# A STUDY OF THE COMBUSTION PROBLEMS OF SOLID MATERIALS AT CONDITIONS EXISTING IN SPACE STATIONS

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## ABSTRACT

Combustion of a solid at microgravity conditions at zero or at very small forced flow velocities is in the first place discussed, pointing out that this is the basic process of a fire in a manned spacecraft, in which might exist small air currents originated by the air conditioning equipment or by the motion of the people.

Results of an experimental programme carried out in the 23rd ESA Flight campaign 96/12 and utilising a NASA aircraft laboratory, are shown and discussed.

Six combustion chambers were utilised provided with video and infrared cameras. Non visible flames in the visual range were originated at two oxygen concentrations, and photographs were taken by means of an infrared camera.

Several ignition tests at different oxygen concentrations were performed and flammability limits were obtained.

Flame spread velocities were measured and compared at three different gravity levels (1 g, $\sim 10^{-2}$ g and $10^{-4}$ g).

A combustion research programme to be carried out in a Texus rocket, already in progress is briefly discussed.

Finally, the scope of a complete research programme, which is in the process of being carried out in the NASA combustion module of the International Space Station is briefly resumed.

## 1.- INTRODUCTION

The School of Aeronautics of the Polytechnic University of Madrid, with the collaboration of the engineering company SENER, have been conducting research programmes on the combustion of solids in $O_2$-$N_2$ atmospheres.

The experimental programme has been carried out by means of parabolic flights, three in the NASA KC-135 aircraft laboratory, and one in the ESA Caravelle (refs. 1, 3 and 4). A very relevant part of this experimental programme has been performed in a MiniTexus sounding rocket; launched in the ESRANGE in Kiruna, in 1995, in which twelve experiments were carried out on the influence of forced flow velocities on the combustion of cylinders of polymethylmethacrylate (PMMA). One of the most important findings was the verification of the existence for a 30 seconds period of a non-visible flame in the visual range at zero flow velocity; the flame becoming very rapidly visible when a flow of very low velocity in a direction parallel to the cylinder axis impinges on the flame. These results were published in the First Symposium on the Utilisation of the International Space Stations (ref. 6).

The existence of these non-visible flames had been already observed for short times in drop towers experiments (ref. 2, for example); but not their existence and stability for such a long time as 30 seconds.

In that work it was commented that fires were, and still are, a high risk area in manned spacecraft, and it will become more acute in space travel in which maintenance work will be severely limited.

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The basic process of a fire in a spacecraft is the combustion of a solid at microgravity conditions and at zero or very low convective flow velocities, such as those originated by the air conditioning equipment or by the motion of the people.

When free convection is absent and forced convection is nil or very small, the combustion process is diffusion controlled and become very involved. Since characteristic diffusion velocities are very small (a few mm/s), the combustion process becomes very sensitive to very small values of forced convective velocities, as well as to oxygen concentration values. The combustion rates are very small, and the flames become in some cases non-visible in the visual range.

The theoretical modelling is very complicated, with the result that theoretical solution do not exist except for a very few simple cases (combustion of spherical particles, for example).

A review of the experimental date available and on the state of the problem may be consulted in refs. 7 to 11.

An experimental programme is developed to study this type of combustion processes and to obtain flammability and flame spread rates.

In the first place the programme has been carried out in parabolic flights, and the results of this programme are presented in this work. It will be followed by a Texus programme already approved by ESA. The launching will be performed in the ESRANGE, Kiruna in 1999.

## 2.- PARABOLIC FLIGHTS EXPERIMENTAL PROGRAMME

### 2.1.- Experiments and Test Equipment

The European Space Agency (ESA) launched its 23rd Parabolic Flight Campaign 96/12, which was carried out in the NASA KC-135 aircraft laboratory utilising the Bourdeaux-Mérignac International Airport, France, with the ground help of the Sogerma-Socea installations at the airport.

Two flights were made available by ESA to perform the experiments. The main objective of the programme was to carry out infrared photographs of non-visible flames in the visual range. Another important objective was to perform flammability limits test by burning hollow cylinders at different oxygen concentrations.

Six chambers already utilised in previous parabolic campaigns were used, refurbishing two of them with infrared transparent windows ($CaF_2$), as well as with an arrangement to permit simultaneous photograph of a video camera and an infrared camera.

The six chambers were placed in a semicircular platform. The video camera was located in the centre and rotated after each flight. The infrared camera was arranged to take photographs of the cameras, provided with infrared windows (Fig. 1).

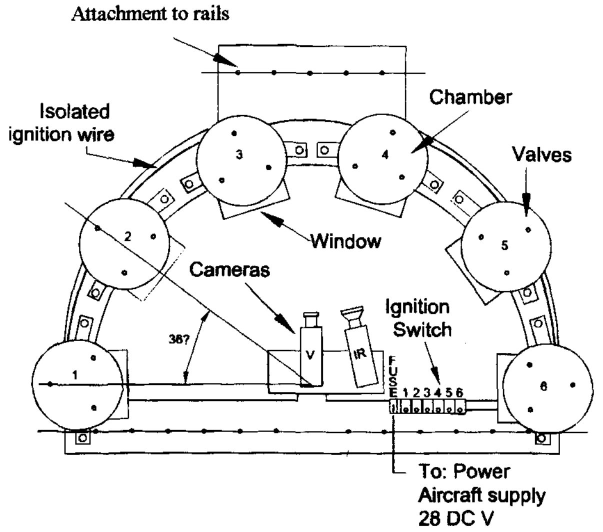


Fig. 1 Test chambers

Twelve experiments were performed, with some additional ignition tests in flammability experiments PMMA hollow cylinders of 6 mm in diameter and wall thickness from 2 to 0.2 mm were utilised. Oxygen mass fraction ranged from 19 to 40%. Pressure was always of 100 kPa and there were no forced convective flow. All the experiments performed are shown in Table I and II.

### 2.2.- Infrared Visualisation Experiments

Two series of non-visible flames were observed simultaneously with video and infrared camera and are shown in Figs. 2 and 3. Oxygen concentration mass fraction was of 21% and 23%, and cylinder wall thickness of 2 mm.

In these experiments, ignition took place before the flight entering at reduced gravity region, and in about 6-7 seconds after ignition or else in 3-4 seconds after low gravity is initiated, the flame becomes non visible. The flame remains in this non visible condition throughout the parabolic flight, becoming again visible once the low gravity concludes. The low gravity period, as usual, was of the order of twenty seconds.

It may be pointed out that for the first time these flames have been observed with infrared cameras.

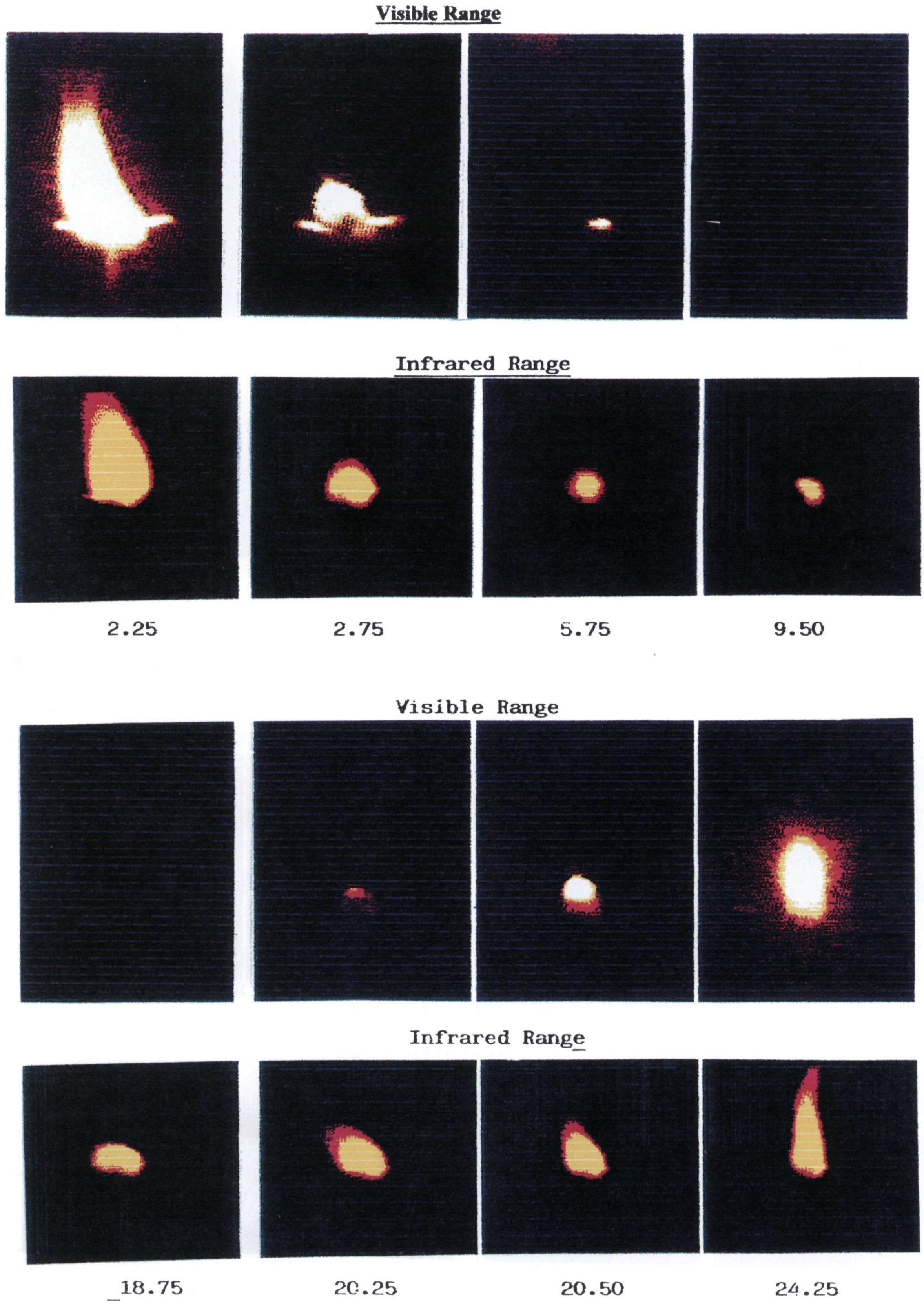


Fig. 2.- Simultaneous video colour and infrared photographs of a PMMA Cylinder burning at reduced gravity. [(Times from ignition (sec)] ($Y_{O2} = 23\%$); (small differences in time of the order of 0.2 s between IR and visible photographs might exist).

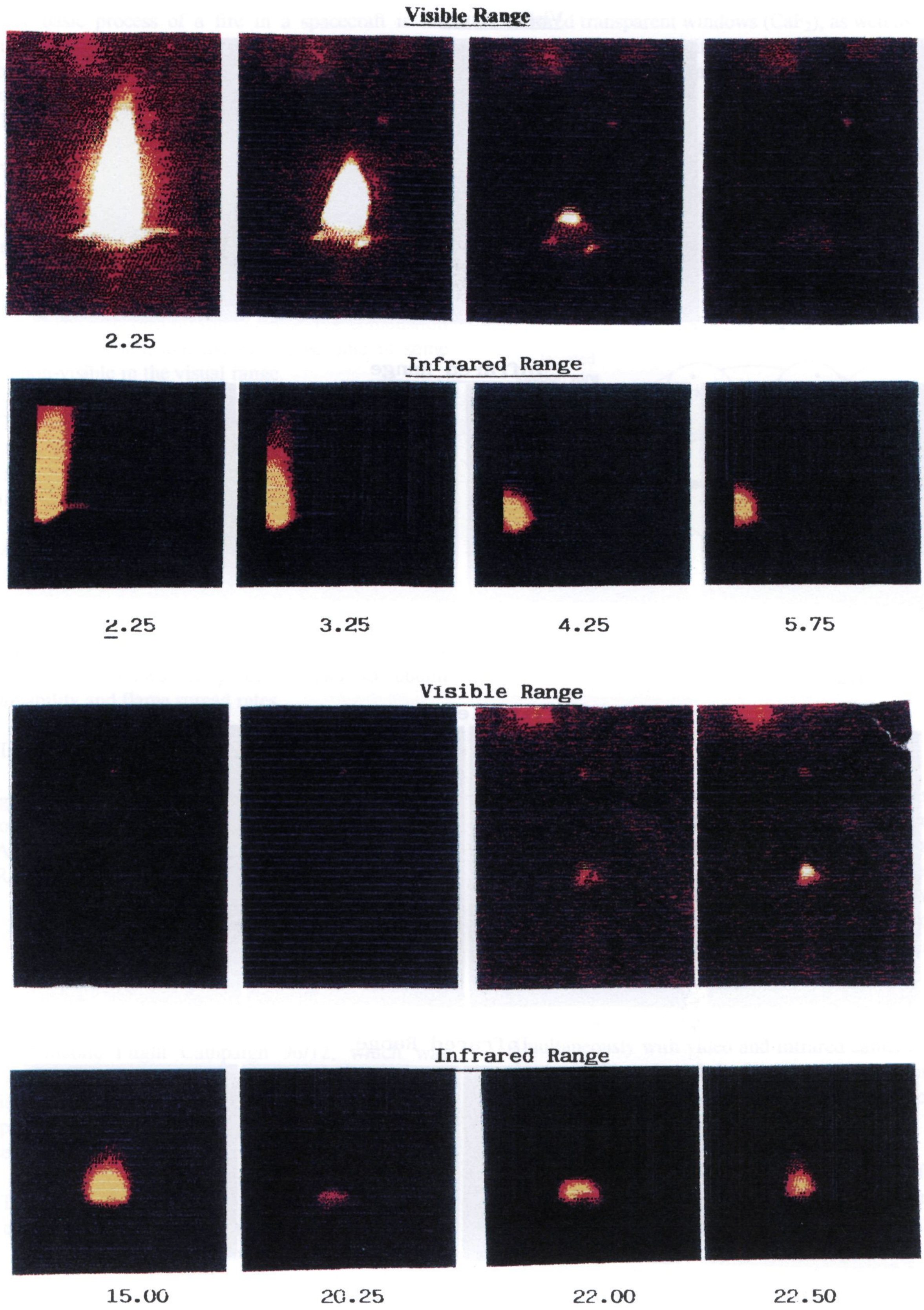


Fig. 3.- Simultaneous video colour and infrared photographs of a PMMA Cylinder burning at reduced gravity. [(Times from ignition (sec)]($Y_{O2}$ = 21%); (small differences in time of the order of 0.2 s between IR and visible photographs might exist).

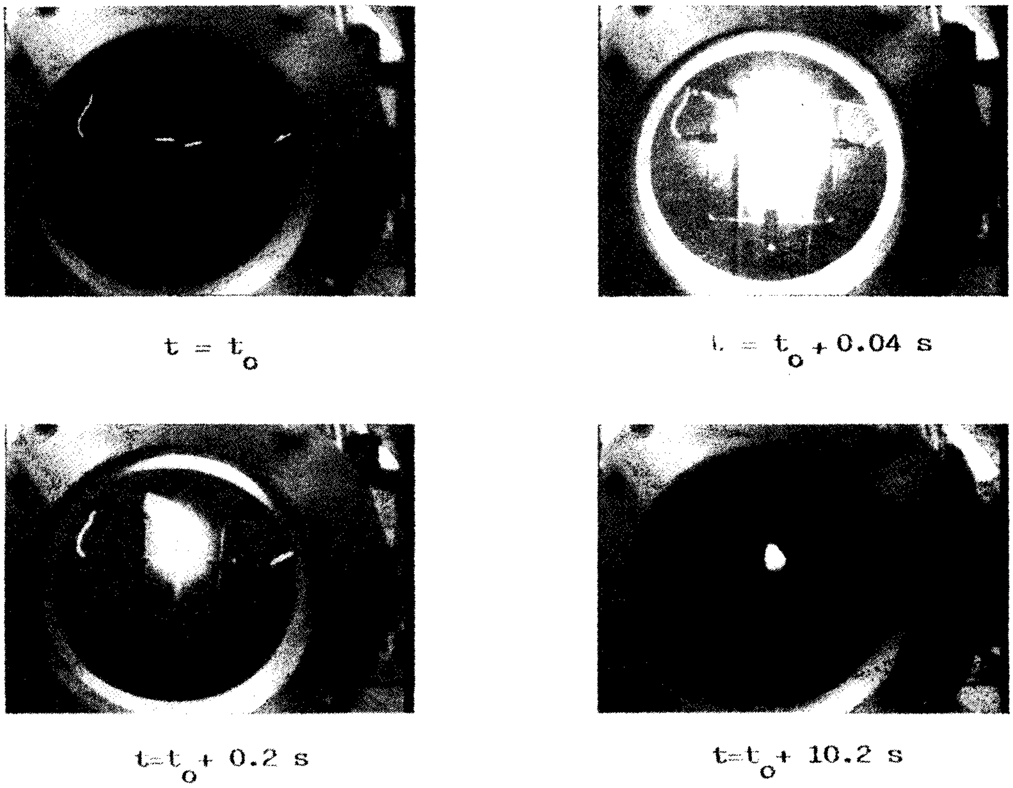


Fig. 4 Ignition and combustion processes. $Y_{O2}$= 40 % , thickness = 2 mm

| Combust. Chamber | Experiment | Remarks |
|---|---|---|
| 1 | 40% $O_2$, 2 mm thick. Reproduction MiniTexus experiment (IR camera) | Visible flame |
| 2 | 23% $O_2$, 2 mm thick. Flame visualisation (IR camera) | Non-visible flame |
| 3 | 40% $O_2$, 1 mm thick. Flame spreading velocity | Visible flame |
| 4 | 23% $O_2$, 0.5 mm thick. Flammability limit | Flaming follows ignition |
| 5 | 23% $O_2$, 0.5 mm thick. Flammability limit | Flaming follows ignition |
| 6 | 23% $O_2$, 0.2 mm thick. Flammability limit | Flaming follows ignition |

TABLE I (Flight No 2)

| Combust. chamber | Experiment | Remarks |
|---|---|---|
| 1 | 19 % $O_2$, 2 mm thick (IR camera) Flame visualisation | Flame extinguish. |
| 2 | 21 % $O_2$, 2 mm thick (IR camera) Flame visualisation | Non-visible flame. |
| 1 | Reigntion tests | Flame extinguish. |
| 2 | Reignition tests | Flame extinguish. |
| 2 | Reignition tests | Flame extinguish. |
| 3 | 19 % $O_2$, 1 mm thick. Ignition tests | Flame extinguish |
| 4 | 21 % $O_2$, 1 mm thick. | Flame spread. vel. measur. |
| 5 | 23 % O, 2 mm thick. | Flame spread. vel. measur. |
| 6 | 23 % $O_2$, 1 mm thick. | Flame spread. vel. measur. |
| 3 | 19 % $O_2$, 1 mm thick. Reignition tests | Flame extinguish. |

TABLE II (Flight 3)

It may be observed that the flame shape become almost spherical, reaching what appears to be a quasi stationary state. Burning rates are very low and difficulties to measure.

An approximate theoretical model is being developed with the aim of explaining the thermal and stability conditions of these flames. Radiation from the flame and from the PMMA surface will be taken into account.

It is important to investigate if these type of non-visible flames, which might present special detection characteristics, might exist in an Space Station at 23% or a somewhat higher oxygen concentrations (up to the maximum values allowed) and at zero or very low convective flow velocities.

2.3.- Flammability Limits and Spread Rates Velocities

No sufficient experiments were available in order to obtain precise value of the flammability limits, and burning rates. The influence of thickness was very limited.

The flames originated by the ignition process and the subsequent onset of the flame spreading process are, in general, very different than those observed in the MiniTexus experiments as shown in ref. 6. This is not only due to the difference in gravity levels ($\sim 10^{-2}$ and $\sim 10^{-4}$), but also to the oscillation of the gravity level in the parabolic flight, quite often of the order of 0.1 g.

However, the following results were obtained:

Flammability limits at 100 kPa for rod wall thickness of 2 mm was of the order of 20% in the parabolic flight ($\sim 10^{-2}$ g) at the ground at 1 g of 18%.

At the same conditions that in the MiniTexus experiment (40% $O_2$, 2 mm wall thickness) the flame was of the normal visible type, as shown in Fig. 4. This shows the important difference of the two gravity levels.

Results of flame spread velocities are shown in Fig. 5, including some results with forced flow velocities. It may be observed the very low values of the spread rate at zero flow velocity and 23% $O_2$, mass fraction when the flame is of the non-visible type.

In Fig. 6 flame spread rates are compared for three gravity levels, showing the very large influence of this parameters.

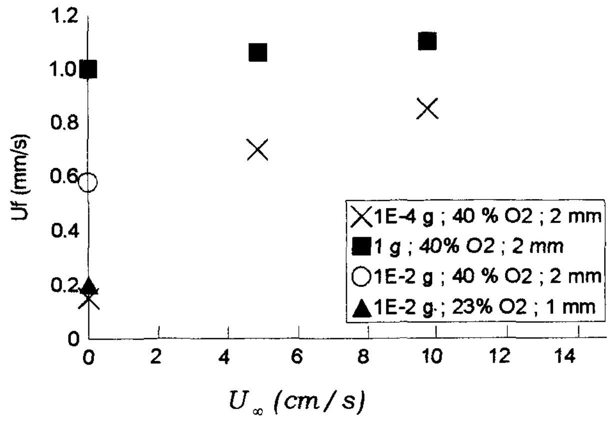


Fig. 5.- Experimental results

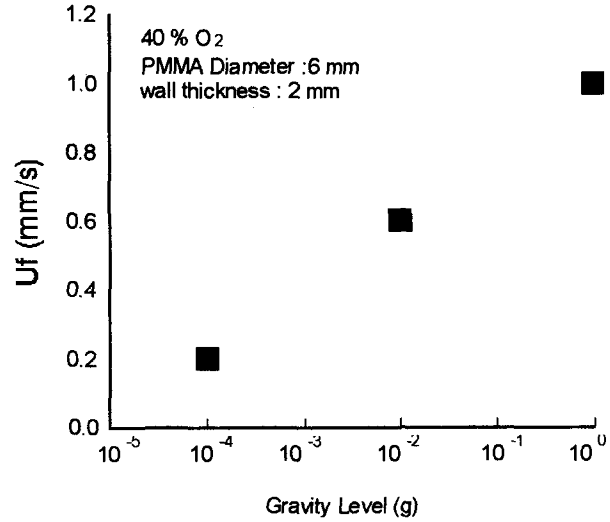


Fig. 6.- Influence of gravity level on flame spread velocities. $Y_{O2}$= 40%, diameter=6 mm, thicknes=2 mm

3.- TEXUS PROGRAMME

An experimental programme sponsored by the European Space Agency to be carried out in a Texus sounding rocket is already in progress.

The experiments are already specified and a preliminary design carried out by the company SENER is already available .

The experiments will be performed with three PMMA hollow cylindrical rods. A video camera and IR camera supplied by ESA will be utilised.

The following experiments will be performed during the 330 seconds microgravity period:

-Measurements of temperature profiles in non-visible flames by means of radially moving thermocouples.

-Flammability limits obtained by reducing continuously the oxygen concentrations at two constant small flow velocities until the flame extinguishes.

-Ignition tests at different oxygen concentrations, at zero and at very small flow velocities at different locations in the rods.

-Measurements of flame spreading velocities.

Launching of the Texus is programmed to take place in the ESRANGE, Kiruna, Sweden, in November 1999.

## 4.- INTERNATIONAL SPACE STATION PROGRAMME

As it has been previously commented a very large matrix of tests is required in order to acquire a sufficient knowledge of the problem of the combustion of solids at conditions existing in a spacecraft, specially if actual materials and configurations are going to be investigated.

A programme of this kind is not practically feasible by utilising only drop towers, parabolic flights and sounding rockets.

The most suitable facility to carry out an extensive research programme of this kind it is an orbital laboratory. At this respect a proposed was presented to NASA, as a response to NR17-97-11EDS-01.

The main scope of the proposed programme is as follows:

-Completion of the research programme on PMMA samples (flammability limits, ignition and flame spread velocities as function of oxygen concentration, forced flow velocities, pressure, configuration and thickness of the samples.

-Research combustion programme (applied) with actual materials in actual configurations.

-Attainment of basic knowledge for possible improvement of fire safety standards.

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