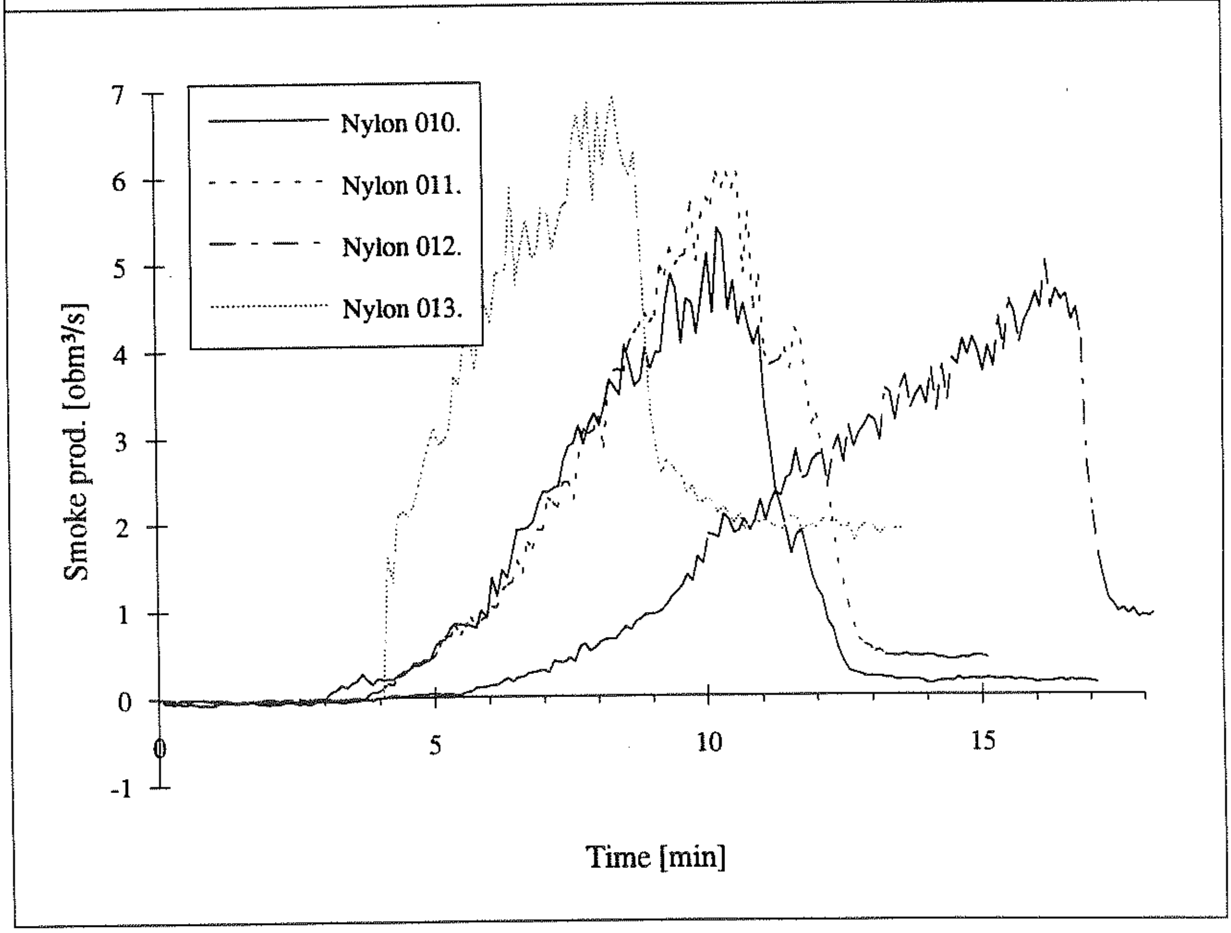

Nylon 006.
Nylon 007.
Nylon 008.
Nylon 009.
CO prod [g/s]
0.012
0.01
0.008
0.006
0.004
0.002
0
0
5
10
15
Time [min]

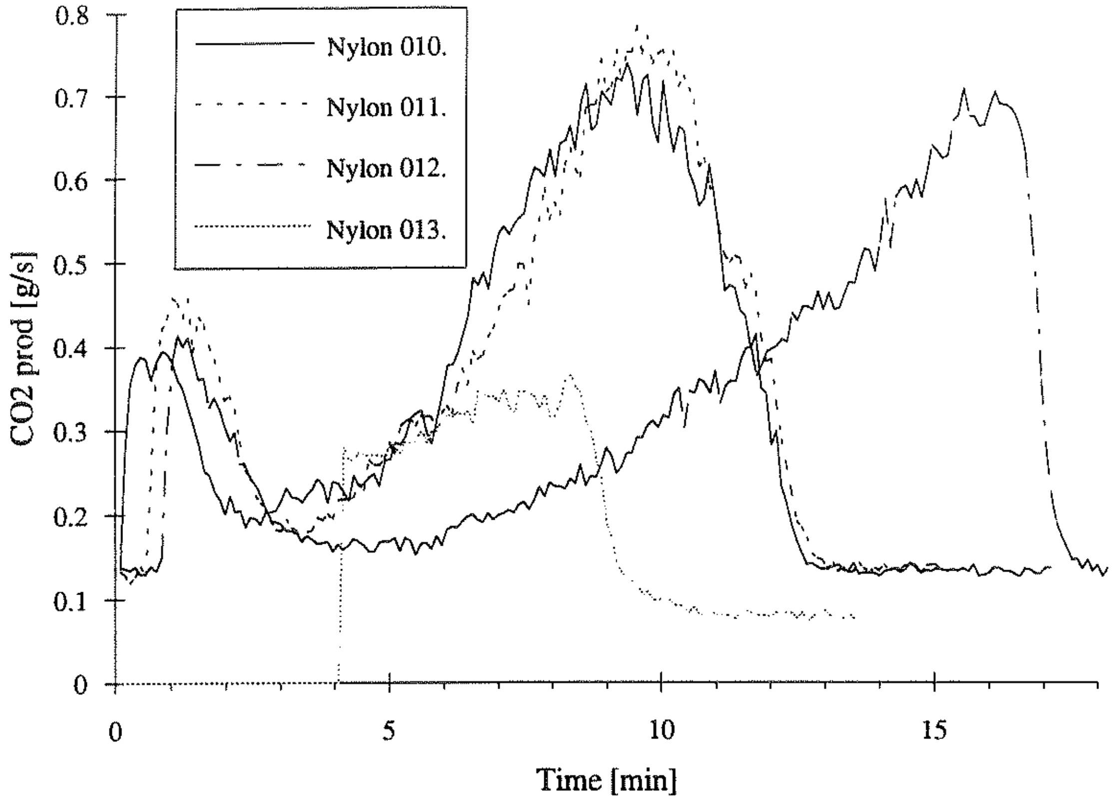

Nylon 006.
Nylon 007.
Nylon 008.
Nylon 009.
NOx prod [µg/s]
10000
8000
6000
4000
2000
0
-2000
0
5
10
15
Time [min]

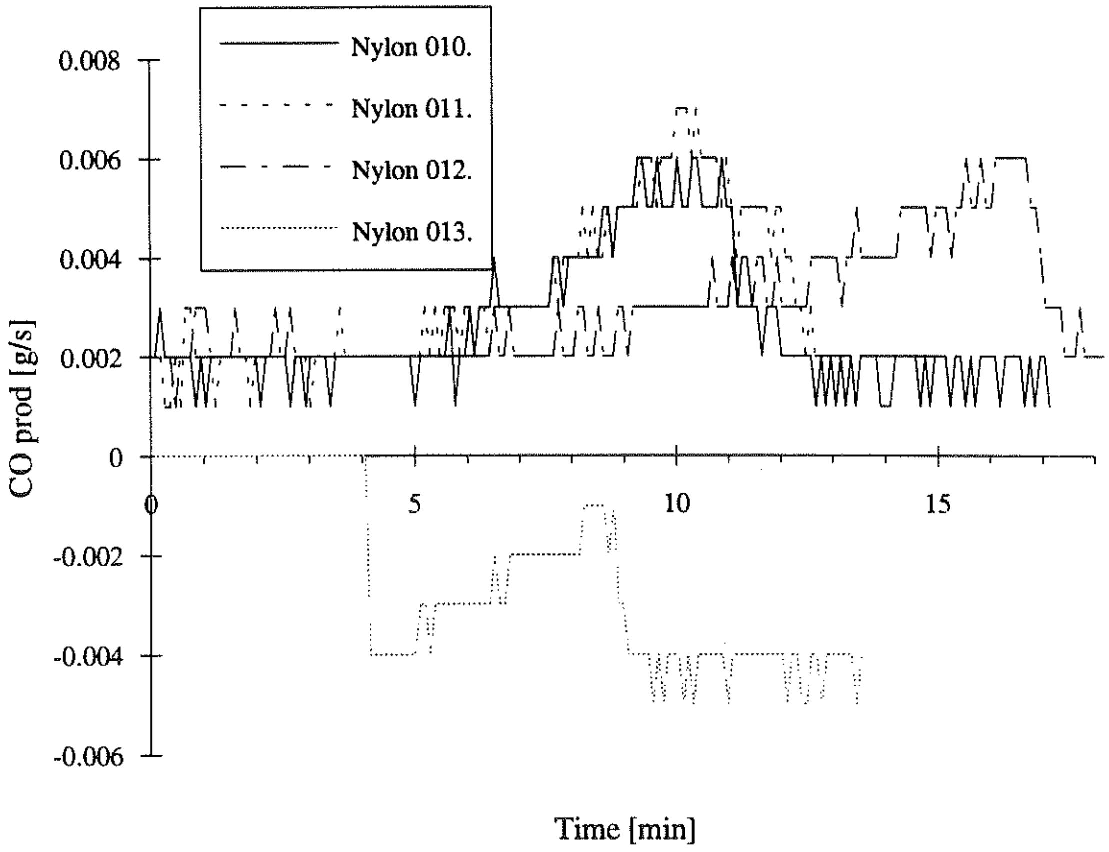

Nylon 006.
Nylon 007.
Nylon 008.
Nylon 009.
CnH2n prod [mg/s]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
Note: The peak is due to the methanol used for ignition.
Time [min]

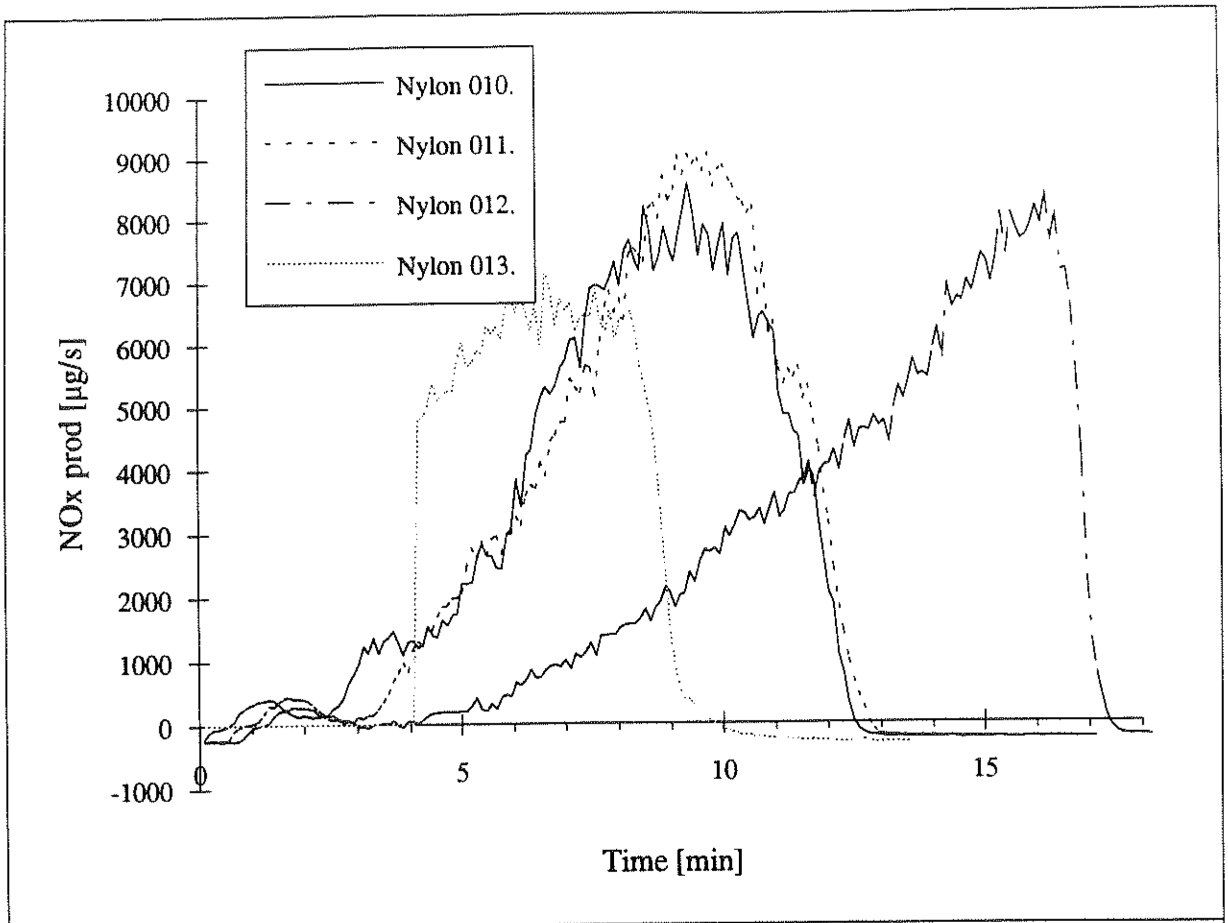

-600
-650
-700
-750
-800
-850
-900
-950
0
5
10
15
Mass loss [g]
Time [min]
Nylon 006.
Nylon 007.
Nylon 008.
Nylon 009.

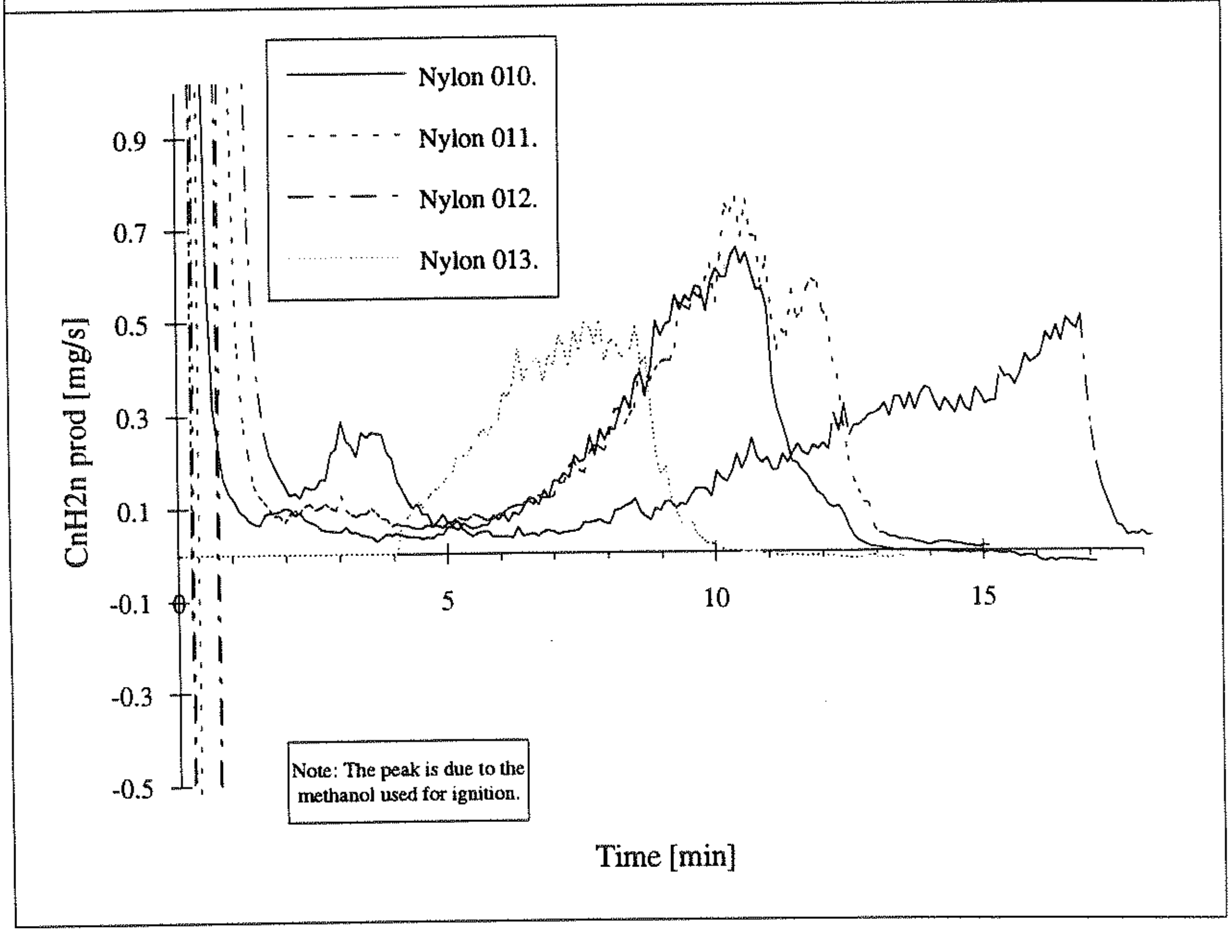

12
10
8
6
4
2
0
-2
RHR [kW]
0
5
10
15
Time [min]
Nylon 010.
Nylon 011.
Nylon 012.
Nylon 013.


7
6
5
4
3
2
1
0
-1
Smoke prod. [obm³/s]
0
5
10
15
Time [min]
Nylon 010.
Nylon 011.
Nylon 012.
Nylon 013.

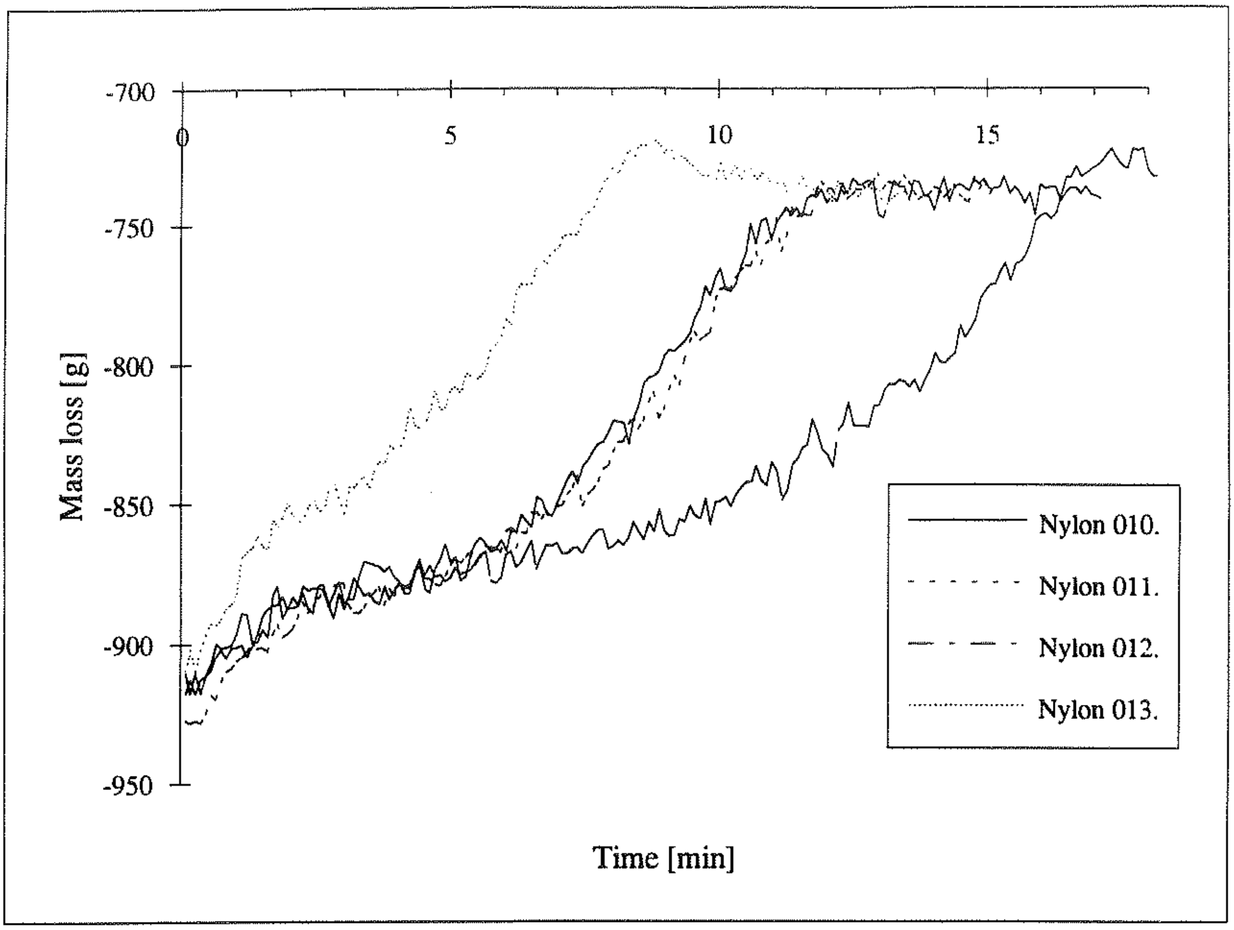

Nylon 010.
Nylon 011.
Nylon 012.
Nylon 013.
CO2 prod [g/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
Time [min]

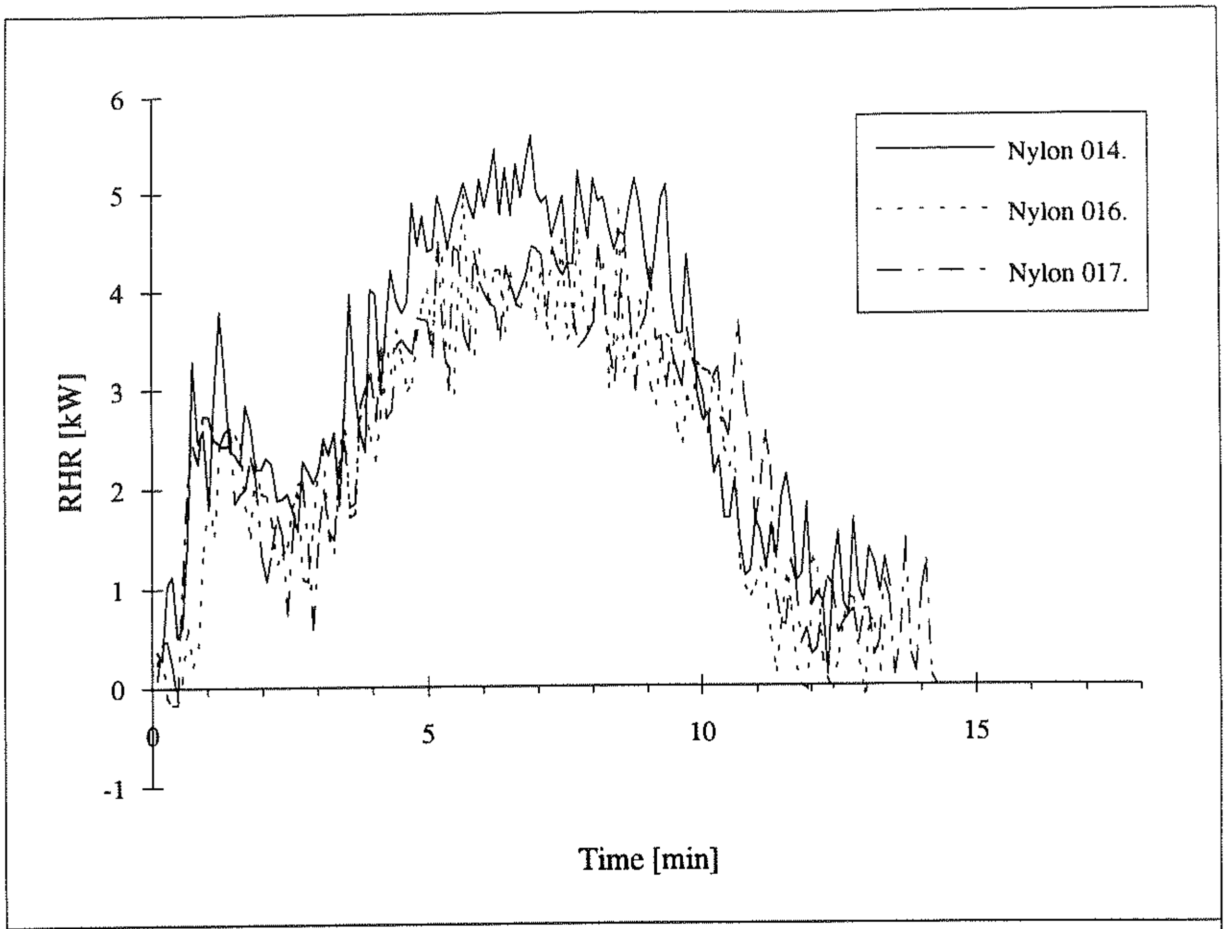

Nylon 010.
Nylon 011.
Nylon 012.
Nylon 013.
CO prod [g/s]
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
0
5
10
15
Time [min]

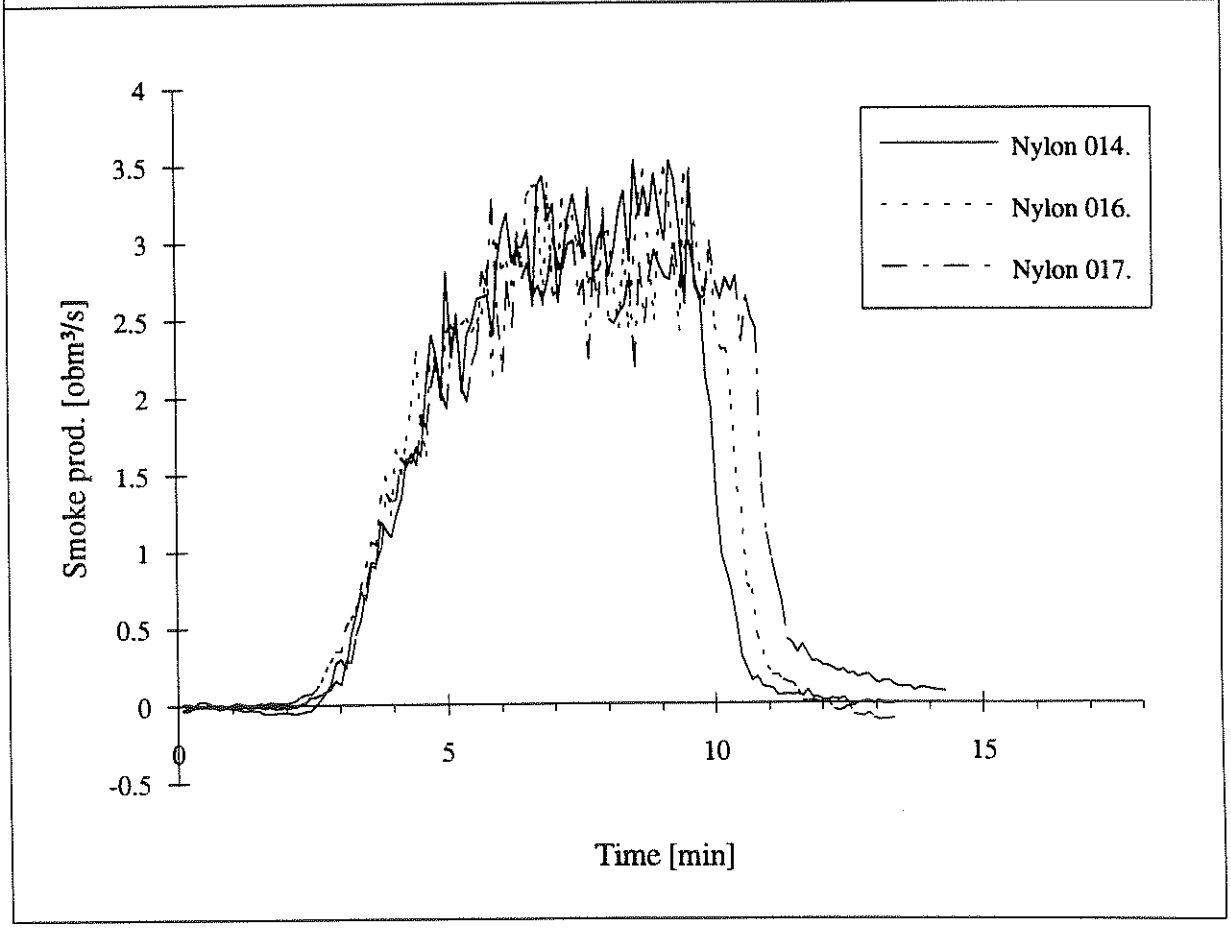


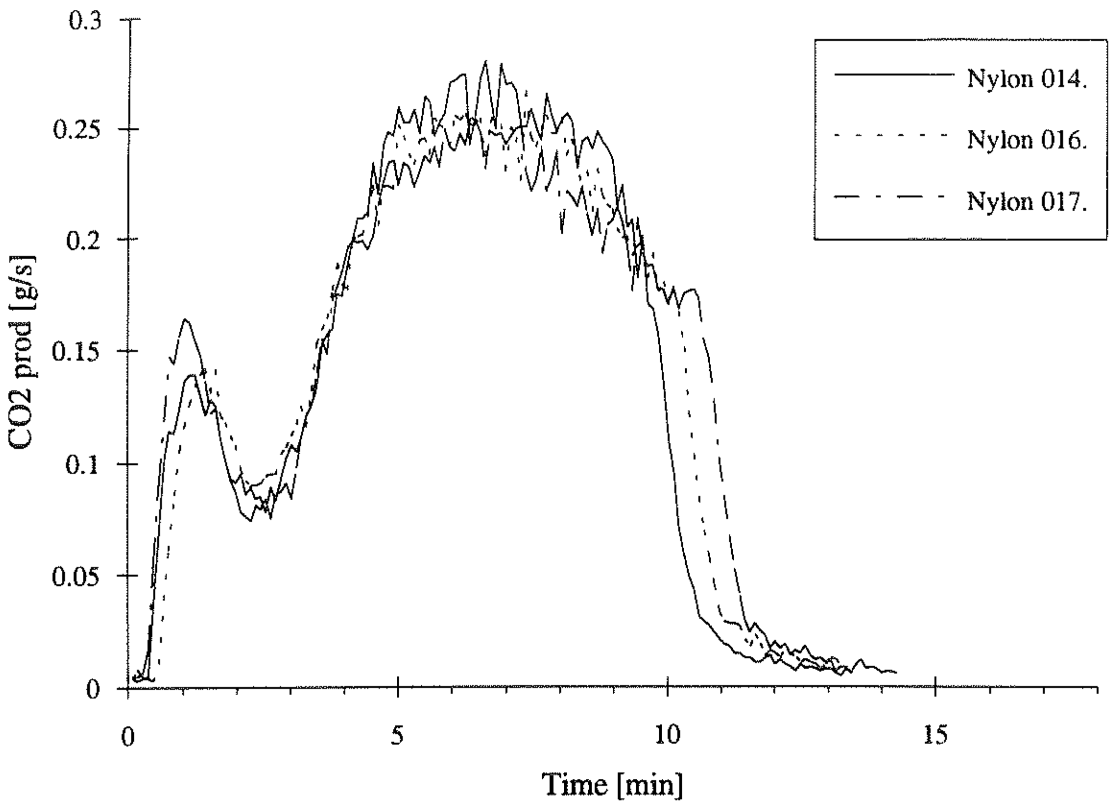


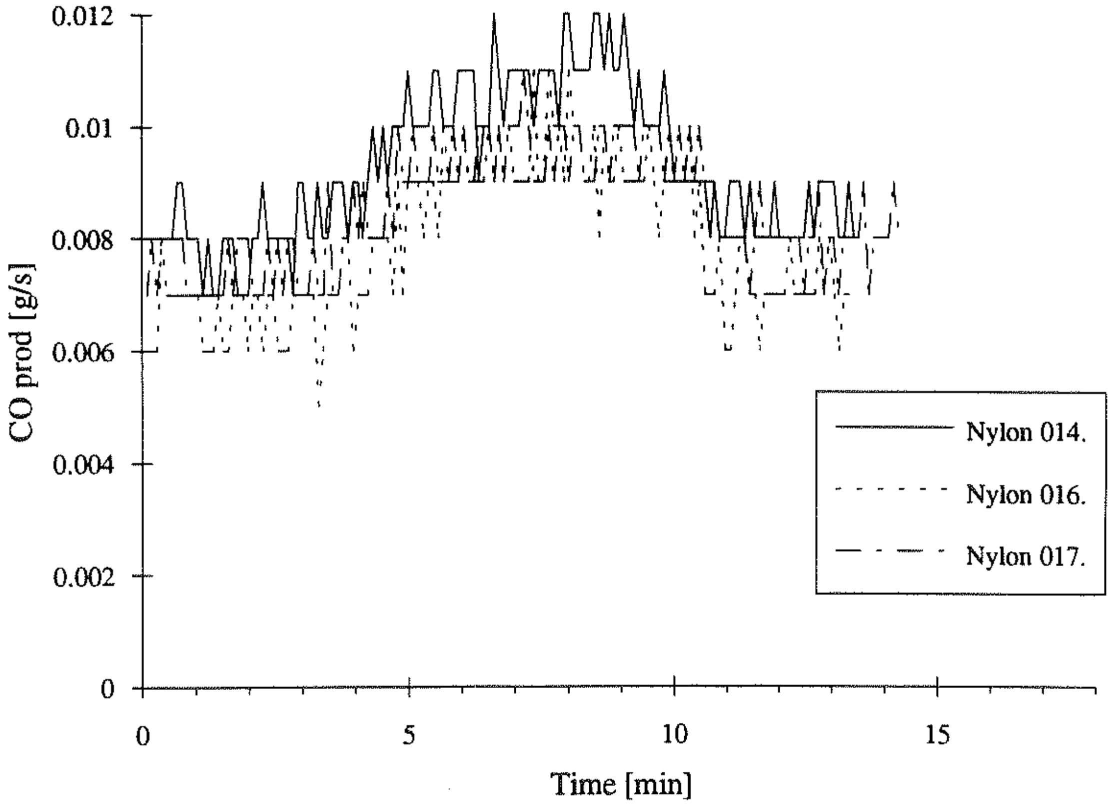
Note: The peak is due to the methanol used for ignition.

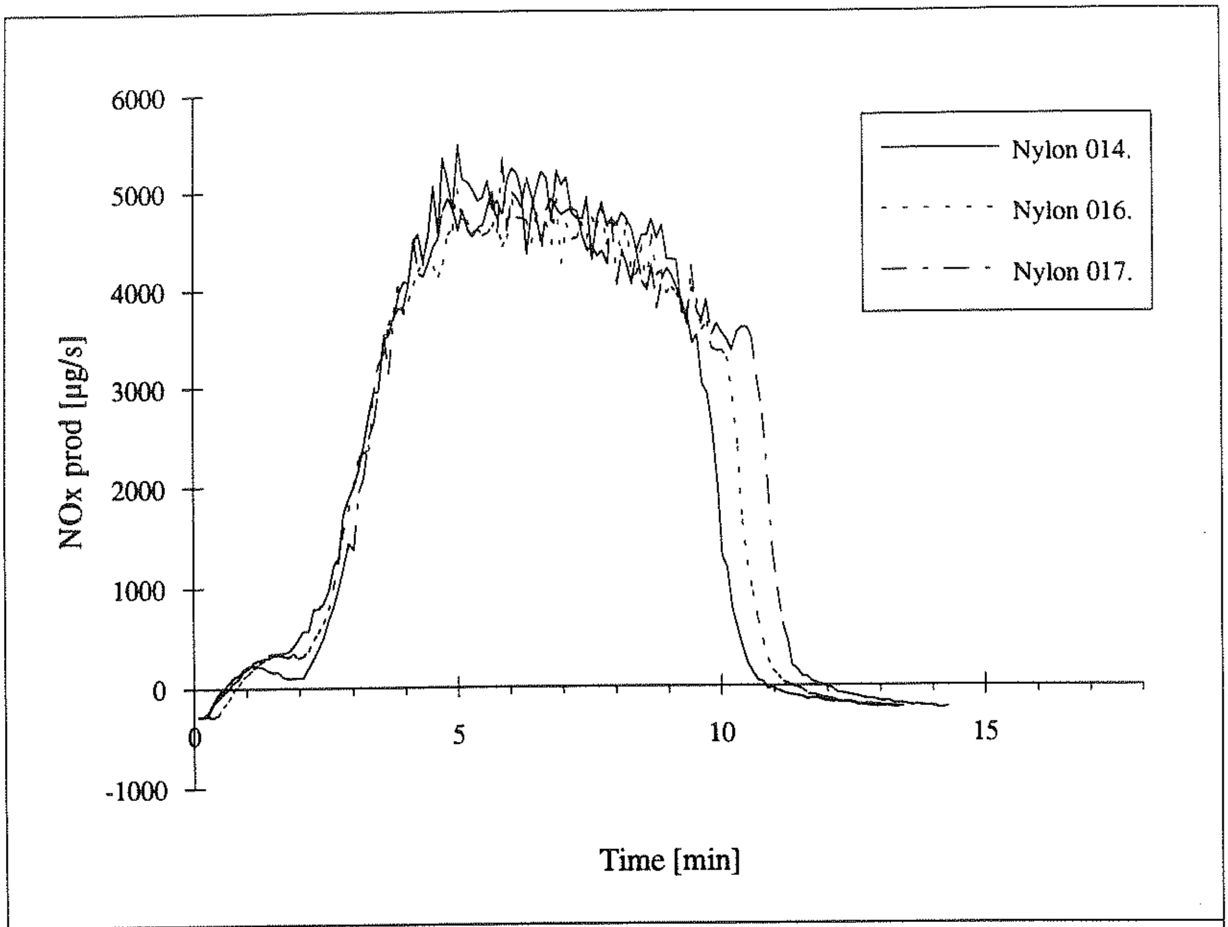

-700
-750
-800
-850
-900
-950
0
5
10
15
Mass loss [g]
Time [min]
Nylon 010.
Nylon 011.
Nylon 012.
Nylon 013.

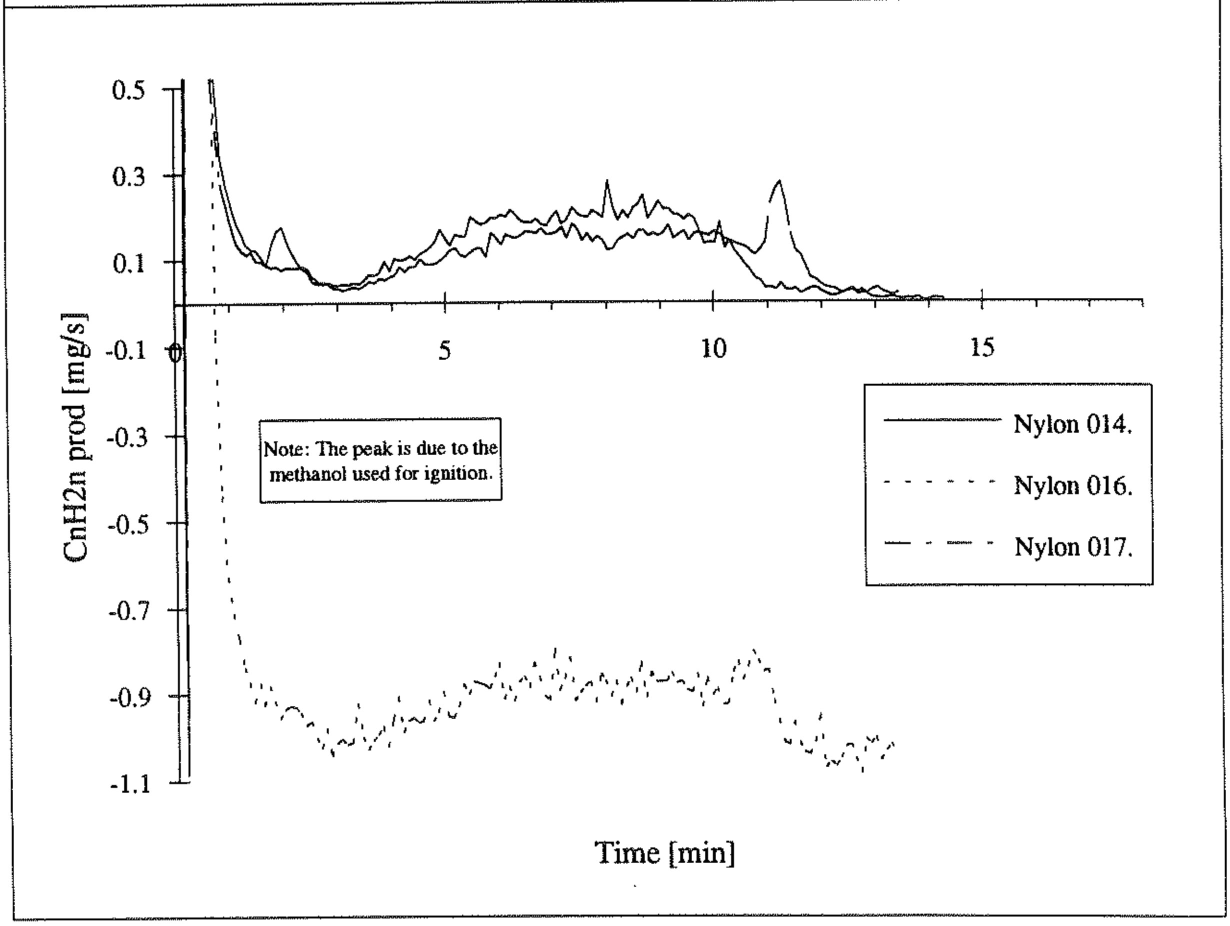

RHR [kW]
6
5
4
3
2
1
0
-1
0
5
10
15
Time [min]
Nylon 014.
Nylon 016.
Nylon 017.


Smoke prod. [obm³/s]
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
5
10
15
Time [min]
Nylon 014.
Nylon 016.
Nylon 017.

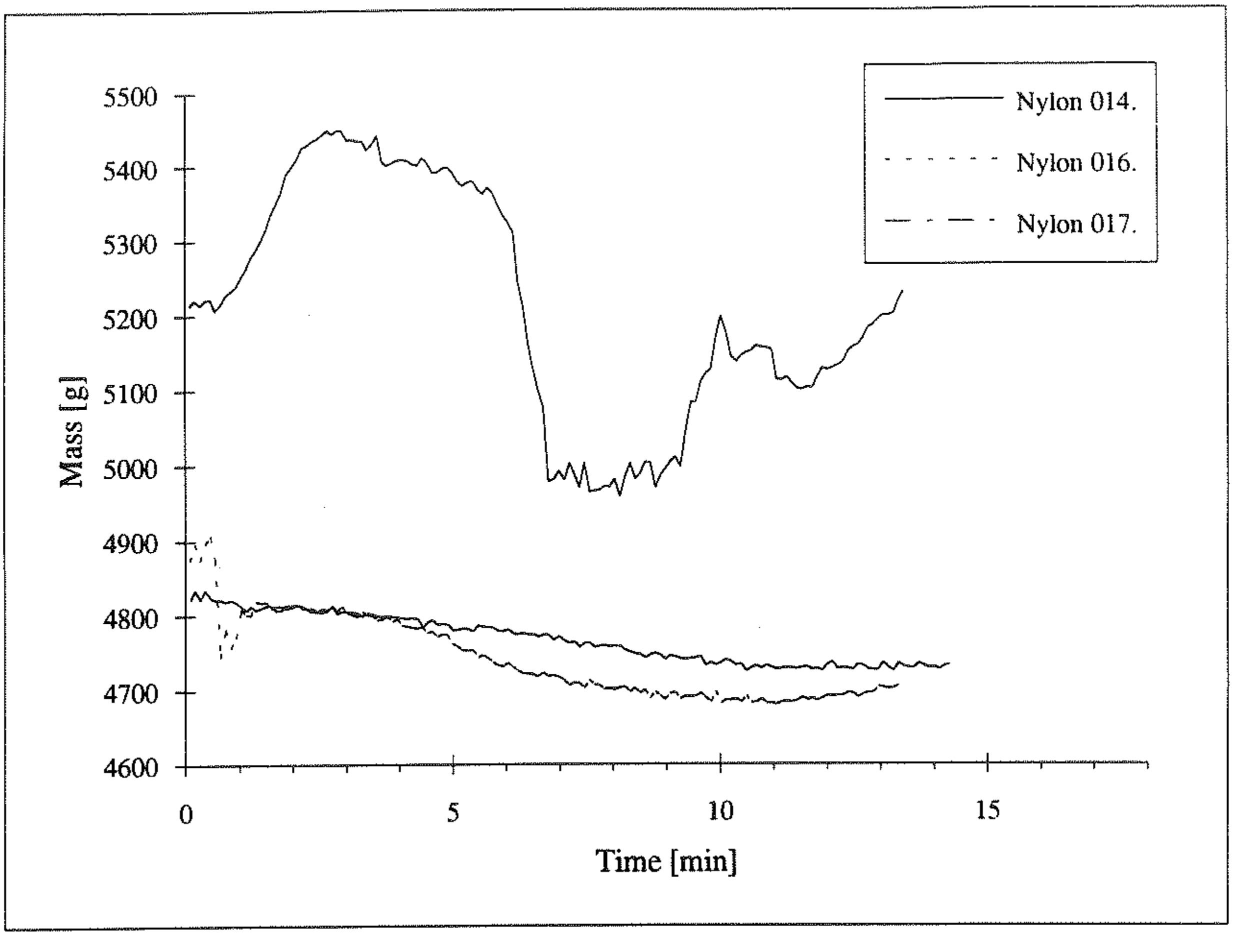

0.3
0.25
0.2
0.15
0.1
0.05
0
CO2 prod [g/s]
0
5
10
15
Time [min]
Nylon 014.
Nylon 016.
Nylon 017.


0.012
0.01
0.008
0.006
0.004
0.002
0
CO prod [g/s]
0
5
10
15
Time [min]
Nylon 014.
Nylon 016.
Nylon 017.





Note: The peak is due to the methanol used for ignition.


5500
5400
5300
5200
5100
5000
4900
4800
4700
4600
Mass [g]
0
5
10
15
Time [min]
Nylon 014.
Nylon 016.
Nylon 017.

Appendix 5: Test results for PVC

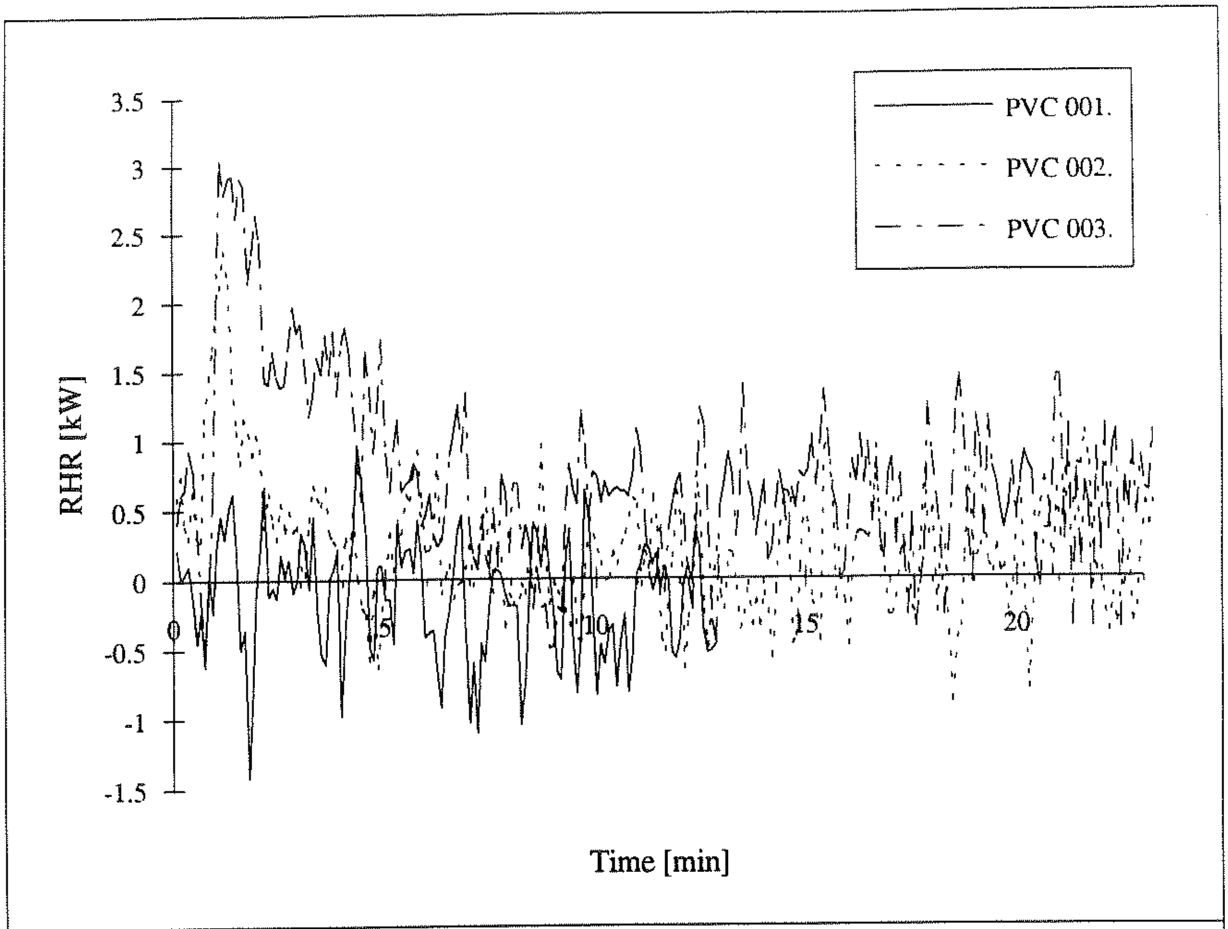
Contents:

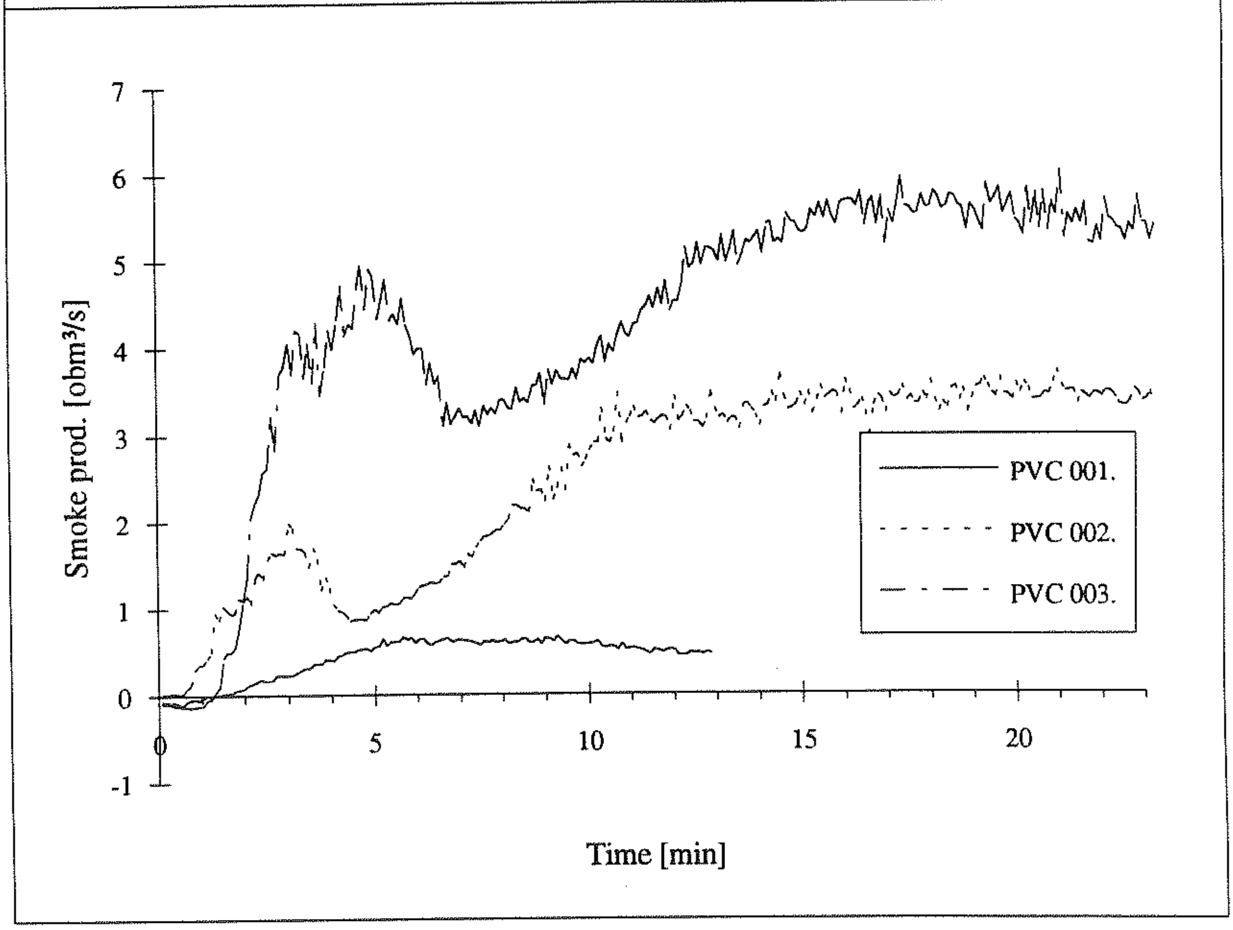
Test	RHR page	Smoke prod. page	CO_2 prod. page	CO prod. page	NO_X prod. page	C_nH_{2n} prod. page	Mass loss page
001	1	1	2	2	3	3	4
002	1	1	2	2	3	3	4
003	1	1	2	2	3	3	4

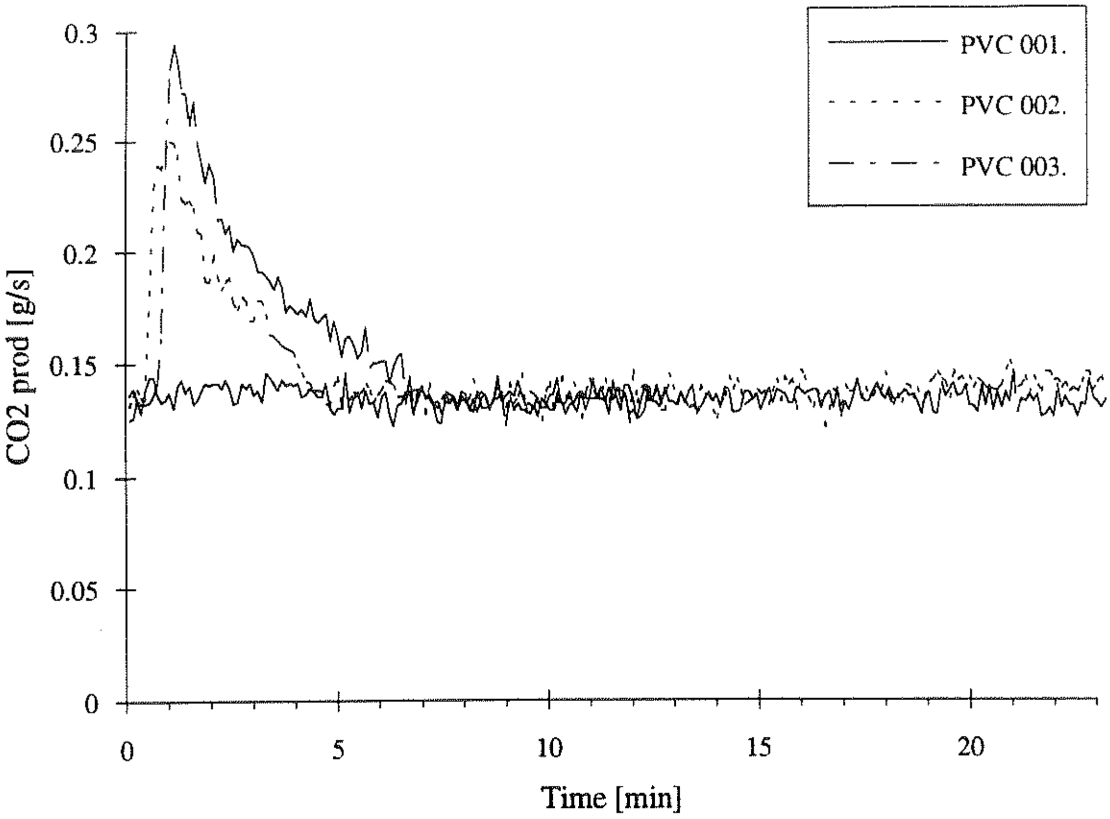
Note that the PVC samples only pyrolysed during test number 001, 002 and 003.

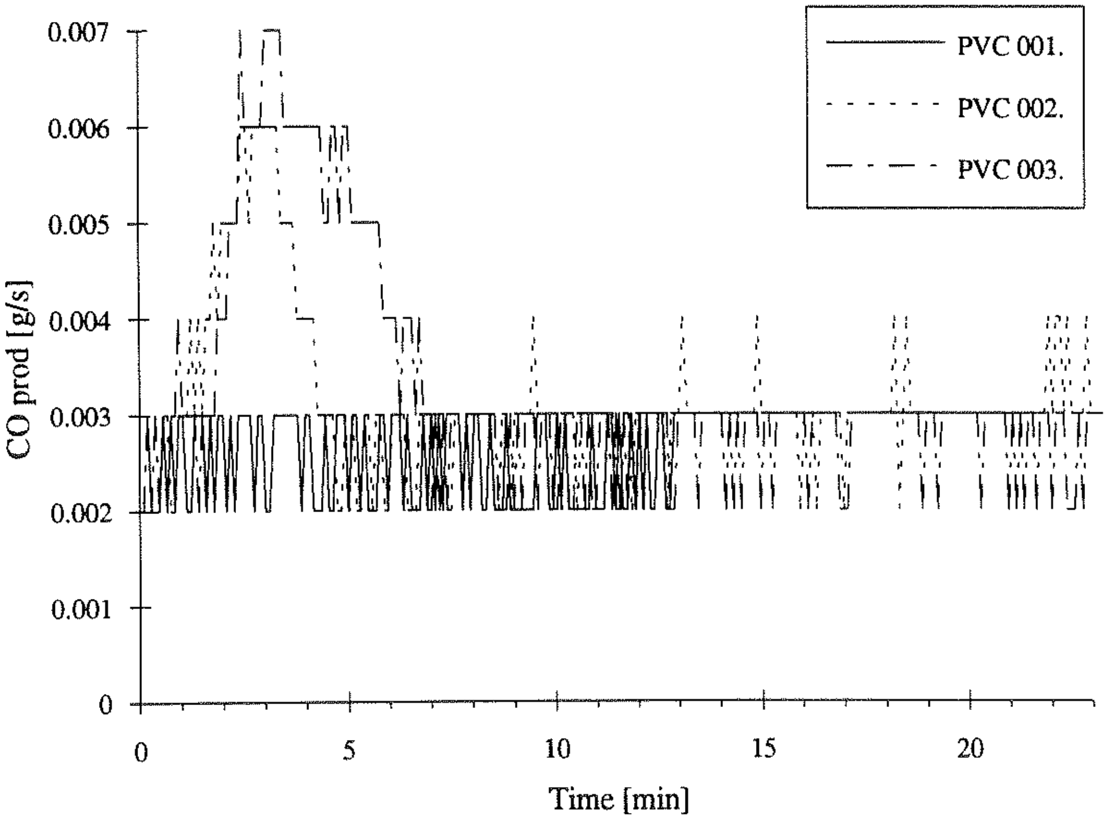
Corrections of the data were made in the study (not carried out in the appendix):

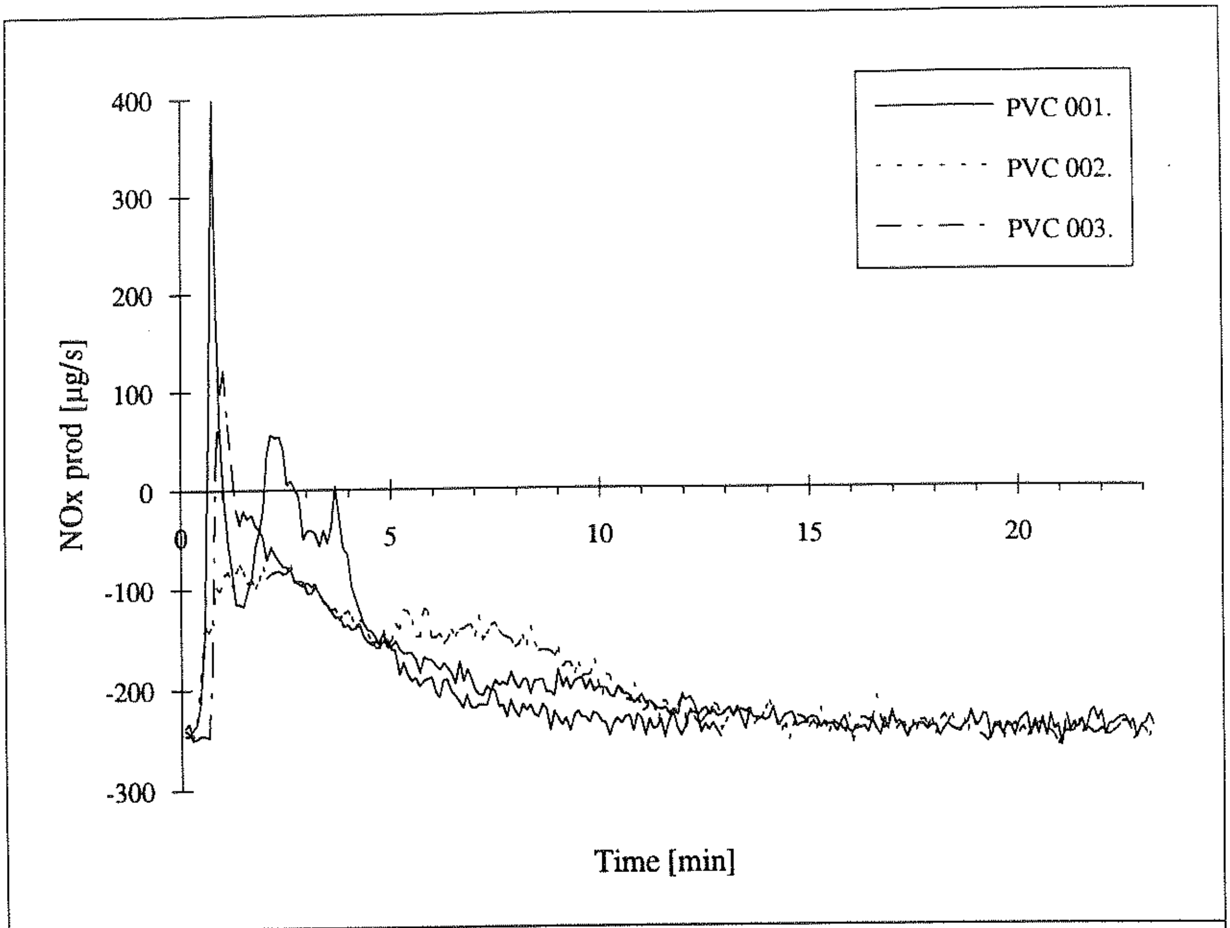
- The RHR values were multiplied with 12.8/13.1 as the measuring program does not consider the actual heat released per unit mass oxygen consumed.
- The CO_2 and CO values were multiplied by 0.91 due to a calibration error in the gas analysis equipment.

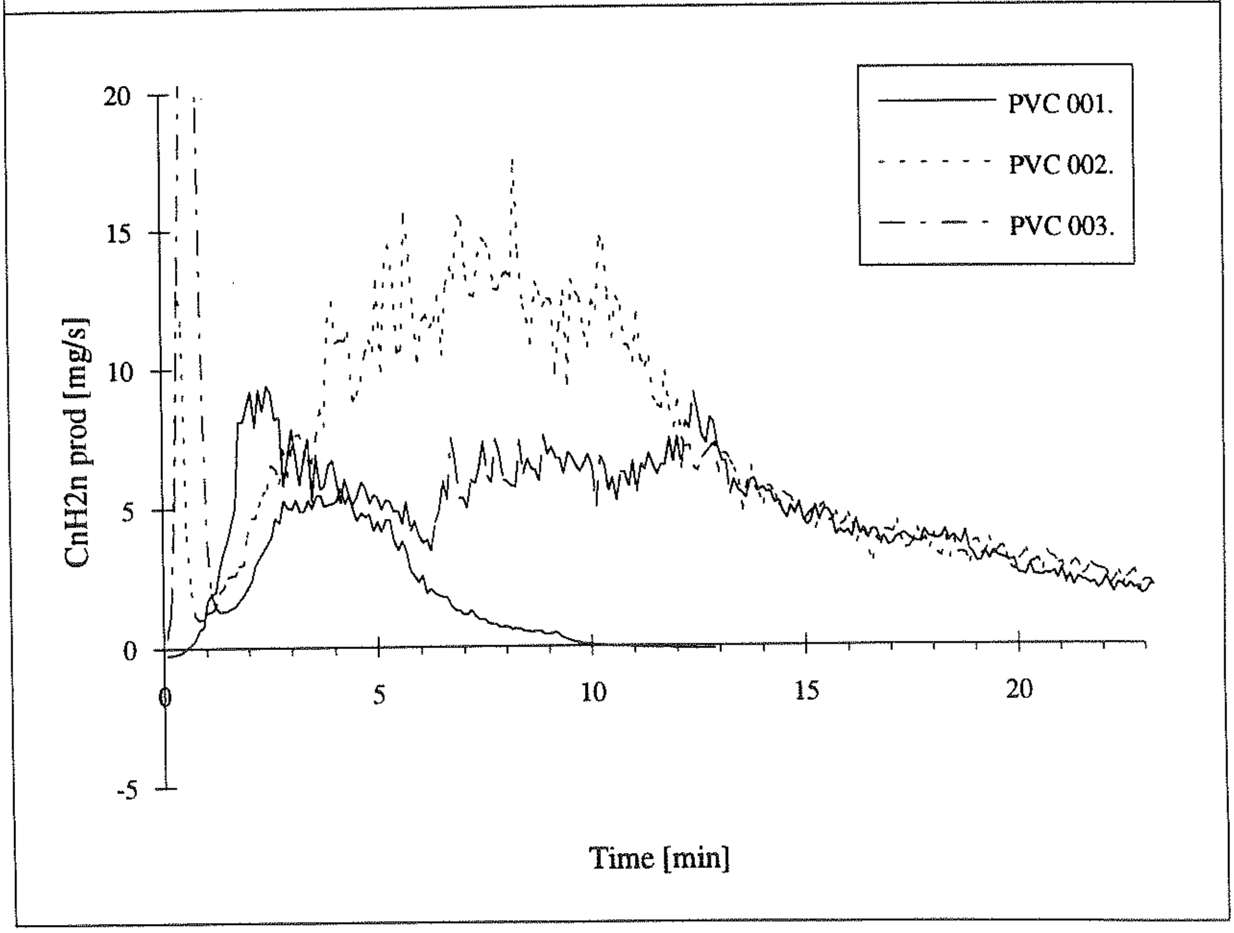

RHR [kW]
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
5
10
15
20
Time [min]
PVC 001.
PVC 002.
PVC 003.

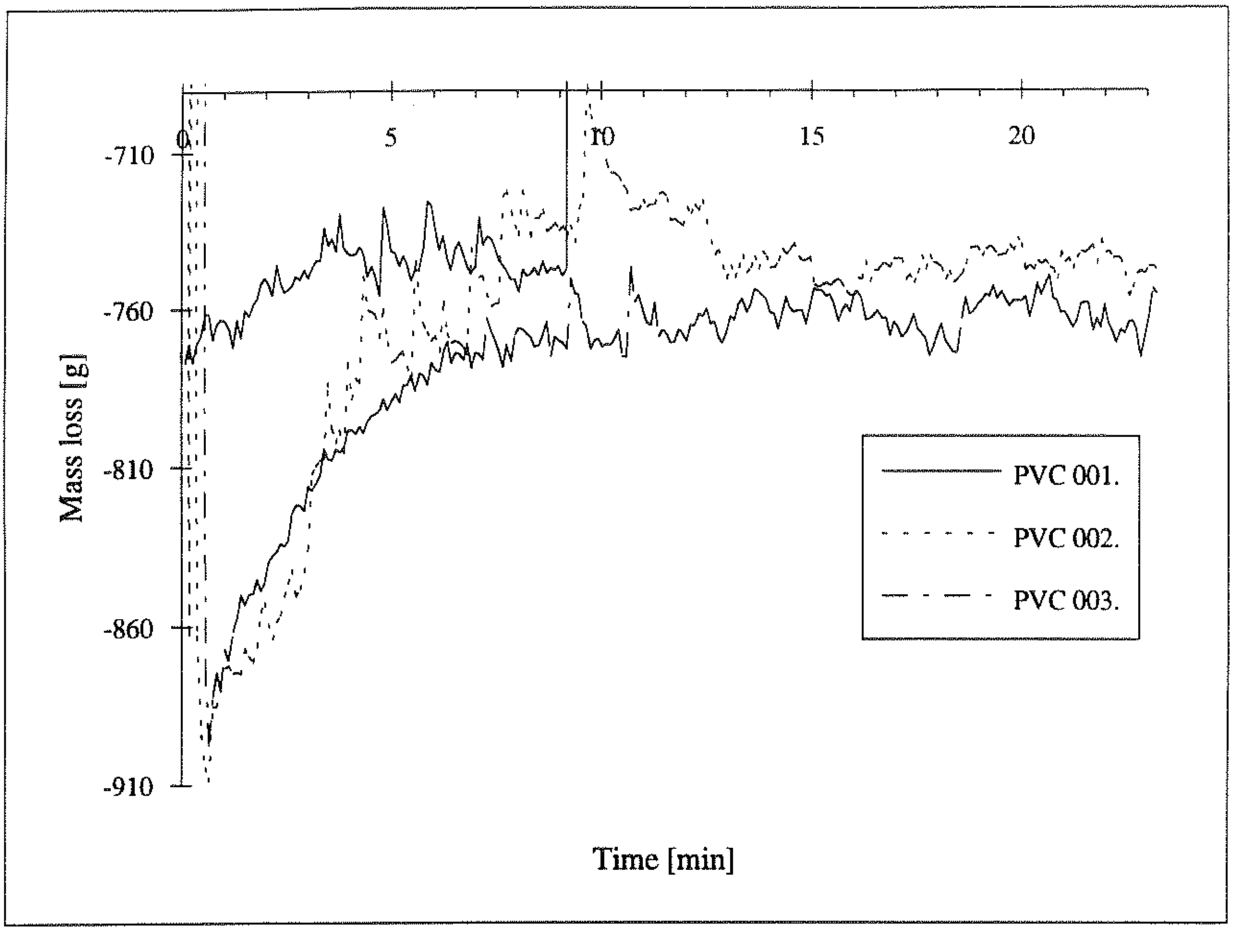

Smoke prod. [obm³/s]
7
6
5
4
3
2
1
0
-1
0
5
10
15
20
Time [min]
PVC 001.
PVC 002.
PVC 003.


0.3
0.25
0.2
0.15
0.1
0.05
0
CO2 prod [g/s]
0
5
10
15
20
Time [min]
PVC 001.
PVC 002.
PVC 003.


0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
CO prod [g/s]
0
5
10
15
20
Time [min]
PVC 001.
PVC 002.
PVC 003.


PVC 001.
PVC 002.
PVC 003.
NOx prod [µg/s]
400
300
200
100
0
-100
-200
-300
0
5
10
15
20
Time [min]


PVC 001.
PVC 002.
PVC 003.
CnH2n prod [mg/s]
20
15
10
5
0
-5
0
5
10
15
20
Time [min]


0
5
10
15
20
-710
-760
-810
-860
-910
Mass loss [g]
Time [min]
PVC 001.
PVC 002.
PVC 003.