TESTING PROCEDURES FOR EXPLOSION ARRESTERS: SOME PROBLEMS AND POTENTIAL SOLUTIONS

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Flame and detonation arresters are a well established means of protecting industrial pipelines against accidental explosions. However, in recent years, the scientific rational underlying some of the current procedures for testing their effectiveness has been called into question. In the present paper some of the underlying problems that may be encountered when using existing arrester testing procedures are reviewed. The results of recent studies are then presented of possible new experimental approaches that generate more reproducible flame velocities and overpressures. In addition, a novel method for the generation of controlled deflagration to detonation transition is demonstrated.

Keywords: Explosion arresters, flame acceleration, transition to detonation.

INTRODUCTION

Flame arresters provide an extremely widely used method for the suppression of explosions in pipelines that transport reactive gases or vapours or where explosive mixtures may be generated accidentally. Surprisingly, little detailed attention has been given to the mechanisms by which they operate. Similarly, it is somewhat surprising, given their widespread use, that the procedures for evaluating arresters are not that technologically well advanced. Current UK procedures for testing flame and detonation arrester performance are embodied in British Standard BS7244[1]. This outlines procedures for assessing the response of arresters when subject to flames, detonations or endurance burning. To qualify, these require that the arrester withstand a set number of flame or detonation impacts without combustion propagating beyond the arrester.

Recent studies have indicated that the procedures outlined in the current standard do not result in as reproducible a test as one might expect. The present paper first discusses the origins of the deficiencies that lead to the variation in the final testing conditions obtained for nominally identical initial conditions. Results are then presented from a research programme to investigate the application of some new approaches for the generation of controlled flame acceleration. Results are then presented of method whereby controlled transition to detonation can be generated. The aim in both of these investigations was is to generate selected test conditions in the vicinity of an arrester in as reproducible a manner as possible.

CURRENT PROCEDURES FOR EXPLOSION ARRESTER TESTING

For flame arresters, the basis of any test evaluation under BS7244 is the determination of the maximum length of pipe, placed before the arrester, for which a propagating flame does not pass through the arrester over ten repeated tests. The test is based on the principle that longer lengths of pipe result in higher flame velocities and thus present a more severe test of the arrester.

For detonations, repeated tests are required where overdriven detonations are incident on the arrester. Initial flame acceleration can be induced by the introduction of an acceleration promoting insert, a Shchelkin spiral. The overdriven detonation phase, which is usually associated with a deflagration to detonation transition (DDT), can exhibit short-lived transient velocities up to 50% in excess of the CJ value. The corresponding peak pressures may be of the order of 70-100 bar.

Other standards currently set world-wide include that published by the International Maritime Organisation (IMO) standard[2] and the U.S. Coast Guard standard[3] for marine vapour recovery systems.

A German standard has been in use for many years. This requires that deflagration arresters be placed no more than 20 pipe diameters from any potential ignition sources, thus reducing the possibility of flame acceleration and any significant overpressures at the arrester when the flame impinges on it. A new Canadian Standard will come into force soon, which is again similar in many respects to other existing standards[4].

Proposals for a new European standard are currently being considered. Recently, the CEN TC/305 committee was established to draft new standard procedures for use throughout the community. The work on explosion arrester performance has been allocated to the subgroup CEN/TC 305/WG 3/SG 1 and the draft standard is expected in mid 1996.

RECENT EXPERIMENTAL STUDIES

Interest in flame arresters world-wide has increased recently as, for environmental reasons, plant operators will soon have to fit vapour recovery systems to their existing plant. This will give the possibility of flammable or even detonable mixtures forming within the system. It is necessary therefore to fit arrester systems to protect both plant and the surrounding environment against accidental explosions in such systems.

To qualify such arrester systems for marine applications the US Coast Guard drafted a set of test procedures. To assess the usefulness of these tests the American Petroleum Institute (API) commissioned South West Research Institute (SWRI) to undertake a wide ranging series of experiments to scrutinise the test procedures[5]. The major problem areas identified by this study were: i) the uncertainty and variability in flame acceleration rates between tests and presumably between different facilities; ii) the uncertainty in what constituted the most severe test of a detonation arrester and iii) uncertainty as to how to repeatably generate test condition for over-driven detonations.

Recently, whilst developing a small scale arrester test facility, Thomas and Oakley[6] identified similar problems to those listed by SWRI. They concluded that there were a

number of deficiencies in the existing UK procedures. Control of flame acceleration rates were identified as a crucial factor. They suggest that more strictly defined accelerating section geometry should be developed to allow more reproducible velocity and pressure histories to be generated.

As for detonation arresters, Thomas and Oakley[6] conclude that any revisions of the standard should identify which aspects of the detonation phenomenon presents the greatest potential hazard, *i.e.* steady state or overdriven conditions during transition to detonation and incorporate a test procedure that will allow the worst case conditions to be generated in a repeatable manner. The API-SWRI investigation has now concluded that overdriven detonations do constitute the worst case for detonation arresters, but there is still much uncertainty as to how to develop a suitable test. The problem lies in the stochastic nature of the flame acceleration and deflagration to detonation transition (DDT) process.

In addition to the work reported by Thomas and Oakley[6], Forster[7] has also provided evidence of the stochastic nature of the flame acceleration that can result. These results are shown in Figure 1 and again relate to flame accelerations in smooth bore tubes. Figure 1(a) shows the variation in flame velocity at an arrester for essentially identical initial conditions. There is some degree of correlation between the flame velocity and pressure, Fig. 1(b), but it still requires a large number of tests to obtain ten tests at the specific conditions of interest.

ORIGINS OF PRESENT DEFICIENCIES

Under existing guidelines, problems originate from the stochastic nature of the flame acceleration process. This arises due to the positive influence of gas turbulence on combustion[8]. Turbulence arises due to viscous forces that distort the velocity flow field.

In explosions this is particularly severe when obstacles are present in the flame's path. The initial flow generates turbulence which increases combustion rates which in turn increases the flow ahead of the flame, giving increased turbulence and even faster combustion. The flame acceleration process, and hence flame velocity histories along a notionally smooth bore pipe, is therefore dependent on the initial conditions and the extent of natural surface roughness at the tube walls.

Eventually, conditions are attained where transition to detonation occurs. The time and position along the tube at which transition occurs is thus determined by the early stages of flame acceleration. This generates a severe problem when testing detonation arresters against transition to detonation, as, at a fixed location, significant variations in peak overpressures result from otherwise identical initial conditions. Also, the initial flame acceleration phase is also influenced by the resistance to flow of the arrester itself, introducing a further non-quantifiable and irreproducible element into the test.

AIMS OF THE PRESENT STUDY

The aim of the work summarised in the present paper was to investigate the possibility of increasing the reproducibility of testing procedures for explosion arresters. A specific

objective was, starting from the existing knowledge base, to develop suitable designs of accelerating sections that give repeatable flame acceleration histories. Significant effort has also been directed in a similar way towards the deliberate controlled initiation of transition to detonation.

EXPERIMENTAL DETAILS

Flame acceleration studies

Flame acceleration occurs in smooth pipes due to turbulence induced by viscous interactions with the tube wall. In this case the process is highly dependent on the initial stages after ignition. If this develops in a slightly different way each time, then subsequent flame development will differ due to the high inter-dependency between the combustion and flow-wall interaction and turbulence generation. One means of overcoming this is to introduce repeated obstacles into the tube so that the obstacle generated turbulence dominates and the acceleration is more repeatable. This has already been demonstrated on both small[9] and large scale[10].

The apparatus used for the present studies is shown schematically in Figure 2 and had an internal diameter of 50 mm. It comprised three 1m long sections, placed before the flame arrester. The internal roughness of this section of the tube was varied by the use of repeated annular disks (2 mm thick). The obstacle dimensions represented a blockage of 40% of the tube cross sectional area, as used previously by Lee *et al.*[9]. The variables investigated were the spacing between disks, S, and the overall length of the accelerating section, M. A further section, 0.5 m long, was placed after the arrester with a slide valve at its end. The latter was opened shortly before each test. Arrester failure was signalled by flame propagation in the downstream 0.5m section, detected by a photo diode.

Before each test the tube was evacuated using a rotary vacuum pump. The test mixture was prepared by introducing the appropriate partial pressure of fuel and re-filling the tube to ambient atmospheric pressure with air. The mixture was then recirculated using an oil-free pump for in excess of five minutes. The fuel-air mixtures were ignited at the closed end of the tube by electric spark, nominal energy 1 J. Three fuels were used in the tests: propane, ethylene and hydrogen in stoichiometric mixture with air.

A number of pressure, photo diode and ion probe flame sensors were fitted to the tube. The gauge outputs were recorded using a custom built microcomputer controlled transient recorder. The sampling rate was 1 MHz per channel. At least 4 tests were performed for each experimental condition in order to establish the repeatability of the results.

Deflagration to detonation transition

A number of the studies have been concerned with the conditions for an eventual transition to detonation. A review of all stages from initial flame front instabilities to complex shock-flame interactions is available[11]. The importance of shock waves in the

transition process has been highlighted by other studies[12,13]. Once a critical shock velocity has been achieved, then transition to detonation becomes inevitable. Thus, if these shock conditions could be established during detonation arrester testing, repeatable testing against transition and overdriven detonations would be possible.

In the present paper we report the use of a method whereby a detonation is temporarily quenched by some attenuating section and then re-initiated by a transition to detonation induced just prior to the arrester. This approached was inspired by earlier observations of the response of a detonation incident on an inert air gap[13,14]. In the present work, five different approaches were attempted to attenuate the incident detonation. These included an air gap, and a section of larger cross section lined with absorbing materials to give a porous walled section of 50 mm internal diameter and are listed below.

1. Enlarged cross-section tube: 0.5 m long, 80 mm in internal diameter;
2. Perforated tube: 0.5 m long, 54 mm ID, 3 mm hole diameter, 21% porosity;
3. Perforated tube and wire mesh as in 2, with 20 layers of mesh made of steel, 0.25 mm wire diameter, 0.46 mm aperture, 42% screening area, plain weave;
4. Perforated tube and steel wool as in 2, with medium grade steel wool;
5. Air gap, 0.1 m or 0.2m long.

Figure 3 shows a schematic of the experimental apparatus. The basic experimental set-and measurement set-up was as for the flame acceleration tests, described above. The tube was re-configured to form a 1 m long booster section, a 3 m long donor section, an attenuating or damping section, a 1 m long acceptor section, detonation arrester and 0.5 m long end section. The booster section was separated from the rest of the tube assembly by a pneumatic slide valve and was filled with stoichiometric oxy-acetylene. The far end of the apparatus was closed by a mylar diaphragm. An ELMAC prototype detonation arrester was used in this case.

Additional pressure perturbations in the acceptor section could be generated by five periodically spaced annular disks, 2 mm thick with 0.4 blockage ratio. The spacing between the disks was 0.1 m. At least three tests were performed for each experimental condition in order to establish the repeatability of the results.

EXPERIMENTAL RESULTS

Flame acceleration studies

A large number of tests were performed covering a range of obstacle spacing (S/D) and lengths of accelerating section (M/D). A series of control tests were also undertaken, without any accelerating section in place. Typical pressure histories obtained with unaccelerated ethylene- and hydrogen-air are shown in Figure 4. For ethylene a gentle pressure rise is first evident, followed by a rapid pressure rise at later times due to eventual flame acceleration. A similar behaviour is observed for hydrogen-air except that in this case the initial flame propagation and higher sound speed in the mixture results in

a weak precursor shock some 12 ms before the main peak overpressure. For propane, the pressure records were significantly more oscillatory in nature, due to acoustic interactions along the tube length and the peak overpressure was much less, with no evidence of flame acceleration.

When an accelerating section was introduced, significant increases in pressure just prior to the arrester (PT2) were observed. These increased pressures are also observed within the arrester housing (PT3) and downstream of the arrester (PT4). Failure is signified by light emission downstream of the arrester noted by the photodiode (H1).

Figure 5 shows pressure histories obtained for propane-, ethylene- and hydrogen-air for an obstacle spacing (S) equal to the tube diameter (D) for two lengths of accelerating section. As might be expected from a considertion of the turbulent burning characteristics of the fuels considered, higher pressures are generated as the mixture reactivity increases, i.e. propane > ethylene > hydrogen. Also, as the length of accelerating section increases the final peak overpressure increases, due to the accumulated acceleration possible in a longer length of pipe. The arrester is seen to have failed in some cases.

Obstacle spacing also has an influence, as shown in Figure 6 for propane-air. Perhaps surprisingly the peak overpressure increases as the obstacle spacing is decreased. For an obstacle spacing to diameter ratio of six the wave is near to transition to detonation and this was in fact observed in some tests, as shown in Figure 6(d). The reduction in peak prressure inother cases is due to the increased energy and momentuum lossesthat arise due to the drag forces generated by the presence ofthe obstacles. The arrester is again seen to fail for some of the more reactive tests.

Whilst it is inevitable that there will be residual scatter in the flame acceleration behaviour, a demonstrable increase in reproducibility was observed. This is shown in Figures 7 and 8 where the wave velocity and peak overpressures just prior to the arrester are presented for a range of accelerating section length and two obstacle spacings. These clearly show the propensity for the more reactive hydrogen-air system to detonate. They also show that for propane and ethylene a greater degree of control over wave velocity and overpressure at a single point is possible when using accelerating sections.

Deflagration to detonation transition

For each of the gas mixtures tested, detonation were readily established in all mixtures using the oxy-acetylene booster section. For propane however the mixture is near to the limits of propagation in a 50 mm internal diameter tube, and oscillatory near limit behaviour is clearly visible on the pressure records, as shown in Figure 9. Following propagation beyond an attenuating region, a 10 cm long inert air gap, a decoupled shock-flame propagates in the acceptor region. In no case was it possible to initiate transition to detonation. In fact, transition to detonation in propane was only observed for the attenuating section formed from using method 1, a 0.5 m long enlarged cross-section tube (to 80 mm).

An ethylene-air detonation propagated successfully through the increased cross-section tube, but was attenuated when the perforated tube was introduced. There was no significant difference when the perforated tube was augmented by steel wool or mesh in

the external annulus, see Figure 10(a).Transition to detonation was however readily triggered by placing some of the obstacles used in the flame acceleration tests just beyond the attenuating section. In this case, rapid transition to detonation could be generated reproducibly over a limited spatial range.

Hydrogen successfully propagated through the perforated tube with or without additional steel wool *etc.*, see Figure 11(a). For hydrogen, detonation quenching and subsequent transition was obtained most reproducibly using a 25 cm air-gap, as shown in Figure 11(b).

DISCUSSION AND CONCLUSIONS

The general result of the flame acceleration tests is that a significant improvement in the reproducibility of flame accelerations can be generated using a deliberately severe obstacle configuration. As might be anticipated, increasing the length of the accelerating section increases the final shock-flame velocity at the arrester. Also of some significance is that this can be achieved without major changes in the tube geometry. Less variation is observed between changes in obstacle spacing than might be expected although optimal combinations of spacing and overall accelerating section length can be inferred. Certainly, optimal configuration can be identified for each mixture to give similar test conditions.

It is also interesting to consider the impulse time histories at the end of the flame tube. Typical plots are shown in Figure 12 for different mixtures for an obstacle configuration of S/D =6 and M/D=60. Also noted on this figure are symbols indicating the times at which failure of the arrester was first detected. Similar plots were obtained for other accelerating section configurations and the failure criteria are remarkably similar in all cases. Whilst not wholly inclusive, failure was always observed for when the time integrated impulse attained a value in the range 0.007± 0.001 bar•s for hydrogen and 0.007± 0.001 bar•s for ethylene. The failure point for propane was greater again. Despite this degree of correlation, it must be stressed that there were cases where arresters survived despite being subject to greater impulses than these values. Further detailed analysis of the actual pressure records must be made before any firmer conclusion can be drawn. A more detailed analysis of the pressure within the arrester housing would perhaps also be of more practical value. Nevertheless, the results are encouraging and it would now be interesting to test with a different flame arrester design.

As to the detonation studies, the experiments have conclusively demonstrated the effectiveness of porous materials and air gaps in damping detonation waves. The resulting combustion waves have the velocity about half the CJ detonation values

The resulting fast deflagration again requires certain distance before a DDT occurs. This distance decreases with the increase of mixture reactivity. However, only for very reactive hydrogen-air mixtures was transition back to detonation observed in a smooth tube within 1 m of the attenuating section. When repeatable annular disks were used in the acceptor section then DDT events were also observed for less reactive ethylene-air mixtures. Only for propane-air mixtures was it not possible to re-initiate detonation in the present experimental configuration. This is probably due

to the small tube diameter, which is only slightly larger than the detonation cell size. At these conditions propane-air detonation has a highly unstable near-limit character.

The results also show that DDT processes can be reproduced in a highly repeatable way with the use of the damping and re-initiation techniques developed in this study. From a practical standpoint however, the projected size of the attenuating sections required for larger initial pipe diameters might be prohibitive.

The work is at present being extended to larger diameter pipes to investigate scaling effects. The flame acceleration studies will involve a direct scaling to a 150 mm diameter tube. Uncertainties in the ability to attenuate detonations across this larger pipe diameter by absorbing walls seem to indicate that an air gap, generated by slide valves provides the easiest way forward for the detonation studies.

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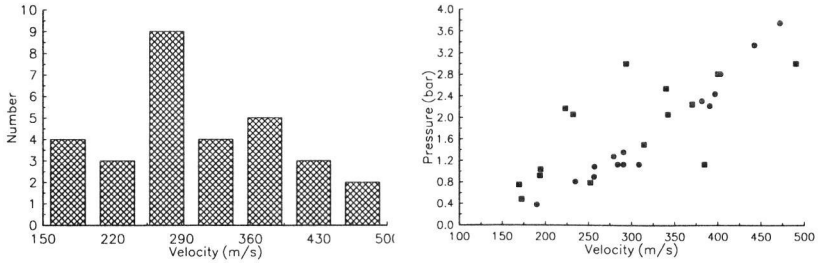
FIGURES



(a) (b)

Figure 1. Graphs showing variations in (a) measured velocities and (b) correlation between pressure and velocity, both obtained for essentially constant initial conditions.

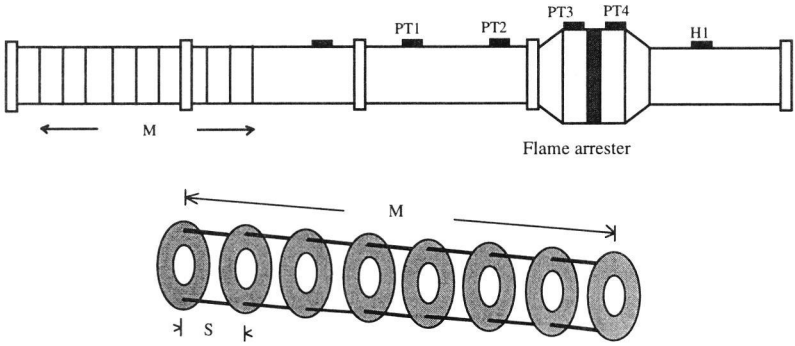


Figure 2. Schematic of basic flame acceleration test configuration

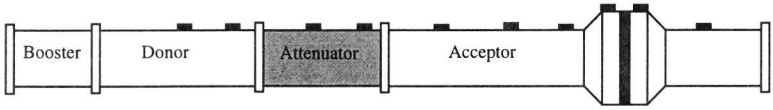
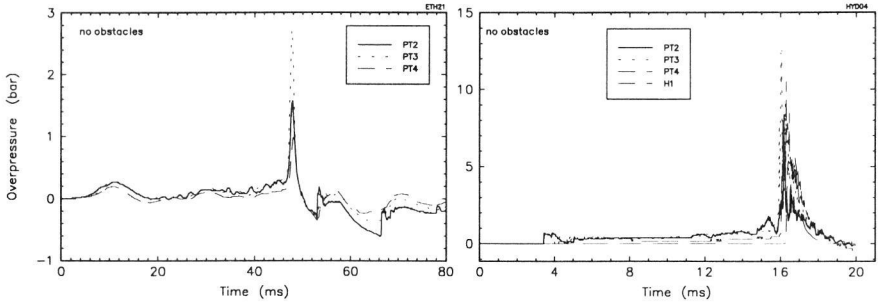


Figure 3. Schematic of overdriven detonation test configuration.



(a) (b)

Figure 4. Pressure time histories at various gauge locations showing the pressure evolution in a 50 mm tube without an accelerating section, (a) ethylene- and b) hydrogen-air.

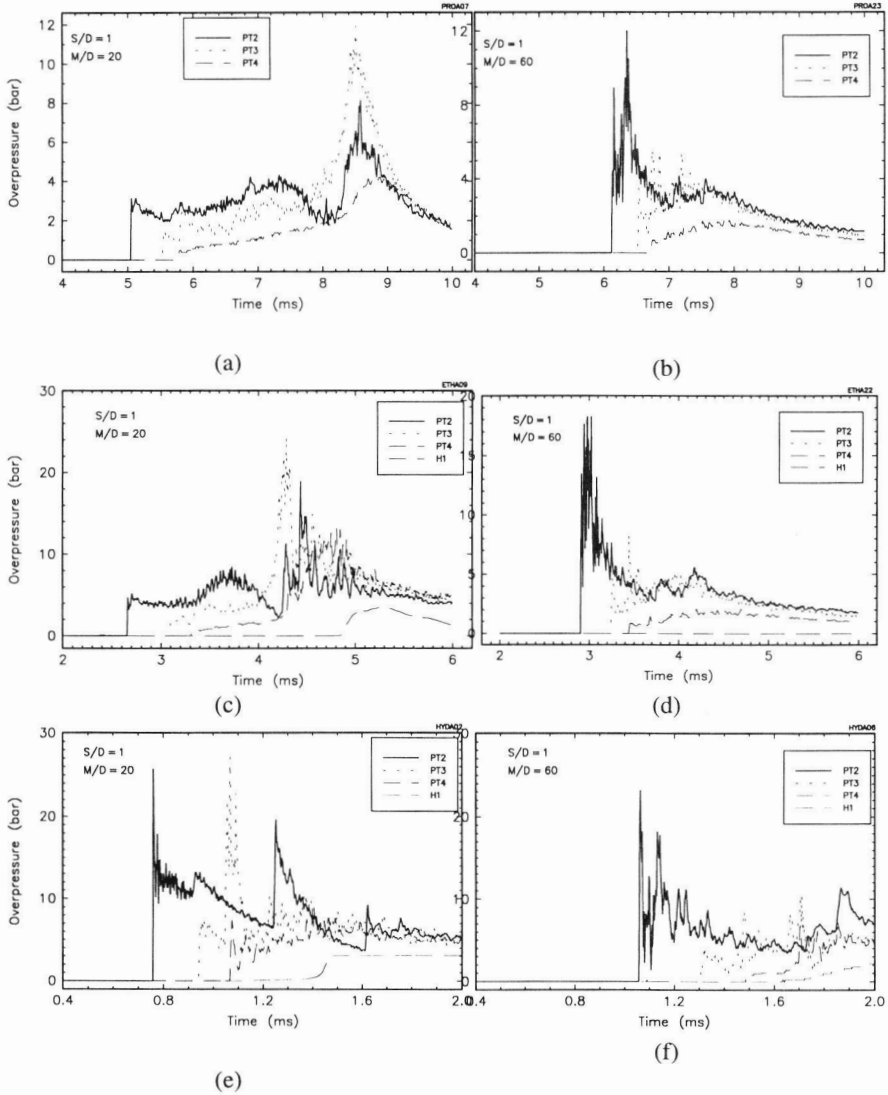


Figure 5. Pressure evolution and light emission downstream of the arrester (H1) for an obstacle spacing of 1 pipe diameter (S/D) and two lengths of accelerating section (M/D) for propane (a and b), ethylene (c and d) and hydrogen (e and f).

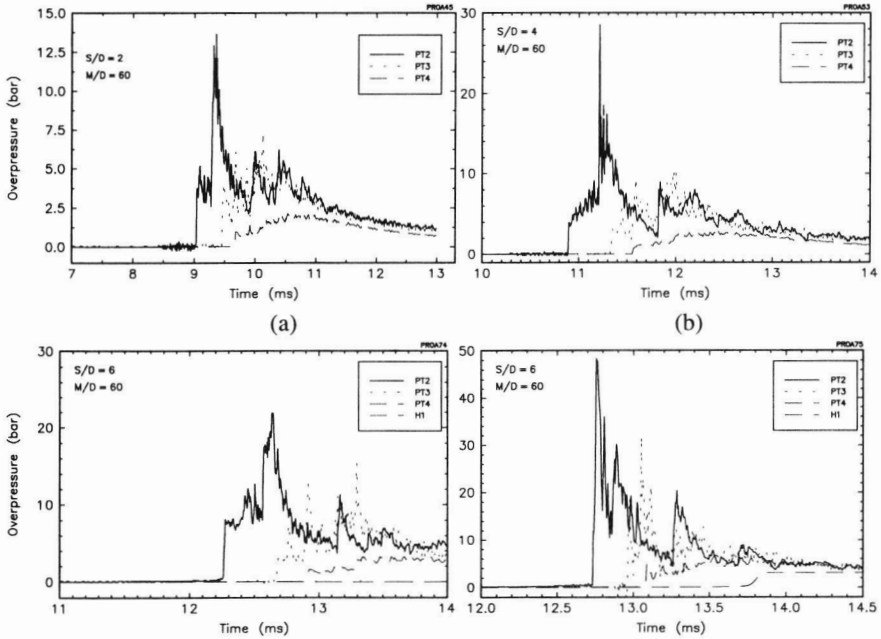


Figure 6. Pressure histories obtained with the maximum length of accelerating section (M/D=60) for a range of obstacle separations (S/D). The mixture is propane-air. (c) and (d) are repeat test showing incipient DDT and an actual transition to detonation.

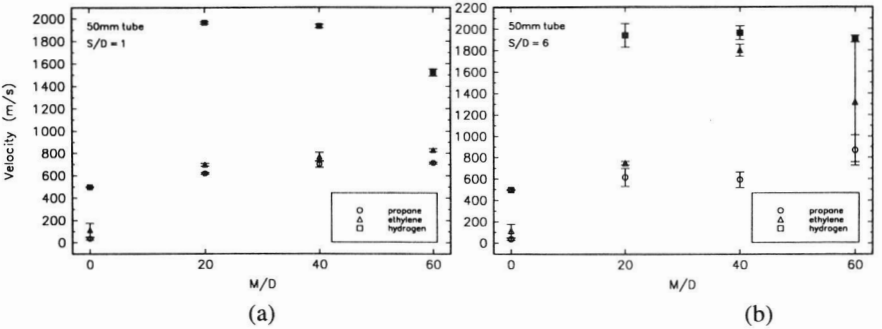
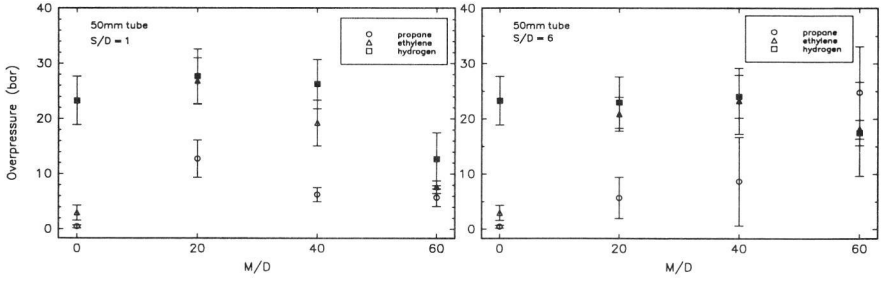


Figure 7. Measured shock-flame front velocity just prior to the arrester as a function of accelerating section length (M/D) for two obstacle spacings; Disks spaced (a) one diameter and (b) six diameters apart.



(a) (b)

Figure 8. Measured peak overpressure just prior to the arrester as a function of accelerating section length (M/D) for two obstacle spacings, (a) one and (b) six diameters apart.

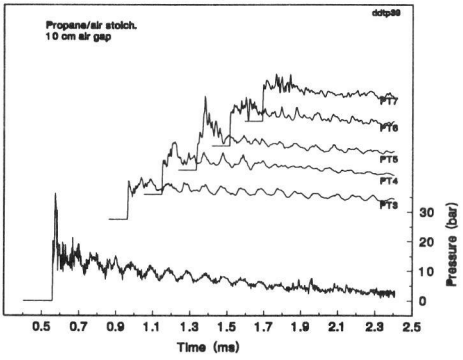


Figure 9. Pressure histories obtained for a propane-air detonation incident on a 10 cm air gap, showing the failure to re-initiate.

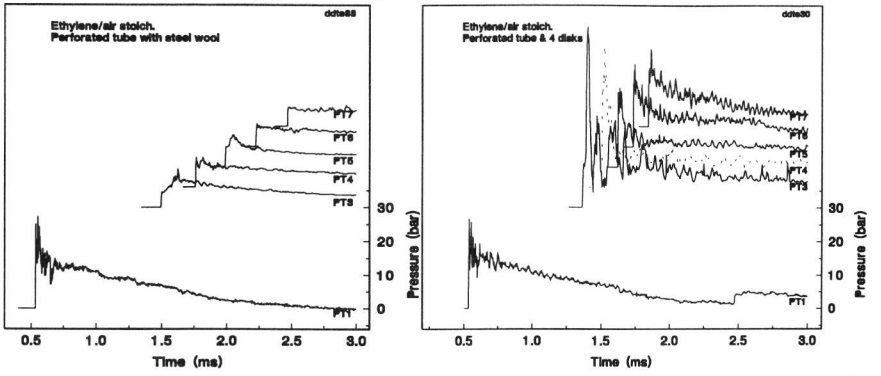
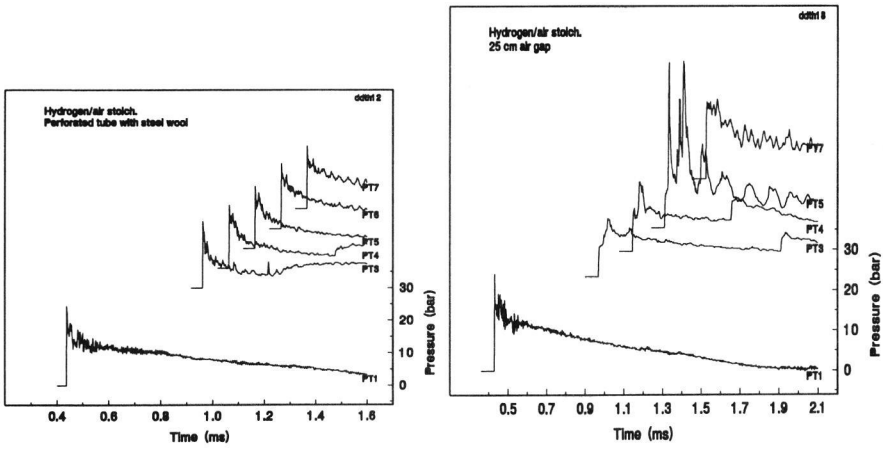


Figure 10. Pressure histories for an ethylene-air detonation showing failure (left) and transition to detonation (right) when a series of disks are introduced downstream of the attenuator.



(a) (b)

Figure 11. Pressure histories for a hydrogen-air detonation showing (a) transmission and (b) transition to detonation when the perforated mesh is replaced by a 25 cm long air gap.

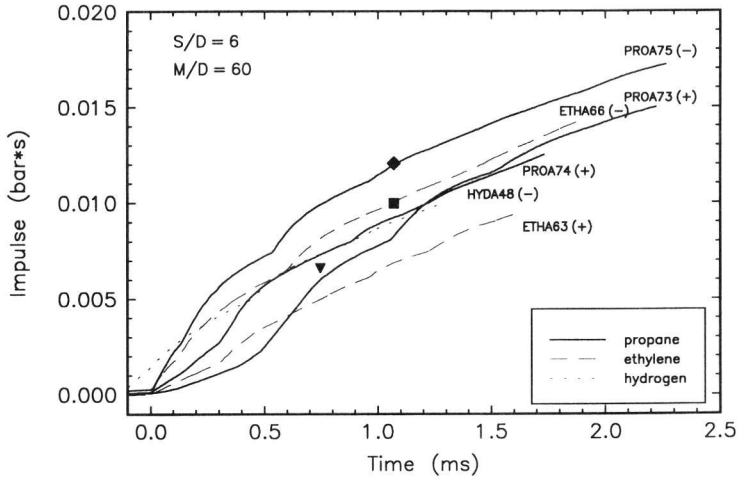


Figure 12. Plot showing impulse time histories for different mixtures for an accelerator section with an obstacle spacing S/D = 6 and overall length M/D = 60. Solid symbols indicate the time at which arrester failure is first observed.