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Studies on Flame Spread with Sudden Expansions of Ports of Solid Propellant Rockets under Elevated Pressure

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ABSTRACT

A detailed experimental study on flame spread over non-uniform ports of solid propellant rockets has been carried out. An idealised, 2-dimensional laboratory motor was used for the experimental study with the aid of cinephotography. Freshly prepared rectangular HTPB propellant with backward facing step was used as the specimen for this study. It has been shown conclusively that under certain conditions of step location, step height and port height which govern the velocity of gases at the step by the partially ignited propellant surface, secondary ignition may occur far downstream of the step. This is very likely to be within the recirculating flow region. The secondary ignition gives rise to two additional flame fronts one of which spreads backward at a relatively lower velocity, presumably due to the low reverse velocities present around the separation zone. This phenomenon is likely to play an important role in the ignition transient of solid propellant rockets with non-uniform ports.

1. INTRODUCTION

Although, a great deal of research has been done in the area of ignition transients of solid propellant rockets[1] for more than three decades, the accurate prediction of ignition peak and instant of ignition peak has remained an elusive problem. The ignition transient can be generally considered to consist of three intervals, namely the induction period, the flame spreading period and the chamber filling period. These three intervals are beset with several uncertainties, which make the overall transient a very complex phenomenon. Flame spreading over a propellant surface is a complex process, because the flame spreading process in a rocket motor depends on the igniter system, port geometry, chamber gas dynamics, propellant characteristics and so on. The flame spreading interval is defined as the time interval between first ignition of the propellant surface and the ignition of the entire propellant grain.

Paul and Lovine[2] and several others have demonstrated the role of flame spread rate in determining the pressure transient. Indeed the rate of pressure rise can, to a certain extent, be controlled by altering the surface conditions governing the flame spread. Flame spreading over double base propellant and propellant ingredients in quiescent atmosphere was studied by McAlevy *et al*[3]. In the experimental investigations, freshly prepared rectangular specimens were mounted in a large vacuum tight test chamber and were ignited by a hot wire. Flame spreading velocity was found to vary directly with pressure and ambient oxygen mass fraction and inversely with the specimen surface smoothness. Raizberg[4] presented an analysis and approximate analytical solution to determine the flame-spreading rate as a function of time. He investigated both convective and radiative heating conditions, and concluded that the flame spreading rate must increase with time.

In most cases, the flame spreading observed over solid propellant is continuous. However, discontinuous flame spreading has also been observed in some laboratory experiments[5,6]. Peretz *et al*[6] found that flame

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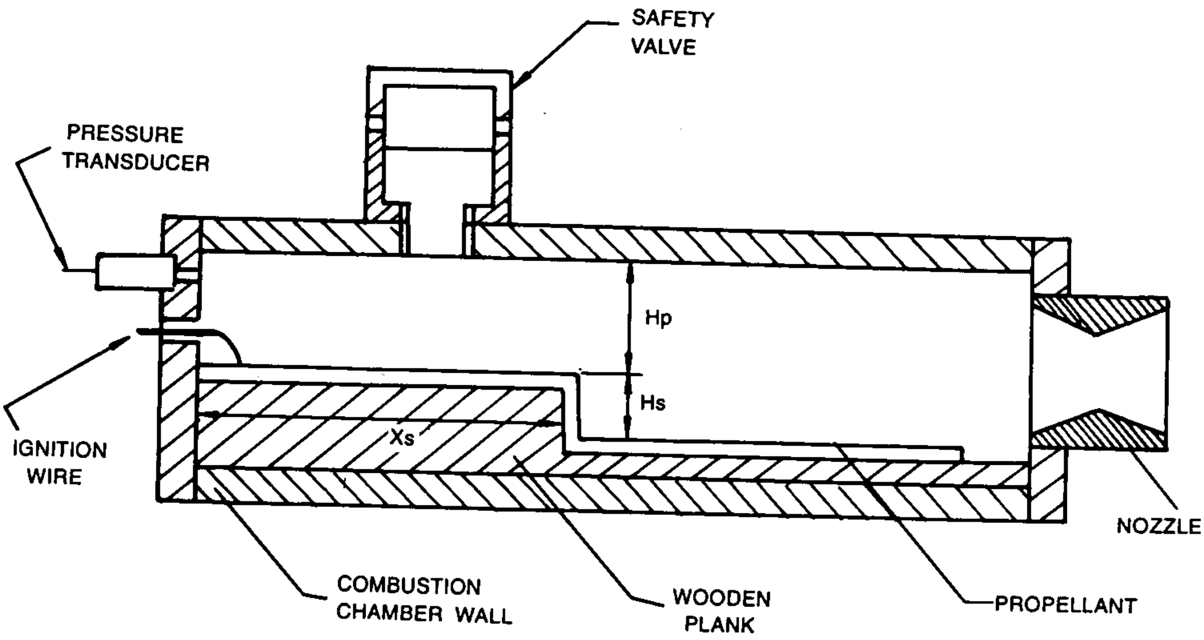

Figure 1. Schematic of the 2-d motor for flame spread studies.

spreading rates increase with increasing igniter mass flow rate and decreasing throat area. The discontinuous flame spreading has been attributed to enhanced radiation heat transfer, delayed reaction in the gas phase, enhanced convective heat transfer and local surface roughness condition. Indeed the actual cause may be a combination of the four causes stated above, which is succinctly stated by Kumar and Kuo[7].

Andoh *et al*[5] have conducted an experimental investigation of flame spreading over non-catalysed and catalysed flat double base solid propellants in a turbulent boundary layer. They observed that flame did not always spread continuously, but that a secondary and/or tertiary ignition downstream of the burning surface may also occur. The appearance of secondary burning was explained in terms of enhanced convective heat transfer rate downstream of a burning surface. The flame spreading velocity was observed to increase with increasing free stream velocity and normal burning rate.

One would easily notice that in all the above studies, whether theoretical or experimental, constant port area configurations are considered. While constant port area geometry is a good approximation to a large number of solid rockets, there are some which are quite distinct. For instance, dual thrust motors with single chamber necessarily have non-uniform port geometry. In such configurations, it is very likely that the flow separation would take place at transition locations. Many segmented rocket motors also have sudden changes in port area along the length. The process of flame spread through such a port which is an input to any model, remains obscure. Surprisingly this topic has not been studied by anybody so far although prediction of ignition transient has been and continues to be a research topic for more than three decades. It may be anticipated that flow separation and reattachment would cause secondary ignition at a downstream point followed by backward spread of the flame in addition to the normal forward spreading. The sudden expansion region is modeled as a backward facing step in the present experimental work. It may be noted that the flow pattern and heat transfer behind backward facing steps have been widely studied which can aid in interpretation of the present results. Recently, similar studies on fuel (PMMA) ignition in a sudden expansion region have been reported[8], but there has been none in the context of flame spread over propellant surface.

2. EXPERIMENTAL DETAILS

A laboratory-size, solid propellant, window motor was designed to withstand 50 kg/cm^2. A schematic view of the experimental set-up is shown in Fig. 1.

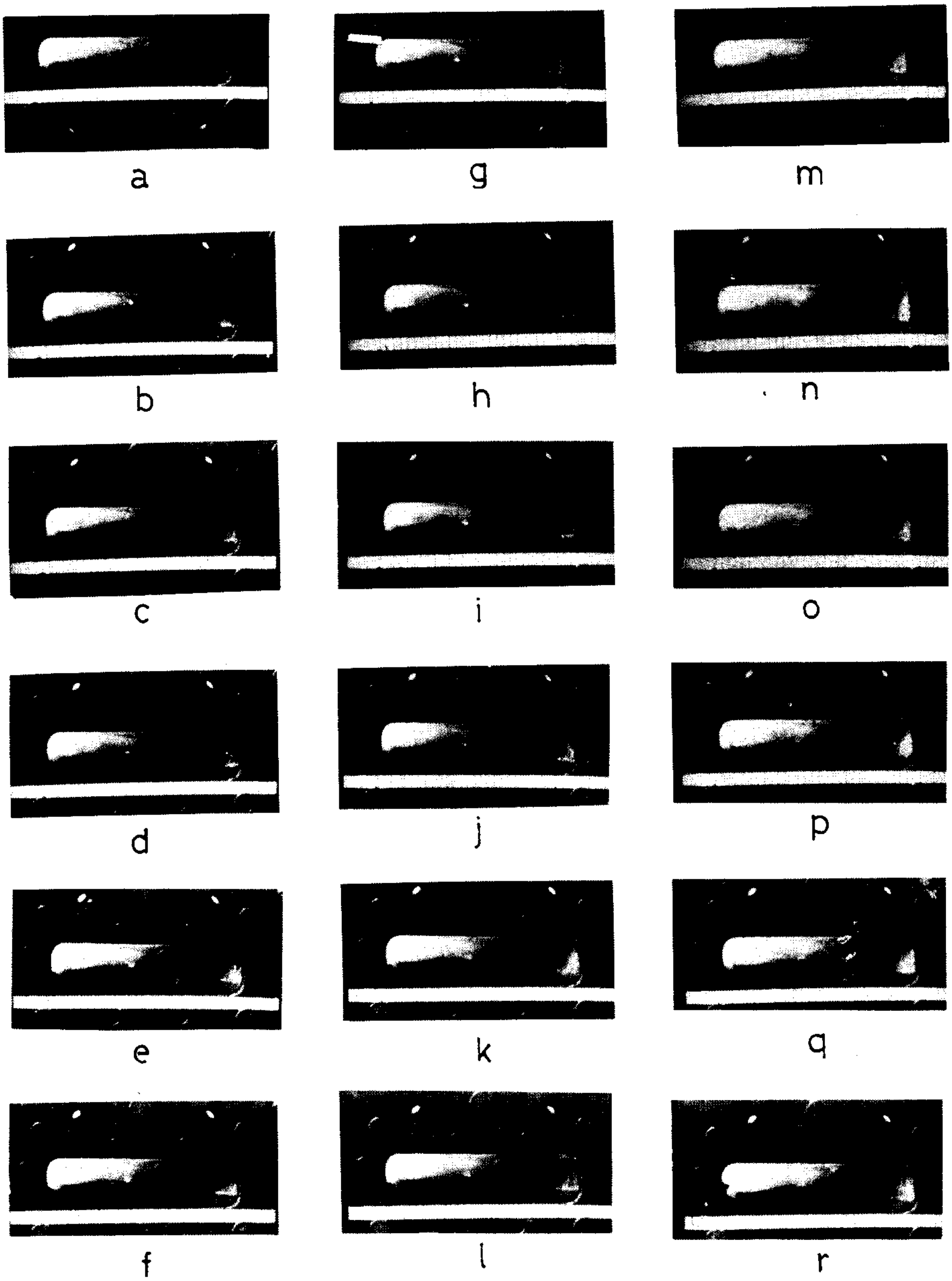

Figure 2. Cine Photographs of flame spread showing secondary ignition. (Framing rate = 100 FPS).

The motor has a chamber of size 250 X 60 X 60 mm. It is fitted with two toughened glass windows, one each on either side to facilitate the cinematographic recording or the event of the flame spreading. At the head end of the motor, a safety valve which can operate at 20 kg/cm^2 is fixed. The ignition is carried out by a thin nichrome wire, which is energised by an AC autotransformer. At the aft-end of the motor a nozzle block assembly is fitted. The propellant used is metallised HTPB which is the same as used in the dual thrust motor being developed at ISRO. The propellant sample is inhibited on all sides other than the top surface. The propellant specimen is glued on a variable height wooden plank and mounted in the motor. Metal plates can be fitted on the top wall of the motor to effect changes in port area.

The two parameters of interest are the flame propagation rate and the chamber pressure of the motor. A high speed camera and a pressure pick up (transducer) are used for this purpose. The processed film is analysed in a motion picture analyser frame by frame. Several problems related to erosion of glass window, illumination of the burning surface and uniform ignition along the width had to be resolved before obtaining accurate experimental data.

The parameters that are changed are the port height H_p, step height H_s, and the step location X_s which are shown in Fig.1. Nearly thirty five firings were conducted and data from only those firings which gave clear and distinct photographic images were analysed.

3. RESULTS & DISCUSSION

Figure 2 (a-r) are a sequence of pictures showing the flame inside the port as viewed through the window. Data generation, both qualitative and quantitative, is through frame-by-frame analysis of the cine photographic records obtained at a speed of 100 FPS. Location of the main flame front (Xf) at different instants of time (t) constitutes the raw data from which the rate of flame spread, occurrence of secondary ignition and other information are deduced.

It takes a few seconds after the nichrome wire becomes white hot for the first burst of flame, i.e. ignition to occur. The first flame seems like a hangfire (virtually stationary) at the beginning, because in this configuration, little convection is present at that stage. The instant when the flame spreading becomes perceptible is arbitrarily denoted as time, t=0. This obviously does not alter any derived information like the rate of spread.

Qualitatively, in all the firings, tiny flamelets are observed well ahead of the flame front, a feature reported by Andoh *et al*[5]. However, these flamelets do not generate additional moving flame fronts, but are

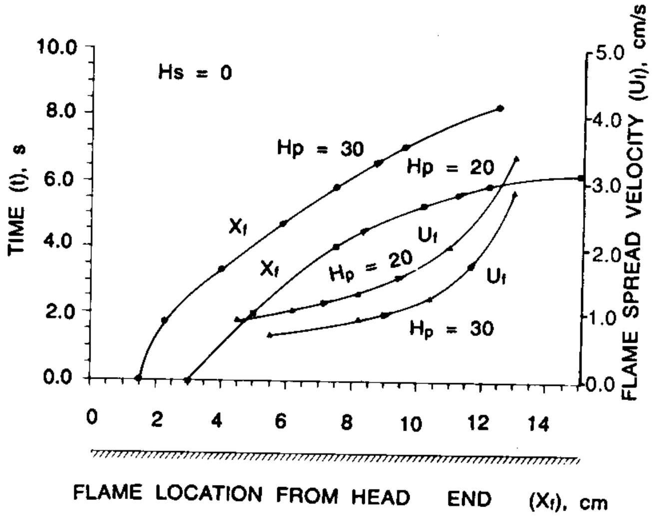

Figure 3. Flame spread through a uniform port without any step.

engulfed by the main flame front. In the discussion to follow, a reference to secondary ignition implies the formation of additional flame fronts that augment the flame spreading.

Both to prove the set-up and to serve as a base set, initial test runs were made with the case without any step, namely that of uniform port area. Figure 3 shows the data of X_f *vs* t and the forward spread velocity (U_f) for two such cases. The observations (i) that the flame spread rate gradually increases along the port length and (ii) that the spread rate is lower with higher port height may be explained in a straightforward way by invoking the convective heat transfer principles. It can be shown that in this 2-d configuration, the heat transfer coefficient, h at any downstream location will vary as h ~ $X_{fn/Hp}$ where the index n takes the value of 0.5 or 0.8 depending on whether the flow is laminar or turbulent. The flame spread being a transient phenomenon, h gradually increases with time. Further, ignition is a cumulative effect of gradual heating of the surface. These factors combine to give rise to an accelerating flame front. The effect is directly seen in the U_f *vs* X_f plot.

When the flow velocities are low enough over a period during which a forward spreading flame approaches the step, the situation may not be too different from the case without a step.

In contrast to the above, when the flow rates are sufficiently high upstream of the step, one could expect

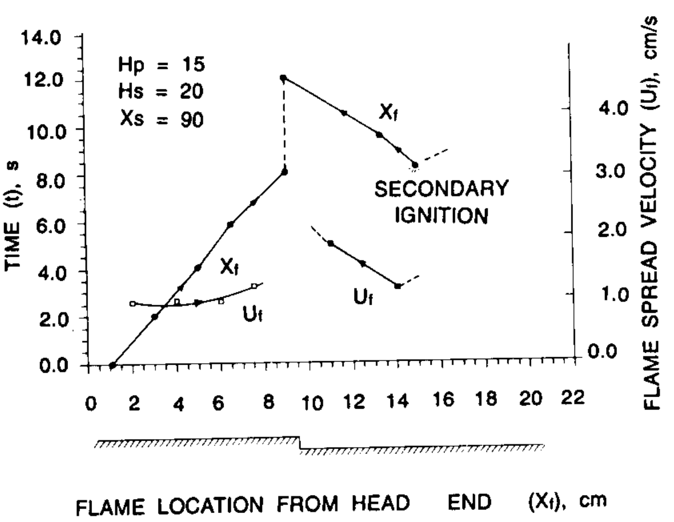

Figure 4. Secondary ignition followed by backward flame spread.

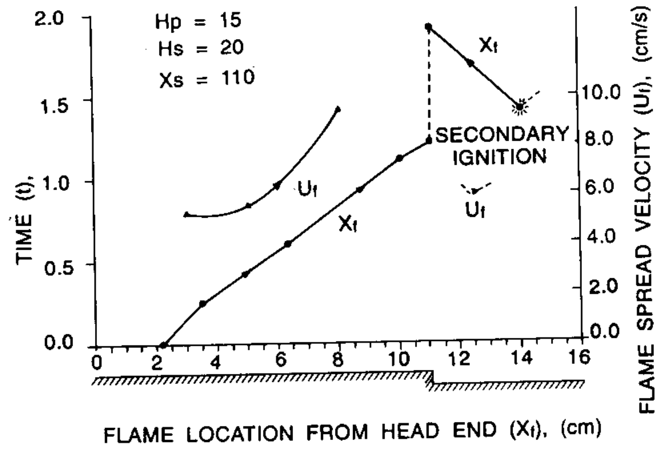

Figure 5. Backward flame spread at higher pressure. (Peak pressure = 1.6 kg/cm^2, $V_{forward}$ (max) ~ 15 cm/s).

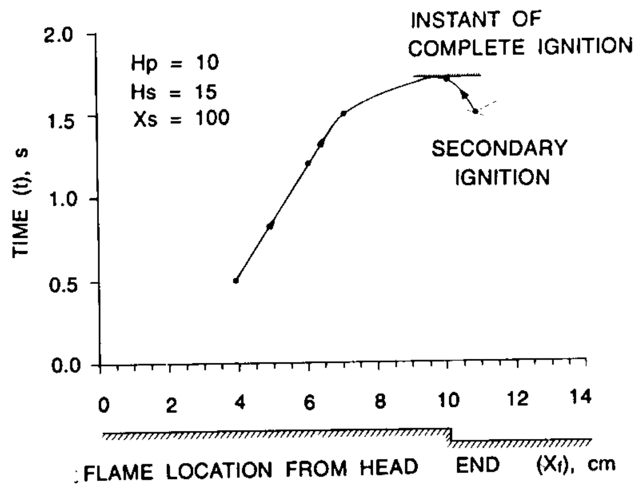

Figure 6: Backward flame spread at higher pressure (Peak pressure = 7.5 kg/cm^2, $V_{forward}$ (max) > 15 cm/s, Secondary flame $V_{backward}$ ~ 4 cm/s).

distinct flow separation. This would be the case when the step is further downstream or the port is narrower. Fig.4 depicts such a case where a secondary ignition (which can be seen on the cine photographs in Fig. 2 followed by a backward spreading flame front is observed. The run corresponds to a test at ambient pressure, the nozzle end being open. Just as the main flame front approaches the step (at X_f = 90 mm), secondary ignition at X = 150 mm, gives rise to a backward moving flame. It is obvious that there will also be another forward spreading front from the point of secondary ignition. But this is beyond the region that is observable through the window. It may be noted that the backward flame spread rate is much lower than what the rate would have been at the same location if only the forward spreading were present as in Fig. 3. Still the overall time taken for the flame to cover the whole burning surface could become shorter because of multiple fronts. In all the tests, with backward step, it is observed that the vertical face of the step is the last part of the specimen to be consumed. Since the propellant thickness and normal burn rate are uniform all over, this is a corroborating evidence for the formation of multiple flame fronts.

Figures 5-7 are some of the plots of flame movement at higher pressure obtained experimentally by fitting nozzles of suitable throat areas to the same slab burner. The data recording has been done by cinephotography and supplemented in some experiments by colour video photography. The pressure transducers used in these tests have shown pressure levels in the range 1.6- 12.6 kg/cm^2 clearly indicating that choking has occurred in each of these cases. Fig. 8 is a typical pressure-time plot for such firings. Total burn time of the order of 2 s gives an indication of average normal burn rate which can be used to estimate the gas velocities in the port.

Compared to the tests conducted at atmospheric pressures, the relatively shorter time scale and higher velocity levels are evident in the figures. The most important feature to be noticed is that the trends of secondary ignition and backward flame spreading continue to be present. Peak pressures attained and the order of magnitude of forward and backward flame

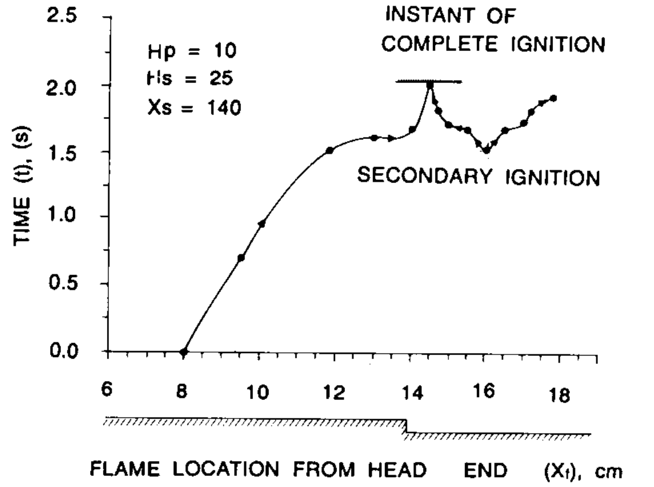

Figure 7. Backward flame spread at higher pressure (Peak pressure = 12.6 kg/cm^2, $V_{forward}$ (max) > 25 cm/s, Secondary flame $V_{backward}$ ~ 2.5 cm/s, $V_{forward}$ ~ 4 cm/s).

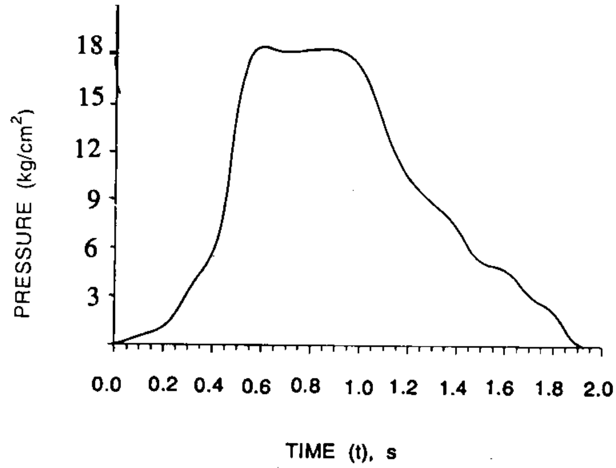

Figure 8. Typical pressure-time plot.

spread rates are given in the figure caption. Once again, secondary flame fronts have lower spread rates especially the backward propagating one. Even the steep rise in primary flame spread rate (see for instance Fig. 7) with pressure does not preclude the phenomenon of secondary ignition and generation of additional flame fronts.

The separated flow characteristics such as size of the separation bubble, flow redevelopment and heat transfer in the recirculation region are known to be dependent on Reynolds number (Re) upstream of the step and the step height. During the flame spreading process, the Reynolds number at the top of the step gradually increases as X_f increases, attaining a maximum as the flame covers the entire propellant surface before the step. For different configurations tested in this work, the peak Reynolds numbers based on step height are estimated to be between 6000 and 40,000 at the propellant flame temperature. At these turbulent Re ranges, the reattachment point is known to lie atleast three times the step height away from the foot of the step. However the zone of secondary ignition for many tests is around 0.8-3.0 times of the step height. Therefore one can conclude that the secondary ignition occurs inside the recirculation bubble. The preheating of the propellant in this zone before the arrival of the flame at the sudden expansion also appears important.

The implication of the secondary ignition can be quite serious for a practical rocket. One secondary ignition would result in two additional flame fronts, one spreading forward and the other backward. This effect will be further accentuated in the case of star grain downstream of sudden expansion where the star points generate multiple flame fronts[9]. The effective time required for the complete burning surface area to be ignited comes down drastically giving rise to a high (*dP/dt*) in the second phase of ignition transient. This in effect could lead to a hard start of the rocket motor.

The work reported here is aimed to prove conclusively that when flow separation is likely to occur during the flow of igniter gases (or gases evolved by partially ignited propellant surface), multiple flame fronts may be generated. Such flow separation might be caused by sudden expansion regions, steep divergences or protrusions over the surface in the port of a rocket motor. Having proved this point, the next step will be to obtain more accurate data and to understand the role of this phenomenon in the ignition transients. It may be conjectured from this experience that this phenomenon of flow separation and reattachment could also modify the nature of erosive combustion, which is also a consequence of convective heat transfer. This also adds to the complexity of the ignition transient.

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