Project proposal

INVESTIGATION OF A SOLID FUEL COMBUSTION CHAMBER (second phase)

This proposal requests a follow-on research program of the STW-project DLR 14.0120

Delft/Rijswijk, The Netherlands

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2. PROJECT TITLE

Investigation of a solid fuel combustion chamber (second phase).
3. INVESTIGATORS/STUDENTS

The research on the solid fuel combustion chamber is carried out in cooperation between the Delft University of Technology and the Prins Maurits Laboratory TNO. It started in the first half year of 1982, with support of STW (project DLR 14.0120, formerly DLR 11.0120) and the Management Office for Energy Research (project 90753.140). The principal and second investigators were ir. H.F.R. Schöyer of the Department of Aerospace Engineering, Delft University of Technology (DUT) and ir. P.A.O.G. Korting, Prins Maurits Laboratory TNO (PML-TNO). Mr. Schöyer has left DUT in October 1984 and his task for DUT has been taken over by prof. H. Wittenberg, head of the disciplinary group of which mr. Schöyer was a member.

In the proposed second phase both prof. Wittenberg and mr. Korting will act as principal investigators. Prof. Wittenberg will be assisted in his task by the successor of mr. Schöyer in his disciplinary group (see section 7).

Besides the project team of members of DUT and PML, partly funded by STW, a number of students/apprentices has given assistance to the project over the past years. They are listed in appendix B. For the design, construction and calibration of the gas supply system, and other components, these persons have given a considerable technical support. In addition it was possible to get for one year a technical assistant from a government program for young unemployed persons.

In the proposed second phase this support by students/apprentices will continue in the same manner.

It is anticipated that more students from the Department of Aerospace Engineering will take part in the second phase than in the first one as the experimental facility is now available. Moreover studies on applications of solid-fuel combustion for aerospace vehicles will be performed as thesiswork. Aerospace students, who choose the propulsion option in the aerospace curriculum, are performing their study under the guidance of prof. Wittenberg.

4. DURATION OF THE RESEARCH PROGRAM

The proposed research program of the second phase is estimated to last four years, starting January 1, 1986.
5. SUMMARY

This summary describes the achievements in the first three years of the project, which started in 1982, followed by a short description of the proposed second phase of research.

Until now the gas supply system, solid-fuel combustion chamber (SFCC), thrust-measuring test stand and control room equipment have been designed, constructed and installed. New measuring equipment has been developed successfully: an accurate mass flow meter (Sonic Control and Measuring Choke, SCMC) and an ultrasonic technique for measuring the instantaneous burning rate. Preliminary experiments on a small hybrid engine, which was already available, have been performed to gain experience in test methods and data-handling. The large SFCC will be fully operational by June 1985, including the vitiator to generate high entry temperatures and the spectrometry equipment for temperature and gas composition measurements. In the period June 1985 - May 1986 the first set of experiments with polymethyl-methacrylate (PMMA) will take place.

In the first phase a theoretical investigation of a circular pipe flow with a sudden expansion has been carried out through successive steps: turbulent flow without and with mass/heat addition and without and with chemical reactions. It is expected that this work will result into a doctor's thesis at DUT in 1986.

In the proposed second phase the research project will be continued and can be divided into two main periods:
- in the first period the theoretical and experimental work of the first phase will be continued mainly with the available equipment, including comparison of theoretical predictions with experimental data. Based on the experience gathered, extension of the diagnostic techniques and equipment will be studied;
- The second period will be devoted to the development of design techniques of solid fuel combustion chambers for different types of fuels, depending on the applications to be expected. It is foreseen that the research will have to be supported by additional test equipment of which the purchase has been prepared in the first period.

6. BUDGET

The total cost of the proposed research amounts to kf 3325, excluding costs for personnel to be funded by STW. This amount may be split into parts to be supported by STW, DUT and PML.
From STW a grant totalling kr 1400,- for large investments, materials, computer costs and travel expenses is required for carrying out the project. In addition, a grant from STW is required to employ a research assistant, a spectroscopist and two technicians. In the course of the project, it is anticipated that hiring of a chemical engineer will be proposed by the project group.

<table>
<thead>
<tr>
<th>Budget breakdown</th>
<th>Grant</th>
<th>DUT</th>
<th>PML</th>
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<tr>
<td><strong>1. PERSONNEL</strong></td>
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<tr>
<td>research assistant (Ph.D. candidate)</td>
<td>STW</td>
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<tr>
<td>spectroscopist (senior research scientist)</td>
<td>STW</td>
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<tr>
<td>technician (HTS level)</td>
<td>STW</td>
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<tr>
<td>technician (LTS level)</td>
<td>STW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>computer programmer*</td>
<td>STW</td>
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<tr>
<td>chemical engineer**</td>
<td>STW</td>
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<tr>
<td>staff</td>
<td>STW</td>
<td>400 kf</td>
<td>800 kf</td>
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| **2. INVESTMENTS**                                    |       |     |     |
| air supply system                                     | 200 kf |     |     |
| laser system**                                         | 500 kf |     |     |

| **3. MATERIALS**                                      |       |     |     |
| small equipment                                       | 100 kf | 50 kf | 50 kf |
| gases                                                 | 100 kf |     |     |
| solid fuels                                           | 250 kf |     |     |

| **4. COMPUTER COSTS**                                 |       |     |     |
| use supercomputer (10 hours/year)                     | 100 kf |     |     |
| use of other computers                                |       | 300 kf (RE) | 300 kf |

| **5. TRAVELLING EXPENSES**                             |       |     |     |
| to promote utilization                                | 20 kf  |     |     |
| to visit scientific meetings                         | 30 kf  | 12,5 kf | 12,5 kf |

| **6. RESERVE**                                         |       |     |     |
|                                                       | 100 kf |     |     |

*) It is intended to look for possibilities to finance this position from other sources.

**) A decision will be made during the first period of the second phase.
7. NAMES OF INVESTIGATORS

The two principal investigators, prof.ir. H. Wittenberg and ir. P.A.O.G. Korting will be supported by two senior research-scientists:
- drs. C.W.M. van der Geld, staff-member of the Department of Aerospace Engineering, DUT, from 15 July 1985;
- dr. T. Wijchers, in charge of the spectrometry measurements during the first phase (position funded by STW and continuation of this position requested in this proposal, see section 8.4).

A curriculum-vitae of both scientists is given in appendix C.

In the first phase the theoretical research has got a strong support from prof.dr.ir. J.A. Steketee of the Department of Aerospace Engineering. Prof. Steketee has expressed his intention to continue his support for the second phase. Moreover the Dean of the Department of Mechanical Engineering of DUT has been informed that the principal investigators would like to have the participation in the project of the part-time professor in combustion to be nominated at this Department. The Dean has expressed the interest in the cooperation on the project.

8. DESCRIPTION OF THE PROJECT

8.1. Introduction

This proposal is based on the work performed in the period 1982-1985 on the investigation of a solid fuel combustion chamber.
A full description of the knowledge and experience gained in this period and the test equipment now available is given in section 8.3.

8.2. Scope of the project

The research on solid fuel combustion is directed at two aims:
- to improve the knowledge of combustion phenomena in turbulent channel flows, which is still a rather unexplored field;
- to develop engineering methods to design solid fuel combustion chambers for fuels of different composition.

The first phase of the project from 1982-1985 has brought the project team in a good position to continue its research (see section 8.3). The progress in
numerical methods to solve the problems in the field of aerothermochemistry and the increased capacity of computers (supercomputers) allow nowadays the calculation of the flow and combustion processes in solid fuel combustion chambers. The available test equipment will be used to perform experiments, which can be compared with the results of the theoretical calculations. During the experiments data on instantaneous burning rates will be provided by the ultrasonic measuring technique and spectroscopic data will provide gas temperatures and gas composition at least, the measuring of gas concentrations being the ultimate goal. These experimental data are well suited for comparison with theoretical results. One of the main goals in the validation of the theoretical flow and combustion model is by experiments on small scale. The present test facility is capable to test cylindrical fuel grains with a maximum length of 100 cm at an outer diameter of 20 cm.

For most practical applications (section 9) combustion chambers of larger scale will have to be used. A validated theoretical model will allow to formulate scaling laws for the design of these large chambers.

Moreover, the research proposed will provide:
- knowledge and experience in the testing techniques for the investigation of burning processes in channel flows;
- practical experience in design of solid fuel combustion chambers.

At the end of the second phase the proposed project aims to have gathered the knowledge and experience on which further development of practical applications can be founded.

8.2.1. Experimental work

In the first phase of the SFCC research project, the installation of the gas supply system and its control system, and the design and construction of the vitiator, shuttle valve, large SFCC and thrust stand required more time than anticipated. For this reason, the experimental work until now has been limited to test runs with an existing hybrid rocket motor. The results of these experiments (Ref. SFCC publ. no. 23) have clearly shown the complicated relation that exists between the regression rate behaviour of the fuel (plexiglas and polyethylene) and parameters such as chamber pressure, fuel grain geometry, mass flux and rearward facing step size.

It is anticipated that experiments with the newly built installation will start by July/August 1985. Emphasis will be laid on combustion experiments with the fuels plexiglas and polyethylene and (hot) air, as plexiglas is transparant and
unzips in its monomer during pyrolysis, while, as a contrast, the pyrolysis products of polyethylene consists of many constituents. The research will concentrate upon:

i) the regression behaviour of these polymers in relation to chamber pressure, mass flux, grain geometry, air inlet temperature, burning time and rearward-facing step size

ii) the combustion efficiency

iii) the flammability limits

iv) the structure of the boundary layer and the flow within the SFCC.

The initial test program to be performed is presented in SFCC publ. no. 26.

For subject (iv), use will be made of the spectrographic equipment to obtain information about the chemical composition and the temperature at various locations in the boundary layer. The results will show whether the available spectrographic equipment indeed will be sufficient or that purchase of e.g. a laser system has to be considered to improve the accuracy. It is obvious that the information gained will support not only the theoretical modelling of the chemical reactions in the boundary layer but also the understanding of the flow and combustion processes in the entire SFCC.

As a next step, it will be established to which extent fuel characteristics (melting and pyrolysis behaviour, heat of formation) determine the combustion behaviour by testing various types of fuels. The relevant fuel properties will be determined by chemical analysis (e.g. Differential Thermal Analysis, Gas chromatography). For specific applications of the SFCC technique it is anticipated to develop, and to test other non homogeneous fuels. These fuels may be polymers with additives such as metals for propulsion or toxic compounds like PCB's and dioxines. For this new type of research in this project the project group has to be extended by a chemical engineer.

Finally, as the present test installation is capable to test fuel grains of various sizes, it will be tried to derive scaling laws. It is clear that this can only be accomplished when also a significant progress has been made with the theoretical modelling. Such scaling laws will provide design data for larger chambers, which may reduce the development risks and avoid very expensive test programs on a purely empirical base.

It is obvious that during the experimental work peculiar phenomena may be encountered, which need to be studied in more detail. The experimental program may be altered accordingly. However, the experimental work is aimed to be
performed along the above described program.

8.2.2. Theoretical research

Status at the start of the project (May 1982)

The flow in an SFCC can be described as high turbulent, in which chemical reactions take place in the boundary layer. At the entrance of the combustion chamber a recirculation zone is present, which serves as a flame stabilizer, and at the fuel surface, heat and mass transfer take place. A prediction of this flow can only be obtained by means of computational methods. At the start of the SFCC-project no adequate computer programs able to describe this flow were available.

Theoretical investigations in the first phase (1982-1985)

The theoretical investigation of the flow and combustion in an SFCC has been divided in four successive steps. In the first step, attention has been given to the theory of transport processes in laminar flows, chemical kinetics and turbulence modelling. In the second step a computer program which describes a 2 Dimensional (axi-symmetrical) turbulent flow incorporating a recirculation region has been developed. Although there existed already several computer codes which can describe this type of flow, it was decided to develop a new computer-code independently. This was reasoned by the wish to develop a program, which would allow the required future extensions. Moreover, the latest versions of numerical algorithms could be used in the program. In the third step the computer program has been extended by accounting for heat and mass transfer at the solid boundaries. Furthermore a combustion model will be incorporated in the computer program. No model which describes turbulent combustion satisfactorily is available yet, due to the very complex turbulence-chemistry interaction which is not well understood. The combustion model initially chosen neglects this turbulence-chemistry interaction, and calculates the mass fraction of the several species in the combustion system by means of detailed chemical kinetics. In the fourth step, attention will be given to the turbulence-chemistry interaction.

In summary, the following status of the theoretical investigation by the end of the first phase is expected:
- a computer program will be available which describes a 2 dimensional turbulent flow with heat and mass transport at the boundaries and which includes a
combustion model which calculates the mass-fractions by means of detailed chemistry kinetics;
- an exploratory investigation into the turbulence-chemistry interaction has been performed.
For this work the planned period will last to June 1, 1986 in accordance with the period of employment on STW-funds of the Ph.D. candidate, who performs the research.

Continuation of the theoretical investigation in the proposed second phase
Continuation of the theoretical investigation of the flow and combustion processes in an SFCC is proposed for several reasons. First of all, comparisons have to be made between the theoretical predicted flow properties in an SFCC, and the data from experiments, including spectroscopic measurements. Secondly the study of the turbulence-chemistry interaction has to be continued, and the combustion model has to be modified to account for this interaction. This study will require experimental data from the spectroscopic measurements. Thirdly, the computer program has to be extended to account for radiative heat transfer to the solid walls. In the literature, it has been pointed out that radiative heat transfer may not be neglected, and is important in calculating the total heat flux to the wall. Finally, an investigation in methods of flame stabilisation is necessary to obtain the most efficient combustion process with a minimum of pollutants. Therefore, the computer program might have to be extended to account for a non-zero angular velocity (swirl).

Use of supercomputer
In the first phase of the project experience has been obtained with the use of supercomputers (Cray-1); a grant for 10 hours computer-time has been made available by the Working Group for Supercomputers of ZWO.
In the second phase even more complex numerical problems have to be solved, for which the use of a supercomputer will be indispensable. The computer time required is estimated to be about 10 hours per year.

8.3. Knowledge, experience and available equipment

8.3.1. Knowledge and experience

Before the SFCC research programme started, DAE-DUT and PML-TNO performed
already several joint research projects to investigate the combustion and flow processes in rocket motors. The experience gained from these research programmes formed a good basis to start an experimental and a theoretical programme on SFCC's. Approval of this research programme by the end of December 1981 increased the activities in this field tremendously and made it possible to
(a) design and build a complex computerized gas supply system that is unique in the Netherlands (see Fig. 8.1);
(b) design and build special equipment such as a Sonic Control and Measuring Choke (Fig. 8.2) for the precise control and measurement of gas mass flows, a Vitiation to heat large amounts of air up to high temperature levels (Fig. 8.3), and an Ultrasonic Regression Rate Analyzer to measure the instantaneous local regression rate of the solid fuel;
(c) design and build a large solid fuel combustion chamber with a thrust-measurement stand (see Figure on cover);
(d) develop a theoretical model for describing the flow processes in an SFCC (section 8.2.2), see Figure 8.4.

The progress of this research is described in a number of SFCC-reports, while various publications have resulted from this research. These reports and publications are listed in Appendix A.

A 'Window on Science' visit to the USA, partially funded by the US Air Force, the US Army and the US Navy, allowed to establish new and to renew old contacts with American researchers in this particular field. It also offered the opportunity to be informed about recent developments in the science and technology of solid fuel ramjets. This is the application of the solid fuel combustion chamber which is being developed in the US for the near future. It is expected that a Data Exchange Agreement on solid fuel ramjet propulsion between the government of the US and the Netherlands soon will be signed from which the proposed project will benefit considerably.
Figure 8.1. View on gassupply system for the SFCC research program.
Figure 8.2. View on a Sonic Control and Measuring Choke for the precise control and measurement of the air mass flow. This device is patented.

Figure 8.3. In the vitiator a specific mixture of air, methane and oxygen is burnt in order to obtain an exhaust gas of high temperature and an oxygen content that resembles air.
Figure 8.4. Calculated velocity profile of a flow through a pipe with a sudden expansion. A recirculation area behind the step is clearly observed.

In the course of the project such an agreement has already been established between the governments of Western Germany and the Netherlands. As a result, a joint research programme between the Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt (DFVLR), Lampoldshausen, and the project group has been established to investigate the regression rate behaviour of solid fuels during the first seconds after ignition. It has been found that this initial regression rate is higher than expected and no explanation has been found yet. This cooperative program will be performed if continuation of the SFCC-research in the Netherlands is approved.

The special capabilities of the computerized gas supply system have drawn the attention of IMI Summerfield which is a company in Great Britain that develops and produces rocket motors. Its research department has asked the project group to conduct tests with an experimental ducted rocket motor. This airbreathing rocket engine is presently being developed by the IMI research department and needs upscaling. A test series is planned to be performed by the end of this year on the SFCC-test facility.
In the first phase contributions to the project have and will be given by guest professors temporarily at the Department of Aerospace Engineering of DUT. From October 1, 1984 - June 1, 1985 prof. Y.M. Timnat from Technion, Haifa, Israel contributed to the analysis of hybrid-rocket engine test data (SFCC publ. no. 23) and advised on the SFCC-test facility. From January 1, 1986 - April 1, 1986 professor Nina of the University of Lisbon (Department of Mechanical Engineering) will take part in the experimental work on the SFCC.

8.3.2. Available equipment

The equipment that is already available for the proposed research programme comprises:
- a solid fuel combustion chamber with a large number of diaphragms as rearward facing steps and nozzles of different sizes;
- a computerized gas supply system. This system consists of air, oxygen, methane, hydrogen and nitrogen supply lines. A vitriator allows heating of the air up to 1000 K.
Mass flows are precisely controlled and measured by sonic control and measuring chokes;
- a test rig with force link to measure thrust;
- pressure transducers to measure rapidly varying pressures;
- thermocouples to measure temperatures;
- equipment for radiation measurement for the determination of rapid temperature variations;
- a computer operated spectrograph provided with an intensified multichannel detector for flame spectroscopy;
- ultrasonic equipment to measure regression rates instantaneously;
- registration equipment consisting of cinecameras (up to 10,000 frames per second), photocameras, a video recorder system, ultraviolet recorders with high frequency response and a 14 track instrumentation tape recorder,
- a data-acquisition system including various software programmes to reduce the experimental data.

Computer facilities comprise an IBM 3083-JX1 computer from DUT, and a CYBER 170/835 computer and a VAX 11/750 computer from PML.
8.4. Required additional personnel and equipment

8.4.1. Personnel

For carrying out the proposed research program, the following additional personnel to be funded by STW is requested:

- one senior researcher for spectroscopy and other diagnostic techniques for 4 years. It is proposed to continue the appointment of dr. T. Wijchers, who has shown to be a well qualified and devoted member of the existing project team;
- one research assistant (Ph.D. candidate) for 4 years to continue the theoretical research as a successor of ir. J.B. Vos, who has performed this task during the first phase successfully;
- one engineer with higher technical training (HTS level) for 4 years to carry out the experiments, data-reduction and development work.
- one technician (LTS level) for 4 years for maintenance of the testinstallation. In addition he will assist with calibration work and with the performance of test runs. In the first phase, this technician could be funded only for a limited period (12 months) by a government program of unemployed.

For continuation of this position funding by STW is required.

In addition it is expected that a computer programmer to assist with the theoretical flow and combustion modelling has to be hired. The project team intends to look for possibilities to fund this programmer from other sources (e.g. 'Beleidsruimte' DUT).

In the first period of the proposed second research programme it will be decided whether a chemical engineer has to be hired for 3 years to study the pyrolysis processes and regression rate characteristics of different fuels. A request for funding will be submitted to STW.

The technical and scientific staff of DUT and PML will be available for assistance and additional work. Graduate students and apprentices in partial fulfilment of the requirements for their engineering degree will contribute to the programme. This also has been the case in the present research program, see Appendix B.

8.4.2. Equipment

It is anticipated that new equipment will have to be purchased. This equipment comprises:

- a pump laser with auxiliary optics and a pulsed dye laser;
- extension of the existing air supply system;
- small equipment to measure and to register temperature, pressure, thrust and possibly other parameters.

The specification of the laser equipment is discussed in Appendix D, while the extension of the existing air gas supply system is motivated in Appendix E.

It is planned that purchase of the expensive laser system first will be studied extensively during the course of the research program and that a final decision will depend on experience still to be gathered with the present available spectroscopic equipment. Extension of the existing air supply system is planned to take place as soon as this proposal is approved.
8.5. Time schedule

(\(\downarrow\) decision point by STW)

1. Application period for research candidate, engineer HTS level and technician LTS level

2. Hiring of above mentioned personnel

3. Extension gas supply system

4. Study extension spectroscopic equipment (laser system) and purchase

5. Experimental research programme with polymethylmethacrylate and polyethylene

6. Joint experimental research programme with DFVLR.

7. Study of other fuels for specific applications

8. Turbulence chemistry interaction modelling

9. Comparison experimental results with theoretical prediction, model refinement

10. Hiring of chemical engineer

11. Study of fuel properties in relation to pyrolysis and regression rate behaviour

12. Derivation of scaling laws
9. UTILIZATION

9.1. Introduction

The proposed research programme is a continuation of research which deals with the fundamental aspects of burning solid fuels in the presence of a high pressure, high velocity air flow. Although the principle of the SFCC is very simple, the complicated interaction between the flow and combustion processes in an SFCC needs a thorough understanding of the mechanisms involved before this technique may successfully be applied for aerospace propulsion, waste combustion (toxic materials etc.) and hot gas generation (for study of materials under extreme conditions and power generation). It should be noted however that this type of research sometimes initiates the development of special equipment that might find many more applications in industry, technology and science. Such equipment also can be considered as a valuable spin-off of this research. For instance, within the framework of the first phase research on solid fuel combustion chambers, a device for gas mass flow measurement and control has been built and tested (SCMC). Presently, this device is being patented.

Another example is the ultrasonic regression rate technique to measure the local regression rate of solid fuels instantaneously. From the scientific world there is much interest in this technique. A cooperative program on this measuring technique will be performed in 1986 within the Southern Flank Support Program of the Advisory Group for Aerospace Research and Development (AGARD).

9.2. Possible application and users

9.2.1. Aerospace propulsion

The application of the solid fuel combustion chamber that has the widest interest is the use in solid fuel ramjets (SFRJ's).

Due to the non explosive nature of the fuels to be employed in a SFRJ, its high performance compared to other propulsion system and its development stage, which is still in an exploratory phase, the SFRJ offers a propulsion unit that might be very interesting for the Netherlands Aerospace industry to get involved. The NIVR considers this research important as it will strongly contribute to an increase of knowledge and know-how that can be applied by the Netherlands aerospace industry. FDO (VMF) and Fokker have already expressed their interest in this application.
In other countries, the interest in the SFRJ as a propulsion unit has increased tremendously during the last years.

In the USA two companies, United Technologies Centre/Chemical Systems Division and Atlantic Research Company, are presently developing SFRJ's. This development is strongly supported by research carried out at the Aero Propulsion Laboratory, the Michelson Laboratory, the Naval Post Graduate School, Georgia University of Technology and California Institute of Technology. The Jet Propulsion Laboratory at Pasadena considers this concept (in combination with a hybrid rocket motor) for launch vehicles such as the Space Shuttle.

To our knowledge, research in Western Germany on SFRJ's is only being carried out by the Deutsche Forschung and Versuchsanstalt für Luft und Raumfahrttechnik, Lampoldshausen. To which extent the companies Messerschmidt-Bolkow-Blohm and Rheinmetall are involved in this research is not known. In Sweden, the SFRJ is studied by the Försvarets Forsknings Anstalt near Stockholm. Although ONERA in France is involved in the research and development of SFRJ's, the state of the art is not known due to the highly confidential nature of this work.

As already mentioned, a Data Exchange Agreement (DEA) on SFRJ's between the government of Western Germany and the Netherlands has been established during the course of the present research programme, while it is expected that such an agreement also will be realized with the government of the USA. Such agreements allow not only the exchange of technical information and ideas but also the exchange of scientific staff members. Therefore it is believed that the DEA's will be highly beneficial for both parties involved.

The application of SFCC's in aerospace vehicles will be studied in the course of the project through thesis work by students of the Department of Aerospace Engineering of DUT. In the first phase three students of the Royal Military Academy (KMA, Breda) have performed some preliminary studies. Contacts with ESTEC (Noordwijk) will be continued on this application.

9.2.2. Combustion of waste material

If waste material is processed into suitable grains, the waste material can be burnt, thereby producing high energy gases. These gases may be used for energy generation. As the burning process takes place at high temperatures and high pressures, the combustion products will be relatively clean, while the generation of highly dangerous substances such as PCB's will not take place.
VAM, FDO, Thomassen, Icopower, Heidemij and Comprimo have expressed their interest in this particular application. Due to high combustion temperatures, the SFCC seems also to be an attractive device to burn toxic materials, such as PCB's and dioxines. Contacts have been established with Comprimo on this application.

9.2.3. Hot gas generation

The SFCC technique allows for the generation of high temperature and high pressure combustion gases. These gases may be used for testing of materials under severe thermal conditions. Thermal shock testing and subsequent study of the ablation behaviour of for instance ceramic materials is important for space re-entry vehicles (Hermes) and MHD power generators. Because of the very compact nature of the SFCC combustion technique, another application might be a small high energy power generator to be used in remote and isolated areas for instance for geochemical research. KEMA, FDO (VMF), Thomassen International have expressed their interest in this application.
APPENDIX A

LIST OF PUBLICATIONS
during the first phase (1982-1985)

1. Project proposal, first phase


2. Progress reports


3. SFCC-publications


J.P.M. Versmissen, 'Het ontwerp van een gas massastroom regelsysteem ten behoeve van de gastoevoerinstallatie voor de Vaste Brandstof Verbrandingskamer', SFCC publication no. 19, DAEDUT/PML TNO, Delft/Rijswijk, to be published (in Dutch).


J.B. Vos, J.H. van Dijk, 'The Development of a computational Model for a 2-Dimensional Turbulent Flow. Part II: Description of the computercode and computational results of various pipe-flows', SFCC publication no. 27, DAEDUT/PML TNO, to be published.

4. Publications in journals

In: Intermediair, 18e jaargang 7-19, February 1982 (in Dutch).

An, 'De Vaste Brandstof Verbrandingskamer'.
In: Innovatie, 13e jaargang nr. 55, July 1983 (in Dutch).

An, 'Solid Fuel Combustion Chamber'.

H.F.R. Schöyer, P.A.O.G. Korting, 'Raketmotoren - van vuurpijl tot energie-opwekking'.
In: Natuur en Techniek, 50e jaargang, nr. 7, July 1982 (in Dutch).


To be presented at the IAF Congress, Stockholm, October 1985.

5. Miscellaneous

## LIST OF APPRENTICES AND STUDENTS INVOLVED IN THE FIRST PHASE (1982-1985)

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<td>2. Z. Nadler (Technion, Israel)</td>
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<td>7. H. Albers (HTS-Zwolle)</td>
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<td>description of control system</td>
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Number indicates time period in months
8. J. Hoogkamer (HTS-Haarlem) design SCMC's, design thrust stand

9. E. Koeleman (HTS-Amsterdam) installing and testing gas-supply system

10. J.J.T. Kops (DAEDUT) structure of a PMMA/air flame

11. G. Alton (Technion, Israel) regression rate measurement by ultrasonic technique

12. H. van Reenen (MTS-Den Haag) testing of gas supply system, calibration of SCMC's, experiments.

13. V. Kramers (HTS-Haarlem) performance calibrations, analysis of regression rate data

14. D. Dijkstra (HTS-Amsterdam) preparatory work for patch-boards

15. J. Mosселman (HTS-Amsterdam) regeneration of molecular

16. P. de Witte (KMA, Breda) SFRJ design study
17. M. van Lent (HTS-Haarlem)  
support flow modeling

18. F. Ronday (HTS-Haarlem)  
calibration SCMC's

19. H. Warnink (HTS-Zwolle)  
development and testing  
software for gas supply  
system

20. A. Israeli (Technion, Israel)  
support flow modeling

21. E. Zwolsman (HTS-Haarlem)  
support flow modeling

22. A. Verburg (HTS-Amsterdam)  
support spectroscopic  
experiments

23. C. Schutte (HTS-Zwolle)  
development and testing  
software gas supply system

24. D. Bakkeren (HTS-Haarlem)  
experimental work

25. H. van der Heiden (MTS-Den Haag)  
technical support paid by  
government program for unemployed
APPENDIX C

CURRICULAE VITAE

1. Drs. C.W.M. van der Geld, geboren 21 april 1954.

1972  Eindexamen Gymnasium B
1979  Doctoraal examen, theoretische natuurkunde, Katholieke
      Universiteit Nijmegen (KUN)
1979-80 Assistentchap KUN (wiskunde, natuurkunde)
1980-85 Wetenschappelijk medewerker Technische Hogeschool Eindhoven,
      Afdeling der Werktuigbouwkunde; promotie-onderzoek: twee-
      fasesstroming, theoretisch en experimenteel
      Promotie: september 1985 (prof.dr.ir. C.W. van Koppen,
      prof.dr. G. Ooms)
1982-heden Adviseur Doomernick B.V.

2. Dr. T. Wijchers, geboren 17 februari 1942.

1962  Eindexamen HBS-B (na tussenopleidingen)
1972  Doctoraal examen, experimentele natuurkunde, Rijksuniversi-
      teit Utrecht
1973-74 Leraar natuurkunde
1974-80 Promotie-onderzoek vlamspectroscopie; Rijksuniversiteit
      Utrecht, Lab. Experimentele Fysica
1981  Promotie faculteit der natuurkunde RU (prof.dr. C.Th.J.
      Alkemade)
1981-82 Leraar natuurkunde
1982-84 Werkzaam bij Fysische Afdeling, Laboratorium voor Ruimte-
      onderzoek, Utrecht
1984-heden Wetenschappelijk ambtenaar, TH-Delft, spectrometrie VBVK-
      projekt
APPENDIX D

LASER EQUIPMENT FOR SPECTROSCOPIC DETERMINATION OF TEMPERATURE AND CHEMICAL COMPOSITIONS IN FLAMES

Present equipment

With the present experimental set up, thermal emission spectra of the combustion process in the SFCC are recorded by means of a 1 m grating spectrograph (Jobin Yvon THR 1000 S, 2400 grooves/mm) provided with a 1024 channel intensified diode array detector (SI IRY 1024). The spectra are processed with a personal computer (DEC, professional 350) and with the computer of the Prins Maurits Laboratory (VAX 11/750). Figure D.1. shows a typical spectrum obtained during a test run with the SFCC.

The chemical composition is determined by comparing the recorded spectra with spectra from the literature of molecules which are likely to be present in the flame. The temperature may be derived by using the Boltzmann law, provided that the flame is in thermal equilibrium.

Limitations of the method

Apart from a not-disturbed thin layer of the flame near the surface of the fuel which is in a non-thermal equilibrium state, a temperature gradient in axial as well as in radial direction is expected. In that case only mean temperatures along the optical path of detection may be derived with the present set up.

In principle it is possible to model the flame by dividing it in concentric shells. Each shell is assumed to have such a temperature that the calculated spectra of the probe molecule, taken at various distances from the flame axis, equals the recorded spectra. However this method will produce unreliable plots of the temperature as a function of location, as the temperature differences in a flame are relatively small. Moreover the results are disturbed by density variations of the probe molecules in the various shells along the optical path. Consequently, a precise determination of the temperature as a function of location can not be performed with the present set up.
Spectra of CH during combustion of PMMA/air with vitiator exposure time 1.7 sec.

Figure D1: Typical spectrum of CH at 391 nm during combustion of PMMA with preheated air in a SFCC

Proposed improvements

An experimental set up where Coherent Anti-Stokes Ramann Scattering (CARS) radiation is detected may avoid the problems as described above. At the intersection of an intense pump laser beam and a (weaker) probe dye laser beam, CARS radiation is created which can be detected by the present spectroscopic set up. With a properly tuned wavelength of the probe dye laser, this radiation partially consists of the spectrum of the probe molecule. It should be noted that this radiation is emitted from only the above mentioned intersection and consequently the temperature determined from that radiation, is the local temperature of that small intersection.

An alternative method which requires the same laser equipment consists of recording fluorescence spectra of probe molecules from a small region in the
flame, which is excited by laser radiation. Although proper probe molecules (or atoms) may probably not be present in the flame and therefore may be added to the flame, the alignment of this setup is less critical while the results are comparable with the CARS method.

**Types and costs of laser equipment**

<table>
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<tr>
<th>Equipment</th>
<th>Cost</th>
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<tr>
<td>Pump laser: Nd:YAG pulsed laser (basic)</td>
<td>kf 250</td>
</tr>
<tr>
<td>Auxiliary optics (freq. doubler, wavelength decoupler)</td>
<td>kf 50</td>
</tr>
<tr>
<td>Probe laser: pulsed dye laser</td>
<td>kf 150</td>
</tr>
<tr>
<td>Miscellaneous (high reflective mirrors, high transparent lenses, mounts, dyes)</td>
<td>kf 50</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>kf 500</strong></td>
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APPENDIX E

EXTENSION OF THE AIR GASSUPPLY SYSTEM

The present air supply system has a storage capability of 750 kg of air at a (maximum) pressure level of 20 MPa. As a proper air supply requires a minimum pressure level in the storage vessels of 10 MPa, only 375 kg of pressurized air is available for experimental work. This implies that at a maximum air mass flow of 2 kg/s the maximum operation time is approximately 3 min.

As about 1 min. is required for the vitiator to provide hot air at steady state conditions, the actual test duration during which a solid fuel is burnt in the solid fuel combustion chamber is relatively short. Due to the small capacity (400 l/min.) at the compressor it takes about 12 hours before a new testrun may be performed.

This situation may hamper the experimental program significantly especially where high mass flows are required.

Therefore the following extension of the air supply system is proposed:

10 air storage vessels each 0,36 m³
max. pressure level 20 MPa

kF 75

1 compressor

kF 100

piping and installation

kF 25

Total kF 200

When this extension can be pursued, the storage capacity of pressurized air will be doubled, while it will take considerably less time to compress the air from 10 to 20 MPa in the storage vessels.
THE DEVELOPMENT OF A COMPUTATIONAL MODEL FOR A 2 DIMENSIONAL TURBULENT FLOW

Part II: Description of the computer code and computational results of various pipe flows

J.B. Vos
J.H. van Dijk

Delft/Rijswijk, The Netherlands

April 1985