FLAME SPREADING OVER SOLID FUELS AT MICROGRAVITY CONDITIONS RESULTS OBTAINED IN THE MINITEXUS ROCKET AND FUTURE PROGRAMMES

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ABSTRACT

The problem of fires in spacecraft is briefly commented, pointing out that they still are a high safety risk in long endurance manned missions.

It is pointed out that the basic process of a fire is the combustion of a solid fuel in an O_2 N_2 mixture, and that this basic process is not yet well understood. The research programme presented in this paper is a contribution in this field.

Experimental results obtained on flame spreading in the MiniTexus rocket are shown. These experimental programmes have been sponsored by the European Space Agency (ESA).

Ignition and flame spreading over hollow PMMA cylinders in O_2 N_2 mixtures against a forced flow with velocities ranging from zero up to 20 cm/s at zero and at 45° incidence angle are presented and discussed.

Special attention is given to the region of very small flow velocities (0-5 cm/s), in which the flame extinguishes or becomes non visible in the optical range if the fuel is thick or the oxygen concentration is not high. The existence of these flames for a relatively long time have been clearly detected in the MiniTexus experiments. The observations of these flames and their theoretical treatment present special difficulties, which are discussed in the paper.

Future programmes to be carried out in the MiniTexus, already approved by ESA are shown, as well as the possible extension of these research programmes, with the possibility of being carried out in space laboratories.

1. INTRODUCTION

Fires still remain as one of the most important safety risks of long endurance travel or orbital missions of manned spacecraft (1), (2). Therefore, the fire related aspects of combustion are one of the highest priority fields in the study of combustion processes at reduced or microgravity conditions.

A variety of research programmes have been carried out on ignition, spread, detection and suppression of fires in spacecraft. However, flammability standards for the selection of materials for spacecraft are those utilized at one g, in aircraft and in many other applications; and fire extinguishing equipments are also similar to those employed in terrestrial applications.

It is a crucial fact that the basic process of a fire: combustion of a solid in a still O_2 N_2 atmosphere at microgravity conditions is not yet well understood.

It is known that the flames are of low visibility spreading very slowly, and that flammability limits depend strongly on oxygen concentration, fuel thickness and on very small values of the velocity of a forced flow reaching the flame. However, there does not exist a valid mathematical model of the flame structure of those combustion processes, except for some special geometrical configurations (very thin solid fuels or combustion processes with spherical symmetry).

The influence of the oxygen concentration is very important and it gives a field to be explored on fire suppression. On the other hand, the influence of small flow velocities, also of fundamental importance, has to be considered since it is the likely scenario existing in the event of a fire, where there would be small air currents originated by the air conditioning equipment or even by personnel moving within the spacecraft.

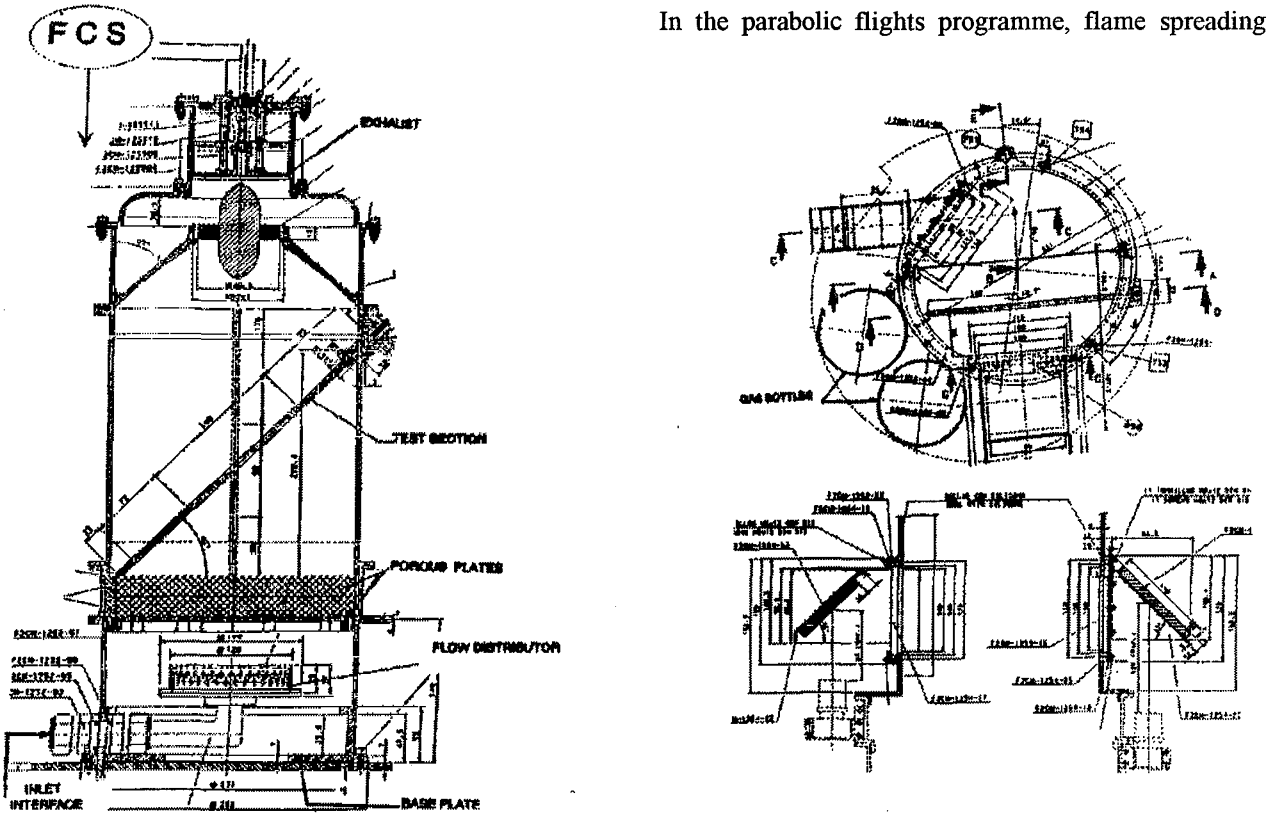


Fig. 1.- SENER F2M Module.

2. RESEARCH PROGRAMME

A research programme on combustion of solid fuels in O_2 N_2 mixtures, at rest and within a slow velocity forced flow is being performed by the Propulsion Department of the School of Aeronautics of the Polytechnic University of Madrid, with the collaboration of the company SENER, in charge of the engineering part of the programme.

The experimental programme was initially carried out in parabolic flights in the NASA Boeing KC-135 aircraft laboratory and in the Caravelle of the European Space Agency. Presently, it is being performed in the MiniTexus sounding rocket, with a launching carried out in 1995 and a second launching already approved by ESA. The parabolic flights experimental programme will be reassumed within a month in the new ESA Airbus laboratory, as a preliminary step to the second MiniTexus launching.

All these programmes are being sponsored by ESA, with small contributions of the Comisión de Investigación Científica y Técnica (CICYT) of Spain.

In the parabolic flights programme, flame spreading velocities over polimethyl-methacrylate (PMMA) cylinders and rectangular slabs in O_2 N_2 mixtures (O_2 concentration higher than 40%) were measured. Results and conclusions have already been published (3), (4), (5), (6).

In parabolic flights there exists residual flow velocities induced by free convection and the available test time is short. Therefore, there are not adequated to study other combustion processes which require lower gravity level or longer test times, such as the influence of small convective velocities on flame spreading and on ignition and flammability limits.

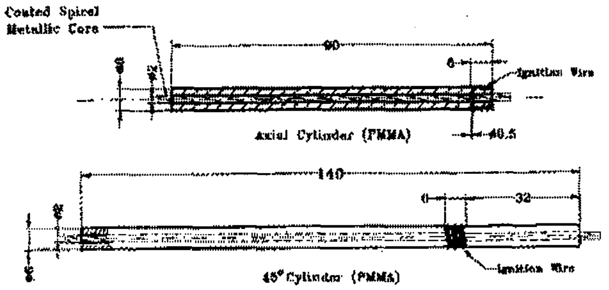
3. MINITEXUS EXPERIMENTS

A combustion module was constructed (Fig. 1). It was axially divided in two chambers, allowing two experiments to be simultaneously performed.

The module was designed to carry out the combustion process at zero and at three preselected flow velocities (0, 5, 10 and 20 cm/s).

A mixture of 40% O2 and 60% N2 was contained in two tanks at different pressure in order to facilitate control.

One hollow cylinder of PMMA was placed axially in one chamber and a similar longer cylinder was placed at 45° in the order chamber. The two cylinders were of 6 mm diameter and 2 mm wall thickness. (Fig. 2).



* Dimensions in mm.

Fig. 2.- Test PMMA hollow cylinders.

Ignition was accomplished with an spiral wire of Kanthal AF alloy, at 21V and 43A for 10 s.

Two video cameras were utilized and flame spread velocities were measured utilizing an image digitalization and processing system. Flow velocities, pressure and temperature in the chamber were automatically recorded.

The three simultaneous experiments were as follows:

Axial cylinder

Ignition in a still atmosphere, followed by flame spread in the quiescent atmosphere during 30s.

Flame spread against an opposed flow (upwind) at velocities of 5, 10 and 20 cm/s; periods of 40s at each velocity.

Inclined (45°) cylinder

Ignition at an intermediate point (closer to the upwind tip), within a flow of 5cm/s velocity.

Simultaneous flame spread both upwind and downwind at flow velocities of 5, 10 and 20 cm/s; 40 s at each velocity.

Mixture composition was: 40% O2 and 60% N2 for all experiments. Pressure was approximately 100 KPa throughout the processes.

4. RESULTS

Experimental results obtained are shown in Fig. 3 and 4, in which comparative results at 1g are also shown.

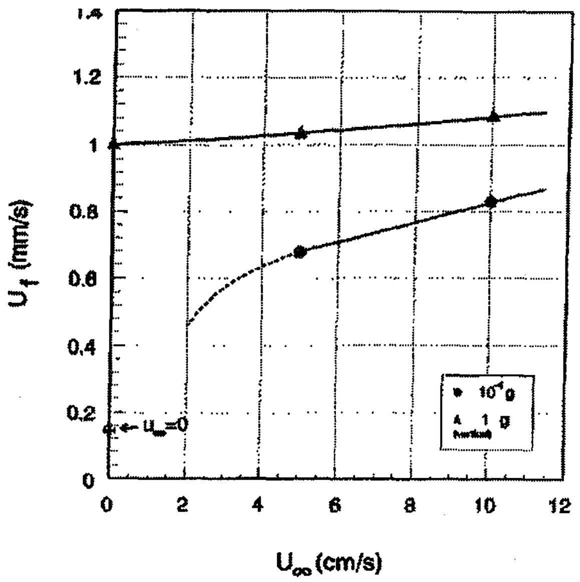


Fig. 3.- Axial cylinder. Upwind flame spread velocities as function of the flow velocity.

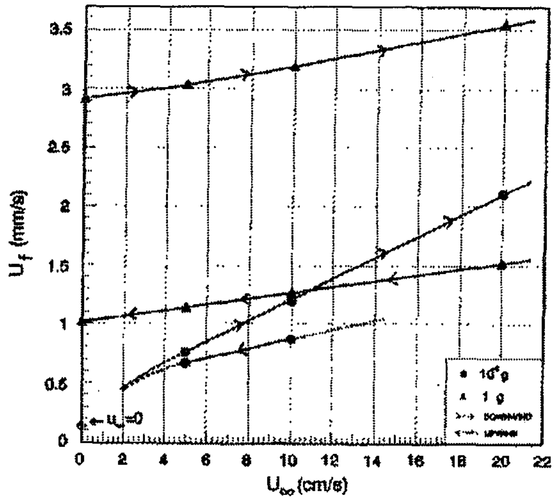


Fig. 4.- Inclined 45° cylinder. Upwind and downwind flame spread velocity.

It was difficult to predetermine the time intervals in the two cylinders and the ignition location in the 45° cylinder, in order to obtain full results up to 20 cm/s flow velocity in the three experiments, since theoretical results do not give a good quantitative approximation. However, in the region of 0-10 cm/s, the most important one, the spread velocities were measured in the three cases, as shown in the figures.

At velocities above 5cm/s, the values of the spread velocities follow the general trends predicted by theory. When the flow velocity increases, the values of the spreading velocities tend towards those at 1g, as it could be expected, since the flow velocity induced by free convection at 1g for the present experiment is of the order of 30 cm/s.

Axial cylinder

The most important results are those obtained in the region of small velocities (0-5) cm/s.

Ignition was carried out at zero flow velocity, beginning with a typical premixed flame, followed by almost spherical diffusion flames. (Figs. 5a to 5f). The diffusion flame begins decreasing in luminosity although the electric current is still applied. The main factors of this phenomenon are probably a decrease in the heat transferred from the flame to the fuel as the flame diameter increases, as well as radiation heat losses from the solid fuel.

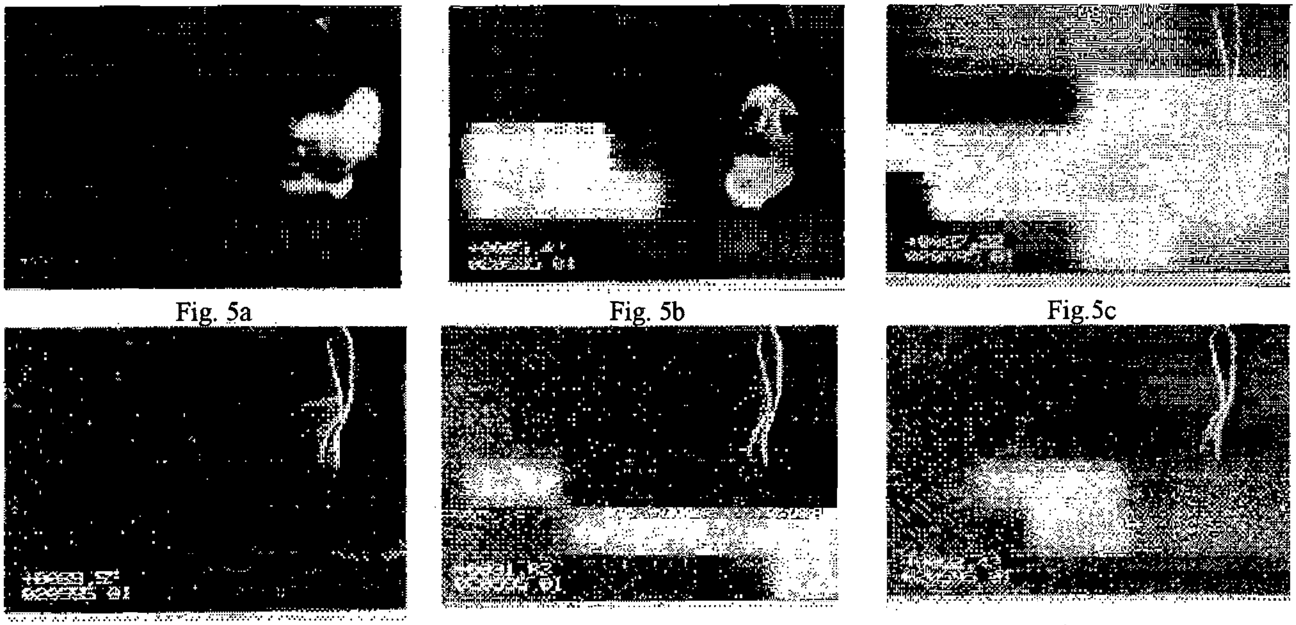


Fig. 5a

Fig. 5b

Fig.5c

Fig. 5d

Fig. 5e

Fig. 5f

Fig. 5.- Sequence of the ignition process of a PMMA cylinder in a still mixture of 40% O_2 60% N_2.

Finally, coinciding with the end of the ignition process the flame becomes non visible, probably originated by low temperature of the flame, coupled, possibly, with lack of sufficient emittance in the visible spectral range.

This situation of a non visible flame in a still atmosphere continues for a period of 30 seconds until a flow valve is open letting the flow to increase its velocity from zero up to 5 cm/s.

Within only 0.2 seconds after opening the valve, the flame begins regaining luminosity, and in about one second. The flame is fully visible (Figs. 6a to 6f). This process is very fast denoting that the whole process occurs in the gaseous phase. It seems that the flame is in a state close to the oxygen lean flammability limit, since when oxygen reaches the flame its visibility increases very rapidly. Time is not long enough for a thermal process in which the flame is forced by the flow to locate closer to the fuel surface increasing the vaporization rate.

These low visibility flames have been observed by several investigators (Ref. 7, for example).

The study of the structure and stability of those low visibility flames, as well as the transition zone from a low velocity down to a still atmosphere is very difficult. The mathematical solution changes from a stationary to a non stationary process; and the assumption of an infinitely fast reaction rate does not seem to be admissible, and, therefore, chemical kinetics has to be taken into account.

There are some mathematical solutions (8), (9) for the combustion of very thin sheets of fuel (~ 0.01 cm thickness), for which the aforementioned conditions (with limitations), might be admitted; but no mathematical solution neither a physical model exist for the aforementioned non luminous flames.

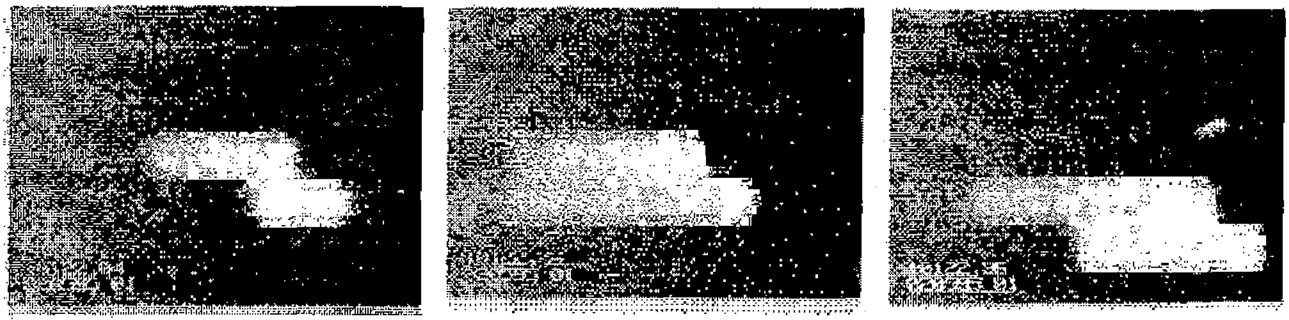


Fig. 6a.- t=0, U_∞=0 Fig. 6b.- Δt=0.2 s., $U_\infty \approx 0.5$ cm/s Fig.6c.- Δt=0.32 s, $U_\infty \approx 0.8$ cm/s

Fig. 6d.- Δt=0.68 s, $U_\infty \approx 1.7$ cm/s Fig. 6e.- Δt=1.08 s, $U_\infty \approx 2.7$ cm/s Fig. 6f.- Δt=1.48 s, $U_\infty \approx$ 3.7 cm/s

Fig. 6.- Sequence of events of the flame becoming luminous when a flow, U_∞, of 0-5 cm/s reaches the flame. Intermediate velocities are approximately determined assuming a linear relationship velocity-time.

Very thin fuels are attractive, because it may be also tested in drop towers.

However, for the study of fires under microgravity conditions the study of combustion of any thickness is an essential process.

It appears that the combustion process proceeds as follows:

When flame temperature reduces due to heat transfer losses, mainly through conduction to the fuel and through radiation from the fuel to the surrounding atmosphere, the reaction rates decrease and with them the oxygen reaching by diffusion the reaction zone. Then, if the flame becomes closer to the fuel surface, the thermal situation might be thermally balanced or else the flame might extinguish.

It appears that the first situation has occurred in the experiment presented in this paper. In Fig. 7 it is shown that the flame appears as located very close to the fuel surface.

It might be mentioned that it seems possible that if the time is long enough, the flame, after heating the fuel, might reach stationary conditions and even regain at least some of its initial luminosity.

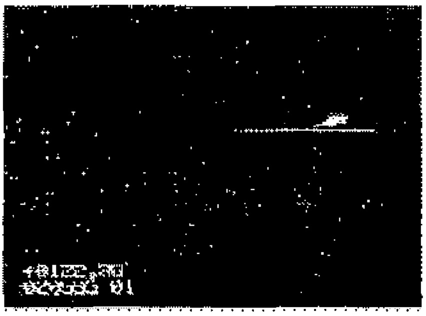


Fig. 7.- Position of the initial luminous spot with respect to the cylinder surface.

Inclined cylinder (45°). Downwind and upwind spread

Ignition took place at a flow velocity of 5cm/s. This experiment was selected in order to study the difference between ignition in a quiescent atmosphere and ignition within a small flow velocity.

Both phenomena are very different. In the inclined cylinder the flame is always visible, small and confined to the zone of the cylinder close to the ignition coil.

When the ignition is switch off, the flame remains visible and with no change in luminosity, but decreasing in size until almost disappears (Figs.: 8a to 8f); requiring a relatively long time (~ 13 seconds), to reach its full size.

The luminosity remaining constant, contrary to the case of ignition in still atmosphere, is probably due to the fact that in this case there is no lack of oxygen, since it is supplied by the flow.

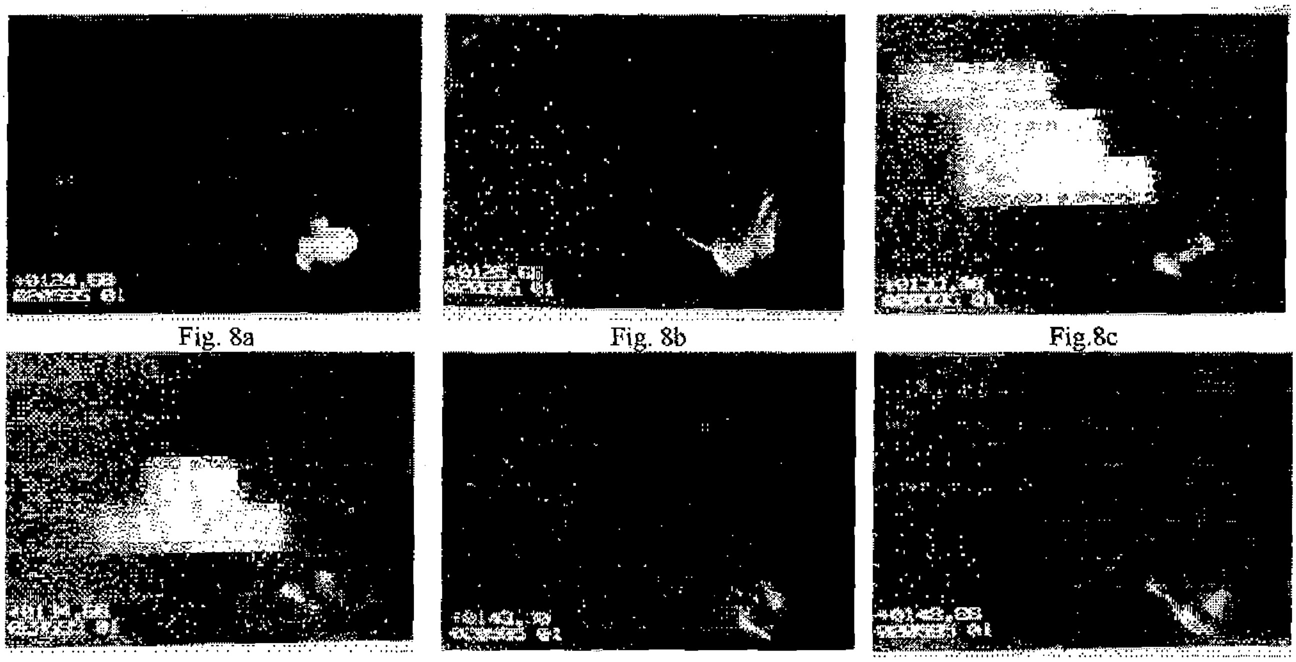


Fig. 8a Fig. 8b Fig. 8c
Fig. 8d Fig. 8e Fig. 8f

Fig. 8.- Sequence of the ignition process of a PMMA cylinder inclined 45 ° with respect to a flow of 5 cm/s.

The decreasing in size might be explained by the difficulty in heating up and vaporizing the PMMA fuel with a small flame within a flow.

Once ignition is concluded, the flame spreads upwind and downwind. For this last case, the spread velocities were measured at the three velocities, but for the upwind spread the flame velocity was measured at 5 and 10 cm/s only.

It may be mentioned that for the first time, combustion flames spreading at a given angle with a forced convective flow have been observed.

The flames appear with many irregularities or small flame pockets (Figs. 9, 10). Similar flame pockets appear in axial upwind spread (Figs. 11, 12), but smaller and far less numerous.

This is probably due to the flow field configuration, which in the inclined cylinder brings the flame very close to the fuel surface, much closer than in other cases. Then, the high temperature of the fuel surface brings forth the unhomogeneties of the PMMA.

A similar, but less noticeable phenomenon, occurs in still flame spread when the O_2 concentration has high values (Refs.: (4) and (5)).

Results at 1g are shown for comparison. As it could be expected, the difference in spread velocities between 1g and at microgravity are considerably greater for the downwind flame spread that for the upwind spread.

Photographs of ignition processes and flames spreading at 1g are included in Figs.: 13, 14 and 15.

They show the striking difference with the corresponding processes at microgravity conditions.

5. CONCLUDING REMARKS AND FUTURE PROGRAMMES

It has been shown that combustion of a solid in a still atmosphere or within a very small velocity flow is the basic process with respect to fires at microgravity conditions. The influence of the oxygen concentration and of the velocity of the flow are of paramount importance and they are linked together.

It has been mentioned that no solution or physical model exist of these processes.

Future programmes are directed to these studies. In the MiniTexus programme a gradual controlled reduction in flight of the oxygen concentration, from 40% down to ambient value will be performed, followed by a gradual reduction of flow velocity from 5 cm/s down to zero. These experiments will be carried out with three hollow cylinders of different thickness and it is expected they will give fundamental information on flammability limits.

However, the number of parameters involved in those combustion problem is very high. Among others, they are:
- materials;
- geometrical configuration and thickness;
- flow velocity;
- oxygen concentration;
- pressure;
- location and type of ignition.

The understanding of these problems would lead to improve fire material standards, and possibly better detection and fire suppression by systems.

The great number of parameters involved will make very lengthy the solution of the problem.

Sounding rockets are an excellent test facility for combustion experiments, but they would require a great number of launches.

The best and ultimate solution is an orbital laboratory or probably better an ejection capsules, but they are very expensive.

Parabolic flights and drop tower might contribute to the solution of the problem, specially for screening the experiments. By using properly these test facilities, the number or experiments in sounding rockets or orbital laboratories could be drastically reduced.

Fig. 9.- Inclined downwind and upwind flames spread, U_∞= 10 cm/s

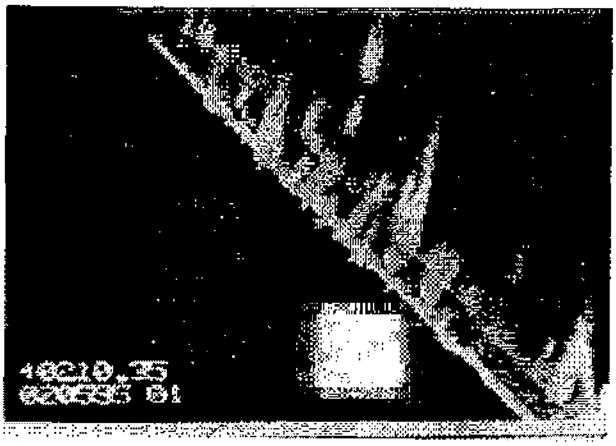


Fig. 10.- Inclined downwind flame spread. U_∞= 20 cm/s.

Fig. 11.- Axial upwind flame spread, U_∞=5cm/s.

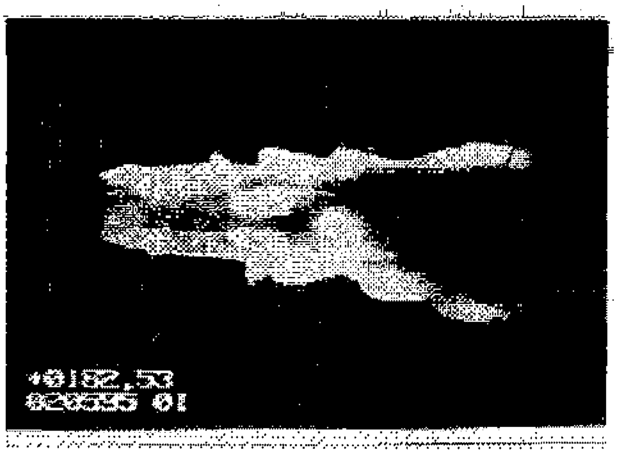


Fig. 12.- Axial upwind flame spread. U_∞= 10 cm/s.

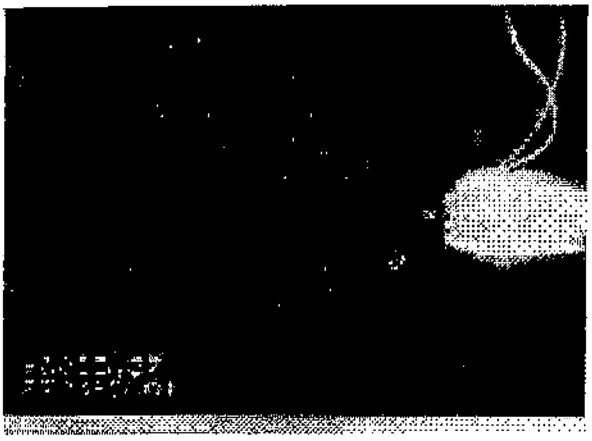


Fig. 13.- Ignition at 1g in a vertical cylinder $U_\infty=0$.

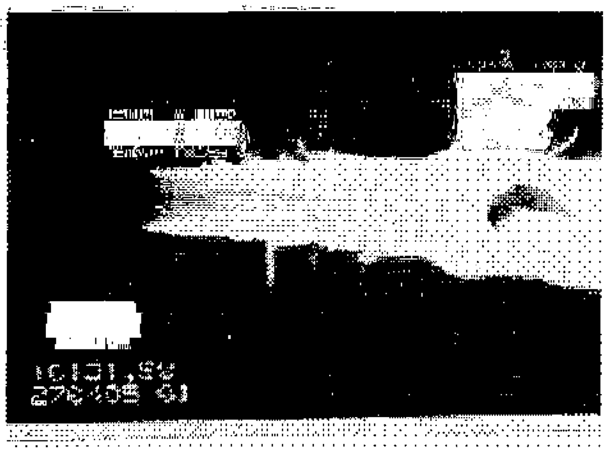


Fig. 14.- Vertical downward flame spread at 1 g. $U_\infty= 5$ cm/s.

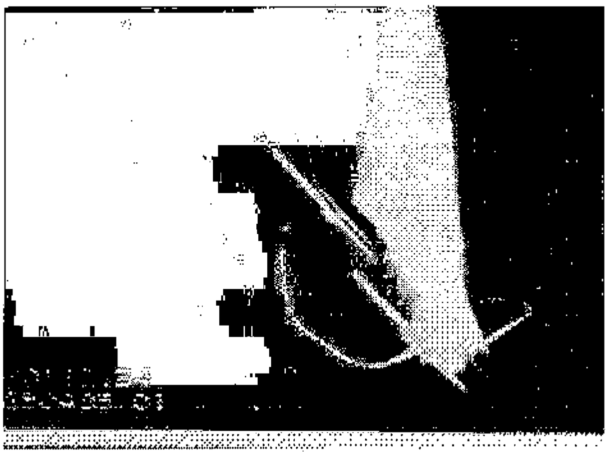


Fig. 15.- Ignition at 1g in an inclined (45°) cylinder. $U_\infty= 5$ cm/s.

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