Delft University of Technology
Department of Aerospace Engineering

Prins Maurits Laboratory
Organization for Applied
Scientific Research TNO
Rijswijk

Report LR-448
Report PML 1985-C3

# SOLID FUEL COMBUSTION CHAMBER PROGRESS REPORT VI

**Fifth phase, July-December 1984**

**H. Wittenberg**
**P.A.O.G. Korting**
**J.B. Vos**
**J.P.M. Versmissen**
**T. Wijchers**
**J.H. van Dijk**

Delft/Rijswijk - The Netherlands

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CONTENTS

## 1. INTRODUCTION

The fifth phase (July-December 1984) of the Solid Fuel Combustion Chamber Project, DLR 14.0120/PBE 90743.140 is described.
The primary aim of the project is to gain a thorough understanding of the flow and combustion processes in solid fuel grains, which will be achieved by a combination of experimental and theoretical research. The project has been extensively described elsewhere [1] and the scope of the project has remained the same since this publication. SFCC's have a potential for energy conversion systems, coal gasification, 'clean' combustion of waste, aerospace propulsion (ramjets) and possible others.

This project is sponsored by the Technology Foundation (Stichting voor de Technische Wetenschappen STW) and the Project Office for Energy Research (Projectbeheer Energie Onderzoek). In addition, money and manpower is made available by a special funding from DUT (Beleidsruimte) while manpower and computer facilities are provided by DAEDUT and PMLTNO. Also PMLTNO provides the project with funding.

At the end of this report the planned activities for the next half year period (January-June 1985) are outlined.

## 2. FINANCIAL SUPPORT

From the additional amount of 100 kƒ that was intended to be spent for the construction of the large SFCC, only 20 kƒ have been used as the manufacturing of this part could take place at the Central Workshop of DUT.
However, a proper installation of the spectroscopic equipment required more funding than anticipated. A request to spent an amount of 30 kƒ from the remaining 80 kƒ for this purpose has been honoured by STW. The hence remaining amount of 50 kƒ has been returned to STW.

## 3. FINANCES

During the period July-December 1984 te following expenditures have been paid by STW:

| | |
|---|---|
| foreign travel expenses | ƒ 17.167,79 |
| gassupply system | ƒ 19.702,05 |
| small equipment and various components for the test stand | ƒ 34.705,24 |

In addition the following payments have been made by PML TNO but have not yet been submitted to STW for refunding:

| | |
|---|---|
| spectroscopic equipment: | |
| monochromator | ƒ 67.305,-- |
| testroom | ƒ 33.000,-- |
| personal computer | ƒ 35.000,-- |

Moreover a detector for spectroscopy has been ordered by PML TNO amounting 100 kƒ; a request for refunding has been submitted to PEO.

By PML TNO the following expenses for the project have been made:

| | |
|---|---|
| infrastructure testroom for spectroscopy | ƒ 30.000,-- |

By DAEDUT the following expenses for the project have been made on the account of a special funding (Beleidsruimte):

| | |
|---|---|
| foreign travel expenses | ƒ 4.000,-- |
| materials for vitiator | ƒ 13.500,-- |
| materials for large SFCC | ƒ 9.000,-- |

## 4. PROJECT MANAGEMENT

Ir. H.F.R. Schöyer, projectleader, has left the project group on 30 September 1984. He has left DUT to continue his carreer at the European Space Technology Center (ESTEC) of ESA. The projectleadership has been temporarily handed over to prof. H. Wittenberg. It is anticipated that a successor of mr. Schöyer at DAEDUT will join the projectgroup by April 1985.

Since August 1, 1984, Dr. T. Wijchers has been added to the projectgroup as a flame spectroscopist. He is employed by DUT (funded by STW).

## 5. HIRING OF PERSONNEL

During this period, a request for a technician to maintain the gassupply system has been submitted to the Department of Labour and Social Affairs. Within the socalled WVM-program this department occasionally offers unemployed people the possibility to work in a non profit organization for a period of 12 months.

The above mentioned request has been honoured and it is anticipated that a technician will be added to the project group by February 1985 for one year. He will be employed by PML TNO but charged to the Department of Labour and Social Affairs.

Some money has been made available by PML TNO to hire an apprentice for making pyrometric studies. Although announcements have been made in several student newsletters, to date no candidate has been found.

## 6. LIST OF PEOPLE INVOLVED IN THE SFCC PROJECT DURING THE PERIOD JULY-DECEMBER 1984

In addition to people employed by DAEDUT, PML and ZWO the following people have contributed directly to the project:

| | |
|---|---|
| H.N. van Reenen | Apprentice MTS-Den Haag, August 15, 1983 - September 14, 1984, Testing of Gassupply system Calibration of SCMC's. |
| F.H. van der Laan | Student assistent DAEDUT, Data reduction of experiments. |
| M.I.P. van Lent | Apprentice HTS-Haarlem, August 15, 1984 - November 30, 1984, Support flow modelling. |
| F.J.N. Ronday | Apprentice HTS-Haarlem, August 13, 1984 - November 30, 1984, Calibration of SCMC's. |
| H.G.D. Warmink | Apprentice HTS-Zwolle, August 15, 1984 - February 28, 1985, Development and testing of software for gassupply system. |
| A. Israeli | Student Technion, Haifa, August 1, 1984 - September 10, 1984, Support flow modelling. |
| E.J. Zwolsman | Apprentice HTS-Haarlem, December 1, 1984 - February 28, 1985, Support flow modelling. |
| A. Verburg | Apprentice HTS-Amsterdam, December 1, 1984 - February 28, 1985, Support spectroscopic experiments. |

Mr. V. Kramers in partial fulfillment of the requirements for his engineering degree (HTS) is designing a windtunnel to be connected with the gassupply system to allow freejet testing of SFCC's in the future.

In this period, Mr. J.J.T. Kops passed his exam for the engineering degree (DUT). He calculated a PMMA-air diffusion flame, including finite chemical kinetics.

## 7. THEORETICAL DEVELOPMENTS

### 7.1. Development of a computational model describing the flow through an SFCC

In this period the final version of COPPEF (a Computer Program for calculating 2-dimensional Parabolic and Elliptic Flows) became available. The several test programs used to calculate the flows described in the previous progress report [2] are merged into one main program, the print routines are rewritten to a more economical form, and routines which control the iteration process have been written. These latter routines are able to terminate the iteration process if convergence is reached, and are also able to terminate the iteration process if divergence occurs. To avoid errors in providing the input of COPPEF, an interactively input program has been developed. By means of a list of questions, the input for the main program can be given, and at every stage it is possible to correct a given answer.
During this period attention has been given to the development of an interpolation scheme which read data from a previous calculation with a coarse gridsystem from disk and transforms it to the initial guess for a calculation with a finer gridsystem. By using this interpolation scheme the number of iterations necessary to obtain a converged solution will be smaller than without using the interpolation scheme. When developing this interpolation scheme problems have been arisen because, due to the very strong gradients of some variables, an accurate polynomial fit could not be made. This problem is still not overcome.
Much attention has been given to reducing the amount of CPU-time COPPEF requires. Test runs made on the Cray-1 supercomputer of Shell laboratories in Rijswijk (see also Section 7.2) showed that some routines could be written more economically. Furthermore, a convergence accellerator has been implemented, resulting in some cases in a decrease of the number of iteration cycles necessary to obtain a converged solution.
Calculations of a turbulent recirculation flow showed that it was possible to obtain a velocity profile that is in very close agreement with the experimental found profiles, Fig. 1. The values of the turbulent kinetic energy however differs much from these experimental data, see Fig. 2. This is in agreement with calculations made by other people using the same turbulence closure model, and is caused by the Boussinesq approximation incorporated in the k-$\varepsilon$ model which assumes isotropic turbulence.

### 7.2. Supercomputers

As mentioned in the previous progress report [2], testruns with COPPEF were made on the Cray-1 supercomputer. These testruns showed that, after several modifications, an acceleration by a factor 10 in CPU time was possible. Some of these modifications should also lead to a more economical performance on the Amdahl and have been implemented in COPPEF. With these modifications, the acceleration factor on the Cray-1 decreased until 7.
A study of the most time consuming routines showed that it was possible to modify them as to allow for vectorisation, without increasing the amount of CPU-time on a scalar computer. A new serie of testruns were made with the modified version of COPPEF on both the Cray-1 and the Cyber-205. These testruns showed an acceleration by a factor 11 on the Cray-1, and by a factor 4 on the Cyber-205, without making any modifications to the program. Larger acceleration factors seem to be possible, but depend on the flow problem to be calculated. Costs of using the Cray-1 supercomputer are estimated to be ƒ 2.500,-- per CPU-hour (ƒ 1.200,-- for using the Cray-1 and ƒ 1.300,-- for using the facilities of ENR), provided that a grant from the 'ZWO-werkgroep gebruik supercomputers' will be obtained. A request for a support totalling 10 CPU-hours has been forwarded

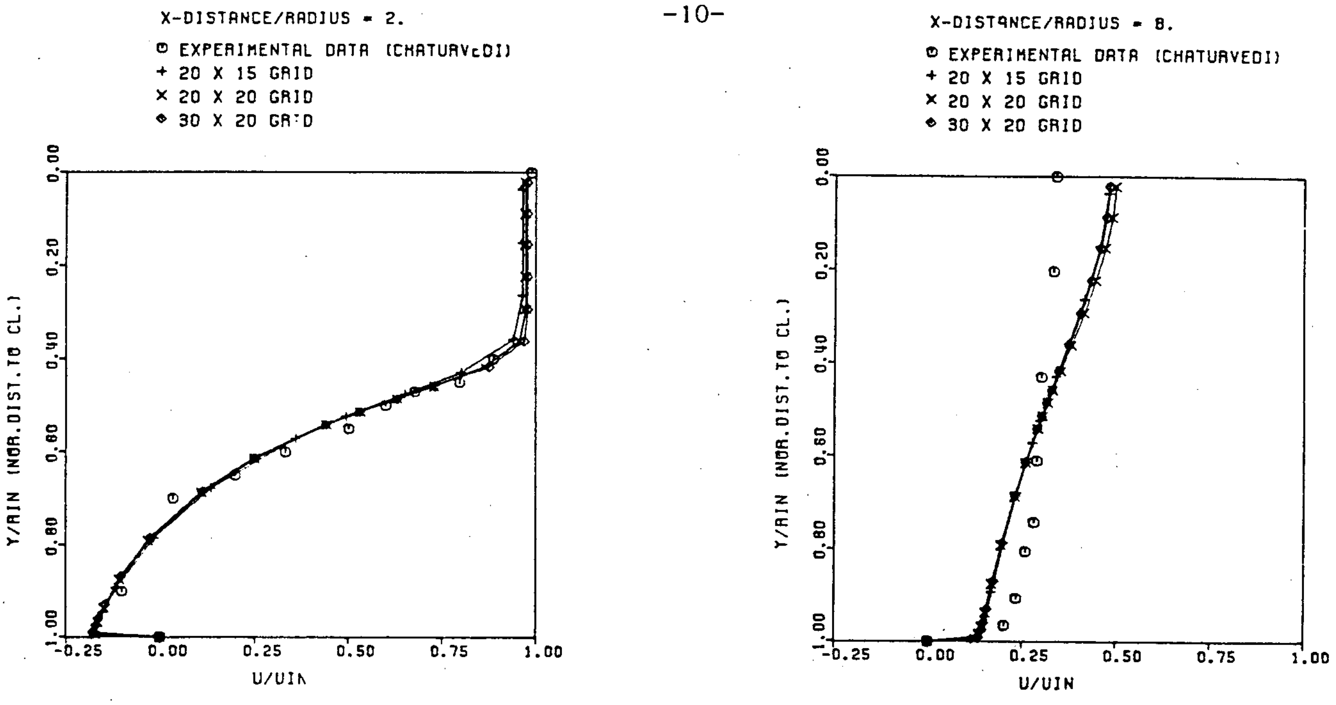


Figure 1: Calculated and experimental velocity profiles at 2 x-locations.

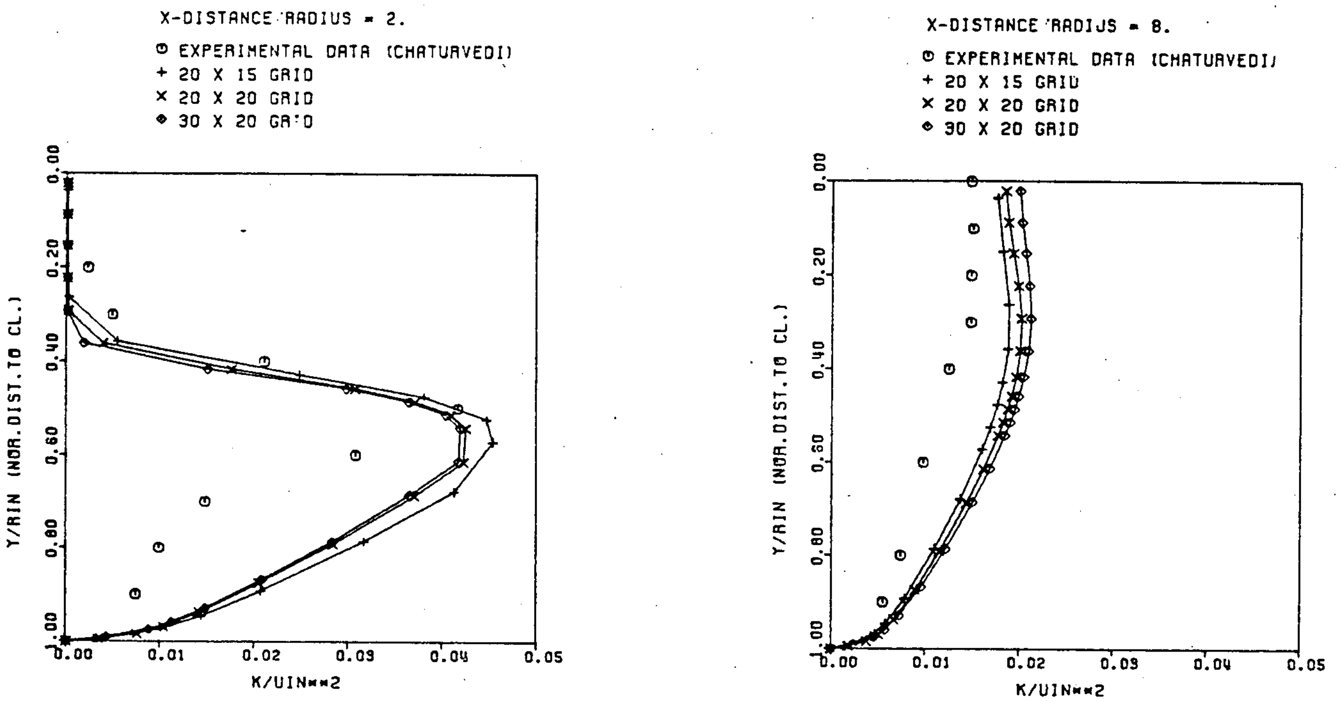


Figure 2: Calculated and experimental profiles of the turbulent kinetic energy at 2 x-locations.

to the chairman of the 'ZWO-werkgroep'. With respect to the remaining costs (25 kƒ), see chapter 11.

## 7.3. Combustion

The combustion processes in an SFCC may be described as a turbulent combustion with non-premixed reactants. It may be assumed that the combustion processes in the recirculation zone differs from the combustion processes in the developing shear layer region.
A literature study showed that there is no combustion model available which is said to work satisfactorily in all cases. Furthermore, a combustion model that accounts for the different combustion in the recirculation region and in the developing shear layer does not exist. The most followed approach to model combustion is using probability density functions, but there exist several forms of probability density functions, and there is no favourite choice of it.
One of the reasons there is no general combustion model available is the extremely complicated nature of the combustion processes, and the complicated nature of the interaction between turbulence and combustion.
In an SFCC, air is fed into the motor through the inlet. Near the wall mixing between fuel and air will take place. This mixing is assumed to be a turbulent process. On a molecular scale, air and fuel diffuse into each other, and combustion may take place, depending on the temperature of the gases. As can be seen from this brief description, several time or length scales play a role in this process, and all these time or length scales have to be modelled in a model describing the turbulent combustion.

## 8. EXPERIMENTS

### Combustion of PE and PMMA with $N_2$-$O_2$ mixtures

In cooperation with Prof. Y. Timnat from Technion Haifa, guest professor at DUT for a period of 10 months, the analysis of combustion experiments using the small SFCC has been continued. The results will be used as a guideline for test-programs with the new large SFCC.

It is anticipated that a report with the results of the experiments with the small SFCC will be available around March 1985.

## 9. STATUS OF THE EXPERIMENTAL FACILITY

### 9.1. Gassupply system

In this period final delivery of the gassupply system has taken place.

It turns out that the gassupply system requires a continuous care for a proper functioning. As already mentioned in chapter 5, a technician will be added to the projectgroup who's main task will be the maintenance of this gassupply system.

### 9.2. Sonic Control and Measuring Choke (SCMC)

The final report about the calibration and the calibration results of the $O_2$-SCMC became available in this period. The final results indicate that the accuracy of this device is better than 2%.
During this period the $CH_4$-SCMC has been calibrated as well. The accuracy of the calibration results was similar to that of the $O_2$-SCMC.

Calibration of the air-SCMC posed difficulties due to an inadequate measurement of the gastemperature in the storage bottles. The first calibration results indicate an accuracy of about 6%.
Improvement can only be obtained by installing thermocouples inside the bottles. This will be accomplished by January 1985. A new calibration program then has to be carried out for the air-SCMC. However it is possible to use the present data for preliminary tests with the vitiator.

### 9.3. Vitiator, three way valve and large SFCC

The SFCC has been delivered by CWDUT by mid July 1984.
As the vitiator, the three way valve and the SFCC contain many specific and interchangeable parts, the various items have been marked to facilitate mounting. Furtheremore detailed mounting drawings have been made while a manual for a proper mounting is being prepared.

As the construction of the test stand for the experimental system whill take more time than anticipated, a preliminary support for the vitiator has been manufactured (see Fig. 3). During this period some preliminary experiments have been taken place with the vitiator, indicating that air with small amounts of oxygen and methane could be ignited by a pilot flame and that combustion is sustained.
During these tests the microprocessor that controls the gassupply systems worked satisfactorily.

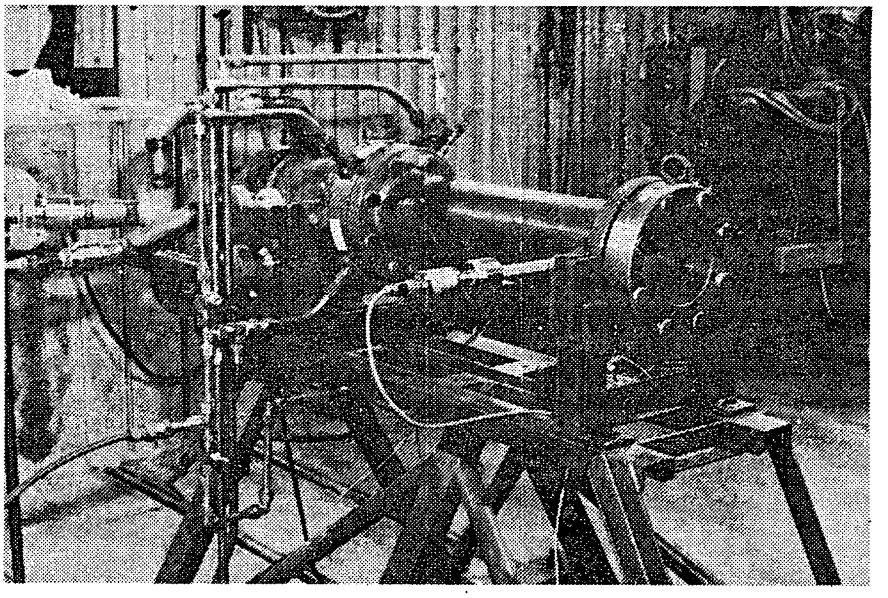

Figure 3: View of the vitiator and its support.

## 9.4. Teststand for the experimental system (including thrust management)

The final construction drawings for the support for the vitiator, three way valve and SFCC became available during this period. Construction of this support has been started but due to the complex nature final delivery will take place not before March 1985.

## 9.5. Control system for SCMC's

A control system for the oxygen supply line has been installed and tested. The results indicate that mass flow control can be achieved by the computer in a proper way. The characteristics of the remaining air and $CH_4$ supply lines have been determined as well; components to install a controll system for these lines have been ordered.

## 9.6. Spectroscopy

To start future spectroscopic observations, the last five months were spent to design an experimental set up and to select and order necessary equipment. Furthermore a program for measurements has been prepared.

A study was made to choose the spectrograph which would meet best the requirements within the budget. The delivery of this instrument (Jobin Yvon THR 1000S) is expected in January 1985.
As detector of this spectograph a MCP intensified diode array (SI IRY 1024(ch)) with controller (ST-110/64) was ordered after a carefull selection of different trade marks. This equipment was delivered by the end of November and has been tested together with the software that was developed by Mr. M.W. Leeuw of PML TNO.

A prefab building, where the spectroscopic measurements will take place, has been erected close to the indoor rocket test stand (Fig. 4). Inside this new building a heave gravite table, on which the spectrograph and supplementary optics will be installed, has been attached firmly to the concrete wall of the indoor rocket test stand via a steel structure.

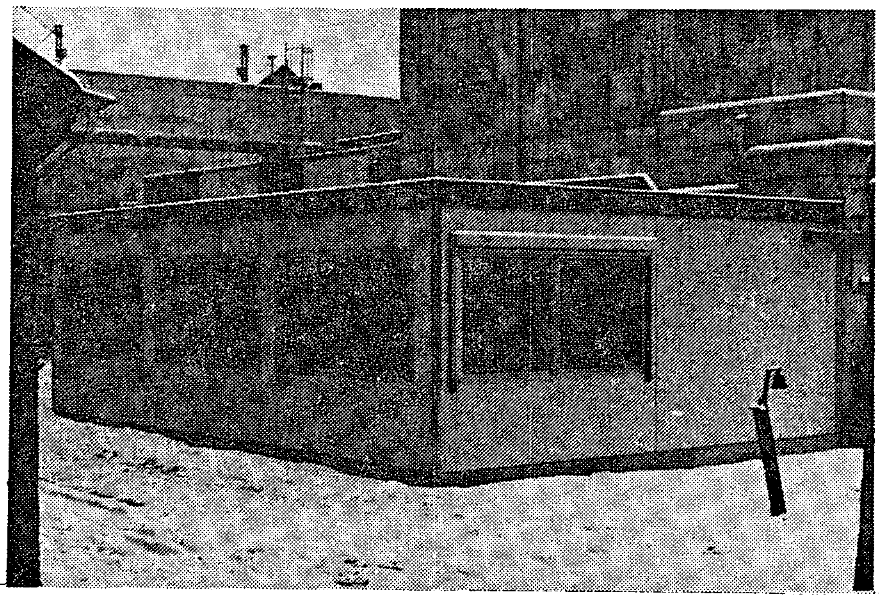

Figure 4: Prefab building for spectroscopic measurements.

A study and following choice has been made for the most efficient and most stable optical set up to transfer the optical signal from the SFCC located in the test stand to the spectrograph. The total optical train between the SFCC and the above mentioned spectrograph consists of 3 or 4 flat mirrors and to achromatic lenses to cover the visible spectrum. For the near ultra violet, optics have been ordered. A program for measurements to test the total set-up and for 'exploratory' measurements at the SFCC has been prepared. The latter part consists of the isoterm, Boltzmann equilibrium approach and of a (much) more complicated shell model approach.

## 10. UTILIZATION

With regard to the reaction from PEO to our proposal (see progress report nr. 4), no reaction has been received.
As indicated in the previous progress report Sproncken BV showed interest in the possible application of the SFCC for solid waste combustion. As has already been pointed out by the projectgroup, at this stage too little knowledge about solid waste combustion in an SFCC is available. Therefore Spronken decided that it is still too early to get involved in this specific technique.
Burning of waste material has, however, the attention of the project group and at the request of the Heidemij it was decided to perform preliminary experiments with organic material. This material has been received from this company and suitable fuel grains have been made by drying and subsequently pressing of this material, see Fig. 5.

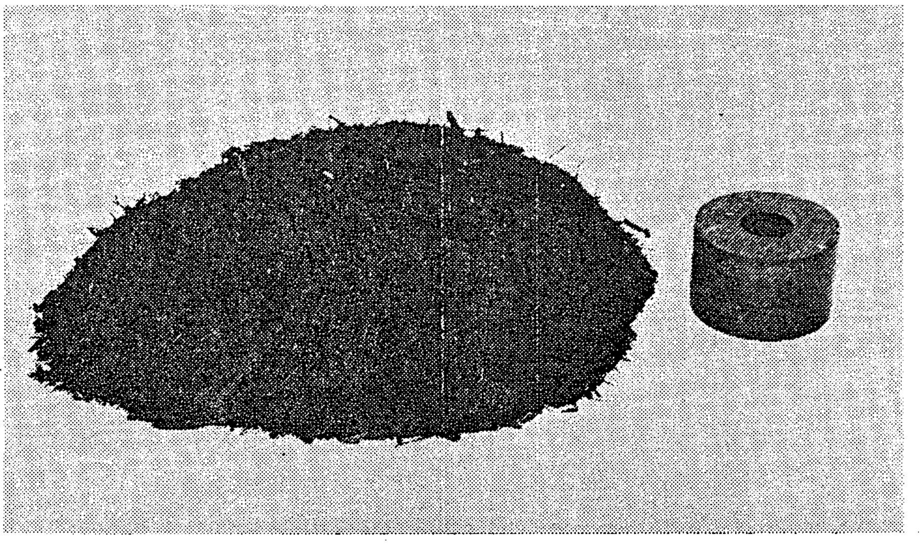

**Figure 5.**

The projectgroup has prepared an article about SCMC's for publication in a Dutch technical journal. In this publication the interest of DINFA is mentioned as a possible manufacturer for such devices.

## 11. USERS COMMITTEE

The Users Committee was convened for the fifth time on Friday, December 21, 1984 at PML TNO.

The following members were present:

| | |
|---|---|
| H. Wittenberg | |
| P.A.O.G. Korting | |
| J.B. Vos | |
| J.P.M. Versmissen | SFCC project group |
| J.H. van Dijk | |
| T. Wijchers | |

| | |
|---|---|
| H.J. Reitsma | PML TNO |
| H.J. Pasman | PML TNO |
| Cdr b.d. R.H. Kerkhoven | TNO |
| C.W. van Koppen | THE |
| J.A. Steketee | DAE DUT |
| R. Roos | NIVR |
| W. Gout | Thomassen International BV |
| H.F.R. Schöyer | ESTECT/ESA |
| F.C.H.D. van der Beemt | STW |
| A. Rijksen | STW |

The following themes were presented:

| | |
|---|---|
| Status of the project | H. Wittenberg |
| Progress on Flow and Combustion Modeling | J.B. Vos |
| Spectroscopy | T. Wijchers |

The Users Committee highly recommended the use of a supercomputer for flowfield calculations. The committee therefore kindly asked STW to honour an additional grant amounting 25 kf that will be submitted by the projectleaders, to allow the projectgroup to continue flowfield calculations on the Cray-1 supercomputer.

Preliminary data for the next meeting will be either on Friday, June 14 or Friday, June 21, 1985.

## 12. CONTACTS

During this period the following contact should be noted.

| Institute | Person(s) | Subject |
|---|---|---|
| DFVLR-Lampoldshausen | G. Schulte<br>A. Kräutner | Joint Research Program on solid fuel combustion |
| KMA, Breda | J.H.J.M. Vriends<br>B.A.F.M. van Hoek | Application study SFRJ |
| IMI Summerfield, Kidderminster | G.I. Evans | Testing of Ducted Rockets |
| NATO HQ, Brussel | DRG | SFCC research in the Netherlands |
| AFRPL, USA | D. George | DFRJ |
| TNO Apeldoorn | A. Verbeek | Combustion |
| DINFA, 's-Gravenzande | W. Kluvers | SCMC |
| ENR, Petten | G. Leendertse<br>H.P. Struch | Testing of flow modeling program on the Cray supercomputer |
| IWIS, Den Haag | S. Geldof | Testing of flow modeling program on Cyber 205 |

Regarding the contact with DFVLR, it was agreed that a cooperation between the research group at DFVLR and the one at DAE DUT/PML TNO would be beneficial for both parties. The DFVLR is mainly interested in the application of SFCC's as propulsion units. The DFVLR has a large test facility in Lampoldshausen and has experience in this field for many years.
Presently a draft proposal for a joint research program is being set up by both parties.

## 13. STATUS OF THE PLANNING PERIOD JULY-DECEMBER 1984

| Planning | Status |
|---|---|
| 1. Calibration $CH_4$ and air SCMC | $CH_4$-SCMC ready; only preliminary results air SCMC |
| 2. Calibration report $O_2$-SCMC | Ready |
| 3. Mass flow control system for $O_2$, $CH_4$ and air supply lines | $O_2$ supply line available, components for remaining lines ordered |
| 4. Design and manufacture thrust stand for SFCC | Design ready, manufacture almost ready |
| 5. Installation of vitiator, shuttle valve and SFCC | Vitiator installed on separate support |
| 6. Testing of vitiator and shuttle valve | Preliminary testing of vitiator took place |
| 7. Testing of software for control gassupply system | On going effort |
| 8. Testing of large SFCC | Nothing done |
| 9. Marking of vitiator and SFCC components. Drafting of mounting drawing | Completed |
| 10. Modification of building for Spectroscopic measurements | Completed |
| 11. Ordering of spectroscopic equipment | Completed |
| 12. Construction of switch panel for simulation unit | Ready |
| 13. Sound velocity versus temperature measurements of PE and PS | Nothing done |
| 14. Report experiments with small SFCC | Nearly finished |
| 15. Report mass flow control system | In preparation |
| 16. Development software for data reduction | Completed, but has to be tested |

17. Theoretical work:

| | |
|---|---|
| - improvement and extensions of existing program | Nearly finished |
| - comparison with various experimental cold flow results | Ready |
| - study of heat and mass transport at the boundaries | Nothing done |
| - selection of a combustion model | Started |

## 14. PLANNED PROGRAM FOR THE PERIOD JANUARY-JUNE 1985

| Subject | Jan. | Febr. | March | April | May | June |
|---|---|---|---|---|---|---|
| 1. Calibration air-SCMC | | — | — | — | | |
| 2. Calibration report $CH_4$ and air SCMC | | | | — | — | |
| 3. Mass flow control system for $CH_4$ and air | | | — | — | | |
| 4. Installation thrust stand with vitiator, three way valve and SFCC | | | — | — | | |
| 5. Testing vitiator, three way valve and SFCC | — | — | — | — | — | — |
| 6. Testing of software for control gassupply system | — | — | — | — | — | — |
| 7. Sound velocity versus temperature measurements of PE and PS | | | — | — | | |
| 8. Report experiments with small SFCC | — | — | | | | |
| 9. Report mass flow control system | — | — | | | | |
| 10. Setting up of an experimental program for the large SFCC | — | — | | | | |
| 11. Experiments with large SFCC | | | | — | — | — |
| 12. Testing of spectroscopic equipment | — | — | — | — | — | — |
| 13. Design of ultrasonic equipment for more than one probe | | | — | — | — | — |
| 14. Theoretical work | | | | | | |
| Selection of a combustion model | — | | | | | |
| Study of heat and mass transport | — | — | — | — | | |
| Extension of computer program | — | — | — | — | — | — |

## 15. PUBLICATIONS

1. H.F.R. Schöyer and P.A.O.G. Korting
Window on science visit USA, March 21-April 22, 1984.
Report LR-426/PML 1984-C25, SFCC Publication nr. 12, April 1984.

2. J.B. Vos
The Development of a Computational Model for a 2-Dimensional Turbulent Flow, Part I: Mathematical Background.
Report LR-436/PML 1984-C52, SFCC Publication no. 13, January 1984.

3. H.N. van Reenen
IJking van een sonische meet- en regeldoorsnede.
Memorandum M-519/Report PML 1984-C58, SFCC Publication no. 15, June 1984.

4. H.F.R. Schöyer and P.A.O.G. Korting
A Sonic Control and Measuring Choke for the Precise Control and Measurement of Gas (oxygen) Mass Flow Rates.
Report LR V-02/PML 1984-C59, SFCC Publication no. 16, August 1984.

5. J.B. Vos
Verslag van het volgen van de cursus 'Numerical Methods in Heat and Fluid Flow', period 18-21 September 1984.
Memorandum M-524/Report PML 1984-C77, SFCC Publication no. 21, September 1984.

6. R.J. van der Wal, P.A.O.G. Korting, H.F.R. Schöyer
Computerprogramma voor het regel/bedieningssysteem van de gastoevoerinstallatie voor de vaste brandstof verbrandingskamer.
Report LR-430/PML 1984-C57, SFCC Publication no. 14, Delft/Rijswijk, July 1984.

7. J.J.T. Kops
Een model voor de verbranding van Poly Methyl methacrylaat in lucht in een laminaire diffusie-vlam.
Report LR-439/PML 1984-C75, SFCC Publication no. 17, Delft/Rijswijk, August 1984.

In addition a paper concerning the present status of the SFCC project in the Netherlands has been presented for the Defense Research Group of NATO at NATO Headquarters in Brussels on 27 September 1984. The contents of this presentation will appear in an SFCC publication.

## 16. REFERENCES


1. An.
   Proposal for the Investigation of a Solid Fuel Combustion Chamber.
   DAE DUT/PML TNO, Memorandum M-395, Delft/Rijswijk, February 1981.

2. H.F.R. Schöyer, P.A.O.G. Korting, J.B. Vos, J.P.M. Versmissen
   Solid Fuel Combustion Chamber Progress Report V; Fourth Phase, January-June 1984, DAE DUT/PML TNO, Report LR-438/PML 1984-C63, Delft/Rijswijk, July 1984.

## 17. ACRONYMS

| | |
|---|---|
| COPPEF | Computer Program for Calculation 2D Parabolic and Elliptic Flow |
| CWDUT | Central Workshop Delft University of Technology |
| DAE DUT | Department of Aerospace Engineering Delft University of Technology |
| ENR | Energie Centrum Nederland Rekencentrum |
| ESA | European Space Agency |
| ESTEC | European Science and Technology Center |
| PEO | Stichting projektbeheerbureau EnergieOnderzoek |
| PML TNO | Prins Maurits Laboratory TNO |
| SCMC | Sonic Control and Measuring Choke |
| SFCC | Solid Fuel Combustion Chamber |
| STW | Stichting voor de Technische Wetenschappen |