Delft University of Technology
Faculty of Aerospace Engineering
Delft

Prins Maurits Laboratory
Organization for Applied
Scientific Research TNO
Rijswijk

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SOLID FUEL COMBUSTION CHAMBER PROGRESS REPORT XII

July-December 1987

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P.A.O.G. Korting
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Delft/Rijswijk, The Netherlands

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ACKNOWLEDGEMENTS

The Solid Fuel Combustion Chamber Project (phase 2) is presently supported by the (Netherlands) Technology Foundation (STW), project no. DLR 15.0120, the Faculty of Aerospace Engineering of Delft University of Technology (FAEDUT), project no. TUDLR A2L3.81.04, both the Prins Maurits Laboratory and the Defence Research Division of the Organization for Applied Scientific Research (PMLTNO and HDOTNO), and the Working group for the use of supercomputers (WGS).

CONTENTS

1. INTRODUCTION

In this report an overview of the July-December 1987 period of the Solid Fuel Combustion Chamber (SFCC) project [1] is given.

In chapters 2-5 an update is presented on project support and project personnel. It is especially noted that STW further extended the term for the project to January 1, 1990.

Chapters 6 and 7 present an overview of the research activities carried out in this period. The research activities included, among others, the modelling of the fuel massflow as a function of the (convective) heat flux, initial experiments with HTPB fuels and the evaluation of the Laser Doppler Anemometry (LDA) technique for local flow velocity measurements (Laser Doppler Velocimetry, LDV).

Many valuable contacts are reported in chapters 8 - 10. Of these, it is especially mentioned that PMLTNO has joined a study group to evaluate the applicability of ramjet propulsion.

Finally, this report also includes a general assessment of the program status (chapter 10), an outline of the next half year period (chapter 11) and an update of the phase 2 timetable (chapter 12).

2. PROJECT SUPPORT

On December 14, 1987, STW informed the project group that the term for the project has been further extended to January 1, 1990.

Presently, the SFCC project is supported by STW, FAEDUT, PMLTNO, HDOTNO and WGS.

An overview of the total support received over the period from January 1, 1986 until now is given below.

- Material support:

The respective contributions are as follows

	Operational support	Investment support
- STW	: 275 kfl	15 kfl
- HDOTNO	: 100 kfl	160 kfl
- PMLTNO	: 50 kfl	- kfl
- FAEDUT	: 50 kfl	- kfl
	495 kfl	175 kfl

- Personnel support:

STW: 1 TA (Technical Assistant) for a period of 4 months (1/1/86-1/5/86)
1 TA 2 years (1/1/87-1/1/89)
1 Ir/Drs[1] 3 years (1/9/87-1/9/90)
1 Dr 3 years (1/1/86-1/1/89)

FAEDUT: project leader
1 Ir (part-time 50%)
1 Ing for a period of 3 years (1/6/87 - 1/6/90)

PMLTNO: 1 Ir (part-time 25%)
1 Ing (part-time 10%)
1 TA starting from 1/1/89

HDOTNO: 1 Ir for a period of ca 2 years (1/10/86 - 1/1/89)

1) HDOTNO contributes 50 kfl.

- Other support

  . WGS : 15 hours on Supercomputer (Cray)
  . STW : 20 kfl for travelling abroad
  . FAEDUT: - Computer time, approximately 300 kRE/yr
    (1986: 150 kRE, 1987: 400 kRE en 1988: 375 kRE)
    - General support: secretarial services, production of small items, etc.
  . PMLTNO: General support: secretarial services, maintenance of testfacility, production of small items, etc.

3. CURRENT RESOURCES

On July 1, 1987, approximately 430 kfl (excluding personnel funds) was available for carrying out the remainder of the planned program, see also chapter 13. Of this, 255 kfl is reserved for small equipment, consumables (gases, fuels), maintenance of the test facility and travelling, and 175 kfl is reserved for large investments.

During the period July-December 1987, expenditures amounted to approximately 70 kfl for small equipment etc. Of this, 22.6 kfl was charged to STW, 8.2 kfl to FAEDUT and the remainder to PMLTNO and HDOTNO.

Current (31/12/87) resources are:

- 185 kfl for small equipment, etc.
- 175 kfl for large investments.

4. MANAGEMENT AND ORGANIZATION

During this period, ir. J.P. de Wilde and ir. B.T.C. Zandbergen joined the project group.

Ir. J.P. de Wilde started his activities on September 1, 1987. He is employed by FAEDUT for a 3 year period on a grant from STW (2 years) and HDOTNO (1 year) and is primarily involved in a study on fuel pyrolysis.

On September 14, 1987 ir. B.T.C. Zandbergen joined the project group on a part-time (50%) basis. Ir. B.T.C. Zandbergen is staff member of FAEDUT, specially assigned to propulsion research. As such, he has taken over from dr. C.W.M. van der Geld.

At the moment the project group has no further vacancies. The group consists of:

- Prof.ir. H. Wittenberg (principal investigator FAEDUT, project leader)
- Ir. P.A.O.G. Korting (principal investigator PMLTNO)
- Ir. B.T.C. Zandbergen (research assistant FAEDUT)
- Dr. T. Wijchers (senior scientist STW)
- Ir. J.P. de Wilde (research assistant STW)
- Ir. P.J.M. Elands (research assistant PMLTNO)
- Ing. F. Dijkstra (assisting engineer FAEDUT)
- Ing. R.P.M. van de Berg (assisting engineer PMLTNO)
- J. van den Brand (technical assistant STW)

During this period, the project organization was slightly adapted. A further change on project organization is presently under discussion.

5. STUDENTS INVOLVED IN THE SFCC PROJECT DURING THE PERIOD JULY-DECEMBER 1987.

In addition to staff members assigned to the project by FAEDUT, PMLTNO and STW, the following students have contributed to the project:

A. Students FAEDUT

H.J. Dorpema	Third year assignment: initial experiments LDV particle generator.
G.C. Klein Lebbink	Thesis work on the effect of surface discontinuities on channel flows with blowing (theoretical study).
R. Koolen	Thesis work: experimental study on Boron combustion; verification of Boron combustion models.

B. Others

A. Buschgens*)	Student Hogeschool Haarlem Thesis work: determination of temperature profile in a solid fuel grain during combustion (experimental study)
G.C. Klein Lebbink	Student assistant FAEDUT: data reduction (software design and programming)

*) Period January-June 1987

6. THEORETICAL WORK

In this period, theoretical work concentrated on three topics:

1) The existing theoretical model, implemented in COPPEF [2], was further improved by implementing a simple linear relationship between the regression rate and the heat flux to the fuel. This allows for the computation of the local regression rate, see section 6.1.

2) An investigation was started aiming at an improved numerical modelling of COPPEF. This is to improve numerical convergence and reduce computing time. Prof.dr. A.E.P. Veldman of the Faculty of Mathematics of Delft University of Technology advises on this investigation. For further information, see section 6.2.

3) On September 1, 1987, a study has been started on fuel pyrolysis. This study followed an earlier study on the pyrolysis of PMMA (report in preparation) and aimes at improving the understanding of the parameters that determine the pyrolysis behaviour of the fuel. For further information, see section 6.3.

6.1. Regression rate modelling (P.J.M. Elands)

In this period, the main modelling effort has been the implementation of the coupling between the heat flux from the main flow to the wall and the regression rate.
In the COPPEF computer program, pyrolysis of the solid polymeric fuel is being simulated by injection of gaseous monomer at the solid fuel boundary into the flow. Until recently, the injection velocity was equal along the fuel grain and its value was to be specified as an input parameter to the computer program. This is considered to be unrealistic. From the experiments it has been found that the regression rate of fuel is dependent on the location along the fuel grain. In the reattachment region the regression rate of the fuel is larger than in the recirculation region or in the boundary layer. This is due to the fact that in the reattachment region hardly any boundary layer exists, the velocity being almost zero, hence the thermal insulation is small. The

heat flux to the wall will cause a larger regression rate compared to the regression rate at a location where there is a thicker thermal boundary layer. The coupling between the heat flux from the main flow to the wall and the regression rate is made as follows. At each near-wall gridpoint the heat flux to the wall is determined from the temperature gradient and the boundary layer variables. The regression rate is then calculated from:

$$Q_w = \rho_{fuel} \cdot r \cdot A \cdot H_v \qquad (6.1)$$

where: Q_w is the heat flux [J/s],
ρ_{fuel} is the density of the solid fuel [kg/m^3],
r is the regression rate [m/s],
A is the regressing area [m^2] and,
H_v is the (effective) heat of gasification [J/kg], see also section 6.3.

The (effective) heat of gasification is defined as the amount of heat which is required to transform 1 kg of the polymeric material into gaseous fuel. In this value the melting heat, the heat of depolymerization and the heat of vaporization are included.
The regression rate is coupled directly to the fuel injection velocity. With this coupling, the regression rate is calculated along the fuel grain. Also the total fuel mass flow is calculated. Together with the oxidizer mass flow this yields the oxidizer/fuel ratio which is defined as the total mass flow of oxidizer divided by the total mass flow of fuel. The mean regression rate is also calculated.

To make a first comparison with experiments, calculations were carried out varying the oxidizer mass flow. The pressure was chosen to be 0.4 MPa to avoid significant radiation effects to be taken into account. As fuel eth(yl)ene (C_2H_4) was taken instead of MMA, because the finite rate chemical kinetics combustion model is not able to handle MMA as a fuel.
In figure 6.1, the mean regression rate is given as a function of the oxidizer mass flow. For H_v, an arbitrary value of 1.7 MJ/kg was taken.

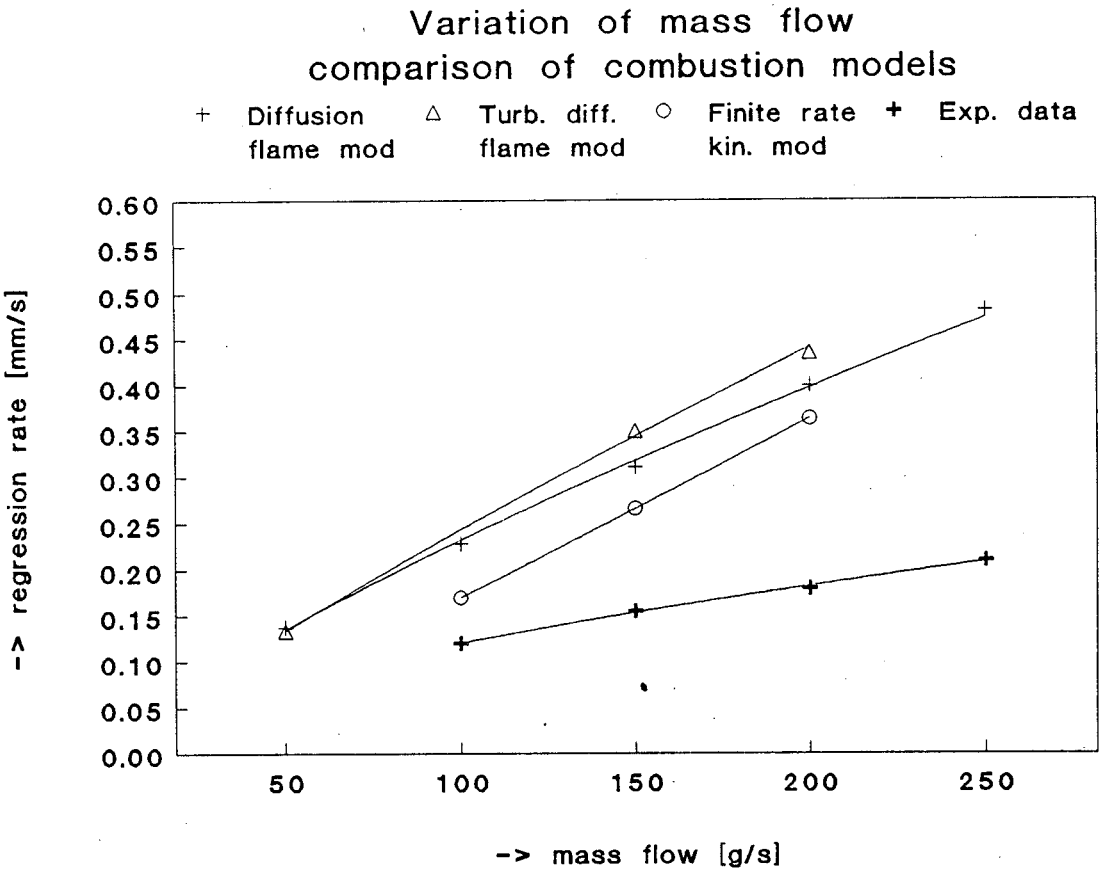


Figure 6.1: Regression rate as function of the oxidizer mass flow; comparison of three combustion models with experimental data, H_v = 1.7 MJ/kg.

In the figure, three lines for computational data are given, representing the three combustion models incorporated in COPPEF, and one line representing the experimental data. From this figure it can be seen that the regression rates predicted for the three combustion models do not differ very much, but the difference with the experimental data is still significant. Some differences between the three combustion models can be pointed out. With the finite rate chemical kinetics combustion model dissociation of species and the formation

of intermediates are taken into account. These phenomena require energy and therefore less heat will be released, and less fuel will be pyrolyzed. Hence the regression rate of fuel, predicted with the finite rate chemical kinetics combustion model, will be less than the regression rate predicted with the diffusion flame concept based models.
The difference between the diffusion flame model and the turbulent diffusion flame model with respect to the heat flux to the wall lies in the temperature distribution. With the turbulent diffusion flame model the reaction region lies more towards the centerline of the channel, and thus maximum temperatures also do. The heat flux from the main flow to the wall, which is merely determined by the temperature gradient between the wall and the near-wall gridpoint, will be somewhat smaller for the turbulent diffusion flame model. Also the total amount of heat released in the reaction will be less for the turbulent diffusion flame model.

Nevertheless, there still is a variable of which the value is not sure, being the (effective) heat of gasification. To investigate the effect of a variation of this variable, a few calculations have been made using the diffusion flame combustion model, varying the (effective) heat of gasification from 1.7 MJ/kg to 4.0 MJ/kg, for different oxidizer mass flows. The results are given in figure 6.2.

From this figure it can be concluded that the (effective) heat of gasification is a very important parameter and needs to be determined as accurately as possible. A variation of the (effective) heat of gasification causes an important variation in the value of the regression rate. Of course some further investigation is required, for instance into the differences between the three different combustion models.
It can be concluded that the modelling of the linear relationship between the heat flux and the regression rate works satisfactorily, although some further research still is required.

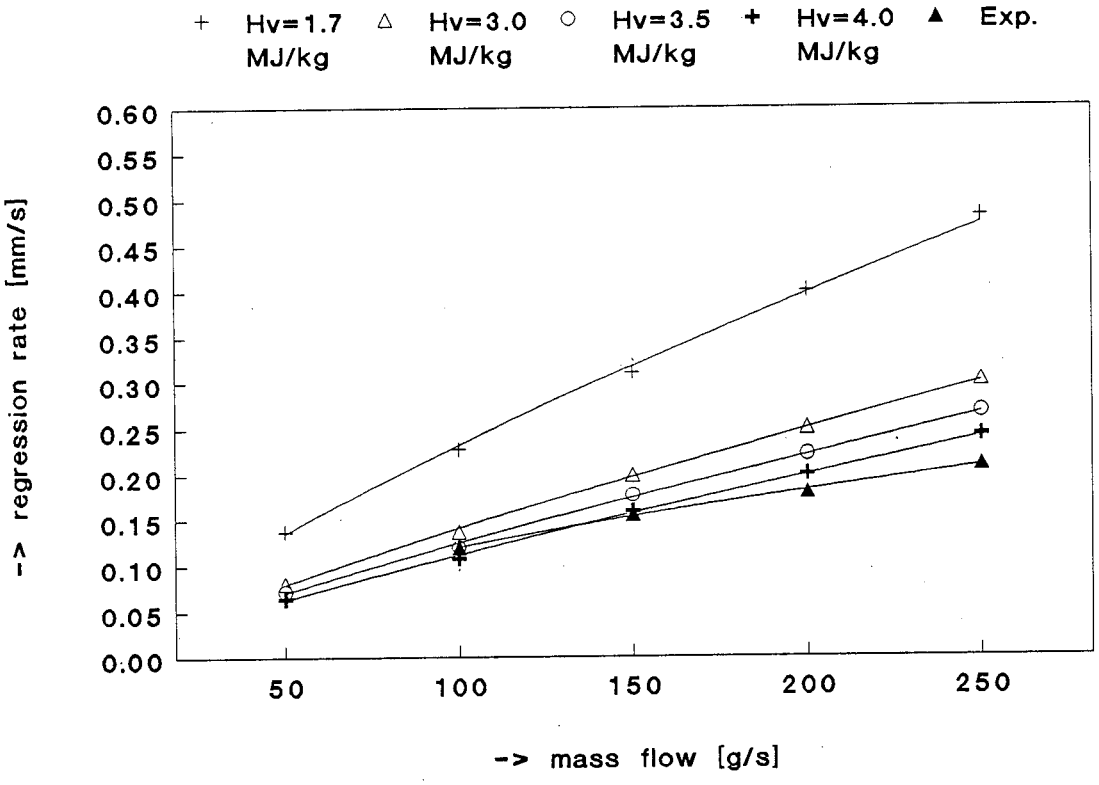


Figure 6.2: Regression rate as function of the (effective) heat of gasification, diffusion flame model.

6.2. Numerical modelling; convergence behaviour investigation (P.J.M. Elands)

The COPPEF computer program uses an iterative solution approach when calculating the flow and combustion in the solid fuel combustion chamber.
In fact, within this iteration process, several other iteration processes are taking place. Both iteration processes have their own convergence behaviour, and the method which is being used, is based upon the splitting of these two iteration processes. For each iteration process, the important parameters such as boundary conditions, relaxation factors, etc. are determined. The final goal of this investigation is to obtain an optimal convergence rate.
If it is possible to reach this goal, computational costs are estimated to reduce by 20% to 30%.

6.3. Fuel pyrolysis (J.P. de Wilde)

6.3.1. Introduction

During the combustion of a polymeric material, there are actually two processes taking place, namely the pyrolysis process during which gaseous fuel is formed and the combustion process during which the actual burning occurs. Hereafter, we will only discuss the pyrolysis process.
Due to the heat flux from the flame to the fuel grain the temperature of the fuel increases. This results in a temperature profile in the fuel grain characterized by the surface temperature (T_s) and the initial temperature (T_o), see figure 6.3.

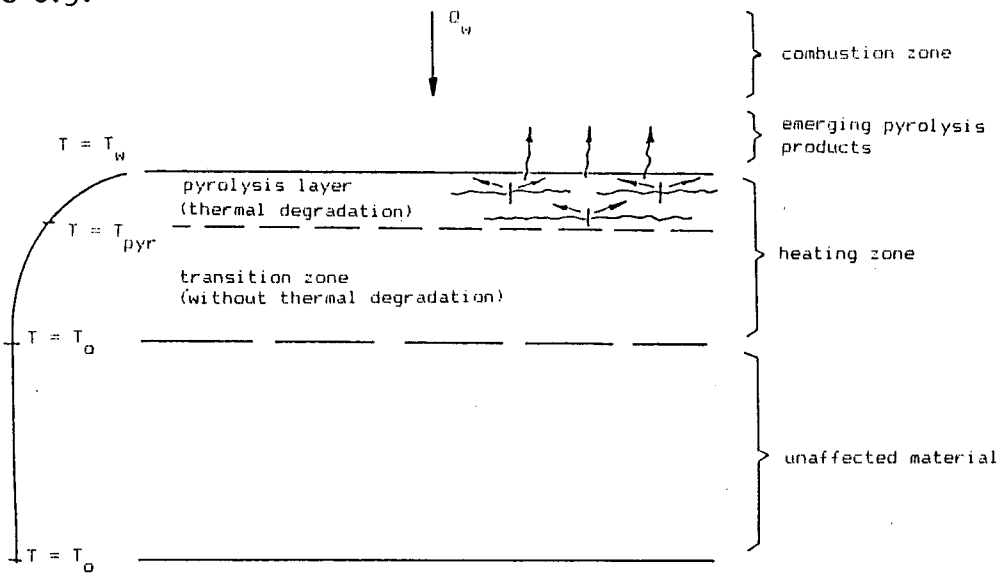


Figure 6.3: Temperature profile in the fuel grain.

As of the temperature of the material we can distinguish a zone where the temperature of the material is not affected and the material remains unchanged, and a heating zone where the temperature of the material increases. The latter can be subdivided in:

- a transition zone ($T_o < T < T_{pyr}$), and
- a pyrolysis zone ($T_{pyr} \leq T \leq T_s$).

In the transition zone the physical properties of the material are changed but its chemical composition does not change. In the pyrolysis zone also the chemical composition of the material is changed. At a certain temperature (T_{pyr}), characteristic for the material, the thermal stability of the material decreases and the molecules of the polymeric material break up into several smaller molecules, the so-called pyrolysis products. If the temperature at which pyrolysis occurs ($T \geq T_{pyr}$) is high enough only gaseous products are formed. These gaseous products emerge into the flame, thereby feeding the combustion. As the solid fuel is gasified at the surface, this will result in a regressing grain surface.

6.3.2. The (effective) heat of gasification

To transform 1 kilogram of original polymeric material into gaseous products (fuel) a certain amount of heat is required. This amount of heat is called the (effective) heat of gasification (H_v) of the polymer. Until recently, an arbitrary value of 1700 kJ/kg has been used for the (effective) heat of gasification of both polyeth(yl)ene (PE) and polymethylmethacrylate (PMMA).

However, a literature study [3] has shown that this value is not correct and that H_v depends on the principal mode of (surface) heating. Three modes can be distinguished:

- Conductive heating

  Conductive heating via hot metal plates has been used but suffers from difficulties in determining the heat flux into the polymeric material.

- Radiative heating

  Radiative heating has been applied using a radiant furnace. The radiant source was an electrical panel. The heat flux was adjusted by regulating the applied voltage. This method also has a few drawbacks. For instance, the radiation that passes through the surface is absorbed in depth. This results in a temperature profile in the grain much different from that in a burning

polymer, where radiative heating is generally negligible compared to convective heating.

- Convective heating

In the convective heating approach, the pyrolysis products are burned in a low-speed impinging jet of oxidant gas just above the pyrolyzing surface. The heat feedback from the flame to the polymer drives the pyrolysis process. Since the test configuration is well enough defined, it allows analytical prediction of the surface heat flux during combustion, and therefore H_v can be determined.

Table 6.1 now summarizes the data for PMMA and PE found in the literature.

	H_v (kJ/kg)	
	radiative heating	convective heating
PE	3000 - 3500	4000 - 5600
PMMA	1300 - 1700	2500 - 2700

Table 6.1: Comparison of various values of the effective heat of gasification (H_v) obtained by using different experimental techniques [3].

According to table 6.1 the value for H_v varies for PE from 3000 to 5600 kJ/kg and for PMMA from 1300 to 2700 kJ/kg. The lowest values belong to radiative heating experiments. Since convective heating, in general, occurs during combustion in an SFCC these values should be employed.

6.3.3. The pyrolysis products

In most literature, and also in the COPPEF computer program, it is assumed that the pyrolysis products of a polymeric material like PE and PMMA only exist of the monomer and that this monomer is burned. However, in reality, this is not true and also other products are formed during the pyrolysis.

From bulk pyrolysis experiments (without combustion) we know that the composition of the pyrolysis products of a polymer greatly depends on the temperature at which the material is heated, see e.g. figure 6.4.

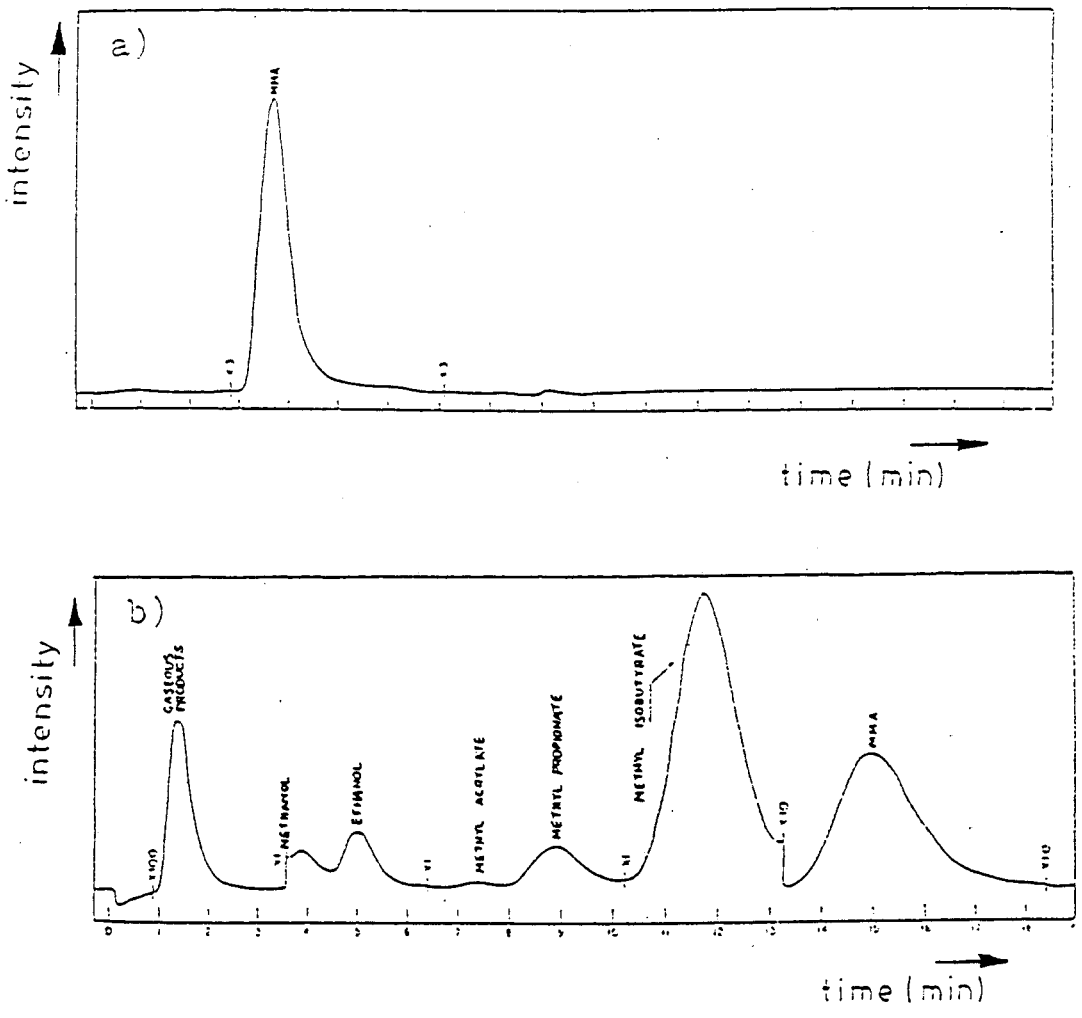


Figure 6.4: Typical bulk pyrolysis results of PMMA heated at different temperatures: a) 700 K, b) 1300 K.

If PMMA is heated to 700 K, it pyrolyzes almost completely into the monomer (fig. 6.4a). However, if PMMA is heated to 1300 K the amount of monomer reduces to about 20% of the total mount of pyrolysis products (fig. 6.4b). The effect of temperature on the pyrolysis of PMMA is also illustrated in figure 6.5.

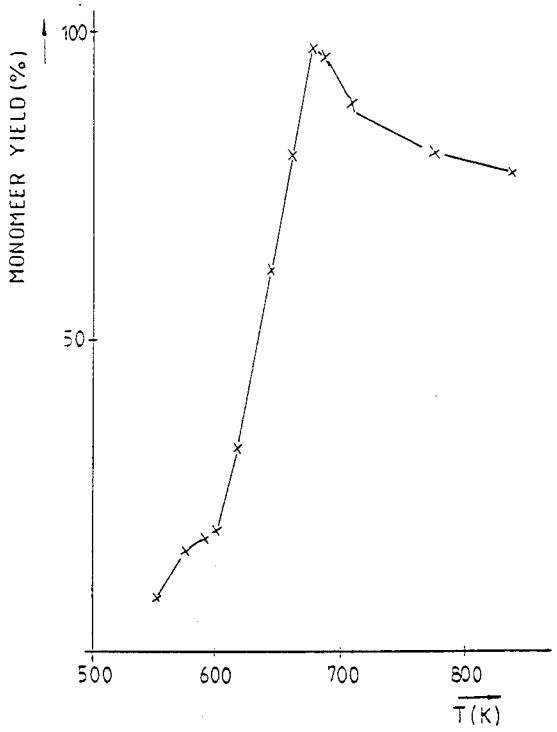


Figure 6.5: The effect of temperature on the monomer formation for PMMA.

Combustion experiments with PMMA have confirmed that during the pyrolysis of the solid fuel also other pyrolysis products than the monomer are formed. Next to the monomer (MMA), the analysis also showed methane. Furthermore, it was shown that the methane/monomer ratio increases with increasing combustion chamber pressure (fig. 6.6).

To convert PMMA into monomer only, a certain amount of heat is required. If also other pyrolysis products are formed, this will influence the amount of heat required. In other words the effective heat of gasification will depend on the composition of the pyrolysis products. In what way this dependancy occurs will be investigated.

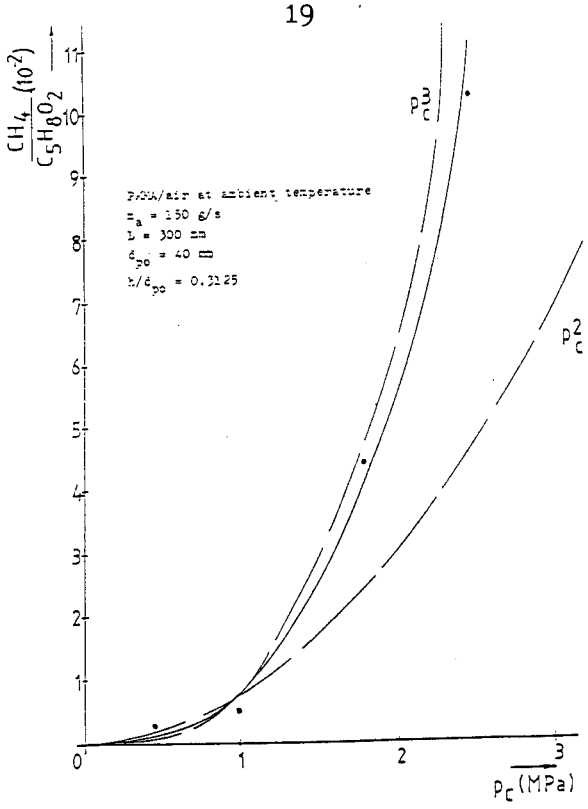


Figure 6.6: The methane/MMA ($CH_4/C_5H_8O_2$) ratio as function of the combustion chamber pressure.

7. EXPERIMENTAL WORK

7.1. Experiments (F. Dijkstra and T. Wijchers)

During the period July-December 1987 a large number of experiments has been performed using PMMA, PE, HTPB and moor materials as a fuel.

- Influence of the oxygen content in the inlet air.

  In the vitiator the inlet air is heated by burning methane with the oxygen in the air. As a consequence, the oxygen content in the inlet air is reduced. To remedy this, additional oxygen is supplied through a separate feed line.
  Recently, experiments for varying oxygen contents in the inlet air have clearly demonstrated the importance of a good control of the oxygen content in the inlet air, see e.g. figure 7.1.

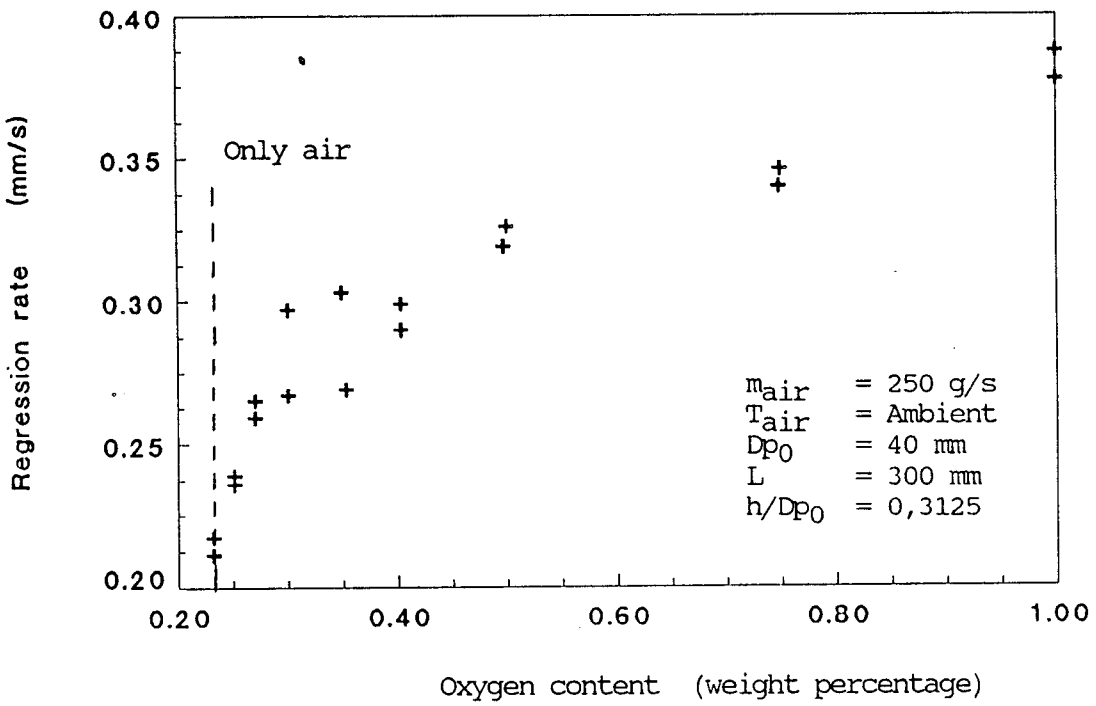


Figure 7.1: The regression rate as a function of the oxygen content in the (inlet) air.

- Influence of aft mixing chamber length.

Figure 7.2 gives the combustion efficiency (PMMA) as a function of the chamber pressure for an aft mixing chamber length of respectively 170 and 270 mm. It is noticed that the efficiency is higher for the longer aft mixing chamber and that this difference increases with increasing pressure. This is due to the fact that:

- The residence time of the fuel is higher for the longer aft mixing chamber, and
- at high pressures there is simply more fuel to be burned.

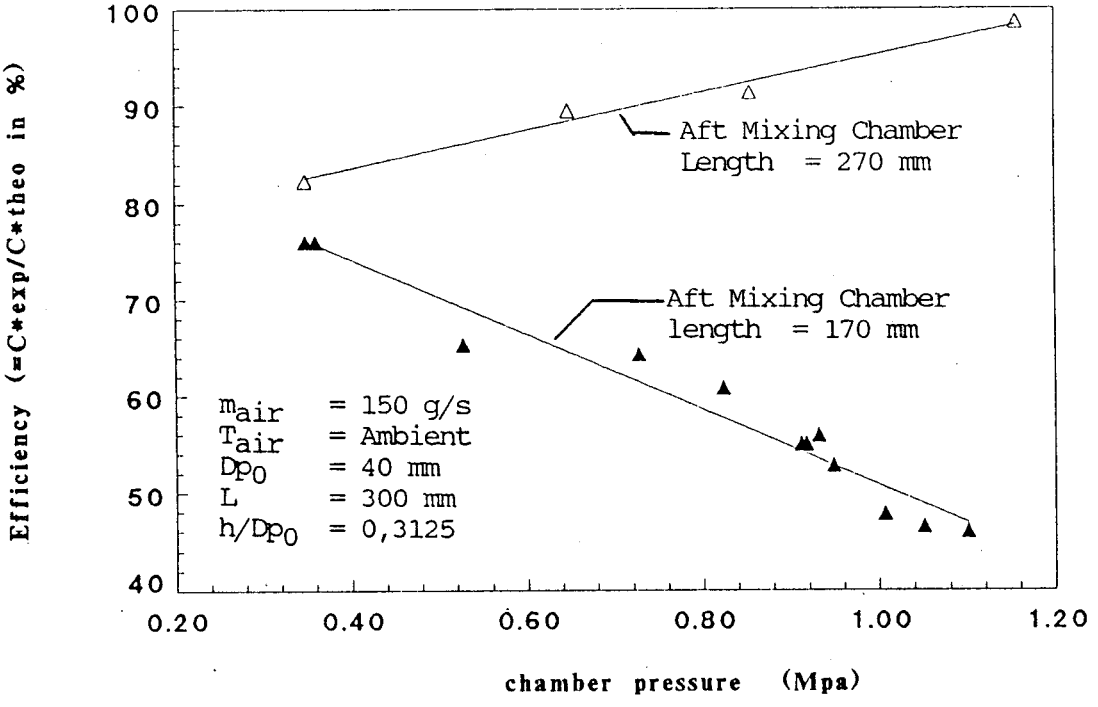


Figure 7.2: Combustion efficiency as a function of chamber pressure for 2 aft mixing chamber lengths.

- Study of PMMA ignition characteristics.

Because of ignition problems with PMMA, some experiments were performed to find the ignition limits of PMMA in a given geometry. The results are summarized in figure 7.3. It is noticed that ignition is not possible with high mass flows and/or small step heights. Furthermore, an area is found where

ignition is problematic. Here, the grain will burn for a few seconds only or will burn very unstable.

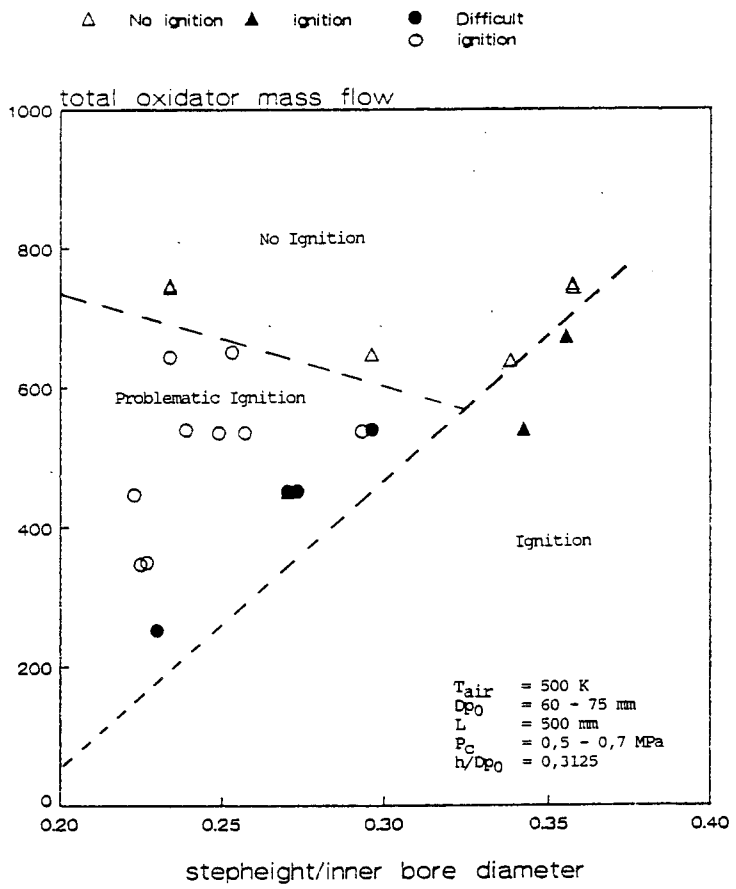


Figure 7.3: PMMA ignition characteristics.

- Combustion of HTPB.

In the period under consideration also several experiments with HTPB as a fuel have been performed. From figure 7.4 we learn that HTPB has a relatively high regression rate, which is linearly dependent on the pressure. Soot production of HTPB is very high at high pressures.

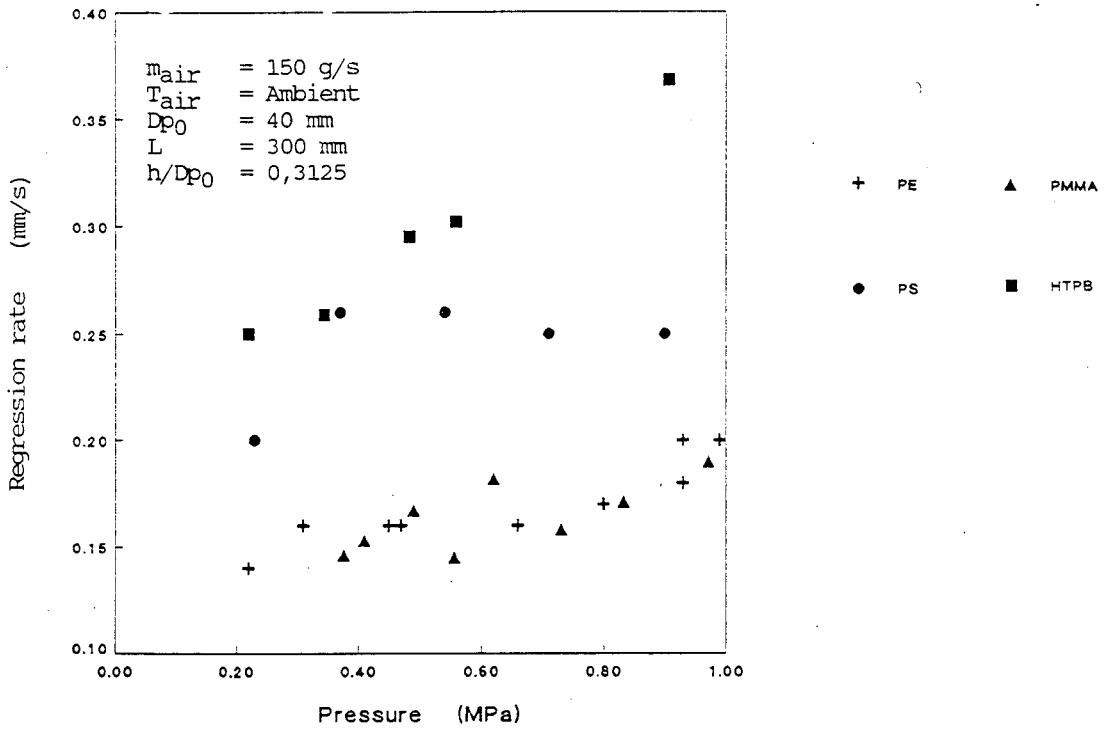


Figure 7.4: Regression rate as a function of chamber pressure for 4 different fuels. Data for PMMA, PE and PS are taken from [4].

- Combustion of moor materials.

In order to investigate whether moor materials can be burned efficiently in an SFCC several experiments have been performed using moor materials as fuel. It was found that it is possible to combust moor materials in the configuration as used. However, the combustion is erosive and incomplete. Furthermore, in some cases oxygen enriched air has to be used to assure ignition and stable burning. Results of these experiments will be reported in a separate note.

- Detection of acethylene (C_2H_2) in the SFCC.

In order to detect C_2H_2 spectroscopically, 10 fuel grains have been provided with radially mounted quartz windows. Spectra have been recorded at the centre wavelengths 228.7, 267.3, 271.3 and 275.0 nm, where C_2H_2-bands exist. [5]. However, no traces of these bands could be observed except for the

noise resulting from the radiation from soot. Possibly the UV-radiation is blocked by the contamination on the windows.
In order to avoid this contamination, the remaining grains have been provided with a nitrogen inlet to purge the windows. This inlet has been especially designed for the high pressures in the burning SFCC. Test experiments have shown that with this technique contamination of the windows is negligible.

7.2. Experimental techniques

7.2.1. The ultrasonic pulse-echo technique

To determine the local instantaneous regression rate the ultrasonic pulse-echo technique (USPET) [6] is used. With this technique the time interval between a sound pulse emitted by an ultrasonic probe attached to the outer surface of the fuel grain and its echo due to the reflection from the burning surface is measured. Following the measurement of this time interval, the so-called pulse travel time, the wall thickness is calculated from the speed of sound in the material and the rate of change in the pulse travel time. The regression rate then follows from the rate of change in the wall thickness.

Some experiments have been performed with PMMA to determine the regression rate by USPET and by visual observations simultaneously. For this, special transparant fuel grains have been made to be able to make cine film recordings of the regressing burning surface.
Figure 7.5 gives a comparison of total regression, observed visually and determined from the pulse travel time. The speed of sound, necessary to calculate the wall thickness, is assumed to be constant throughout the grain and equal to the speed of sound at ambient temperature. Here an assumption is made which could cause problems. Due to the heat flow to the grain there is a layer where temperatures are higher than the ambient temperature. Consequently also the speed of sound will be different from ambient. However, from figure 7.5 we learn that,even when assuming constant speed of sound throughout the grain, the results agree quite well.

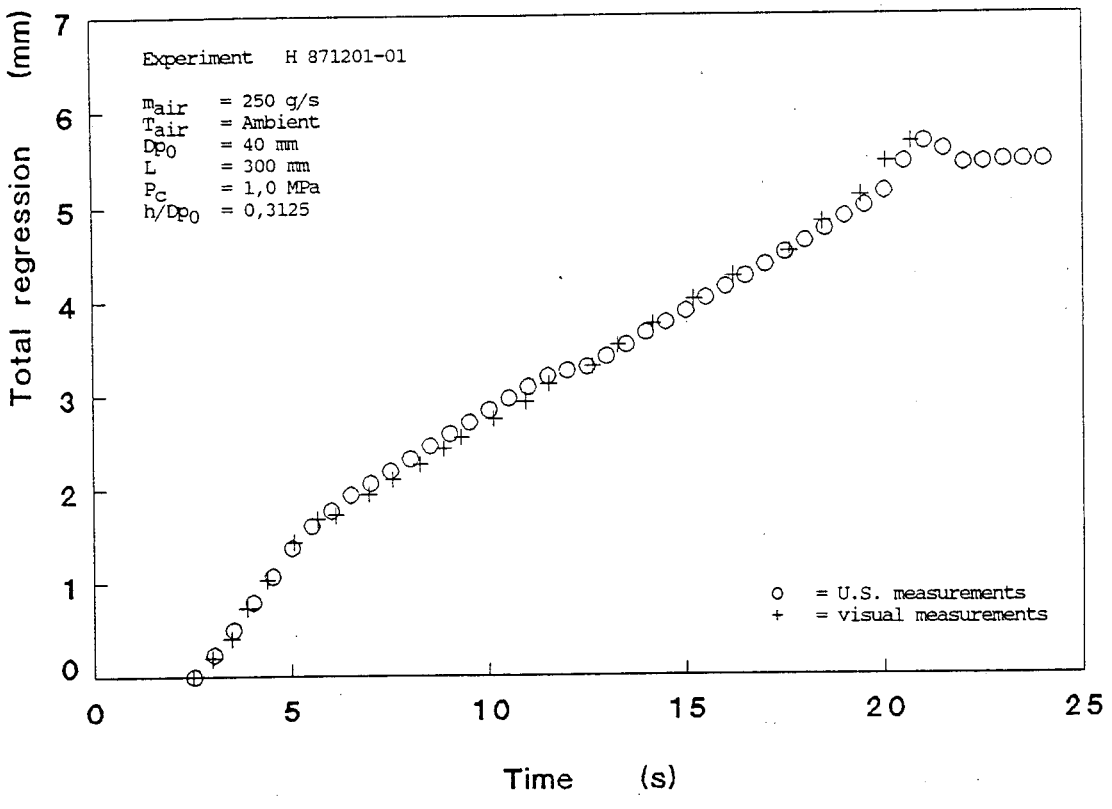


Figure 7.5: Comparison of total regression obtained both visually and from ultrasonic measurements.

Some results of the regression rate as a function of time determined with the help of USPET are given in figure 7.6.

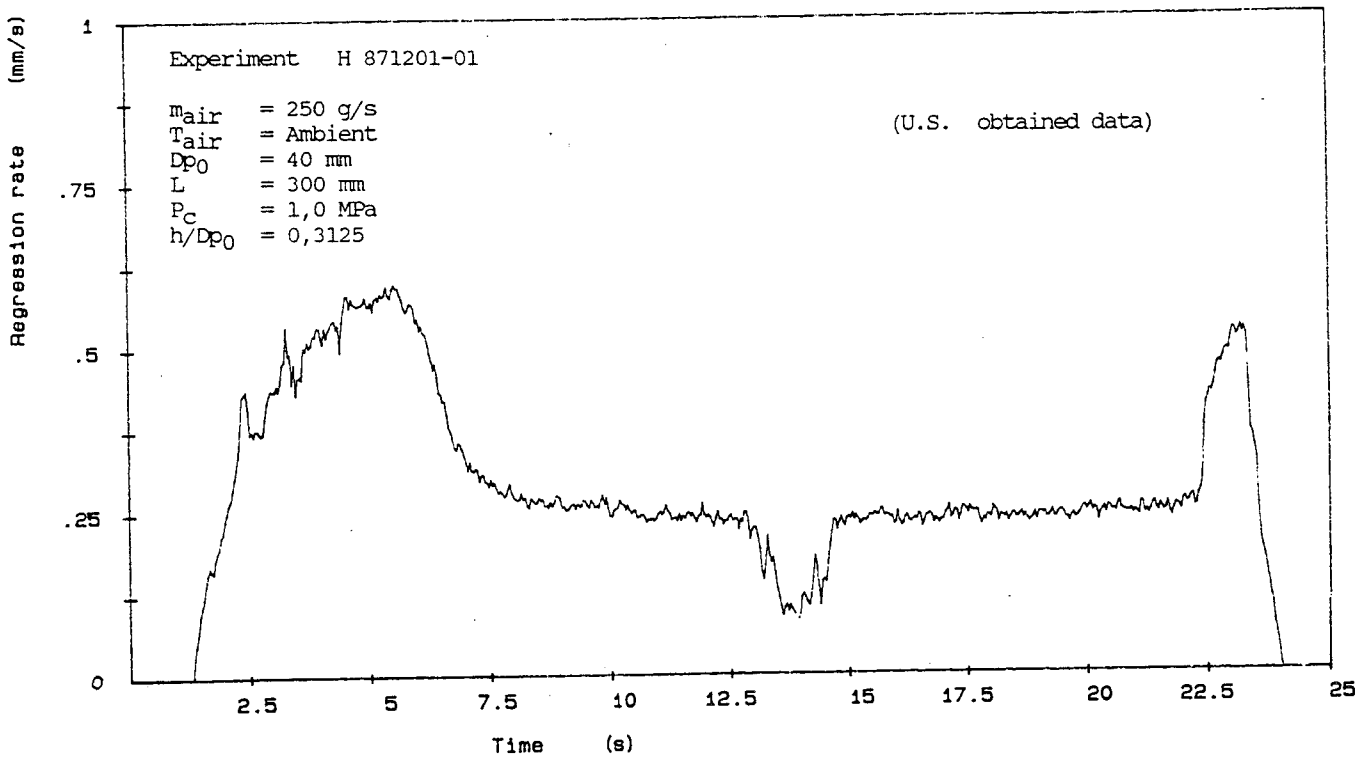


Figure 7.6: Regression rate as a function of time.

7.2.2. LDV particle generator

To measure gas velocities with the LDV technique, small particles (1-5 μm) have to be added to the gas with a particle generator. When the particle generator is applied, the particle concentration (I) in the air will generally depend on air mass flow (m), air pressure (p) and the setting of the inlet valve of the generator.

A series of experiments has been carried out, to investigate the influence of these parameters on the particle concentration. A part of this work comprised the development of optical equipment to determine the relative particle concentration.

From theory, it was found that I is roughly proportional to m x p.

The results of the experiments show the same tendency, although the I vs. m and the I vs. p graphs are curved "lines" instead of straight lines. Possible

causes of these differences were condensation and non uniform sizes of the particles used.
Further details are given in [7].

7.2.3. LDV experiments at the SFCC with commercial equipment; a demonstration

In November Dantec has demonstrated the applicability of LDV to determine cold flow gas velocities in the SFCC.
A description of this demonstration can be found in [8].

7.2.4. Pyrometry

The data acquisition system has been programmed successfully, to convert the pyrometer output signals into colour temperatures. The program uses calibration data, obtained from measurements at a calibrated tungsten ribbon lamp.

8. UTILIZATION

- Solid Fuel Ramjet (SFRJ).

  NLR, PMLTNO and Stork Product Engineering B.V. have issued a draft proposal to investigate the potential of (solid fuel) ramjets for launcher propulsion. This draft proposal has been discussed with NIVR and DWOO, who, in principle, were very interested. A final proposal, ready for submission to NIVR and DWOO, is expected to appear around mid January 1988.

- SFCC testfacility.

  IMI, Summerfield, has used the SFCC testfacility for a period of 2 weeks. Further use of the SFCC testfacility by IMI is expected around mid 1988.

- Sonic Control and Measuring Choke (SCMC).

  In principle, Dinfa is interested in manufacturing the SCMC (including the servo control mechanism). However, the actual manufacturing of the SCMC depends on whether a customer can be found. To our information, Unilever Research has shown interest in the SCMC and is presently conducting an investigation on the applicability of the SCMC in the process industry.

9. USER'S COMMITTEE

The User's Committee convened for the eleventh meeting on Tuesday, December 15, 1987 at PMLTNO.

The following committee members were present:

FAEDUT	H. Wittenberg (project leader and chairman of the committee)
STW	F.C.H.D. van den Beemt (secretary of the committee)
PMLTNO	H.J. Reitsma
PMLTNO	H.J. Pasman
Kon. Mij. 'de Schelde", B.V.	J.H.C. Hoefnagels
FAEDUT	J.A. Steketee
FAEDUT	H.J. Bos
ESTEC	H.F.R. Schöyer
TNO MT	A. Verbeek
Stork Product Engin. B.V.	G.K. Troost

In addition, several members of the SFCC project group were present:
P.A.O.G. Korting (principal investigator PMLTNO)
B.T.C. Zandbergen
T. Wijchers
P.J.M. Elands
R.P. van den Berg
F. Dijkstra
J.P. de Wilde

The following topics were presented and reviewed:

- Status and planning of the project : H. Wittenberg
- LDV, an evaluation of ... : T. Wijchers
- PE, a comparison of experimental and theoretical data : P.J.M. Elands
- Fuel pyrolysis : J.P. de Wilde
- Combustion experiments : F. Dijkstra

The committee, in general, agreed with the work. The few questions that were raised during the meeting were discussed to the satisfaction of the participants, see also chapters 11-13. Furthermore, with respect to LDV, it was advised by the User's Committee to visit dr. Veefkind of TUE who has performed many experiments using LDV, see Contacts (chapter 10).

10. CONTACTS

For this period, the following contacts can be listed:

Institute	Persons	Subject
Technion, Haifa, Israel	Prof. Y.M. Timnat	Solid Fuel Ramjets
Cornell University, USA	Prof. de Boer	Combustion of waste material
Kon.mij. "de Schelde" B.V., Nucl. Eq. Div.	Ir. Huisman Ir. J.C. Hoefnagels Ing. J.E. Meyers	Combustion research
DFVLR, BRD	Prof. Sternfeld G. Schulte	DEA-BRD
Dinfa	Ir. Kluvers	SCMC prototype
IMI, Summerfield, GB	Dr. G. Owen Dr. P. Boszko	Testing of Ducted Rocket Motor in SFCC testfacility
LIOC	Drs. Flamman	SCMC License
Instituto Superior, Tècnico, Portugal	Prof. M.N.R. Nina Dr. M.G.M.S. Carvalho Prof. J.C. Pereira	Joint research program on combustion
TUD Fac. der Wiskunde & Informatica	Prof.dr. A.E.P. Veldman	Numerical modelling

Institute	Persons	Subject
Naval Post Graduate School, California, U.S.A.	Dr. D.W. Netzer	Combustion modelling and Fuel pyrolysis
Lab. for Computational Physics and Fluid Dynamics, NRL, Washington, U.S.A.	Dr. J.D. Baum	Flow and combustion modelling (consultant request)
NWC, California, U.S.A.	Dr. K. Schadow	Joint research program on combustion
Sverdrup Technology Inc., Tenessee, U.S.A.	A.Shabayek	Combustion modelling
Ohio State University, Ohio, U.S.A.	Dr. R.H.Essenhigh	Fuel pyrolysis
Capital Systems Group, Inc. U.S.A.	P. Eiblum	Measurement equipment and testfacility
Heidemij Uitvoering B.V.	Ing. A.C.M. Groenendijk	Combustion experiments on compressed moor material

In addition, as advised by the user's committee, contacts were established with dr. Veefkind. However, it was found that the LDV set-up had already been taken away years ago. Fortunately, the set-up has been briefly described [9]. This showed that only one velocity component in a quite narrow velocity region had to be determined, an extremely simple (but useful) set-up was used. In literature, many examples of similar instrumentation can be found. For velocity determinations in an SFCC with expected velocities ranging between 10-250

m/s, an equipment yielding useful results at (much) worse S-N ratios than encountered with the above mentioned equipment, is needed.

11. STATUS OF THE PERIOD JULY-DECEMBER 1987

In this chapter, the status of the period July-December 1987 is summarized. In addition to the planned program [10], work has also started on the final development of the Ultra Sonic Pulse-Echno Technique (USPET) which, in contrast to the presently available techniques, allows for the instantaneous measurement of the (local) regression rate in an SFCC.

During this period, the SFCC project group has furthermore published 4 reports, presented 3 presentations and 1 publication was accepted in an international journal. For further information see chapter 14.

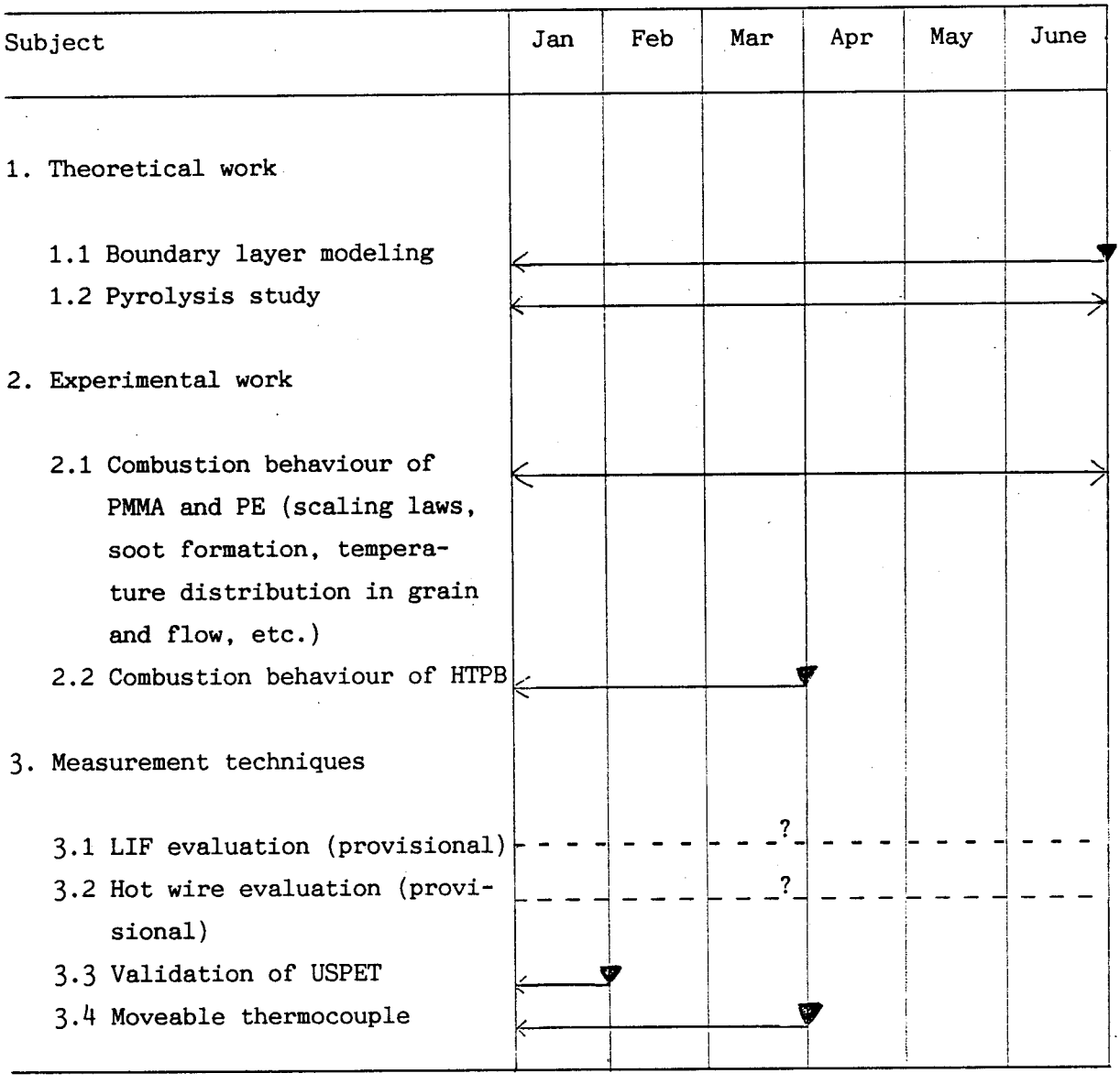
Subject	Status
1. SFCC Experiments	(See also section 7.1)
1.1. Combustion behaviour of polymers: PMMA, PE and PS	Many experiments have been performed to investigate the combustion behaviour of polymers with varying: - aft mixing chamber length (PMMA) - inlet geometry (PMMA) - oxygen content in inlet air (PMMA) - pressure (PE) - mass flow (PE) - pressure and mass flow at elevated air inlet temperatures (PMMA, PE and PS)
1.2. Combustion behaviour of HTPB	Initial experiments on HTPB
1.3. Combustion of moor materials	Experiments on combustion of moor materials have been reported to Heidemij.

Subject	Status
1.4. Ignition characteristics of PMMA	The ignition characteristics of PMMA have been determined as a function of mass flow and stepheight to bore diameter ratio
2. Experimental techniques	(See also section 7.2)
2.1. Laser Doppler Velocimetry (LDV)	Final evaluation report in preparation
2.2. Validation of USPET	In progress
2.3. Extension of USPET	In progress
3. Experimental facility	Operational/no modifications
4. Theoretical work	(see also chapter 8)
4.1. Coupling between heat flux and regression rate	Accomplished
4.2. Calculations with COPPEF	Regression rate is calculated as a function of oxydizer mass flow, stepheight/-bore diameter ratio, surface temperature of the propellant, heat of gasification, turb. Prandtl number and the Von Karman constant.
4.3. Modelling of aft mixing chamber	In progress

Subject	Status
4.4. Pyrolysis study	Definition phase A report on the pyrolysis of PMMA is in preparation
5. Computing	
5.1. Testing of COPPEF on different computers to compare computing time	COPPEF has been tested on Cray XMP-24, Convex C1 and IBM 3083 JX1. Results will be published in journal "Supercomputer"
5.2. Convergence problems of COPPEF	Under investigation

12. SHORT TERM PLAN, PERIOD JANUARY-JUNE 1988

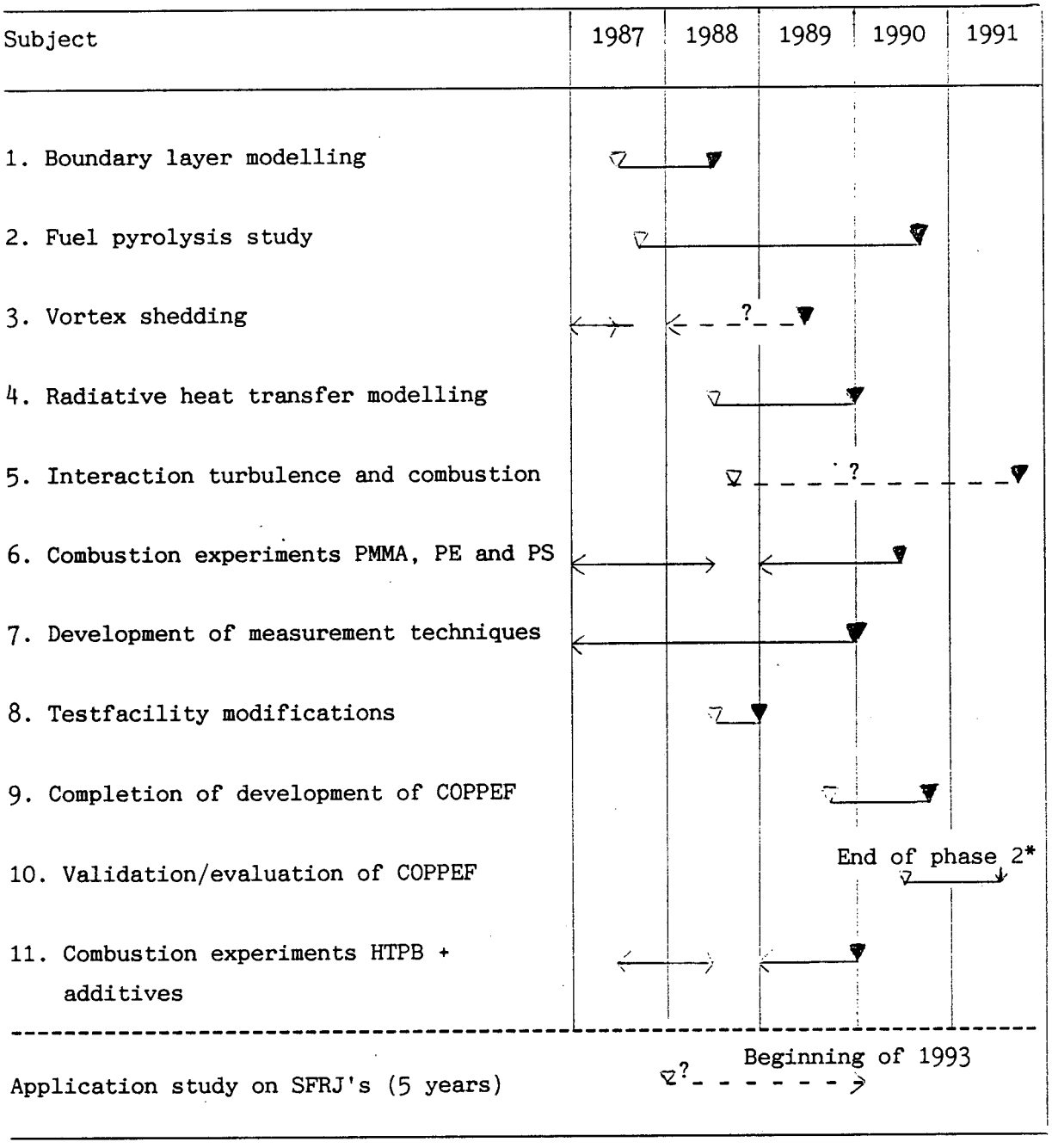
This Chapter presents an outline on the planned program for the period January-June 1988. This plan was discussed in concept at the eleventh meeting of the user's committee on December 15, 1987. In general, the plan was agreed except that the decision to evaluate LIF was postponed until more clarity exists on the use of 1D-LDV, instead of 2D-LDV, for the validation of the COPPEF (cold)flow model. In addition, it will also be tried to extend spectroscopic measurements.



Subject	Jan	Feb	Mar	Apr	May	June
4. Other activities						
4.1 Study on convergence problems COPPEF						
4.2 DEA US						
4.3 DEA BRD						
4.4 Combustion behaviour of HTPB + additives (application study)						

13. LONG TERM PLAN FOR THE SFCC PROJECT (PHASE 2)

In this Chapter, an updated plan for the SFCC project (phase 2) is given. This plan has been discussed at the eleventh meeting of the user's committee. In general, the committee agreed with the plan.



*) Excluding interaction turbulence and combustion.

14. PUBLICATIONS AND PRESENTATIONS

SFCC publications

1. SFCC no. 42
   LR-514
   PML 1987-C18
   "Combustion of PMMA, PE and PS in a ramjet", by C.W.M. van der Geld, P.A.O.G. Korting and T. Wijchers, April 1987.

2. SFCC no. 46
   LR-524 A/B
   PML 1987-C144
   "Beschrijving van een computerprogramma voor de verwerking en analyse van VBVK-metingen", Part A and B, by G.C. Klein Lebbink, December 1987.

3. SFCC no. 47
   LR-528
   PML 1987-C103
   "Gebruik van het gastoevoersysteem en de vitiator voor de vaste brandstof verbrandingskamer", (limited distribution), by P.A.O.G. Korting, August 1987.

4. SFCC no. 48
   LR-530
   PML 1987-C123
   "Ontwerp van een pyrometer t.b.v. temperatuurmetingen aan de vaste brandstof verbrandingskamer", by W.J.A.M. Aarts and T. Wijchers, October 1987.

Publications in Journals

1. "Calculating Turbulent Reacting Flows Using Finite Chemical Kinetics", by J.B. Vos, AIAA Journal, vol. 25, No. 10, October 1987, pp. 1365-1372.

Presentations

1. "A theoretical investigation of the flow and combustion in a solid fuel combustion chamber", by P.J.M. Elands and J.B. Vos, presented at the Combustion Institute: International Specialists' Meeting on Solid Fuel Utilisation, July 6th to 9th, 1987, Lisbon, Portugal.

2. "Combustion of PMMA, PE and PS in a ramjet", by C.W.M. van der Geld, P.A.O.G. Korting and T. Wijchers, presented at the Combustion Institute: International Specialists' Meeting on Solid Fuel Utilisation, July 6th to 9th, 1987, Lisbon, Portugal.

3. "A numerical technique to calculate reacting flows using finite rate chemical kinetics", by J.B. Vos, presented at the 7th GAMM conference on numerical methods in fluid dynamics, September 9th-11th, 1987, Louvain la Neuve, Belgium.

15. REFERENCES

1. Project proposal "Investigation of a Solid Fuel Combustion Chamber (second phase)"; report LR-470/PML 1985-C46, FAEDUT/PMLTNO, Delft/Rijswijk, July 1985.

2. Vos, J.B.,
The Calculation of Turbulent Reacting Flows with a Combustion Model Based on Finite Chemical Kinetics; Ph.D. thesis, Delft University of Technology, April 1987.

3. Wilde, J.P. de
The (effective) heat of gasification of polyethylene and polymethylmetacrylate; Memorandum (in preparation).

4. Geld, C.W.M. van der, Korting, P.A.O.G. and Wijchers, T.
Combustion of PMMA, PE and PS in a ramjet; report LR-519/PML 1987-C18, FAEDUT/PMLTNO, Delft/Rijswijk, April 1987.

5. Pearse, R.W.B. and Gaydon, A.G.
The Identification of Molecular Spectra, third ed., Chapman and Hall Ltd. London.

6. Korting, P.A.O.G. and Schöyer, H.F.R.
Determination of the Regression Rate of Solid Fuel Combustion Chambers by means of the Ultrasonic Puls-Echo Technique, Part 1; report LR-453-I/PML 1985-C5, Delft/Rijswijk, April 1987.

7. Dorpema, H.J.
De Deeltjesgenerator, een hulpmiddel bij LDV-snelheidsmetingen; Internal report, FAEDUT/PMLTNO, Delft/Rijswijk, December 1987.

8. Wijchers, T.
Laser Doppler Snelheidsmetingen ten behoeve van het VBVK-project; (Memorandum in preparation), FAEDUT/PMLTNO, Delft/Rijswijk.

9. Vaesen, P.H.M.
Heat and Momentum Transfer from an atmospheric Plasma Jet to Spherical Particles; Ph.D. thesis, Eindhoven University of Technology , Eindhoven.

16. ACRONYMS

COPPEF	COmputer Program for Calculation of (2D) Parabolic and Elliptic Flows
DEA	Data Exchange Agreement
DFVLR	Deutsche Forschungs und Versuchsanstalt für Luft- und Raumfahrt
DUT	Delft University of Technology
DWOO	Direktie Wetenschappelijk Onderzoek en Ontwikkeling
ESTEC	European Space Research and Technology Centre
EUT	Eindhoven University of Technology
FAEDUT	Faculty of Aerospace Engineering, DUT
HDOTNO	Hoofdgroep Defensie Onderzoek (Defense Research Division), TNO
HTPB	Hydroxy Terminated Poly Butadiene
IMI	Imperial Materials Industries
LDV	Laser Doppler Velocimetry
LIF	Laser Induced Fluorescence
TNO-MT	TNO-Maatschappelijke Technologie
NEOM	Nederlandse Energie Ontwikkelings Maatschappij
NLR	National Aerospace Laboratory
NRL	Naval Research Laboratory
NWC	Naval Weapons Center
PE	Poly Et(hy)lene
PMMA	Poly Methyl Methacrylate
PS	Poly Styrene
PMLTNO	Prins Maurits Laboratory, TNO
SCMC	Sonic Control and Measuring Choke
SFCC	Solid Fuel Combustion Chamber
STW	Stichting voor de Technische Wetenschappen (Technology Foundation)
TNO	Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Organization for Applied Scientific Research)
USPET	Ultra Sonic Pulse-Echo Technique
WGS	Werkgroep Gebruik Supercomputers (working group for the use of supercomputers)
ZWO	Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek